Australian Government

BIOREGIONAL
ASSESSMENTS

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

# Conceptual modelling for the Hunter subregion

## Product 2.3 for the Hunter subregion from the Northern Sydney Basin Bioregional Assessment

2018

A scientific collaboration between the Department of the Environment and Energy,
Bureau of Meteorology, CSIRO and Geoscience Australia

## The Bioregional Assessment Programme

The Bioregional Assessment Programme is a transparent and accessible programme of baseline assessments that increase the available science for decision making associated with coal seam gas and large coal mines. A bioregional assessment is a scientific analysis of the ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of the potential impacts of coal seam gas and large coal mining development on water resources. This Programme draws on the best available scientific information and knowledge from many sources, including government, industry and regional communities, to produce bioregional assessments that are independent, scientifically robust, and relevant and meaningful at a regional scale.

The Programme is funded by the Australian Government Department of the Environment and Energy. The Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia are collaborating to undertake bioregional assessments. For more information, visit http://www.bioregionalassessments.gov.au.

## Department of the Environment and Energy

The Office of Water Science, within the Australian Government Department of the Environment and Energy, is strengthening the regulation of coal seam gas and large coal mining development by ensuring that future decisions are informed by substantially improved science and independent expert advice about the potential water related impacts of those developments. For more information, visit https://www.environment.gov.au/water/coal-and-coal-seam-gas/office-of-water-science.

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Authorship is listed in relative order of contribution.

## Copyright

## Disclaimer

## Cover photograph

Oblique view west of Muswellbrook showing Bengalla coal storage (left foreground) with irrigated agriculture and riparian vegetation either side of the Hunter River and Mount Arthur coal mine in the distance (right background), NSW, 2014

© Google earth (2015), Sinclair Knight Merz Imagery date 16 December 2008. Position 32°17’58’’ S, 150°48’51’’ E, elevation 136 m, eye altitude 1.59 km

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# Executive summary

Conceptual models are abstractions or simplifications of reality. During development of conceptual models, the essence of how the key system components operate and interact is distilled. In the bioregional assessments (BA), conceptual models are developed to describe the *causal pathways*, the logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water resources and water-dependent assets.

***Methods***

This product details the conceptual model of causal pathways for the Hunter subregion, following the methods described in the companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways. It identifies the:

- key system components, processes and interactions, which essentially define pathways over and through which water can move (Section 2.3.2)
- ecosystems in the Hunter subregion in terms of landscape classes and their dependence on water (Section 2.3.3)
- baseline and coal resource development pathway (CRDP) (Section 2.3.4)
- causal pathways from coal resource developments using an Impact Modes and Effects Analysis (IMEA) hazard analysis approach (Section 2.3.5).

***Summary of key system components, processes and interactions***

The Hunter subregion is a little over 17,000 km$^2$, and contains portions of the Western, Hunter and Newcastle coalfields. The subregion is not considered to have any groundwater connections with areas to the north-east due to the geological basin divides that define its boundary, although the Hunter river basin extends north-east of the subregion boundary. Surface water catchments define the subregion boundary to the south and west of the subregion, but regional-scale groundwater connections with the Sydney Basin and Northern Inland Catchments bioregions may exist where suitable gradients and conductive aquifers exist. Although cross-boundary flows are not expected to be significant to the water balance of the Hunter subregion, suitable margins and boundary conditions are required in numerical modelling to minimise possible edge effects. Regional groundwater systems extend east of the coastline, which defines the eastern boundary.

The surface water catchment of the Hunter subregion contains rivers that flow into the Hunter river basin and Macquarie-Tuggerah lakes basin. Salinity of the Hunter River has been a significant issue; however, since the introduction of the Hunter River Salinity Trading Scheme (HRSTS), this has improved considerably. The Hunter River lies within an extensive alluvial aquifer, which has exchanges with the river as both a source and sink, and with the underlying fractured rocks where permeable pathways exist. Under HRSTS rules, industries may release saline water to the river under high-flow conditions as long as this does not elevate river salinity above target levels. The use of dam releases and the HRSTS have tended to reduce some of the variability in river flow and stage in the regulated reaches of the river.

### *Ecosystems*

The landscape classification describes the main ecological and human systems (including agricultural production systems, industrial and urban uses), and provides a high-level conceptualisation of the subregion at the surface. Most assets are related to one or more *landscape classes*, which are defined for BA purposes as ecosystems with characteristics that are expected to respond similarly to changes in the groundwater and/or surface water due to coal resource development. The Assessment team refined the landscape classification and high-level conceptualisation of the subregion following discussions at the 'Conceptual modelling of causal pathways' workshop held in August 2015. The landscape classes were grouped into five broad landscape groups, defined to reflect different connections to surface water and groundwater systems:

- 'Riverine'
- 'GDE'
- 'Estuaries and coastal lakes'
- 'Non-GDE vegetation'
- 'Economic land use'.

These landscape groups are expressed as a percentage of the preliminary assessment extent (PAE) area, which in the Hunter subregion coincides with the subregion boundary. Of the approximately 17,000 $km^2$ of the Hunter PAE, 620 $km^2$ (or 3.6%) fell within the 'GDE' and 'Coastal lakes and estuaries' landscape groups. In addition, there is 15,000 km of rivers and streams. Just over 10,400 $km^2$ of native vegetation within the Hunter PAE is not classified as GDE. The remainder of the PAE is classified as the 'Economic land use' landscape group.

### *Coal resource development*

Coal mining has been occurring in the Hunter subregion for over 100 years. To quantify impacts of coal resource development in the Hunter subregion, two potential futures are considered:

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

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

In December 2012, there were 42 mining operations in the Hunter subregion, comprising 22 open-cut mines and 20 underground mines. As of September 2015, 22 proposals for coal resource developments were identified for the Hunter subregion, including 3 new open-cut coal mines, 3 new underground mines and 16 projects of baseline mining operations. A further ten proposed coal resource developments were deemed to be too exploratory or unlikely to proceed and do not comprise the additional coal resource development. As of May 2015, there is no CSG production in the Hunter subregion, nor any proposals for CSG development in the future. Therefore, the CRDP includes the 42 mining operations in the baseline, plus the 22 coal resource developments, which are new or expanded coal mines.

### *Hazard analysis*

A dedicated hazard analysis, using IMEA, is used to systematically identify coal resource development hazards with the potential to impact hydrology. Details of the IMEA are outlined in companion submethodology M11 (as listed in Table 1) for hazard analysis. A large number of hazards were identified, many of which are beyond the scope of an Assessment or are assumed to be adequately addressed by site-based risk management processes and regulation. Hazards for CSG were not considered in the Hunter subregion as there are no proposals for CSG development as of May 2015. The four highest ranked hazards (listed with the syntax [Activity]:[Impact mode]) in the Hunter subregion are in the production life-cycle stage and include:

(i) Waste rock blasting, excavation and storage: Disruption of natural surface drainage: Pit expansion
(ii) Longwall coal extraction: Subsurface fractures (create new, enlarge or existing)
(iii) Mine dewatering, treatment, reuse and disposal (multi-seam mining): Incremental, mine water increase (unplanned) – from old workings
(iv) Longwall coal extraction: Subsidence, which is related to (ii).

The hazards are grouped according to the four causal pathway groups (refer to Appendix B in companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways):

- ‘Surface water drainage’
- ‘Operational water management’
- ‘Subsurface depressurisation and dewatering’
- ‘Subsurface physical flow paths’.

### *Causal pathways*

The ‘Surface water drainage’ causal pathway group involves the physical disruption and disturbance of surface topography and near-surface materials (vegetation, topsoil, weathered rock). Most disruptions to surface water drainage arise from changes directly at the surface, but can also be caused indirectly, such as from subsidence. Mine subsidence is a lowering of the land surface due to collapse of the regolith above an underground mine. The collapsed zone is highly fractured and often has enhanced hydraulic conductivity and storage. In the Hunter Valley, the following have all been affected by subsidence: Eui Creek, Wambo Creek, Bowmans Creek, Fishery Creek and Black Creek. Damage has occurred in the form of enhanced streambed erosion leading to degraded water quality, loss of streamflow and death of riparian vegetation.

The ‘Operational water management’ causal pathway group involves the modification of water management systems to facilitate sourcing, storing, using and disposing water at the coal resource development site. For salt concentrations related to mine water releases in the Hunter Regulated

River above Singleton, the process is covered by the HRSTS. The quantitative models used in the Assessment do not model water quality parameters; however, rules governing the discharge of water from industry to the Hunter River under the HRSTS have been incorporated into the river model. Monitoring of water quality for other pollutants, such as heavy metals or BTEX (benzene, toluene, ethylbenzene and xylene), and their removal or disposal, is the responsibility of individual mining companies under their environment protection licences (EPLs).

The ‘Subsurface depressurisation and dewatering’ causal pathway group arises when coal mines and coal seam gas (CSG) operations intentionally dewater and depressurise subsurface hydrostratigraphic units (such as coal seams and aquifers) to permit coal resource extraction. This causal pathway group includes degradation of the water resource in terms of availability or quality in the surface water system, and conjunctively in the alluvial aquifer. Under the Water Sharing Plan for the Hunter Unregulated and Alluvial Water Sources, there are specific rules under low- and no-flow conditions to prevent pumping that may stress the alluvial aquifer under drying conditions. For example, at the Mount Arthur Coal Mine, the change of direction of the groundwater gradient toward Permian rocks and away from the Hunter River alluvial aquifer through depressurisation has occurred; however, this has been without a change to water levels in the alluvial aquifer.

The ‘Subsurface physical flow paths’ causal pathway group involves physical modification of the rock mass or geological architecture by creating new physical paths that water may potentially infiltrate and flow along. Surface and underground mine operations may cut through several aquifer layers and their intervening layers. This may also lead to connection of layers that were previously separated. Furthermore, leakage may now occur of other material introduced by industrial activities, through these connected systems. Minerals, including sulfides, which are exposed by mining to both oxygen and water can create sulfuric acid, and the resulting drainage water is termed ‘acid rock drainage’. There are several inactive mine sites in the Lower Hunter that are leaking, or have leaked, acid-rock drainage to surface water courses at Aberdare East, Testers Hollow, Neath, Dagworth, Greta and Rothbury. Groundwater modelling has indicated that filled-in mining voids and lake pits can be a groundwater sink for decades or centuries, and that mine closure is a whole-of-landscape development.

### *Gaps*

A good conceptual understanding of a system is underpinned by good data. In the Hunter subregion, there is a good streamflow monitoring network, with many gauging stations also collecting salinity readings. Exchanges between surface water and groundwater are less well known, as they are not routinely monitored. The various methods for estimating baseflow produce widely varying estimates of its contribution to streamflow.

Although the location of major faults are known, the extent to which they act as conduits of water between strata over different depths is not well understood. Many smaller geological features have not been mapped, but while they may be an important control on local groundwater flows, for regional scale modelling, they are less important and therefore not a significant knowledge gap.

For some additional coal resource developments, the availability of data or scale of proposed changes means they cannot be represented in the numerical modelling. While inferences about their effects on surface water and groundwater can be made, for the purposes of the numerical modelling, this is a knowledge gap.

Subsidence is an inevitable consequence of longwall mining, but the effects on hydrology can be hard to predict. Depth of mining and properties of the inter-burden influence the extent of subsidence at the surface and magnitude of changes in hydraulic properties due to fracturing. Hydraulic properties can be varied in a groundwater model to reflect this uncertainty.

***Further work***

The causal pathways described in this product guide how the modelling (product 2.6.1 (surface water numerical modelling), product 2.6.2 (groundwater numerical modelling) and product 2.7 (receptor impact modelling)) is conducted, and how product 3-4 (impact and risk analysis) is framed.

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# Acknowledgements

This technical product was reviewed by several groups:

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- Technical Assurance Reference Group: Chaired by Peter Baker (Principal Science Advisor, Department of the Environment and Energy), this group comprises officials from the NSW, Queensland, South Australian and Victorian governments
- Additional Reviewers: Jodie Dabovic (NSW Department of Primary Industries (Office of Water)) Steven Palmer (Department of Industry, Innovation and Science) Kyle Horner (Environmental Protection Authority).

# Currency of scientific results

The modelling results contained in this product were completed in April 2016 using the best available data, models and approaches available at that time. The product content was completed in February 2017.

All products in the model-data analysis, impact and risk analysis, and outcome synthesis (see Figure 1) were published as a suite when completed.

# Introduction

The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) was established to provide advice to the federal Minister for the Environment on potential water-related impacts of coal seam gas (CSG) and large coal mining developments (IESC, 2015).

Bioregional assessments (BAs) are one of the key mechanisms to assist the IESC in developing this advice so that it is based on best available science and independent expert knowledge. Importantly, technical products from BAs are also expected to be made available to the public, providing the opportunity for all other interested parties, including government regulators, industry, community and the general public, to draw from a single set of accessible information. A BA is a scientific analysis, providing a baseline level of information on the ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of the potential impacts of CSG and coal mining development on water resources.

The IESC has been involved in the development of *Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources* (the BA methodology; Barrett et al., 2013) and has endorsed it. The BA methodology specifies how BAs should be undertaken. Broadly, a BA comprises five components of activity, as illustrated in Figure 1. Each BA will be different, due in part to regional differences, but also in response to the availability of data, information and fit-for-purpose models. Where differences occur, these are recorded, judgments exercised on what can be achieved, and an explicit record is made of the confidence in the scientific advice produced from the BA.

## The Bioregional Assessment Programme

The Bioregional Assessment Programme is a collaboration between the Department of the Environment and Energy, the Bureau of Meteorology, CSIRO and Geoscience Australia. Other technical expertise, such as from state governments or universities, is also drawn on as required. For example, natural resource management groups and catchment management authorities identify assets that the community values by providing the list of water-dependent assets, a key input.

The Technical Programme, part of the Bioregional Assessment Programme, will undertake BAs for the following bioregions and subregions (see http://www.bioregionalassessments.gov.au/assessments for a map and further information):

- the Galilee, Cooper, Pedirka and Arckaringa subregions, within the Lake Eyre Basin bioregion
- the Maranoa-Balonne-Condamine, Gwydir, Namoi and Central West subregions, within the Northern Inland Catchments bioregion
- the Clarence-Moreton bioregion
- the Hunter and Gloucester subregions, within the Northern Sydney Basin bioregion

- the Sydney Basin bioregion
- the Gippsland Basin bioregion.

Technical products (described in a later section) will progressively be delivered throughout the Programme.

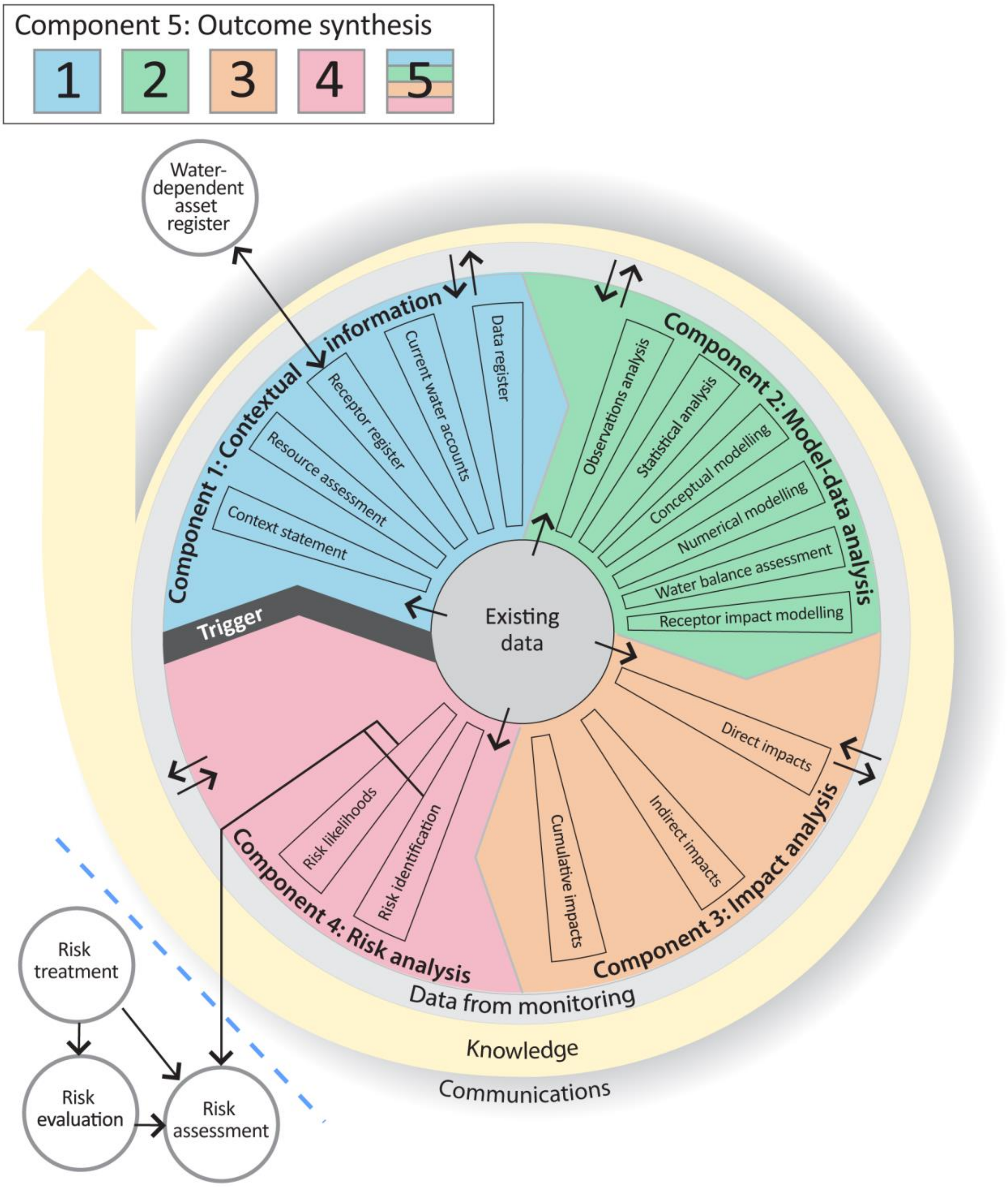

**Figure 1 Schematic diagram of the bioregional assessment methodology**

The methodology comprises five components, each delivering information into the bioregional assessment and building on prior components, thereby contributing to the accumulation of scientific knowledge. The small grey circles indicate activities external to the bioregional assessment. Risk identification and risk likelihoods are conducted within a bioregional assessment (as part of Component 4) and may contribute activities undertaken externally, such as risk evaluation, risk assessment and risk treatment.
Source: Figure 1 in Barrett et al. (2013), © Commonwealth of Australia

# Methodologies

The overall scientific and intellectual basis of the BAs is provided in the BA methodology (Barrett et al., 2013). Additional guidance is required, however, about how to apply the BA methodology to a range of subregions and bioregions. To this end, the teams undertaking the BAs have developed and documented detailed scientific submethodologies (Table 1), in the first instance, to support the consistency of their work across the BAs and, secondly, to open the approach to scrutiny, criticism and improvement through review and publication. In some instances, methodologies applied in a particular BA may differ from what is documented in the submethodologies – in this case an explanation will be supplied in the technical products of that BA. Ultimately the Programme anticipates publishing a consolidated 'operational BA methodology' with fully worked examples based on the experience and lessons learned through applying the methods to 13 bioregions and subregions.

The relationship of the submethodologies to BA components and technical products is illustrated in Figure 2. While much scientific attention is given to assembling and transforming information, particularly through the development of the numerical, conceptual and receptor impact models, integration of the overall assessment is critical to achieving the aim of the BAs. To this end, each submethodology explains how it is related to other submethodologies and what inputs and outputs are required. They also define the technical products and provide guidance on the content to be included. When this full suite of submethodologies is implemented, a BA will result in a substantial body of collated and integrated information for a subregion or bioregion, including new information about the potential impacts of coal resource development on water and water-dependent assets.

**Table 1 Methodologies**

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

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

## Technical products

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

The information included in the technical products is specified in the BA methodology. Figure 2 shows the relationship of the technical products to BA components and submethodologies. Table 2 lists the content provided in the technical products, with cross-references to the part of the BA methodology that specifies it. The red outlines in both Figure 2 and Table 2 indicate the information included in this technical product.

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

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

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

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

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

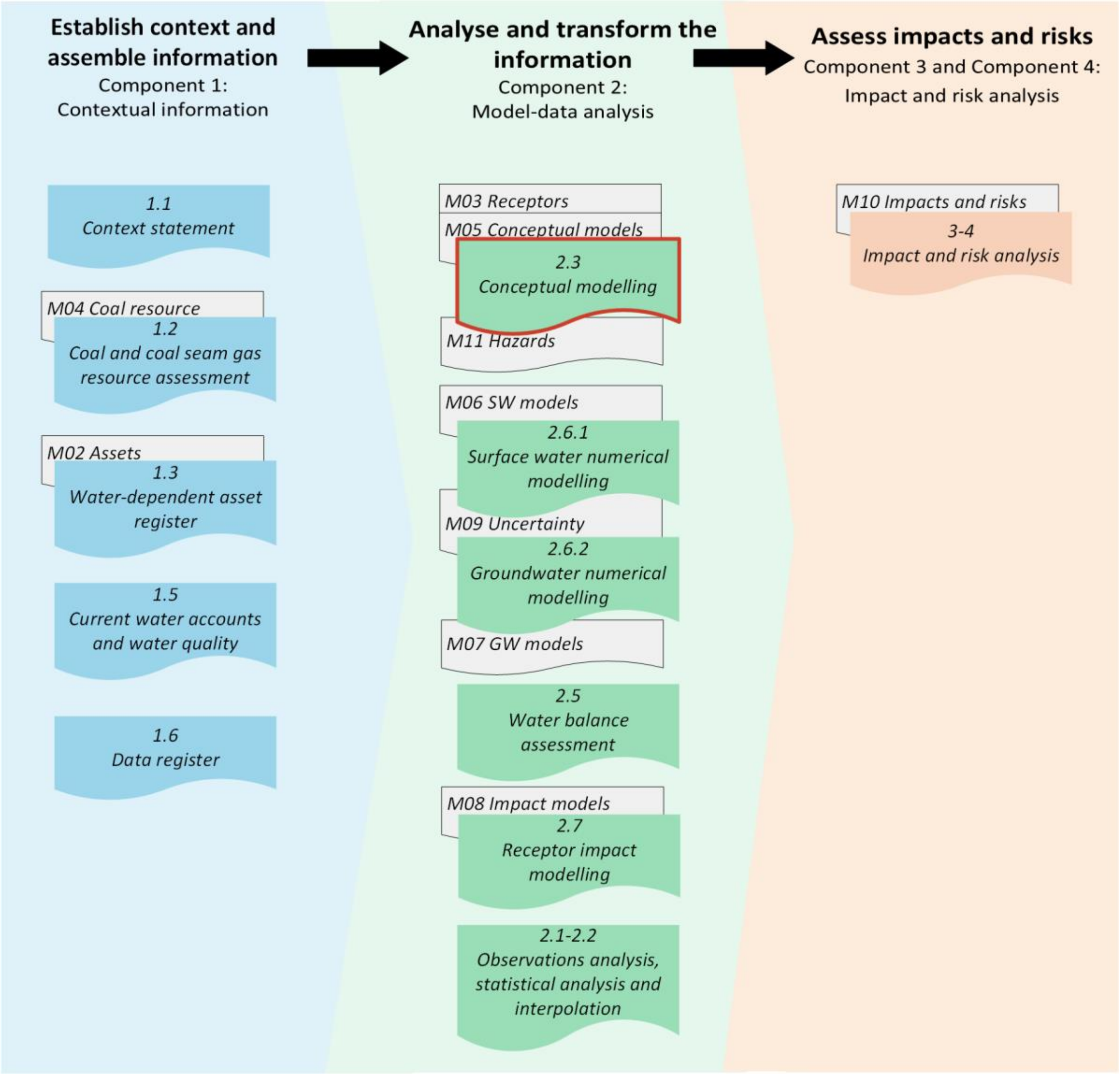

**Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment**

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

**Table 2 Technical products delivered for the Hunter subregion**

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

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

[a] The types of products are as follows:

- 'PDF' indicates a PDF document that is developed by the Northern Sydney Basin Bioregional Assessment using the structure, standards and format specified by the Programme.
- 'HTML' indicates the same content as in the PDF document, but delivered as webpages.
- 'Register' indicates controlled lists that are delivered using a variety of formats as appropriate.

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

# About this technical product

The following notes are relevant only for this technical product.

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# 2.3 Conceptual modelling for the Hunter subregion

This product firstly summarises key system components, processes and interactions for the geology, hydrogeology and surface water in the Hunter subregion. It describes its ecosystems using a landscape classification.

The product then characterises the two potential futures considered in bioregional assessments:

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

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

The Impact Modes and Effects Analysis method is then used to identify *hazards*, defined as events, or chains of events, that might result in an *effect* (change in the quality and/or quantity of surface water or groundwater).

Next are presented causal pathways, the logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water *resources* and water-dependent assets. Causal pathways for hazards are identified by considering coal resource development activities, impact causes, impact modes and the resulting water-related effects. This product describes the causal pathways from the coal resource development to the hydrological changes (represented by hydrological response variables); product 2.7 (receptor impact modelling) describes the subsequent causal pathways from the hydrological changes to the impacts

(represented by the receptor impact variables, which are linked to the landscape classes and assets).

The product concludes *by describing* causal pathways for the baseline and CRDP, which guide how the modelling (product 2.6.1 (surface water numerical modelling), product 2.6.2 (groundwater numerical modelling) and product 2.7 (receptor impact modelling)) is conducted, and how product 3-4 (impact and risk analysis) is framed.

## 2.3.1 Methods

**Summary**

The conceptual model of causal pathways characterises the *causal pathway*, the logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water and water-dependent assets. This section details the specific application to the Hunter subregion of methods described in the companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016). It closely follows these methods.

Key concepts and terminology are explained, and the overall steps are summarised: (i) synthesis of the key system components, processes and interactions for the geology, hydrogeology and surface water of the subregion; (ii) landscape classification; (iii) definition of the baseline coal resource development (baseline) and the coal resource development pathway (CRDP); (iv) hazard analysis; and (v) description of the causal pathways that potentially link baseline and CRDP coal resource developments to subregion assets via hydrological pathways.

Consultation with mining companies, state agencies and other external stakeholders were important for refining the conceptual understanding of key system components, processes and interactions; identifying and rating the coal resource development hazards relevant to the Hunter subregion; defining the baseline and additional coal resource developments; and identifying the relevant causal pathway groupings in the Hunter subregion.

### *2.3.1.1 Background and context*

This product presents information about the conceptual model of causal pathways for the Hunter subregion, which was developed using methods outlined in the companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016). The application to the Hunter subregion is described in Section 2.3.1.2, with more specific details in the individual sections that follow.

