Australian Government

BIOREGIONAL ASSESSMENTS

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

Systematic analysis of water-related hazards associated with coal resource development

Submethodology M11 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

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Executive summary

This submethodology describes how to apply a type of hazard analysis in bioregional assessments (BAs). The hazard analysis presented here is based on the Failure Modes and Effects Analysis (FMEA) methodology that has been successfully applied to complex industrial systems for many decades. In BAs, it is referred to as Impact Modes and Effects Analysis (IMEA) to recognise that many of the hazards associated with coal resource development do not arise through system failures.

IMEA is a systematic and rigorous technique for identifying and ranking hazards associated with whole-of-life-cycle CSG operations and coal mines. 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* (the logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water and water-dependent assets). An impact might be equivalent to an effect, or it might be a change resulting from those effects (for example, ecological changes that result from hydrological changes).

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

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

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

The hazard analysis reflects the conceptual models and beliefs that domain experts hold about the ways in which coal resource development might impact surface water and groundwater, and the relative importance of these potential impacts. As a result, the analysis enables these beliefs and conceptual models to be made transparent. It is important to emphasise, however, that even if a hazard is identified as possibly occurring, it does not mean that it will definitely happen.

A case study for the Gloucester subregion is presented as an illustration of how to apply this method to coal resource development. A large number of hazards are identified but some of these are beyond the scope of BA, such as accidents, or are adequately addressed by site-based risk management processes and regulation. While individual chains of events or hazards constitute causal pathways, many of these hazards group naturally by common cause and mode of impact and are represented by a smaller number of aggregated causal pathways for consideration in the BA.

In the Gloucester subregion, coal resource development includes CSG operations and open-cut mines. CSG operations have their immediate impact below ground, with aquifer depressurisation, enhanced inter-aquifer connectivity, and the storage and disposal of co-produced water the main impact modes. Open-cut mines most directly affect surface water flows and aquifers, with disruption of natural surface drainage, inter-aquifer connectivity, and the storage and disposal of water the main impact modes.

Results from hazard analyses (such as for Gloucester subregion) complete the understanding of the causal pathways and priority impacts associated with coal resource development, when the results are combined with:

- results from surface water modelling and groundwater modelling, which determine the predicted maximum spatial extent of hydrological changes
- the list of landscape classes that are subsequently impacted
- the list of assets within these landscapes classes.

The hazard analysis is reported in product 2.3 (conceptual modelling). In addition, the full output of the hazard analysis for each subregion or bioregion is registered as a dataset and cited in product 2.3 (conceptual modelling), to ensure transparency with respect to the underpinning results.

The hazard analysis is an important precursor to the impact and risk analysis. A full risk assessment is outside the scope of a BA; instead, a BA identifies and analyses risks, then others can use these for their own full risk assessment.

Contents

Figures

Tables

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This technical product was reviewed by several groups:

- Senior Science Leaders: David Post (Projects Director)
- Technical Assurance Reference Group: Chaired by Peter Baker (Principal Science Advisor, Department of the Environment and Energy), this group comprises officials from the NSW, Queensland, South Australian and Victorian governments
- Additional reviewers: Paul Wilkes.

Valuable comments were also provided by Emily Turner.

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.

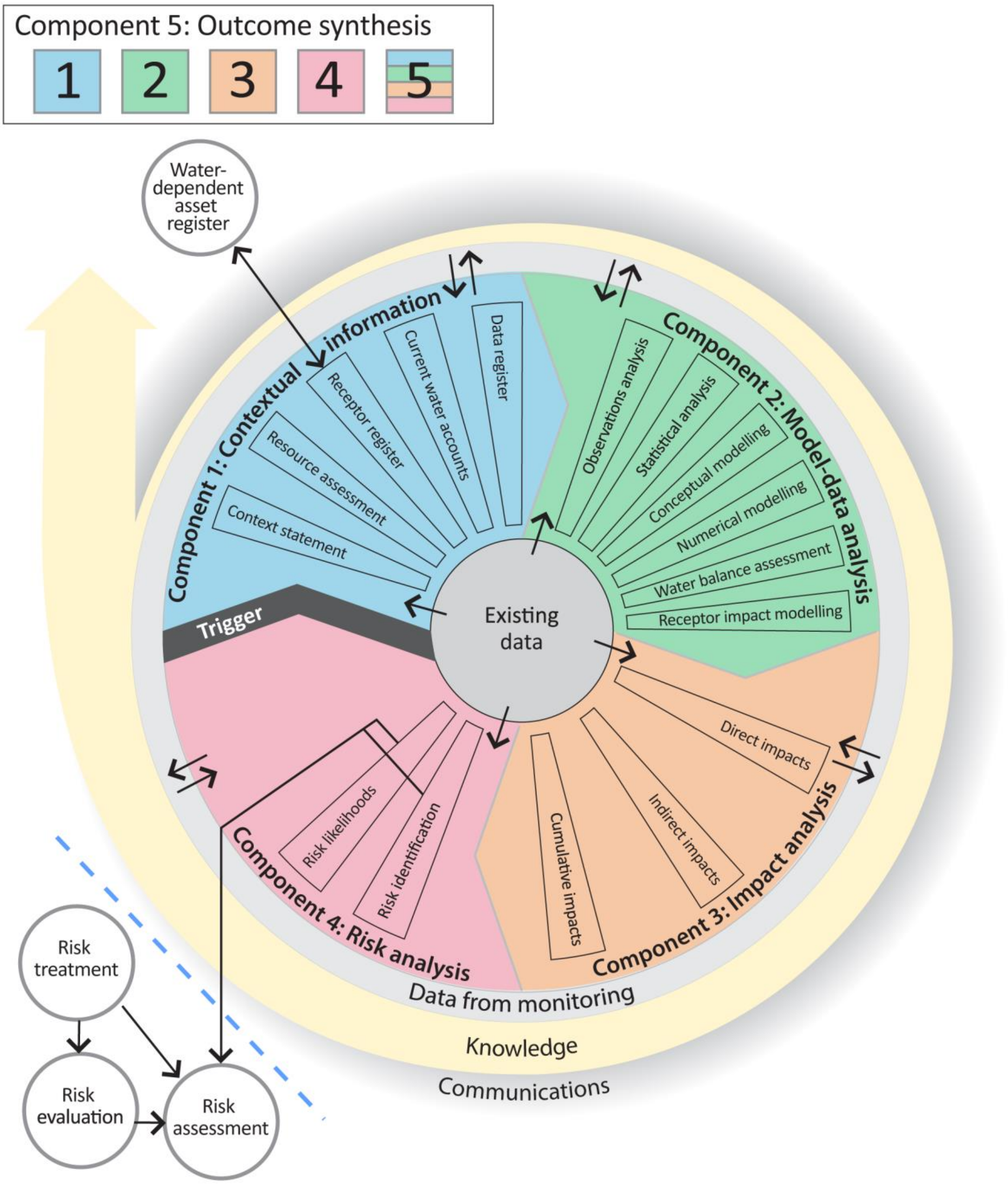

Figure 1 Schematic diagram of the bioregional assessment methodology

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.
- Visit http://bioregionalassessments.gov.au to access metadata (including copyright, attribution and licensing information) for datasets cited or used to make figures in this product.
- In addition, the datasets are published online if they are unencumbered (able to be published according to conditions in the licence or any applicable legislation). The Bureau of Meteorology archives a copy of all datasets used in the BAs. This archive includes datasets that are too large to be stored online and datasets that are encumbered. The community can request a copy of these archived data at http://www.bioregionalassessments.gov.au.

- The citation details of datasets are correct to the best of the knowledge of the Bioregional Assessment Programme at the publication date of this submethodology. Readers should use the hyperlinks provided to access the most up-to-date information about these data; where there are discrepancies, the information provided online should be considered correct. The dates used to identify Bioregional Assessment Source Datasets are the dataset's created date. Where a created date is not available, the publication date or last updated date is used.

Table 1 Methodologies

Each submethodology is available online at http://data.bioregionalassessments.gov.au/submethodology/XXX, where 'XXX' is replaced by the code in the first column. For example, the BA methodology is available at http://data.bioregionalassessments.gov.au/submethodology/bioregional-assessment-methodology and submethodology M02 is available at http://data.bioregionalassessments.gov.au/submethodology/M02. Submethodologies might be added in the future.

Code	Proposed title	Summary of content
bioregional-assessment-methodology	*Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources*	A high-level description of the scientific and intellectual basis for a consistent approach to all bioregional assessments
M02	*Compiling water-dependent assets*	Describes the approach for determining water-dependent assets
M03	*Assigning receptors to water-dependent assets*	Describes the approach for determining receptors associated with water-dependent assets
M04	*Developing a coal resource development pathway*	Specifies the information that needs to be collected and reported about known coal and coal seam gas resources as well as current and potential resource developments
M05	*Developing the conceptual model of causal pathways*	Describes the development of the conceptual model of causal pathways, which summarises how the 'system' operates and articulates the potential links between coal resource development and changes to surface water or groundwater
M06	*Surface water modelling*	Describes the approach taken for surface water modelling
M07	*Groundwater modelling*	Describes the approach taken for groundwater modelling
M08	*Receptor impact modelling*	Describes how to develop receptor impact models for assessing potential impact to assets due to hydrological changes that might arise from coal resource development
M09	*Propagating uncertainty through models*	Describes the approach to sensitivity analysis and quantification of uncertainty in the modelled hydrological changes that might occur in response to coal resource development
M10	*Impacts and risks*	Describes the logical basis for analysing impact and risk
M11	*Systematic analysis of water-related hazards associated with coal resource development*	Describes the process to identify potential water-related hazards from coal resource development

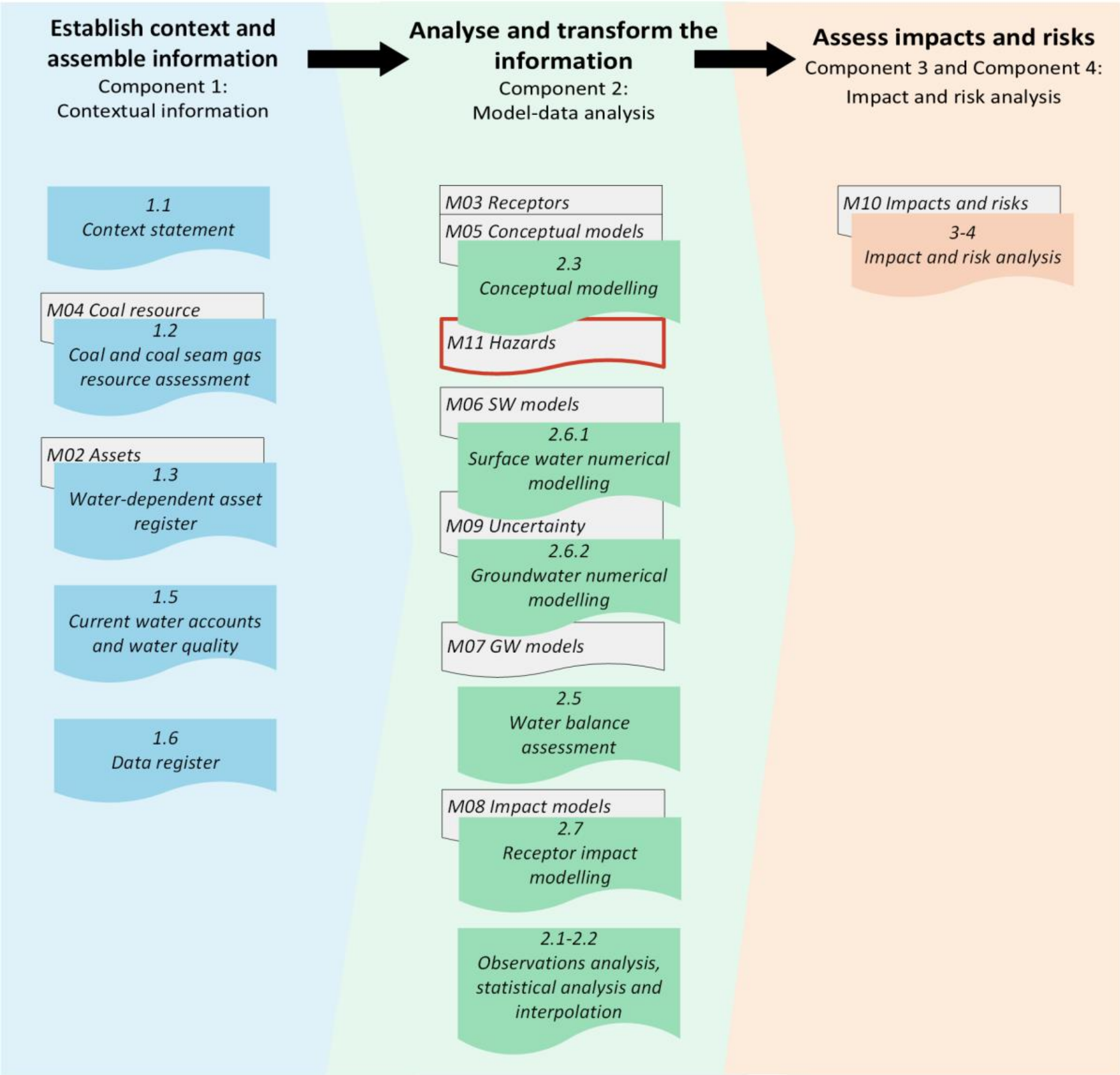

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

In each component (Figure 1) of a bioregional assessment (BA), a number of technical products (coloured boxes, see also Table 2) are potentially created, depending on the availability of data and models. The light grey boxes indicate submethodologies (Table 1) that specify the approach used for each technical product. The red outline indicates this submethodology. The BA methodology (Barrett et al., 2013) specifies the overall approach.

Technical products

The outputs of the BAs include a suite of technical products presenting information about the ecology, hydrology, hydrogeology and geology of a subregion or bioregion and the potential impacts of CSG and coal mining developments on water resources, both above and below ground. Importantly, these technical products are available to the public, providing the opportunity for all interested parties, including community, industry and government regulators, to draw from a single set of accessible information when considering CSG and large coal mining developments in a particular area.

The BA methodology specifies the information to be included in technical products. Figure 2 shows the relationship of the technical products to BA components and submethodologies. Table 2 lists the content provided in the technical products, with cross-references to the part of the BA methodology that specifies it.

Technical products are delivered as reports (PDFs). Additional material is also provided, as specified by the BA methodology:

- unencumbered data syntheses and databases
- unencumbered tools, model code, procedures, routines and algorithms
- unencumbered forcing, boundary condition, parameter and initial condition datasets
- lineage of datasets (the origin of datasets and how they are changed as the BA progresses)
- gaps in data and modelling capability.

In this context, unencumbered material is material that can be published according to conditions in the licences or any applicable legislation. All reasonable efforts were made to provide all material under a Creative Commons Attribution 3.0 Australia Licence.

Technical products, and the additional material, are available online at http://www.bioregionalassessments.gov.au.

