Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development

Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources

Summary

The scientific input for this report was commissioned in May 2012 by the Office of Water Science on behalf of the Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining through the Department of the Environment and has been reviewed and refined by the Statutory Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development.

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Acronyms

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
AWRIS	Australian Water Resources Information System
BA(s)	bioregional assessment(s)
BA framework	bioregional assessment framework
BA methodology	bioregional assessment methodology
CAPAD	Collaborative Australian Protected Area Database
COAG	Council of Australian Governments
CSG	coal seam gas
DEH	Department of Environment and Heritage
DEM	digital elevation model
EPBC Act	the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999*
GDE	groundwater-dependent ecosystem
GPS	global positioning system
IBA	important bird area
IBRA	Interim Biogeographic Regionalisation for Australia
IESC	Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development
IIESC	Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining
InSAR	Interferometric Synthetic Aperture Radar
ISO	International Organization for Standardization
LiDAR	Light Detection and Ranging
LTCC	Longwall Top Coal Caving
MNES	Matters of National Environmental Significance
NAF	National Aquifer Framework
NGIS	National Groundwater Information System
VAST dataset	Vegetation Assets, States and Transitions dataset for Australia
WHA	World Heritage Area

Executive summary

The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) has been established under the *Environment Protection and Biodiversity Conservation Amendment (Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development) Act 2012* to provide advice to the Federal Environment Minister on potential water-related impacts of coal seam gas (CSG) and large coal mining developments.

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. 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 direct, indirect and cumulative impacts of CSG and coal mining development on water resources.

The present document (the BA methodology or BRAM) is intended to articulate the scientific and intellectual basis for a consistent approach to all BAs. This methodology provides guidance to research scientists and managers preparing BAs within research agencies that have been charged with the task of researching and preparing BAs to provide advice on impacts.

The purpose of a BA is to:

- define, characterise and explain conceptual models that establish causal pathways describing the chain of interactions and events connecting depressurisation and dewatering of coal seams at depth with impacts on anthropogenic and ecological receptors located at depth or the surface
- generate quantitative, semi-quantitative or qualitative analyses of the likelihood of impacts of CSG and coal mining developments on receptors from the application of ecology, surface water and groundwater hydrology, hydrogeology and CSG or coal resource development models
- develop improved assessments of the likelihood of risks to receptors and the subsequent values of water-dependent assets from CSG and coal mining developments
- provide information on the level of confidence of scientific advice on these impacts
- identify monitoring programs, BA review frequency and additional risk assessment studies that could be undertaken outside of the bioregional assessment process to help minimise impacts of CSG and coal mining developments on water resources.

A BA is conducted within a specified area termed a ‘bioregion’. The bioregion itself contains identified key water-dependent ‘assets’ within which are located ‘receptors’. A water-dependent asset is an entity, such as a Ramsar or state significant wetland, within a bioregion with characteristics having value and which can be linked directly or indirectly to a dependency on water quantity or quality. Receptors are discrete, identifiable attributes, such as a particular rare or threatened species, contained within assets that are measurably impacted by a change in water quantity or quality resulting from CSG or coal mining development. It is through receptors that the impacts of CSG and coal mining development are defined within a BA. These impacts include changes in baseline variables, flow regimes, hydraulic conditions, surface water – groundwater connections, inundation patterns and effects of salt or salinity. Other impacts such as ecotoxicology, human health or water quality impacts, from heavy metal contamination or impacts of hydraulic fracturing fluids are being considered by other research and studies (such as the ‘National Assessment of Chemicals associated with coal seam gas extraction’) and will be able to be linked to the BAs. From these impacts on receptors, positive or negative effects of CSG and coal mining development on the values of assets can be determined. While a BA provides advice on the receptors and assets, it does not analyse the economic or social impacts and risks of CSG and coal mining development. The information from a BA will provide a regional context for providing advice for decision makers. However, it is not a development-specific environmental impacts assessment. At the same time, BAs will undoubtedly inform development-specific assessments.

A BA comprises five components of activity:

- **Contextual information**: Component 1 presents the context and background against which qualitative and quantitative assessments of impact and risk of CSG and coal mining development are generated.
- **Model-data analysis**: Component 2 evaluates and synthesises information from data and models to develop a quantitative description of the hydrologic relationship between coal seam depressurisation and dewatering and associated impacts on anthropogenic or ecological receptors.
- **Impact analysis**: Component 3 reports and records the direct, indirect and cumulative impacts and associated uncertainties of impacts of CSG and coal mining development on receptors within assets and their associated uncertainties.
- **Risk analysis**: Component 4 provides a scientific assessment of the likelihood of impacts on receptors contained within assets based on the propagation of uncertainties from models and data.
- **Outcome synthesis**: Component 5 delivers a synthesis of outcomes used by the IESC to support scientific advice on impacts and risk of CSG and coal mining development on water resources.

These five components guide and organise the overall BA. A key element to any bioregional assessment is the development of baseline information so that impacts can be assessed against the current state of the region. The key baseline information requirements are outlined in this document. Information generated during the contextual information and model-data analysis components accumulates to provide knowledge used in the impact analysis and risk analysis components. The impacts and risks are focused through the receptors contained within water-dependent assets (as described above). The components are not sequential in time; rather they are largely overlapping, and information passes between components of the BA via multidisciplinary interactions. In this way groundwater and hydrogeology information on dewatering at depth can inform ecological impacts on receptors at the surface. A key aspect of a BA is the characterisation and propagation of uncertainties in order to provide scientific advice on the likelihood of impacts on receptors and their associated risks.

Specific workflows will vary between BAs in response to the availability of existing data, information and fit-for-purpose models. The products derived from a BA are subject to review and updates to ensure they provide an enduring source of scientific information with which to frame ongoing advice to the Minister.

While a BA ideally is a quantitative analysis of impacts, it is recognised that data, information and model deficiencies may preclude this. In this case, semi-quantitative and qualitative methods are to be substituted – supported by multiple lines of evidence – to provide the best and most current scientific advice possible to date on the impacts of dewatering on receptors and water-dependent assets.

Where decisions are made in the exercising of the BRAM within a bioregion or subregion and scientific judgment must be exercised, the resulting decisions must be recorded in the workflows and made transparent. In each case, measures of confidence are required to be provided in the scientific advice. As such, the BA provides a defensible baseline statement as to the current state of scientific knowledge on the impacts of CSG and coal mining development on water resources within a bioregion and its subregions.

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1 Introduction

1.1 Background

This document presents the bioregional assessment methodology (BA methodology or BRAM) agreed by the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC). It is intended to set the scientific and intellectual basis upon which a consistent approach to all bioregional assessments (BAs) can be undertaken, to assist decision making in relation to the water-related impacts of coal seam gas (CSG) and coal mining.

The BA methodology provides the scientific basis or the 'how to' undertake bioregional assessments which addresses one of the requirements of the IESC under the *Environment Protection and Biodiversity Conservation Amendment (Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development) Act 2012.*

From a scientific perspective, the BA methodology records the process to collect and present bioregional information; to determine the direct, indirect and cumulative impacts of CSG and coal mining development on water resources; and to estimate the risks to anthropogenic and ecological receptors that arise from such impacts.

The BA methodology is not intended to be a customised blueprint or 'recipe book' for exact specification of a BA in any particular bioregion or sub-region, as each bioregion or sub-region will differ in data availability and physical characteristics. However, the BA methodology has a generic role in guiding and enabling consistency and rigour in each assessment despite differences among bioregions or sub-regions. The BA methodology is written for science researchers within agencies that are charged with the task of undertaking a BA.

1.2 Purpose

The BA methodology is the underpinning scientific approach to – and guidance on – conducting BAs, which will provide an information source for the IESC in preparing its advice to the Minister and regulators on project proposals and research priorities.

The role of the IESC is to provide scientific advice on the likelihood of significant impacts of proposed CSG and large coal mining developments on water resources (including impacts of associated salt production and/or salinity). The IESC endorses risk-based approaches to advising on the impacts of proposed developments on the values of water-dependent assets.

A BA, as defined in the National Partnership Agreement, is 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 CSG and coal mining development on water resources. The IESC was established under the Commonwealth's *Environment Protection and Biodiversity Conservation Amendment Act (2012)* to:

- improve the science base in relation to the interaction of CSG and large coal mining developments and water resources
- provide Commonwealth, state and territory governments with expert scientific advice relating to CSG and large coal mining development proposals likely to have a significant impact on water resources.

Within a BA, data and information are assembled for formulating expert scientific advice on specific bioregions.

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

Outputs from a BA consist of:

- scientific advice on the likelihood of direct, indirect and cumulative impacts on anthropogenic and ecological receptors contained within water-dependent assets
- conceptual modelling of the causal pathway establishing the chain of interactions connecting depressurisation and dewatering of coal seams at depth with impacts on receptors located at or near the surface
- quantitative, semi-quantitative and qualitative results from relevant ecological, surface water hydrology, groundwater, hydrogeology and CSG or coal mining development models that provide information on the extent and nature of impacts in response to pathways of CSG and coal mining developments
- measures of confidence in the advice regarding impacts on receptors
- advice on the likelihood of risks to receptors and water-dependent assets under CSG and coal mining development pathways – and the potential consequences
- information on monitoring programs, the frequency of future BA reviews, the nature and type of additional risk assessment studies that may be required, and possible approaches to risk mitigation for minimising significant impacts.

It is not possible to define a prescriptive process that would produce a BA for any given bioregion when followed step by step, due to the differences in data, geology, hydrogeology and ecology across regions, as well as differing CSG and coal resource development pathways:

- the highly multidisciplinary and integrative nature of a BA
- the plethora of different philosophies, methods and languages used in each of the disciplines
- the technical details of specific measurement and modelling methods undertaken.

Instead of a prescriptive process, this document specifies an overarching principle to the generation of BAs. Where departures from this principle occur (due to deficiencies in data, information and models), 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 principle underpinning a BA is as follows:

> *The methodology must be, to the extent possible, a quantitative analysis of the impacts of dewatering and depressurisation of coal seams on surface or near-surface receptors contained within water-dependent assets located within a bioregion. The applied methodology will use coupled models for hydrogeology, surface hydrology, and impacts (both anthropogenic and ecological). The modelling will be constrained by groundwater and surface water observations and incorporate a quantitative assessment and propagation of statistical uncertainties from the event (dewatering and depressurisation) to location of*

impact (anthropogenic and ecological receptors). Where quantitative methods are not feasible (due to knowledge deficiencies), semi-quantitative and qualitative methods will be substituted, supported by multiple lines of evidence to provide scientific advice on the impacts and risks to assets and receptors. Where decisions are made and scientific judgment exercised, these decisions and judgments will be recorded and made transparent in the reporting process. A bioregional assessment will provide scientific advice on the likelihood of direct, indirect and cumulative impacts of the event on receptors and identify and quantify associated risks to the value of water-dependent assets.

In this way, the BA builds a compendium of knowledge across multiple disciplines that begins with the best scientific information available at the present time; includes what is known and what is not known about the impacts of CSG and coal mining development on water-dependent assets; and provides a pathway for iterative improvement of this knowledge into the future by way of monitoring and new research.

The BA methodology supports the following objectives, from the Council of Australian Governments (COAG) and others:

- understand the hydrogeologic and flow regimes of a bioregion prior to future CSG and coal mining development
- understand the state and natural variation of key water-dependent assets located in the bioregion undergoing CSG and coal mining development
- understand the characteristics of the target CSG and coal resources and hence the likely techniques, and associated water volumes, involved in their exploitation
- for receptors identified for key water-dependent assets, understand the:
  - impacts of CSG and coal mining development during the extraction phase
  - post-mining impacts of CSG and coal mining development
  - direct, indirect and cumulative impacts of CSG and coal mining development
  - effects of natural variability on exacerbating or suppressing impacts of CSG and coal extraction.

1.3 Focus on significant water resources

The National Partnership Agreement on Coal Seam Gas and Large Coal Mining Development prescribes that the BAs focus on the impacts on water resources. CSG and large coal mining developments may have multiple impacts on the environment (National Research Council, 2010). For potential impacts to be assessed using the BA methodology, they must be considered (or mediated) through changes in water resource dependencies of receptors contained within water-dependent assets (see Sections 3.4 and 3.5 for more detail on water-dependent assets and receptors). For example, it is outside the scope of the BAs to assess changes in air quality that do not ultimately also influence the quality of water required by assets or receptors.

A **water-dependent asset** is an entity contained within a bioregion where the specific characteristics can be ascribed a defined value and which can be clearly linked, either directly or indirectly, to a dependency on groundwater or surface water quantity or quality. **Receptors** are discrete, identifiable attributes or entities associated with water-dependent assets that are materially impacted by change in water quality or quantity arising from CSG or coal mining development. Receptors are the primary mechanism for reporting on the direct, indirect and cumulative impacts in a BA. **Response variables** associated with receptors link receptors with impact models and recommended monitoring programs. These links are explained in detail in this document.

According to the National Partnership Agreement, a significant impact on water resources is caused by a single action – or the cumulative impact of multiple actions – that would directly or indirectly:

- result in substantial change in the quantity, quality or flow regimes of surface water or groundwater
- substantially alter groundwater pressure and/or watertable levels
- alter the ecological character of a wetland that is state or nationally significant or Ramsar-listed
- divert or impound rivers or creeks or substantially alter drainage patterns
- reduce biological diversity or change species composition or ecosystem processes
- alter coastal processes and inland processes, including sediment movement or accretion, or water circulation patterns
- result in persistent organic chemicals, heavy metals or other potentially harmful chemicals accumulating in the environment such that biodiversity, ecological integrity, human health or other community and economic use may be adversely affected, or
- substantially increase demand for – or reduce the availability of water for – human consumption or ecosystem services.

This scope of potential impacts guides local natural resource management and catchment management authorities in identifying the assets and receptors to be studied in BAs. Much of the impact and risk to receptors is dealt with, or mediated, through changes in water quantity or quality (with focus on salinity). For anthropogenic receptors, the impacts may be direct and quantifiable (see Section 3.5 for examples of receptors). For anthropogenic and/or ecological receptors, the variability – including the magnitude, frequency, reversibility and duration of these changes – is important to characterise.

The BA methodology is a 'best-practice' approach using best available data, information and models, and/or timely investment to fill gaps in data, information or models. It is anticipated that practical considerations will influence the degree to which any specific assessment achieves implementation of the full BA methodology. Where this occurs, the BA methodology specifies that science-based judgment is used, decisions are documented, and that products and workflow of BAs (as implemented in practice) are documented and made publicly available. Such documentation is critical to transparency and to the independent replication and confirmation of outcomes from BAs.

Because scientific knowledge used to inform policy and regulatory decision making is often incomplete, but continually improving, the BA methodology emphasises that uncertainty in the results from BAs be characterised and reported. There is a relationship between uncertainty in assessment outcomes and the degree to which the full BA methodology is implemented. It is expected that uncertainty is influenced by the availability of existing data, information and models, and to the degree that gaps in such are filled through investment in new data, new information, model enhancement or model development.

1.4 Organisation of this report

Chapter 2 provides a summary of components of the BA methodology. Chapters 3, 4 and 5 provide more details for components in the BA methodology summarised in Chapter 2. In order to achieve compatibility of data outputs, it is anticipated that coordinated archival and access to data resulting from BAs will be undertaken by the Bureau of Meteorology and that the lead research agencies, CSIRO and Geoscience Australia, will be engaged to undertake significant components of BAs. Importantly, state government agencies, natural resources management agencies and universities will provide crucial data and expert knowledge into the development of BAs.

2 The methodology for bioregional assessments

2.1 Overview

The BA methodology guides the analysis of potential direct, indirect and cumulative impacts on receptors that can be assessed at a regional scale. It is not a development-specific environmental impact assessment but does result in BAs that can inform development-specific assessment.

The BA methodology is conducted in five components (Figure 1):

- **Component 1**: Contextual information
- **Component 2**: Model-data analysis
- **Component 3**: Impact analysis
- **Component 4**: Risk analysis
- **Component 5**: Outcome synthesis.

Information generated during the contextual information and model-data analysis components accumulates to provide knowledge used in the impact analysis and risk analysis components. The impacts and risks are focused through the receptors contained within water-dependent assets (described in Section 2.5.1.3). The components are not undertaken sequentially in time; rather all components are largely overlapping in time and information passes between components via multidisciplinary interactions. In this way groundwater and hydrogeology information on dewatering at depth can inform ecological impacts on receptors at the surface. A key aspect of a BA is the characterisation and propagation of uncertainties in order to provide scientific advice on the likelihood of impacts on receptors and their associated risks.

Products are generated during each component and range from publicly accessible data and contextual information (Component 1) to products that summarise outcomes such as regional-scale analyses of impact and risk (Component 5). In components 3 and 4, impacts and risks to receptors are assessed for a range of pathways of regional CSG and coal mining development that could be expected to occur in the future. Development pathways can vary widely among assessed bioregions in relation to factors including the extent of current development, status of existing tenements, and the bioregion's geology and coal resources.

The BA methodology used to undertake a BA within each bioregion or sub-region is shown in Figure 1. It indicates an appropriate best practice to be achieved during the assessment process. Where best practice cannot be achieved due to insufficient data, information or models, the best available data and models are to be used. Deviations from the BA methodology are to be identified and documented in the workflow with justifications.

The BA methodology is applied to bioregions and their subregions. The application of the BA methodology to bioregions or subregions is referred to as a BA project (a 'project') and the output from each project is a series of BA products ('products'). The products are described in more detail in Section 2.5.5. The products generated from the BA are the tools to support scientific advice provided by the IESC to the Federal Minister. The BA also provides advice on knowledge and data gaps, recommended revision frequency and monitoring programs, and additional studies.

In applying the BA methodology, the workflow used needs to be captured, decision points recorded, and gaps in data and relevant capability recognised. In setting up the workflow, consideration must be given to minimum duration and workforce requirements of each component. The documentation of the project and its subsequent reporting through products must be of sufficient detail and clarity that the veracity of the assessment can be ascertained by an independent external reviewer and the work repeated by any individual or group external to the assessment process.