*Conceptual models* are abstractions or simplifications of reality. A number of conceptual models are developed for a BA, including conceptual models for geology, groundwater and surface water, which underpin the numerical modelling.

Another type of conceptual model is a conceptual model of causal pathways, which characterises the *causal pathway*, the chain of logic or activities – either planned or unplanned – that link coal resource development and potential impacts on water resources and water-dependent assets. The conceptual model of causal pathways brings together a number of conceptual models developed in a BA, and might be expressed in a variety of ways, with narrative, pictorial graphics, and influence diagrams all important.

The causal pathways play a critical role in focusing the BA on the most plausible and important *hazards*, defined as events, or chains of events, that might result in an *effect* (change in the quality and/or quantity of surface water or groundwater). The causal pathways associated with these hazards underpin the construction of groundwater and surface water models, and frame the assessment of the *severity* and *likelihood* of impacts to water-dependent assets. A *water-dependent asset* is an asset potentially impacted, either positively or negatively, by changes in the groundwater and/or surface water regime due to coal resource development. Some assets are solely dependent on incident rainfall and will not be considered as water-dependent if evidence does not support a linkage to groundwater or surface water that may be impacted by coal resource development.

The construction of causal pathways requires the Assessment team to first synthesise and summarise the key system components, processes and interactions for the geology, hydrogeology and surface water of the subregion (as presented in Section 2.3.2). Emphasising gaps and uncertainties is as important as summarising what is known about how various systems work.

Section 2.3.3 presents the development of a *landscape classification*, which aims to systematically simplify a complex system that contains a large number of assets identified by the community. The landscape classification describes the main biophysical and human ecosystems, and provides a high-level conceptualisation of the subregion at the surface. Most assets are related to one or more *landscape classes*, which are defined for BA purposes as ecosystems with characteristics that are expected to respond similarly to changes in groundwater and/or surface water due to coal resource development. Landscape classes are present on the landscape across the entire subregion and their spatial coverage is exhaustive and non-overlapping. Conceptually, landscape classes can be considered as types of *ecosystem assets*, which are ecosystems that may provide benefits to humanity (Bureau of Meteorology, 2013; United Nations et al., 2014).

Section 2.3.4 then defines two potential futures (Figure 3), namely the:

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

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

Figure 4 illustrates this fundamental comparison of these futures, with the baseline in the top half of the figure and the CRDP in the bottom half of the figure. It emphasises that in order to assess potential impacts on assets, it is important to compare the changes of two types of variables at specific points in space and time:

- *hydrological response variables*, the hydrological characteristics of the system that potentially change due to coal resource development (for example, drawdown (Figure 3) or the annual streamflow volume)

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

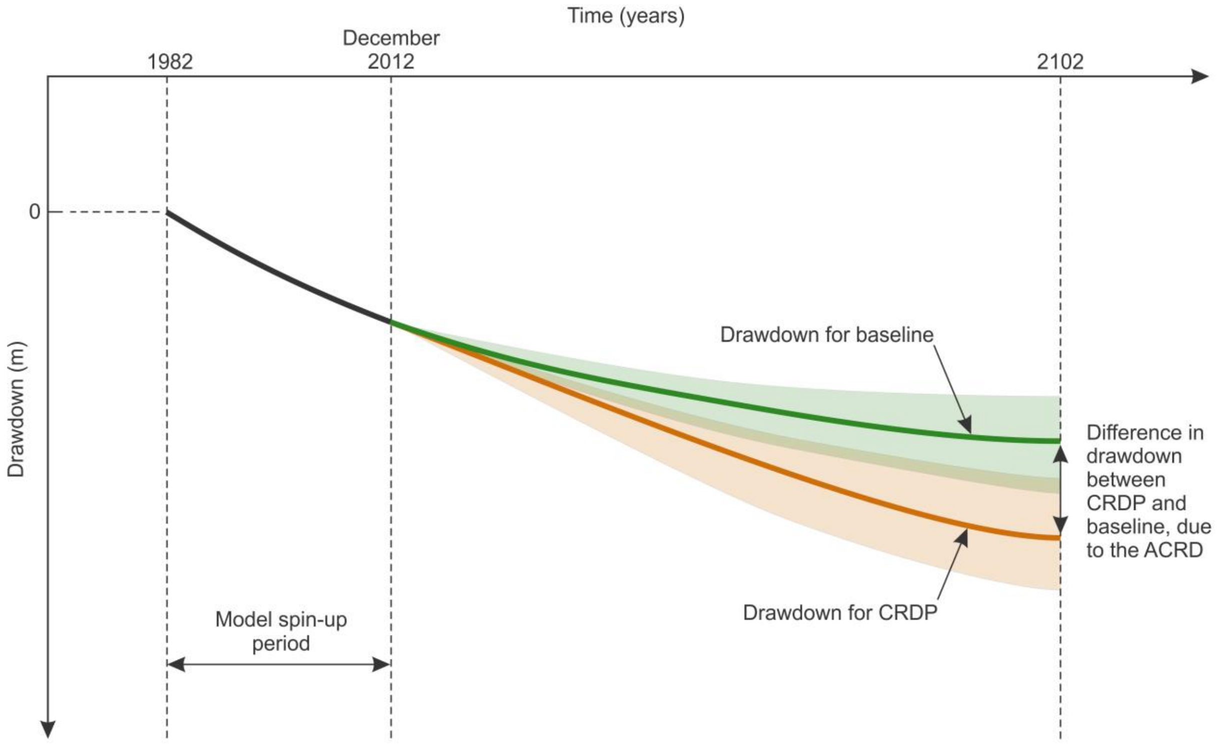

**Figure 3 Generic example of drawdown at a specific location over time for the baseline coal resource development (baseline) and the coal resource development pathway (CRDP). The difference in drawdown between CRDP and baseline is due to the additional coal resource development (ACRD)**

The lighter shades indicate the uncertainty in results. Model spin-up period is a warm-up period for the models.

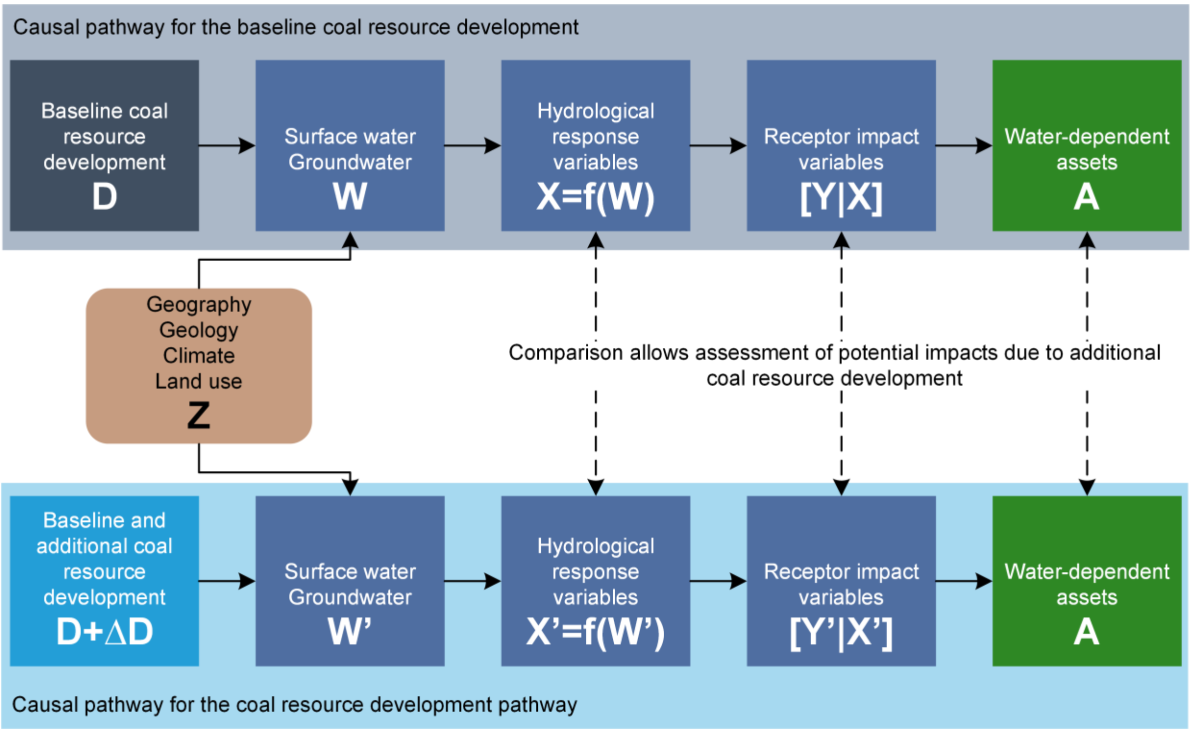

**Figure 4 The difference in results between coal resource development pathway (CRDP) and the baseline coal resource development (baseline) provides the potential impacts due to the additional coal resource development (ACRD)**

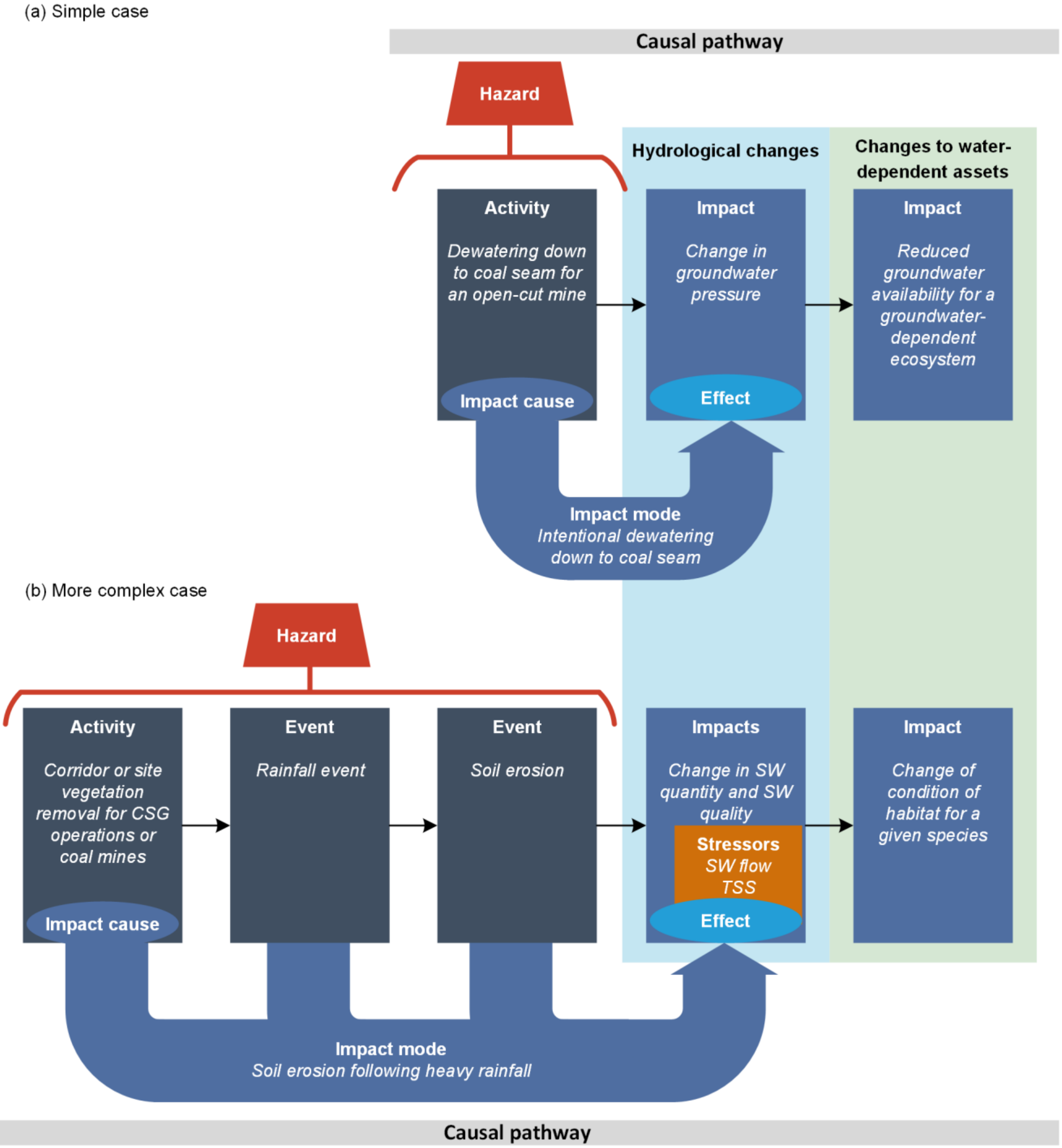

**Figure 5 Hazard analysis using the Impact Modes and Effects Analysis**

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

Section 2.3.5 details the hazard analysis, using the Impact Modes and Effects Analysis (IMEA) method, as described in companion submethodology M11 (as listed in Table 1) for hazard analysis (Ford et al., 2016), and illustrated in Figure 5. Potential causal pathways for both baseline and CRDP are identified by considering:

- *activities* – planned events associated with a CSG operation or coal mine. For example, activities during the exploration and appraisal life-cycle stage in a CSG operation include drilling and coring, ground-based geophysics and surface core testing. Activities are grouped into components, which are grouped into life-cycle stages
- *impact causes* – activities (or aspects of an activity) that initiate a hazardous chain of events
- *impact modes* – the manner in which a hazardous chain of events (initiated by an impact cause) could result in an effect (change in the quality and/or quantity of surface water or groundwater). There might be multiple impact modes for each activity or chain of events
- *effects* – changes in the quantity and/or quality of surface water or groundwater. An effect is a specific type of an *impact* (any change resulting from prior events).

This product only specifies the causal pathways from coal resource development to hydrological response variables (see Figure 4). For BAs undertaking receptor impact modelling, the subsequent causal pathways (from hydrological response variables to impacts on landscape classes and water-dependent assets) are reported in the companion product 2.7 (receptor impact modelling). These causal pathways are reported for only those landscape classes with potential hydrological changes, as reported in product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling).

### 2.3.1.2 Developing causal pathways

The approach undertaken in the Hunter subregion closely follows the process laid out in the companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016).

The key system components, processes and interactions for the geology, hydrogeology and surface water of the subregion were synthesised based on contextual information provided in companion product 1.1 for the Hunter subregion (McVicar et al., 2015) and in conjunction with the development of the companion products for surface water modelling (companion product 2.6.1 (Zhang et al., 2018)), groundwater modelling (companion product 2.6.2 (Herron et al., 2018c) and water balance assessment (companion product 2.5 (Herron et al., 2018a)) for the Hunter subregion.

The geological conceptualisation is based on the geological model developed by the Assessment team for the Hunter subregion (see companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018b)). A landscape classification was chosen that reflects the water dependence of the main biophysical and human ecosystems of the subregion.

Coal mining has occurred within the Hunter subregion for more than a century. Existing (as of May 2015) and potential new coal resource developments in the Hunter subregion are detailed in companion product 1.2 for the Hunter subregion (Hodgkinson et al., 2015). The list of potential new developments (including expansions to existing operations) identified in this product were presented to the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) in March 2015 and approved as the basis for defining the additional coal resource developments in the bioregional assessment (BA) for the Hunter subregion. This list was subsequently reviewed and discussed with representatives from mining companies with operations in the subregion at a workshop in Singleton in August 2015. Discussions were focused on knowledge gaps and uncertainties identified by the Assessment team. A revised list of additional coal resource developments was generated based on feedback obtained at the workshop and follow-up conversations with some mining companies.

There are no CSG developments currently operating, approved, or under consideration in the Hunter subregion.

A hazard analysis workshop for the Hunter subregion was undertaken in April 2015 with a small group of hydrological, geological and coal mining experts present from CSIRO, Geoscience Australia and the NSW Department of Primary Industries Water. The hazards were prioritised and subsequently aggregated by common impact causes to a reduced set of causal pathways for baseline and CRDP. No causal pathways or hazards associated with CSG developments are evaluated in this BA.

A conceptual modelling workshop for the Hunter subregion was held in Newcastle in August 2015 to socialise and discuss the modelling approach for the BA for the Hunter subregion with mining company, state agency and local government representatives. It was an opportunity to:

- test the Assessment team's regional-scale conceptual understanding of the Hunter subregion with local experts
- present results from the hazard analysis and describe the approach to classifying hazards into the main causal pathway groups
- explain how this conceptualisation of system components, processes and interactions is reflected in the numerical surface water and groundwater models
- introduce the landscape classification approach for grouping water-dependent assets into hydrologically-similar ecosystem groupings, to simplify the impacts analysis
- for each of the foregoing, provide external stakeholders with the opportunity to share their knowledge, comment on the Assessment team's approach, raise issues of concern (e.g. representation of local-scale features in regional models) and respond to questions from the Assessment team.

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## 2.3.2 Summary of key system components, processes and interactions

***Summary***

Surface water and groundwater flows in the Hunter subregion are dominated by the nature of surface regolith layering and faulting. Diffuse recharge from rainfall occurs across the subregion, with increased rates in sandy alluvial deposits, in areas of exposed rock where weathering has resulted in increased hydraulic conductivities, and in coastal dunes and sand deposits. Discharge can occur locally – to springs, alluvial aquifers and rivers – and become increasingly regional in scale where flows discharge to the ocean. Rivers and streams in the Hunter subregion are closely coupled with alluvial deposits and aquifers, with bi-directional flows expected. The balance between river leakage and baseflow discharge is dependent on climatic variation.

Coal mine operations can affect surface water flows directly by altering surface water flow paths, or changing groundwater gradients in the immediate vicinity of operations. Underground mines reduce the groundwater level in their local coal seams, and may induce land surface changes through subsidence and upsidence. The role of faults as either conductors of water or barriers to flow in their pre-mining state is not understood equally across the subregion. Changes to the way faults operate, or the creation of new fractures, that may occur as the result of their interaction with open-cut and underground mining activities is recognised as a knowledge gap.

### *2.3.2.1 Scope and overview*

In this section, the key physical characteristics of the Hunter subregion that determine the nature of hydrological connections across the subregion are summarised, based on information reported in the companion product 1.1 for the Hunter subregion (McVicar et al., 2015). The conceptual model of Hunter system architecture and associated water flows and pathways developed provides the basis for assessing the impacts of coal mining developments on regional hydrology in this subregion. Although coal seam gas (CSG) development is not currently part of the coal resource development pathway (CRDP) for the Hunter subregion, the conceptual model of structural controls and hydrological connectivity is equally pertinent to any possible future CSG developments. Existing and potential water flows and pathways in the subregion are summarised conceptually, without detailed descriptions of any individual component. In Section 2.3.5, the coal mine activities identified in the hazard analysis for the Hunter subregion are grouped according to the flow pathways they affect, thereby establishing the causal pathways that potentially link changes in hydrology caused by coal mine activities to water-dependent assets.

The spatial limits of the Hunter subregion and the Hunter preliminary assessment extent (PAE) are the same and described in companion product 1.1 for the Hunter subregion (McVicar et al., 2015; see also Figure 6). The boundaries are the Hunter-Central Coast surface water catchment on the southern and western boundaries, a very short length of the geological Sydney Basin at Ulan in the south-west, a length of the geological Werrie Basin in the north-west corner, the Hunter-Mooki

Thrust Fault along the northern boundary from Murrurundi to Maitland, and the natural coastline with the Tasman Sea to the east (see Figure 4 in companion product 1.1 for the Hunter subregion (McVicar et al., 2015)). The enclosed area is about 17,000 km$^2$, and contains portions of the Western, Hunter and Newcastle coalfields (Figure 6). The Hunter subregion is not considered to have any groundwater connection with other areas where geological faults define its boundary, even in the north-east area where surface water flows originate outside the PAE. There may be a groundwater connection in the north-west at the boundary with the geological Gunnedah Basin, where shallow basement rocks are believed to divide the Sydney and Gunnedah basins, but there is a significant thickness of sedimentary rock which may allow a connection (see Section 1.1.3.4 in companion product 1.1 for the Hunter subregion (McVicar et al., 2015, p. 79)). Most of the southern boundary is defined by the surface water divide. Although regional-scale groundwater flows may occur across this boundary where head gradients and a suitable aquifer exist, they are considered to be small enough to not be significant in the water balance of the Hunter subregion. Suitable consideration, however, must be given during numerical modelling of this boundary to minimise any potential edge effects.

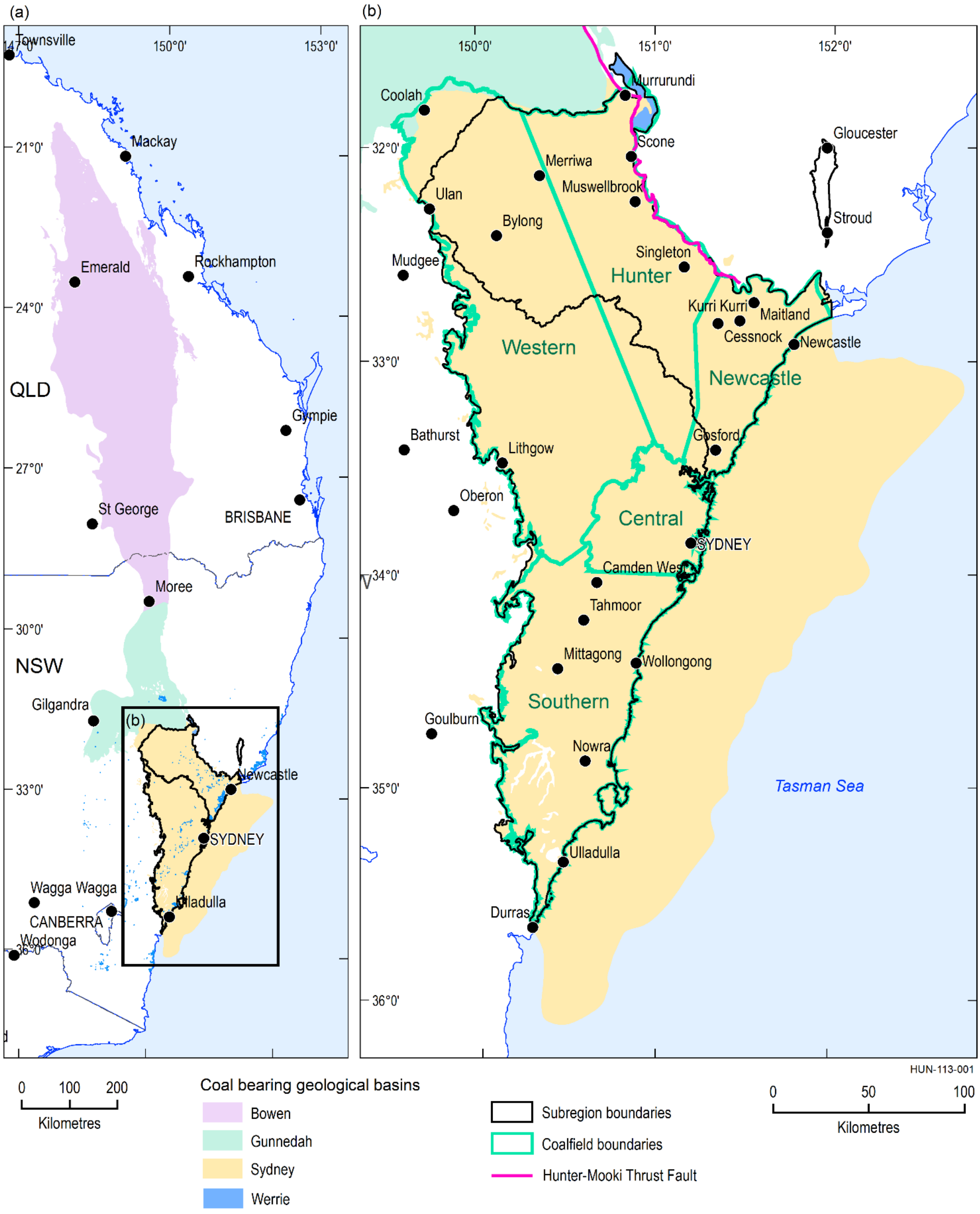


**Figure 6 Location of (a) Sydney Basin and (b) Hunter subregion, showing main coalfields of the basin**

Data: NSW Trade and Investment (Dataset 5), Geoscience Australia (Dataset 6)

Coal mining in the Hunter subregion first commenced in the 1790s from outcropping seams around Nobbys Head in Newcastle (NSW Mineral Council, 2016). Production in the Newcastle Coalfields increased due to the completion of a breakwater at Nobbys Head in 1846, which made transfer by ship much safer; the opening of railways from Sydney to Parramatta in 1855 and from

Newcastle to Maitland in 1857, allowing rapid overland transport; and expansion into the Hunter Coalfields following the discovery of the Greta Coal Measures in the 1890s.

As of May 2015, there were 18 operating mines, 7 operating complexes containing multiple mining operations, and 6 mines in care and maintenance or recently closed in the Hunter subregion (see companion product 1.2 for the Hunter subregion (Hodgkinson et al., 2015)). Some mines have been operating for over 100 years, while others are less than a decade old. Hodgkinson et al. (2015) identified 42 proposals for coal resource developments that had commenced or were likely to commence after December 2012. This list included 27 proposals for extensions and modifications to existing mines, and 15 proposals for new operations. Feedback from mining companies following compilation of this preliminary list, including a review of approval and development commencement dates, plus review of availability of data to inform modelling have since been factored into defining what mining activities are represented in the baseline coal resource development (baseline) and CRDP for the Hunter subregion (detailed in Section 2.3.4). As of May 2015, there was no CSG production in the Hunter subregion, nor any proposals for future CSG development.

In general the groundwater flow paths follow the direction of the subregion’s topography from the uplands toward the central valley and then to the ocean. Mine operations may influence or interrupt flow paths within the geological layers from which they are physically removing coal and overburden, and potentially surrounding areas. Open-cut mining may affect streams and rivers, surface overland flows and shallow groundwater directly due to the area of active mine pits, dewatering of pits and construction of associated mine infrastructure. Underground mining may directly affect flows within the target coal seams and adjacent interburden layers, depending on connectivity. If longwall mining causes a collapse of the overlying material (subsidence) or localised uplift (upsidence), then the structure and architecture of the rock mass may change, thereby affecting its hydrogeological characteristics such as hydraulic conductivity and specific storage. These processes will affect flows and pathways up to and including surface flows.

### ***2.3.2.2 Geology and hydrogeology***

#### 2.3.2.2.1 Geology

A new generalised geological model of the Hunter subregion was developed from the heterogeneous deep bore data as no comprehensive model was readily available (see companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018b)). This model focused primarily on delineating the main stratigraphic surfaces of the Carboniferous to Triassic sequences, with the coal seams mainly within Permian strata (Figure 7). Near surface layers that are geologically younger were not of direct interest as they do not contain economic coal resource. The layering and depth profiles generated were a key input to the numerical groundwater modelling (see companion product 2.6.2 for the Hunter subregion (Herron et al., 2018c)). The hydrological modelling explicitly includes overlays of the important surface layers where water fluxes are active. This section is a summary of the geological data presented in companion product 1.1 for the Hunter subregion (McVicar et al., 2015).