The Bureau of Meteorology archives a copy of all datasets used in the BAs. This archive includes datasets that are too large to be stored online and datasets that are encumbered. The community can request a copy of these archived data at http://www.bioregionalassessments.gov.au.

Table 2 Technical products delivered by the Bioregional Assessment Programme

For each subregion or bioregion in a bioregional assessment (BA), technical products are delivered online at http://www.bioregionalassessments.gov.au. Other products – such as datasets, metadata, data visualisation and factsheets – are also provided online. There is no product 1.4; originally this product was going to describe the receptor register and application of landscape classes as per Section 3.5 of the BA methodology, but this information is now included in product 2.3 (conceptual modelling) and used in products 2.6.1 (surface water modelling) and 2.6.2 (groundwater modelling). There is no product 2.4; originally this product was going to include two- and three-dimensional representations as per Section 4.2 of the BA methodology, but these are instead included in products such as product 2.3 (conceptual modelling), product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling).

Component	Product code	Title	Section in the BA methodology[a]
Component 1: Contextual information for the subregion or bioregion	1.1	Context statement	2.5.1.1, 3.2
	1.2	Coal and coal seam gas resource assessment	2.5.1.2, 3.3
	1.3	Description of the water-dependent asset register	2.5.1.3, 3.4
	1.5	Current water accounts and water quality	2.5.1.5
	1.6	Data register	2.5.1.6
Component 2: Model-data analysis for the subregion or bioregion	2.1-2.2	Observations analysis, statistical analysis and interpolation	2.5.2.1, 2.5.2.2
	2.3	Conceptual modelling	2.5.2.3, 4.3
	2.5	Water balance assessment	2.5.2.4
	2.6.1	Surface water numerical modelling	4.4
	2.6.2	Groundwater numerical modelling	4.4
	2.7	Receptor impact modelling	2.5.2.6, 4.5
Component 3 and Component 4: Impact and risk analysis for the subregion or bioregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3
Component 5: Outcome synthesis for the bioregion	5	Outcome synthesis	2.5.5

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

References

Barrett DJ, Couch CA, Metcalfe DJ, Lytton L, Adhikary DP and Schmidt RK (2013) Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources. A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment. Department of the Environment, Australia. Viewed 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 systematically analysing water-related hazards associated with coal resource development. This submethodology applies overarching principles outlined in the BA methodology to the specifics of undertaking such a hazard analysis, which is reported in product 2.3 (conceptual modelling).

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.

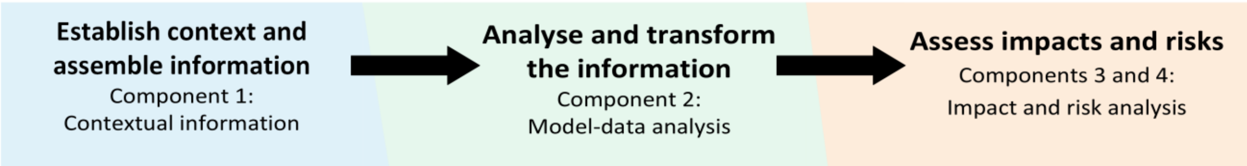

Figure 3 The components in a bioregional assessment

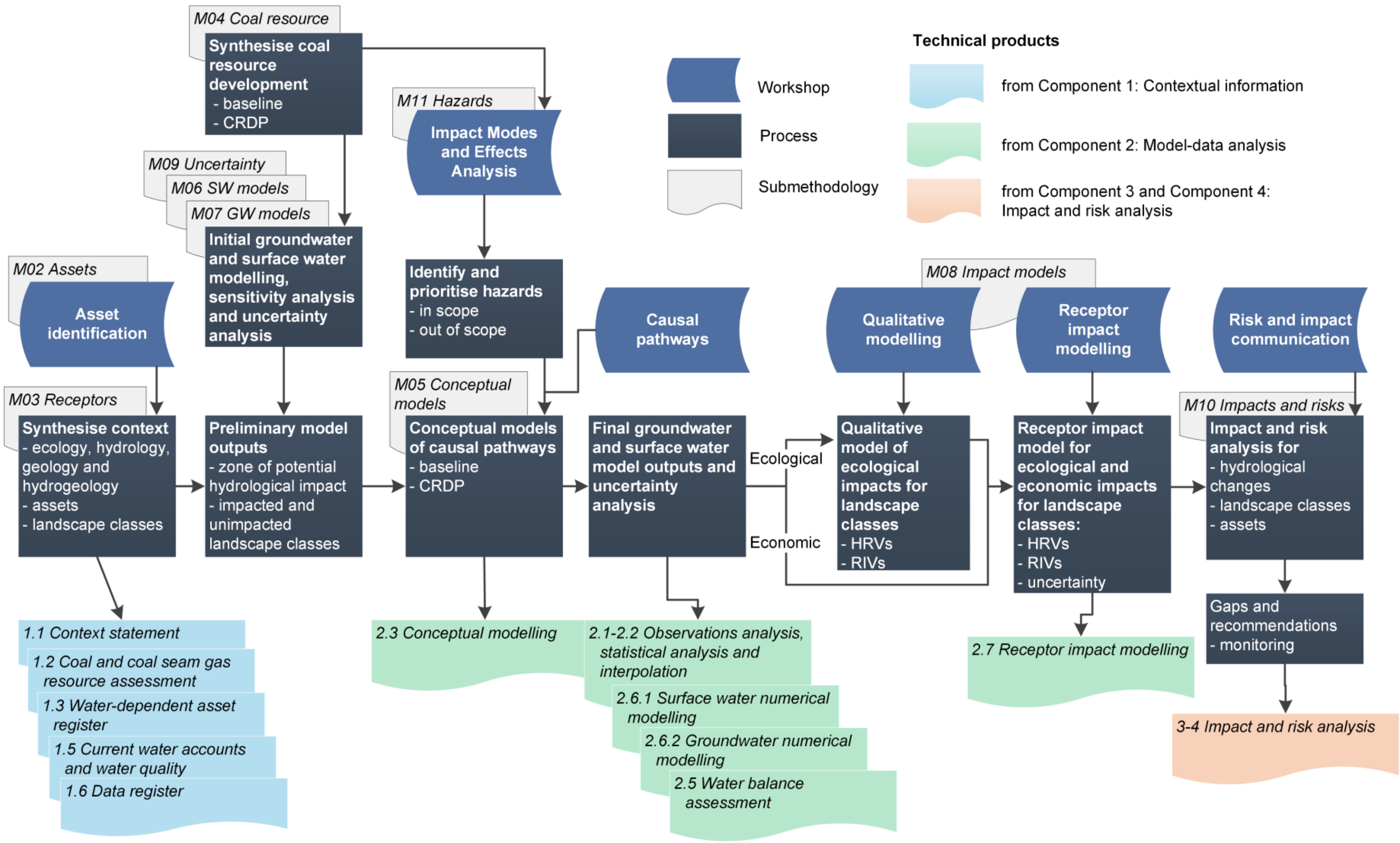

Figure 4 A bioregional assessment from end to end, showing the relationship between the workflow, technical products, submethodologies and workshops

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 existing information about its ecology, hydrology, geology and hydrogeology, as well as water-dependent assets, coal resources and coal resource development.

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

A *bioregion* is a geographic land area within which coal seam gas (CSG) and/or coal mining developments are taking place, or could take place, and for which BAs are conducted. A *subregion* is an identified area wholly contained within a bioregion that enables convenient presentation of outputs of a BA.

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

The *water-dependent asset register* is a simple and authoritative listing of the assets within the *preliminary assessment extent* (PAE) that are potentially subject to water-related impacts. A PAE is the geographic area associated with a subregion or bioregion in which the potential water-related impact of coal resource development on assets is assessed. The compiling of the asset register is the first step to identifying and analysing potentially impacted assets.

Given the potential for very large numbers of assets within a subregion or bioregion, and the many possible ways that they could interact with the potential impacts, a *landscape classification* approach is used to group together areas to reduce complexity. For BA purposes, a *landscape class* is an ecosystem with characteristics that are expected to respond similarly to changes in groundwater and/or surface water due to coal resource development. Note that there is expected to be less heterogeneity in the response within a landscape class than between landscape classes. They are present on the landscape across the entire BA subregion or bioregion and their spatial coverage is exhaustive and non-overlapping. The rule set for defining the landscape classes is underpinned by an understanding of the ecology, hydrology (both surface water and groundwater), geology and hydrogeology of the subregion or bioregion.

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

Two potential futures are considered in BAs:

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

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

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

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 landscape class or water-dependent assets 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.

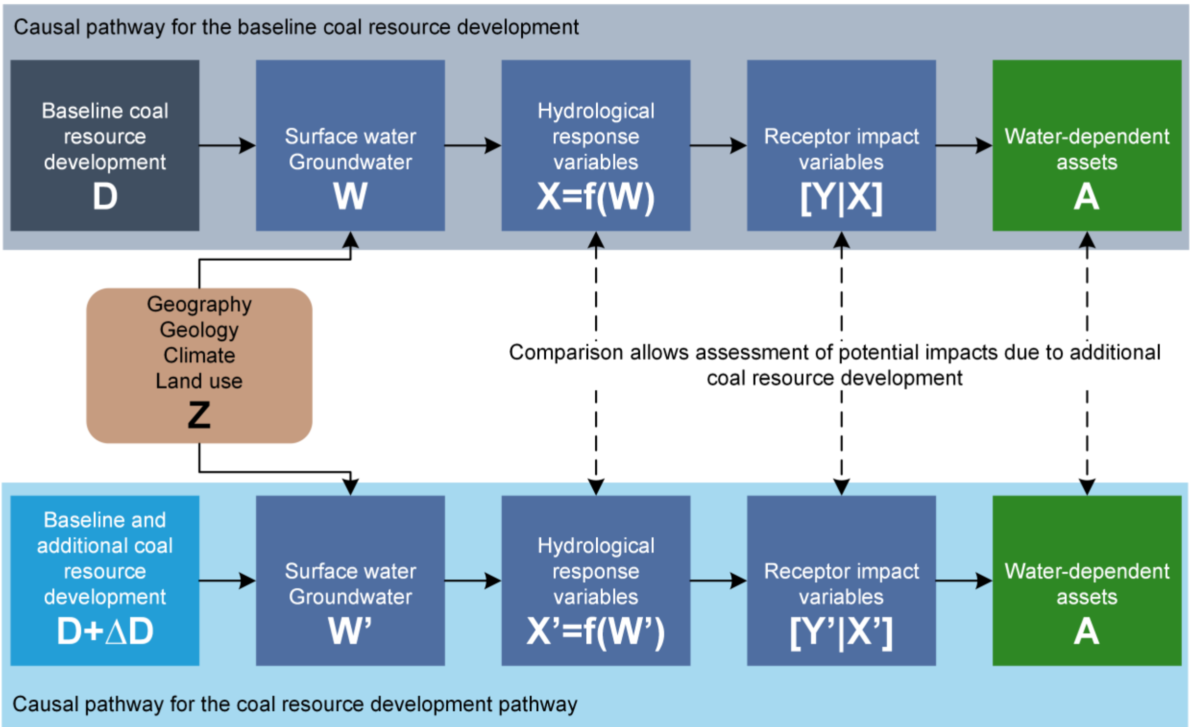

Figure 5 The difference in results for the coal resource development pathway (CRDP) and the baseline coal resource development (baseline) provides the potential impacts due to the additional coal resource development (ACRD)

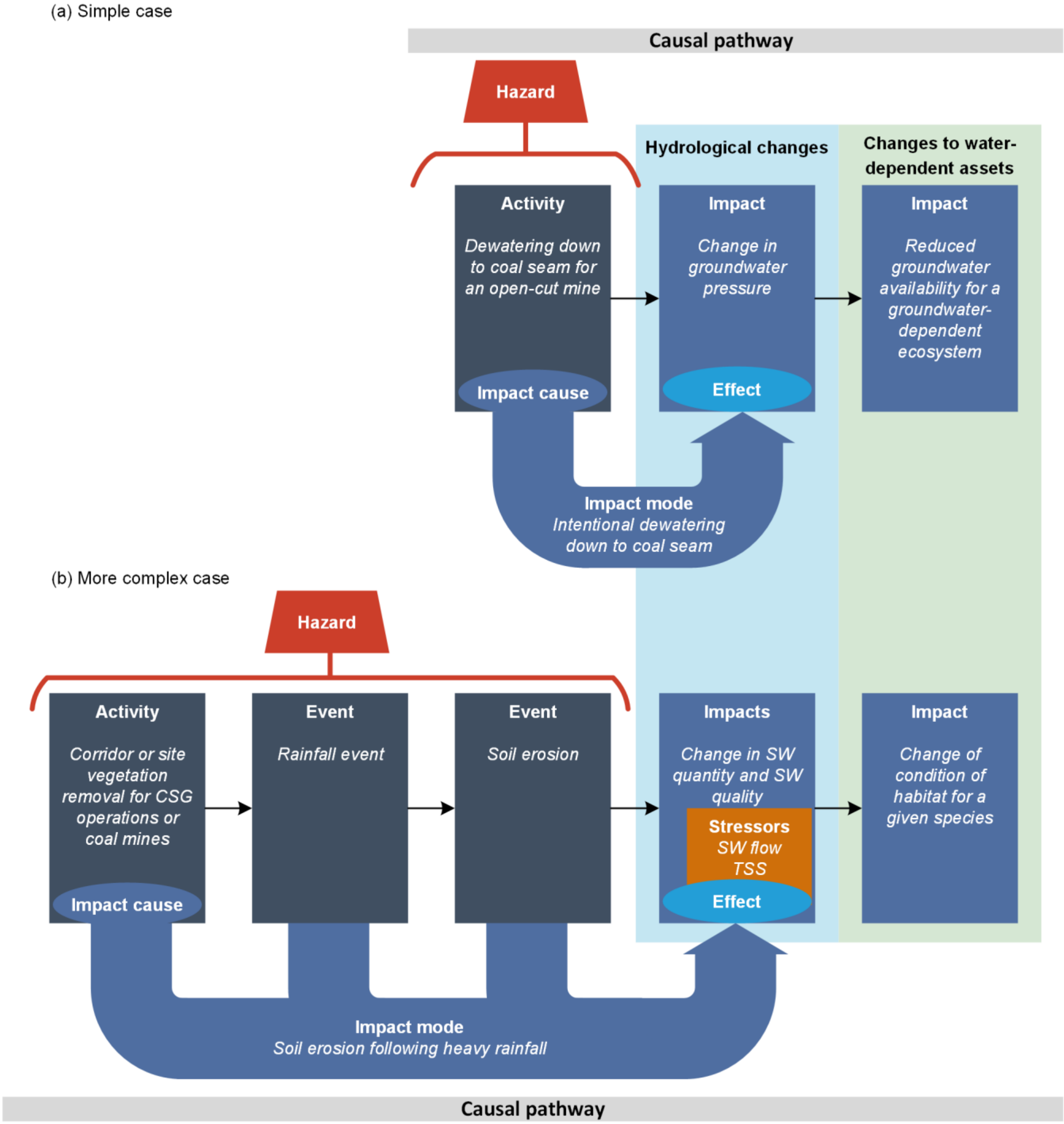

Figure 6 Hazard analysis using the Impact Modes and Effects Analysis

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(s) (for example, surface water (SW) flow and total suspended solids (TSS)), causes a hydrological change which in turn causes an ecological change. The hazard is the initial activity plus the subsequent chain of events that lead to the effect.