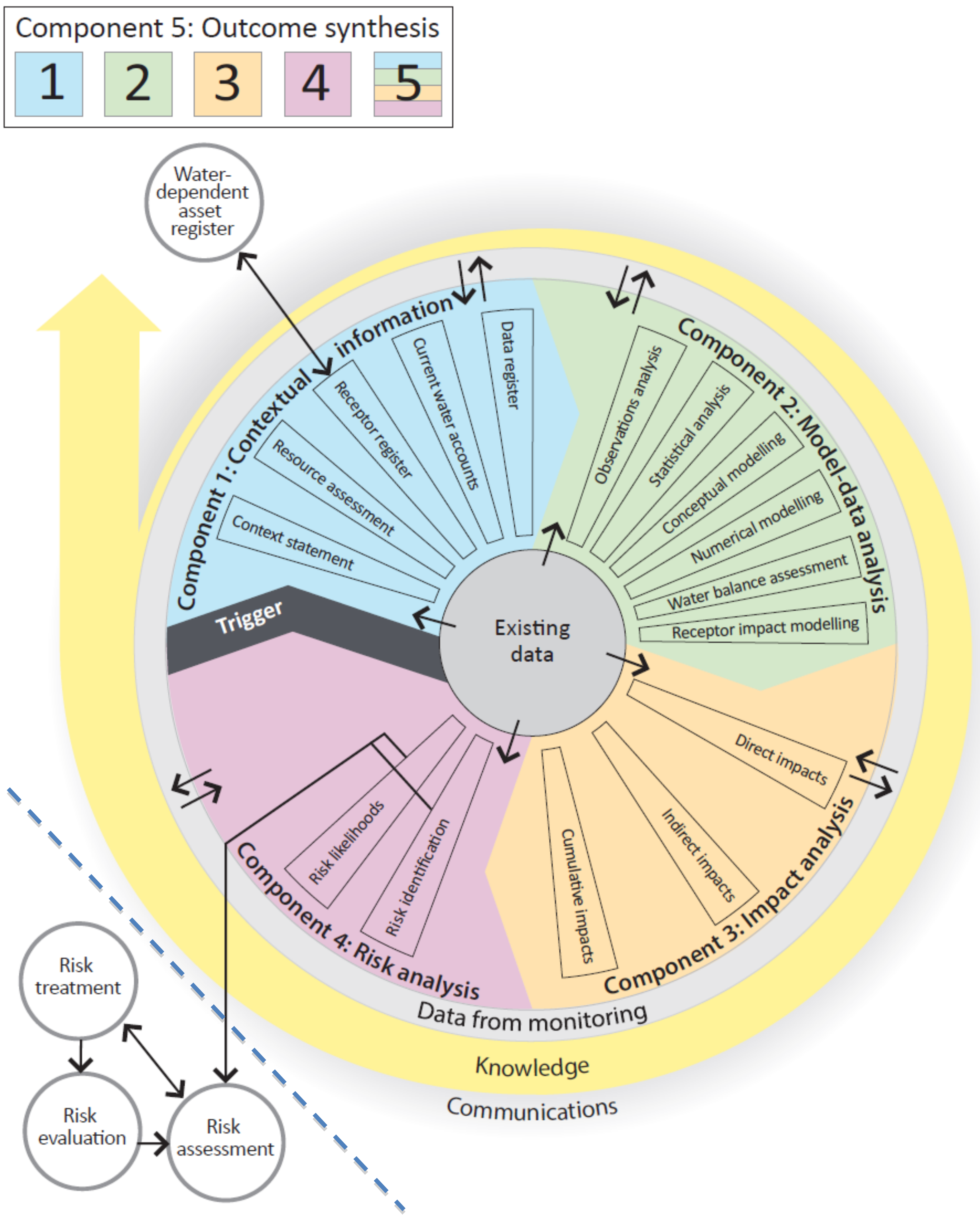

Figure 1. Schematic diagram of the bioregional assessment methodology. The methodology comprises five components each delivering information into the assessment and building on prior components thereby contributing to the accumulation of scientific knowledge. The risk identification and risk likelihood components are conducted within a bioregional assessment and may contribute to risk evaluation, risk assessment and risk treatment undertaken externally

2.2 Definition of a bioregion

A ‘bioregion’ is usually defined as an area of broadly comparable climate, lithology, terrain, geography, vegetation, fauna and land use attributes. However, this definition is too narrow for use here.

In the BA methodology, a bioregion is:

> *the land area that constitutes a geographic location within which is collected and analysed data and information relating to potential impacts of coal seam gas or coal mining developments on receptors identified for key water-dependent assets.*

In this context, a bioregion is the area within an arbitrarily defined boundary on the land surface that takes into account the spatial domain of influence linking water-related impacts of CSG and coal mining development to the material direct, indirect and cumulative impacts on receptors.

For the convenience of processing large volumes of data and clarity of presentation, a bioregion may be divided into a set of ‘sub-regions’. Each subregion is an identified area wholly contained within a bioregion that enables convenient presentation of outputs of the BA largely independent from other subregions.

Complex relationships between the geographical distribution of coal resources, water resources, assets and receptors can make the selection of a bioregion boundary difficult. For example, various configurations of ecosystems, water uses, and complex below-ground surface geology may be encompassed. Downstream and distant impacts and connectivity pathways between distant ecosystems need to be considered. Primary sources of data to define bioregion boundaries include water catchments (as defined by the Bureau of Meteorology), coal basins (Geoscience Australia) and natural resource management boundaries (SEWPaC, 2010). Final determination of the location of bioregional boundaries lies with government based on advice from the IESC.

2.3 ‘Far-field’ impacts beyond a bioregion boundary

There may be limited circumstances where isolated impacts may occur over restricted areas at great distances from a CSG or coal mining development. Alternatively, impacts may occur across several bioregions or subregions such as in the eastern Australian coal fields of Queensland and New South Wales. For example, direct drawdown effects on a watertable can change the availability of groundwater or surface water, which in turn may cause indirect impacts on water-dependent assets such as springs elsewhere in a basin. Furthermore, some cumulative impacts may have the greatest potential to be significant outside the prescribed bioregion boundary.

Under these circumstances, it may be unfeasible or impractical to extend a bioregion boundary to incorporate ‘far-field’ and isolated impacts. In this case, the impacts and risks are to be evaluated by the BA methodology as though the assets and receptors were inside the bioregion boundary. The analysis of impacts and risks is to be undertaken and included in the BA reporting process and the workflow updated to reflect the judgment and decisions as to why the boundary was not extended to encompass all impacts areas.

2.4 Temporal scales for assessing impact

The impacts of dewatering and depressurisation due to CSG and coal mining may reach far into the future. For example, groundwater systems may take decades to centuries to reach a new steady state. Therefore, all modelling time domains must be of sufficient duration that model dynamics have achieved quasi-equilibrium to within a stated tolerance. In addition, as the timescale of impacts increases, external factors such as climate change, population growth and agricultural expansion will interact with impacts from CSG and coal mining developments. As far as practicable, and within the bounds of uncertainties, BAs need to consider these interactions when framing advice. For example, where dewatering for coal production materially impacts a wetland over a 50-year life-of-mine, climate change impacts on that wetland may also need to be taken into account if long-term rainfall change is a co-factor in those impacts. For consistency across BAs, the same climate change scenarios must be used by all assessments and recorded or a specified general climate model output is to be used (e.g. the CSIRO Mk III GCM output).

Development pathways of coal resource development for bioregions must take into account all available information on CSG and coal mining exploration and production time frames. It is recognised that development timelines of CSG or coal mining development projects are subject to economic and technological determination with associated uncertainties. However, judgment is required to specify particular and realistic development pathways for consideration in a BA. Such considerations will include all stages of mine life including exploration, production, closure and mine legacy issues.

2.5 Components of the methodology for bioregional assessments

The BA methodology is undertaken in five components:

- **Component 1**: Contextual information
- **Component 2**: Model-data analysis
- **Component 3**: Impact analysis
- **Component 4**: Risk analysis
- **Component 5**: Outcome synthesis.

These components should be concurrent or largely overlapping in time, with each component designed to build on information gathered from prior components. In this way, information acquired during the contextual information and model-data analysis components is synthesised to develop the impact and risk analyses. It should be noted that the definition of 'model' used in this methodology includes all scientific definitions of the term model: that is, conceptual, numerical, analytical, semi-quantitative and qualitative representations of physical, chemical, biological and ecological processes.

As noted throughout this methodology, the degree to which each component achieves 'best practice' depends on data availability, model completeness and knowledge status for different bioregions. Deviations from best practice, due to insufficient data, inadequate models or lack of knowledge, is to be recorded in the workflows, and judgment exercised as to how best proceed and the BA completed. In all cases, though, the BA is a statement of the current state of best scientific knowledge concerning impacts of CSG and coal mining development on water-dependent assets within bioregions.

Monitoring and review comprise an important additional program that improves the assessment over time as periodic updates or revisions of BAs occur. Given the development of a monitoring program, the BA methodology anticipates consideration and evaluation of the review frequency of bioregional advice as part of a BA. This additional program will be concerned with ongoing acquisition of data for improvement in model performance and developing a review process for iterative improvement of a BA in a given bioregion. The monitoring and review program must also advise on the costs and benefits of recommended additional work to ensure that monitoring effort maximises a reduction in uncertainty in a future update of a BA.

Advice that BAs should provide on the monitoring program includes:

- an explicit description of knowledge gaps
- specifications for sampling
- periodic evaluation of results
- establishment of clear links between sampling and updating of model outputs
- locations and types of measurements to maximally reduce uncertainties in impacts
- identified development points for conceptual and numerical models
- where management authorities and companies can improve monitoring

While information flow is sequential from Component 1 through to Component 5, most activities undertaken within each component must be conducted in parallel with other components. For example, work on impact analysis (Component 3) and risk analysis (Component 4) would be initiated at the same time as work conducted to compile contextual information (Component 1) or data analysis and numerical modelling (Component 2). This is necessary because the impact and risk analyses must be framed in context of the available data and model outputs, while data evaluation and model conceptualisation and development must consider the requirements of impact and risk analyses. Iteration between components ensures that the information requirements of all components are met. In this way, the required knowledge base associated with CSG and coal mining development (namely, improved understanding of the direct, indirect and cumulative impacts on receptors and risks to those receptors and assets) grows during application of the BA methodology. Using a synthesis of information from key observations, outputs from data analysis and models, and a quantitative analysis of uncertainties, a risk analysis is obtained based on the best available information for a bioregion. In applying the BA methodology, new data will be analysed, and uncertainties in observations, datasets and models will be characterised. Transparency and objectivity are the cornerstones of the BA methodology with data and analytical techniques fully reported.

In five components, the BA methodology provides steps to assess the impacts of CSG and coal mining development within a bioregion for both current and future development pathways. The culmination of the first three components of the BA methodology is an integrated assessment of the impact of CSG and coal mining development on receptors identified for key water-dependent assets of a bioregion. This assessment will inform Component 4, the risk analysis. The impact and risk analyses are conducted for ‘receptors’ identified for all key water-dependent assets. The final component is the reporting and delivery of outcomes in products; the enduring process and products from a BA will ensure the lasting benefit of this approach.

2.5.1 Contextual information

The contextual information component (Component 1) provides a series of information products that describe the character of the bioregion, and are used to support qualitative or quantitative assessment of impact and risk. Contextual information includes all relevant datasets, background studies and subsidiary information on the ecology, hydrology, geology and hydrogeology of a bioregion that is necessary to interpret the impacts and risk analyses. Sub-components of the contextual information component are described in Sections 2.5.1.1 to 2.5.1.6 with more detailed guidance on selected components provided in Chapter 3.

2.5.1.1 Context statement

The context statement summarises the current extent of knowledge on the ecology, hydrology, geology and hydrogeology of a bioregion and provides baseline information. In some bioregions the context statement may be the first available summary of information relevant to understanding the regional context of water resources within which CSG and coal mining development is occurring.

The context statement is a collation of all information regarding a bioregion that is relevant to interpret the impact and risk analysis and outcomes of the BA. It characterises geology, climate, land use, hydrology, current water accounts, water quality, geomorphology, geography and land use of a bioregion. The statement should include materially relevant characteristics of a bioregion that are needed to adequately interpret output from ecological, surface water and groundwater datasets and models, and from this develop improved knowledge of whole-of-system functioning.

2.5.1.2 Coal seam gas and coal resource assessment

The CSG and coal resource assessment provides an evaluation of CSG and coal mining development over time, current reserves, and current and expected future levels of exploitation from exploration and approval through to production and mine closure. The impacts of these mine life stages on water dependent assets may occur over multiple decades and extend hundreds of years. These are considered in the model-data analysis (Component 2). Information or assumptions used to define the CSG and coal mining development pathways, such as mine type, mining methods and management, must be specified. For example:

- use of caving
- open-cut long-wall mining methods
- void treatment
- consequences on land surface through subsidence
- dewatering management methods
- water treatment
- decommissioning methods
- pit lake management plans
- CSG drilling methods including hydraulic fracturing and well stimulation
- treatment of associated water
- decommissioning and sealing wells.

The information on CSG and coal resource assessment will be used to define current and future development pathways to be used in the numerical modelling (Section 2.5.2.5). Further details on the CSG and coal resource assessment are provided in Section 3.3.

2.5.1.3 Water-dependent asset register

The water-dependent asset register consists of the identification, description and listing of all significant water-dependent assets within the bioregion. A water-dependent asset is defined as an entity within a bioregion where the particular characteristics can be ascribed value and which can be clearly linked directly or indirectly to a dependency on water quantity or quality. The asset register needs to consider the identification and representation of different types of water-dependent ecosystems within a bioregion including taking into account developments in a national freshwater bioregional classification and species distribution schemes (e.g. the TraCK program; Kennard et al., 2010) such as those under discussion by the Commonwealth Environmental Water Holder and the Commonwealth Environmental Water Scientific Advisory Panel. Further guidance is provided in Section 3.4.

2.5.1.4 Receptor register

The receptor register contains a catalogue of all receptors for which direct, indirect and cumulative impacts are to be assessed through the BA methodology. One or more receptors are registered for each water-dependent asset. A receptor is defined as a discrete attribute or component of a water-dependent asset that may be measurably impacted by a change in water quantity or quality resulting from CSG or coal mining development. Further guidance is provided in Section 3.5.

2.5.1.5 Current water accounts and water quality

The current water account statement provides an assessment of:

- water resources (rainfall, runoff, evapotranspiration, surface water, groundwater, groundwater recharge and discharge)
- water infrastructure (weirs, dams, offtakes, bores)
- water allocations, licences, extractions and use within the bioregion broken down by sector (such as agriculture, forestry, urban, industry, mining).

Information on surface water and groundwater quality is required, particularly baseline condition and the identification of existing water quality threats and trends, and current measures to address them. A discussion on groundwater composition should cover naturally occurring gases in groundwater that not only identifies the source aquifer and age of recharge (National Research Council, 2010) but also indicate existing connections with coal strata.

2.5.1.6 Data register

The data register is a library of all datasets used in the model-data analysis and risk analysis. It describes their provenance, history, metadata and an analysis of confidence or uncertainty in these data expressed as far as possible in quantitative terms (standard deviations, root mean square error, coefficient of variance or other forms). Metadata are provided to describe all data and datasets used in the numerical modelling, including driver data of models and initial and boundary conditions for model simulations.

The data register includes the provision of advice on data deficiencies and if new sampling programs are required. It should be noted that the use of currently available observations as constraints on numerical models for the purpose of assessing impacts of regional dewatering on receptors will push the restricted information content of these datasets to their limit. Existing datasets would be expected to be augmented with new monitoring programs to be able to improve the quality of advice from successive updates of a BA.

2.5.2 Model-data analysis

The model-data analysis component of the BA evaluates and synthesises information obtained from observations (data) and the understanding of processes from models to develop a qualitative or quantitative description of hydrological relationships between coal seams and associated anthropogenic and ecological receptors. Confidence in inferences (based on models and data) must be assessed, and this uncertainty analysis used (in turn) for estimating impacts and risks in components 3 and 4.

2.5.2.1 Observations analysis

The observations analysis is an analysis and synthesis of data to determine key characteristics and processes of receptors and assets within a bioregion. The data may be used directly, or as input to interpretation tools.

The observations analysis includes an assessment of all forms of data errors and uncertainties; the spatial and temporal resolution of observations; and algorithms used in development of derived datasets (e.g. remote sensing datasets). It requires development of summary statistics that describe the nature, variation and uncertainty for all datasets – including observational, forcing and other data. It also incorporates an assessment of data gaps and requirements for new sampling.

2.5.2.2 Statistical analysis and interpolation

The aim of the statistical analysis and interpolation is to develop a quantitative understanding of the ecology, hydrology, geology and hydrogeology of the bioregion based on available observations alone. The statistical analysis relies on the observations analysis (Section 2.5.2.1) to characterise the state of knowledge of groundwater and surface water resources based on interpretation and analysis of data. The statistical analysis and interpolation differs from the observations analysis in that it attempts to characterise knowledge of the water resources of a bioregion or sub-region where observational data exist and then uses this data to interpolate into data-sparse locations. Importantly, the statistical analysis will provide an evaluation of the confidence in the datasets and the characterisation of statistical errors in observations used to assess impacts. This information contributes to the robustness of the interpretation of impacts and risks that can be achieved using existing information. The statistical analysis will identify areas that potentially cannot be characterised without collection of additional data.

Interpolation, filtering and inference methods are well known and used regularly. For example, in geology, hydrogeology and groundwater observations, geostatistical methods are well developed. In surface water hydrology, prediction tools for spatial processes are available. For ecology, spatial modelling of species distributions and their responses have been developed (e.g. TRaCK; Kennard et al. (2010)).

The interpolated fields from statistical analyses can be used in the numerical modelling as a means of constraining model states and parameters. It includes the application of spatial analysis and interpolation methods for assessing the distribution and uncertainties in aquifers, aquitards, rivers, wetlands and groundwater-dependent ecosystems and coal-bearing strata across the bioregion. It provides a supplementary information source (in addition to output from the numerical modelling) and, in some cases, may provide interpolated spatially distributed data needed to constrain dynamics of the numerical models.

The statistical analysis includes an assessment of data gaps and the design of a sampling network needed to maximally reduce uncertainties through future observations and field sampling programs. Such an assessment must be undertaken even if the spatial and/or temporal distribution of data is insufficient to allow statistical treatment as it will inform an assessment of the appropriate level of effort required for data collection and system conceptualisation in subsequent updates of the BAs.

2.5.2.3 Conceptual modelling

A conceptual model is a qualitative description of the systems and sub-systems within a bioregion. It describes the set of hypotheses as to how these systems interact with impacts of CSG and coal mining development and link closely with the qualitative, semi-quantitative and quantitative models used to describe impacts on receptors. Conceptual models in the BAs describe the causal pathway from CSG and coal mining development to the direct, indirect and cumulative impacts on receptors. They may comprise broad-scale coarse-resolution conceptual models within which fine-scale conceptual sub-models are nested to take into account the range of scales over which processes occur. Conceptual models developed for the BA must be comprehensive and detailed enough to satisfy known characteristics of interactions in a system, cognisant of the availability of data.