The stratigraphic units of the main coalfields of the Sydney Basin are shown in Figure 7. The Hunter subregion contains parts of the Western, Hunter and Newcastle coalfields (Figure 6). The vertical scale in the figure is based on formation age rather than depth below topographic surface, so it shows the correlation of the coal seams and intervening layers across the different coalfields (McVicar et al., 2015, Section 1.1.3).

In the Western Coalfields in the west of the subregion, the Hawkesbury Sandstone and Wianamatta Group form extensive, layered mesa-like plateaux, with the quartzose sandstone and conglomerate layers commonly acting as aquifers, whereas the lower-permeability shale and claystone layers of the Wianamatta Group are commonly aquitards. These stratigraphic units occur at or close to the surface across much of the south and south-west of the subregion and range in thickness from 90 to 700 m, generally thickening from west to east. Locally there are outcrops of the Illawarra Coal Measures, which dip gently to the east in the south-west and toward the north-east in the north-west of the subregion.

The Hunter and Newcastle coalfields, in the centre and eastern parts of the subregion, respectively, have a well-correlated stratigraphy, with mainly terminology differences between them (Figure 7). Various sandstone and conglomerate units, collectively part of the Narrabeen Group, cover the land surface to variable depth. In the northern section of these coalfields the Greta and Wittingham coal measures can be exposed at the surface and lend themselves to both open-cut and underground mining. The Greta Coal Measures thin toward the south and its expression is restricted to the west of the Lochinvar Anticline (Figure 8). The Newcastle and Tomago coal measures thicken from west to east in the Newcastle Coalfields, and coal seams outcrop at the surface along the coastline of the subregion.

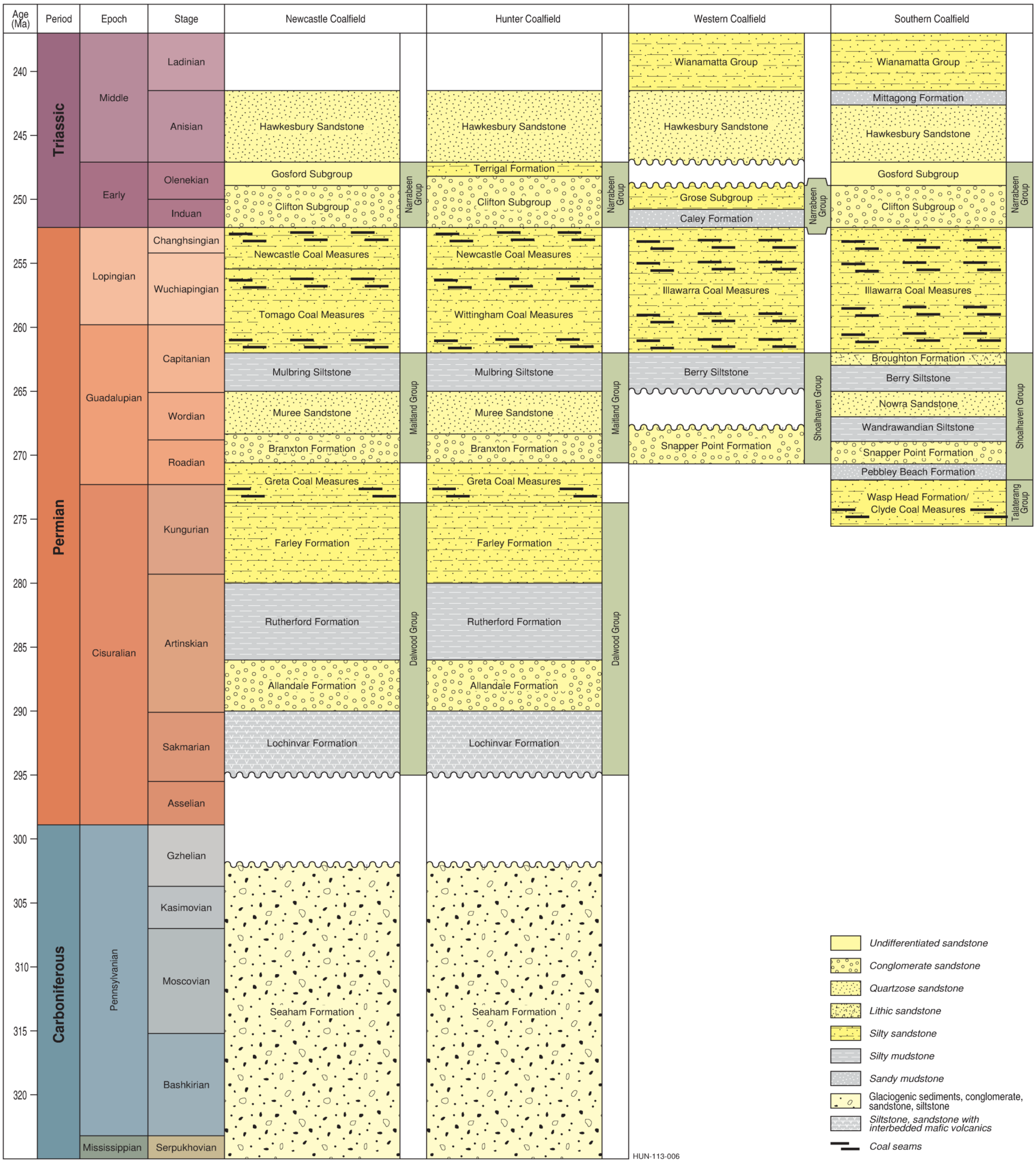


**Figure 7 Generalised stratigraphic column of the Carboniferous to Triassic units in the main coalfields of the Sydney Basin. The Southern Coalfields are not present in the Hunter subregion**

Younger Jurassic and Cenozoic units that occur in the Hunter subregion are not shown as they do not contain economic coal resources.
Source: produced for Bioregional Assessment Programme based on stratigraphic unit information from Geoscience Australia and Australian Stratigraphy Commission (2016)
This figure has been optimised for printing on A3 paper (297 mm x 420 mm).

#### 2.3.2.2.2 Hydrogeology

This section presents a summary of the hydrogeological characteristics of the Hunter subregion, based on companion product 1.1 for the Hunter subregion (McVicar et al., 2015). In general, the groundwater flow paths follow the direction of the subregion's topography from the uplands toward the central valley and then to the ocean. Groundwater yield and quality varies across the subregion, and water flow characteristics vary according to whether the aquifers are fractured rock, hard rock, or sand and clay deposits.

The Hunter subregion is dominated by fractured rock aquifers in the Cenozoic Liverpool Range Volcanics and Jurassic, Triassic and Permian sedimentary deposits (Figure 8). Groundwater yields from the volcanic aquifers are typically about 400 $m^3$/day, however, there are water hardness issues due to calcium and magnesium carbonates; the highest yields occur where cavities connect with fractures, and where weathering has occurred in the lava sheet (see Section 1.1.4.1.1 of companion product 1.1 for the Hunter subregion (McVicar et al., 2015)). The surficial fractured rocks often host local groundwater flow and provide baseflow to streams.

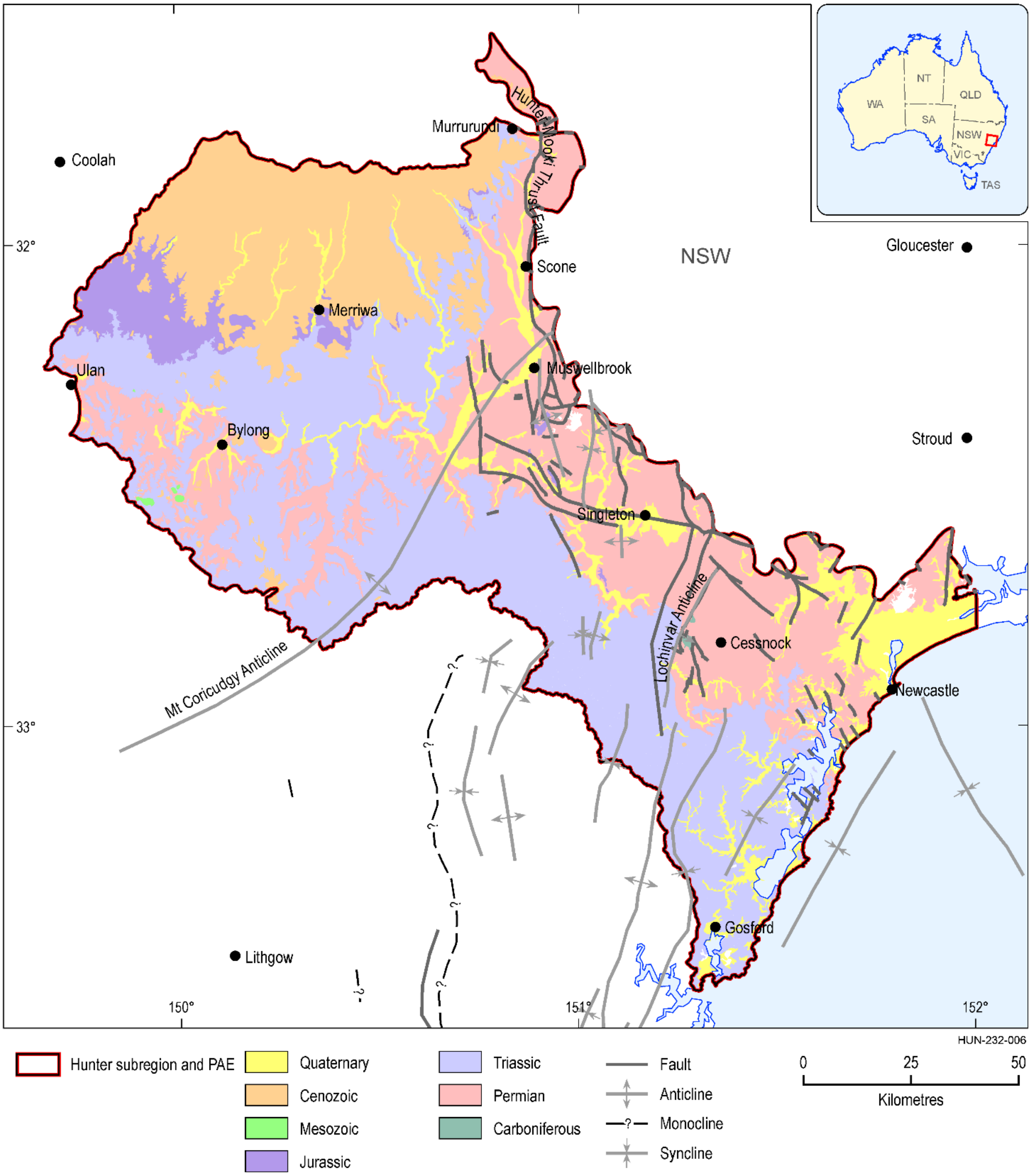


Figure 8 Surface geology of the Hunter subregion

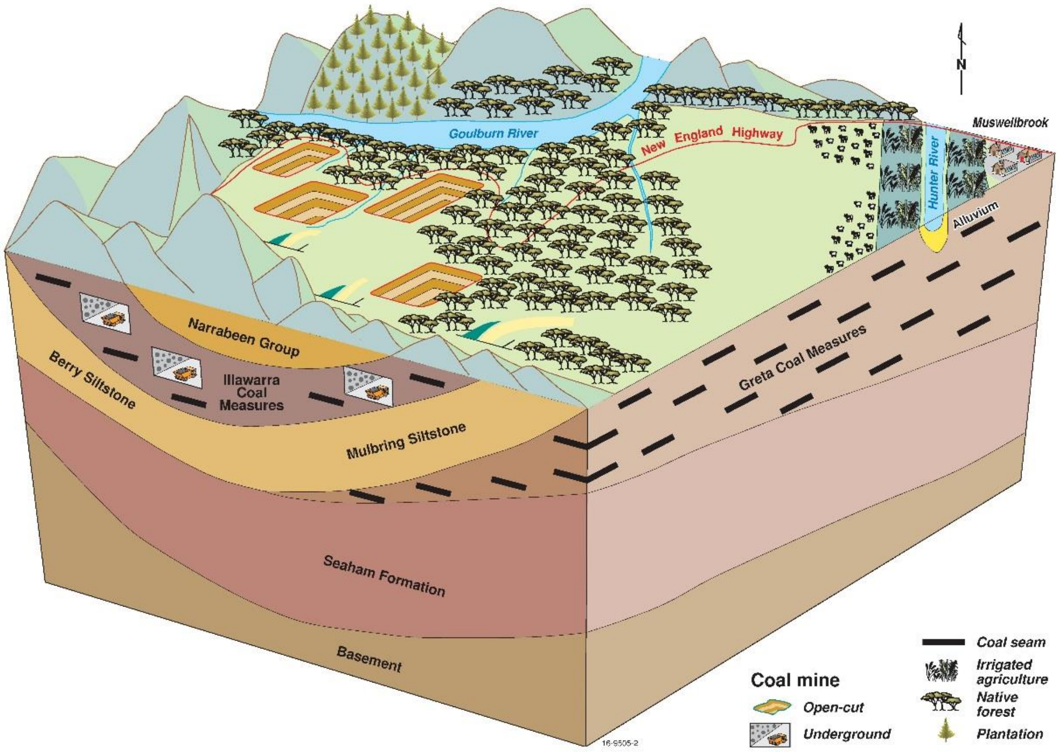
Data: Stewart and Adler (1995), Geoscience Australia (Dataset 1)

Bore yields in the Jurassic rocks and Triassic Narrabeen Group range widely from 17 to 216 m$^3$/day. These stratigraphic units typically form a sub-horizontal sedimentary sequence of fractured aquifers and aquitards, which provide baseflow to streams in the area. Aquifers may feed springs that are located in the Blue Mountains area in the western part of the subregion. Change in hydraulic conductivity with depth is typically described as an exponential decrease, reaching $10^{-4}$ m/day at 400 m depth (Ward and Kelly, 2013, p. 22).

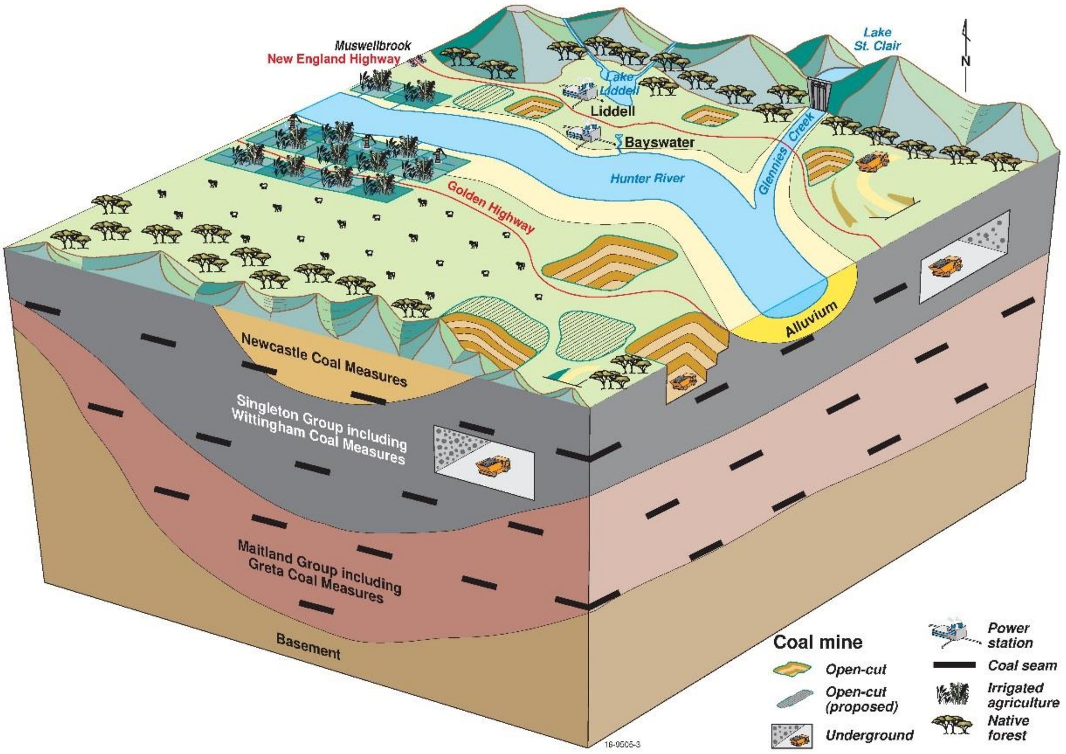
The Permian sedimentary sequence hosts several coal-bearing units, including the Newcastle, Wittingham and Tomago coal measures. The various Permian rock units are commonly fine-grained and have very low primary porosity. Most groundwater flow in these units occurs preferentially along zones of enhanced secondary porosity, such as fault and fracture networks. Enhanced hydraulic conductivity occurs in some coal seams, for example, focused along cleats. Within the Wittingham Coal Measures there are marine transgressions recorded by laminites of the Bulga and Denham formations (Creelman, 1994). They contain the most saline groundwater in the subregion, and discharge of this water via the alluvium is thought to have a controlling influence on the salinity of the Hunter River (Kellett et al., 1989).

The Tomago Tomaree Stockton Sandbeds in the north-east of the Hunter subregion are a major urban water source for the Newcastle-Lower Hunter region. They cover an area of about 183 km$^2$, have the highest diffuse recharge rates in the region at about 25% of rainfall and have transmissivity estimated at 400 to 600 m$^2$/day (Crosbie, 2003). The local groundwater level is responsive to individual rainfall events, which in turn make the aquifer susceptible to contamination so that it has been protected as a water reserve and is listed as a high-priority groundwater-dependent ecosystem (DIPNR, 2003). This area is close to the ocean and has not been subject to mining previously, nor is future mining planned. It is not considered to be hydrologically connected to any mining activity nor considered to be affected by coal mine operations in the Hunter River valley.

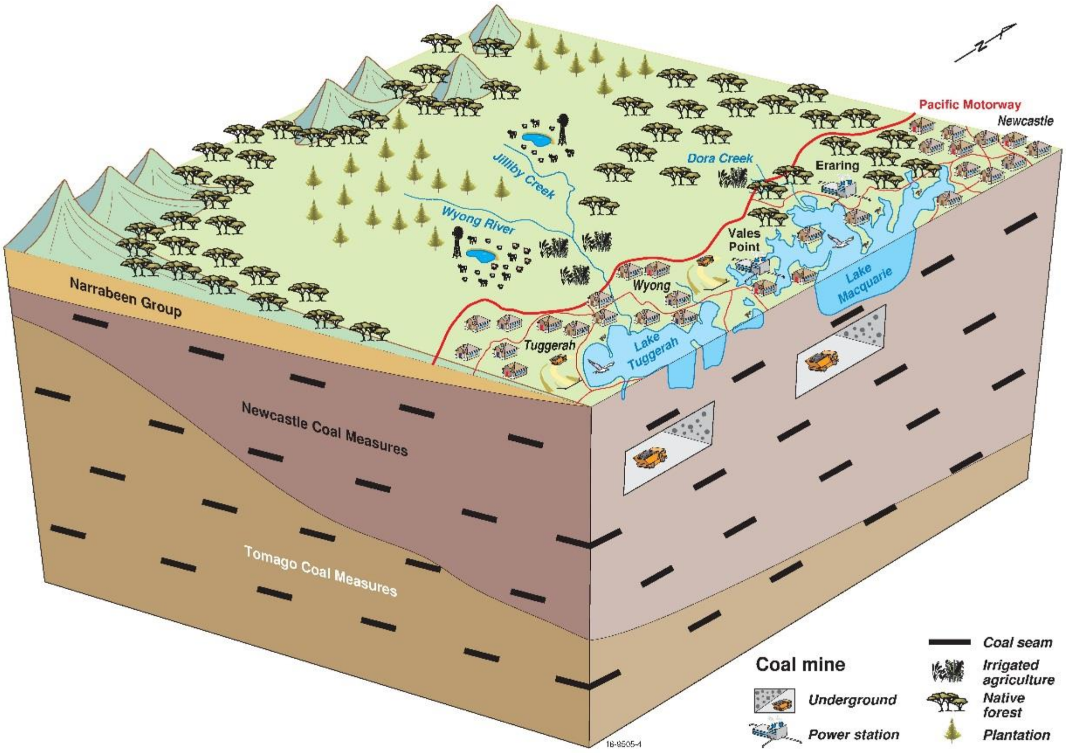
The regulated Hunter River alluvium is a significant aquifer for water supply in the subregion with about 76 GL of groundwater entitlements (see Table 10 in companion product 1.1 for the Hunter subregion (McVicar et al., 2015,)). It is a groundwater management unit (GMU) within the NSW Department of Primary Industries (DPI) and has its own water sharing plan (WSP) (DPI, 2005, 2013). These aquifers commonly have coarser material at their base, and vary in thickness from 3 to 17 m, generally increasing in depth downstream. The Goulburn river basin in the west of the alluvium has higher clay content, particularly at the surface, whereas downstream in the Hunter River there are greater fractions of coarse-grained sand and gravel. Hydraulic conductivity varies widely from 10 to 240 m/day (Australian Groundwater Consultants Pty Ltd, 1984). The rivers and alluvium are closely connected, with exchange between the river and near-surface groundwater in the alluvial aquifer. The major recharge source for the alluvial aquifer is considered to be river leakage, although both diffuse recharge from rainfall and upward leakage from underlying rocks contribute water.


N
Goulburn River
New England Highway
Muswellbrook
Hunter River
Alluvium
Narrabeen Group
Berry Siltstone
Illawarra Coal Measures
Greta Coal Measures
Mulbring Siltstone
Seaham Formation
Basement
Coal mine
Open-cut
Underground
Coal seam
Irrigated agriculture
Native forest
Plantation
16-9505-2

(a)


Muswellbrook
New England Highway
Lake St. Clair
N
Lake Liddell
Liddell
Bayswater
Glennies Creek
Hunter River
Golden Highway
Alluvium
Newcastle Coal Measures
Singleton Group including Wittingham Coal Measures
Maitland Group including Greta Coal Measures
Basement
Coal mine
Open-cut
Open-cut (proposed)
Underground
Power station
Coal seam
Irrigated agriculture
Native forest
16-9505-3

(b)



(c)

**Figure 9 Block diagrams of the Hunter subregion from a regional geological model**

(a) block from west to east through the Goulburn river basin, (b) block representing activities adjacent to the Hunter River in the centre of the subregion, (c) block showing activities on the coastline near lakes
Block diagrams are not to scale, but are representative based on the geological model.
Data: Bioregional Assessment Programme (Dataset 7)

Three regional-scale block diagrams of the Hunter subregion are shown in Figure 9 that have been generalised from the regional geological model (see companion product 2.1-2.2 (Herron et al., 2018b)). The first block (Figure 9a) is a section through the Goulburn river basin, just north of the Goulburn River, representing the area from Gulgong to Muswellbrook. In the Western Coalfields the Berry Siltstone is near the surface and provides an aquitard that moves water laterally and feeds surface springs and streams. The coal seams of the Illawarra Coal Measures are also near the surface in the west and subject to both open-cut and underground mine operations. In the west, the Greta Coal Measures become thicker and nearer to the land surface.

The next block (Figure 9b) shows a representative area near the central Hunter River. The surface Hawkesbury Sandstone layers are absent when mapped at this scale, and the Wittingham Coal Measures are the thickest individual unit underlying the region and most of it is close to the surface. This area contains a high density of coal mine operations in the Hunter subregion, most of which target the Wittingham Coal Measures for mining. Localised lateral flows are controlled by spatial variability in aquitard layers and may be different for mine operations targeting different seams in the area and at increasing depth below ground.

The third block (Figure 9c) illustrates operations near the coastal lake systems south of the city of Newcastle. In this area Hawkesbury Sandstone (not shown) and Narrabeen Group form the uplands between river floodplains while coal-bearing deposits, known as the Newcastle and Tomago coal measures, form thick layers and are mined both at the surface and underground. Careful planning is involved for mining close to and below lakes.

As with any underground mining venture, very careful planning and appraisal is required, and each mine is different based on local geological configurations. This lack of regional-scale understanding of the geological structure, and the varying local behaviour of folds, faults and stratigraphic layering, is a gap that needs to be addressed for each mine.

### *2.3.2.3 Surface water*

The surface water system of the Hunter subregion has both regulated and unregulated portions. The Goulburn River in the west and Wollombi Brook to the south are unregulated and within the subregion, whereas Pages River and Moonan Brook above Glenbawn Dam are unregulated but outside the subregion. The Paterson, Allyn and Williams rivers all contribute to flow in the lower Hunter River below Greta. This is the tidally-influenced reach of the river and may also be influenced by regulation of flows from the Lostock and Chichester dams. Tidal influences are not represented in the river modelling undertaken in the bioregional assessment (BA) for the Hunter subregion.

The Hunter River from Glenbawn Dam to Newcastle, and Glennies Creek below Glennies Creek Dam, are classified as the regulated reaches of the Hunter River. These river reaches are subject to the NSW Government's Hunter River Salinity Trading Scheme (HRSTS) in three blocks: the upper block of the Hunter River from Glenbawn Dam to Denman, middle block to the confluence with Glennies Creek and lower block to Singleton (shown in Figure 10). The HRSTS allows for discharge of saline water from mines and other industry during high-flow events so that river salinity at key monitoring locations is maintained below target levels. This has allowed miners, power generators and agricultural users to share the river as a resource without conflict, while sustaining economic development. The flow and salinity of the Hunter River in the regulated sections is carefully monitored and described in Section 1.1.5 of companion product 1.1 for the Hunter subregion (McVicar et al., 2015). River modelling in this BA includes simple rules for adding discharge to rivers under the scheme, but the river salinity is not explicitly modelled (see companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018)).

A flow accumulation for surface water flows is shown in Figure 10 for rivers that originate in, or flow through, the Hunter subregion. The presentation of the data provides a visual impression of the variability of flow in the individual streams of the subregion, and the relativity of flow contributions from the various tributaries of the Hunter River. These data are not gauged river values but are from a climatological equilibrium model based on spatially variable long-term precipitation and potential evaporation. Flow in the Hunter River increases substantially after the confluence with the Goulburn River, increasing steadily as it flows east to the coast. Near the coast the flow appears to become much larger; however, this reach of the river is under tidal influence, which the modelling here does not take into account. Within the Macquarie-Tuggerah lakes basin the Wyong River, Dora Creek and Ourimbah Creek are unregulated; however, the Mardi Dam storage is located in the lower part of the Wyong River.