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

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

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

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

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

1.1.2 Component 2: Model-data analysis

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

The analysis and transformation in Component 2 depends on a succinct and clear synthesis of the knowledge and information about each subregion or bioregion; this is achieved and documented through conceptual models (abstractions or simplifications of reality). A number of conceptual models are developed for each BA, including regional-scale conceptual models that synthesise the geology, groundwater and surface water. Conceptual models of causal pathways are developed to characterise the *causal pathways*, the logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water resources and water-dependent assets. The conceptual models of causal pathways bring together a number of other conceptual models developed in a BA, for both the baseline and the CRDP. The landscape classes and the hazard analysis are also important inputs to the process. Emphasising gaps and uncertainties is as important as summarising what is known about how various systems work.

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

Surface water models and *groundwater models* are developed and implemented in order to represent and quantify the hydrological systems and their likely changes in response to coal resource development (both baseline and CRDP). Surface water models are drawn from the Australian Water Resources Assessment (AWRA) modelling suite, which includes the landscape model AWRA-L for streamflow prediction and river systems model AWRA-R for river routing and management. The latter is only used in a subset of subregions or bioregions and depends on the nature of the river regulation and the availability of existing streamflow data. The groundwater modelling is regional, and the choice of model type and coding is specific to a subregion or bioregion depending on data availability and the characteristics of the coal resource development in the area.

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

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

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

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

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

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

1.1.3 Component 3 and Component 4: Impact and risk analysis

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

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

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

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

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

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

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

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

1.2 Role of this submethodology in a bioregional assessment

Virtually all risk assessment frameworks have a separate hazard identification and analysis stage that starts once the stakeholders and assessment and measurement endpoints have been identified, and the temporal and spatial scope of the assessment has been determined. While this is sometimes represented as part of the 'risk identification' in risk frameworks such as International Organization for Standardization (2009), the hazard identification and analysis stage typically serves several roles:

- It is the point in the risk assessment that asks the question 'what can go wrong?' (i.e. it identifies hazards associated with the activity in question).
- It may rank hazards according to the extent to which they meet certain criteria. These criteria may be risk related – such as the likelihood of the hazard occurring and its consequences – but they may be much broader and reflect a wider range of issues such as the likelihood that the hazard will be detected if it occurs, or the extent to which the hazard is managed by current legislative controls.
- It is the point in the risk assessment where potential risks that will be addressed by the assessment (i.e. 'in scope') are separated from those that will not be addressed (i.e. 'out of scope') for whatever reason. The rationale for excluding certain hazards is typically unique to each risk assessment, and may sometimes be reflected in a set of screening criteria that is applied to each hazard to determine whether or not it is 'in scope'.

The hazard identification and analysis stage is arguably the most important step of any risk assessment. Hazards that are not identified in the early stages of a risk assessment will not be carried through the assessment, and this can ultimately lead to surprises and underestimation of risk.

Hazard identification techniques also play two other important roles in a risk assessment. First, they are an effective and appropriate way to involve stakeholders and other interested parties in the risk assessment – indeed the views and opinions of these groups can provide a deeper and richer appreciation of the problem in hand (Stern and Fineberg, 1996). Second, they can help in the design of statistically valid monitoring strategies by highlighting where and when to look for potential adverse events – it is much easier to monitor a situation when you know what to look out for.

The *Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources* (BA methodology; Barrett et al., 2013) refers to hazard identification as the 'risk identification' stage of an assessment, terminology that is consistent with an international standard (International Organization for Standardization, 2009), and notes that 'Identification of risks within a bioregion begins with understanding the exposure of receptors to impacts from CSG and open-cut mining development and how this exposure may affect values of water-dependent assets'.

The BA methodology does not, however, identify nor recommend a specific process for identifying hazards when conducting a BA. Methods for identifying and ranking hazards vary according to application and novelty of the risk-generating activity. Simple checklists, for example, are sometimes used to list hazards and ensure risk mitigation strategies have been applied to activities that have a long history of successful operation (i.e. to activities where the long operation history provides assurance that the risks are well understood, or have been successfully managed in the past).

Hazard identification for novel technologies, with which there is little (if any) history of operation, is more demanding. Without the hindsight that a long operating experience provides, the analyst must try to identify – in a careful and systematic manner – all the possible ways things may go wrong. In complex systems this is difficult so scientists and engineers have developed techniques to assist the analyst in this task. Examples of these techniques include Fault Tree analysis (Vesely et al., 1981), Hazard and Operability studies (Kletz, 1999), Hierarchical Holographic Modelling (Haimes, 1981), and Failure Modes and Effects Analysis (Ozog and Bendixen, 1987).

This submethodology demonstrates the application of a technique, based on Failure Modes and Effects Analysis (described in Section 2.1), to identify the hazards associated with coal resource development. The analysis only focuses on water-related hazards (i.e. hazards that might lead directly or indirectly to impacts on groundwater or surface water). All other hazards (e.g. effects on air quality) are explicitly excluded from this analysis.

The hazard analysis described in this submethodology reflects the conceptual models and beliefs that domain experts hold about the ways in which CSG and large coal mining development may 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 transparent. When combined with the: (i) results of initial surface water modelling (Viney, 2016) and groundwater modelling (Crosbie et al., 2016) which determine the maximum (spatial) extent of groundwater drawdown and modification of the hydrograph; (ii) identification of landscape classes that are subsequently impacted (O'Grady et al., 2016) and (iii) identification of assets within these landscapes classes (O'Grady et al., 2016), the hazard analysis completes the understanding of the causal pathways and priority impacts associated with CSG and large coal mining development (Figure 4).

The hazard analysis relies on input from:

- the context statement (product 1.1)
- the coal and coal-seam gas resource assessment (product 1.2)
- the water-dependent asset register (product 1.3)
- surface water numerical modelling (product 2.6.1) and groundwater numerical modelling (product 2.6.2).

Readers should consider this submethodology in the context of the complete suite of methodologies and submethodologies from the Bioregional Assessment Programme (see Table 1), particularly the BA methodology (M01 as listed in Table 1; Barrett et al., 2013), which remains the foundation reference that describes, at a high level, how bioregional assessments should be undertaken. Submethodology M11 is most strongly linked to the following submethodologies (as listed in Table 1):

- submethodology M04 for developing a coal resource development pathway (Lewis, 2014)
- submethodology M05 for developing a conceptual model of causal pathways (Henderson et al., 2016)

- submethodology M08 for receptor impact modelling (as shown in Table 1)
- submethodology M10 for identifying and analysing risk (as shown in Table 1).

The application of M11 to a BA in a subregion or bioregion will deliver hazard analysis suitable for use in the conceptual model of causal pathways described in the companion submethodology M05 (Henderson et al., 2016) and also for impact and risk analysis as described in the companion submethodologies M08 (as shown in Table 1) and M10 (as shown in Table 1).

2 Methods

2.1 Failure Modes and Effects Analysis

Failure Modes and Effects Analysis (FMEA) is a structured process for identifying hazards in complex systems that are typically composed of many components. It was originally developed by the US military in 1949 to determine the effect of equipment and system failures, and was subsequently developed in the mid-1960s to improve safety in the aerospace industry (Ericson, 2005; McDermott et al., 1996). It has since been widely adopted for other industries that operate complex plants, such as the petrochemical industry and the automotive industry, and has also been applied to mining operations in relation to mine equipment safety (Daling and Geffen, 1983; Dhillon, 2009), and the construction and operation of a tailings dams (Correia dos Santos et al., 2012).

FMEA is a 'bottom-up' hazard analysis tool. It begins with a thorough description of the overall system, its subsystems and individual components. It then identifies all the possible ways in which each component can fail (the 'failure modes') and assesses the severity of the effects of these failures on other components and the overall functioning of the system (Ozog and Bendixen, 1987). It then considers the likelihood of the failure modes and likelihood of their detection given current controls.

In industrial systems, the process is usually formalised in six steps:

1. Identify and list all components.
2. Identify all failure modes, considering all possible operating modes.
3. List the potential effects of each failure mode and score their severity.
4. List the potential causes of each failure mode and score their likelihood.
5. List the current controls to prevent the failure mode and score the likelihood of detection.
6. Calculate the hazard priority number.

The severity, likelihood and detection ratings are usually scored from 1 (lowest rating) to 10 (highest rating). The *hazard priority number* is the product of the three scores and is the traditional measure used to rank hazards.

A small team of people usually conducts an FMEA, with a coordinating team leader. Each member of the team must be familiar with one or more aspects of the system in question. For example, an industrial FMEA team might consist of a team leader, design engineers, process engineers, plant operatives and their supervisors.

The main advantages of FMEA are that it is systematic, thorough and transparent, and does not require specialised training (but it does require a detailed knowledge of the system under examination). The main disadvantages of FMEA are that it can be time consuming to complete, and does not normally consider the effects of multiple failure modes occurring simultaneously within the system. Nonetheless, it has proven to be an effective hazard analysis tool when implemented correctly (Ostrom and Wilhelmsen, 2012).

2.2 Impact Modes and Effects Analysis

In a traditional FMEA, the failure of an industrial system's components is defined as a deviation from the function for which it has been designed, or a deviation from its intended operation. In the application of FMEA to BAs, however, the focus is not only on deviations from intended design but also in water-related hazards associated with the intended CSG and coal mining development. In this context hazards can arise as part of the normal operation of the coal mine or CSG operation. The use of the term 'failure' is therefore inappropriate and potentially misleading for BAs, so the analysis has been renamed Impact Modes and Effects Analysis (IMEA) to reflect the reporting of impacts, rather than failures. In this IMEA the 'components' of the system under study are the whole-of-life-cycle-stage *activities*, which are planned events associated with a CSG operation or coal mine. Therefore, references to 'component failures modes' (in FMEA) are replaced with 'activity impact modes', where 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.

The IMEA reported in this submethodology was specifically designed to meet the risk identification requirements of the BA methodology. The IMEA begins by identifying all activities and processes that occur throughout the life-cycle stages of CSG operations and coal mines. The analysis then considers how each of these activities and processes may potentially impact on water-dependent assets. Each of the impact modes are then scored for severity, likelihood and time to detection (see Figure 7) under a set of control measures that might reasonably be assumed to be in place as part of standard Australian industry operating procedures.

The analysis occurs via workshops; for example, for the Gloucester subregion, the IMEA was completed over three face-to-face workshops. The first workshop focused on identifying all activities associated with the life-cycle stages (from exploration and appraisal through to decommissioning) of CSG operations and coal mines. The remaining two workshops focused on identifying the ways in which this coal resource development potentially impacts on water-dependent assets.

This process was completed in a systematic activity-by-activity fashion, during which each impact mode was scored in terms of:

- severity of effect, where *severity* is defined as the magnitude of the impact resulting from a hazard
- likelihood of effect, where *likelihood* is defined as the probability of a hazard occurring
- time to *detection* (discovery of a hazard) given *current controls* (the methods or actions currently planned, or in place, to detect hazards when they occur or to reduce the likelihood and/or consequences of these hazards should they occur).

IMEA is an expert-driven approach to hazard identification, mitigation and prioritisation. Its value relies on having the appropriate knowledge and expertise available when identifying and scoring impact modes. For this reason, and due to the focus on groundwater and surface water effects, the workshop for the Gloucester subregion included participants with expertise in geology, hydrology, and mine operation and performance. Workshops for other bioregions typically also require expertise in these areas.

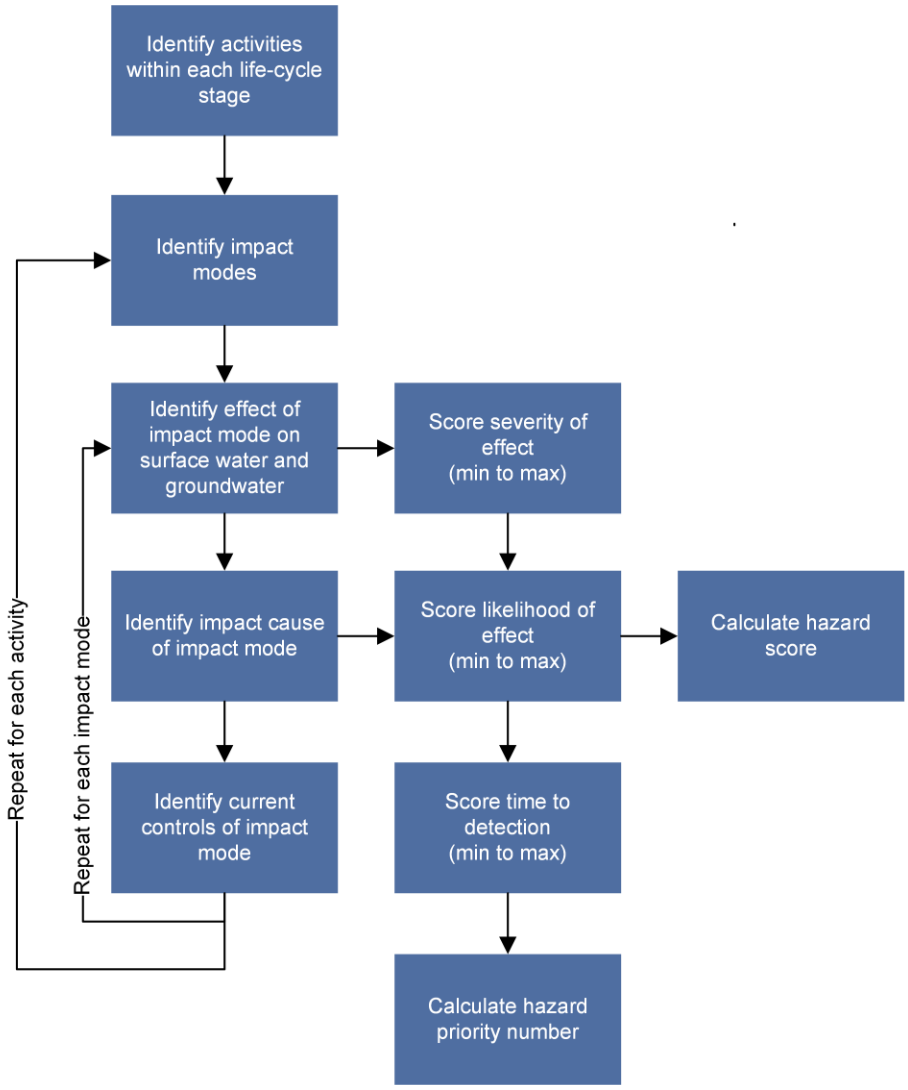

Figure 7 Flow chart showing the steps in an Impact Modes and Effects Analysis (IMEA)

IMEA is a structured hazard analysis methodology that identifies all the activities of a system and the ways in which these activities might have an impact on groundwater and surface water. It then identifies the effects and causes of each impact, and scores the severity and the likelihood of this effect on an interval (min to max). Finally, it identifies current controls that are in place and scores the likelihood of detecting an impact under these controls. This process is repeated for all of an activity's impact modes and for all the activities of the system under study. At each iteration the sum of the three scores (on a logarithmic scale) is used to rank hazards via the hazard priority number (or two scores in the case of hazard score).