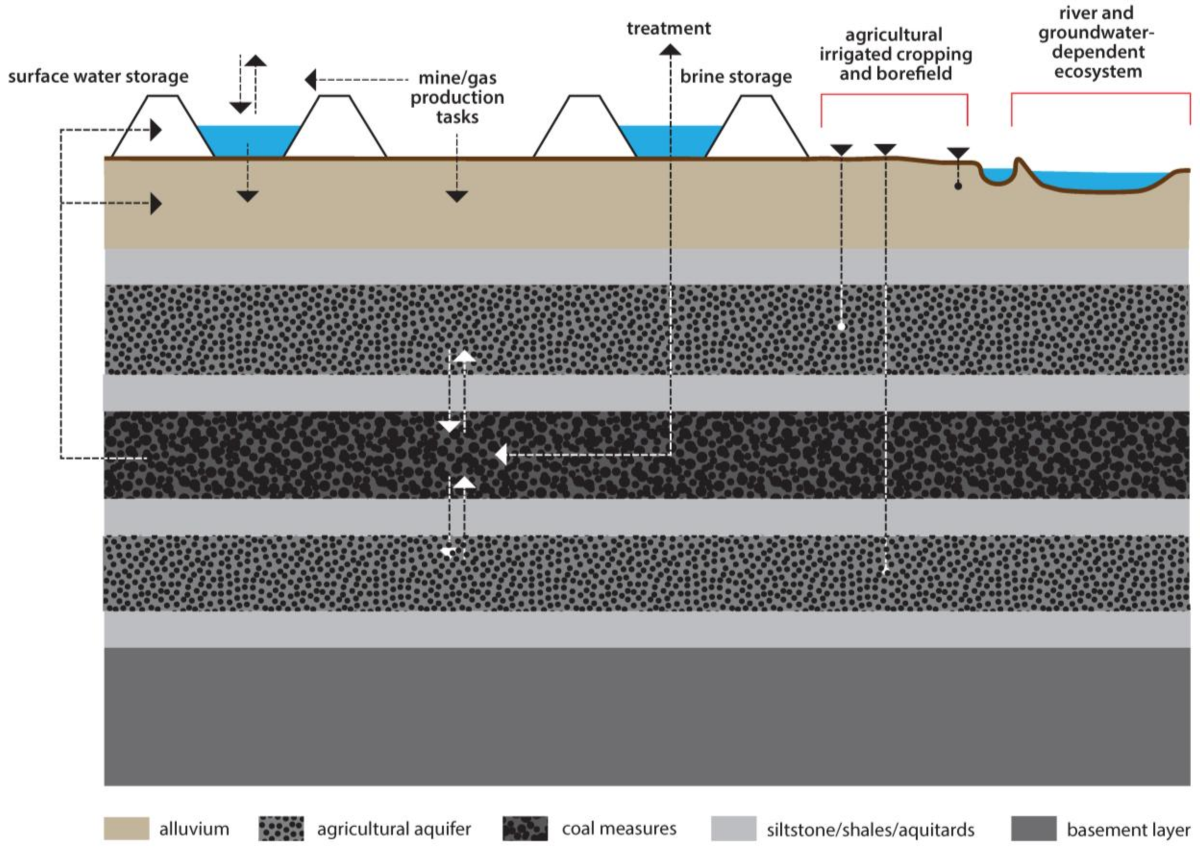

Figure 2. An example conceptual model of a bioregion

The conceptual model shall include:

- broad concepts of inflows and outflows to a bioregion in surface water and groundwater domains
- the location of catchment boundaries (including groundwater divides) and ecological distributions of receptor species
- the response functions of anthropogenic and ecological receptors
- the identification of receptors sensitive to changes in flow, groundwater levels and/or water quality.

Consideration of the timing of flow events, and of the impacts of seasonal and longer term fluctuations, is also a key component of the conceptual model. The Australian classification of unimpeded streams and rivers (Kennard et al., 2010) should be consulted to develop a baseline of flow regimes and their variance in space and time. Furthermore, evaluation of current status of a bioregion, or parts of it, in terms of degree of disturbance or perturbation of the natural system, is an important part of understanding the nature of baseline conditions and variation that exist prior to the commencement of any new CSG or coal mining development.

Conceptual models are iterative tools and, as knowledge improves incrementally during the course of the assessment, the number of possible conceptual models (or alternative hypotheses) decreases and the confidence in any individual conceptual model and their nested sub-models increases. The necessary changes in conceptualisation will cascade into the water balance assessment and into the fundamental parameters of numerical models; two- and three-dimensional visualisations will assist in communicating these concepts.

2.5.2.4 Water balance assessment

The water balance assessment is integral to a conceptual model and represents an analysis, over specific time periods, of:

- water inputs and allocations
- river and surface water management
- groundwater recharge and discharge
- water needs of floodplains, wetlands and groundwater-dependent ecosystems
- surface water – groundwater exchange
- natural surface water and groundwater flow
- the role of wetlands and floodplains in determining a bioregion water balance
- the impact of agricultural, forestry and urban or peri-urban development on the availability and use of water resources.

The provision of current data and/or estimations of all surface water and groundwater extraction in the bioregion (including that for current coal mining and CSG extraction) is a critical part of this assessment, together with an identification of the river reach or source aquifer, the water use, the measurement and estimation methods used to calculate the extracted volume, and the legislation that covers each form of extraction. The water balance assessment must include an estimation of the impacts of future water extractions, such as the activation of unused entitlement and the increase in use not subject to entitlement (e.g. extraction for stock and domestic purposes, uncapped bores and interception activities if relevant). The impacts of anticipated increases in extraction related to CSG and coal mining activities, as well as collateral impacts on the water balance extending beyond the water body in which dewatering activities are occurring, should also be assessed. Water balances developed for CSG and coal mining developments are likely to be in use by industry for active or proposed projects or can be estimated from expected production data, state agency datasets and environmental impact assessments.

Multiple water balances are required to represent both a bioregion and the time periods in which the anticipated activities will occur. A water balance is dynamic and requires an analysis of its temporal and spatial variation (due to natural and anthropogenic influences). As for conceptual models, water balance assessments are iterative and, with increased understanding of a bioregion, the water balance assessment will need to be refined.

2.5.2.5 Surface water and groundwater numerical modelling for current and future development pathways

Best-practice surface water and groundwater numerical modelling requires:

- a conceptual model
- representative data (both spatially and temporally) to inform parameterisation and calibration of models
- comprehensive flow modelling of groundwater dynamics for aquifers, coal seams and aquitards within the bioregion based on availability of data
- explicit connectivity of processes between coal seam(s), overlying and underlying aquifers, and assets that depend on surface water and groundwater
- fully coupled surface water – groundwater interactions using present-day climate forcing, water balance and land use or land management datasets
- qualification or quantification of conceptual and numerical uncertainties.

A numerical flow model is required to represent a complex hydrogeological system including physical flow processes, multiphase flow, calibration of model dynamics against multiple datasets, predictive runs and propagation of uncertainties. This requires development of fully coupled flow models that represent surface water – groundwater interactions and that update surface water and groundwater states dynamically during the simulation. The numerical modelling should conform to the checklist and guidelines of appendices F and H of Middlemiss (2001) and Tables 9-1 and 9-2 of Barnett et al. (2012). Simulation run times must be sufficient to represent all transient states in the model in order that slow processes and state variables (e.g. for groundwater dynamics) approach equilibrium to within a stated tolerance (e.g. within 1% of state variables such as hydraulic head). The time period for the modelling also needs to be relevant to the receptor of interest. Time periods extending for decades must account for climate change effects on model dynamics taking into account relevant Intergovernmental Panel on Climate Change scenarios.

The numerical modelling generates results for both current and future development pathways, which are defined in the CSG and coal resources assessment (Section 2.5.1.2 and Section 3.3). The future development pathways represent a range of plausible development pathways across the stages of coal or CSG extraction.

A key component of the numerical modelling is the quantification of statistical uncertainties associated with model outputs, covered in detail in Chapter 4. Model outputs and their uncertainties are to be propagated through the receptor impact modelling and the risk analysis.

2.5.2.6 Receptor impact modelling

Ecological knowledge and data are essential to developing an understanding of the impacts of coal seam depressurisation and dewatering on receptors contained within water-dependent assets. Extensive work already carried out by existing programs – for example technical assessments for water resource planning, the National Atlas of Groundwater Dependent Ecosystems, the Queensland GDE Mapping Project, Aquatic Conservation Assessments, and High Ecological Value

Aquatic Ecosystem Project – provide fundamental data forming the foundations of the BAs and underpin the receptor impact modelling.

The impacts of CSG and coal mining developments are mediated through changes in water resources requirements and/or dependencies of receptors. Integral to receptor impact modelling are consideration of the dependence of receptors (and through them asset values) on groundwater and surface water; the attributes of those dependencies; and the resilience, resistance, vulnerability and response of receptors (and hence assets). To put these impacts in context (Section 2.5.3) requires information from the contextual component of a BA.

Output from the numerical modelling (Section 2.5.2.5) is used as input into qualitative, semi-quantitative or quantitative receptor impact models. The conceptual models (Section 2.5.2.3) are used to guide development and implementation of the receptor impact models. These models are required to estimate the direct, indirect and cumulative impacts on anthropogenic and ecological receptors. The range and variety of receptor impact models will vary among bioregions, depending on the type of water-dependent assets and receptors contained therein. The large majority of receptors would be expected to be near or at the surface. However, some receptors (e.g. stygofauna and agricultural wells) may be at depth.

Whether receptor impact modelling is qualitative or quantitative will depend on the level of understanding of the relationship between a receptor and water quality or quantity, and on output from the surface water and groundwater modelling. Estimation of impacts may be semi-quantitative where some components can be determined numerically with some confidence, but other components are less precisely defined or are not linked to numerical models. Qualitative models may be appropriate for estimating impacts on hydrological processes such as recharge. Conceptual models may be appropriate for some ecological receptors such as breeding success where the links between numerical modelling data outputs and impacts are less straightforward. Expert judgment is required in these cases and all decisions based on judgment must be recorded in the workflow for external scrutiny.

2.5.3 Impact analysis

All receptors contained in the receptor register within each water-dependent asset will be assessed in the impact analysis. This component will report the direct, indirect and cumulative impacts – and associated uncertainties – obtained in the surface water and groundwater numerical modelling, and the receptor impact modelling (Section 2.5.2.6), for current and future development pathways (Section 2.5.2.5 and Section 4.4). The impact analysis needs to consider the potential effects and consequences of CSG and coal mining development, thereby estimating the severity of impacts on the hydrogeology, as well as the causal chain connecting hydrogeology, surface water hydrology and ecological processes with receptors. Alternatively, the causal chain may link the application of desalination permeate, and the production, storage and disposal of brine, with agricultural receptors such as irrigated crops, alluvial aquifers or receiving aquifers from reinjection programs. As noted in the previous section, it is recognised that explicit, calibrated and validated models of many biophysical and ecological processes that impact on receptors as a result of dewatering and depressurisation of coal seams may not be sufficiently comprehensive and quantitative for high-confidence assessment of impacts on receptors. Therefore, the impact analysis is required to draw on all available information sources – including external peripheral datasets, empirical relations, auxiliary studies, literature reviews and any other sources – in order to assess receptor impacts using a 'multiple lines of evidence' approach. Where uncertainties are too large for quantitative assessment of impacts, qualitative assessments are to be provided with accompanying logic structure and evidence recorded in the workflow.

The integrated nature of the impact analysis requires clear statements of logic, evidence and confidence regarding impacts on receptors. A key challenge is isolating the impacts of CSG and coal extraction from the aggregate and incremental impacts from other sources (e.g. agriculture) that may impact on receptors over time. Where uncertainties are too large to assess cumulative impacts, this must be recorded in the BA workflow and advice must be given as to the research, sampling and monitoring programs that are needed to reduce these uncertainties substantially. An additional difficulty will be to differentiate between 'impacts' and 'change'. Baseline monitoring of systems coupled with receptor impact modelling are the tools by which natural variability of a system's response to dynamic forcing (e.g. by climate) is to be distinguished from changes that can be linked to impacts. Cumulative impacts of proposed new CSG and coal mining developments are to be considered at least over the time horizon of development pathways and longer if impacts occur beyond this.

2.5.4 Risk analysis

The IESC endorses the use of risk-based assessments as the best approach in providing scientific advice on proposed CSG and coal mining developments and their impacts on water-dependent assets. Risk is the 'the effect of uncertainty on objectives' where effect is 'a deviation from the expected' and uncertainty 'the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequence, or likelihood' (AS/NZS ISO 31000:2009 Risk management – principles and guidelines).

A risk analysis undertaken within a BA is concerned with likelihood of impacts on receptors contained within identified water-dependent assets and does not consider other risks (e.g. to landscape functioning and biodiversity).

An emphasis on rigorous assessment and propagation of uncertainty in BAs is key to their ability to provide robust scientific advice on risks. BAs must provide sufficient scientific advice as to the level of risk associated with impacts on water-dependent assets (e.g. Matters of National Environmental Significance and other important ecological and cultural water features). The analysis of risk is a key outcome of an assessment that utilises both:

- output from model-data analysis to define consequences via direct, indirect and cumulative impacts
- uncertainties to provide information on likelihoods required by the risk analysis.

Qualitative risk analysis methods (where likelihoods are provided in a descriptive way) provide a rapid and simple method for assessing first order or comparative risks to receptors – and subsequently key water-dependent assets – from CSG and coal mining development. With increasing reliability of observations and models, and adequate spatial and temporal distribution of observations, semi- or fully quantitative risk analyses are to be used to provide transparent, consistent and robust information on the likelihood of specified events occurring, and the potential consequences on receptors and, hence, water-dependent assets. The events under consideration within a BA include depressurisation and dewatering of coal seams; potential regulated and unregulated discharge of stored worked water on mine sites; and fate of CSG permeate and brine derived from treatments of associated water. A key component to the analysis is the use of formal logic procedures to ensure that the assignment of likelihoods and consequences is transparent and consistent. In particular, developing correct conditional statements for the likelihood of events occurring (Barry, 2011) is important to achieving accurate qualitative or quantitative risk analyses and assessments.

To ensure consistency between risk-related work undertaken among bioregions, the BA methodology requires compliance with the ISO 31000:2009 standard; however, full application of the ISO 31000:2009 standard is outside scope, terms of reference and budget of a BA. The components of the ISO risk assessment to be undertaken in a BA are:

- **risk identification:** the identification of risks within a bioregion through understanding exposure of receptors to impacts from CSG and coal mining development and how this exposure may affect values of water-dependent assets
- **risk analysis:** an analysis that combines likelihood of event occurrence, uncertainties associated with impacts, and information from the risk register to generate (i) a **consequence table** describing the nature of impacts, and (ii) a **risk rating matrix** describing the severity of impacts.

The risk evaluation and risk treatment components of the ISO 31000:2009 Risk Management Standards are the role of the proponent in the first place, and of Government, as the regulator of the proponents activities. For Government, risk evaluation and treatment requires careful consideration of a number of non-scientific matters that are outside the scope of the BA.

2.5.5 Products

The outputs of the BAs are five products that must contain at a minimum the following:

- **Product 1:** 'Bioregional assessment of NNNN basin/MMMM catchment: contextual information' contains sections on:
  - context statement
  - CSG and coal resource assessment
  - water-dependent asset register
  - receptor register
  - current water accounts and water quality
  - data register.
- **Product 2:** 'Bioregional assessment of NNNN basin/MMMM catchment: model-data analysis' contains sections on:
  - observations analysis
  - statistical analysis and interpolation
  - conceptual modelling
  - two- and three-dimensional visualisation
  - water balance assessment
  - surface water and groundwater numerical modelling for current and future development pathways
  - receptor impact modelling.

- **Product 3:** 'Bioregional assessment of NNNN basin/MMMM catchment: impact analysis' contains sections on:
  - direct impacts on receptors
  - indirect impacts on receptors
  - cumulative impacts on receptors.
- **Product 4:** 'Bioregional assessment of NNNN basin/MMMM catchment: risk analysis' contains sections on:
  - risk identification
  - risk analysis
- **Product 5:** 'Bioregional assessment of NNNN basin/MMMM catchment: Outcome synthesis' contains sections that synthesise the results from components 1 to 4:
  - summary of contextual information
  - summary of model-data analysis
  - summary of impact analysis
  - summary of risk analysis.

All data syntheses and databases are to be made available through existing Commonwealth Government data access systems linked to the Office of Water Science. All unencumbered tools and model code, procedures, routines and algorithms and all forcing, boundary condition, parameter and initial condition datasets used to generate the BAs are to be made publically available. Where commercial models are used, complete details of name, type, version and ancillary data are to be provided to a sufficient resolution that a third party in possession of these models could repeat the analyses.

Publication of the workflow associated with each BA is also required. This workflow comprises a record of all decision points along the pathway towards completion of the assessment, gaps in data and modelling capability, and provenance of data.

3 Contextual information

The contextual information component provides a series of information products that characterise the bioregion, and are used to support qualitative or quantitative assessments of impact and risk.

3.1 Bioregional context

3.1.1 Definition of bioregion as used in bioregional assessments

The concept of a bioregion (a biologically distinct or defined region) is well known and understood across a range of disciplines, including ecology, biogeography and conservation management. Consequently, a number of bioregional concepts have already been defined in the literature and in practice, but none of these clearly encompasses the mixture of CSG and coal resources, assets, receptors and management units required in the BA methodology. To provide clarity, a bioregion in the context of the BA methodology is defined in this section. The principles of 'materiality of impacts' and 'receptors' are critical to the delineation of the spatial extent of a bioregion. In general, receptors are sensitive to changes in flow and/or water quality and so the spatial extent of a bioregion should be sufficient that it covers all receptors contained within water-dependent assets that are materially affected (or likely to be) by CSG and coal mining development. After all of these considerations, the ultimate decision as to the spatial extent of a bioregion is arbitrary and lies with the government, with advice from the IESC. The bioregion may be subdivided for convenience into a series of subregions to facilitate presentation of outputs and analyses. Sub-regions are wholly contained within bioregions and to a large degree are independent of other sub-regions.