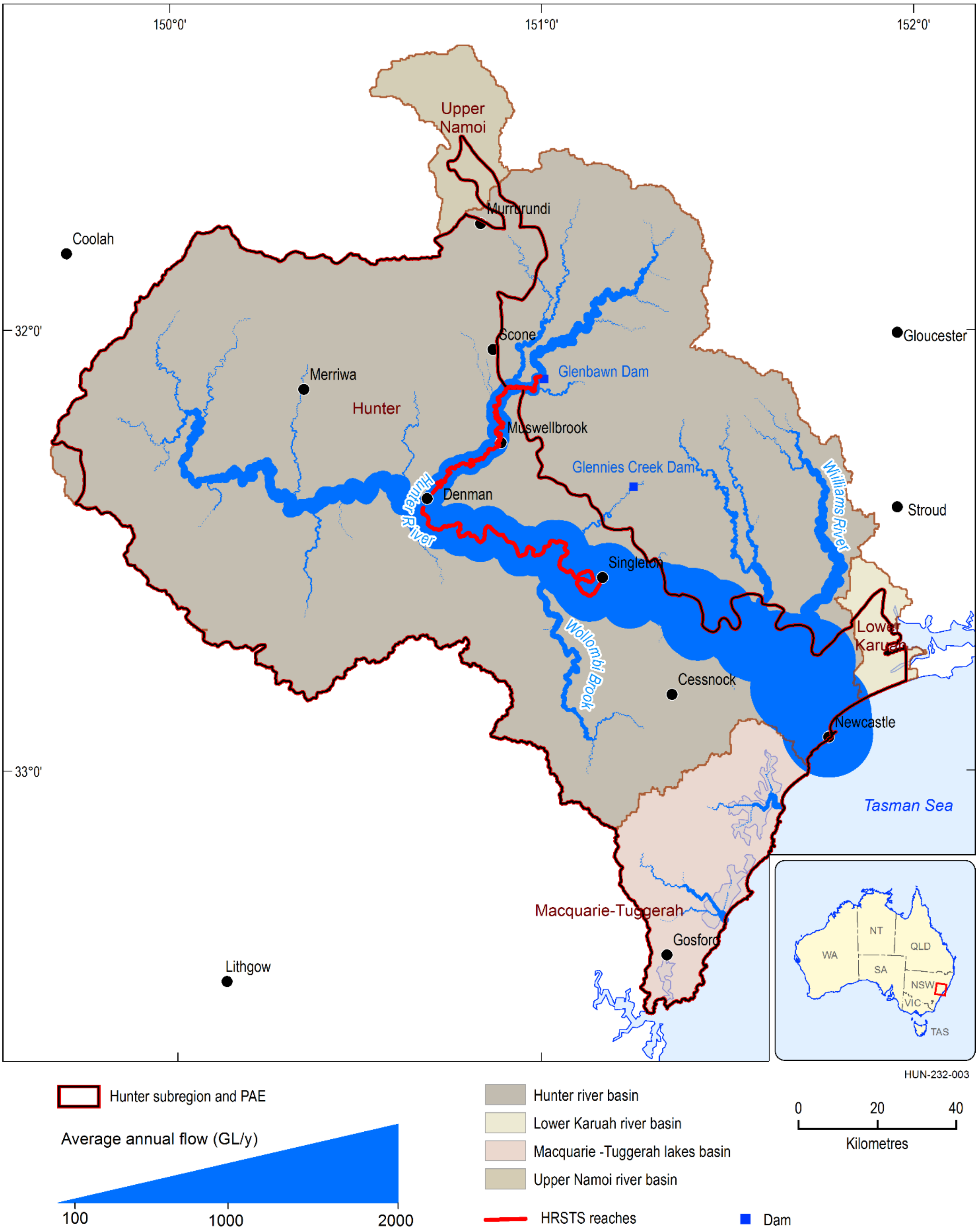


**Figure 10 Accumulated modelled surface water flows for river basins that interact with those originating in, or passing through, the Hunter subregion**

Long-term annual flow is estimated using water balance technique of Budyko (1974), as described by McVicar et al. (2015), and does not consider any impoundment or regulation of river flow. HRSTS is an acronym of Hunter River Salinity Trading Scheme.
Data: Bioregional Assessment Programme (Dataset 2, Dataset 3, Dataset 4)

#### 2.3.2.4 Water balance

A water balance provides a succinct summary of the key stores and flows in a hydrologic domain for a specified period. At a minimum, a water balance will include rainfall, evapotranspiration and streamflow, and some quantification or assumptions made about storage. More detailed water balances will include estimates of catchment runoff, diffuse recharge and groundwater discharges, including the baseflow contribution to streamflow. Activities or events that lead to changes in inputs to a system, changes in storage capacity and/or changes in the pathways through the system will lead to changes in the water balance terms. Thus the impacts of coal resource development on regional hydrology can be reported in terms of changes to the regional water balance. This section provides some estimates of mean annual rainfall, recharge, streamflow and baseflow for the Hunter subregion, based on published information. Evapotranspiration is viewed as the value required to close the water balance, assuming that change in storage is zero. This is done as in many cases due to the size of this term, errors in estimating it may be larger than the small residual terms, such as recharge, that are more important to estimate accurately.

The average annual rainfall gradient across the subregion is from 640 mm at Ulan in the western Goulburn river basin, to 1100 mm at Newcastle on the coast and 1300 mm at Gosford in the Macquarie-Tuggerah lakes basin (see Figure 24 in companion product 1.1 for the Hunter subregion (McVicar et al., 2015, p. 44)). The 1982 to 2012 annual average rainfall over the Hunter subregion was 793 mm.

Groundwater recharge is commonly estimated at 2% of rainfall or less but with higher values in areas of higher regolith permeability (Mackie Environmental Research, 2006). Assuming 2% applies uniformly across the subregion, an estimate of average annual recharge of 15.9 mm is obtained from an average annual rainfall of 793 mm. The subregion-wide estimate from the spatially-variable recharge surface generated for the BA for the Hunter subregion (see Section 2.1.3 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018b)), which reflects the spatial variation in rainfall and regolith permeability, is 9 mm.

The average annual streamflow recorded in the Hunter River at Greta (station 210064) between 1968 and 2015 was 709.5 GL/year, which yields a depth equivalent flow of 41.0 mm across 17,320 $km^2$ contributing area (DPI, 2015).

In a steady-state situation, assuming all groundwater recharge is discharged to the stream network, this equates to a maximum baseflow contribution from groundwater of between 22% and 39% of streamflow, using the foregoing estimates of subregion-wide average annual recharge. The gauging station at Greta is used for this estimate because it is the most downstream gauge on the Hunter River that is not tidally influenced, and hence the most downstream point represented in the river model. Other estimates of baseflow using a digital filter approach ranged from 40% to 66% for Hunter subregion rivers (see companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018b)).

A crude water balance is provided for the Hunter subregion (upstream of Greta) in Table 3. Companion product 2.5 for the Hunter subregion (Herron et al., 2018a) provides a number of water balances from the surface water and groundwater modelling of the coal resource development futures modelled in the BA for the Hunter subregion.

**Table 3 Estimates of the Hunter subregion water balance**

| Water balance term | Depth (mm/y) | Volume (GL/y) | Percentage of rainfall % |
|---|---|---|---|
| Rainfall | 793 | 13,735 | 100% |
| Recharge | 9–16 | 156–277 | 1–2% |
| Streamflow<br>(baseflow) | 41<br>(9–27) | 710<br>(156–469) | 5%<br>(22%–66% of streamflow) |
| Residual | 752 | 13,025 | 95% |

Residual is calculated as rainfall minus streamflow. Recharge is assumed to discharge to stream as baseflow and baseflow is a component of streamflow. Conversion from mm/year to GL/year is based on contributing area of 17,320 km$^2$.

### 2.3.2.5 Gaps

The distribution of streamflow gauging stations in the Hunter subregion enables a reasonable understanding of the total flux of water within the river network. With monitoring for the HRSTS there is also a good dataset for stream salinity at several places in the regulated Hunter River alluvium. Although there is also acceptance of the close coupling of the river and alluvial aquifer, there is generally less knowledge of the magnitude and timing of exchanges and their contribution to maintaining baseflow. This gap makes generating a consistent and robust regional water balance of recharge and discharge very difficult.

The Assessment team does not have a good understanding of the spatial and temporal variance in the river-shallow aquifer hydrological exchange. These variations are important in maintaining redox gradients and biogeochemical processes in the river sediments that play major roles in river metabolism, especially during low flows.

The locations of many faults and geological structures are mapped in the normal course of geological exploration and mining developments. Their mere presence, however, provides no indication of the extent to which they act as conduits of water between strata over different depths. Inferences can be made about the hydrological function of faults by measuring stream salinity and chemistry with a run of river. Such measurements have not been carried out consistently across the subregion, so the role of faults, if any, in enhancing hydrological connectivity remains to be investigated. Targeted monitoring would be required for such a set of measurements to ensure the greatest chance of detecting discharge from a fault in the river chemistry, by ensuring the right flow conditions and being unimpeded by anthropogenic causes such as dam management or operation of HRSTS releases.

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## 2.3.3 Ecosystems

### *Summary*

To deal with the complexity of a large number of diverse assets, a landscape classification approach was developed specifically for the bioregional assessment (BA) for the Hunter subregion to systematically class landscape features that are hydrologically and biologically similar or connected. Landscape classes were identified within five broad landscape groups: ‘Riverine’, ‘GDE’, ‘Coastal lakes and estuaries’, ‘Non-GDE vegetation’ and ‘Economic land use’.

Four riverine landscape classes were defined based on hydrology and river bed substrate. Ephemeral streams (11,000 km) form the dominant ecohydrological class with 1900 km of perennial streams, 1200 km of moderately to highly intermittent streams and 800 km of lowly to moderately intermittent streams.

Nine landscape classes within the ‘GDE’ landscape group were defined based on vegetation formations (grassy woodlands, heathlands, semi-arid woodlands, rainforest, forested wetland, freshwater wetland, wet sclerophyll forest and dry sclerophyll forest) in addition to springs. The total area identified as groundwater-dependent ecosystems (GDEs) was 358 km$^2$.

A little over 10,400 km$^2$ of native vegetation within the preliminary assessment extent (PAE) of the Hunter subregion is not classified as GDE. Both the mapping of vegetation and the nature of the water dependence of some identified GDEs is a significant source of uncertainty. The accuracy of landscape classes in the ‘GDE’ landscape group depends on the accuracy of vegetation mapping and remote sensing of groundwater dependence.

Seven landscape classes within the ‘Coastal lakes and estuaries’ landscape group were defined with the majority of the Hunter subregion falling within the ‘Lake’ and ‘Seagrass’ landscape classes. These totalled 263 km$^2$.

Five landscape classes in the ‘Economic land use’ landscape group were defined (~6000 km$^2$), dominated by ‘Dryland agriculture’ (3820 km$^2$) and ‘Intensive use’ (1070 km$^2$) landscape classes of the subregion.

### *2.3.3.1 Landscape classification*

#### 2.3.3.1.1 Methodology

Subregions or bioregions contain a large number and diverse range of assets. To deal with this complexity, a landscape classification approach is used to systematically class landscape features that are hydrologically and biologically similar or connected. Landscape classification aims to reduce asset complexity to a limited number of regional-scale classes appropriate for the Assessment. The classes are mutually exclusive and comprehensive such that all assets in a BA are a member of at least one landscape class. Landscape classes guide the development of conceptual models that underpin receptor impact models and reporting of risk and impacts. Wherever possible, landscape classes use existing data sources and classifications. This section describes the methodology and datasets used to arrive at the landscape classification for ecological assets within the PAE of the Hunter subregion. Landscape classes were defined within five broad landscape groups: ‘Riverine’, ‘GDE’, ‘Coastal lakes and estuaries’, ‘Non-GDE vegetation’ and ‘Economic land use’ (Table 4).

**Table 4 Landscape groups and landscape classes in the Hunter subregion**

| Landscape group | Landscape class |
|---|---|
| **Riverine** | Permanent or perennial |
| | Lowly to moderately intermittent |
| | Moderately to highly intermittent |
| | Highly intermittent or ephemeral |
| **GDE** | Rainforest |
| | Wet sclerophyll forest |
| | Dry sclerophyll forest |
| | Freshwater wetland |
| | Forested wetland |
| | Grassy woodland |
| | Heathland |
| | Semi-arid woodland |
| | Spring |
| **Coastal lakes and estuaries** | Drowned valleys |
| | Lakes |
| | Barrier river |
| | Seagrass |
| | Saline wetlands |
| | Lagoons |
| | Creeks |
| **Non-GDE vegetation** | Non-GDE vegetation |
| **Economic land use** | Plantation or production forestry |
| | Dryland agriculture |
| | Irrigated agriculture |
| | Intensive use |
| | Water |

Data: Bioregional Assessment Programme (Dataset 1)

The water dependencies of landscape classes were classified as follows:

- surface water – these landscapes may rely on surface flows from flooding events for their maintenance
- local groundwater – these landscapes may rely on local aquifers that are unconnected to regional groundwater aquifers (e.g. perched aquifers above basement rock). They may not be affected by abstraction of regional groundwater or changed surface water flows, yet could be impacted by local development such as open-cut mining (depending on distance between the operation and the vegetation community and hydrological conductance of the alluvial system)
- regional groundwater – these landscapes may rely on water from regional groundwater aquifers for their productivity and survival at least occasionally. Some may be dependent on access to groundwater at all times. Some may be able to survive or adjust to removal of groundwater, depending on the rate of abstraction, but their current structure and floristic composition may be altered as a result
- tidal – estuarine communities are sensitive to tidal flows in addition to groundwater and surface water flows. They can be impacted by changes in geomorphology of the estuary and patterns of sedimentation that might result from altered surface water flows, and by changes in salinity in upper estuarine reaches in situations of altered fresh surface water and groundwater inflows
- uncertain – may depend on any of regional groundwater, local groundwater or surface water, and water dependence may be location specific.

The water dependence of landscape classes was assessed by the BA teams in consultation with external experts but will be explored in greater depth during the development of qualitative models (see companion product 2.7 for the Hunter subregion (Hosack et al., 2018)).

***'Riverine' landscape group***

A classification system for rivers was provided by DPI Water (formerly the NSW Office of Water) that combined ecohydrology (flow percentiles and hydrology class) and landscape considerations (stream order) and applied to the Bureau of Meteorology's Geofabric stream network (Bureau of Meteorology, Dataset 2). This classification scheme yielded four riverine landscape classes, broadly based on Kennard et al. (2008):

- 'Permanent or perennial' (strong baseflow contribution)
- 'Lowly to moderately intermittent' (rarely cease to flow; moderate baseflow contribution)
- 'Moderately to highly intermittent' (regularly cease to flow; runoff dominated)
- 'Highly intermittent or ephemeral' (rarely flow; runoff dominated).

The 'Permanent or perennial' landscape classes broadly correspond to the 'stable baseflow' classes from Kennard et al. (2010; Classes 1, 2 and 3) while the 'Lowly to moderately intermittent' river landscape classes correspond broadly to the 'unstable baseflow' and 'rarely intermittent' classes from Kennard et al. (2010; Classes 4 and 5). Perennial streams have flow at least 80% of the year, and an appreciable contribution of groundwater to baseflows. Kennard et al. (2008)

reported a baseflow index of 0.15–0.40 for perennial streams. ‘Lowly to moderately intermittent’ landscape classes are characterised by streams that cease flowing more often than perennial streams and have a lesser (0.15–0.20) baseflow contribution (Kennard et al., 2008).

### *‘GDE’ landscape group*

The DPI Water methodology (Kuginis et al., 2016) defines groundwater-dependent ecosystems (GDEs) as ecosystems ‘that require access to groundwater to meet all or some of their water requirements so as to maintain their communities of plants and animals, ecological processes and ecosystem services’. Dependence on groundwater can range from obligate to partial or infrequent (Zencich et al., 2002) but excludes species that rely exclusively on soil water in the unsaturated zone. The classification of mapped GDEs is based on Sivertsen et al. (2011) which adopts Keith’s (2004) classification of vegetation communities into ‘formations’ and ‘classes’. ‘Vegetation formation’ is the top level of the hierarchy in Keith’s vegetation classification system. Formations represent broad groups distinguished primarily by structural and physiognomic features, with the addition of functional features such as salinity and drought tolerance in some cases (Keith, 2004).

Landscape classes within the ‘GDE’ landscape group were based on mapping of GDEs by DPI Water (NSW Office of Water, Dataset 3). The DPI Water’s methodology combines vegetation mapping, optical remote sensing and watertable level data (where available) with expert knowledge to compile maps of high probability, high ecological value and high priority GDEs. This data source was chosen ahead of alternatives such as the National atlas of groundwater dependent ecosystems (Bureau of Meteorology, Dataset 5) owing to its local detail and currency. Furthermore, the vegetation classification intrinsic to Dataset 3 (NSW Office of Water) allowed the classification of landscape classes to reflect the underlying function of the wetlands with which they are associated (Table 5). Of the 12 vegetation formations defined across NSW, eight have been identified in the Hunter PAE (Table 5), and all are identified as high probability GDEs. In addition, four springs (not listed in Table 5) were identified and included as a landscape class.

**Table 5 Description of Keith's vegetation formations within the 'GDE' landscape group**

| Vegetation formation | Description |
|---|---|
| Rainforest | Forests with a closed canopy generally dominated by non-eucalypt species with soft, horizontal leaves, although various eucalypt species may be present as emergents. Rainforests tend to be restricted to relatively fire-free areas of consistently higher moisture and nutrient levels than the surrounding sclerophyllous forests. |
| Wet sclerophyll forest | Sclerophyll forests are dominated by trees of the Myrtaceae family, particularly of the genera *Eucalyptus, Angophora, Corymbia, Syncarpia* and *Lophostemon*. Dominant tree species tend to have smaller, hard leaves and be adapted to varying extents to the occurrence of wild fires. Wet sclerophyll forests are restricted to areas of higher rainfall and moderate fertility and often include a dense understorey of soft-leaved rainforest shrubs and small trees in moister situations (shrubby subformation). In drier situations these forests may have an open, grassy understorey (grassy subformation) with a sparse, sclerophyllous shrub layer. |
| Dry sclerophyll forest | Open forests include a wide range of structural and floristic types. In general they occur on poorer substrates and relatively drier situations than the wet sclerophyll forests. On moderately poor soils these forests may develop a dense, grassy understorey with a more open shrub layer (shrub / grass subformation) while on the poorest substrates (sands and sandstones) a dense, sclerophyllous shrub layer dominates. Fire often plays an important role in the ecology of these forests. |
| Freshwater wetland | Freshwater wetlands occur on areas where perennial or permanent inundation by water, either still or moving, dominates ecological processes. They occur in a range of environments where local relief and drainage result in open surface water at least part of the time and often play a range of vital roles in the functioning of ecosystems. The periodicity and duration of inundation in wetlands often determines to a large extent the suite of species present as do the extent and depth of water. |
| Forested wetland | This formation is made up of various wetlands dominated by tree species occurring on major riverine corridors and floodplains. These communities are dominated by sclerophyllous species similar to those in drier sclerophyll communities, but with hydrophilic species dominating an inundated understorey. |
| Grassy woodland | This formation is a prominent feature of the landscape over much of the drier (500 to 900 mm) parts of the study area on soils of medium to high fertility. It is characterised by an open to very open canopy dominated by eucalypts, particularly various box and red gum species. The ground layer is typically dense and composed of a diverse range of tussock grasses and other grasses and herbs. |
| Heathland | Heathlands are characterised by a general lack of tree species. This formation occurs typically on low-nutrient, silica-rich soils and many of the common species have adapted in various ways to acquiring trace amounts of nutrients and water from these soils. |
| Semi-arid woodland | The semi-arid zone comprises those lands where average annual rainfall is between 250 mm and 500 mm. Dominant tree species are a few species of eucalypts, wattles, sheoaks and cypress pines. Communities on floodplains tend to have a grassy understorey while communities on more elevated sites tend to have a shrubby understorey. |

Springs are not described because they are not a vegetation formation.
Data: Somerville (2009) and Keith (2004)

### *'Coastal lakes and estuaries' landscape group*

The landscape classes within this landscape group are based on mapping of coastal lakes and estuaries (NSW DECCW, Dataset 4), and mapping of saline wetlands (mangroves and saltmarshes) and seagrasses (Victorian DPI, Dataset 6). For estuaries and lakes the Assessment team adopted the classification scheme used by the NSW Department of Environment and Heritage (Roper et al., 2011), which classifies estuaries and lakes based on dilution factors, tidal flushing times and geomorphology. The dilution factor is the ratio of the estuary volume to the volume of runoff from a large rainfall event, assumed at 10% of the total annual inflow. As an example, a factor of 15 would indicate that the estuary volume is 15 times larger than the runoff from a large rainfall event (Roper et al., 2011). Roper et al. (2011) provides details on the calculation of tidal flushing times. This classification scheme reflects the vulnerability of the water bodies to changes in the volume and quality of flows entering the estuarine systems. The names of the estuarine classes represent the dominant geomorphic type within each of three groups with different hydrologic conceptual models:

- The landscape classes 'Drowned valleys' and 'Lakes' are permanently open systems with large dilution capacities (greater than 3) and only minor deterioration in water quality during rainfall. Tidal flushing times range from 10 to 1000 days. These include systems such as Lake Macquarie and Tuggerah Lakes, and Port Stephens Estuary. No bays are present in the Hunter PAE.
- The 'Barrier river' landscape class includes permanently open systems that are typically mature barrier riverine estuaries or mature forms of wave dominated estuaries. Dilution factors range from 0.1 to 3 and flush times range from 3 to 30 days. Within the Hunter PAE, the Hunter and Karuah rivers fall within this class.
- The two landscape classes 'Lagoons' and 'Creeks', are small, intermittently open lakes, lagoons and creeks. Dilution factors range from very small values (0.001) to 3, meaning that the water quality in these systems will quickly reflect that of the inflowing water and that inflow can completely displace existing water. Tidal flushing times are short when open. Within the Hunter PAE, Avoca and Cochrone lakes, and Glenrock and Terrigal lagoons, fall within these classes.

Although Keith (2004) grouped saltmarshes, mangroves and seagrasses together as a single vegetation formation, for BA purposes seagrasses are treated separately owing to their being fully submerged and completing their entire life cycle under water. Hence, two additional landscape classes have been identified within the 'Coastal lakes and estuaries' landscape group:

- The 'Saline wetlands' landscape class occurs on areas of impeded drainage with high levels of salt, such as estuarine areas or inland lakes where high levels of evaporation lead to the accumulation of surface salts, and are dominated by halophilic species, including mangroves and saltmarshes (Somerville, 2009) but exclude seagrasses.
- The 'Seagrass' landscape class includes simple communities ranging from open to dense in their cover, usually with just a single flowering plant species (Keith, 2004). They are fully submerged although the leaves may float on the water surface. There may be many species of algae present as epiphytes on their leaves.

#### *'Non-GDE vegetation' landscape group*

Native vegetation that was not classified as a high probability GDE and not placed in the 'GDE' landscape group was placed in this group. This vegetation was represented by the same vegetation formations and classes as the GDE vegetation.

***'Economic land use' landscape group***

All areas of the subregion that did not fall into one of the above categories were assigned to landscape classes based on the Australian Land Use and Management (ALUM) classification (for catchment-scale land use classification in Australia), Update 14 (ABARE-BRS, Dataset 8), was used.

### 2.3.3.1.2 Description of landscape classes

***'Riverine' landscape group***

All four stream hydrology classes are present in the Hunter PAE. The 'Perennial' and 'Lowly to moderately intermittent' landscape classes are likely to have significant groundwater dependence, whereas moderately and strongly intermittent streams are strongly surface water (runoff) dependent. Of the nearly 15,000 km of river length within the Hunter PAE (Figure 11) that were classified using the DPI Water approach (Section 2.3.3.1.1), over 11,000 km are highly intermittent ephemeral streams, 1900 km are perennial, 1200 km are moderately to highly intermittent and 900 km are lowly to moderately intermittent.

The riverine aquatic habitats of the Hunter PAE range from fresh montane streams to lowland floodplains and associated wetlands. The rivers and streams provide in-channel habitat for fish such as gudgeon and hardyhead, breeding habitat for various amphibians including the Booroolong, stuttering and giant burrowing frogs, the green and gold bell frog and the giant barred frog, as well as a migration pathway between estuarine and freshwater environments for species of fish such as perch, bass and mullet. Platypus can be found in the major permanent river systems of NSW, including the Hunter subregion.

**Figure 11 Landscape classes of the 'Riverine' landscape group within the Hunter preliminary assessment extent**

Rivers are classified using the method of DPI Water (Section 2.3.3.1.1), which is based on stream order and ecohydrology and have not been verified.
Data: Bioregional Assessment Programme (Dataset 10)

### *'GDE' landscape group*

The total area of GDEs identified in the Hunter PAE is 358 $km^2$, and is dominated by the 'Forested wetland' (150 $km^2$) and 'Dry sclerophyll forest' (90 $km^2$) landscape classes, with significant areas of 'Rainforest' and 'Freshwater wetland' landscape classes. The areas of each landscape class and associated Keith vegetation class within the PAE are given in Table 6, and their distribution is shown in Figure 12.

In the Hunter subregion, the 'Forested wetland' landscape class is dominated by the Keith vegetation class 'Coastal swamp forest', although there are large areas of Keith's 'Coastal floodplain wetlands' and 'Eastern riverine forests' classes. The 'Rainforest' landscape class is dominated by the Keith vegetation class 'Northern warm temperate rainforests', the 'Wet sclerophyll forest' landscape class is dominated by Keith's 'North Coast wet sclerophyll forests' class, and the 'Freshwater wetland' landscape class is dominated by Keith's 'Coastal freshwater lagoons' vegetation class. Other large areas of GDEs include Keith's Coastal dune dry sclerophyll forests', 'Sydney coastal dry sclerophyll forests' and 'Sydney sand flats dry sclerophyll forests' vegetation classes within the 'Dry sclerophyll forest' landscape class (Table 6).