It is important to emphasise that the focus of the IMEA is on hazard identification and relative ranking, not absolute risk estimation. *The likelihood and severity scores elicited should not be used as an absolute measure of risk.* Expert judgments about the likelihood of uncertain events are known to be prone to a number of biases and errors that occur because humans tend to rely on simple rules of thumb ('heuristics') to solve complex problems quickly (Kahneman and Tversky, 1982; Tversky and Kahneman, 1974; Kynn, 2008).

Good risk elicitation exercises employ a series of techniques that are designed to try and avoid the biases and systematic errors that these heuristics induce. These techniques were deliberately not employed when the IMEA scores were elicited because they are time consuming, and the objective of the IMEA scores is to provide a relative measure of each hazard's importance (i.e. a hazard score where the rank is important, not its absolute value).

2.3 Impact Modes and Effects Analysis structure

2.3.1 Components, life-cycle stages and activities

IMEA attempts to identify all the ways in which all the parts of a complex system may potentially impact on water-dependent assets. Here the 'parts' of the system are the activities associated with the major components of a CSG operation or coal mine:

- For CSG operations, the activities were subdivided into those associated with (i) wells, (ii) processing facilities, (iii) pipelines, and (iv) roads and infrastructure.
- For open-cut coal mines, the activities were subdivided into those associated with (i) open pit, (ii) surface facilities, and (iii) infrastructure.
- For underground coal mines, the activities were subdivided into those associated with (i) underground mine layout, (ii) surface facilities, and (iii) infrastructure.

Prior to identifying these activities, each subsystem was further expanded into *life-cycle stages,* phases in the sequence of activities in a coal mine or CSG operation:

- For CSG operations, these comprised: (i) exploration and appraisal, (ii) construction, (iii) production, (iv) decommissioning, and (v) work-over.
- For open-cut coal mines, these comprised: (i) exploration and appraisal, (ii) development, (iii) production, (iv) closure, and (v) rehabilitation.
- For underground coal mines, these comprised: (i) exploration and appraisal, (ii) development, (iii) production, and (iv) rehabilitation.

It is important to allocate activities to their appropriate life-cycle stage because the scale and duration of similar activities can be quite different across the different life-cycle stages, and this is often reflected in the scores for severity and/or likelihood of the impact modes associated with these activities.

2.3.2 Impact causes, impact modes, effects and stressors

The IMEA identifies all the possible ways in which the activities (as described in Section 2.3.1) may have an impact on groundwater or surface water. The resulting list of hazards occur as a result of various mechanisms (i.e. they have numerous impact causes), and lead to various types of changes in groundwater and surface water (i.e. they have numerous impact modes). These changes in groundwater or surface water are described in terms of effects (i.e. change in the quantity and/or quality of surface water or groundwater). These effects may also be associated with stressors (chemical or biological agent, environmental condition or external stimulus that might contribute to an impact mode). In the case of water quantity, however, the stressor may simply be the change described by the effect (e.g. change in surface water flow). Examples of impact causes, effects and stressors for water quality and quantity are:

- Anthropogenic activities that are deliberate and expected to occur with CSG operations or open-cut coal mines, such as clearing the vegetation along a pipeline corridor (the impact cause), may lead to erosion following heavy rains that increases the concentration of total suspended solids (TSS, the stressor) in surface waters leading to a decrease in water quality (the effect).
- Accidental events due to human error, failures in infrastructure or poor implementation of the operating procedures associated with an activity, such as pipeline containment loss due to accidental rupture or spillage of petrol around refuelling facilities (the impact causes), may lead to organic pollutants (the stressors) reducing the quality of groundwater or surface water (the effects).
- Abnormal natural events, such as heavy rainfall or floods, may compound the impacts of deliberate events or lead to accidental events such as the collapse of a containment pond wall (the impact cause) that leads to a temporary increase in the quantity of surface water flow (the stressor and effect) which may or may not be polluted with anthropogenic contaminants (additional stressors).

The participants in the IMEA workshops are invited to step through a pre-defined list of activities associated with the components of each life-cycle stage and postulate plausible impact modes on an activity-by-activity basis, along with the potential effects of these impact modes on groundwater and/or surface water assets, and any additional stressors.

2.3.3 Scoring severity, likelihood and detection

Traditionally FMEA elicits from experts a single score for the severity, likelihood and probability of, or equivalently time to, detection given current controls. The potential effects (hazards) are then ranked (highest to lowest) according to the product of these scores, known as the *hazard priority number* (Equation 2).

In our experience, however, the elicitation of scores proceeds far more efficiently if experts are allowed to provide an interval for each score, where the range between the lower and upper bound of this interval represents their uncertainty (Burgman, 2005; Garthwaite et al., 2005). Allowing for a range via the interval also provides a quick and efficient way to envelop and thereby reconcile the opinions of multiple experts in a single elicitation. This avoids forcing the experts to agree on a single most appropriate value, which sometimes they are reluctant to do.

The traditional approach to FMEA scoring is also amended in IMEA by adopting the logarithmic scale recommended by Lin et al. (2013). In this approach scores are provided on a base-ten logarithmic scale. This has two notable advantages over other traditional scoring methods. First, the magnitude of change is a constant multiple (× 10) from one score to the next, thereby assisting with the elicitation and interpretation of the scores. Second, the logarithmic scale creates the opportunity to compare the experts’ scores for the likelihood and detection of events with actual known outcomes, and thereby provide a means to calibrate their scores against actual outcomes.

2.3.3.1 Severity

The IMEA *severity score* is used to measure the severity of the potential environmental effects of a hazardous activity. Table 3 shows the definitions and corresponding score adapted from Lin et al.

(2013) and Adani Mining Pty Ltd (2013). The IMEA elicits an interval (upper and lower score) for each hazard that all participants were able to agree upon. Here a one-unit increase, for example from ‘tiny’ to ‘minimal’, corresponds (roughly) to a ten-fold increase in environmental impact. While the definitions and scores presented in Table 3 relate to the severity of the environmental impact, other types of impact (e.g. economic) may be calibrated to these severity categories as per Jarrett and Westcott (2010).

It is theoretically possible to calibrate the severity scores against actual environmental outcomes. In practice, however, this would be a much more difficult task due to the ambiguity associated with terms used to define the severity scores, despite the guidance provided by the definitions in Table 3. The magnitude of direct impacts associated with CSG and mining operations are quantified in a much more formal, carefully structured elicitation procedure at a later stage in the BA. Again, *the role of the impact scores at this stage is to develop an overall hazard ranking, not an absolute measure of risk.*

2.3.3.2 Likelihood

The likelihood of a hazard occurring is scored in a similar fashion, so that a one-unit change in score indicates a ten-fold increase or decrease in the probability of occurrence (Table 4). The scores indicate a rate per year, so that:

$$\text{Annual occurrence rate} = 10^{\text{Likelihood score}} \quad (1)$$

Hence a likelihood score of –2 (rare) equates to a predicted annual occurrence probability (or annual frequency) of 10^{-2}, which equals 1/100 or 0.01. Note that the likelihood of a hazard occurring can be readily defined in a much more precise manner than its associated impact. It is therefore easier to compare the likelihood scores with actual outcomes and thereby calibrate the experts’ opinions if data on the hazard (e.g. the incidence of failure of well integrity) are available.

2.3.3.3 Detection

The probability of detection, or time to detection, is very different from the probability of occurrence. It was scored in the same fashion as the likelihood score but on a scale specifically developed for the IMEA (Table 5). Again these definitions are readily defined in a precise manner; hence these scores can also be calibrated against real-world outcomes given appropriate datasets.

Table 3 Environmental consequence (severity) levels and their corresponding scores

Impact level	Environment	Severity score
None	No impact	3
Tiny	Minimal impact on ecosystem; contained on mining lease, reversible in 1 year	4
Minimal	Moderate impact on ecosystem; contained on mining lease, reversible in 1 to 5 years	5
Minor	Moderate impact on ecosystem; contained on mining lease, reversible in 5 to 10 years	6
Moderate	Significant impact on ecosystem; impact at level of exploration lease, reversible in ~10 years	7
Major	Significant harm or irreversible impact (for example to World Heritage area); widespread, catchment area, long term, greater than 10 years	8
Catastrophic	Incident(s) due to unforeseen circumstances causing significant harm or irreversible impact (for example to World Heritage area); widespread, long term	9

Modified from Lin et al. (2013) and Adani Mining Pty Ltd (2013)

Table 4 Likelihood, indicative recurrence and associated likelihood score

Likelihood	Indicative recurrence	Likelihood score
Extremely rare	One event in 1000 years	–3
Very rare	One event in 333 years	–2.5
Rare	One event in 100 years	–2
Very unlikely	One event in 33 years	–1.5
Unlikely	One event in 10 years	–1
Possible	One event in 3 years	–0.5
Likely	One event in 1 year	0
Almost certain	Three events in 1 year	0.5
Most certain	Ten events in 1 year	1
Frequently	33 events in 1 year	1.5
Very frequently	100 events in 1 year	2
Every day	365 events in 1 year	2.5

Table 5 Detection, indicative days to detect, and associated detection score

Detection	Indicative days to detection	Detection score
Almost impossible	33,333 days	4.5
Extremely hard	10,000 days	4
Very hard	3,333 days	3.5
Hard	1,000 days	3
Quite hard	333 days	2.5
Easy	100 days	2
Quite easy	33 days	1.5
Very easy	10 days	1
Almost same day	3 days	0.5
Same day	1 day (within 24 hours)	0
Less than a day	0.3 of a day (<8 hours)	–0.5

2.3.4 Hazard ranking

Hazards identified by the IMEA can be ranked according to the hazard priority number (Equation 2) or the hazard score (Equation 3). Ranking according to hazard priority number is the traditional or 'reactive' approach to prioritise management actions, whereas ranking according to hazard score is referred to as the 'proactive' approach because it aims to reduce the likelihood and severity of impact modes before allocating resources to improve detection (Palady, 1995).

$$\text{Hazard priority number} = \text{severity score} + \text{likelihood score} + \text{detection score} \tag{2}$$

$$\text{Hazard score} = \text{severity score} + \text{likelihood score} \tag{3}$$

As noted in Section 2.3.3, FMEA scores are normally based on a single elicited value. In the IMEA, however, experts are allowed to provide an interval (see Section 2.3.3). The additional information provided by the interval provides a number of alternative options for calculating the overall score of any given hazard. Several potential alternatives were considered, including ranking by:

- lowest, midpoint or highest hazard score or hazard priority number
- lowest, midpoint or highest hazard score or hazard priority number weighted according to the inverse of the range of the score.

The range of the hazard score or hazard priority number may be interpreted as a measure of the experts' certainty; hence weighting by the inverse of the range places greater emphasis on the hazards that the experts are more certain of (i.e. those that have a smaller range). Ranking hazards in this manner, however, overemphasised a large number of low-priority hazards and was considered misleading. As a result, this manner of ranking hazards was not pursued further.

A high hazard priority number may result from average severity and likelihood scores, and high detection score (difficult to detect), whereas a lower ranking may occur from high severity and likelihood scores, but low detection score (easy to detect). Although this is entirely within the scope of the hazard analysis, the hazard priority number can mask the potential importance of hazards with high severity and likelihood. Comparing the hazard priority number to the hazard score, which focuses only on the severity and likelihood of the impact modes, helps avoid this. As such, hazards were ranked by the midpoint of the hazard score and midpoint of the hazard priority number.

2.3.5 Reporting the hazard analysis

The results of the hazard analysis are reported in product 2.3 (conceptual modelling). See Chapter 4 in the companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016) for guidance on which content to include. Examples of recommended outputs – and the way to present the outputs – are provided in the case study described in Chapter 3, Appendix A and Appendix B.

In addition, the full output of the hazard analysis will be registered as a dataset and cited in product 2.3 (conceptual modelling), to ensure transparency with respect to the underpinning results.

3 Case study: Gloucester subregion

This submethodology was trialled using the Gloucester subregion as a case study. The results are presented in this chapter (and in Appendix A and Appendix B) as an illustration of how to apply this submethodology in practice.

Unique activities for CSG operations and open-cut coal mines are listed in Appendix B. The IMEA activities are a complete list of all the things that occur during each life-cycle stage of a CSG operation and open-cut coal mining, starting with (for example) ground-based geophysics during the exploration and appraisal life-cycle stage of a CSG operation, through to pressure concrete completion during the decommissioning life-cycle stage. These activities are the core of the IMEA analysis and represent the source of potential hazards associated with CSG operations and open-cut coal mines.

A total of 261 activities were identified for CSG operations, and 351 activities for open-cut coal mines. Although these were all activities identified during the IMEA, the results described in Section 3.1 are based on a subset of activities with complete scores. Although all decisions were recorded, some activities were left unscored if there was incomplete information, or if they were considered not applicable to the case study for the Gloucester subregion.

Activities and impact modes were addressed for CSG and open-cut coal mining operations. Underground mining, however, is not currently planned for the Gloucester subregion. As a result, most of the impact modes for this activity were not completed in this case study.

Furthermore, as the participants identified hazards they were also requested to explicitly identify the associated stressors (i.e. the physical, biological or chemical process or contaminant that causes the effect). This was a deliberate strategy designed to identify and clarify the stressors that potentially threaten water-dependent assets, and hence may need to be ‘in scope’ for the purposes of the BAs.

3.1 Coal seam gas operations

3.1.1 Effects, stressors and impact causes

The results analysis begins by compiling all the unique effects identified during the IMEA (see Table 12, Appendix A). The objective here is to identify all the possible ways (the unique effects) in which surface water and groundwater assets may be influenced by CSG activities. It is important to note that each hazard may have multiple effects and thus the total count of unique effects will differ from unique hazards.

The potential impacts on water-dependent assets identified by the IMEA were grouped into 11 unique categories, including impacts on surface water and groundwater quality, quantity and composition (see Table 12, Appendix A; note that groundwater composition refers to the degree of mixing of groundwaters of different composition (in terms of natural dissolved solids)). Of these, impacts on surface water quality were the most frequently identified (117) followed by impacts on groundwater quality (50), surface water volume (25) and groundwater quantity (14).

The next compilation step in the results analysis is to list all the unique stressors. The objective here is to identify all the possible changes to, or contaminants of, groundwater and surface water in order to identify what variables would need to be modelled if these stressors were to be included within a probabilistic risk assessment. Note, however, that a full risk assessment is outside the scope of a BA; instead, a BA identifies and analyses risks, then others can use these for their own full risk assessment.