In an Australian natural resource management context, the most common understanding of the term 'bioregion' is that used in the Interim Biogeographic Regionalisation for Australia (IBRA; SEWPaC, 2012). The IBRA bioregions are derived from the work of those state and territory agencies that map vegetation communities and land systems. The bioregions and subregions within them are the reporting units for assessing the status of native ecosystems and their protection in the National Reserve System. Much of the data collected at the IBRA scale will be relevant to the BA methodology. However, IBRA regions and subregions (derived from topographical and climatic factors which influence vegetation composition and structure) are poorly correlated with the distribution of CSG and coal resources, or with groundwater or surface water catchments.

Other examples of bioregional definitions recognised in an Australian legislative context include those employed under the Ramsar Convention, and the Convention on Biological Diversity. The Ramsar Convention (2006) recognises a biogeographic region as being a 'scientifically rigorous determination of regions as established using biological and physical parameters such as climate, soil type, vegetation cover, etc.' and goes on to note that 'in some circumstances, the nature of biogeographic regionalisation may differ ... according to the nature of the parameters determining natural variation'. Bioregions recognised by Ramsar (for example, the Riverland, South Australia) tend to recognise component parts of terrestrial catchments and so sit within bioregions recognised by this report and as such may provide valuable contextual data and information both on assets and potential means of exposure of those assets to changes in environmental water quality or quantity due to CSG or coal mining development.

The definition of a bioregion adopted in the BA methodology is compatible with 'a geographical space that contains one whole or several nested ecosystems' (Miller, 1996). A bioregion encompasses a discrete set of assets and receptors and is defined on the basis of CSG or coal mining development, impacts or management boundaries, whichever proves the most appropriate (see Section 2.2). The bioregion takes into account the vertical and horizontal distribution of surface and subsurface features associated with surface water and groundwater hydrology and the CSG and coal resources (see Table 1). This definition builds on the existing recognition that the definition of a particular bioregion depends on the scale at which its characteristic features are measured (DEH, 2006).

Table 1. Vertical and horizontal distribution of features that influence the spatial extent of a bioregion considered in a bioregional assessment

Vertical location	Features	Determining factors
Surface	Landform, vegetation, community, surface water hydrology, catchments, groundwater recharge and discharge zones	Soils, climate, land use, geomorphology
Subsurface	Groundwater systems, alluvium	Geology, geomorphology, climate
Subsurface	CSG and coal mining development	Geology

Figure 3 illustrates these concepts with a stylised representation of a bioregion as defined in the BA methodology. The bioregion takes into account the vertical and horizontal distribution of surface and subsurface features associated with surface water and groundwater hydrology and the CSG and coal resource where it intersects or has direct, indirect or cumulative impacts with surface assets (quantified through the impacts on receptors). The identified assets in this hypothetical bioregion are irrigated cropping, a gaining or losing river, and a groundwater-dependent ecosystem (GDE). The receptors within these assets are water levels in wells tapping shallow and deep aquifers for use in irrigated cropping; flow at nodes along the river system; and specific aspects of the GDE such as abundance of nesting sites or communities dependent on seasonal inundation for part of their life cycle. The bioregion contains four ecosystems with the GDE embedded within ecosystem 3, an alluvial aquifer adjacent to a shallow aquifer that are both actively recharged, two deeper aquifers used to supplement irrigation water during dry periods, two coal measures from different geologic basins (one overlying the other), and all underlain by a deep aquifer. The horizontal scale is of the order of 100 km and the vertical scale is approximately 0.5 km. In this hypothetical example, the shallow coal measure is depressurised using vertical drilling for CSG extraction while the deeper coal measure is horizontally drilled. An open-cut and underground coal mine exists where coal seams occur within 150 m and 200 m of the surface, respectively, and dewatering of the associated aquifers is required for coal extraction.

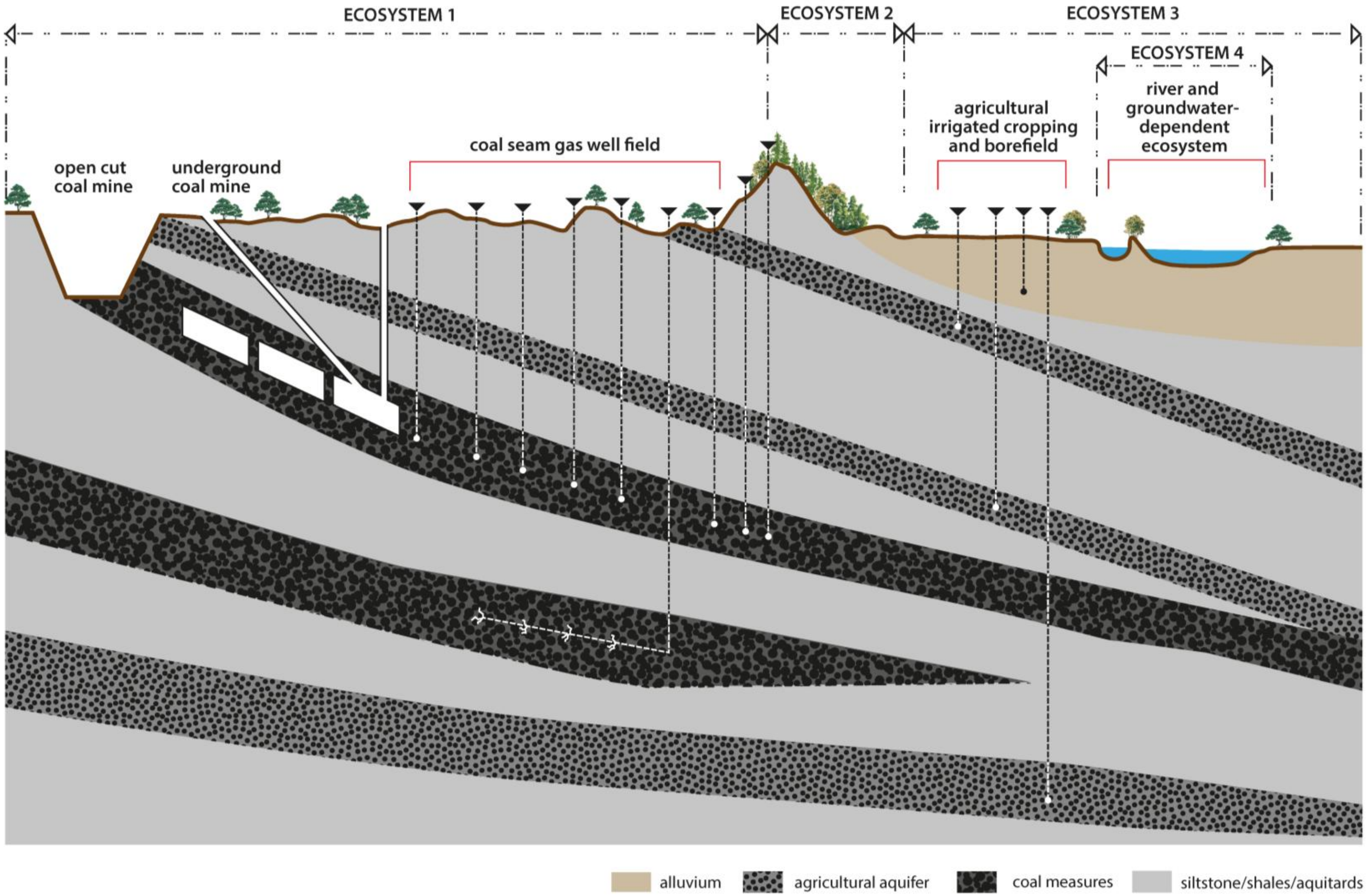

Figure 3. Stylised depiction of relationships between coal resources, mining, coal seam gas extraction, water resources and uses, and ecosystems within a hypothetical bioregion

3.1.2 Relevant spatial scales for different assets

Data available to support the BA methodology (identified and acquired in Component 1) will have been generated for various purposes by a variety of individuals, organisations and agencies. It is also likely to have been generated at a variety of spatial scales, some of which will have more relevance to the BA methodology than others.

Data and model resolutions of 1 km^2 may be sufficient for some broad applications (e.g. the Rapid Regional Prioritisation Process; IIESC, 2012). This was adequate to assess the likelihood of broad asset classes intersecting with CSG and coal mining development, but in considering exposure of assets and receptors, other spatial scales may be more appropriate to fully realise the potential for impacts and their amelioration. For example, vegetation is typically mapped at the 1:50,000 or 1:100,000 scale, and for management, conservation and statutory protection under the EPBC Act vegetation units of 1 ha may be considered, so for listed communities such a resolution is preferable for consideration rather than the 1 km^2 scale.

When dealing with protected species, the spatial scale considered should be determined with reference to their biology, and to the life history stages potentially affected through changes in water quality or quantity. This may mean that for some assets any potential exposure needs to be considered at a supra-regional scale, while for other assets point-source impacts may be more appropriate.

3.2 Context statement

The context statement assembles, organises and reports pre-existing data sets and information on the ecological, hydrological, geological and hydrogeological characteristics of a bioregion and its sub-regions, as well as its anthropogenic and ecological receptors . A key component of the contextual statement is a scientific review of all relevant literature and evidence on:

- the direct, indirect and cumulative impacts of CSG and coal mining development on human and natural systems
- the time and space scale of these impacts
- key receptors and response variables to be considered in a BA.

The information is relevant as a descriptive baseline.

3.2.1 Geology

The geology of bioregions provides the fundamental information for understanding CSG, coal and groundwater resources. An understanding of the geology allows the determination of the spatial distribution of future mining activities and their potential impacts. The geological characterisation of a bioregion requires analysis of all available information including the (i) geological structural framework, (ii) stratigraphy and rock types, and (iii) basin history.

3.2.1.1 Geological structural framework

The size and form of the major sedimentary basins and their controlling basement structures provide an important basis for understanding bioregions and their interaction with extractive industries. The location of major coal-bearing basins within the bioregions will define the spatial distribution of potential locations for coal mining and CSG extraction. Detailed structural mapping of the basin needs to be undertaken and key stratigraphic units (aquifers, aquitards, coals) identified. Basin boundaries need to be mapped and groundwater movement through the basin understood.

The depth of coal-bearing units from the surface is the primary controlling factor in the identification of bioregions where coal mining is possible and CSG extraction likely. Presently, coal mining is restricted to areas where coal can be found at depths of less than 600 m. Therefore only bioregions where coal occurs at less than this depth are likely to be mined by open pit and underground techniques.

Depth of the objective coal sequences is also a significant control on CSG development. CSG developments in Australia have traditionally targeted coal sequences between 200 m and 1000 m below the land surface (Draper and Boreham, 2006). The depth cut-off for CSG developments reflects decreasing permeability with depth and the high cost of drilling the many deep wells required to achieve viable CSG production. While technological advances may improve the efficiency of deep CSG drilling, the depth of the objective coal beds will remain a critical limiting factor on the location of CSG developments.

Structural framework studies should also include mapping of major faults, folds and other tectonic features. Faults form discontinuities that may allow enhanced vertical fluid migration between units and between aquifers and the surface. Conversely, faults and folds may isolate parts of rock units from fluid flow. Faults, folds and joints are important in some CSG fields in enhancing coal permeability (Draper and Boreham, 2006). To assist in the understanding of fault orientation and distribution within a basin and the potential behaviour of sedimentary rocks that may be subjected to hydraulic fracturing as part of a CSG development, analysis of tectonic stress regimes may be required.

3.2.1.2 Stratigraphy and rock type

The distribution and character of sedimentary units should be determined (facies analysis). At a basic level, the presence or absence of coal in part of a bioregion determines whether there will be any direct impacts, downstream effects or no impacts at all. Sedimentary units are rarely homogenous and frequently exhibit great vertical and lateral variability. Palaeogeographic and lithofacies analysis of coal-bearing sequences, aquifers and aquitards is therefore required. Overburden thickness, the volume of accessible coal and coal rank determine the distribution of coal mining activity within a basin. While the thickness of individual coal seams is a key determinant of coal mine viability, the total amount of coal present within a sedimentary unit(s) is a key determinant of CSG potential. Understanding groundwater resources, groundwater flow, CSG potential and the risks associated with CSG extraction requires a detailed knowledge of the structural geology of the basin and an understanding of the sedimentary units found within the stratigraphic succession.

An integrated approach to stratigraphic analysis that includes quantitative well log analysis, core and cuttings analysis, petrophysical measurements (porosity, permeability) and geophysical interpretation should be used to quantify the properties and the distribution of the key sedimentary units (coal, sandstone, shale, mudrocks) within the basin, with particular reference to their ability to allow or impede the flow of groundwater. This will improve the understanding of the basin architecture and heterogeneity within aquifers and aquitards. Where geophysical and well data are either sparse or absent, the applicability of methodologies such as geostatistics should be investigated.

3.2.1.3 Basin history

Basin history – with particular reference to coal-bearing units, aquifers and aquitards – needs to be obtained from pre-existing modelling and exploration data. The thermal history of a basin must be documented as this determines coal rank, the composition (including CO_2 content) and volume of gas associated with coal and coal permeability. These are key factors in determining the potential of a coal to constitute either a mineable deposit and/or a source of CSG. Basin history must include an understanding of the evolution of groundwater systems. This approach will enable factors in a basin's evolution to be identified that may have an impact on potential viability of CSG and coal resource development pathways.

3.2.2 Hydrogeology and groundwater quality

Existing information on the hydrogeology of a bioregion must be obtained and documented so that the potential impacts of coal mining and CSG extraction (such as saline water and fraccing chemicals) may be evaluated. Pre-existing information should include hydrostratigraphic characterisation of the bioregion from the surface to basement rocks. While the hydrostratigraphy will refer to the units discussed in Section 3.2.1, they will be identified in terms of their main hydrogeological characteristics (aquifer, aquitard, aquiclude). The assessment should include mapping of the lateral and vertical extents of individual hydrostratigraphic units, identifying recharge and discharge areas and zones of potential leakage between units.

Pre-existing information on hydraulic properties (such as hydraulic conductivity, porosity and interaction with other units) should be documented for each hydrostatigraphic unit. In cases where there are insufficient data to adequately characterise hydrostratigraphic units, this too must be identified at this stage. The degree to which the available data adequately characterises individual hydrostratigraphic units should also be assessed and documented. Prior evidentiary material used to describe the hydraulic and flow characteristics of these units should be clearly identified and referenced. Studies on the extent and integrity of hydrostratigraphic units must be discussed in the context of how they contribute to the understanding of their hydraulic characteristics and flow behaviour. A discussion of the lateral variability within individual hydrostratigraphic units should be included.

Where possible, estimates of baseline groundwater chemistry, including hydrocarbon concentration and composition, is required to allow reliable detection and attribution of any changes which may take place due to CSG activities. This information, when incorporated with hydrodynamic and geological models, will assist in detecting and estimating existing inter-aquifer connection. Further, the spatial variability of hydrochemistry in groundwater can contribute to the conceptualisation of existing groundwater flow regimes.

Hydrodynamic baseline information on physical groundwater conditions (level, pressure, temperature and flow direction) should be provided. In the absence of appropriate data, an appropriate data collection program should be undertaken as part of the BA to establish the baseline information against which the impact of future activities may be measured. Any baseline data collected should be viewed and reported in the context of historical trends (e.g. a single water level measurement may be misleading if long-term trends are not considered).

The assessment should include a discussion of the influence of structural and/or stratigraphic features (building upon features identified by the geological assessment in Section 3.2.1) on hydraulic properties and flow behaviour within and between hydrostratigraphic units.

The potential for interconnection between hydrostratigraphic units and between surface water bodies, including the support of groundwater-dependent ecosystems (GDEs), should be articulated. This information will provide the basis to clearly identify the extent of understanding of the groundwater system in the bioregion, both laterally and vertically.

3.2.3 Surface water hydrology and water quality

Surface drainage networks and associated hydrological features are available through the Australian Hydrological Geospatial Fabric (Geofabric) at <www.bom.gov.au/water/geofabric>. Hydrologic flow data and models are available from respective state water resource agencies and from the Murray–Darling Basin Authority for the Murray–Darling Basin. Ambient water quality data and contaminated water body information are available through state resource agencies and natural resource management authorities. Where information on water quality guidelines is required the Australian and New Zealand Guidelines for Freshwater and Marine Water Quality (ANZECC, 2000) should be consulted.

3.2.4 Geography

In addition to a range of assets, each bioregion will also support regional communities. The distribution and extent of human habitation in Australia has been influenced strongly by the quality and quantity of water, in particular inland freshwater resources. The size and distribution of the human population within a bioregion will be a significant factor in assessing the potential impact of CSG and coal mining development, because the size of the population base will not only determine human water use, but have a major influence on local land use patterns, including access to water bodies for recreational purposes. For these purposes, human water use is defined to include the use of water resources for household and industrial processes where industrial uses represent agriculture, urban, mining and other industry.

The population for each bioregion can best be calculated using census data, which are available as population density (number of people per square kilometre) for the whole of Australia. Population density estimates are available for 2005/06 from ABARES. Data on land use activity, which refers to the spatial distribution of permanent uses of land (including urban, industrial and agricultural uses), may be overlain with the population data to indicate potential exposure of human use systems to changes in the quality and quantity of inland waters. Catchment-scale land use maps of Australia as at May 2010 are available from ABARES. Each assessment should summarise water accounts (including current under-utilised entitlements) and domestic, agricultural, environmental and industrial uses, including mining.

3.2.5 Ecology

Water is available to organisms in a range of spatial and temporal patterns, and the combination of this availability and a species' abilities to use it generates a range of water-based dependencies. The significance of water, particularly in an arid continent such as Australia, has also resulted in a wide range of cultural and spiritual associations between people and water bodies or between water-dependent species and ecosystems.

In providing the environmental context for each BA, an attempt should be made to draw together the biotic components with the abiotic drivers for the bioregion, namely the climate, geology, soil, and groundwater factors, which together determine the nature, dynamics and resilience of the environment and ecosystems. These abiotic components also largely shape the agricultural utility of a landscape, though potentially supplemented through irrigation and fertiliser application.

The primary data layers should comprise vegetation, wetland, floodplain, species, river flow, and groundwater dependency spatial datasets that identify the distribution of organisms, communities and ecosystems comprising assets and receptors. It is necessary to acquire all available information on aquatic dependencies of vegetation and fauna and to sufficiently define the distribution of organisms and processes to link dewatering and depressurisation at depth with impacts on receptors at or near the surface. Secondary layers should include finer-resolution vegetation and land-cover maps, local-scale mapping and distribution of species, and single studies on single ecosystems or communities to develop an understanding of condition, extent, conservation and management status of assets and receptors. In addition to the landscape-scale understanding of the environment, detailed contextual information about receptors also needs to be compiled. Identification of species of international, national, regional and local conservation concern is required, which for motile species should consider significant locations for key activities such as nesting, spawning or feeding. For some taxa, the available distribution data will be of limited extent, particularly for lower plants and many invertebrate groups. A precautionary approach is suggested, with best available information extrapolated into unsurveyed regions; expert advice sought, as appropriate; or supplementary survey effort commissioned, as appropriate.