**Table 6 Area of landscape classes within the 'GDE' landscape group, their percentage of the total 'GDE' landscape group area and their hypothesised water dependency for the Hunter subregion**

| **Landscape class** | Keitha (2004) **vegetation class** | **Landscape class area ($km^2$)** | **Percentage of total area of 'GDE' landscape group (%)** | **Hypothesised water dependency** |
|---|---|---|---|---|
| **Dry sclerophyll forest** | Coastal dune dry sclerophyll forests | 28.1 | 7.8% | Uncertain |
| | Hunter-Macleay dry sclerophyll forests | 8.3 | 2.3% | Uncertain |
| | North Coast dry sclerophyll forests | 1.6 | 0.4% | Uncertain |
| | North-west Slopes dry sclerophyll woodlands | 0.0 | 0.0% | Uncertain |
| | South Coast sands dry sclerophyll forests | 3.1 | 0.9% | Uncertain |
| | Sydney coastal dry sclerophyll forests | 28.0 | 7.8% | Uncertain |
| | Sydney hinterland dry sclerophyll forests | 0.8 | 0.2% | Uncertain |
| | Sydney montane dry sclerophyll forests | 0.1 | 0.0% | Uncertain |
| | Sydney sand flats dry sclerophyll forests | 20.7 | 5.8% | Uncertain |
| | Western Slopes dry sclerophyll forests | 0.4 | 0.1% | Uncertain |
| **Forested wetland** | Coast and tableland riverine forests | 17.7 | 4.9% | Regional groundwater; surface water |
| | Coastal swamp forests | 64.2 | 17.9% | Regional groundwater |
| | Coastal floodplain wetlands | 39.9 | 11.2% | Regional groundwater; surface water |
| | Eastern riverine forests | 29.0 | 8.1% | Regional groundwater; surface water |

| **Landscape class** | Keith[a] (2004) **vegetation class** | **Landscape class area ($km^2$)** | **Percentage of total area of 'GDE' landscape group (%)** | **Hypothesised water dependency** |
|---|---|---|---|---|
| **Freshwater wetland** | Coastal freshwater lagoons | 31.6 | 8.8% | Regional groundwater |
| | Coastal heath swamps | 3.0 | 0.8% | Local groundwater |
| **Grassy woodland** | New England grassy woodlands | 0. 6 | 0.2% | Uncertain |
| | Western slopes grassy woodlands | 12.0 | 3.4% | Uncertain |
| **Heathland** | Coastal headland heaths | 1.4 | 0.4% | Uncertain |
| | Sydney coastal heaths | 1.2 | 0.3% | Uncertain |
| | Wallum sand heaths | 11.4 | 3.2% | Uncertain |
| **Rainforest** | Dry rainforests | 0.5 | 0.1% | Regional groundwater |
| | Littoral rainforests | 1.9 | 0.5% | Regional groundwater |
| | Northern warm temperate rainforests | 37.8 | 10.6% | Local and regional groundwater |
| | Subtropical rainforests | 0 | 0.0% | Regional groundwater; surface water |
| **Semi-arid woodland** | Riverine plain woodlands | 0.6 | 0.2% | Surface water |
| **Wet sclerophyll forest** | North Coast wet sclerophyll forests | 9.2 | 2.6% | Uncertain |
| | Northern escarpment wet sclerophyll forests | 0.2 | 0.1% | Uncertain |
| | Northern hinterland wet sclerophyll forests | 0.2 | 0.0% | Uncertain |
| | Northern tableland wet sclerophyll forests | 4.5 | 1.3% | Uncertain |
| | Southern escarpment wet sclerophyll forests | 0.1 | 0.0% | Uncertain |
| **Spring** | Springs | ~0.01 | 0.0% | Regional groundwater |

The Hunter subregion and PAE cover 17,045 $km^2$.
GDE = groundwater-dependent ecosystem
[a] Keith's (2004) classification of vegetation communities into 'formations' and 'classes'
Data: Bioregional Assessment Programme (Dataset 1)

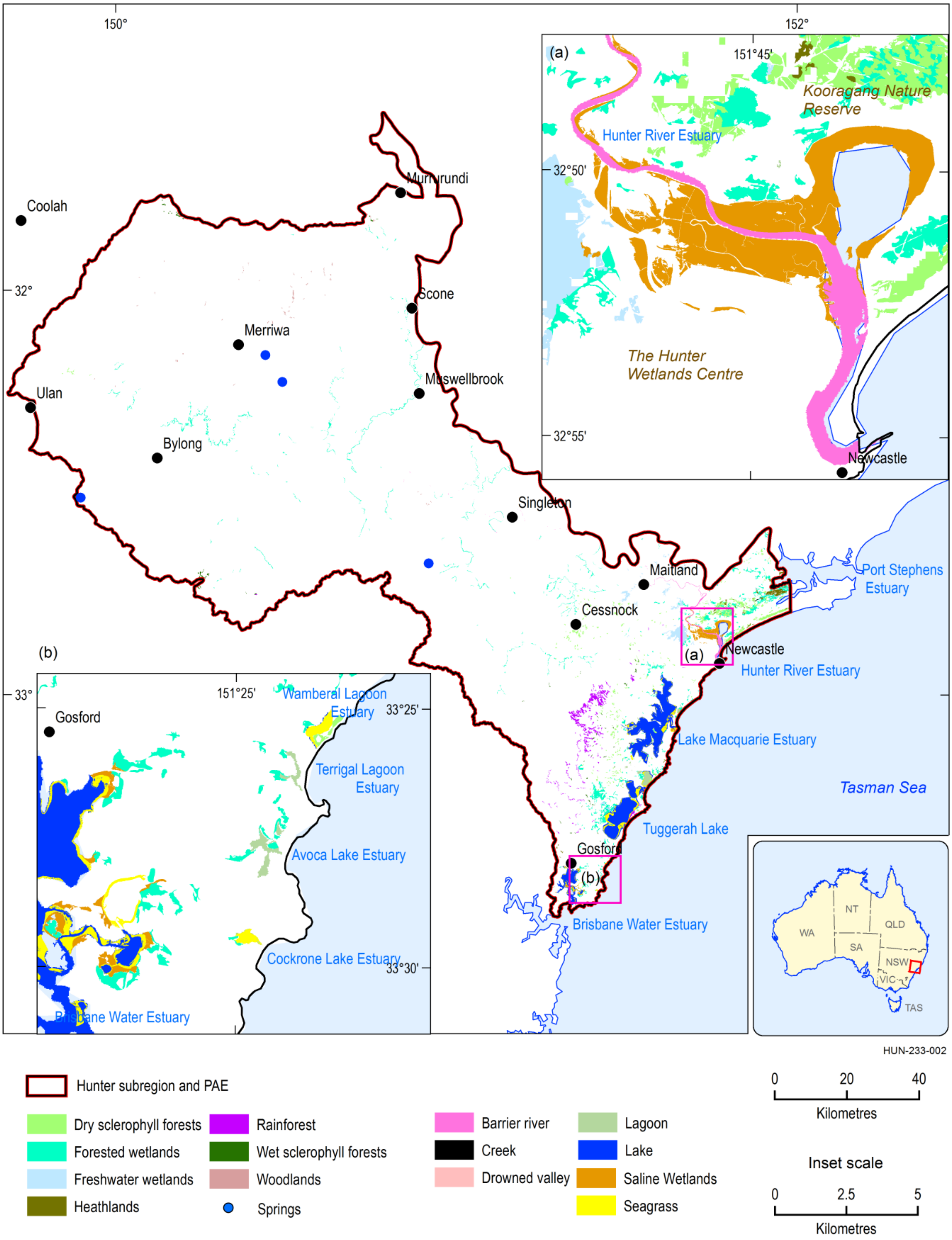

**Figure 12 Landscape classes of the 'GDE' and 'Coastal lakes and estuaries' landscape groups within the preliminary assessment extent of the Hunter subregion**

Data: NSW Office of Water (Dataset 3), NSW DECCW (Dataset 4), Bureau of Meteorology (Dataset 5), Victorian DPI (Dataset 6)

GDEs provide habitat for many of the species whose potential distributions form part of the water-dependent asset register (Bioregional Assessment Programme, Dataset 9). For example, animals such as koalas, birds of prey, honeyeaters and flying foxes may live, roost or nest in trees within GDEs. GDEs along riverbanks provide travel corridors and feeding sites for animals such as quolls, ground nesting locations for animals such as platypus, and breeding locations for some frogs. Some state and Commonwealth-listed plant species, such as the leafless tongue orchid, may be associated with GDE vegetation.

The hypothesised water dependencies of Keith's vegetation formations and associated vegetation classes (Keith, 2004) in the PAE of the Hunter subregion are presented in Table 6. These are based on general information about the location of the classes within the landscape, their characteristics and associated species from Keith (2004), and state agency sources (OEH, 2015). Although some vegetation formations have been judged as uncertain to be water dependent for the purposes of the BA, they are nonetheless present in the DPI Water mapping of GDEs (NSW Office of Water, Dataset 3). This reflects the large uncertainties associated with the remote classification of both vegetation formations (Hunter, 2015) and groundwater dependency (Eamus et al., 2015) (discussed in Section 2.3.3.2). A recent study (Eco Logical Australia, 2016) concluded that, although there was not great accuracy in the mapping of individual plant community types (about 40% accuracy), there was much larger certainty (about 76% accuracy) in the identification of sites that were likely to be groundwater dependent. This uncertainty is a key reason why vegetation formation, rather than vegetation class, was adopted as the landscape class for the Hunter BA. GDEs in landscape classes that are potentially impacted by development will have more detailed conceptual models developed as part of receptor impact modelling (see companion product 2.7 for the Hunter subregion (Hosack et al., 2017)). Where a landscape class contains Keith's vegetation classes that are likely to be heterogeneous with regard to their water requirements (e.g. 'Forested wetland' and 'Freshwater wetland' landscape classes), it may be necessary to develop multiple receptor impact models for that landscape class within a region.

### *'Coastal lakes and estuaries' landscape group*

Most of the 'Coastal lakes and estuaries' landscape group comprises the 'Lake' (172 km$^2$) and 'Seagrass' (39 km$^2$) landscape classes. 'Lagoon' (9 km$^2$), 'Barrier river' (13 km$^2$) and 'Saline wetland' (30 km$^2$) landscape classes made up most of the remainder of this landscape group; there are only 27 ha of 'Creek' and 'Drowned valley' landscape classes. The 'Coastal lakes and estuaries' landscape group is of great economic, social and environmental value (Ryan et al., 2003), supporting tourism and recreation as well as fisheries and aquaculture and may also serve as ports and sites for industrial development. The 'Coastal lakes and estuaries' landscape group supports numerous ecological communities including saline wetlands and seagrasses, which are shelter, breeding grounds and nurseries for marine, estuarine and terrestrial species. This landscape group supports ecological functions such as sediment trapping between coastal catchments and the marine environment, storing and cycling of nutrients, and absorbing, trapping and detoxifying pollutants. Saline wetlands are habitat for many birds (e.g. White-fronted Chat, kites and harriers), some mammals such as bats, kangaroos and wallabies, as well as invertebrates, and juvenile and small fish when inundated (Daly, 2013; Stewart and Fairfull, 2008). Migratory wading birds use estuaries and coastal lakes for summer feeding and roosting habitat. All landscape classes within the 'Coastal lakes and estuaries' landscape group, and especially aquatic landscape classes such as 'Lake', 'Lagoon', 'Barrier river', 'Creek' and 'Drowned valley' are likely to have a dependence on surface water, in addition to marine water and tidal flows, as described in the definition of those landscape classes in Section 2.3.3.1.1. Large water bodies will have the least sensitivity to fresh surface water flows, whereas small water bodies are likely to be more sensitive. In addition, the 'Saline wetland' landscape class may be indirectly impacted by groundwater extraction, which can alter surface elevations and thus the periodicity of inundation resulting in shifts between saltmarsh and mangrove communities (Rogers and Saintilan, 2008; Saintilan and Rogers, 2009).

### *'Non-GDE vegetation' landscape group*

Nearly 10,414km$^2$ of native vegetation within the Hunter PAE is not classified as GDE. All the native vegetation outside that mapped in the 'Riverine', 'GDE' and 'Coastal lakes and estuaries' landscape groups is considered to not be dependent on surface water or groundwater. Of this 10,414 km$^2$, over 96% is classified as 'Dry sclerophyll forest', 'Wet sclerophyll forest', 'Woodland' or 'Grassland'; 2% is classified as 'Rainforest'; 1% is classified as 'Forested wetland'; 0.1% is classified as 'Saline wetland'; and 0.1% is classified as 'Freshwater wetland'. The fact that some of the native vegetation classified as 'Forested wetland' or 'Freshwater wetland' was not classified as GDE reflects the large uncertainties (see Section 2.3.3.2) associated with the remote classification of both vegetation formation (Hunter, 2015) and groundwater dependency (Eamus et al., 2015).

### *'Economic land use' landscape group*

These landscape classes were classified using ALUM (for catchment-scale land use management classification in Australia), Update 14 (Figure 13; ABARE-BRS, Dataset 8) as follows:

- 'Plantation or production forestry' (726 $km^2$) – corresponding to ALUM classes 2.1 ('Grazing native vegetation'), 2.2 ('Production forestry'), 3.1 ('Plantation forestry') and 4.1 ('Irrigated plantation forestry')
- 'Dryland agriculture' (3819 $km^2$) – corresponding to ALUM classes 3.2 ('Grazing modified pastures'), 3.3 ('Cropping'), 3.4 ('Perennial horticulture'), 3.5 ('Seasonal horticulture') and 3.6 ('Land in transition')
- 'Irrigated agriculture' (252 $km^2$) – corresponding to ALUM classes 4.2 ('Grazing irrigated modified pastures'), 4.3 ('Irrigated cropping'), 4.4 ('Irrigated perennial horticulture'), 4.5 ('Irrigated seasonal horticulture') and 4.6 ('Irrigated land in transition')
- 'Intensive use' (1068 $km^2$) – land is subject to substantial modification, generally in association with closer residential settlement, commercial or industrial uses. This class includes mining
- 'Water' (142 $km^2$) – mainly reservoirs and dams.

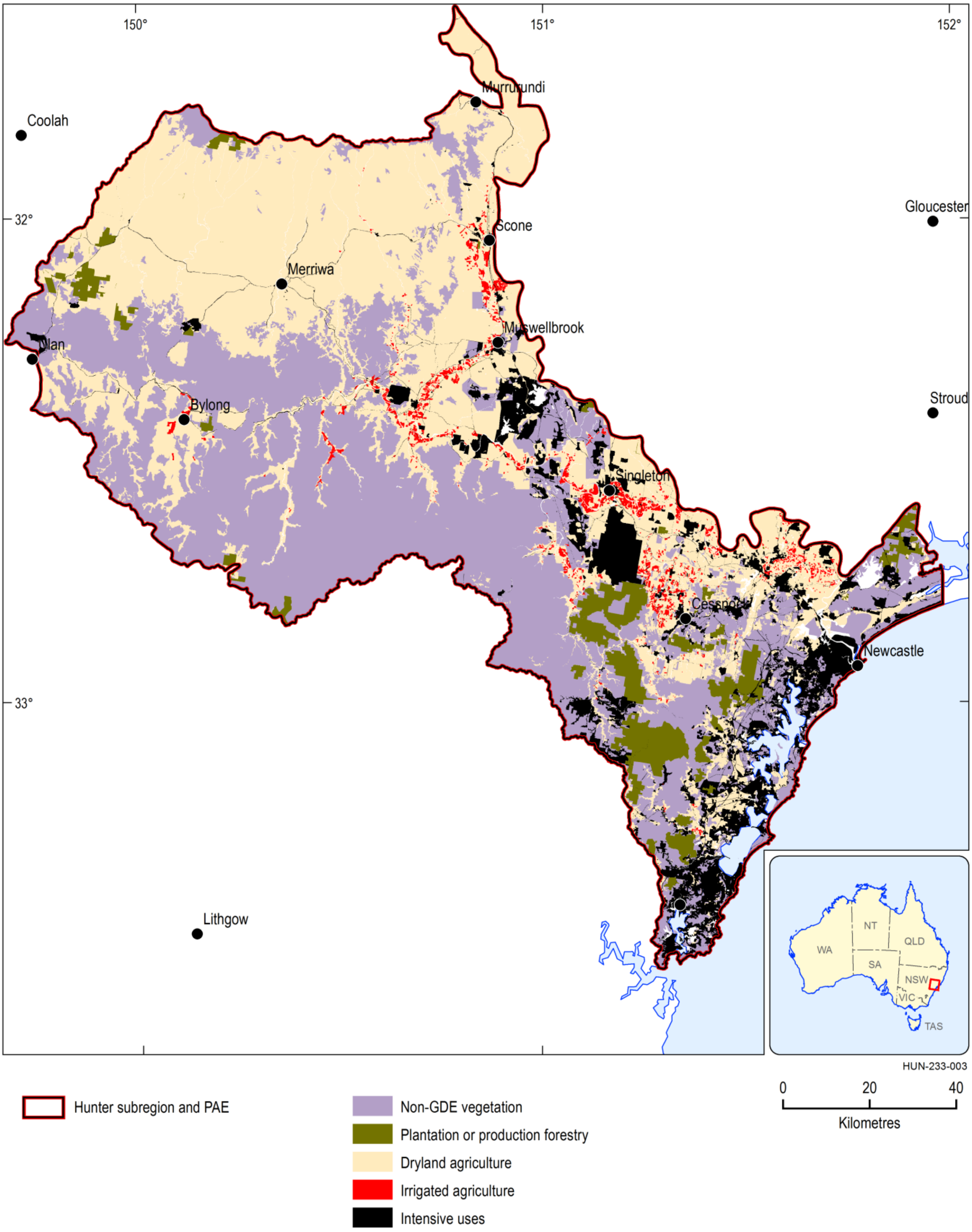

**Figure 13 Landscape classes for the 'Non-GDE vegetation' and 'Economic land use' landscape groups within the preliminary assessment extent of the Hunter subregion**

GDE = groundwater-dependent ecosystem
Data: ABARES-BRS (Dataset 8)

#### *2.3.3.2 Gaps*

BAs seek to use the best available data, given licensing and other constraints. However, even the best available data have significant constraints. The Greater Hunter mapping of vegetation (Bioregional Assessment Programme, Dataset 7) on which the mapping of GDEs is based (NSW Office of Water, Dataset 3) is a good example. A recent ground-truth study in the Upper Hunter (Hunter, 2015) found that only 7% of plant community types (PCTs) were reliably mapped. Even at the level of vegetation formation only dry sclerophyll forests and woodlands were mapped with greater than 50% accuracy. On this basis, the BA landscape classes were not defined at detailed hierarchical levels such as vegetation class or PCT. Even at the level of vegetation formation there is great uncertainty and this would have been exacerbated by attempting to deal with landscape classes at even more detailed levels.

The nature of groundwater and/or surface water dependence of much GDE vegetation is also uncertain. GDEs may occur at any position in the landscape where factors such as topography, geology and landform allow groundwater to concentrate at the surface or close enough to the surface for phreatophytic vegetation (deep-rooted vegetation that obtains a large fraction of its water needs from the saturated zone or capillary fringe) to access (Cole et al., 1997). The dependence of terrestrial vegetation on groundwater is difficult to predict or even quantify (Eamus et al., 2006). Riparian and near-riparian vegetation may have an absolute dependency on groundwater (obligate phreatophyte), whereas vegetation farther from surface expression of groundwater, where depth to groundwater is greater, may make occasional use of groundwater (facultative phreatophyte). Other vegetation may utilise local groundwater sources such as local (perched) watertables. It is possible for a vegetation community to have more than a single water dependence; for example, a community may require flooding events for seedling recruitment and survival, but be reliant on groundwater in adult life stages. Groundwater levels would be likely to fluctuate naturally as a result of climate variability and the vegetation is likely adapted to deal with this. However, rapid, large changes to groundwater levels resulting from extraction for public water supply have been shown to result in morbidity and death of GDE vegetation (Groom et al., 2000).

This uncertainty adds to the overall uncertainty regarding the impact, if any, of coal resource developments on assets such as potential habitats of threatened or endangered species and communities. Assigning such assets to landscape classes is necessarily highly uncertain due to both the high hierarchical level of the landscape classes (a species might use some vegetation within a formation as habitat but not others) and the uncertainty as to whether the vegetation formation is, in fact, present where it has been mapped. All of this is in addition to the uncertainty already associated with the potential habitat modelling undertaken by the Environmental Resources Information Network (ERIN). ERIN utilises maximum entropy (MAXENT) modelling to define the geographic extent of potential habitats based largely on physical parameters and past observations of the presence and absence of a species (Elith et al., 2011). The results of this modelling may predict potential habitat in areas where the ecosystems that support such species may not be present. Where the ecosystem, and thus the ‘potential’ habitat, is present the species itself may not be present due to many other factors, such as predation and habitat fragmentation.

There will also be great uncertainty associated with any predicted impacts on landscape classes within the 'Riverine' landscape group. In addition to the simplified landscape classification adopted for the BA, it is also important to note that for the purposes of a BA (where subregions or bioregions can be tens and hundreds of thousands of hectares), it is not possible to model riverine systems at the scale of pools and riffles. Even the 'reach' scale (1 to 3 km river lengths) is already quite detailed for a regional-scale analysis. Individual hillslope processes are not being quantitatively modelled. Changes in geomorphology that might result from coal resource development activities or remedial activities to improve geomorphology of degraded river sections are not within scope of this Assessment. This would require detailed cross-sections for river reaches in proximity to such development and remediation activities, and more detailed modelling than is currently possible. Where developments have the potential to create local-scale impacts, the acquisition of detailed riverbed cross-sections and monitoring of both geomorphology and key biological indicators such as macro-invertebrates, diatoms and water quality (Boulton et al., 2014, p. 276) should occur to track and assess such local impacts.

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Dataset 9 Bioregional Assessment Programme (2015) Asset database for the Hunter subregion on 20 November 2015. Bioregional Assessment Derived Dataset. Viewed 3 August 2016, http://data.bioregionalassessments.gov.au/dataset/0bbcd7f6-2d09-418c-9549-8cbd9520ce18.

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## 2.3.4 Baseline and coal resource development pathway

### *Summary*

There are 42 mining operations in the baseline coal resource development (baseline) in the Hunter subregion, comprising 22 open-cut mines and 20 underground mines. These baseline mines are used to quantify the impact on regional hydrology of mines that were operating at December 2012. Some baseline mines are not included in the surface water and groundwater numerical modelling of the Hunter subregion (reported in companion products 2.6.1 (Zhang et al., 2018) and 2.6.2 (Herron et al., 2018b)) due to lack of data or because the models do not represent key processes influencing local hydrology.

Additional coal resource developments (i.e. those considered likely to commence production after December 2012) proposed for the Hunter subregion include 3 new open-cut coal mines, 3 new underground coal mines and 16 expansion projects of baseline mining operations at December 2012. Ten potential mining operations were deemed too uncertain to include as additional coal resource developments.

For the Hunter subregion, the mines in the baseline and those identified as additional coal resource developments define the coal resource development pathway (CRDP).

Mine water use in NSW is governed by various legislation, pertaining to protection of the environment and the extraction and use of shared water resources. This regulatory framework ensures that the mining industry prepares mine water management plans for each operation, which identify environmental impacts and provide options for minimising impacts; require licences for water extractions and discharges; and attach conditions to licences that protect the environment on- and off-site.

Based on the regulatory framework, some common assumptions can be made about mine effects on hydrology to inform bioregional assessment (BA) hydrological models:

- All rainfall on the mine site is retained on site.
- Extractions of water from groundwater and the river network must be licensed. Licences specify entitlement volumes.
- An environment protection licence (EPL) is required to export mine water from the site. For mines along the Hunter regulated river, this is managed as a system of salinity credits through the Hunter River Salinity Trading Scheme (HRSTS). For mines that are not part of this scheme, discharge conditions are as required under their EPL.
- Rehabilitation of mine sites is a condition of the mining licence. In open-cut mines, rehabilitation is progressive, but removal of surface drainage diversion channels occurs at the end of mine life.
- Open-cut mines generally leave a final void, which means landscape runoff does not completely return to pre-disturbance conditions.

This section describes how coal resource development in the Hunter subregion will be addressed in the quantitative modelling. Section 2.3.4.1 identifies the mining operations that are included in the baseline and the CRDP. Section 2.3.4.2 presents how mine water management is generically represented in the modelling; therefore, water management by individual mines are not the focus here, but rather what assumptions can be made about the off-site effects of mine water management for representation in the quantitative models. Specific details of the parameterisation of mining operations for representation in the numerical models are provided in the surface water modelling (companion product 2.6.1 (Zhang et al., 2018)) and groundwater modelling (companion product 2.6.2 (Herron et al., 2018b)) for the Hunter subregion, and in data observations and statistical analyses (see Section 2.1.6 of companion product 2.1-2.2 (Herron et al., 2018a)) for the Hunter subregion.

### *2.3.4.1 Developing the coal resource development pathway*

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

The difference in results between CRDP and baseline is the change that is primarily reported in a BA. This change is due to the additional coal resource development, which includes all coal mines and coal seam gas (CSG) fields, including expansions of baseline operations that are expected to begin commercial production after December 2012. Developments that were approved before December 2012 but were not commercially producing at that time are additional coal resource developments.

The CRDP is informed by companion product 1.2 for the Hunter subregion (Hodgkinson et al., 2015). Hodgkinson et al. (2015) summarised existing and proposed mining developments in the subregion based on publicly available information as of May 2015. Updates were made to some sections during the review process, but most of the information presented in that product is current as of May 2015. Baseline and additional coal resource development mining operations were determined according to the approach outlined in companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis, 2014).

The list of candidate mines for the baseline and additional coal resource development for the Hunter subregion (see Section 1.2.4 of companion product 1.2 for the Hunter subregion (Hodgkinson et al., 2015)) was presented for review and comment to representatives of many mining companies with operations in the Hunter subregion at a workshop on 18 August 2015 in Singleton, NSW. Stakeholders from the Office of Water Science, DPI Water (formerly NSW Office of Water), WaterNSW and NSW Department of Industry’s Division of Resources and Energy also attended the workshop. The list was updated based on information obtained at the workshop, from follow-up conversations with mine representatives and from review comments by the mining sector of companion product 1.2 of the Hunter subregion (Hodgkinson et al., 2015). In September 2015, the Assessment team finalised the list of mines and mining operations in the CRDP.

There were no CSG fields proposed in the Hunter subregion at this time.

### 2.3.4.1.1 Baseline coal resource developments

Although coal mining has occurred in the Hunter subregion for over 100 years, not all historical mines are included in the baseline. Baseline mines are those that were operating or in care and maintenance as of December 2012. Mines that are in care and maintenance are included because it is assumed that mining could resume within the life of their existing approvals and/or dewatering is often continued through the care and maintenance period. Table 7 summarises the 42 mining operations (referred to hereafter as simply ‘mines’) that are included in the baseline for the Hunter subregion. In companion product 1.2 for the Hunter subregion (Hodgkinson et al., 2015), the number of operating mines as of May 2015 is reported as 18 mines, 7 mine complexes and 6 in care and maintenance, or a total of 31 operations. The discrepancy with the 42 baseline mines in Table 7 reflects:

1. definition of baseline mines as operating as of December 2012
2. complexes often include open-cut and underground operations, and these have been separated out in Table 7 because they have different hydrological effects and are differentiated in the numerical modelling (e.g. separate entries for Ravensworth Complex underground and Ravensworth Complex open-cut)
3. differences in what is or is not part of a complex (e.g. Glendell and Ravensworth East mines are listed individually in Table 7, but in companion product 1.2 for the Hunter subregion (Hodgkinson et al., 2015) are included as part of Mount Owen complex).