For the purposes of the BA, some of these stressors will be considered in scope and some will not. By listing all stressors, the hazard analysis provides a transparent statement of what is in scope and out of scope for the BA. Some of the stressors that are deemed in scope will become (perhaps in a more detailed characterisation) the *hydrological response variables*, the hydrological characteristics of the system that potentially change due to coal resource development (Viney, 2016; Crosbie et al., 2016). The impact and risk analysis is conditioned upon these hydrological response variables.

In most cases the unique stressors provide additional detail to the identified effects. For example the particular pollutants that may cause changes in surface water or groundwater quality are listed. A specific example is shown in Figure 6 where there is potentially a change in water quality (an effect) following vegetation clearance with a particular stressor related to total suspended solids (TSS). In some instances, however, the precise stressor is unspecified, or the stressor and associated effect are the same. The latter indicates that the change to water-dependent asset is the stressor.

The unique stressors identified during the IMEA for CSG operations in the Gloucester subregion, together with the frequency with which they were identified during the analysis indicate the most commonly cited were: TSS, pollutants (including metals, trace elements, sulfides and phosphorus), salts (expressed as total dissolved solids (TDS)), hydrocarbons and changes to surface water flow (see Table 13, Appendix A).

The last compilation step in the results analysis is to list all of the unique impact causes. This step has two objectives: (i) to separate deliberate or inevitable events from accidental events and (ii) to gauge their importance by the number of times each impact cause is cited. To carry accidental impacts forward requires the analyst to quantify their annual (for example) frequency. This step is not necessary for inevitable or deliberate events, hence impact and risk analysis for the latter is simpler.

The unique impact causes, together with the frequency that they were identified during IMEA for CSG operations in the Gloucester subregion, suggest:

- A good proportion of the hazards associated with CSG operations were attributed to accidental incidents or human error.
- Litter and spills associated with ground support operations are a potential source of hazards in many contexts, but these hazards were deemed to be of a very low priority and well managed given current controls.
- Containment failure, leaching, or flooding were also frequently cited, whether by lining material failure, plant or mechanical failure, or pipe fatigue.

- Removal of vegetation and diversion of site drain lines are cited relatively frequently in the list of potential impact causes. Their potential impacts are not deemed negligible (due to the potential for weed invasion, habitat fragmentation and soil erosion) but neither do they rank in the top hazards (see below). By virtue of their frequency these types of impacts may warrant additional attention in relation to the potential for cumulative effects.

3.1.2 High-priority hazards

The overall hazard score and hazard priority number provide a means to rank hazards relative to each other. Ranking hazards in this fashion allows the analyst to focus attention on the impact causes and/or stressors that were deemed most important by the experts involved in the IMEA. The ranking also provides a formal mechanism for recording the overall priority of hazards that are not carried forward.

The analysis identified impacts upon aquifers as the highest ranked hazard associated with CSG operations in the Gloucester subregion. The analysis identifies at least five ways in which aquifer impacts may occur including:

- fault-mediated depressurisation and pressurisation – caused by faults opening or closing due to CSG operations
- aquitard mediated depressurisation – an aquitard is absent (i.e. the coal seam is linked to the aquifer)
- aquitard mediated depressurisation – the integrity of the aquitard is compromised
- coal seam mediated depressurisation – the coal seam is part of the aquifer and it is deliberately depressurised
- connecting previously separated aquifers by (incorrect) hydraulic fracturing or incomplete well casings.

After impacts upon aquifers, the potential hazards associated with using production water for irrigation rate as high priority hazards. Increased discharges to surface water, raised groundwater levels, soil salt mobilisation and changes to soil chemistry were all identified as potentially important in this context.

Table 6 and Table 7 list the 30 highest ranked hazards, by hazard score (Table 6) and hazard priority number (Table 7), together with their associated stressors and frequency in the top 30. Figure 8 shows the 30 highest ranked hazardous activities and impact modes by hazard priority number mid-point. The figure also shows the lowest and highest hazard priority number and hazard score values for these hazards. Disruption of natural surface drainage was the most frequently identified hazard in the top 30 highest ranked hazards. This hazard appears 24 times in the Gloucester subregion CSG IMEA and 8 times in the top 30 hazards. It appears so frequently because many of the activities associated with CSG operations – such as site vegetation removal and diverting site drain lines – lead to this type of impact mode. This activity is identified as hazardous as it may lead to impacts upon surface water volume, direction and quality, and in extreme cases impacts upon groundwater quantity, which was also identified as a possible outcome.

Other high priority CSG hazards identified for the Gloucester subregion were:

- gas leakage into groundwater caused by incomplete or compromised cement casing
- subsidence
- leaching from brine storage ponds, pumps, water disposal pipelines and hypersaline brine ponds
- soil erosion following heavy rainfall, with TSS as the associated stressor
- inevitable loss of seal integrity after decommissioning of CSG wells.

The overall distribution of hazard priority number and hazard scores are shown in Figure 9. The dashed lines indicate the top 30 scores as displayed in Table 6 and Table 7. This is an arbitrary cut-off, used to identify the top ranked hazards for communication purposes. This selection is not intended to imply that these hazards are the only important hazards for consideration.

Table 6 Frequency of occurrence of impact mode, and associated stressors, for top 30 impact modes (as ranked by hazard score) from coal seam gas in the Gloucester subregion

Rows are ranked by frequency in the top 30.

Impact mode	Stressors	Frequency in top 30
Soil erosion following heavy rainfall	TSS	6
Disruption of natural surface drainage	TSS, SW flow, GW flow	5
Aquifer depressurisation	Change in GW pressure	1
Aquifer depressurisation (aquitard-absent)	Change in GW pressure	1
Aquifer depressurisation (coal seam)	Change in GW pressure	1
Aquifer depressurisation (fault-mediated)	Change in GW pressure	1
Aquifer depressurisation (loss of aquitard integrity)	Change in GW pressure	1
Aquifer pressurisation (fault-mediated)	Change in GW pressure increase	1
Changing target aquifer properties (physical or chemical)	Aquifer properties	1
Connecting aquifers	GW composition, hydrocarbons	1
Containment failure	TSS, TDS pH, pollutants (e.g. metals, trace elements, sulfides or phosphorous)	1
Contaminate target aquifer (chemical)	Hydraulic fracturing chemicals	1
Incomplete or compromised cementing/casing (gas leakage)	TDS, hydrocarbons	1
Incomplete or compromised cementing/casing (linking aquifers)	GW composition, hydrocarbons	1
Increase discharge to rivers following irrigation	TDS, SW flow	1
Leaching from storage ponds	TDS	1
Overflow and/or loss of containment	TSS, drilling mud products, TDS	1
Raise watertable following irrigation	TDS, GW flow	1
Soil chemistry changes following irrigation	Soil quality	1
Soil salt mobilisation following irrigation	TDS	1
Subsidence	Subsidence	1

TSS = total suspended solids; SW = surface water; GW = groundwater; TDS = total dissolved solids

Table 7 Frequency of occurrence of impact mode, and associated stressors, for top 30 impact modes (as ranked by hazard priority number) from coal seam gas in the Gloucester subregion

Rows are ranked by frequency in the top 30.

Rows ranked by frequency in the top 30 impact modes	Stressors	Frequency in top 30
Disruption of natural surface drainage	TSS, SW flow, GW flow	8
Leaking	TSS, TDS, pH, pollutants (e.g. metals, trace elements, sulfides or phosphorous)	2
Soil erosion following heavy rainfall	TSS	2
Aquifer depressurisation	Change in GW pressure	1
Aquifer depressurisation (aquitard absent)	Change in GW pressure	1
Aquifer depressurisation (coal seam)	Change in GW pressure	1
Aquifer depressurisation (fault mediated)	Change in GW pressure	1
Aquifer depressurisation (loss of aquitard integrity)	Change in GW pressure	1
Aquifer pressurisation (fault mediated)	Change in GW pressure increase	1
Connecting aquifers	GW composition, hydrocarbons	1
Contaminate non-target aquifer (chemical)	Hydraulic fracturing chemicals	1
Incomplete seal	TDS, hydrocarbons	1
Incomplete or compromised cementing/casing (gas leakage)	TDS, hydrocarbons	1
Incomplete or compromised cementing/casing (linking aquifers)	GW composition, hydrocarbons	1
Increase discharge to rivers following irrigation	TDS, SW flow	1
Leaching from storage ponds	TDS	1
Raise watertable following irrigation	TDS, GW flow	1
Seal integrity loss	TDS, hydrocarbons	1
Soil chemistry changes following irrigation	Soil quality	1
Soil salt mobilisation following irrigation	TDS	1
Subsidence	Subsidence	1

TSS = total suspended solids; SW = surface water; GW = groundwater; TDS = total dissolved solids

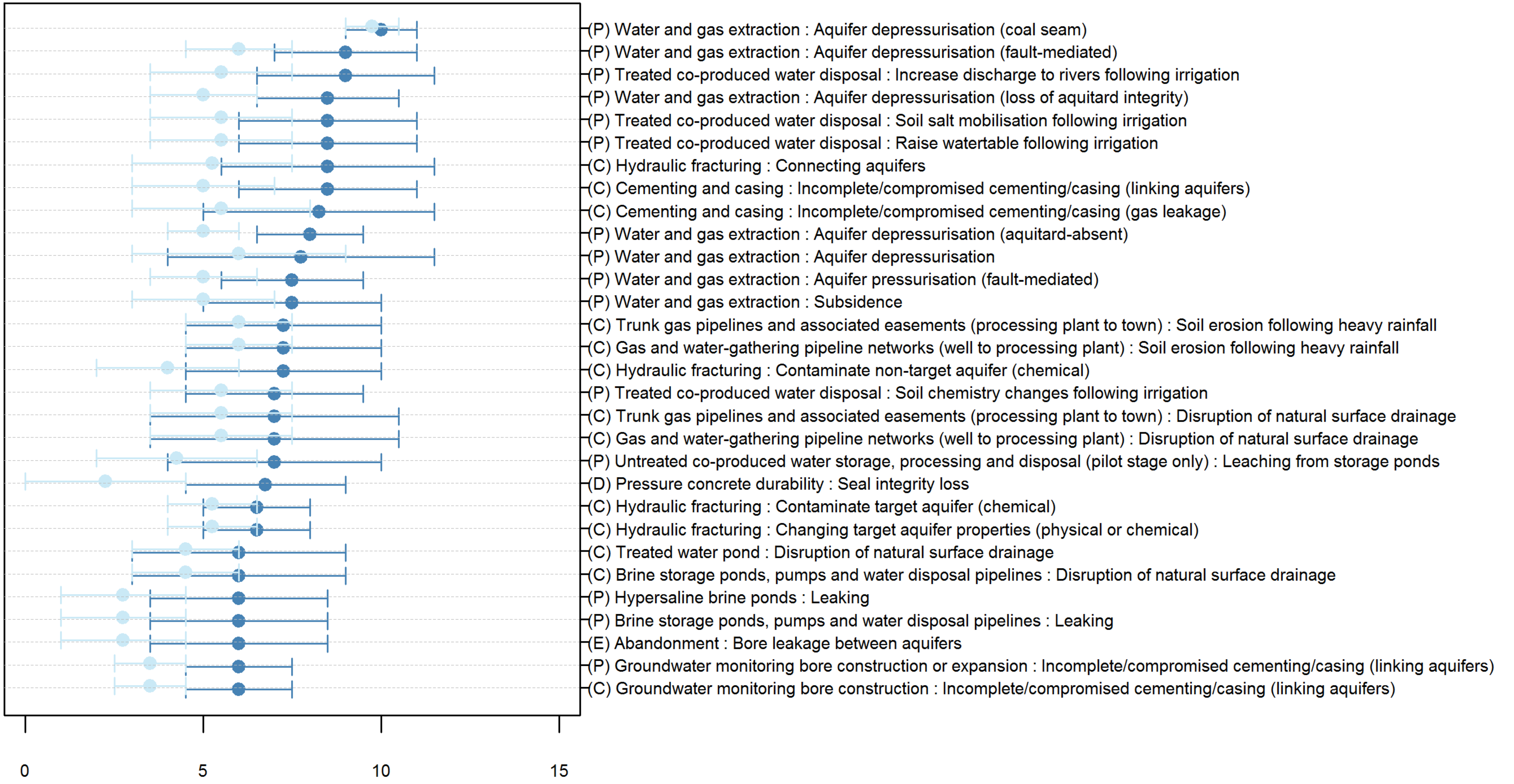

Figure 8 Highest ranked hazards (and their associated activities and impact modes) for coal seam gas operations in the Gloucester subregion, ranked by midpoint of hazard priority number

The x-axis shows the hazard priority number and hazard score for potential hazards. The intervals between the highest and lowest hazard priority number are shown in dark blue; the intervals for hazard score are shown in light blue. The same hazard may appear multiple times, as it may arise from a number of different life-cycle stages and activities. Hazards are listed with the syntax [Life-cycle stage][Activity]:[Impact mode], where life-cycle stages are indicated by (E) for exploration and appraisal, (D) for development, (P) for production, (C) for closure and (R) for rehabilitation.

This figure has been optimised for printing on A3 paper (420 mm x 297 mm).