3.3 Coal seam gas and coal resource assessment

3.3.1 Available coal seam gas and coal resources

Methodologies and protocols for the assessment of coal resources are well established in Commonwealth and state government agencies, with spatial data available from existing databases (e.g. Geoscience Australia's OZMIN database). These data can be extracted and adapted to provide products and to support other aspects of the BAs as they progress.

CSG resource assessment is an emerging field where the methodologies used to estimate gas resources are evolving. The methodology used for conventional gas resource assessment is not applicable to CSG resource assessment. The situation is complicated by the observation by industry that 'every CSG field is different'. Regional CSG resource assessments have yet to be undertaken in Australia.

The identification of locations likely to contain viable CSG reserves will require the geological structural framework studies described in Section 3.2.1.1 and a consistent methodology to assess CSG resources in all bioregions and sub-regions. This methodology will need to be developed in close consultation with state and federal government groups responsible for petroleum resource assessment and industry to ensure it is rigorous and consistent with prevailing industry practice.

3.3.2 Existing mining activity and tenements

Coal mining activities and tenements are documented in state and federal databases. The assessment should use data on current mining operations and historical mines. Historical mines – and their impacts – can indicate potential issues with current and future developments. Data on existing activities and tenements are managed by state authorities. Engagement with industry will be required to ensure that the implications of various development options are canvassed.

3.3.3 Proposals and exploration

Existing coal resource assessments – combined with overburden mapping – will allow prediction of likely locations of future mining and the type of mining that will be undertaken (for example, open pit, longwall, or board and pillar). The potential impacts of different extractive approaches can then be assessed.

Coal resource development proposals across their development horizon must provide as much engineering information as possible in order to comprehensively address the sets of assumptions associated with the development pathway and be based on the proven and probable (2P) gas reserves. Modelling of basin geological development and strata reconstruction should be undertaken where possible. This should include (to the extent possible for mining):

- the engineering methods to extract coal (for example, caving, open pit, longwall underground)
- life of mine plan
- impacts of mining on land surface subsidence
- dewatering method, well layout and water treatment methods
- mine dump and tailings locations and hazards
- decommissioning methods, well capping and goaf closure
- pit lake management plans.

For CSG extraction, details should include:

- drilling methods (vertical and horizontal)
- hydraulic fracturing methods
- origin and management of water for hydraulic fracturing
- volume, quantity and destination expected for associated water and its treatment
- decommissioning plans of CSG facility (for example, sealing of wells).

3.4 Water-dependent asset register

A water-dependent asset is defined as:

> *an entity contained within a bioregion where the characteristics can be ascribed a* ***defined value*** *and which can be clearly linked, either directly or indirectly, to a dependency on groundwater or surface water quantity or quality.*

Examples of water-dependent assets may include a particular wetland spring system and associated surface features, or a named species or ecological community.

The documentation of assets occurs in a water-dependent asset register prepared by external natural resource management and state agencies in consultation with stakeholders. The register includes those assets which are covered by Council of Australian Governments agreements (e.g. Paroo River, Lake Eyre Basin). Where state research initiatives and/or projects have identified water-dependent assets, including statutory water planning initiatives, these must be included directly in the asset register. Any available information on the nature of the value of these assets, including that on resilience, threat, vulnerability or susceptibility to change, should be listed in the register. For each water-dependent asset described in the register, a set of receptors are identified and listed in a separate receptor register. Consideration should also be given particularly to those assets or receptors that are sufficiently mobile that they intersect with a single bioregion for only part of their life history, and to those that have a short but significant interaction with a hydrological feature. Such assets or receptors may include organisms that rely on surface water availability during critical seasons for reproduction, or that are critically dependent on water bodies for food resources or shelter during brief times. Other such assets may be agricultural irrigation districts or regional cities located in portions of catchments that are outside of a bioregion. In such cases, the boundary of a bioregion should be extended to incorporate these assets if cumulative impacts are of concern.

Each BA is expected to have some variation in the water-dependent asset register reflecting differing environmental laws or protections, scientific understanding, and those identified values derived from regional communities.

Assets in the water-dependent asset register should include, but not be limited to, the following:

- **landscape elements** that have statutory protection over them, for example, sites on the World Heritage List or recognised under the Ramsar Convention; national and state parks and their equivalents; and areas designated under the Indigenous Protected Areas program (listings held by SEWPaC in CAPAD, MNES, WHA and Ramsar data)
- **ecological communities** that are protected under federal legislation, such as critically endangered communities as scheduled under the EPBC Act (data held by SEWPaC)
- **species** that are protected by international (e.g. IUCN red lists), federal (EPBC Act) or state and territory (e.g. Queensland's *Nature Conservation Act 1992*) legislation (listings in MNES data held by SEWPaC and important bird areas (IBAs) for migratory species as identified by Birds Australia)
- **ecological systems** such as riverine floodplains, rivers, streams (e.g. TRaCK program), groundwater-dependent ecosystems (e.g. Australian National GDE Atlas), springs, mound springs, karst formations, wetlands (including bog mosses), terminal lakes, estuaries, aquifers (hard rock, sedimentary, perched and alluvial), and groundwater stygofauna
- significant **cultural sites**, whether areas concerned are declared under Native Title legislation, or whether they have pending decisions on Native Title claim over them. Native Title does not confer legislative protection to areas per se, but many determinations allow Indigenous Australians who hold native title, or who have a pending native title claim, the right to be consulted and, in some cases, to participate in decisions about activities proposed to be undertaken on the land (listings held by SEWPaC)
- significant **hydrological processes** such as recharge of important aquifers, or provision of water for competing industrial, recreational or domestic purposes (data from National Water Commission)
- areas that are significant for **agricultural production** dependent on water, including irrigated cropping, irrigated or groundwater-dependent plantation forestry, and other areas that may support high levels of production and have a dependency on water resources. Rainfed cropping, pasture and forestry areas are excluded from assets because of their lack of material connectivity with groundwater depressurization under CSG and caol mining development
- **species or communities** that are currently not protected in their own right, but have been identified as being **of management or conservation concern**, and that may be exposed to

the extent that they will be forced to meet criteria for legislative protection. Note that stygofauna (species that live permanently underground in water) are recognised as a factor for environmental consideration under the Queensland *Environmental Protection Act 1994*; are valued as indicators of ancient aquifers and their water quality by the Western Australian Department of the Environment and Conservation; and are being actively researched in South Australia, New South Wales and the Northern Territory.

The development of the water-dependent asset register will require integration of different data sources and consideration of the water-dependent assets already identified by natural resource management agencies. Such data sources would include state and territory listings of species and communities 'of concern'; the National Water Commission's Groundwater Dependent Ecosystems Atlas; vegetation condition data extracted from the VAST dataset (Thackway and Lesslie, 2006; Lesslie, Thackway and Smith, 2010) held by SEWPaC; and land use and management (ACLUMP) data held by ABARES. Appropriate complementarity analyses may be necessary to determine potential cumulative impacts on species and communities of habitat disruption or fragmentation (*sensu* Ferrier et al., 2007). These analyses could identify, for example, those ecosystems and assemblages of species that are under-represented in the national reserve system and where higher levels of representation may be needed to account for the relatively poor condition of remaining locations (due to land uses causing habitat disruption or fragmentation).

3.5 Receptor register

Anthropogenic or ecological receptors are defined as:

> *a discrete attribute or component of a water-dependent asset that may be* ***measurably impacted*** *by a change in water quantity or quality resulting from coal seam gas or coal mining development*.

For each water-dependent asset, one or more receptors are identified and inventoried in a receptor register. The receptors are the primary mechanism for determining the assessment of direct, indirect and cumulative impacts are categorised as either anthropogenic or ecological receptors (Chapter 5). The receptor register defines and describes discrete and specified receptors that comprise water-dependent assets. For both anthropogenic and ecological receptors, **response variables** must be identified that relate parameters, state variables and/or fluxes in groundwater and surface water models with impacts on receptors. Response variables also link receptors with subsequent advice on monitoring programs. An example of a response variable might be hydraulic head in an agricultural well (anthropogenic receptor) or concentration of a particular solute in a water body that impacts on an endangered species (ecological receptor). All receptors are contained within a water-dependent asset defined in the water-dependent asset register. Both the receptor register and the water-dependent asset register are compiled by relevant natural resource management agencies working with associated stakeholders, university academics and research scientists conducting a BA. This is a key point of external stakeholder interaction in the assessment process. Each identified asset can have one or many identified receptors. The impacts on receptors can be either positive or negative but, irrespective of their direction, the expected impact must be stated explicitly for each receptor in the register.

The concept of materiality is used to determine those potential impacts on receptors that need to be focused on. Materiality is the threshold of likely or potential impact on receptors based on contextual information and is based on judgment following consideration of proximity, causal pathway and expected level of exposure. Where receptors are not linked to events, are too far away or only briefly exposed, impacts may be non-material. Non-material impacts are identified and recorded in the workflow but do not require further analysis. The decision about whether a particular asset and its receptor are included in the registers is based on spatial relationships such as scale, proximity and connectivity.

4 Model-data analysis

4.1 Data, information and model acquisition

4.1.1 Assessment of existing data extent and quality

Geological and hydrogeological data will primarily be obtained from holes drilled for conventional hydrocarbons, CSG exploration, mineral exploration, groundwater extraction, coal exploration and stratigraphic tests. Basins within the bioregions of interest have as few as 14 wells (Pedirka Basin) to as many as several thousand (Surat Basin). Recent database listings at Geoscience Australia show nearly 4000 conventional petroleum wells and stratigraphic holes and over 5000 CSG wells in the areas of interest, mostly in the Surat, Bowen, Clarence-Moreton and Gunnedah basins. It is expected that a significant number of new observations will be needed for each BA. Wells will have to be selected on the basis of spatial distribution and data quality. Wireline log data will need to be analysed to provide additional data on rock types, porosity, permeability and coal distribution.

In spite of the large number of drill holes, there are still major gaps in areas not considered prospective in the past. In some areas, seismic reflection data may be needed to map basin structure and unit thickness and, in others, outcrop data will be needed. Alternative geophysical techniques, such as time-domain airborne electromagnetics, may also be applicable. The method will depend on the geology and the salinity of groundwater.

4.1.2 Use of existing syntheses in bioregional assessments

Existing syntheses of data and information in the bioregion or sub-regions of the BA should be accessed, such as:

- Permian coals of Eastern Australia (Harrington et al., 1984)
- Geology and petroleum potential of the Clarence-Moreton Basin (Wells and O’Brien, 1994) and the Namoi Catchment Water Study (Schlumberger, 2012)
- Geology of the Surat Basin in Queensland (Exon, 1976)
- Great Artesian Basin Water Resource Assessment <www.csiro.au/Organisation-Structure/Flagships/Water-for-a-Healthy-Country-Flagship/Sustainable-Yields-Projects/Great-Artesian-Basin-Assessment.aspx>
- Healthy HeadWaters program in the Upper Condamine <www.nrm.qld.gov.au/water/health/healthy-headwaters/index.html>.

4.1.3 Cost–benefit considerations of data and modelling

Undertaking a BA will always entail consideration of the marginal benefit versus cost associated with the time and price of project components. A balance must be achieved between costs, complex model formulation and simulation, data acquisition and processing, and accuracy of model output and impact analyses. This balance requires exercising judgment that must be recorded in the workflow. During the contextual information component of the BA, consideration must be given to the costs of modelling and measurement relative to risks associated with water-dependent receptors and assets, which bears on the appropriate level of detail required in any bioregion. It is likely that that amount of knowledge is typically the limiting factor in any BA and investments in different components should maximise the marginal benefit relative to cost (i.e. maximally reduce uncertainties). Decisions made at each point must be recorded in the workflow and supported by reasons. The assembly of datasets as part of the data register and identification of data gaps must include, to the best estimate possible given the extent of knowledge within a bioregion, an assessment of how new data is to be used in the analysis and how important those data are in determining impacts of CSG and coal mining development on water-dependent receptors and assets. In the case of data gaps, a priority ranking on new datasets is required that takes into account, to the extent possible in the experience of the agency conducting the research, the cost and benefit of obtaining those data in relation to the goals of the BA. Where models need to be developed or adapted to undertake quantitative uncertainty analyses, an assessment of the degree of development of these analyses relative to best practice and the assigned time frame of the project needs to be made. An appropriate achievable end-point for this development must be identified within the project time frame and recorded in the workflow. The workflow must also identify where future revisions of the BA would modify, advance or improve current analyses.

4.1.4 Relevant existing models, maps, datasets and monitoring

4.1.4.1 Data

Commonwealth agencies collaborate with states and territories to maintain national geological, topographic and biological spatial data as part of the Australian Spatial Data Infrastructure. Examples of databases containing relevant information are:

- **OZMIN**: Geoscience Australia maintains the OZMIN database that contains coal reserves and coal resource estimates and spatial data relating to deposits. The database contains commercially sensitive information but outputs of non-sensitive information will be possible and useful.
- **PEDIN**: Geoscience Australia maintains a national database of petroleum wells containing basic metadata such as location, operator and total depths. This database links to other databases of stratigraphic information (Stratdat), organic geochemistry (ORGCHEM) and petrophysical analyses (RESFSCS). Wells for which metadata are not available in existing databases (PEDIN) will need to be loaded and then transferred to GIS for mapping and spatial analysis and the geophysical logs loaded into the analysis systems.
- **AWRIS**: The Australian Water Resources Information System (AWRIS) is a national database of water information that is supplied to the Bureau of Meteorology by over 200 organisations across Australia, as defined in the Regulations to the Commonwealth's *Water Act 2007*. The Bureau collects 75 variables across ten categories of water information, including streamflow, groundwater, climate, water storages, water entitlements, allocations, trades, restrictions and use.
- **Geofabric**: The Australian Hydrological Geospatial Fabric (Geofabric) is a framework for discovering, querying, reporting and modelling water information. It is a specialised geographic information system (GIS) that registers the spatial relationships between important hydrological features such as rivers, water bodies, aquifers, monitoring points and catchments. The Geofabric currently defines national surface water hydrology at 1:250,000 scale and groundwater aquifers at 1:1,000,000 scale. Future releases will

improve the surface water resolution to ~1:100,000 scale based on a 30 m resolution national digital elevation model.

- **NGIS**: The National Groundwater Information System (NGIS) is a spatially-enabled groundwater database based on ArcHydro for Groundwater. NGIS has been populated with bore and bore log data (lithology, hydrostratigraphy and bore construction) from state and territory groundwater databases. NGIS also contains two- and three-dimensional aquifer geometry for some areas.
- **NAF**: The National Aquifer Framework (NAF) is a three-tiered system for naming and grouping geologic units, hydrogeologic units and hydrogeologic complexes in Australia. The NAF has been developed in conjunction with Geoscience Australia and groundwater agencies and is used to standardise state and territory terminology for aquifers in the NGIS.
- **GDE Atlas**: The National Atlas of Groundwater Dependent Ecosystems (GDE Atlas) presents the current knowledge of GDEs across Australia, and includes known GDEs as well as ecosystems that potentially use groundwater, divided into three broad classes: vegetation, surface water and subterranean ecosystems. It incorporates previous fieldwork, literature and mapped GDEs as well as potential GDEs based on interpreted remote sensing data. The GDE Atlas was developed by the National Water Commission with input from every state and territory and is hosted by the Bureau of Meteorology.

Well reports and geophysical logs are mostly held by state agencies. Open file reports are available, though digital copies of geophysical logs for older wells may need to be purchased from a commercial supplier.

Hydrogeological data are available through a number of state agencies (such as state geological surveys and state water departments); federal agencies (such as Geoscience Australia and ABARES); universities and private companies. In some states (such as Queensland) a significant amount of the groundwater monitoring data is collected from private bores and the licensing arrangements for using those data may be complex and prescriptive.

4.1.4.2 Maps

The BAs should use authoritative vector datasets maintained by federal and state agencies wherever possible. For example, the process of defining bioregions should use geological basin boundaries from the Geoscience Australia Geological Provinces database. Modifications and additions to these datasets should be fed back into the custodian agency.

4.2 Two- and three-dimensional representations of basins

Understanding the hydrogeology and the distribution of CSG resources within a bioregion will require, in addition to a thorough analysis of observations, the development of vertical cross-sections and three-dimensional representations of the geology and hydrogeology within the bioregion. Ideally, these representations would include three-dimensional distributions in space of coal-bearing sediments, aquifers and aquitards, as well as hydrodynamics. While these will initially be based on conceptual models (Section 2.5.2.3 and Section 4.3), where possible the representations should be quantitative, representing variations in important parameters in space to allow numerical modelling of groundwater behaviour in response to current and future development pathways (Section 2.5.2.5 and Section 4.4).

These three-dimensional representations will also form the basis of visualisation products to enhance interpretation and communication of results. Generating visualisation products is a discrete task that is required following development of two- and three-dimensional representations of the bioregion.

4.3 Conceptual modelling

A conceptual model is a qualitative description of the systems and sub-systems within a bioregion and a hypothesis or set of hypotheses as to how they interact with respect to impacts of CSG and coal mining development on these systems. It is a key component of the refinement of key aspects of the assessment's focus and is the primary mechanism by which the various contributors across disciplines develop a shared understanding of the assessment's goals. The conceptual models are closely linked with – and are used to aid the development of – the qualitative, semi-quantitative and quantitative models used to describe impacts on receptors (see Section 2.5.2.6). During the development of a BA, the conceptual model will undergo refinement as understanding improves. The conceptual model is the key device in the BA used to determine numerical model complexity, data requirements and uncertainty sources. It is also a key communications device on the state of scientific knowledge underpinning the BA.

In BAs, the conceptual models must define a causal pathway from depressurisation and dewatering of coal seams (event) to the direct, indirect and cumulative impacts on anthropogenic and ecological receptors (impact). They must emphasise the linkages between the key features of conceptualisation, numerical modelling, the system's water balance and impacts. The conceptual model also identifies key sources of uncertainty. All aspects of the conceptual models will be made fully transparent for external scrutiny. The conceptual models also have a role in explaining complex scientific processes to a broader community using two- and three-dimensional visualisation techniques.