Table 7 identifies which mines are part of a mine complex, as well as which mines and mining operations have been included in the surface water and/or groundwater modelling for the baseline. Fourteen baseline mines are not included in the surface water modelling because:

- The mining method is bord and pillar – this method always results in less subsidence than longwall mining (Commonwealth of Australia, 2014). For first workings, the mine is not collapsed following coal extraction and surface subsidence is unlikely; for second workings, some coal pillars are removed and can lead to some collapse of the immediate roof strata over the mined void, but surface subsidence is minimal. Disruption to surface water drainage from the mined area and the site facilities can reasonably be assumed to be negligible, relative to changes in groundwater from mine water pumping.
- Mining takes place predominantly under the coastal lakes and/or urban areas.
- The distance down-catchment before discharge to the coastal lakes is negligible.
- The mine is located downstream of Greta on the Hunter River, which is approximately the point at which tidal influences impact Hunter River flows. This interaction cannot be represented in the river model.
- Mining had ceased prior to the end of December 2012.

One baseline mine, Ulan Open-Cut, is not included in the groundwater modelling due to lack of data. Groundwater modelling for Wambo’s baseline underground operations includes only the North Wambo area, as flow rate data for the other underground extraction areas were not found.

Table 8 lists the mines or mining operations for which surface water or groundwater modelling is not undertaken and provides the rationale for exclusion.

The start date reflects the year that published information indicates mining commenced, although for some this reflects the long-term history, whereas others reflect a start date under the ownership of the current company or the start date of the development consent for the current suite of mining activities. These are not necessarily the same start years used for modelling, although many are: availability of data and the period chosen for modelling have determined the start dates for representing the hydrological effects of historical mines in the hydrological models.

End dates represent the year to which mining has been approved or, if mining is known to have ceased, the year when mining ceased. End dates in Table 7 can also differ from those used in the hydrological models because pumping and other hydrological effects of excavations can continue beyond the cessation of coal extraction. The start and end dates used in the numerical modelling are provided in Table 23 for groundwater modelling and Figure 38 for surface water modelling in companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018a).

Figure 14 shows the distribution of baseline mines across the subregion. Underground mines dominate the eastern part of the subregion, and both open-cut and underground mines occur in the central and western parts of the subregion.

Table 7 Mines in the baseline coal resource development (baseline)

Baseline is a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing (or in care and maintenance under a current approval) as of December 2012. Baseline mines are date stamped to September 2015 and reflect information obtained at that time.

| Mine | Open-cut or underground | Company | Start or estimate of start of mining | End of mine life or estimated project life | Comments | Modelled?[a] | |
|---|---|---|---|---|---|---|---|
| | | | | | | GW | SW |
| Abel | UG | Donaldson Coal (Yancoal) | 2008 | 2028 | Part of Donaldson Coal Complex.<br>Ongoing operation. | Y | N |
| Ashton | OC | Yancoal | 2004 | 2011 | Mining ceased in North East Open Cut (NEOC) in early 2011. Proposed South East Open Cut (see Table 9). | Y | Y |
| Ashton | UG | Yancoal | 2006 | 2023 | Planning approval granted in October 2002.<br>Consent to extract from four overlying seams (2006, 2012, 2014 and 2019).<br>Extraction from Upper Liddell seam commenced August 2012. | Y | Y |
| Austar | UG | Yancoal | 2005 | 2026 | This is an amalgamation of older mines (Bellbird, Pelton-Ellalong and Southland), operating since 1974. Stage 1 operations under Yancoal Australia began in 2005. Stage 2 completed in 2012. Stage 3 commenced in 2013. Modification to Stage 3 longwall panels approved November 2015 (see Table 9). | Y | Y |
| Awaba | UG (B&P) | Centennial Coal | 1947 | 2012 | Mine closed. Still pumping to keep water out of Newstan. | Y | N |
| Bengalla | OC | Rio Tinto Group | 1999 | 2015 | Development consent granted in 1996. Commenced production in 1999. Expansion of operation (see Table 9). | Y | Y |
| Bloomfield | OC | Bloomfield Collieries | 2006 | 2021 | Mining since 1840s. Current development since 2006. Mining is occurring at less than the approved rate. Have sought extension of current approvals for Stages 3, 4 and 5. Modification 3 approved February 2013. | Y | N |
| Bulga | OC | Glencore Coal | 1986 | 2014 | Part of Bulga Coal Complex.<br>Ongoing operation to 2035. Baseline to 2014; ACRD from 2015 (see Table 9). | Y | Y |
| Bulga | UG | Glencore Coal | 2008 | 2031 | Part of Bulga Coal Complex.<br>Mining approved in four seams and commenced prior to 2012. | Y | Y |
| Chain Valley | UG | Lake Coal (LDO Coal) | 1962 | 2013 | Current operations approved to end 2027, includes baseline to end 2013 and ACRD to 2027 (see Table 9). | Y | N |

| Mine | Open-cut or underground | Company | Start or estimate of start of mining | End of mine life or estimated project life | Comments | Modelled?[a] | |
|---|---|---|---|---|---|---|---|
| | | | | | | GW | SW |
| Cumnock | UG | Glencore Coal | 1950 | 2011 | Part of Ravensworth Complex.<br>Formerly known as Liddell State Coal mine. Wash Plant Pit was mined until 2011. In care and maintenance since 2011. Current operations limited to pumping of wet tailings. | Y | N |
| Dartbrook | UG | Anglo American | 1997 | 2006 | Construction began in 1993. Commercially producing in 1997.<br>Mining ceased on 1 January 2007. In care and maintenance. | Y | Y |
| Donaldson | OC | Donaldson Coal (Yancoal) | 2001 | 2013 | Part of Donaldson Coal Complex.<br>This mine closed in July 2013 after exhaustion of reserves. | Y | N |
| Drayton | OC | Anglo American | 2007 | 2021 | Ongoing operation since 1983. Current operations commenced 2007 and approved to 2021. Mining to wind down in 2016, following decision by the Planning Assessment Commission to not support Drayton South expansion. | Y | Y |
| Glendell | OC | Glencore | 2008 | 2023 | Part of Mount Owen Complex since 1997.<br>Approval granted in 1983, but not commenced until 2008, with commercial production in 2010. | Y | Y |
| Hunter Valley Operations | OC | Rio Tinto Group | 1968 | 2030 | Ongoing operation. Mining commenced in West Pit (Howick Coal mine) in 1968. Hunter Valley No. 1 (North Pit) mine commenced in 1979. In 2009, multiple approvals were replaced by single approval to 2030. | Y | Y |
| Integra | OC | Vale Australia | 1991 | 2035 | Development approval in 1991. Camberwell open-cut mine commenced in 1991. Current approval to 2035.<br>In care and maintenance since July 2014, based on poor economic outlook. | Y | Y |
| Integra | UG | Vale Australia | 1996 | 2035 | Development approval in 1991. Underground development commenced in 1999 at Glennies Creek, with first coal produced in 2002. Current approval to 2035.<br>In care and maintenance since July 2014, based on poor economic outlook. | Y | Y |
| Liddell | OC | Glencore | 1946 | 2014 | Ongoing operation. Expansion of operations to development consent boundary approved in 2014 (see Table 9). | Y | Y |

| Mine | Open-cut or underground | Company | Start or estimate of start of mining | End of mine life or estimated project life | Comments | Modelled?[a] | |
|---|---|---|---|---|---|---|---|
| | | | | | | GW | SW |
| Mandalong | UG | Centennial Coal | 2005 | 2017 | Current operation approved to 2035, including expansion.<br>Based on current extraction rates: baseline to 2017; ACRD from 2018 (see Table 9). | Y | N |
| Mangoola | OC | Glencore | 2006 | 2026 | Approved and operating in December 2012. Modification 6 – extraction rate increase approved April 2014. | Y | Y |
| Mannering | UG | Lake Coal (Centennial Coal) | 1960 | 2022 | Modification 2 (linking Mannering and Chain Valley) approved November 2014. This is assumed to be change to an existing approval.<br>In care and maintenance since January 2013. Baseline to 2019. | Y | N |
| Moolarben | OC | Yancoal Australia | 2010 | 2038 | Ongoing operation. Stage 1 (including UG4) approved in 2007. Commercial production in OC1 in 2010.<br>Modification 3 (approved in January 2015) extends mining operations out to December 2038. Includes new pit (see Table 9). Baseline to 2019. | Y | Y |
| Moolarben | UG | Yancoal Australia | 2010 | 2038 | Part of Stage 1 approval in 2007 (see above). New UG operations approved in January 2015 (see Table 9). Baseline to 2014. | Y | Y |
| Mount Arthur | OC | BHP Billiton | 2001 | 2022 | Part of Mount Arthur Coal Mine Complex.<br>Mining since 1960 in Bayswater OC2 and OC3.<br>North OC approved in 2001. Production commenced in April 2002. Expansion approved in 2014 (see Table 9), plus extension of mining to 2026. | Y | Y |
| Mount Owen | OC | Glencore | 1993 | 2015 | Part of Mount Owen Complex.<br>Ongoing operation approved to 2025, but expect currently approved area will be mined out by 2018. Mount Owen Continued Operations project will expand mine area and extend life of operations. Assume baseline to 2015; ACRD from 2018 (see Table 9). | Y | Y |
| Mount Thorley–Warkworth | OC | Coal and Allied (Rio Tinto) | 1980 | 2018 | An integrated ongoing operation of two adjacent open-cut mines. Expansion approved in October 2015 (see Table 9). | Y | Y |

| Mine | Open-cut or underground | Company | Start or estimate of start of mining | End of mine life or estimated project life | Comments | Modelled?[a] | |
|---|---|---|---|---|---|---|---|
| | | | | | | GW | SW |
| Muswellbrook | UG (B&P) | Muswellbrook Coal Company (MCC) (Idemitsu) | 1907 | 1997 | Underground operations from 1907 to 1997. Pumping of water has been ongoing since cessation of mining. | Y | N |
| Muswellbrook | OC | MCC (Idemitsu) | 2005 | 2018 | Open-cut operation since 1944. Current operations in No. 1 OC extension (since 2005). Mining in No. 2 OC has ceased, but extended into previous B&P workings. | Y | Y |
| Myuna | UG (B&P) | Centennial Coal | 1982 | 2032 | Approval to extend operations until end of 2032 granted in January 2012. Approval to increase annual permissible extraction from 2 to 3 tonnes granted in February 2015. | Y | N |
| Newstan | UG | Centennial Coal | 1999 | 2020 | Mining for over 125 years.<br>Current operations approved for 21 years from 1999. In care and maintenance in 2008 due to difficult geological conditions, and since early 2014 due to poor economic outlook. Ongoing pumping is occurring to keep water out of Awaba. | Y | N |
| Ravensworth | UG | Glencore | 1999 | 2023 | Part of Ravensworth Complex.<br>In care and maintenance in October 2014 due to economic outlook. Pumping at 80% of full rate as at August 2015. | Y | Y |
| Ravensworth | OC | Glencore | 1993 | 2039 | Part of Ravensworth Complex.<br>Includes Narama, West and North OC pits. Mining ceased in Narama OC in 2014. West OC was mined between 2006 and 2011. North OC is a continuation of West OC which was approved with a mine life of 29 years and producing before December 2012. | Y | Y |
| Ravensworth East | OC | Glencore | 2000 | 2027 | Part of Mount Owen Complex since 2004.<br>Production commenced in 2000. Approved to mine in West Pit and BNP until March 2021; is expected to commence in BNP in 2015. Mount Owen Continuation Project would extend operations to 2027 but not increase area of mining (see Mount Owen Complex in Table 9). | Y | Y |

| Mine | Open-cut or underground | Company | Start or estimate of start of mining | End of mine life or estimated project life | Comments | Modelled?[a] | |
|---|---|---|---|---|---|---|---|
| | | | | | | GW | SW |
| Rix's Creek | OC | Bloomfield Collieries | 1990 | 2018 | Approval to increase production rate granted in November 2014.<br>Seeking extension of project to 2038, but no increase in extraction volume. Exhibition of EIS closed on 3 December 2015. | Y | Y |
| Tasman | UG (B&P) | Donaldson Coal (Yancoal) | 2006 | 2013 | Part of Donaldson Coal Complex.<br>Approved to mine until 2025, but ceased production in July 2013. | Y | N |
| Ulan | OC | Glencore | 1981 | 2021 | Mining at Ulan has taken place since the 1920s. Part of Ulan Coal Complex. Open-cut mining ceased in 2008. Recommenced in 2010 – expected to continue for 7 to 11 years. | N | Y |
| Ulan | UG | Glencore | 1986 | 2021 | First longwall mine (replacing B&P) commenced in 1986. Approved to 2021. In 2011, a 21 year extension was approved, including continuation of Ulan No. 3 (part of baseline) and the new Ulan West UG mine (Table 9). | Y | Y |
| Wambo | OC | Peabody Energy | 1993 | 2017 | Part of Wambo Mine Complex.<br>Mining since 1970s. Existing operations commenced in 1993. Mining expected to continue to 2017. | Y | Y |
| Wambo | UG | Peabody Energy | 2005 | 2016 | Part of Wambo Mine Complex.<br>Ongoing operation since early 1970s. Includes North Wambo, South Bates, Arrowfield and Bowfield developments. North Wambo UG mine commenced in November 2005 (in GW model). There are plans to expand (see Table 9). | Y[b] | N |
| West Wallsend | UG | Glencore | 1969 | 2015 | Started as B&P mining operation. Longwall unit installed in 1989.<br>In care and maintenance as at September 2015. | Y | N |
| Wilpinjong | OC | Peabody Energy | 2006 | 2027 | Ongoing operation, comprising multiple pits, with plans for expansion (see Table 9). | Y | Y |

[a] See Table 8 for reasons why some mines were not modelled.

[b] only part of the baseline underground developments is modelled.

ACRD = additional coal resource development, baseline = baseline coal resource development, B&P = bord and pillar, EIS = environmental impact statement, GW = groundwater, OC = open-cut, SW = surface water, UG = underground

Full company names: Bloomfield Collieries Pty Ltd (Bloomfield Collieries ), Coal and Allied Industries Ltd (Coal and Allied), Donaldson Coal Ltd (Donaldson Coal), Glencore Coal Australia Pty Limited (Glencore Coal), Muswellbrook Coal Company Limited (MCC), Peabody Energy Australia Ltd (Peabody Energy), Yancoal Australia Ltd (Yancoal)

Table 8 Reasons for not modelling some mines in the baseline coal resource development (baseline)

| Mine | Open-cut or underground | Company | Excluded from SW or GW modelling? | Reasons for not modelling |
|---|---|---|---|---|
| Abel | UG | Donaldson Coal (Yancoal) | SW | Downstream of Greta, hence in the tidal zone of Hunter River. Cannot be represented in the river model.<br>No additional coal resource development at this site. Modelled changes will be identical in baseline and CRDP. |
| Awaba | UG (B&P) | Centennial Coal | SW | Bord-and-pillar mine – assumed to not cause subsidence, hence no impact on surface drainage.<br>Panels mostly under Lake Macquarie and/or surrounding urban areas. Models do not represent interactions with lake or account for urban runoff processes.<br>Surface areas (i.e. site facilities) have negligible downstream catchments before entering Lake Macquarie. |
| Bloomfield | OC | Bloomfield Collieries | SW | Downstream of Greta, hence in the tidal zone of Hunter River. Cannot be represented in the river model.<br>No additional coal resource development at this site. Modelled changes will be identical in baseline and CRDP. |
| Chain Valley | UG | Lake Coal (LDO Coal) | SW | Panels mostly under Lake Macquarie and/or surrounding urban areas. Models do not represent interactions with lake or account for urban runoff processes.<br>Surface areas (i.e. site facilities) have negligible downstream catchments before entering Lake Macquarie. |
| Cumnock | UG | Glencore Coal | SW | Mining ceased in 2011, so not technically a baseline mine. Open-cut mining at Ravensworth occurs over top of former underground panels, so impact on surface water part of Cumnock area is modelled. |
| Donaldson | OC | Donaldson Coal (Yancoal) | SW | Downstream of Greta, hence in the tidal zone of Hunter River. Cannot be represented in the river model.<br>No additional coal resource development at this site. Modelled changes will be identical in baseline and CRDP. |
| Mandalong | UG | Centennial Coal | SW | No stream network represented in the groundwater model in this area, therefore no modelled baseflows.<br>Changes on streamflow could not be modelled properly without the changes in baseflow. |
| Mannering | UG | Lake Coal (Centennial Coal) | SW | Panels mostly under Lake Macquarie and/or surrounding urban areas. Models do not represent interactions with lake or account for urban runoff processes.<br>Surface areas (i.e. site facilities) have negligible downstream catchments before entering Lake Macquarie. |
| Muswellbrook | UG (B&P) | Muswellbrook Coal Company (Idemitsu) | SW | Bord-and-pillar mine – assumed to not cause subsidence, hence no impact on surface drainage.<br>Not strictly baseline as not commercially producing in December 2012. Pumping has continued and GW changes are modelled. |

| Mine | Open-cut or underground | Company | Excluded from SW or GW modelling? | Reasons for not modelling |
|---|---|---|---|---|
| Myuna | UG (B&P) | Centennial Coal | SW | Bord-and-pillar mine – assumed to not cause subsidence, hence no impact on surface drainage.<br>Panels mostly under Lake Macquarie and/or surrounding urban areas. Models do not represent interactions with lake or account for urban runoff processes.<br>Surface areas (i.e. site facilities) have negligible downstream catchments before entering Lake Macquarie. |
| Newstan | UG | Centennial Coal | SW | Panels mostly under Lake Macquarie and/or surrounding urban areas. Models do not represent interactions with lake or account for urban runoff processes.<br>Surface areas (i.e. site facilities) have negligible downstream catchments before entering Lake Macquarie. |
| Tasman | UG (B&P) | Donaldson Coal (Yancoal) | SW | B&P mine – assumed to not cause subsidence, hence no impact on surface drainage.<br>Downstream of Greta, hence in the tidal zone of Hunter River. Cannot be represented in the river model.<br>No additional coal resource development at this site. Modelled changes will be identical in baseline and CRDP. |
| Ulan | OC | Glencore | GW | Did not have flow rate data. |
| Wambo | UG | Peabody Energy | SW | As at May 2015, only extraction from North Wambo UG had commenced. About half of this area under the open-cut mine, which is modelled. Unclear when mining of South Bates, Arrowfield and Bowfield will occur. |
| West Wallsend | UG | Glencore | SW | Downstream of Greta, hence in the tidal zone of Hunter River. Cannot be represented in the river model.<br>No additional coal resource development at this site. Modelled changes will be identical in baseline and CRDP. |

ACRD = additional coal resource development, baseline = baseline coal resource development, B&P = bord and pillar, CRDP = coal resource development pathway, GW = groundwater, OC = open-cut, SW = surface water, UG = underground

Full company names: Bloomfield Collieries Pty Ltd (Bloomfield Collieries ), Donaldson Coal Ltd (Donaldson Coal), Glencore Coal Australia Pty Limited (Glencore Coal), Muswellbrook Coal Company Limited (MCC), Yancoal Australia Ltd (Yancoal)

**Figure 14 Mines in the baseline coal resource development (baseline)**

A mine with both open-cut and underground operations is shown as a dot with a ring around it.
Data: Bioregional Assessment Programme (Dataset 1)

### 2.3.4.1.2 Additional coal resource development

The mines in the CRDP are the sum of those in the baseline and those identified as additional coal resource developments. In determining which development proposals (from Table 5 in the companion product 1.2 for the Hunter subregion (Hodgkinson, 2015)) would be included as additional coal resource developments (and hence the CRDP), the following were considered:

1. Whether the development proposal sought to extend the life of a baseline mine beyond the end date for which it was originally approved or to expand the area mined beyond that covered by approvals granted prior to 31 December 2012.
    a. A proposal to extend the completion date of a baseline mine was deemed to be baseline. This is because there is no increase to the already approved area and volume of extraction, hence no new hydrological impact, just a delay in timing.
    b. A proposal to increase the area mined was deemed to be an additional coal resource development because it would lead to an increase in the hydrological impact to what had already been approved.
2. What the status of the proposal was in terms of the approval process at the time of finalising the baseline and additional coal resource development mines in September 2015. Generally, a proposal was deemed to be an additional coal resource development if:
    a. it had been approved, but coal production had not commenced before 31 December 2012, or
    b. an environmental impact statement (EIS) had been submitted and there were no apparent reasons why it would not be approved.

Table 9 summarises the list of mining developments that met the criteria for inclusion in the CRDP as an additional coal resource development. There are 22 additional coal resource developments comprising 13 open-cut and 9 underground mining proposals. Out of these 22 coal resource developments, 6 proposals are for new mines (3 open-cut and 3 underground mines) and 16 are expansions to existing open-cut and longwall operations. There are no CSG development proposals.

Where a mine development is already known to have commenced (i.e. since 31 December 2012), the start date reflects the actual start year. Where a mine development is yet to commence, the start date reflects the date reported in the mine's EIS as the start year for the proposal or, if this is not known, Assessment team estimated a start date (2018 when start date unknown; or if based on documented dates, mining should have commenced but had not, the current (2016) or subsequent (2017) year was adopted). The reported end dates reflect what has been approved or is being sought in the approval. Start dates and end dates will almost certainly deviate from these assumptions. The additional coal resource development reflects an assessment in September 2015, from which coal resource development plans have since deviated. For example, on 27 November 2015, the Planning and Assessment Commission recommended that the Drayton South Coal Project not proceed; at this time it had already been modelled in the CRDP.

Sixteen additional coal resource developments have sufficient information available to be able to model their hydrological impact into the future (see companion submethodology M04 (Lewis, 2014)). However, three proposals are not included in surface water or groundwater models:

- West Muswellbrook Project – insufficient data were available to represent the hydrological impact in the models
- Austar proposal – which involved some retraction of already approved longwall panels, plus some expansion of the same panels at the other end, the net change in area mined was negligible and deemed not to significantly change what had already been approved
- Wambo – flow rates were not available for the proposed new panels and therefore not represented in the groundwater model; with respect to surface water modelling, the new panels were located beneath existing panels and it was assumed there was no net change in surface drainage.

In addition, the Wilpingjong Coal Mine is also not included in the groundwater modelling for the CRDP due to lack of flow-rate data. Mount Arthur Coal Mine Complex is not included in the groundwater modelling because the increase in mined area (~70 ha) is negligible and the model is largely insensitive to this scale of change. The Chain Valley Colliery is not included in the surface water modelling because the footprint is largely underneath Lake Macquarie and any effects are assumed to be swamped by lake and tidal processes. The Mandalong Southern Expansion Project is not included in the surface water modelling because the stream network incorporated into the groundwater model to represent groundwater – surface water interactions inadvertently did not include the streams in this area. As a result, changes in baseflow from groundwater drawdown were not generated for input into the surface water model. A decision was made to not present results from runoff interception only, as this would give an incomplete and inaccurate estimate of the potential changes on streamflow from the additional coal resource development. Table 10 identifies the additional coal resource development proposals that are not included in groundwater and/or surface water modelling for the CRDP, and the reasons for exclusion.

The distribution of the mines identified as additional coal resource developments (listed in Table 9) is shown in Figure 15. There are three developments in the coastal area, but most of the proposed new coal mines and expansions are further inland around the Hunter Coalfield and the Western Coalfield.

The potential hydrological changes from the additional coal resource developments that are not included in the surface water and/or groundwater modelling are considered in companion product 3-4 for the Hunter subregion (as listed in Table 2). Where appropriate, the conceptual model of the Hunter subregion, results from the numerical modelling of the modelled additional coal resource development and/or information that has become available since the numerical modelling was completed are used to infer potential hydrological changes and potential for impacts on landscape classes and assets.