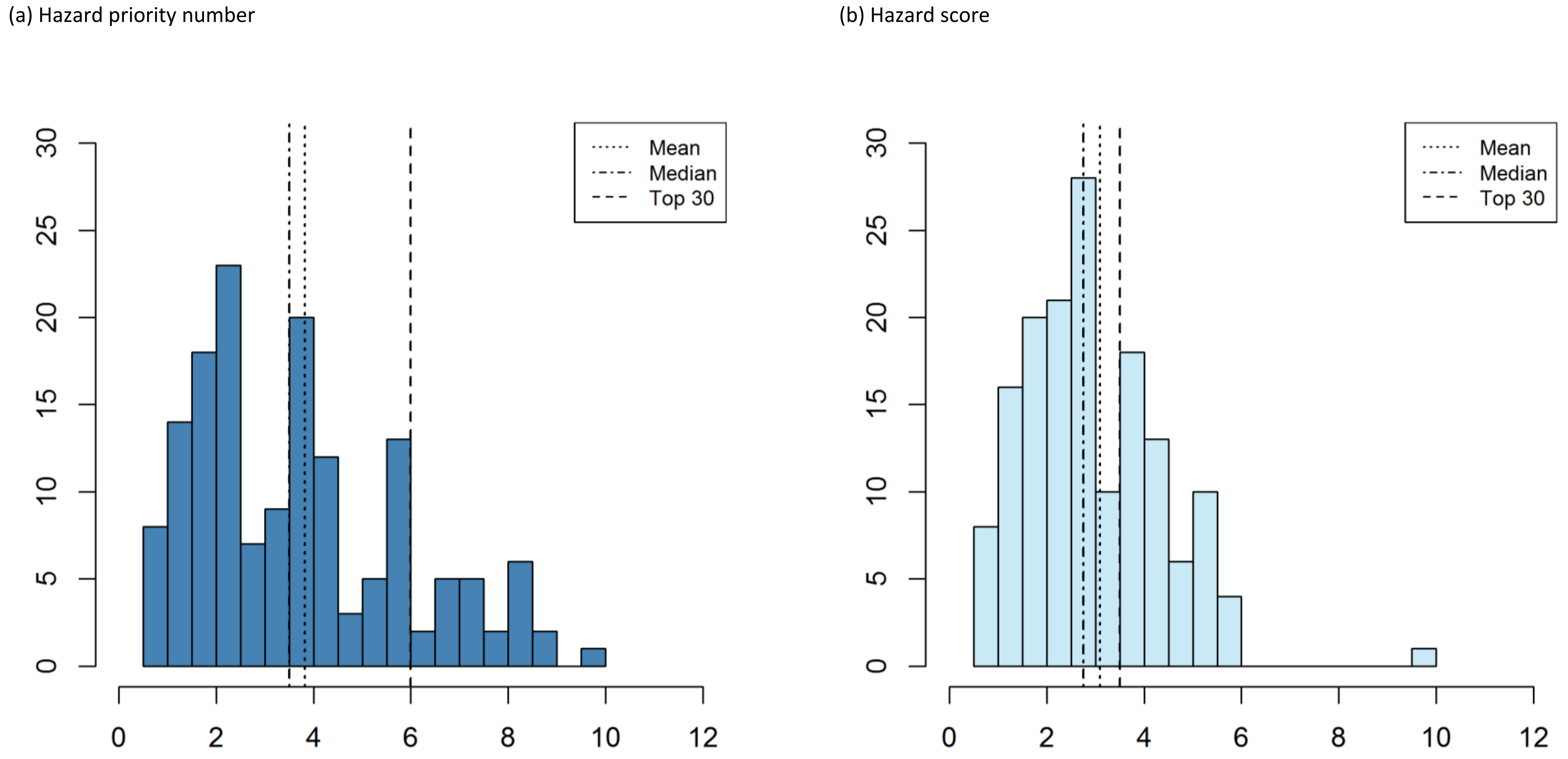

Figure 9 Histogram of (a) hazard priority number and (a) hazard score for coal seam gas operations in the Gloucester subregion

The x-axis shows the hazard priority number (a) and hazard score (b) respectively. The y-axis shows the frequency. Three dashed lines indicate the mean, median and top 30 ranked hazards as identified in the legend in the top right of each figure.

3.2 Open-cut coal mines

3.2.1 Effects, stressors and impact causes

The results analysis begins by compiling all the unique effects identified during the IMEA. The objective is to identify all the possible ways (the unique effects) in which surface water and groundwater assets may be influenced by open-cut coal mining activities. It is important to note that each hazard may have multiple effects and thus the total count of unique effects will differ from unique hazards.

The potential impacts of open-cut coal mining on water-dependent assets in the Gloucester subregion were grouped into 13 unique effect categories, including impacts on surface water quality, volume/quantity, direction and flow; and impacts on groundwater quality, quantity/volume, pressure, composition and directional characteristics (see Table 15, Appendix A). Of these, as with CSG, impacts on surface water quality was the most frequently identified impact (95) followed by groundwater quality (43), surface water directional characteristics (including flow paths, direction and drainage patterns) (23) and surface water volume/quantity (18).

The unique stressors identified during the IMEA for open-cut coal mining, together with the frequency with which they were identified during the analysis indicate the two most frequently identified stressors are TSS (72) and pollutants (including metals, trace elements, sulfides and phosphorus) (42). Following these, the next most common stressors are changes to surface water flow, salts (expressed as TDS), hydrocarbons and pH changes.

The unique impact causes, together with the frequency that they were identified during the IMEA for open-cut coal mining in the Gloucester subregion indicate the most frequently cited impact causes are similar to the CSG components, namely:

- A good proportion of the hazards associated with open-cut coal mining operations were attributed to accidental incidents or human error.
- Removal of vegetation and diversion of site drain lines are cited relatively frequently in the list of potential impact causes. Their potential impacts are not deemed negligible (due to the potential for weed invasion, habitat fragmentation and soil erosion) but neither do they rank in the top hazards (see below).
- Litter and spills associated with ground support operations are a potential source of hazards in many contexts, but again these hazards were deemed to be of a very low priority and well managed given current controls.
- Containment failure, leaching, or flooding were also frequently cited, whether by lining material failure, plant or mechanical failure, or pipe fatigue.

3.2.2 High-priority hazards

Table 8 and Table 9 list the 30 highest ranked impact modes, by hazard score and hazard priority number respectively, together with their associated stressors and citation frequencies. There are fewer unique impact modes in the top 30 for open-cut coal mining, compared to CSG operations, with multiple impact modes occurring several times. Figure 10 plots the 30 highest ranked hazardous activities by hazard score and hazard priority number midpoint. The figure also shows the lowest and highest hazard priority number and hazard score values for these activities.

The analysis identifies disruption of, and changes to, natural surface drainage and runoff as some of the most important impact modes associated with open-cut coal mining. These potential impact modes are listed six times in the top 30 hazards, and occur because open-cut coal mines may potentially divert rivers and creeks, and divert the natural direction of rainfall-runoff by the construction (or expansion of) the pit, as well as by re-contouring landforms.

The potential impact of leaching is another important hazard, featuring seven times in the top 30 hazards (Table 9). The most important potential impacts of leaching were leaching from in pit waste rock dumps, leaching from waste rock dumps outside of the pit, leaching from coal stockpiles (in and out of the pit) and from run-of-mine (ROM) plants (Figure 10).

Incomplete or compromised cementing casing of groundwater monitoring bores, supply bores, mine dewatering bores and abandoned exploration and appraisal bores were identified as having the potential to link, or cause leakage between, aquifers. This – together with deliberate pit wall dewatering, subsidence, and enhanced aquifer interconnectivity caused by post-closure water filling the pit – were also identified as potentially important hazards. The remaining top 30 hazards include soil erosion caused by heavy rainfall or failure to successfully rehabilitate abandoned mines, artificial groundwater recharge (following pit abandonment), groundwater and surface water contamination via drill cutting disposal or negligent decontamination of mines post-closure.

When prioritised by hazard score, soil erosion following heavy rainfall, with TSS as the stressor, was the most frequent high-priority hazard. Following this was leaching, changes to natural surface drainage and erosion. TSS was a stressor in all but four of the top 30 impact modes when ranked by hazard score. When detection is accounted for, with impact modes prioritised by hazard priority number, leaching (difficult to detect) was the most frequent cited high-priority hazard, followed by disruption to natural surface drainage, erosion and incomplete or compromised cement casing (leading to linking of aquifers).

The overall distribution of hazard priority number and hazard scores is shown in Figure 11. The dashed lines indicate the top 30 scores as displayed in Table 8 and Table 9.

Table 8 Frequency of occurrence of impact mode, and associated stressors, for top 30 impact modes (as ranked by hazard score) from open-cut coal mines in the Gloucester subregion

Rows are ranked by frequency in the top 30.

Impact mode	Stressors	Frequency in top 30
Soil erosion following heavy rainfall	TSS	6
Erosion	TSS, SW flow	3
Leaching	TSS, TDS, pH, pollutants (e.g. metals, trace elements, sulfides or phosphorous)	3
Change to natural surface drainage	TSS, SW flow, GW flow	2
Disruption of natural surface drainage	TSS, SW flow, GW flow	2
Equipment failure: pipe failure between pit and dam	TSS, Pollutants (e.g. metals, trace elements, sulfides or phosphorous)	2
Failure of the storage: slope failure	SW flow	2
Leaching: waste storage	TSS, TDS, pH, Pollutants (e.g. metals, trace elements, sulfides or phosphorous)	2
Containment failure	TSS, TDS, pH, Pollutants (e.g. metals, trace elements, sulfides or phosphorous)	1
Deliberate	GW flow, change in GW pressure	1
Disruption of natural surface drainage: Pit	TSS, SW flow, GW flow	1
Disruption of natural surface drainage: Pit - expansion	TSS, SW flow, GW flow	1
Enhanced aquifer interconnectivity	TSS, TDS, pH, pollutants (e.g. metals, trace elements, sulfides or phosphorous)	1
Equipment failure (pipe)	TSS, TDS, pH, pollutants (e.g. metals, trace elements, sulfides or phosphorous)	1
Leaching: in pit waste rock dump	TSS, TDS, pH, pollutants (e.g. metals, trace elements, sulfides or phosphorous)	1
Runoff changes	GW quantity or volume, SW volume or quantity	1

TSS = total suspended solids; SW = surface water; GW = groundwater; TDS = total dissolved solids

Table 9 Frequency of occurrence of impact mode, and associated stressors, for top 30 impact modes (as ranked by hazard priority number) from open-cut coal mines in the Gloucester subregion

Rows are ranked by frequency in the top 30.

Impact mode	Stressors	Frequency in top 30
Leaching	TSS, TDS, pH, pollutants (e.g. metals, trace elements, sulfides or phosphorous)	4
Erosion	TSS, SW flow	3
Incomplete or compromised cementing/ casing (linking aquifers)	GW composition, hydrocarbons	3
Change to natural surface drainage	TSS, SW flow, GW flow	2
Disruption of natural surface drainage	TSS, SW flow, GW flow	2
Leaching: waste storage	TSS, TDS, pH, pollutants (e.g. metals, trace elements, sulfides or phosphorous)	2
Artificial point of recharge	GW quantity or volume	1
Bore leakage between aquifers	GW composition, hydrocarbons	1
Bore leakage to surface	SW composition, hydrocarbons	1
Creation of artifical lake	TSS, TDS, pH, Pollutants (e.g. metals, trace elements, sulfides or phosphorous)	1
Deliberate	GW flow, change in GW pressure	1
Disruption of natural surface drainage: Pit	TSS, SW flow, GW flow	1
Disruption of natural surface drainage: pit – expansion	TSS, SW flow, GW flow	1
Enhanced aquifer interconnectivity	TSS, TDS, pH, pollutants (e.g. metals, trace elements, sulfides or phosphorous)	1
Equipment failure (pipe)	TSS, TDS, pH, pollutants (e.g. metals, trace elements, sulfides or phosphorous)	1
GW and/or SW contamination	TSS, drilling mud products, TDS	1
Leaching: in pit waste rock dump	TSS, TDS, pH, pollutants (e.g. metals, trace elements, sulfides or phosphorous)	1
Negligence	Pollutants (e.g. metals, trace elements, sulfides or phosphorous), hydrocarbons	1
Runoff changes	GW quantity or volume, SW volume or quantity	1
Subsidence	Subsidence	1

TSS = total suspended solids; SW = surface water; GW = groundwater; TDS = total dissolved solids

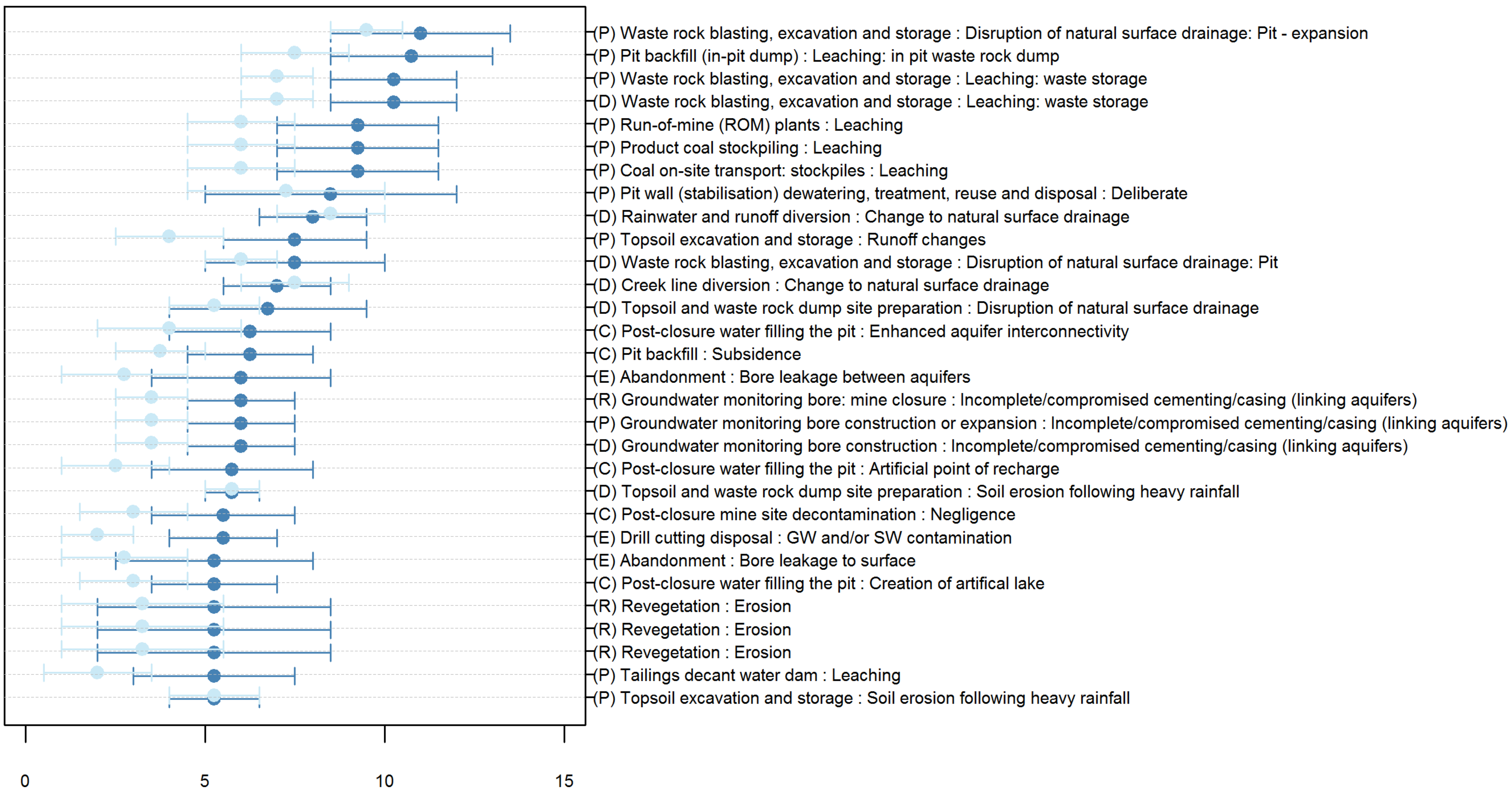

Figure 10 Highest ranked hazards (and their associated activities and impact modes) for open-cut coal mines in the Gloucester subregion, ranked by midpoint of hazard priority number

The x-axis shows the hazard priority number and hazard score for potential hazards. The intervals between the highest and lowest hazard priority number are shown in dark blue; the intervals for hazard score are shown in light blue. The same hazard may appear multiple times, as it may arise from a number of different life-cycle stages and activities. Hazards are listed with the syntax [Life-cycle stage][Activity]:[Impact mode], where life-cycle stages are indicated by (E) for exploration and appraisal, (D) for development, (P) for production, (C) for closure and (R) for rehabilitation.