Using the ecological, geological, hydrological and hydrogeological data, and the future development pathways (for CSG and coal resources), a conceptual model of the groundwater and surface water dynamics of a bioregion is to be constructed in accordance with the principles outlined in Section 2.5.2.3. The conceptual model begins with the geologic, seismic and stratigraphic data on vertical and lateral variation in rock types, faults and structure to identify potential compartmentalisation, cross-aquifer contamination risks and dewatering characteristics. It must define the main stratigraphic units and features; dominant mechanisms and locations of recharge, discharge and flows; surface water – groundwater interactions; and the location of CSG- and coal-associated impacts on surface or near-surface anthropogenic and ecological receptors taking into account the causal pathway of processes. This will set the design parameters for any numerical modelling, focus the objectives of the assessment, and guide the development of outputs towards assessment of impacts on receptors. As such, the conceptual model for any bioregion may comprise a comprehensive broad-scale model along with nested conceptual sub-models to take into account the range of time and space scales and connectivity over which processes occur. Many examples of conceptual models exist for different programs of research from which conceptual models for the BAs can be developed (e.g. groundwater modelling conceptual models in Barnett et al. (2012), conceptual models for surface water – groundwater interactions in Patterson et al. (2008), and the 'Healthy Waterways Program' ecological conceptual models for Southeast Queensland and the Queensland Wetlands Program). However, the conceptual model(s) developed in a BA are required to be more comprehensive and detailed to satisfy known characteristics and available data.

The conceptual model should capture important features of the physical properties of the groundwater and surface water systems within a bioregion and convey an understanding of spatial and temporal variation in those properties. It should:

- define the boundaries of the physical system under consideration
- summarise the major stratigraphic units, faults and other hydrogeologic features (such as distribution of hydraulic conductivity and porosity, trends in hydraulic head and flow characteristics, and assumptions about interconnectivity of strata)
- identify the dominant mechanisms and locations for recharge, discharge, flows and surface water – groundwater interactions
- identify the location of anthropogenic impacts on the surface water and groundwater hydrology
- identify uncertainties
- identify key questions that the assessment should answer.

One product of a BA is a well-defined conceptual model.

4.4 Surface water and groundwater numerical modelling

4.4.1 Flow model development

Modelling undertaken within a BA should adhere to recommended current best practice. Model complexity should be commensurate with data availability and complexity of the domain over which processes are to be simulated. However, it is expected that the complexity achieved in each BA will be at best practice such that groundwater and surface water responses to regional CSG and coal mining development and their impacts will be able to be assessed with an appropriate level of certainty.

A fully described, quantitative BA comprises a set of fully coupled groundwater, surface water and ecological impact models that directly link the dewatering of coal seams with impacts on receptors. These coupled models must also propagate statistical uncertainties associated with parameters and states through to uncertainties in impacts that can then be transformed to risk likelihoods. It is recognised that such a goal is difficult to achieve even in well-studied basins. However, these difficulties do not negate the requirement that a necessary condition for assessing impacts of coal seam dewatering on receptors is the linking of coal seam depressurisation effects on receptors via their water resource requirements. In most locations, such a high modelling capability will not be possible and more generalised modelling approaches will be required. In these cases, linkages between models may be indirect (i.e. not coupled) and rely on reasoning to establish links between component processes. The intent of the BA methodology is to specify an upper limit to what could be achieved in the best of circumstances. What is actually achieved in any particular BA may necessarily be of reduced scope and the BA methodology prescribes that all decisions are recorded in the workflow.

In light of the above, 'best-practice' BAs require a suite of tools and models covering groundwater and surface water dynamics, coupling of groundwater and surface water processes, and assessment of impacts. These should be capable of estimating quantitatively the uncertainties in state variables and parameters. Although fully quantitative models are desired, several different types might be suitable (empirical, qualitative, chemical speciation, statistical, etc.). Achieving 'best practice' in such a multidisciplinary environment requires:

- clear articulation of goals
- accurate definition of the state of knowledge
- appropriate use of models, data and calibration tools across a range of disciplines
- identification of uncertainties, assumptions and biases
- transparent recording of decisions
- successful marrying of information at different time and space scales from the water resource and petroleum industries
- an adaptive approach that iterates towards a final position within the time frame of the project.

For example, it may be necessary to resolve aquifer compartments within a bioregion undergoing coal seam dewatering in order to assess the risks of fault movement (and resultant connectivity) on an agricultural aquifer. It is recognised, however, that such a study would only be possible in locations where sufficient data and knowledge of model processes exist so that a comprehensive analysis of surface water and groundwater dynamics could be undertaken.

A detailed assessment of groundwater chemistry and isotopic composition for individual hydrostratigraphic units (including aquifers and coal seams) should be used where data are available to better understand the inter-aquifer connectivity in bioregions. This assessment should include analysis of naturally occurring hydrocarbon compounds present and their isotopic compositions in order to understand their likely origins and migration pathways before further major developments take place (Draper and Boreham, 2006). Appropriate data are unlikely to be available; therefore recommendations for a data collection program must be provided as part of the BA to establish the baseline groundwater chemistry information against which the impact of future activities may be measured. A comprehensive groundwater baseline survey would typically include field measurements, major and minor ions, trace elements, stable isotopes, organic compounds and dissolved gases. Since baseline data are essential for the detection of future changes, a baseline survey must take account of the spatial and temporal variation of groundwater chemistry and be undertaken in the context of a risk analysis and other risk assessments relating to the introduction of industrial chemicals.

A key component to the modelling is to explicitly link changes in hydrogeological characteristics of coal seams at depth and their adjacent aquifers and aquitards to those processes operating at the surface that impact on the receptors identified within key water-dependent assets. Without these explicit connections, a quantitative analysis of the direct impacts of dewatering will not be possible. Note that the explicit representation of 'causal pathways' is necessary to ensure that the receptor impact modelling (Section 2.5.2.6 and Section 4.5) is achieved.

From the conceptual model (Section 4.3), and the resulting specifications and objectives, the numerical model is to be constructed to an appropriate level of complexity. Groundwater modelling is to fully represent all relevant hydrostratigraphic units within the system and bioregion and their relevant interactions. A variable resolution model grid may be required where bioregions are complex and/or data are sparse.

Various industry and scientific models are available that have been designed for specific purposes and are able to perform components of a BA within a priority region (for example, models such as Petrel, Eclipse, RMS Roxar, MODFLOW or FEFLOW each explore different aspects of groundwater dynamics). Other models (either deterministic or statistical) deal with ecological function, thresholds and responses of receptors to forcing variables (for example threat–pathway–receptor models that explicitly link driver variables with impacts on receptors identified in the contextual information component). A BA will require synthesis of information (and uncertainties; Section 4.6) from a range of these models that operate on different time and space scales. As a result, it is important to define the extent and resolution of each model within a bioregion. For example, the following need to be commensurate with data availability, system knowledge and purpose:

- the spatial distribution and resolution of aquifer permeability
- vertical leakage rates between aquifers via fractures and faults
- pore space volumes
- hydraulic conductivity of aquitards and seals
- surface water flows and drainage
- receptor ecological responses (including vegetation and wetland data).

The appropriate methods for groundwater flow modelling, including calibration, prediction and uncertainty analysis, are provided in the Australian groundwater modelling guidelines by Middlemiss (2001) and Barnett et al. (2012) and these should be consulted as required.

Surface water modelling must represent spatially distributed rainfall-runoff processes, streamflow routing, evapotranspiration, deep drainage, and the impacts of climate variation on these flows. River models are to be used where required to assess impacts of changes in flow and recharge associated with CSG and coal mining development. These river models also need to address the potential influences of water management – such as flow diversions and infrastructure – on surface water hydrology. Where possible, the surface water models should be fully coupled to groundwater models. However, fully coupled models may not be possible due to the complexity involved in highly non-linear processes that are difficult to measure. A pragmatic solution might be to develop a suite of nested models and – based on explicit assumptions governing interactions between models at different scales – develop schemes for passing information between component models within the model suite. For example, nested surface water models may be required that use groundwater models as boundary conditions (e.g. Neumann boundary conditions for water fluxes). These boundary conditions provide constraints in addition to the usual observations of rainfall, evapotranspiration, runoff, offtakes, and storages in weirs and dams (see also Section 4.4.2 on calibration). Judgment will be required in determining the appropriate complexity and resolution of numerical models that maximise the advantages of simple models and utility of complex models. Decision points and action pathways associated with all aspects of modelling, calibration and simulation must be recorded in the workflow.

An assessment of the water balance needs to take into account surface water – groundwater interactions. The models need to simulate fluctuations in flow in rivers, connections with groundwater (including seasonal variation in baseflow), discharge to surface, flow through the unsaturated zone and deep drainage, and flows in saturated zones.

It should be noted that best-practice groundwater numerical modelling and impact analysis within useful uncertainty bounds will push the capability of current numerical models to their limit, even in well-studied locations. To achieve best practice, it is likely that significant model development will be required specifically on the topics of:

- using multiple observation types as multiple constraints on model dynamics
- improved representation of coupled surface water – groundwater processes in models
- implementation of computationally efficient methods to quantitatively estimate uncertainty.

Given differences in characteristic timescales of surface water and groundwater processes, it may be necessary to run the surface water and groundwater models on different time steps to ensure that the computation remains tractable. It will also be necessary to run groundwater and surface water systems to a 'dynamic equilibrium' (Rassam et al., 2008) and for sufficient time periods to fully realise impacts of dewatering.

In large, complex and data-sparse bioregions, this will likely necessitate a hierarchical approach to the numerical modelling of groundwater with variable resolution in time and space of processes across bioregions. For example, in high-priority bioregions, complex and highly resolved models may be required for important processes governing the dynamics of groundwater responding to development pathways of highly localised CSG and/or coal mining development. In low-priority bioregions that are relatively uniform areas away from CSG and/or coal mining developments, simpler models at coarser resolution may suffice. Irrespective of these requirements, the choice of model type may be dictated by data availability. Choices – as well as justification of these choices – need to be catalogued during model development in the workflow.

4.4.2 Calibration

Model calibration will need to use multiple lines of evidence and different types of data as constraints on the surface water and groundwater modelling to provide the most accurate numerical description possible of the current condition of water resources and the direct impact of water use across sectors including CSG and coal mining development.

Parameters and their uncertainties should be estimated using appropriate inverse methods and calibration techniques. Where possible, state estimation using data assimilation techniques may be required. Methods must be cognisant of the needs to quantify uncertainties in states, fluxes and parameters. Best-practice performance measures for model calibration should be used to explicitly quantify model performance and calibration against observations (including correlation, root mean square error, residual plots, etc.).

In the case of groundwater modelling, model scope, resolution, and calibration must use – where possible and appropriate – all available data as constraints on model dynamics, including constraints on boundary conditions, initial conditions, states and parameters. This includes, for example:

- geophysical data (TDEM, seismic, well log, gravity and electromagnetic) to better define boundary conditions and compartmentalisation of aquifers
- geochemical measurements (structural geology; fault characterisation; paleogeography; stratigraphy; noble gases; isotopes; tracers; and groundwater temperatures, pressures and chemistry) to estimate aquifer permeability and porosity.

Thus, calibration of groundwater models needs to focus on both geological and hydrological constraints. In some cases, these calibrated models may not provide a quantitative definitive prediction of coal seam behaviour under depressurisation; rather, they may supply information on significant impacts thereby underpinning an assessment based on multiple lines of evidence. Calibration methods must adopt, wherever possible, quantitative methods (i.e. state or parameter estimation and inverse methods) that are capable of:

- enabling quantitative propagation of statistical uncertainties
- communicating uncertainties in ways third parties can repeat results
- enabling assessment of future sampling and observation programs that maximally reduce uncertainties
- contributing to automation of updates to BAs as new data become available
- providing a means of integrating deterministic hydrologic models with the risk analysis
- In cases where insufficient data exist for model calibration given uncertainties, advice on impacts will be provided by the conceptual model(s) and through exploration of development pathways by bounding likely system responses. These models are also useful for designing field investigations to generate sufficient data for future BAs.

4.4.3 Prediction

The objectives of the numerical modelling are to:

- quantitatively assess the impacts of dewatering associated with CSG and coal mining development on aquifer properties, flows, pressure heads, the watertable, and chemical characteristics and transformations
- link depressurisation of coal seams (at depths of between a few tens of meters and less than 1000 m) to impacts on surface water dynamics, flows and groundwater-dependent systems
- reconcile multiple sources of observations on hydraulic characteristics, chemical constituents, pressure potentials and flows.

Output from the numerical modelling will be used to assess direct impacts on receptors (Section 2.5.3 and Section 5.2.1) given climate forcing and variation. This will also require a gap analysis to understand the significance of missing data and the development of ongoing sampling and monitoring programs for model improvement. Modelling time series must take into account the seasonal, inter-annual and inter-decadal climatic variability associated with regions within which CSG and coal mining development is taking place. In addition, while the time horizon for the development pathways may be decades, the modelling time horizon must be sufficiently long that model dynamics approach equilibrium within a specified tolerance. Thus, the time horizon for impacts may be centuries.

Output from the numerical simulations should be displayed using two- and three-dimensional visualisation tools as required for both model input and output data.

4.5 Receptor impact modelling

Modeling and analysis of the direct, indirect and cumulative impacts of CSG and coal mining development on anthropogenic and ecological receptors is the pivotal component of a BA. It is the point where all prior information along a causal pathway from depressurisation and dewatering of a coal seam to the surface impacts on receptors is 'synthesised' into conditional statements about the likelihood of impacts and the risks posed to values of water-dependent assets. For this reason, ecological knowledge acquired from a range of sources is required to provide advice on the resilience, resistance, vulnerability and response of ecological receptors (and hence assets). Anthropogenic receptors may require ecological or additional information to undertake impact modelling. The receptor impact modelling is closely connected with the impact analysis (Section 5.2).

4.5.1 Model development

Receptor impact modelling will be required for each identified receptor or group of receptors. Receptors may indicate the condition and trend of several assets, or several receptors may be conceptually expected to respond similarly to changes in water quality or quantity. As a result, aggregation of receptors may be required, particularly if it is necessary to ensure manageable amount of work in the BA given time constraints.

Responses of anthropogenic and ecological receptors to dewatering of coal seams will depend on the distance, stratigraphic proximity, connecting pathways, resistance, resilience, response, and threshold condition of a receptor to the forcing perturbation (i.e. dewatering). An assessment of receptor exposure is necessary to determine whether impacts are chronic or acute, whereas receptor resilience determines whether receptor state will return to pre-perturbation condition following the dewatering event. An assessment of threshold levels may also be required if there is potential for chronic exposure or significant perturbation to lead to impacts that change receptor baseline state or condition. The impact modelling will need to consider relationships between environmental driver variables and changes in response variables in receptors.

Anthropogenic receptors (e.g. agricultural wells) in many cases will potentially experience direct impacts of dewatering from CSG and coal mining development (e.g. loss of hydraulic head) and, in circumstances where multiple developments exist, these direct impacts will be cumulative. Ecological receptors (e.g. a rare and threatened freshwater species within a wetland) will potentially experience indirect impacts (e.g. loss of flow arising from a decrease in hydraulic head in a groundwater-connected surface wetland). The degree of impacts on receptors will depend on the distance from dewatering, vertical stratigraphic proximity to dewatering, connecting pathways between depressurisation and dewatering and receptors, as well as the resistance, resilience, response and threshold condition of receptors to dewatering.

Receptor impact model development should consider:

- clear articulation of the aim of the model
- baseline data providing current status
- identification of uncertainties, assumptions and biases in identifying presumed magnitude and direction of change.

Depending on the level of understanding of the type, magnitude and direction of change that impacts may have on receptors, data from conceptual, semi-quantitative or quantitative numerical models will need to be incorporated. The levels of confidence around each of these must be recorded. Given existing data and modelling knowledge, it will be a significant challenge to quantitatively relate direct impacts of coal seam depressurisation and dewatering to groundwater and surface water flows and then subsequently (via a causal pathway) to impacts on receptors. Judgment as to the type of models and their application lies with individual researchers undertaking assessments and so it is not possible to be prescriptive as to the detailed methods to be applied. Nevertheless, all decisions based on researcher judgment must be recorded in the workflow and are subject to scrutiny by peer review as part of the process to ensure project transparency. As such, 'best practice' in this context constitutes balancing the complexity of receptor impact models with available data and knowledge, taking into consideration confidence in the data.

In some instances, particularly for ecological assets, it may prove impossible to adequately model receptors due to lack of understanding of mechanisms involved, need for potentially invasive techniques to monitor, or insufficient baseline data. In such instances, appropriate surrogates may be nominated which reflect the impact in a manner more amenable to monitoring. All inferences associated with the identification of surrogates should also be recorded.

4.5.2 Prediction

The objective of receptor impact modelling is to provide a robust framework within which to assess the potential exposure of assets through understanding the magnitude, direction and nature of changes effected on nominated receptors. The models need to be sufficiently clearly documented to allow reappraisal of impact in light of new or improved numerical modelling or other pertinent data, to contribute to understanding and monitoring of cumulative impacts, and to identify the means by which remediation or avoidance approaches may act.

Output from receptor impact modelling should be displayed using two- and three-dimensional visualisation tools as required for both model input and output data.

4.6 Uncertainty analysis

The BA methodology requires that uncertainties in observations and modelling be propagated to model output and expressed in quantitative terms wherever possible. The workflow should capture decisions made as to the level of sophistication of methods used, data availability and expression of forms of uncertainties.

The quantification of uncertainties is fundamental to many aspects of the BA methodology:

- the analysis of direct, indirect and cumulative impacts
- risk analysis
- design of future sampling programs to ensure new data maximally reduce uncertainties in modelling (e.g. Dausman et al., 2010).

Any qualitative or semi-quantitative methodology for risk analysis must ensure transparency and logical consistency in its consideration of likelihoods and consequences. Transparency means that qualitative descriptors are defined unambiguously and in a way that can be assessed and tested against data either now or in the future. This transparency will ensure that the decision taken will be based on common assumptions and understanding. Logical consistency will enable risk rating matrices to be constructed in a rigorous way. Best practice in this context refers to analytical or numerical methods used for quantifying likelihoods of parameters, measures of bias in model inputs and outputs, and characterisation of goodness-of-fit of model states to observations. Other sources of uncertainty arise from imprecision, ambiguity, vagueness and lack of clarity; these must also be considered.