**Table 9 Mines comprising the additional coal resource development**

The mines in the coal resource development pathway (CRDP) are the sum of those in the baseline and the additional coal resource development (ACRD). The ACRD is all coal mines and coal seam gas (CSG) fields, including expansions of baseline operations that are expected to begin commercial production after December 2012. This table reflects decisions made in September 2015 with information obtained at that time.

| Mine | Open-cut or underground | Company | Start year | End year | Comments | Modelled? | |
|---|---|---|---|---|---|---|---|
| | | | | | | GW | SW |
| Ashton | OC | Yancoal | 2018[b] | 2025 | Expansion. South East Open Cut (SEOC) mine.<br>Recommendation made to PAC August 2011 and initially approved in October 2012 for 7-year mine life to 2025. Appealed. Approval not finalised.<br>For bioregional assessment purposes, assumed likely to proceed. | Y | Y |
| Austar | UG | Yancoal | 2014 | 2026 | Modification to Stage 3 area approved December 2013. Entails retraction of some longwall panels at one end and expansion at other end. Production commenced in the stage 3 area in 2013.<br>Note: an environmental assessment was submitted for public exhibition in November 2015 for development of three new longwall panels and was approved on 2 February 2016. This expansion is not included as an ACRD as it occurred after the ACRD mines were finalised for modelling (September 2015). | N | N |
| Bengalla | OC | Rio Tinto Group | 2016 | 2039 | Expansion approved March 2015. | Y | Y |
| Bulga | OC | Glencore | 2015 | 2035 | Bulga Coal Optimisation Project. Expansion project approved December 2014. | Y | Y |
| Bylong | OC | Korea Electric Power Corporation (KEPCO) | 2017[b] | 2025 | Bylong Coal Project. New mine.<br>DGRs issued June 2014. EIS submitted on 23 September 2015. Contentious project, considerable community concern.<br>For bioregional assessment purposes, assumed likely to proceed. | Y | Y |
| Bylong | UG | KEPCO | 2022 | 2044 | Bylong Coal Project. Proposed new mine.<br>EIS submitted on 23 September 2015.<br>For bioregional assessment purposes, assumed likely to proceed. | Y | Y |
| Chain Valley | UG | Lake Coal (LDO Group) | 2014 | 2027 | Chain Valley Modification 1.<br>Approval to expand into newly acquired sub-lease areas granted on 23 December 2013. | Y | N |

| Mine | Open-cut or underground | Company | Start year | End year | Comments | Modelled? | |
|---|---|---|---|---|---|---|---|
| | | | | | | GW | SW |
| Drayton South | OC | Anglo American | 2016 | 2030 | Drayton South Coal Project.<br>PAC refused project approval October 2014. Gateway application was submitted in January 2015. EIS submitted in May 2015. Gone to IESC.<br>For bioregional assessment purposes, assumed likely to proceed.<br>Note: On 27 November 2015, the PAC recommended Drayton South Coal Project not proceed. However, the decision to include Drayton South as an ACRD was made in September 2015 and it has been modelled as part of the CRDP. | Y | Y |
| Liddell | OC | Glencore | 2015 | 2028 | Expansion of operations to development consent boundary approved in December 2014. DA Modification 1 assumes mine life of 10 years, with a 3-year buffer to allow for changes in economic environment. | Y | Y |
| Mandalong | UG | Centennial Coal | 2018[b] | 2040 | Mandalong Southern Extension Project. Expansion of mine area and extension of development consent to 2040.<br>Project under PAC review as at August 2015.<br>For bioregional assessment purposes, assumed likely to proceed. | Y | N |
| Moolarben | OC | Yancoal | 2020 | 2035 | Expansion. Project life of 24 years.<br>Stage 2 comprising one open-cut (OC4) and two underground mines (UG1 and UG2) approved in January 2015. | Y | Y |
| Moolarben | UG | Yancoal | 2015 (UG1),<br>2025 (UG2) | 2025 (UG1),<br>2028 (UG2) | Stage 2 comprising one open-cut (OC4) and two underground mines (UG1 and UG2) approved in January 2015. Longwalls to commence in series.<br>Modifications to stages 1 and 2 for optimisation of underground operations submitted for exhibition July 2015. | Y | Y |
| Mount Arthur | UG | BHP Billiton | 2016[b] | 2030 | Approved in 2008, but no mining has commenced. Project life is 21 years, but end date reflects current approval. | Y | Y |
| Mount Arthur | OC | BHP Billiton | 2022 | 2026 | Expansion of South Pit into Bayswater No.3 mining lease. Approved in 2014. | N | Y |
| Mount Owen | OC | Glencore | 2018[b] | 2030 | Mount Owen Continued Operations Project. Proposes to expand North Pit by 382 ha and extend mine life to 2030 and, extend Ravensworth East mine life by 6 years (2027). Proposed disturbance area of 485 ha.<br>EIS submitted for review. Exhibition stage ended. | Y | Y |

| Mine | Open-cut or underground | Company | Start year | End year | Comments | Modelled? | |
|---|---|---|---|---|---|---|---|
| | | | | | | GW | SW |
| Mount Pleasant | OC | Rio Tinto Group | 2018[b] | 2037 | New mine with four pits. EIS in 1997. Development consent granted in 1999, but mining not commenced. Modification 1 approved in September 2011 did not involve changes that would impact mine footprint. Current approval is to 2022, although original DC indicated a mine life of 20 years. | Y | Y |
| Mount Thorley–Warkworth | OC | Rio Tinto Group | 2016 | 2037 | Expansion. Two separate developments with project life of 21 years.<br>Approved October 2015 | Y | Y |
| Ulan | UG | Glencore | 2014 | 2031 | Expansion. Ulan West.<br>Commercially producing in May 2014 (pumping from 2012). | Y | Y |
| West Muswellbrook | OC | Muswellbrook Coal Company | Not known | Not known | West Muswellbrook Project. New mine.<br>Gateway application submitted December 2014. Approved. | N | N |
| Wallarah 2 | UG | Wyong Coal | 2018[b] | 2046 | New mine. Awaiting approval as at August 2015. For bioregional assessment purposes, assumed likely to proceed.<br>Anticipated mine life of 25 years plus 3 years for construction. | Y | Y |
| Wambo | UG | Peabody Energy | Not known | 2025 | Various modifications involving additional longwall panels: Modification 13 – two additional longwall panels in North Wambo UG; Modification 14 – one additional panel in North Wambo UG; Modification 15 – three additional panels in South Bates UG. All have been approved (Mod 15 on 10 November 2015). | N | N |
| Wilpinjong | OC | Peabody Energy | 2026 | 2033 | DGRs for expansion project issued December 2014. Pre-EIS. Proposal involves 500 ha increase to existing pit, plus 300 ha new pit with 7-year extension. | N | Y |

[a] See Table 10 for reasons why some mines were not modelled.

[b] Start date uncertain – estimated for modelling

DGRs = Director General Requirements (for the environmental assessment to be prepared by the proponent), EIS = environment impact statement, GW = groundwater, OC = open-cut, PAC = Planning Assessment Commission, SW = surface water, UG = underground

Full company names: Glencore Coal Australia Pty Limited (Glencore Coal), Muswellbrook Coal Company Limited (MCC), Peabody Energy Australia Ltd (Peabody Energy), Yancoal Australia Ltd (Yancoal)

**Table 10 Reasons for not modelling some mines comprising the additional coal resource development**

The mines in the coal resource development pathway (CRDP) are the sum of those in the baseline and the additional coal resource development (ACRD). The ACRD is all coal mines and coal seam gas (CSG) fields, including expansions of baseline operations that are expected to begin commercial production after December 2012.

| Mine | Open-cut or underground | Company | Excluded from SW or GW modelling | Reasons for not modelling |
|---|---|---|---|---|
| Austar | UG | Yancoal | SW and GW | The proposed modification to approved Stage 3 longwall panels entails retraction of starting locations and/or extension at other end of four longwall panels. Net change in longwall extent is around 5% to 10% of existing approved extent and <1% of the entire baseline extent. |
| Chain Valley | UG | Lake Coal (LDO Group) | SW | Mine footprint is predominantly under Lake Macquarie. Surface water models not able to represent hydrological changes. |
| Mandalong | UG | Centennial Coal | SW | The stream network in this area was inadvertently not represented in the groundwater model, resulting in no modelled changes in baseflow due to drawdown. Thus a complete and accurate estimate of streamflow changes was not possible. |
| Mount Arthur | OC | BHP Billiton | GW | Small increase in existing open-cut mine footprint. Groundwater model is not sensitive to this scale of change. |
| West Muswellbrook | OC | Muswellbrook Coal Company | SW and GW | Insufficient data to represent in surface water and groundwater models |
| Wambo | UG | Peabody Energy | SW and GW | Insufficient data to represent in groundwater models.<br>Additional panels all underlie already approved panels and use existing site facilities, so no additional impact at surface to that under baseline conditions. |
| Wilpinjong | OC | Peabody Energy | GW | Insufficient data to represent in groundwater models. No EIS available. |

baseline = baseline coal resource development, EIS = environmental impact statement, GW = groundwater, OC = open-cut, SW = surface water, UG = underground
Full company names: Muswellbrook Coal Company Limited (MCC), Peabody Energy Australia Ltd (Peabody Energy), Yancoal Australia Ltd (Yancoal

**Figure 15 Mines comprising the additional coal resource development**

Data: Bioregional Assessment Programme (Dataset 1)

### 2.3.4.1.3 Identified coal resources not in the coal resource development pathway

There are ten other coal resource exploration and development proposals with economically demonstrated resources that could potentially be extracted at some stage in the future (see companion product 1.2 for the Hunter subregion (Hodgkinson et al., 2015)). These proposals were not included as additional coal resource developments in the CRDP for the Hunter subregion as the Assessment team determined that, on the basis of available information at September 2015, they are unlikely to become commercially producing mines within the next 10 to 15 years. Table 11 provides a summary of the proposals that were considered and the rationale for not including them as additional coal resource developments, and hence part of the CRDP. In general, projects that were still in an exploration phase were considered too immature in their development to include as additional coal resource developments. Two projects (Doyles Creek and Mount Penny) were not included in the CRDP because they have been the subject of Independent Commission Against Corruption (ICAC) inquiries and had their exploration licences suspended.

Figure 16 shows the location of the ten identified coal resources not included in the CRDP.

**Table 11 Reasons for not including some mines as additional coal resource development in the coal resource development pathway (CRDP)**

Listed coal resource developments were deemed unlikely to proceed or too immature in development to include as additional coal resource developments (ACRDs). The mines in the coal resource development pathway (CRDP) are the sum of those in the baseline and in the ACRD. The ACRD is all coal mines and coal seam gas (CSG) fields, including expansions of baseline operations that are expected to begin commercial production after December 2012. Status of mines reflects information obtained prior to September 2015.

| Mine | Open-cut or underground | Company | Reasons for not including as an additional coal resource development |
|---|---|---|---|
| Bickham Coal Project | UG | Bickham Coal Company | Potential new mine. Pre-EIS as at September 2015. Original proposal for OC mine not approved. Changed proposal to UG. Exploration licence renewed.<br>Considered too immature in its development to include as an ACRD. |
| Dellworth Project | OC | NuCoal Resources | Potential new mine. Pre-EIS as at September 2015. Reports that Savoy Hill more likely to progress.<br>Based on data and information available to the Assessment team as of September 2015, the potential for future commercial production at this site is considered unlikely. |
| Doyles Creek | OC / UG | NuCoal Resources | NSW Government suspended exploration licence (EL) in 2014 on recommendation from ICAC. Subsequent judicial review and constitutional challenges have followed. No mining to date.<br>Based on data and information available to the Assessment team as of September 2015, the potential for future commercial production at this site is considered unlikely. |
| Ferndale Project | OC | Whitehaven Coal | Potential new mine. Pre-EIS. EL 7430 expired 17 December 2014 and the status of its renewal, the EIS and the future of this project is unclear (as of September 2015).<br>Considered too immature in its development to include as an ACRD. |
| Kayuga Project | OC | Anglo American | Expansion of Dartbrook, which was in care and maintenance as at September 2015. Mining lease applications were rejected by NSW Court of Appeal; decision appealed, but approval still not obtained. Size of resource is not specified. Not included in OZMIN database (Geoscience Australia, Dataset 2).<br>Based on data and information available to the Assessment team as of September 2015, the potential for future commercial production at this site is considered unlikely. |
| Mitchells Flat Project | OC | Glencore | Still in exploration phase as at September 2015.<br>Considered too immature in its development to include as an ACRD. |
| Monash Deposit | OC | Yancoal Australia | Potential new mine. Pre-EIS as of September 2015.<br>Considered too immature in its development to include as an ACRD. |
| Mount Penny Deposit | OC | Cascade Coal | NSW Government suspended exploration licence (EL) in 2014 on recommendation from ICAC. No mining to date.<br>Based on data and information available to the Assessment team as of September 2015, the potential for future commercial production at this site is considered unlikely. |

| Mine | Open-cut or underground | Company | Reasons for not including as an additional coal resource development |
|---|---|---|---|
| Savoy Hill | UG | NuCoal Resources | Potential new mine. Still in exploration phase.<br>Considered too immature in its development to include as an ACRD. |
| Spur Hill Project | | Malabar Coal | Potential new mine. DGRs issued in July 2014. No EIS submitted (September 2015). Environmental and engineering studies continuing.<br>Considered too immature in its development to include as an ACRD. |

DGRs = Director General Requirements (for the environmental assessment to be prepared by the proponent, EIS = environmental impact statement, EL = exploration licence, ICAC = Independent Commission Against Corruption

**Figure 16 Mines not included in the coal resource development pathway (CRDP) as additional coal resource development**

The listed coal resource developments were deemed unlikely to proceed or too uncertain to include as additional coal resource developments (ACRDs). The mines in the coal resource development pathway (CRDP) are the sum of those in the baseline and the ACRD. The ACRD is all coal mines and coal seam gas (CSG) fields, including expansions of baseline operations that are expected to begin commercial production after December 2012.
Data: Bioregional Assessment Programme (Dataset 1)

### 2.3.4.1.4 Coal resource development pathway

The mines in the CRDP comprise the baseline mines in Table 7 and those identified as additional coal resource developments in Table 9. As stated in Section 2.3.4.1.1 (see Table 8) and Section 2.3.4.1.2 (see Table 10), not all mines in the CRDP have enough data or information to be quantitatively assessed through surface water and/or groundwater modelling; rather, they will be discussed as commentary only. This section focuses only on those mines in the CRDP that have been included in the surface water and/or groundwater modelling.

The CRDP maximum footprint for surface water modelling is shown in Figure 17 and has been differentiated into its baseline and additional coal resource development parts. The maximum footprint for surface water modelling reflects the largest extent of disrupted surface over the life of the operation, and includes the excavation areas, site facilities and areas affected by drainage changes. Rehabilitation is assumed to commence at the end of coal extraction. The maximum surface water footprint for the mines in the baseline, based on the spatial data obtained for the Assessment, is 463.0 $km^2$ and for the mines in the CRDP is 704.6 $km^2$. This means that the additional surface water footprint from the additional coal resource development is 241.6 $km^2$, a 52% increase on the baseline maximum footprint.

The CRDP maximum footprint for groundwater modelling is shown in Figure 18 and has also been differentiated into its baseline and additional coal resource development components. The maximum footprint for groundwater modelling is represented at the ground surface by the union of the area disturbed by open-cut mining and the area overlying the underground extraction areas. The maximum groundwater footprint for the baseline, based on the spatial data that has been obtained for the BA, is 598.4 $km^2$ and for the CRDP is 710.7 $km^2$. The additional groundwater footprint at the surface from the additional coal resource developments is 212.3 $km^2$, almost a 35% increase on the baseline maximum footprint. However, the additional coal resource development footprint overlaps the baseline footprint by an additional 80.6 $km^2$. This reflects that some of the proposed developments occur below existing baseline activities. This is important for groundwater modelling, where mine water pumping rates and depths of extractions are more important inputs than the area of excavation.

Timelines of baseline and additional coal resource development mines are shown in Figure 19 in chronological order. These timelines provide a future snapshot of the intensity and duration of mining in the Hunter subregion. Although some mines were operating prior to 1980, Figure 19 shows the period relevant to the BA numerical modelling. Baseline developments extend out to 2039 (at Ravensworth Complex), while the CRDP includes mining developments that extend to 2046 (at Wallarah 2).

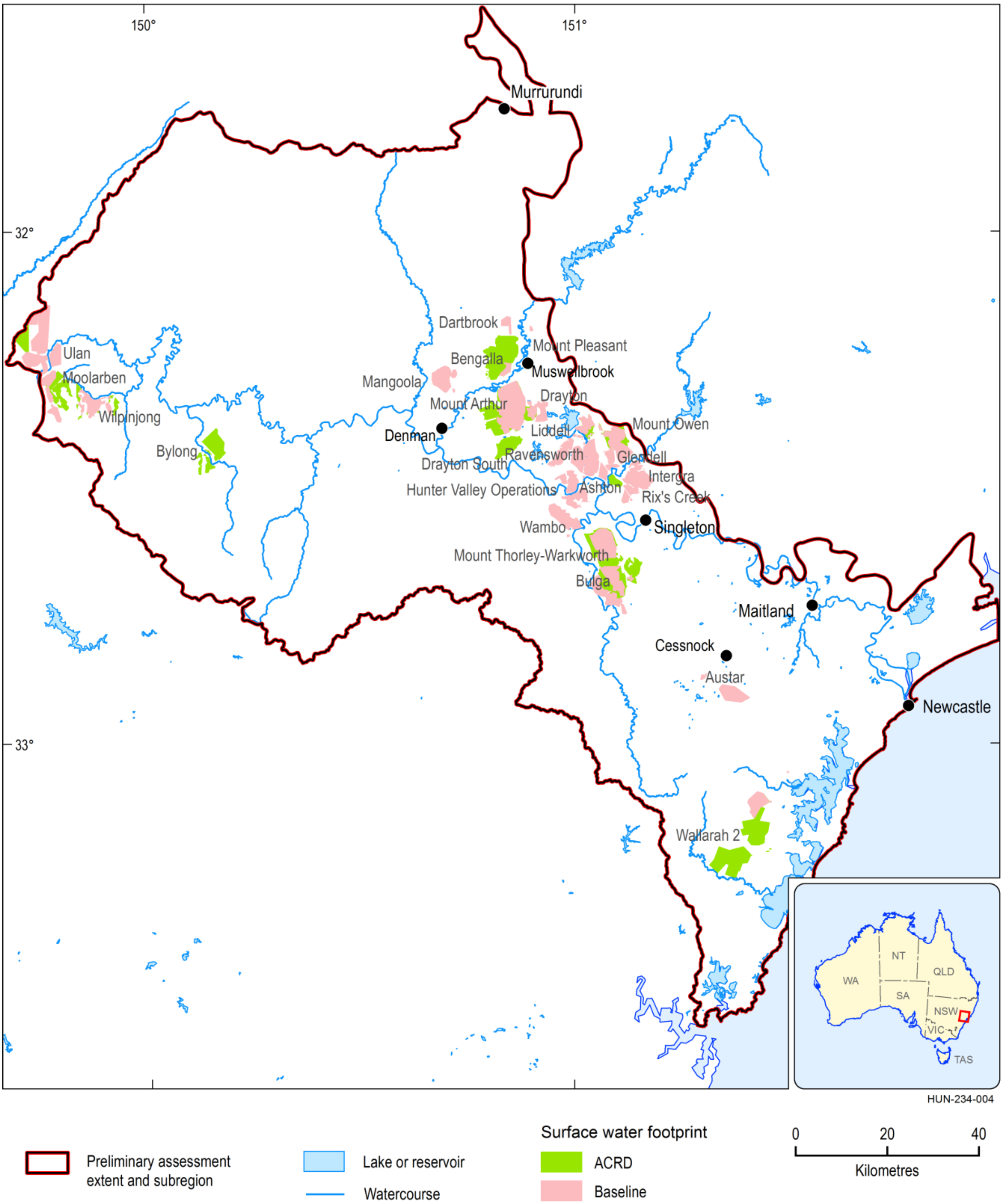

**Figure 17 The maximum mine footprint for coal resource developments in the coal resource development pathway that are included in the surface water modelling**

The maximum footprint of the coal resource development pathway (CRDP) is the union of the footprints for the baseline and additional coal resource development.
Data: Bioregional Assessment Programme (Dataset 3)

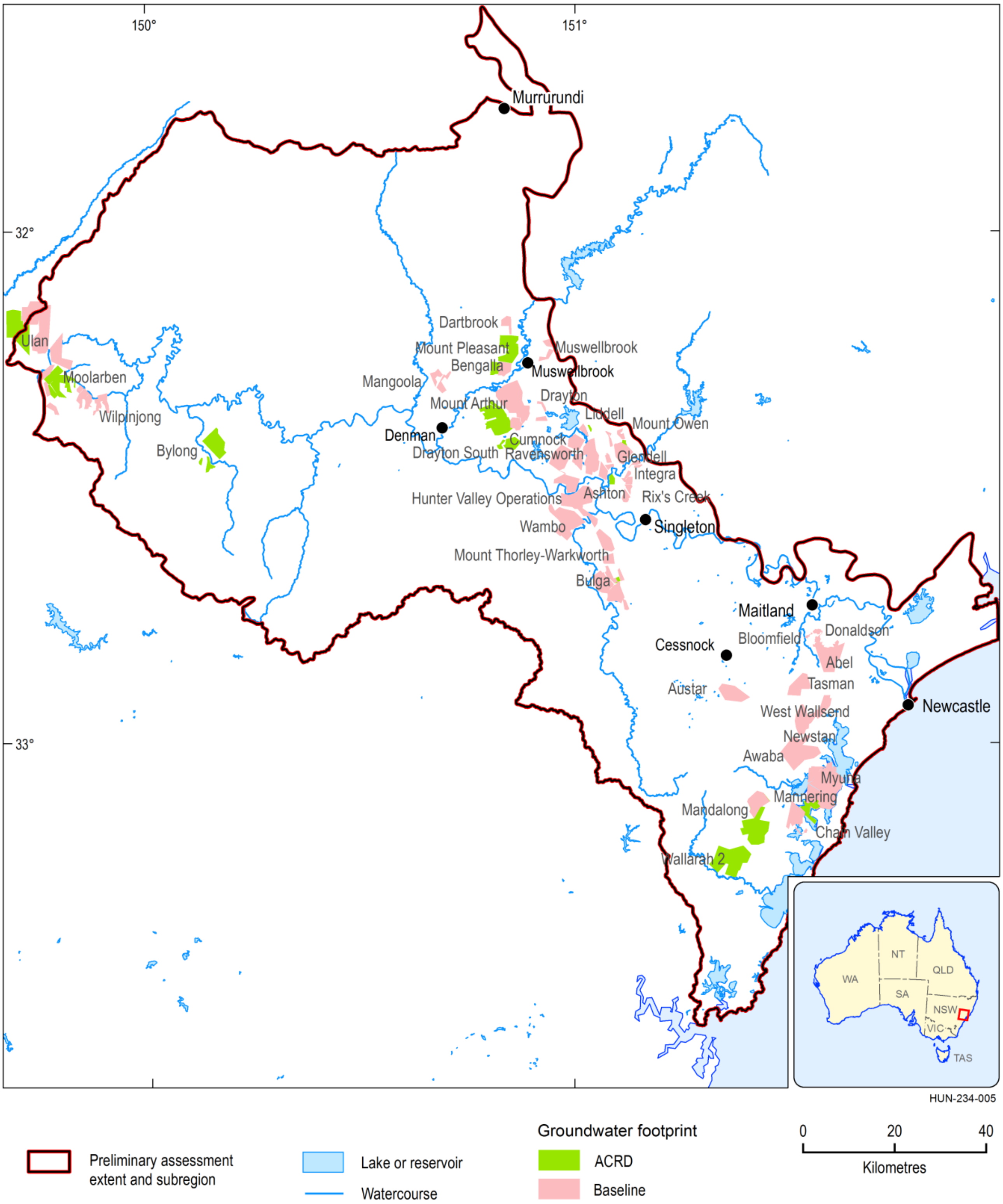

**Figure 18 The maximum mine footprint for coal resource developments in the coal resource development pathway that are included in the groundwater modelling**

The maximum footprint of the coal resource development pathway (CRDP) is the union of the footprints for the baseline and additional coal resource development.
Data: Bioregional Assessment Programme (Dataset 4)

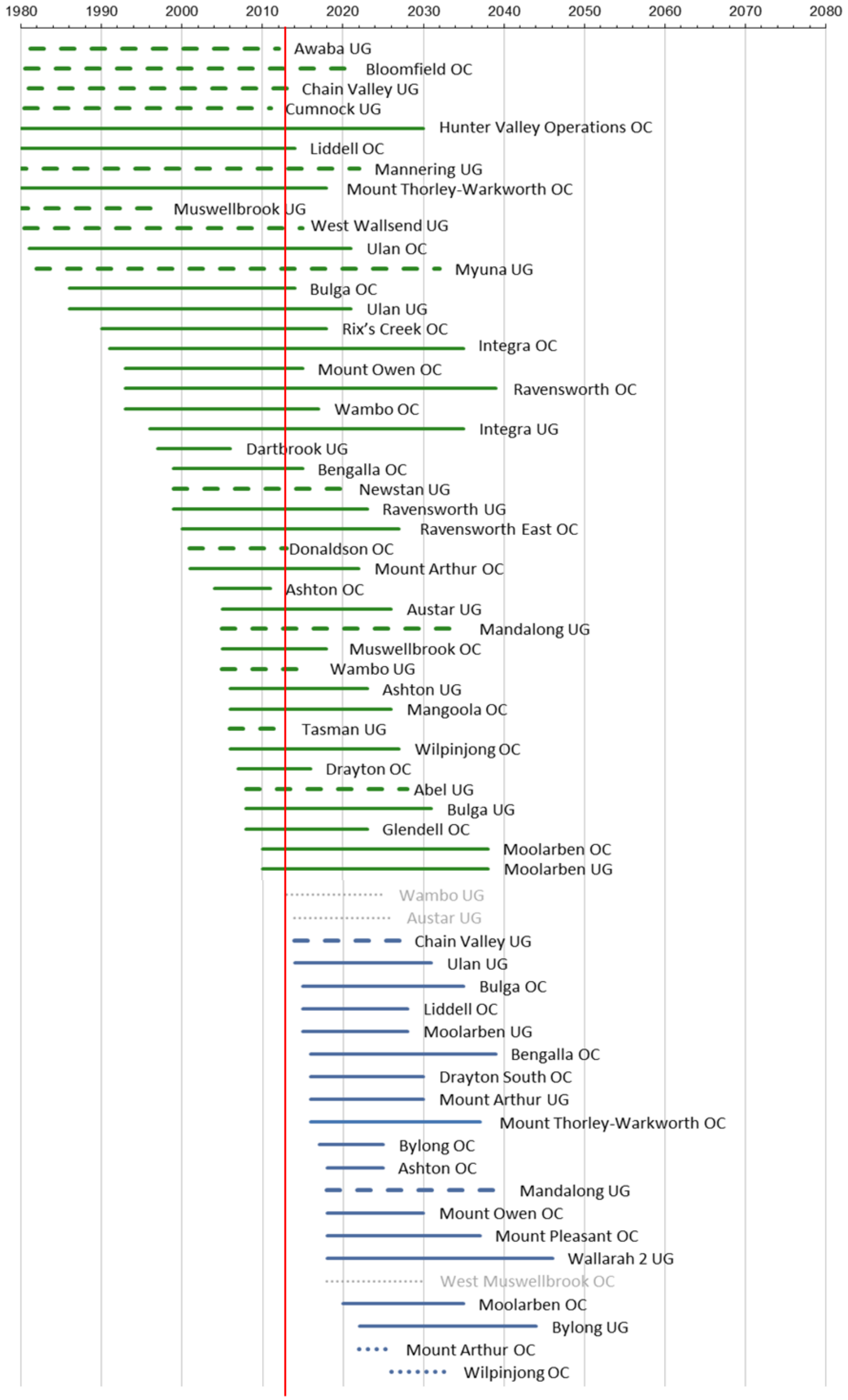

**Figure 19 Timeline for coal resource developments in the coal resource development pathway**

Green = baseline, blue = additional coal resource development, red line = December 2012, light grey = not modelled, dashes = groundwater model only, dots = surface water model only, OC = open-cut, UG = underground
The dates reflect the expected period of coal extraction and may not coincide precisely with the dates used for mine pumping in the modelling.
Data: Bioregional Assessment Programme (Dataset 5)

### *2.3.4.2 Water management for coal resource developments*

This section summarises the general characteristics of mine water management in the Hunter subregion in the context of the existing Commonwealth and NSW regulatory framework for managing on-site water to minimise impacts off site, as detailed in Table 12. It identifies the common elements that are important to inform the representation of the effects of mining operations on regional hydrology. It makes a connection between specific mine activities and the groundwater and surface water pathways that can lead to an off-site impact (discussed in more detail in Section 2.3.5). Mine-specific data used in the groundwater and surface water modelling such as start and end dates, mine footprints, flow rates, pumping depths, discharge rules, and surface water extractions, are provided in companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018a).

During all life stages of a mine from construction, production and through to mine closure and rehabilitation, the water balance of the mine site and surrounding areas can be affected. Changes at the land surface through clearing of vegetation and disturbance of top soil in developing the mine site, as well as changes in the fluxes of water between water stores during mine operations, have implications for the quality of water. In particular, the disposal of lower quality groundwater from worked seams has the potential to degrade the quality of receiving waters, for example, if discharged to the stream network. Runoff from areas disturbed at the surface can often be sediment laden and carry other impurities. Minimising the discharge of low-quality water to the wider environment and ensuring the mine has sufficient water of sufficient quality for on-site uses, whether that be for human consumption, coal washing, dust suppression or irrigation, are key objectives of mine water management.