This figure has been optimised for printing on A3 paper (420 mm x 297 mm).

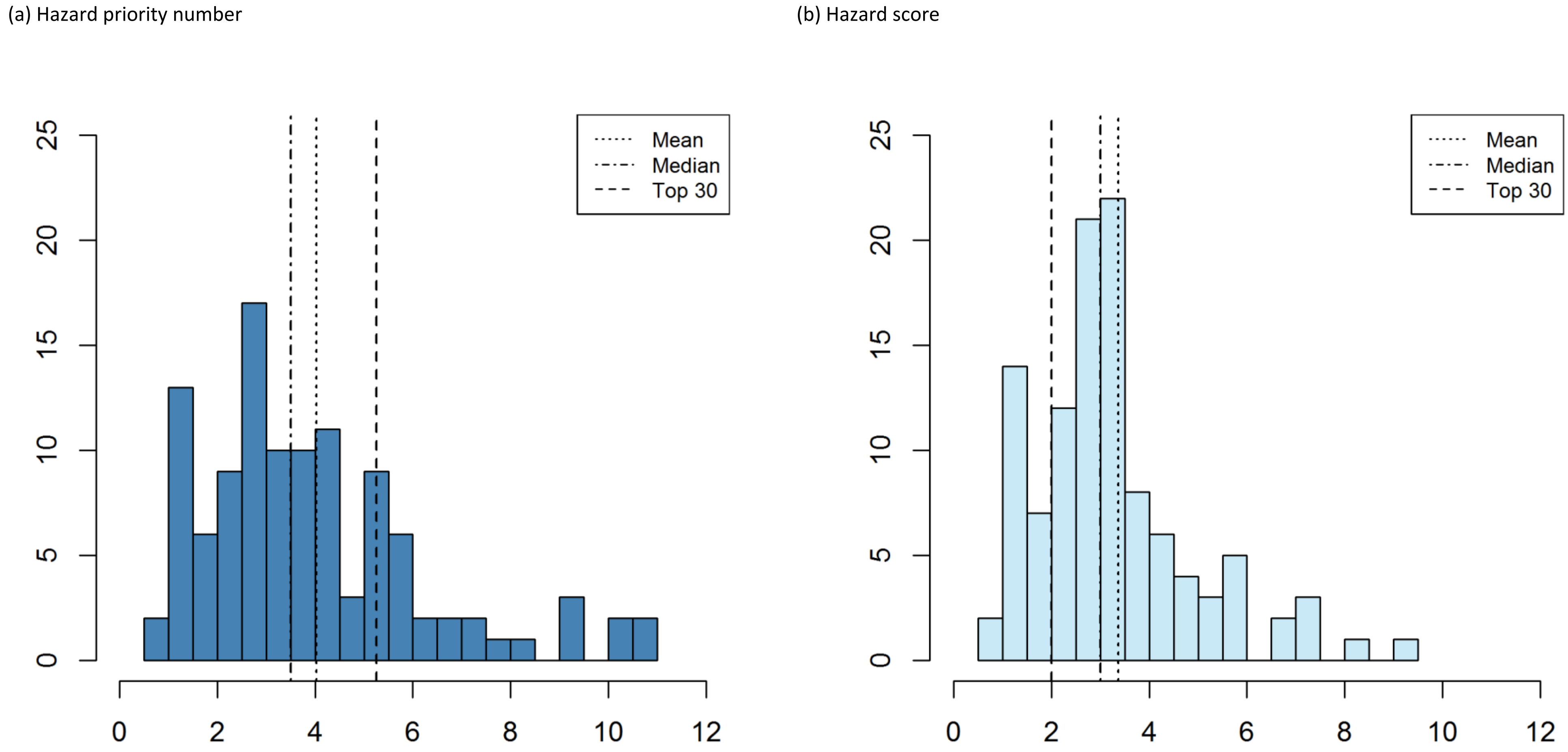

Figure 11 Histogram of (a) hazard priority number and (b) hazard score for open-cut coal mines in the Gloucester subregion

The x-axis shows the hazard priority number (a) and hazard score (b) respectively. The y-axis shows the frequency. Three dashed lines indicate the mean, median and top 30 ranked hazards as identified in the legend in the top right of each figure.

4 Discussion

4.1 Hazard identification and analysis

Rigorous, systematic hazard analysis is an essential component of any scientific risk assessment process. In this analysis a proven and well-trusted hazard analysis technique designed for complex industrial systems, Failure Modes and Effects Analysis, has been adapted for CSG and open-cut coal mining operations in the Gloucester subregion, with some small amendments to the scoring process that help communicate and facilitate the process. The modified technique was renamed Impact Modes and Effects Analysis (IMEA). This method has been adapted for the BA Technical Programme; the Gloucester subregion is one case study of the application of this adaptation. The IMEA has been completed for CSG, open-cut and underground coal mines (where each is applicable), for seven other regions.

There are two primary objectives of the IMEA: (i) to identify and rank the water-related hazards associated with CSG and open-cut coal mining operations in the Gloucester subregion and (ii) to identify potentially important stressors, and the balance of deliberate versus accidental events, associated with CSG and open-cut coal mining operations more generally, to inform the scope of the BAs, and thereby determine what should be in and out scope.

CSG extraction and large coal mining operations are complex processes. They involve a large number of activities spanning distinctly different life-cycle periods, and thereby entail a large number of potential environmental hazards. The analysis reported in this submethodology is restricted to potential impacts on water-dependent assets, but nonetheless still identified in excess of 250 and 350 potential hazards for CSG extraction and large coal mining developments respectively.

It is important to emphasise that despite the use of effect severity and effect likelihood scores, *this assessment does not provide an absolute or even relative measure of risk*. IMEA provides a relative rank of hazards. The value of this assessment lies in the systematic and thorough identification of hazards (impact modes) and in their ranking relative to each other.

The IMEA suggests that potential impacts on aquifers and the effects of production water disposal (CSG), and disruption of, or changes to, natural surface drainage, along with leaching of contaminants (mines) are amongst the most important water-related hazards in the Gloucester subregion. This does not, however, imply that the risks associated with these potential hazards are high or in some way significant, only that it is important that these hazards (along with many others) are considered for inclusion in the BA.

The IMEA also points to the possibility of cumulative impacts associated with vegetation removal and diversion of site drainage lines around CSG plants, mines and pipeline corridors. Individually these hazards are not deemed to be relatively important, but they were in the top five most frequently identified impact causes for open-cut coal mining and CSG operations. These hazards are deliberate and associated with many open-cut coal mining and CSG activities, and are therefore likely to contribute to other stressors in the environment.

Accidental events and stressors that can have detrimental effects on surface water and groundwater quality, particularly TSS, pollutants (metals, trace elements, sulfides and phosphorus), TDS and hydrocarbons, feature prominently in the IMEA.

Quantifying the risks associated with accidental events entails additional calculations over deliberate events, namely the probability that the accidental event will occur over a specified period of time. The historical rates of identical or similar accidents can provide some guidance in this respect so long as the operating conditions during the record period are relevant to modern Australian operating standards.

Quantifying the risks associated with changes in surface water and groundwater quality, as well as quantity, also entails an additional modelling overhead, as described in Chapter 5 in the companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016).

Finally, whilst the results reported here are specific to the Gloucester subregion, much of the progress and lessons learnt will be applicable to other bioregions and subregions. The list of activities developed for the IMEA for Gloucester subregion (see Appendix B) are generic for similar coal mines and CSG operations, and provide a template for application in other bioregions or subregions. Highly-ranked hazards may vary somewhat between bioregions and subregions, particularly for those with underground mining because this was not relevant for the Gloucester subregion. Accidental events and impacts on water quality are likely to be equally important across all bioregions and subregions.

4.2 Scope

The hazard analysis presented here has provided a systematic consideration of activities associated with all life-cycle stages of coal resource development, their potential causes and pathways to impact, and the possible changes to aspects of surface water or groundwater. A long list of hazards has been generated across both coal mining and CSG. The hazards of primary focus from a BA perspective are those that extend beyond the development site and that may have cumulative impacts, as these are consistent with the regional focus of BA, and are where BA will add value beyond site specific Environmental Impact Statements (EIS). Ultimately, however, BA need to be able to address all identified hazards by considering the scope, modelling, other literature or narratives, and specifying where science gaps may exist.

The following guidelines and analysis categories broadly describe how various hazards may be handled. It is important to note that changes may occur in individual subregions in response to their development or biophysical context. Three categories were considered when determining if the hazards identified by IMEA were in or out of the BA scope: (i) in scope and addressed by the BA modelling, (ii) in scope but addressed by a narrative, (iii) out of scope because the hazard would typically be handled by site-based risk management following an EIS.

In the case of hazards that are deemed to be in scope but handled by a narrative, the hazard priority number and hazard score should be used as a guide to determine the length and detail of the narrative, and may also be used to identify priorities for future research and quantitative analysis.

The following guiding principles were considered in deciding how individual hazards are allocated to each of the three categories:

- BA are constrained by considering only impacts that can happen via water, and so hazards such as dust, fire or noise are deemed out of scope and addressed by site-based risk management unless there is a water mediated pathway.
- Best practice is assumed and accidents are deemed to be covered adequately by site-based risk management procedures and beyond the scope of BA, for example the failure of a pipe between the pit and a dam is covered by site-based risk management.
- Hazards that pertain to the development site and with no off-site impacts will typically be covered by site-based risk management procedures.
- The hazard priority number or hazard scores indicate the relative importance of the hazard. Hazards with low scores are of lower priority.

These categorisations are presented here to provide guidance on which hazards are in and out of the BA scope. How these hazards are carried forward, however, may be altered by local considerations for each subregion (e.g. additional narrative around discharge to a river that may increase the level of the watertable in contributing streams may be warranted) and the availability of data or information to support the modelling (e.g. water extraction from stream for operation needs to be known if it is to be incorporated into the modelling).

4.2.1 Coal seam gas operations

Table 10 categorises the hazards and impact pathways to the water-related effects and changes in surface water or groundwater for CSG operations.

There are a range of other hazards identified that are also covered by site-based risk management but that may be considered to have more negligible potential impacts, for example the effect of ground staff, local watertable reduction from exploration bores, or drill control issues. These hazards should be noted but the extent of the narrative may be more limited to reflect their lower priority.

Table 10 Hazards and impact pathways to the water-related effects and changes in surface water or groundwater for coal seam gas operations

Modelling (pathways that are expected to be modelled through surface water or groundwater models)	Narrative (pathways that are not modelled but are important to provide comment on)	Narrative – site-based risk management (pathways that are believed to be important to acknowledge but are handled by site-based risk management procedures)
Depressurisation of coal seam and non-target aquifers from water and gas extraction	Faults (fault mediated aquifer depressurisation, accidental intersection of faults by wells). Note: that this may be partially covered in modelling via sensitivity analysis	Equipment/infrastructure failure (e.g. pipeline failures)
Discharge of co-produced water to stream	Bore and well construction (integrity, leakage, connecting aquifers, well failure rate and implications)	Leaching/leaking from storage ponds and stockpiles
Extraction of water from surface water or groundwater for operations (where known / if appropriate)	Hydraulic fracturing and potential contamination of target/non-target aquifers	Containment failure due to construction or design
	Subsidence	Spillages and disposals (diesel, mud, cuttings, fluid recovery)
	Unregulated or forced release of water due to dam / containment failure	Disruption of surface drainage network (site-based infrastructure, plant and facilities, roads, creek crossings)
	Changes to water quality associated with depressurisation and connecting aquifers	Vegetation clearance and subsequent soil erosion following heavy rainfall
	Disruption of natural surface drainage (pipelines)	Abandonment practice

4.2.2 Open-cut and underground coal mines

The following represent categorisations of the hazards and impact pathways to the water-related effects and changes in surface water or groundwater for open-cut and underground coal mines (Table 11).

There are a range of other hazards identified that are also covered by site-based risk management but that may be considered to have more negligible potential impacts, for example the effect of ground staff, spillage, incomplete removal of equipment following mine closure, fire, or dust suppression. Again these hazards should be noted but the extent of the narrative may be more limited to reflect their lower priority.

Table 11 Hazards and impact pathways to the water-related effects and changes in surface water or groundwater for open-cut and underground coal mines

Modelling (pathways that are expected to be modelled through surface water or groundwater models)	Narrative (pathways that are not modelled but are important to provide comment on)	Narrative – site-based risk management (pathways that are believed to be important to acknowledge but are handled by site-based risk management procedures)
Disruption of natural surface water drainage and change in run-off (interception of run-off by pit / site)	Faults (fault mediated aquifer depressurisation). Note: that this may be partially covered in modelling via sensitivity analysis	Equipment / infrastructure failure (e.g. pipeline failures, plant failures)
Groundwater dewatering of target seam (underground) and layers to coal seam (open-cut)	Unregulated or forced release of water due to dam / containment failure.	Leaching/ leaking from storage ponds and stockpiles
Changes to baseflow and connections between GW and SW	Changes to water quality associated with depressurisation and connecting aquifers	Loss of containment (due to construction or design, slope failure)
Subsidence due to underground mining (modelled by change in properties rather than geotechnical modelling given scale)	Disruption of natural surface drainage (beyond site, e.g. rail)	Inter aquifer connectivity - Shaft construction for underground (integrity) & bore and well construction (integrity, leakage)
Discharge of mine water to stream		Spillages and disposals (diesel, mud, cuttings, fluid recovery)
Change to surface water drainage following mine closure, backfilling and rehabilitation		Disruption of surface drainage network (site-based infrastructure, plant and facilities, roads, creek crossings)
Post mining - creation of groundwater sink, artificial point of recharge		Vegetation clearance and subsequent soil erosion following heavy rainfall
		Re-contouring, compaction and settlement following backfill

4.3 Connection to causal pathways

The hazards identified by the IMEA represent a conceptual model of the chain of events that begins with an activity and ends with a potential impact on a water-dependent asset. For BAs, this chain of events is a *causal pathway*, the logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water and water-dependent assets (see companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016)).

Grouping hazards by common impact cause – the event that initiates a causal pathway – provides a useful starting point for summarising and representing the causal pathways associated with CSG operations and coal mines, and focusing on those causal pathways that are in scope. The Gloucester subregion case study, for example, identifies more than 20 unique impact causes for CSG operations (see Table 14, Appendix A). However, the most frequently cited impact causes for CSG operations are out of scope for the BAs (see Section 4.2): namely human error, accident (e.g. containment loss, digging, ignition, logging machine fault, formation variation) and litter spills.