Other significant sources of error must be incorporated into analyses – for example, the effects of non-steady state conditions when a steady state assumption has been used in groundwater model calibration or biases introduced through linearisation methods. Accurate baseline conditions and human-induced impacts of CSG and coal mining development must be determined as best as possible. This is important in distinguishing change due to, for example, climate variation from causal impacts due to dewatering for coal resource extraction. A key issue will be the separation of background Earth processes (dominated by geology) from processes triggered by dewatering and/or drilling practices. In many cases, it will be difficult to obtain definitive data to distinguish 'natural' impacts from impacts from coal resource development. Under these circumstances, impacts need to be described in terms of multiple lines of evidence. Bioregional analyses must identify, for example:

- **conceptual model uncertainty:** epistemic uncertainty or imprecision (which represents an absence of knowledge). This could, for example, include the uncertainties associated with potential connectivity and flow systems between aquifers, fault movement and seal leakage, and lateral distribution of seams and aquitards
- **parameter uncertainty or random effects:** uncertainties associated with aquifer transmissivity or porosity over space derived from random errors in observations using model calibration methods
- **development pathway uncertainty:** the uncertainty associated with CSG and coal mining development must be assessed and incorporated in the development pathways used in the impact analysis
- **model and data biases:** the source and quantity of bias arising from datasets and models must be assessed and bias correction procedures implemented where possible.

These sources of uncertainty provide a basis for impact analysis using analytic or numerical methods for the propagation of uncertainties in models as appropriate. For example, the Monte Carlo method coupled with Latin hypercube sampling is a computationally efficient approach to developing co-variances among model driver variables that are needed to generate likelihoods of output variables. Stochastic realisations of models based on these co-variances (or expected variations in driver variables and parameters in the absence of other information) is the best available means of determining model behaviour arising from uncertainty in parameters such as base and peak flows of streams, and porosity, hydraulic conductivity and storativity of aquifers. In some cases, coupling of simple and complex models will provide a means to estimate and remove bias while addressing issues of data availability and assessing impacts on receptors at relatively fine scales (Doherty and Christensen, 2011). Data paucity is not necessarily a justification for application of simple models if those models do not address impacts on the receptors identified in the contextual information component (Hunt et al., 2007). In order to estimate impacts and their uncertainties within localised regions, it may be necessary to use more complex models, or, for example, nested models with variable resolution in locations of interest.

A checklist of sources of uncertainty must be developed and used as a basis for developing the impact analysis. A checklist will include, but not be limited to, uncertainties in the following:

- boundary conditions
- driver data
- model parameters
- conceptual model structure

- discretisation
- scale transitions
- computation and numerical routines.

It is recognised that developing robust quantitative estimates of model uncertainties will be difficult given available data and limited knowledge in some bioregions. In data-sparse bioregions, and in the absence of a fully quantitative analysis of probabilities of model outputs, a sensitivity analysis should accompany numerical modelling in order to support semi-quantitative or qualitative estimates of uncertainty.

Model predictions that result from assuming a given future development pathway should provide means for testing and validation, recognising both the uncertainties in model output and that the development of groundwater responses to depressurisation may take several decades.

Practitioners undertaking BAs will need to decide:

- the appropriate time and space scales to focus on
- how outputs from numerical groundwater models will be translated to surface water models
- how to express ecological impacts via direct links or use of metrics or surrogate variables in terms that can be readily understood by a wide audience (Hancock et al., 2009).

The estimates of uncertainty need to be clearly expressed in a manner that is understandable to an outside audience and decision makers. Engagement with external agencies and stakeholders must occur early in the project during the assembly of contextual information to determine suitable representations of uncertainties and levels in confidence in models. In the case of coupled models (for example, coupled surface water and groundwater models), suitable schemes for transferring uncertainties between scales need to be devised and recorded in the workflow. The transfer of information between models must take into account variation in the time and space scales associated with each model. For example, decadal processes in a groundwater model may be represented as slowly evolving boundary conditions in an ecological impact model. In turn, daily processes within a surface water model may be 'seen' by a groundwater model as a mean with stochastic variation.

5 Impact and risk analysis

5.1 Demonstrated reliance on water either directly or indirectly

Water-dependent assets have a demonstrated reliance on water, either directly or indirectly, and are likely to be exposed to change in water quantity or quality through either coal mining or CSG extraction. There are three ways in which this reliance can occur:

1. **Identified assets may be directly or indirectly and materially affected by exposure to changes in water quality or quantity from CSG or coal mining.** For example:
   - Assets and receptors may be directly affected by exposure to changes in water quality or quantity through permanent or ephemeral streams or water bodies; through overland flow or subterranean aquifer discharges; or (in the case of stygofauna) through subterranean aquifers. A substantial number of nominally aquatic species rely on access to open or flowing water for part or the majority of their life cycles. This group includes fish, frogs, turtles, crocodiles, many birds, migratory species, invertebrates, other biota and a range of mammal species and ecological processes, plus a large number of plants that grow submerged or semi-submerged in water bodies or require permanent or seasonal inundation in swamp and marsh habitats. Many of these species, or the assemblages they form, also have cultural associations for both Indigenous and non-Indigenous Australians, including waterbirds (such as magpie geese), turtles, crocodiles, platypus and fish (such as eels and barramundi). Recognition of these associations is paramount to Indigenous people, but also to many non-Indigenous people, for whom the health of their environment is measured through the presence of fish in rivers and birds on lakes. Consequently, existing environmental legislation not only recognises species and communities that are threatened at the local, national or international scale, but also protects many aquatic environments by limiting activities that may be directly harmful to them. Groundwater availability is also important at drier times of year for the persistence of many natural communities and some agricultural systems.
   - Assets and receptors may be **indirectly** affected by exposure to changes in water quality and quantity through material reliance on another species or community that have been directly affected by exposure to changes in water quality and quantity. For example, the majority of plant assemblages in Australia depend on groundwater to survive drier parts of the year, and associated fauna require their persistence to provide shelter and food. Other animals that are not considered aquatic may rely on aquatic ecosystems for feeding, breeding or shelter at particular times of the year. Such animals may include domestic stock in extensive (rangeland) contexts, or where watering points are on-stream.
2. **For some identified assets, impacts are potentially chronic rather than acute**. Rapid changes in population size or structure may result from acute impacts on water quality or quantity. Less marked – but equally significant – chronic impacts can affect populations over time through chronic exposure to change with repeated but subtle effects on reproductive success, dispersal, succession, predation, etc. Assets affected through

exposure to chronic impacts include species and communities, but also processes such as aquifer recharge. Agricultural assets may be exposed through changes in water quality or availability for irrigation.

3. **Reversible or irreversible receptor and asset responses**. Some direct, indirect and cumulative impacts may be considered irreversible (for example, subsidence impacts on water flows in groundwater or surface water systems). These impacts may be positive or negative in nature and may cease when depressurisation stops or continues. Other irreversible impacts may include species extinction, invasive species or transgression beyond an ecosystem 'tipping point'. As such, all impacts must be considered as reversible or irreversible and reported in the BA.

Some identified assets may not be materially affected by changes in water quality or quantity if they have low dependence on groundwater or obtain their water from other areas, such as direct or occult precipitation. These assets should be recorded in the workflow but not considered further in the analysis.

5.1.1 Tractability for measuring or monitoring

Coal mining or CSG extraction may lead to water quality and quantity impacts that are spread over space and time. As a result, a range of anthropogenic and ecological assets may be affected, and those changes may be perceived to be either positive or negative depending on context, timing or perspective. For those assets that have been clearly demonstrated to rely on groundwater, the potential to measure or monitor them needs to be determined, as without adequate baseline measurement or ongoing monitoring, the magnitude and direction of change is likely to be uncertain and possibly contentious. A series of levels of tractability exist, from the highly measurable to the unmonitorable.

Some receptors of certain asset classes are likely to be highly measurable and monitorable. The following asset classes are likely to be sufficiently well understood in a spatial and temporal context that they can be accurately and repeatedly measured:

- processes, such as within-bank flow
- environmental metrics, such as water quality
- agricultural assets
- ecological assets, such as fish populations and waterbird breeding success.

Some receptors are likely to be measurable but not tractable to monitor. These may include receptors that are very difficult to adequately sample. For instance, samples of deep groundwater may be analysed for stygofauna content, which would allow a measurement of species diversity and abundance, but with limited understanding of the ecology and distribution of various stygofaunal groups. Monitoring change – and drivers of change – may be logistically too demanding. Some cultural values may also prove measurable, but may combine such complexity or inertia that they are inappropriate to monitor.

For some receptors, accurately measuring the baseline condition may be difficult, but monitoring changes may be feasible. For example, hydrological processes such as recharge of aquifers may be difficult to measure in absolute terms, but changes could be implicitly understood by monitoring aquifer levels (using observation bores), aquifer discharge to mound springs, or dry-season baseflow in streams.

It may prove impossible, impractical or unfeasible to measure or monitor receptors of certain asset classes. Such receptors may represent processes such as movement of water between subterranean aquifers, and some ecological phenomena that depend on climate and are thus stochastic.

5.1.2 Locations of potential exposure for species with a water-dependent phase in their life history

For those species that have a clearly understood water-dependent phase in their life history, there exists a range of possibilities for how and when they may potentially be exposed to changes in water quality or quantity due to CSG and coal mining development.

Some completely aquatic species will have life histories completely constrained to a single site, whether it is a spring, a wetland, a reach or some other discrete water body. Some terrestrial species that have limited ability to disperse but possess key dependencies on aquatic systems for food may also be explicitly linked to a single site.

For other aquatic species that move between water bodies within a catchment, only some parts of that catchment may be exposed to impacts from mining activities, but those impacts may be more widely felt indirectly or cumulatively through effects on, for example, breeding success or food webs. Most terrestrial species with direct reliance on aquatic systems for food will also fall into this category.

For species that spend some time in fresh water and some in marine systems, only the freshwater phase may be affected. For example, for catadromous fish like eels and barramundi, recruitment of fingerlings to maturity may be affected, even though breeding takes place at sea. Some terrestrial species may also be affected in such a way, particularly birds that range between marine and freshwater habitats. For species with only a transitory aquatic phase, such as many amphibians, the potential exposure may be limited both spatially and temporally. This is also true of species that are terrestrial yet have key dependencies on aquatic systems for parts of their life histories, for example, migratory birds that over-winter in wetland systems.

5.2 Impact analysis

The impact analysis (Component 3) requires an integrated approach to determine the direct, indirect and cumulative impacts of CSG and coal mining development. The impact analysis is not separate to the model-data analysis or risk analysis components but is integrally linked through the identified water-dependent assets and receptors.

The impact analysis is influenced by a number of factors that affect the method adopted. The methods should be practical and suitable for adoption in the bioregion under study given data, time and financial resources available. The nature of the impacts, the availability and quality of data, and the available capability and skills to undertake an analysis all influence the methods adopted. Decisions made should be documented in the workflow.

The concept of ‘materiality’ applies to the analysis of impacts on each receptor. It defines the magnitude and priority or scale of impacts on receptors. Those impacts regarded as immaterial are omitted from further analysis. In this way, efficient effort is directed towards the most important (i.e. material) receptors. Examples of material impacts on receptors might be:

- a loss of seasonal river flow volumes in *n* years out of 10 that eliminates breeding conditions for a particular arthropod (receptor: arthropod population in River *X* at location [*x*, *y*])
- declining pressure head on agricultural wells leading to *x* m reduction in pressure head and pumping flow rates that are less than 50% of current values (receptor: agricultural wells at location [*x*, *y*])
- a change in a water quality parameter that renders a habitat no longer suitable for a particular receptor (receptor: A particular species at location [*x*, *y*])
- an accumulation of salt concentration in agricultural soils from use of associated water leading to a significant (greater than *X*%) reduction in cereal crop production over 10 years (receptor: cropping land at location [*x*, *y*]).

The impact analysis relies on methods adopted and implemented by governments to assess the materiality of impacts on receptors. These methods include:

- expert opinion through consultation, workshops and panels
- consultation with stakeholders, including questionnaires
- checklists and matrices of impacts and causes
- spatial analysis using geographic information systems.

Natural resource management agencies have been requested to provide assets for input to BAs through the Office of Water Science for the priority bioregions. Once the water-dependent asset registers are provided by the natural resource management agencies, the following methods are used within the BA methodology for an impact analysis:

- network and systems analysis and conceptual models
- analysis of thresholds, carrying capacity and ecotoxicology
- numerical modelling of direct impacts
- numerical modelling of causal pathways to determine indirect and cumulative impacts
- conceptual modelling of causal pathways to determine indirect and cumulative impacts.

As part of Component 1 (contextual information) for a bioregion, baseline data are required for all receptors that are studied in the impact analysis. The acquisition of baseline data is ongoing and iterative, and is an integral part of the monitoring program extending beyond the current BAs. A correctly formulated monitoring program forms the basis for updating BAs. Data collection during monitoring should be cognisant of the development of the coal resource, the level of reduction in uncertainty, climate variation effects and impacts from other sectors.

5.2.1 Direct impacts

Direct impacts are those associated with CSG and coal mining developments that impact on natural resources without intervening agents or pathways. The direct impacts of CSG or coal mining development are the changes to the physical or chemical characteristics of groundwater and surface water resources that occur as a one-to-one result of dewatering of coal seams due to CSG or coal mining development. Examples of direct impacts are:

- the loss of pressure head in an aquifer as a result of the dewatering of a coal seam

- changes in groundwater chemistry due to a change in hydraulic relationships
- changes in hydraulic properties, such as porosity of an aquifer due to pressure reduction.

The results of direct impacts are estimated directly from numerical modelling of surface water and groundwater responding to current and future development pathways, and are expressed in units associated with state variables and parameters of these models. Uncertainties in direct impacts are derived from formal treatment of uncertainties in the numerical groundwater or surface water model. Where there are insufficient data, information or models, semi-quantitative or qualitative methods for assessing direct impacts may be adopted. Decisions, datasets and choices must be logged in the workflow.

Underground coal mining and extraction of water can cause subsidence of the land surface which can modify surface drainage, affecting land use. Common mining subsidence detection programs include global positioning system (GPS) surveys, conventional precise levelling and theodolite surveys, EDM surveys, and remote electronic monitoring (Hebblewhite et al., 2000). These techniques measure ground subsidence on a point-by-point basis and are, therefore, relatively time consuming and costly. Hence, they are usually constrained to localised areas, and it is very difficult to detect any regional deformation induced by underground mining or CSG extraction using these techniques. In the context of the regional-scale BAs, methods for detecting subsidence are most useful if they provide rapid assessment of spatial variations in subsidence rather than spot measurements. The tool best suited for this work is InSAR (Interferometric Synthetic Aperture Radar) using satellite platforms (Bürgmann et al., 2000). InSAR routinely detects land surface changes in the order of millimetres at rates of millimetres per year. This capability is available in Australia. InSAR requires repeated acquisition of satellite data, thus the method will require nomination of areas of concern for repeat surveys with sufficient time between surveys to detect changes. Other data, including LiDAR DEMs (Light Detection and Ranging-derived digital elevation models), are equally powerful datasets for detecting subsidence if repeat surveys are available. LiDAR can be very costly to acquire relative to InSAR; in cases where the data already exists, LiDAR DEMs may be appropriate to detect subsidence.

For specific, high-value features that may be affected by subsidence (such as infrastructure or important natural features), ground movement can be measured by Geodetic global positioning system (GPS) units. These units can measure millimetre-scale movement in the ground surface and rates of millimetres per year, if they are in place for a sufficient time, with the general rule that the smaller the rate of change, the longer it takes to measure it reliably. Geodetic GPS will be the preferred method for assessing subsidence if the soils in a location contain swelling clays. These soils can swell and shrink (Chertkov, 2005) at a level that can exceed the annual movement caused by mining or fluid extraction. These short-term natural movements could potentially mask subsidence in InSAR data.

5.2.2 Indirect impacts

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

Indirect impacts of CSG or coal mining development are the effects on receptors that arise in direct response to the direct effects of coal seam dewatering. Examples of indirect impacts are:

- the effect of dewatering on a gaining or losing stream via the direct impact of loss of pressure head in an aquifer
- the drying of agricultural wells or natural springs
- salinisation of freshwater aquifers due to depressurisation of coal seams.

The results of indirect impacts are analysed through impact pathways which link the direct and indirect impacts on individual receptors defined in the receptor register for each water-dependent asset listed in the water-dependent asset register. The impact pathway may be derived as an explicit set of model functions that quantitatively relate the influence of direct impacts on the indirect impacts of individual receptors. This is the ideal approach and allows for a quantitative estimate of the magnitude of the indirect impacts. In addition, uncertainties in the numerical model can be propagated analytically or numerically through the impact analysis model to provide a quantitative level of confidence in the indirect impact. Alternatively, semi-quantitative or qualitative estimates of indirect impacts are to be determined where there is insufficient process knowledge or data to provide quantitative estimates of the indirect impacts. Decision points and course of action must be documented in the workflow.

5.2.3 Cumulative impacts of mining

Cumulative impacts are the aggregate, successive and incremental impacts on receptors, distributed in time and space, that occur in addition to the direct and indirect impacts of CSG and coal mining development. Cumulative impacts may be additive or multiplicative ('synergistic'), and are either positive or negative. They result from incremental changes caused by other past, present or reasonably foreseeable actions together with the CSG or coal mining development project. The interactions between impacts – whether between the impacts of just one project or between the impacts of other projects in the CSG and coal mining sectors – contribute to cumulative impacts (Walker and Johnston, 1999; Franks et al., 2010).

In the present context, cumulative impact analysis aims to identify the aggregate effects of CSG or coal mining development (in addition to the direct and indirect impacts identified in Section 5.2.1 and Section 5.2.2) on receptors within water-dependent assets, and to understand the response by regional groundwater and surface water resources to these impacts. This understanding then can assist with decisions that ensure the sustainable use of water resources. Cumulative impacts may result from the compounding effect of CSG and coal mining development from a single mine through time; multiple mines operating within a landscape; or legacy effects of past mining activities impacting on the present. They may also be generated where the distribution of CSG wells in a landscape affects – in an aggregate way – receptors that depend on groundwater and surface water.

Cumulative impacts aggregate in three ways (Franks et al., 2010):

- The interaction between spatially distributed impacts of different mine sites, or from multiple gas wells, may give rise to a cumulative impact greater than the sum of individual impacts from any single mine or well on its own.
- The accumulation of impacts through time may lead to synergistic effects that result in cumulative impacts emerging over time.
- Linkages between impacts may result in the triggering of further associated impacts that otherwise would not have occurred if such a threshold had not been exceeded.