Eliminating those initiating events that are out scope allows the impact and risk analysis to identify and focus on the causal pathways that are in scope. Ranking provided by the hazard priority number and/or hazard score provides further guidance on their potential importance. Causal pathways that are deemed within scope can be further distinguished by their likely spatial footprint and the manner in which they are addressed within the BA. For example after human error and accident, the next two most frequently cited impact causes for mining in the Gloucester subregion are corridor or site vegetation removal and diverting site or corridor drain lines (see Table 17, Appendix A). The footprint of both of these causal pathways may be mapped for communication purposes. The first, however, is addressed within the impact and risk analysis via a simple narrative (Section 4.2), whereas the latter is accounted for in the surface water numerical modelling by reducing surface water flows into the rivers and streams of impact catchments, which ultimately feeds through into the quantitative stages of the impact and risk analysis via impacts on surface water-dependent landscape classes in the affected region (Figure 4).

The impact and risk analysis ensures that all causal pathways are accounted for by stepping through each of the unique impact causes, and with reference to the impact modes within common cause categories, determining which are in and out of scope, and how those causal pathways that are in scope are handled. In all cases particular attention should be paid to highly ranked hazards. Highly ranked hazards may be focus points for community concerns, hence it is important to carefully consider the implications of treating these as out of scope or handling them via a simple narrative.

Appendix A Effects, stressors and impact causes for the Gloucester subregion

A.1 Coal seam gas operations

Table 12 Unique effects (for coal seam gas operations) identified during the Impact Modes and Effects Analysis for the Gloucester subregion

Effect	Frequency
SW quality	117
GW quality	50
SW volume	25
GW quantity	14
Change in GW pressure	10
SW directional characteristics	10
GW composition	7
SW flow	6
Aquifer properties	2
GW flow (reduction)	1
Soil quality	1

SW = surface water; GW = groundwater; SW flow = change in surface water flow volume; GW composition = mixing groundwaters of different composition (in terms of natural dissolved solids)

Table 13 Unique stressors (for coal seam gas operations) identified during the Impact Modes and Effects Analysis for the Gloucester subregion

Stressor	Frequency
TSS	68
Pollutants (e.g. metals, trace elements, sulfides or phosphorous)	39
TDS	34
Hydrocarbons	32
SW flow	30
Drilling mud products	13
GW flow	12
Change in GW pressure	11
GW composition	8
pH	6
Chemicals	4
Hydraulic fracturing chemicals	4
Organic pollutants	4
Aquifer properties	2
Change in GW pressure increase	1
Soil quality	1
Subsidence	1
SW composition	1

SW = surface water; GW = groundwater; TSS = total suspended solids; TDS = total dissolved solids, salts; SW or GW flow = change in surface water or groundwater flow volume; GW or SW composition = mixing waters of different composition (in terms of natural dissolved solids); Pollutants = anthropogenic contaminants

Table 14 Unique impact causes (for coal seam gas operations) identified during the Impact Modes and Effects Analysis for the Gloucester subregion

Impact cause	Frequency
Human error, accident (e.g. containment loss, digging, ignition, logging machine fault, formation variation)	33
Litter, spills	24
Containment failure/leaching/flooding (e.g. lining material failure, loss of holding capacity, pipe failure, dam failure)	21
Corridor/site vegetation removal	19
Diverting site/corridor drain line	17
Inevitable, Deliberate	13
Natural disaster (e.g. bushfire, flooding, earthquake)	8
Poor design, construction, implementation, management (e.g. abandonment practice, bore location, lack of knowledge, historical data records, sealing practices, geological characterisation)	8
Number of drilling control issues	5
Inappropriate disposal	4
Ignition following pipe failure	3
Incomplete grouting	3
Incidental to vegetation removal and compaction in pipeline corridor	2
Aquifer connected to coal seam	1
Aquitard leaks	1
Chemical interactions in soil	1
Depressurisation	1
Evaporation concentrates salt on surface	1
Fault closing	1
Fault open or opening	1
Incomplete reservoir knowledge, too much pressure	1
Increase baseflow	1
Interrupting ephemeral watercourses	1
Production of water	1
Salt mobilisation due to irrigation	1

A.2 Open-cut coal mines

Table 15 Unique effects (for open-cut coal mines) identified during the Impact Modes and Effects Analysis for the Gloucester subregion

Effect	Frequency
SW quality	95
GW quality	43
SW directional characteristics	23
SW volume/quantity	18
GW quantity/volume	10
SW flow	9
GW composition	6
GW directional characteristics	4
Change in GW pressure	2
GW flow	2
GW recharge	1

SW = surface water; GW = groundwater; SW flow = change in surface water flow volume; GW composition = mixing groundwaters of different composition (in terms of natural dissolved solids)

Table 16 Unique stressors (for open-cut coal mines) identified during the Impact Modes and Effects Analysis for the Gloucester subregion

Stressor	Frequency
TSS	72
Pollutants (e.g. metals/trace elements/sulfides/phosphorous)	42
SW flow	28
TDS	20
Hydrocarbons	19
pH	14
GW flow	8
Drilling mud products	6
GW composition	6
change in GW pressure	2
GW quantity/volume	2
Subsidence	1
SW composition	1
SW volume/quantity	1

SW = surface water; GW = groundwater; TSS = total suspended solids; TDS = total dissolved solids, salts; SW or GW flow = change in surface water or groundwater flow volume; GW or SW composition = mixing waters of different composition (in terms of natural dissolved solids); Pollutants = anthropogenic contaminants

Table 17 Unique impact causes (for open-cut coal mines) identified during the Impact Modes and Effects Analysis for the Gloucester subregion

Impact causes	Frequency
Human error, accident	19
Diverting site drain line	17
Corridor, site vegetation removal (e.g. removing rocks and topsoil)	14
Litter, spills	14
Containment failure, leaching, flooding (e.g. lining material failure, plant failure, mechanical failure, pipe fatigue)	12
Inevitable, Deliberate (e.g. mining below watertable, in recharge areas, removal of rock mass, more than one aquifer intersected by pit)	11
Coal characteristics, waste characteristics, spontaneous combustion, bushfire	8
Poor design, construction, implementation, management (e.g. Abandonment practice, bore location, lack of knowledge, historical data records, sealing practices, geological characterisation)	8
Incomplete grouting	4
Ineffective revegetation due to (e.g. disease, poor topsoil, fire, weather, weeds)	4
Natural disaster (e.g. earthquake)	3
New topography, combined with timing of new vegetation and rainfall	3
Number of drilling control issues	3
Consolidation of loose backfill	1
Interrupting ephemeral watercourses	1

Appendix B Activities for the Gloucester subregion

B.1 Life-cycle stages and activities for coal seam gas operations

Table 18 Unique activities (for coal seam gas operations) during exploration and appraisal life-cycle stage for the Gloucester subregion

Activity
Abandonment
Construction of access roads and easements (e.g. for drilling rigs and equipment)
Drill cutting disposal
Drill stem testing (extraction)
Drilling and coring
Fuel and oil
Ground-based geophysics
Materials delivery and storage
Power and communications
Pump testing
Site clean-up and rehabilitation
Site preparation
Slug testing (injection)
Surface core testing
Surface water and mud storage and evaporation
Temporary Accommodation, administration, workshop, depots, service facilities

Table 19 Unique activities (for coal seam gas operations) during construction life-cycle stage for the Gloucester subregion

Activity
Accommodation, administration, workshop, depots, service facilities
Brine storage ponds, pumps and water disposal pipelines
Cementing and casing
Construction of access roads and easements (e.g. for drilling rigs and equipment)
Drill cutting disposal
Drill stem testing (extraction)
Drilling and logging
Fuel and oil
Fuel and oil storage facilities
Gas-gathering pipeline networks
Gas and water-gathering pipeline networks (well to processing plant)
Gas compression stations
Gas processing plant
Groundwater monitoring bore construction
Groundwater supply bore
Hydraulic fracturing
Hydraulic fracturing concentrate delivery
Hydraulic fracturing fluid injection and disposal
Hypersaline brine ponds
Materials delivery and storage
Perforation
Power and communications
Power generation facility (for processing plant)
Remediation
Sewage treatment and disposal
Site preparation
Surface water and mud storage and evaporation
Treated water pond
Trunk gas pipelines and associated easements (processing plant to town)
Water treatment plant (RO, fixed resin, fixed disc, electrochemical, etc)

Table 20 Unique activities (for coal seam gas operations) during production life-cycle stage for the Gloucester subregion

Activity
Accommodation, administration, workshop, depots, service facilities
Brine storage ponds, pumps and water disposal pipelines
Fuel and oil
Fuel and oil storage facilities
Gas-gathering pipeline networks
Gas and water-gathering pipeline networks (well to processing plant)
Gas compression stations
Gas processing plant
Groundwater monitoring bore construction or expansion
Groundwater supply bore
Hypersaline brine ponds
Materials delivery and storage
Operation access roads and easements (e.g. for drilling rigs and equipment)
Power and communications
Power generation facility (for processing plant)
Sewage treatment and disposal
Staff movement and activities
Treated co-produced water disposal
Treated water pond
Trunk gas pipelines and associated easements (processing plant to town)
Untreated co-produced water storage, processing and disposal (pilot stage only)
Water and gas extraction
Water treatment plant (RO, fixed resin, fixed disc, electrochemical, etc)

Table 21 Unique activities (for coal seam gas operations) during decommissioning life-cycle stage for the Gloucester subregion

Activity
Fuel and oil
Materials delivery and storage
Pressure concrete completion
Pressure concrete durability
Process production plant
Sewage treatment and disposal

Table 22 Unique activities (for coal seam gas operations) during work-over life-cycle stage for the Gloucester subregion

Activity
Materials delivery and storage
Site preparation
Waste disposal
Water sourcing (for injection)

B.2 Life-cycle stages and activities for open-cut coal mines

Table 23 Unique activities (for open-cut coal mines) during exploration and appraisal life-cycle stage for the Gloucester subregion

Activity
Abandonment
Drill cutting disposal
Drilling and coring
Ground-based geophysics
Materials delivery and storage
Site clean-up and rehabilitation
Site preparation and construction for drilling activities
Slug testing (injection)
Surface core testing
Surface water and mud storage and evaporation
Temporary accommodation, administration, workshop, depots, stock piles, service facilities

Table 24 Unique activities (for open-cut coal mines) during development life-cycle stage for the Gloucester subregion

Activity
Administration, workshop, service facilities (construction phase)
Creek diversions, levee bunds, creek crossings
Creek line diversion
Dam construction
Dam construction for freshwater storage
Dam construction for mine water storage
Dam construction for tailings storage
Groundwater monitoring bore construction
Groundwater supply bore
Haul road construction
Mine dewatering, treatment, reuse and disposal
Off-lease and on-lease roadways (construction phase)
Power, water and communications network: connection to existing grids
Rail easement construction
Rainwater and runoff diversion
Temporary diesel generators (construction phase)
Topsoil and waste rock dump site preparation
Waste byproduct: treatment of water
Waste rock blasting, excavation and storage

Table 25 Unique activities (for open-cut coal mines) during production life-cycle stage for the Gloucester subregion

Activity
Coal excavation
Coal on-site processing
Coal on-site transport
Coal on-site transport: stockpiles
Coal processing waste material: handling, transport, storage
Daily operational use of roads: haulage, inspection, maintenance, etc.
Groundwater monitoring bore construction or expansion
Haul road construction
Materials storage facilities (e.g. fuel, oil and explosives)
Mine dewatering, treatment, reuse and disposal
New haul road construction
Off-lease and on-lease roadways
Onsite mine equipment storage
Pit backfill (in-pit dump)
Pit wall (stabilisation) dewatering, treatment, reuse and disposal
Product coal stockpiling
Run-of-mine (ROM) plants
Tailings decant water dam
Topsoil excavation and storage
Waste rock blasting, excavation and storage

Table 26 Unique activities (for open-cut coal mines) during closure life-cycle stage for the Gloucester subregion

Activity
Dismantling and removal of built infrastructure
Pit backfill
Post-closure mine site decontamination
Post-closure water filling the pit
Water management structures (dams, levee bunds and diversions)

Table 27 Unique activities (for open-cut coal mines) during rehabilitation life-cycle stage for the Gloucester subregion

Activity
Groundwater monitoring bore: mine closure
Recontoured landforms (slopes, gradients, etc.)
Recontoured landforms (slopes, gradients, etc.): from building, rail and road infrastructure
Revegetation

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Glossary

The register of terms and definitions used in the Bioregional Assessment Programme is available online at http://environment.data.gov.au/def/ba/glossary (note that terms and definitions are respectively listed under the 'Name' and 'Description' columns in this register). This register is a list of terms, which are the preferred descriptors for concepts. Other properties are included for each term, including licence information, source of definition and date of approval. Semantic relationships (such as hierarchical relationships) are formalised for some terms, as well as linkages to other terms in related vocabularies.

activity: for the purposes of Impact Modes and Effects Analysis (IMEA), a planned event associated with a coal seam gas (CSG) operation or coal mine. For example, activities during the production life-cycle stage in a CSG operation include drilling and coring, ground-based geophysics and surface core testing. Activities are grouped into components, which are grouped into life-cycle stages.

additional coal resource development: all coal mines and coal seam gas (CSG) fields, including expansions of baseline operations, that are expected to begin commercial production after December 2012

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

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

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

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

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

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

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

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

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

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

conceptual model: abstraction or simplification of reality

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

consequence: synonym of impact

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

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

current controls: the methods or actions currently planned, or in place, to detect hazards when they occur or to reduce the likelihood and/or consequences of these hazards should they occur

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).

detection score: for the purposes of Impact Modes and Effects Analysis (IMEA), 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

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

discharge: water that moves from a groundwater body to the ground surface or surface water body (e.g. a river or lake)

diversion: see extraction

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

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

ecosystem asset: an ecosystem that may provide benefits to humanity. It is a spatial area comprising a combination of biotic and abiotic components and other elements which function together.

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

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

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

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

Gloucester subregion: The Gloucester subregion covers an area of about 348 km^2. The Gloucester subregion is defined by the geological Gloucester Basin. It is located just north of the Hunter Valley in NSW, approximately 85 km north-north-east of Newcastle and relative to regional centres is 60 km south-west of Taree and 55 km west of Forster.

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

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

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

hazard priority number: for the purposes of Impact Modes and Effects Analysis (IMEA), one of two ranking systems that indicate the relative importance of a hazard. It is the sum of severity score, likelihood score and detection score.

hazard score: for the purposes of Impact Modes and Effects Analysis (IMEA), one of two ranking systems that indicate the relative importance of a hazard. It is the sum of the severity score and likelihood score.

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

likelihood score: for the purposes of Impact Modes and Effects Analysis (IMEA), the annual probability of a hazard occurring, which is scored so that a one-unit increase (or decrease) in score indicates a ten-fold increase (or decrease) in the probability of occurrence

material: pertinent or relevant

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

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

recharge: see groundwater recharge

risk: the effect of uncertainty on objectives

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

severity: magnitude of an impact

severity score: for the purposes of Impact Modes and Effects Analysis (IMEA), 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

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

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

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

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

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

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'.

www.bioregionalassessments.gov.au

Australian Government

Department of the Environment and Energy

Bureau of Meteorology

Geoscience Australia

CSIRO