The BA methodology requires an analysis of the cumulative impacts of CSG and coal mining developments. The cumulative impact analysis may be quantitative, semi-quantitative or qualitative depending on the level of confidence in data, information and models available and should build on and extend information obtained as part of the direct and indirect impact analysis (Section 5.2.1 and Section 5.2.2). Decisions regarding the type of analysis should be documented in the workflow.

The quantification of cumulative impacts can be difficult due to the complex nature of interactions among various components of a system that includes mining, agriculture, cities and the environment. As a result, the integrated approach outlined here in the BA methodology is necessary: first quantitatively assess the direct and indirect impacts, and then estimate the cumulative impacts that exist over and above the direct and indirect impacts. Cumulative impacts are receiving increasing attention by regulatory authorities and approval processes. As a result there is a pressing need to develop applied methodologies so as to streamline their analysis. It will become increasingly necessary for CSG and coal mining development projects to quantify and address the cumulative impacts in all regions of mining and petroleum sector activity whether previous activity by these sectors has been dense, sparse or absent.

The EPBC Act does not, in its present form, contain a specific requirement to assess cumulative impacts of development. However, Federal Court rulings have interpreted the EPBC Act to require an assessment of cumulative impacts of development proposals (Franks et al., 2010). Queensland and New South Wales state government Acts regarding environmental protection, infrastructure development and environmental impact statements require consideration of cumulative impacts. This assessment involves short- and long-term effects of development on the environment, visual amenity, air quality and water resources.

5.2.4 Background usage for other sectors

In addition to cumulative impacts within the mining sector, it is possible for impacts to be generated between sectors. For example, the operation of mining and irrigated agriculture within the same bioregion may generate impacts on the background usage of groundwater and surface water resources that are in addition to the separate impacts of either agriculture or mining separately.

The BA methodology requires an estimate of the water availability and use by other sectors, and the associated probability. This estimate may be quantitative, semi-quantitative or qualitative depending on the level of understanding of the impacts and the complexity of interactions among multiple stakeholders. The regional scale of these assessments provides a basis for removing duplication of assessments at the level of the CSG and coal mining development projects, reducing the regulatory burden and providing greater certainty for development proposals. In order to understand the potential for cross-sector background usage impacts, it is integral to refer to the contextual information, water balance assessment and the uncertainties in information. The risk analysis (Section 5.3) is to consider both the likelihood and consequence of these impacts.

5.3 Risk analysis

5.3.1 Background

Risk assessment and management are central components to any strategic management that seeks to identify and minimise threats while maximising opportunities. The IESC endorses the use of risk-based assessments as the best approach to providing scientific advice on proposed CSG and coal mining developments and their impacts on water-dependent assets. The aim of BAs will be to provide sufficient scientific advice to analyse the level of risk associated with impacts on water-dependent assets, particularly those of high value such as listed threatened species, state-listed wetlands and other important ecological and cultural water features. The BA methodology aims to ensure that the risk analysis work undertaken in a BA is compatible with further focused risk management projects within a bioregion. There are many approaches to assessing risks across the industrial, mining, environmental, agricultural, health, and safety sectors and thousands of published papers on methods and tools. To ensure consistency between risk-related work undertaken among different bioregions, the BA methodology will use AS/NZS ISO 31000:2009 Risk management – principles and guidelines. This standard builds on the earlier AS/NZS 4360:2004 standard. The ISO 31000:2009 standard uses a structured approach to identifying, defining, evaluating and treating risks. Monitoring, evaluation and stakeholder interactions are key components of best-practice risk management. The risk consequence table generated in the BAs (see Table 2) is a key point of stakeholder interaction with natural resource management agencies, state government agencies and community groups. The process to implement the ISO 31000:2009 standard is shown in Figure 4.

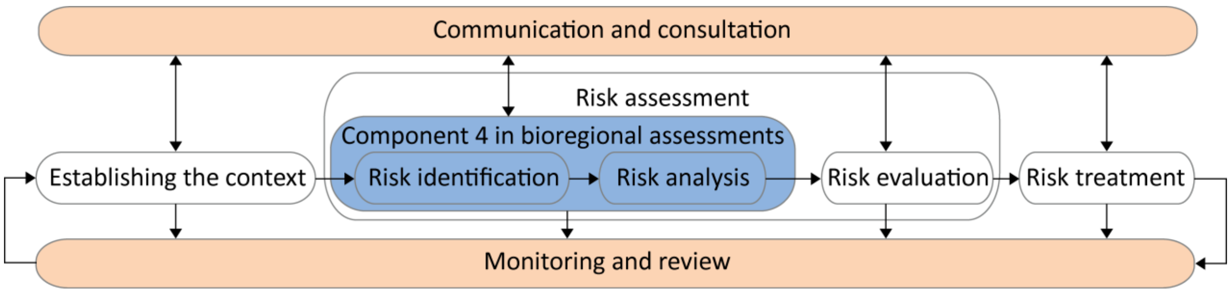

Figure 4. The risk management process, adapted from AS/NZS ISO 31000:2009 Risk management – principles and guidelines. The blue rectangle indicates the part of the process which will be implemented as part of the bioregional assessments

In the context of BAs and their purpose (namely to assist the IESC in providing advice on the likelihood of impacts of CSG and coal mining development on water-dependent assets), full application of the ISO 31000:2009 standard is outside scope, terms of reference and budget. However, in the context of providing risk-based scientific advice, it is important that any risk-related work undertaken within a BA is available to – and consistent with – other studies either underway or to be undertaken in the future. This consistency is provided by adoption of the ISO 31000:2009 standard.

The risk analysis undertaken within a BA is concerned only with water-related impacts on receptors contained within identified water-dependent assets. There is no consideration within a BA of the risks of CSG and coal mining development on vegetation, biodiversity, fauna or soils that have no water dependency and are not associated with assets.

This section of the BA methodology describes those components of the ISO 31000:2009 standard that are to be completed within a BA and those components that link to – but are outside of – the BA.

The purpose of assessing risk varies depending on use and on the individuals or organisations undertaking them. The purposes of applying risk assessment processes include Barry (2011):

- greater exploration and understanding of risks by a research team
- to meet an organisation's outcome requirement
- to ensure that a 'minimum level' of understanding of relative risks is achieved.

For the BA methodology, the purpose of the risk analysis is to:

- explore the issues of impact, likelihood and risk within a scientific and logical framework
- provide insights into where high-value water assets (for example water dependent listed threatened species and state-listed important water features) may face high risks
- identify where risks may occur that have previously not been identified or have been underestimated (i.e. surprises).

New knowledge on risks of CSG and coal mining development must be reported in the BA products.

5.3.2 AS/NZS ISO 31000:2009 Risk management – principles and guidelines

Risk is defined in the ISO 31000:2009 standard as 'the effect of uncertainty on objectives', with effect being 'a deviation from the expected' and uncertainty 'the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequence, or likelihood'. This definition makes an important distinction between the 'event' and the 'effect' of that event. This distinction leads to a fundamental change in how risk is characterised in the new standard; that is, by the consequence of an event and the likelihood of that consequence rather than by the probability of the event itself (Purdy, 2009). Thus, the consequence of a risk occurring may be negative (hazard), positive (opportunity), or may, in fact, result in increased uncertainty (AIRMIC, Alarm and IRM, 2010). The ISO 31000:2009 standard also places strong emphasis on the setting of objectives within organisations that match community and stakeholder values, thereby necessitating considerable stakeholder interaction. In general, a risk assessment cannot therefore be conducted by isolated 'experts' acting independently of communities, industry and other stakeholders. The process involves stakeholder feedback and consultation at all stages through the risk assessment (Figure 4).

5.3.3 Risk analysis in the bioregional assessments

Risk analysis (Component 4) in the BAs is a key component that synthesises information from the impact analysis and model-data analysis components. It is important that:

- outputs from model-data analyses inform the direct, indirect and cumulative impacts which are used to define consequences required by the risk analysis
- outputs from propagation of uncertainties inform likelihoods required by the risk analysis.

The emphasis on rigorous assessment and propagation of uncertainty in models is key to their ability to provide robust scientific advice on risks. This represents a significant challenge and in many cases will require the use of qualitative or semi-quantitative approaches due to large uncertainties. Subsequent update and review of the BAs will lead to improved risk analyses in the future. However, where it is feasible, quantitative methods of risk analysis are preferred in a BA.

The BAs focus effort on the risk identification and risk analysis components of the ISO 31000:2009 standard (Figure 4):

- **risk identification:** Identification of risks within a bioregion begins with understanding the exposure of receptors to impacts from CSG and coal mining development and how this exposure may affect values of water-dependent assets. This includes taking into account existing mines and activities and risk mitigation and control measures already in place. A key component is the mapping of uncertainties associated with impacts on receptors to likelihoods of risks. This requires establishing clear and logical coupling between the impact analysis and risk analysis. It also requires a clear definition of what risk events exist within a bioregion informed by natural resource management agencies and their stakeholders. From this process, a **risk register** must be generated to inform the risk analysis.
- **risk analysis:** The risk analysis combines likelihood of event occurrence, uncertainties associated with impacts, and information from the risk register to generate (i) a **consequence table** (Table 3) describing the nature of impacts, and (ii) a **risk rating matrix** (Table 2) describing the severity of impacts. The consequence table will need to take into account receptor significance (for example, agricultural significance for an anthropogenic receptor or conservation ranking for an ecological receptor) in order to develop a robust measure of severity of impacts. The consequence table may contain social, cultural, historical, ceremonial or ecological consequences. Severity of impact will depend on who is affected by a risk. The risk rating matrix may be qualitative, semi-quantitative or quantitative depending on the degree of confidence in specifying events and their likelihood.

A key component to the analysis is the use of formal logic procedures to ensure that the assignment of likelihoods and consequences is transparent and logically consistent. In particular, developing correct conditional statements for the likelihood of events occurring (Barry, 2011) is critical to accurate risk analysis irrespective of whether they are qualitative or quantitative. Transparency means that qualitative descriptors are defined unambiguously and in a way that can be assessed and tested against other information sources either now or in the future. This will ensure that scientific advice is based on common assumptions and understandings and that the risk rating matrix is constructed in a rigorous way. Risk matrices can be unreliable and error prone leading to poor measures of risk exposure (Cox, 2008) unless careful attention is paid to: (i) the logical constructs and conditional probabilities of likelihoods used as input to the risk matrix; and (ii) clear definitions and care are used to determine severity of consequence. These are components of the risk analysis that require special attention in the BAs in each bioregion. Examples of these approaches are given in Barry (2011) and DRET (2008). The risk analyses must take into account the expected variation in surface water, groundwater and ecology of systems subject to impacts from CSG and coal mining development. This includes the impacts (both positive and negative) due to:

- depressurisation and dewatering of coal seams
- the regulated and unregulated discharge of worked water
- the release into the environment of associated CSG water or permeates and brines from treated associated water
- the recovery or recharge of coal seams (and associated connected aquifers) once dewatering has ceased.

It also refers to long-term impacts on anthropogenic and ecological receptors on the surface. Where surface water, groundwater and/or ecological systems move to a different state following dewatering and recovery, these states need to be characterised, likelihoods and consequences (risks) assessed, and uncertainties reported.

There are multiple quantitative approaches to dealing with uncertainty quantification, uncertainty propagation and risk analysis that can be used to assist with generating accurate quantitative estimates of likelihood of impacts on receptors. These include (Tartakovsky, 2013):

- probabilistic risk assessment methods and fault tree analyses for exposure pathways which are flexible and combine well with logic statements to generate conditional probabilities of events
- approaches based on random domain decomposition and transition probability for delineating boundaries from point observations
- Bayesian methods for calculating model structural uncertainties
- stochastic optimisation methods for quantifying propagation of uncertainties in parameters in models
- decision theory and 'optimisation-under-uncertainty' methods to assist with risk management and mitigation choices.

The particular methods to be applied in any bioregion will vary between bioregions based on characteristics of the geology, lithology, geomorphology, hydrology, ecology and coal development pathways.

Table 2. An example of a qualitative risk rating matrix (DRET, 2008) where consequence ratings range from 'insignificant' (1) to 'catastrophic' (5) and likelihoods range from 'rare' (E) to 'almost certain' (A). This is the minimal and simplest form of a risk rating matrix and is useful where consequences and likelihoods can be defined in qualitative terms

			1	**2**	**3**	**4**	**5**
		Descriptor	**Insignificant**	**Minor**	**Moderate**	**Major**	**Catastrophic**
Likelihood level	A	**Almost certain**	A1	A2	A3	A4	A5
	B	**Likely**	B1	B2	B3	B4	B5
	C	**Possible**	C1	C2	C3	C3	C5
	D	**Unlikely**	D1	D2	D3	D3	D5
	E	**Rare**	E1	E2	E3	E3	E5

Low	Moderate	High	Extreme

Table 3. An example of a consequence table (DRET, 2008) used to determine the consequences of impacts given certain specific events occurring. A consequence table must be developed for each bioregional assessment based on discussions with state natural resource management agencies and stakeholder local knowledge for consideration in the risk analysis component of an assessment

		Consequence level				
		Negligible	**Minor**	**Moderate**	**Major**	**Extreme**
		0.1	**1**	**10**	**100**	**1000**
Property	Replacement cost	$0–0.1M	$0.1–1M	$1–10M	$10–100M	$100–1000M
Environment	Ecosystem function	No detectable change	Minor change		Major change	Irreversible change
	Habitat	1% area	1–5% area	5–30% area	30–90% area	> 90% area
	Species	Small population change	Recovery, 1 year	Recovery, 2 years	Recovery, 10 years	No recovery
Health			Minor injury		Major injury	Fatality

6 Conclusion

This report has presented the bioregional assessment methodology . The methodology is the basis on which bioregional assessments are to be conducted for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development. A bioregional assessment is the key delivery mechanism through which the best available science and independent expert knowledge are provided to the IESC on impacts of coal seam gas and coal mining development on water-dependent assets. The IESC formulates advice for the Federal Environment Minister on the basis of information contained within the bioregional assessment and other sources, as required. This methodology report has provided detailed guidance to researchers undertaking bioregional assessments on their purpose and background, the specification of bioregions and subregions, the identification and role of water dependent assets, receptors and response variables, and the components that comprise an assessment. The components are:

1. **Contextual information:** Information providing context and background against which qualitative and quantitative assessments of impact and risk of CSG and coal mining development are generated
2. **Model-data analysis**: Output and synthesises from data and models used to develop a quantitative description of the hydrologic relationship between coal seam dewatering and impacts on anthropogenic or ecological receptors
3. **Impact analysis**: The reporting on the direct, indirect and cumulative impacts and of impacts of CSG and coal mining development on receptors within assets and their associated uncertainties
4. **Risk analysis**: A scientific assessment of the likelihood of impacts on receptors contained within assets based on the propagation of uncertainties from models and data
5. **Outcome synthesis**: A summary of outcomes used by the IESC to support scientific advice on impacts and risk of CSG and coal mining development on water resources.

Uncertainty analyses are critical to the characterisation and definition of the levels of confidence associated with estimated impacts and risks to water dependent assets. The methodology requires all workflows, information sources, models, data and outputs to be publically available and fully transparent. The outputs from a bioregional assessment consists of:

1. Scientific advice on the likelihood of direct, indirect and cumulative impacts on anthropogenic and ecological receptors contained within assets
2. Conceptual models of causal pathway connecting depressurisation and dewatering of coal seams at depth to impacts on receptors either at depth or located at or near the surface
3. Quantitative, semi-quantitative and qualitative output from models of ecological, surface water hydrology, groundwater, hydrogeology and coal resources development processes
4. The extent, nature and consequences of impacts
5. Measures of confidence on estimated impacts including likelihoods of risks to receptors and assets
6. Options for monitoring programs and review frequency of future BAs, risk assessments or other studies.

The resulting bioregional assessment for any given bioregion is a defensible baseline statement on the best and most current state of scientific knowledge regarding the impacts of CSG and coal mining development on water resources. BAs are an important tool in improving regional-scale management and regulation of CSG and coal mining developments. They provide crucial knowledge and information for the IESC in developing its advice on cumulative impacts, water balances and risk assessments associated with project proposals. Application of this methodology will provide significant improvements in the scientific understanding and availability of information to help protect water resources, assets and values.

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Glossary

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 wells 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.

Artesian aquifer: an aquifer that has enough natural pressure to allow water in a bore to rise to the ground surface.

Assets: see water-dependent assets.

Bioregion (as defined in the bioregional assessment (BA) methodology): the land area that constitutes a geographic location within which is collected and analysed data and information relating to potential impacts of coal seam gas or coal mining developments on receptors identified for key water-dependent assets.

Bioregional assessments: A bioregional assessment is 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 CSG and coal mining development on water resources. The central purpose of BAs is to analyse the impacts and risks associated with changes to water-dependent assets that arise in response to current and future pathways of CSG and coal mining development.

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, well or piezometer.

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

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

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.

Ecosystem: organisms and the non-living environment, all interacting as a unit.

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.

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

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

Groundwater system: see water system.

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

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

Impact: a change or changed state occurring in a receptor as a result of water-mediated effects of coal seam gas or coal mining development or production.

Material: pertinent or relevant.

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

Porosity: the proportion of the volume of rock consisting of pores, usually expressed as a percentage of the total rock or soil mass.

Receptors: discrete, identifiable attributes or entities associated with water-dependent assets that are materially impacted by change in water quality or quantity arising from CSG or coal mining development. Receptors are the primary mechanism for reporting on the direct, indirect and cumulative impacts in a BA.

Recharge: see groundwater recharge.

Response variables: variables that relate parameters, state variables and/or fluxes in groundwater and surface water models with impacts on receptors. Response variables also link receptors with subsequent advice on monitoring programs.

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

Saturated zone: the part of the ground in which all the voids in the rocks or soil are filled with water. The watertable is the top of the saturated zone in an unconfined aquifer.

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

Stratigraphy: stratified (layered) rocks.

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

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

Unsaturated zone: the zone in soils and rocks occurring above the watertable, where there is some air within the pore spaces.

Water allocation: the specific volume of water allocated to water access entitlements in a given season, defined according to rules established in the relevant water plan.

Water-dependent asset: an entity contained within a bioregion where the characteristics can be ascribed a defined value and which can be clearly linked, either directly or indirectly, to a dependency on groundwater or surface water quantity or quality.

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

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

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

Well: a human-made hole in the ground, generally created by drilling, to obtain water (also see bore).