In NSW coal mining began near Nobbys Head in Newcastle in the 1790s, with the first coal shipment leaving Newcastle in 1799 (NSW Minerals Council, 2016). Over that time policies, legislation and practices have developed to manage the impacts of mining developments both on and off the mine site. Mines are required to prepare mine water management plans that demonstrate how they will ensure their activities minimise the negative consequences on the environment from extraction and use of water, both in terms of quantity and quality of water. The policy/management context defines operating rules which can be used to inform the modelling of mine impacts. It is assumed that policies are adhered to and that generalisations about mine water management can be made that apply to all mines; however, this section notes any mines known to significantly depart from the generalisations.

The key legislation and policies that govern the management of water in relation to mining in NSW are outlined in Table 12. They are listed in the order in which they came into effect, although they will usually have had amendments since first enacted.

**Table 12 Legislation and policies governing mine water management in the Hunter subregion**

| Legislation/Policy | Agency | Purpose and relevance to mine water management |
|---|---|---|
| NSW's *Water Act 1912* | DPI Water | Under this Act, a licence or an approval is required by the mine:<br>• to take water from water sources not subject to a water sharing plan<br>• for any 'controlled works' on designated floodplains not covered under *Water Management Act 2000*<br>• to construct and operate some monitoring bores |
| NSW's *Environmental Planning and Assessment Act 1979* (EP&A Act) | Department of Planning and Environment | Mining developments classified as 'State significant development' (SSD), require preparation of environmental impact statements (EIS) / environmental impact assessments (EIA) as part of obtaining development consent. An EIS should include assessment of water related impacts.<br>Extraction plans (formerly subsidence management plans) are required for underground mines that describe how subsidence will be managed to minimise impacts. |
| NSW's *Mining Act 1992* | Department of Industry, Resources and Energy | Part 11 of this Act specifies the various requirements as well as conditions required to conserve and protect the natural environment (flora, fauna, fish, fisheries, scenic attractions, features of Indigenous, architectural, archaeological, historical, geological interest) as part of development consent. Also, specifies the conditions and requirements for rehabilitation of the mine sites. |
| NSW's *Protection of the Environment Operations Act 1997* (POEO Act) | Environment Protection Authority (EPA) | Mining operations can produce polluted water and require an environment protection licence (EPL) under Schedule 1 of the POEO Act.<br>An EPL authorises discharges to both surface waters and groundwater, and to land, and contains conditions relating to the concentration limits of those discharges, operating practices, discharge and ambient monitoring and reporting. The EPL may also specify requirements for pollution reduction programs (e.g. for site stormwater management). |
| Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) | Commonwealth Department of the Environment and Energy | Provides the legal framework to protect and manage matters of national environmental significance.<br>The 2013 'water trigger' amendment empowers the Australian Government to approve, refuse and place water-specific conditions on large coal resource developments that are likely to significantly impact water resources. |
| NSW's *Water Management Act 2000* | DPI Water | Under this Act, a licence or an approval is required by the mine:<br>• to take water for water sources where a statutory water sharing plan is in place<br>• to construct and use a water supply work (e.g. bore or pump) and ensure that the infrastructure has minimal impact on local stream flows, natural drainage, and groundwater resources<br>• to define the purpose for which water taken under a water access licence will be used<br>• to carry out an activity on or under waterfront land such as installation of flow gauging stations, or other structures within 40 m of the high bank of any river, lake or estuary |
| NSW's *Protection of the Environment Operations (Hunter River Salinity Trading Scheme) Regulation* 2002 | Environment Protection Authority (EPA) | Under this regulation, mines on the Hunter River below Glenbawn Dam and upstream of Singleton, require an EPL to discharge saline water to the Hunter River. |

| Legislation/Policy | Agency | Purpose and relevance to mine water management |
|---|---|---|
| NSW's Aquifer Interference Policy (DPI Water, 2012) | DPI Water | Defines the regime for protecting and managing the effects of aquifer interference activities on NSW's water resources. |

Data: DPE (2015)

The Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) empowers the Australian Government to approve, refuse and place conditions on actions that are likely to have a significant impact on matters of national environmental significance, including world heritage properties, national heritage sites, wetlands of international importance, Commonwealth marine areas, listed threatened species and ecological communities. In 2013, under the 'water trigger' amendment, the definition of matters of national environmental significance was expanded to include water resources, in relation to CSG and large coal mining developments. Thus, since 2013, approval is required from the Australian Government Minister for the Environment (now Minister for the Environment and Energy) if a proposed development is likely to have a significant impact on water resources. Guidelines were published in late 2013 to assist coal mining proponents to decide whether an impact is likely to be significant (Commonwealth of Australia, 2013).

Projects that are deemed likely to have a significant impact on water resources are referred to the Independent Expert Scientific Committee (IESC), established in 2012 to provide scientific advice to the Australian Government Minister for the Environment and State regulators on the impacts of proposed large-scale developments on matters of national significance. BAs, such as this one for the Hunter subregion, are being undertaken to strengthen the science underpinning decision-making around actions that are likely to significantly impact water resources.

Prior to this, mine water management was predominantly a state matter. The other legislation and policies listed in Table 12 are NSW regulatory instruments for protecting water resources and water-dependent assets in NSW from developments, including CSG development and coal mining. NSW's *Mining Act 1992* makes provision for the protection of the environment in the course of mining. The definition of environment encompasses ecological and sociocultural assets, which are in or on the land over which authority or claim is sought (Part 11, section 237(1)). Under this Act, the Minister may require environmental impact studies to be carried out.

Under NSW's *Environmental Planning and Assessment Act 1979*, major developments, including mining, must prepare environmental impact statements (EIS) / environmental impact assessments (EIA) detailing the impacts to natural and human environments and the options to minimise damage for consideration by the regulatory authority and the public in making a determination. Mining EIAs must assess the changes to surface water and groundwater and include a mine water management plan and rehabilitation planning documents, which satisfy the Minister that the impacts of the mine on water resources during and following mine closure are minimised. For underground operations, modern development consents require the preparation of an extraction plan that describes how impacts of subsidence will be managed to meet the requirements of the development consent. With respect to water resources, these extraction plans are particularly concerned with identifying and managing the risks to surface water courses and alluvial aquifers, but may also consider effects on drainage more generally through interception of rainfall and runoff in subsidence-induced depressions.

A typical mine water management plan in the Hunter subregion provides details of expected pumping rates from the open-cut or underground workings, runoff diversions and on-site water storage, discharge locations to the river network, on-site water treatment, requirements for clean water and post-mining hydrology following rehabilitation. Figure 20 illustrates the mine water management system for the Bulga Coal Complex, which comprises both open-cut and underground operations. It includes a combination of permanent structures that will continue to operate post closure and temporary structures that will only be required until the completion of rehabilitation works. Various components of water management at the Bulga Coal Complex are:

- four main water storage areas (Vaux Pit, Bayswater Pit, Coal Handling and Preparation Plant (CHPP) Surge dam and Dam 13) with total storage capacity of up to approximately 5400 ML
- Dam C3 with capacity of 21 ML to capture surface runoff from coal handling process plant, workshops, run of mine (ROM) pad areas
- clean water catchment areas upstream of mining with diversion channels. Water is collected and pumped to an unnamed tributary of Nine Mile Creek
- sediment dams to collect surface water runoff from mine disturbance areas and transferred to main storage areas through pipelines
- discharge locations under the Hunter River Salinity Trading Scheme (HRSTS)
- proposed and current mine rehabilitated areas in order to repair the impact of mining on the environment.

For modelling the effects of mine developments on regional scale hydrology, the specifics of water movements on site are not necessary. Instead it is the changes in fluxes to and from the site as a consequence of mining development that need to be quantified and spatially represented.

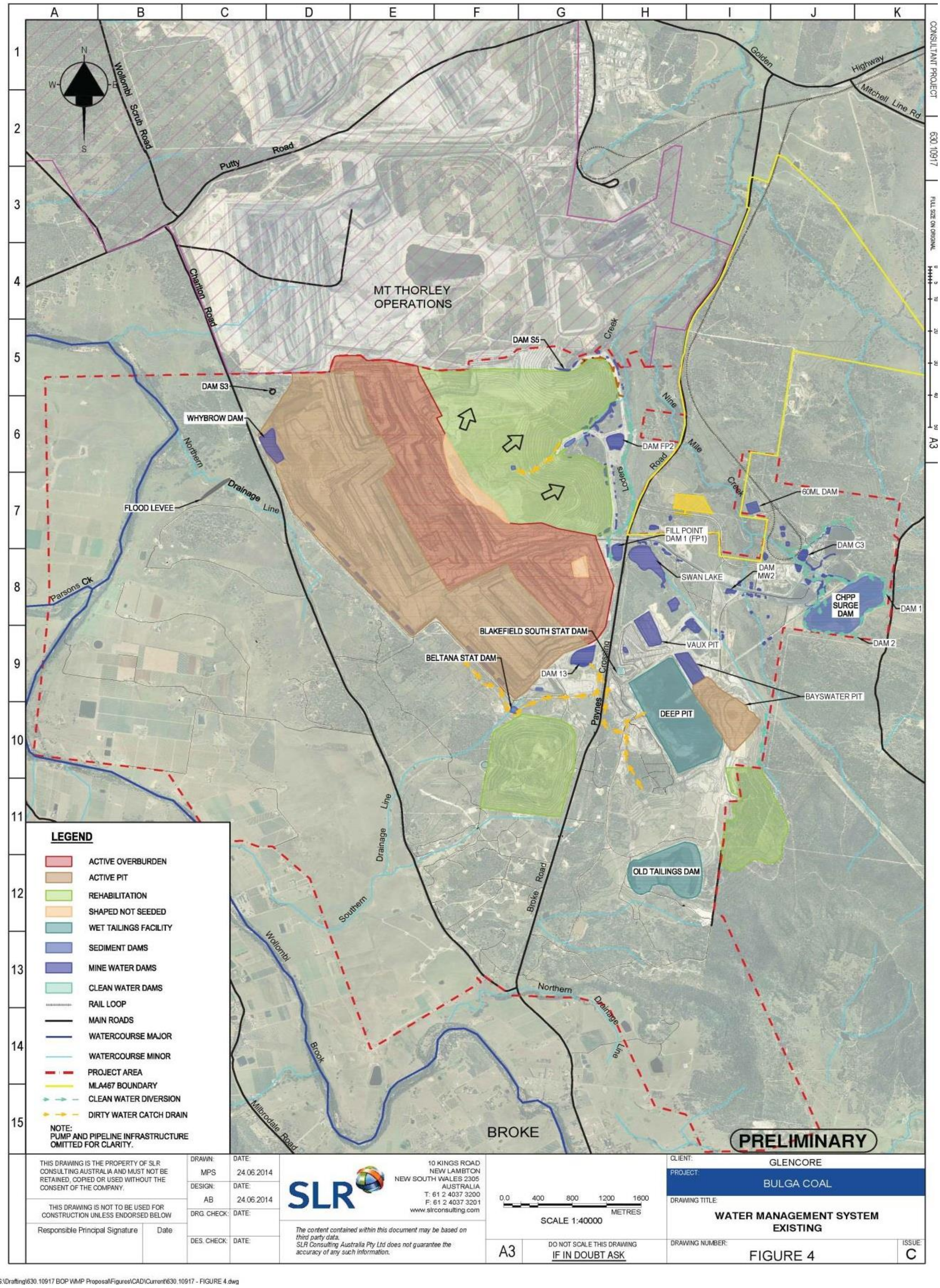

**Figure 20 Bulga Coal Complex water management system**

Source: Glencore (2015)

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The following generalisations are used to inform hydrological modelling of the Hunter subregion. They reflect regulatory requirements relating to mine site water management and are assumed to be reflected in practice. Details of the numerical model development and the modelling assumptions that relate to the representation of the hydrological changes from coal resource development can be found in companion product 2.6.1 (Zhang et al., 2018), companion product 2.6.2 (Herron et al., 2018b) and companion product 2.1-2.2 (Herron et al., 2018a) for the Hunter subregion.

1. Mine working areas are largely isolated from the wider surface water drainage network early on in the development process through construction of diversion drains.
2. Rain that falls on the mining area is retained on site.
3. Groundwater pumped from mine workings is retained on site, unless the mine has an environment protection licence (EPL) which entitles it to discharge it from site. Managing mine water make to minimise pollution of surface water and groundwater resources is a key aspect of site water management. Retained water is used on-site for mine and coal processing water requirements or, in some cases, irrigation (e.g. Ulan). It may need to be treated for other uses. Ultimately it is lost to evaporation and seepage.

For surface water modelling, the foregoing are interpreted to mean that all runoff generated on site, including from undisturbed areas, which are intercepted by a mine dam, is retained on site. For groundwater modelling, mine water make is only discharged to the river if the mine has a licence to do so. The modelling ignores unintended spills and leakage from on-site storages, which are assumed to be sufficiently dealt with through the approvals process and conditions imposed on mine-site operations. For river modelling purposes, rules to reflect the operation of the HRSTS need to be incorporated into the model construction.

4. At mine closure following open-cut mining, a void is left in the final landform, unless stated otherwise in mine rehabilitation plans.

This is traditional practice, particularly for mines with low overburden to coal ratios (such as those in the Hunter Valley). The void acts as a local sink for both surface water and groundwater, and if the void is large enough, the evaporation will continue to drive the groundwater flow into the void and the local and regional groundwater may never fully return to pre-mining conditions (Mitchell, 2009). Leaving final voids is an increasingly controversial practice, and the requirement for mines to undertake complete rehabilitation of open-cut mines is probably becoming more common. Companion products 2.1-2.2 and 2.6.1 for the Hunter subregion (Herron et al., 2018a; Zhang et al., 2018) provide details of how final voids are specified in the surface water modelling.

5. Rehabilitation of open-cut mined-out areas is typically progressive, with worked areas being infilled, landscaped and re-vegetated as the pit faces advance. Thus, the hydrological changes from mining disturbance can vary over the life of mine. However, the normal practice is for surface water diversions to be removed and drainage returned to a pre-disturbance state at the end of mining whenever and wherever this is possible (DITR, 2006).

For modelling purposes, rehabilitation is assumed to commence following the cessation of mining (rather than represented progressively) and the effects of mining on surface water are sustained for a defined period, before being reduced over time to a pre-disturbance level.

The amount of runoff retained on site will vary significantly between open-cut and underground mine operations. Generally, a larger surface area is disturbed during open-cut mining than for underground mining; thus, there will be bigger changes in surface water hydrology from open-cut mines than from underground mines. However, underground mines can cause subsidence at the land surface and changes in the hydraulic properties of subsurface layers, leading to increased interception of runoff in the area of subsidence. Since mining consent in NSW is contingent on minimising the negative effects of subsidence, as specified through an approved extraction plan, for modelling purposes the reduction in surface runoff from areas above longwall mines is assumed to be 5% during and following the cessation of mining. Details are reported in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018).

In NSW, surface water extracted from rivers and used on site has to be licensed under NSW's *Water Act 1912* or NSW's *Water Management Act 2000*. Extractions from the stream network are modelled in the Australian Water Resources Assessment river model (AWRA-R), based on patterns of extraction for irrigation and mining from NSW DPI Water. Details are provided in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018).

Similarly, the removal of groundwater from mine workings and extractions of groundwater from production bores have to be licensed under the NSW *Water Act 1912* or NSW *Water Management Act 2000*. The amount of groundwater extracted from mine workings can vary significantly between mines, depending on the hydrogeology of the worked area, including volumes of stored water and hydraulic conductivity and connectivity between the different stratigraphic layers. Modelling of groundwater changes, undertaken by the mining companies as part of their EIAs, is used to estimate likely flow rates and requirements for water access licences. Flow rates (licensed volumes of water pumped from the mine workings) have been obtained from mine water management reports for each mine represented in the baseline and CRDP in the groundwater model (see companion product 2.6.2 for the Hunter subregion (Herron et al., 2018b)) and are provided in companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018a).

Groundwater pumped from the mine workings is often of lower quality than surface water. In the Hunter subregion this can be due to the marine origins of the groundwater and/or the accumulation of leachates as recharge water percolates the regolith and rock formations. Discharges of low quality water from mining operations need to be managed carefully. NSW's *Protection of the Environment Operations Act 1997* (POEO Act) protects the quality of the environment in NSW from pollution. Mining, coal working and coking are scheduled activities under this Act and require an environmental protection licence (EPL) to discharge off-site. The NSW Environment Protection Authority, who administers the Act, can stipulate the conditions relating to pollution prevention and monitoring on mine sites as part of their EPL, including:

- mine water discharge volumes to water bodies (such as lakes, river, creeks) and land
- concentration limits for various water quality parameters for discharge mine water
- site water management operating practices
- discharge and ambient monitoring and reporting.

To ensure that discharges to the river do not exceed specified thresholds, mines may have to treat low quality water to the required standard prior to discharge. Not all mines will necessarily have an EPL to discharge water. Without a licence, discharges to the stream network are not permitted.

In the Hunter river basin, the *POEO (Hunter River Salinity Trading Scheme) Regulation* 2002 was enacted to specifically manage the potentially large volumes of low water quality discharges from the high concentration of industrial developments in the regulated part of the Hunter River between Glenbawn Dam and Singleton. It provides for discharges of mine water off-site during periods of high river flow. Under the regulation, mines and power stations within the HRSTS area are required to purchase credits under licence from the NSW Environment Protection Authority to discharge saline water to the Hunter River. There are a total of 1000 salt discharge credits in the scheme, 200 of which expire every two years and are redistributed via public auction. Credit holders (mines and power stations) and their credits as of 23 February 2016 are listed in Table 13. Flows in the Hunter River are notionally divided into blocks, a body of water that flows down the Hunter River that is predicted to pass through the lower sector reference point (gauging station at Singleton) in a 24-hour period. During high flow, each participant is entitled to discharge a share of the total allowable discharge on each block according to the number of salt credits they hold. The AWRA-R model used in the Hunter BA to model Hunter River flows incorporates rules to represent mine discharges under the HRSTS (see companion products 2.1-2.2 and 2.6.1 of the Hunter subregion (Herron et al., 2018a; Zhang et al., 2018)). Coal resource developments, such as the proposed Bylong mine, and the Moolarben, Wilpinjong and Ulan mines, which are upstream of Kerrabee in the Goulburn river basin and are not part of the Hunter River Salinity Trading Scheme, require an EPL under the *POEO Act 1997* to discharge off site.

**Table 13 Hunter River Salinity Trading Scheme licence holders and credit allocations (as of 23 February 2016)**

| Licence holder | River sector | Number of credits |
|---|---|---:|
| Bengalla Mine | Upper | 30 |
| Dartbrook Coal Mine | Upper | 10 |
| Mangoola Coal | Upper | 20 |
| Mount Arthur Coal | Upper | 13 |
| Bayswater Power Station | Middle | 233 |
| Hunter Valley Operations | Middle | 146 |
| Liddell Colliery Holding | Middle | 72 |
| Mt Owen Complex | Middle | 11 |
| Narama Mine (Ravensworth Complex) | Middle | 170 |
| Mount Thorley Operations | Lower | 94 |
| Redbank Power Station | Lower | 36 |
| Saxonvale Colliery Holding | Lower | 54 |
| Wambo Mine | Lower | 48 |
| Warkworth Colliery Holding | Lower | 48 |
| Mount Arthur North Mine | Not in a sector | 10 |
| Mount Owen Coal Mine | Not in a sector | 3 |
| United Colliery | Not in a sector | 2 |

Data: EPA (2016a)
This table lists the name of the Hunter River Salinity Trading Scheme (HRSTS) participants as given on the NSW Environment Protection Authority’s HRSTS website and they may not be the mine name.

Some examples of EPL conditions attached to mines in the Hunter subregion are provided to illustrate differences between Hunter River Salinity Trading Scheme (HRSTS) participants and non-HRSTS mines:

- Bulga Coal Complex operates under EPL 563 (Glencore, 2015) and is part of the HRSTS. As per EPL 563, pH of mine water discharge should be between 6.5 and 9.5 and concentration of total suspended solids (TSS) should be less than 120 mg/L. The discharge under the HRSTS from Dam 3 and CHPP Surge Dam should not exceed 55 ML/day and 130 ML/day respectively (EPA, 2016b). Locations of surface water monitoring points, frequencies and parameters to be recorded at the discharge points are also stipulated in the EPL.
- Hunter Valley Operations operates under EPL 640 and is part of the HRSTS. EPL 640 requires that the pH of discharge mine water be between 6.5 and 9.5; TSS concentrations should be less than 120 mg/L at discharge points 3 and 4; and the electrical conductivity of water should be less than 400 µS/cm at discharge point 5. Allowable discharge volumes under the HRSTS range from 100 ML/day (Point 3) to 130 ML/day (Point 4), and 7 ML/day to alluvial

lands (EPA, 2016c). Locations of surface water monitoring points, frequencies and parameters to be recorded at the discharge points are also stipulated in the EPL.

- Ulan Coal Mine operates under EPL 394 and is not part of the HRSTS. The EPL specifies seven discharge points, including three discharge locations for Ulan Creek and one for land (irrigation) (EPA, 2016d). In EPL 394, concentration limits for pH, iron, zinc, oil and grease, TSS and discharge volumes at various points to land (irrigation), unnamed watercourse and Ulan Creek were stipulated. Locations of surface water monitoring points, frequencies and parameters to be recorded during discharge events at the discharge points are also stipulated in the EPL 394 for Ulan Coal Mine.

Mines that are not part of the HRSTS can trade their saline water with the HRSTS credit holders through a water sharing agreement. Examples are:

- Drayton Mine, which does not have any EPL to discharge mine water to the river, but has a water sharing agreement with Mount Arthur Coal Mine to transfer up to 600 ML/year of excess mine water (Anglo Coal, 2010).
- Ashton Coal Mine, which does not hold an EPL for discharging mine water, but has a water sharing agreement with the Glennies Creek Mine (now called Integra) for the supply of up to 900 ML/year of mine water from the operations (Ashton Coal, 2015).
- Hunter Valley Operations, a HRSTS participant, which has a water sharing agreement to transfer water to and from Liddell (Glencore) and Wambo (Peabody) mines (Rio Tinto, 2015).

Water transfers between mines owned by different companies are managed through formal agreements. Transfers of water between mines operated by the same company do occur. These movements of water are not regulated by the Environment Protection Authority. For assessing regional-scale hydrological changes, these transfers are assumed to be water retained on site.

This section has provided an overview of the regulatory framework governing mine water management in the Hunter subregion and identified the key elements needed to inform representation of hydrological effects of mines in the quantitative modelling in companion products 2.6.1 and 2.6.2 for the Hunter subregion (Zhang et al., 2018; Herron et al., 2018b).

Mine-specific water management data, used to represent individual mines in the modelling, are detailed in Section 2.1.6 of companion product 2.1-2.2 for the Hunter subregion (Herron et al., 2018a).

### *2.3.4.3 Gaps*

The additional coal resource developments included in the CRDP reflect the Assessment team’s best assessment of the most likely future in September 2015. There are no gaps per se, just uncertainty about if and when some of the additional coal resource developments will go ahead.

The additional coal resource developments for which data are not available represent a gap in the quantitative assessment of hydrological changes undertaken in the surface water modelling (companion product 2.6.1 (Zhang et al., 2018)) and groundwater modelling (companion product 2.6.2 (Herron et al., 2018b)). Qualitative assessments of the potential hydrological changes of these developments and potential impacts on landscape classes and assets are reported in companion product 3-4 for the Hunter subregion (as listed in Table 2).

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## 2.3.5 Conceptual modelling of causal pathways

### *Summary*

Causal pathways are the logical chain of events –either planned or unplanned – that link coal resource development and potential impacts on water resources and water-dependent assets. In the Hunter subregion, the hazards stem from open-cut and underground coal mining operations; there are no existing, approved or planned coal seam gas (CSG) development activities.

Coal mining operations can affect surface water resources through land subsidence, interception of runoff, extraction from and disposal to surface water features, and depressurisation of aquifers. Both water quantity and water quality may be adversely affected by these hazards. Changes in water quantity are the focus of the bioregional assessments (BAs), but implications for stream salinity are considered as part of the analysis in the impact and risk analysis (companion product 3-4 for the Hunter subregion (as listed in Table 2). Groundwater flows and resources can be affected by changes in aquifer connectivity, which enable the movement of water between previously disconnected, or weakly connected, aquifers. Mining voids that are left, or backfilled, may act as sinks for water flows, or as contamination sites for surface water or groundwater resources.

The hazard analysis for the Hunter subregion identified and scored 271 hazards. The top four hazards (listed with the syntax [Activity]:[Impact mode]) identified are in the production life cycle stage and include: (i) Waste rock blasting, excavation and storage: Disruption of natural surface drainage: Pit expansion; (ii) Longwall coal extraction: Subsurface fractures (create new, enlarge or existing); (iii) Mine dewatering, treatment, reuse and disposal (multi-seam mining): Incremental, mine water increase (unplanned) – from old workings; and (iv) Longwall coal extraction: Subsidence, which is related to (ii).

Hazards associated with open-cut and underground mining operations were grouped into four main causal pathway groups that represent the causal pathway via which each hazard potentially impacts water resources and water-dependent assets on and off site. These four causal pathway groups are: 'Surface water drainage', 'Operational water management', 'Subsurface depressurisation and dewatering' and 'Subsurface physical flow paths'. For the 'Surface water drainage' and 'Operational water management', hazards associated with open-cut and underground coal mines affect surface water flows primarily through modifications to surface water drainage and water management systems; hazards that impact groundwater flows do so through subsurface depressurisation and dewatering and modification of subsurface physical flow paths.

### *2.3.5.1 Methodology*

Conceptual models of causal pathways are a specific type of conceptual model which characterises the *causal pathways*, the logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water resources and water-dependent assets.

These conceptual models bring together the existing understanding and conceptual models of the key system components, processes and interactions for the geology, hydrogeology, surface water, and surface ecosystems, and consider the most plausible and important impact and their spatial and temporal context. The conceptual modelling draws heavily on companion products from Component 1: Contextual information, which is summarised in Section 2.3.2, Section 2.3.3 and Section 2.3.4.

The causal pathways underpin the construction of groundwater and surface water models, and frame the assessment of the impacts on and risks to water and water-dependent assets. The approach taken in the Hunter subregion has leveraged existing NSW based resources and knowledge of geological, surface water and groundwater conceptual models. The Assessment team summarised the key system components, processes and interactions for the geology, hydrogeology and surface water of the subregion at the 'Conceptual modelling of causal pathways' workshop held in Newcastle in August 2015. Discussion with representatives at the workshop focused on the description of the causal pathways, the testing of knowledge gaps and uncertainties identified by the Assessment team, and the identification of potentially impacted landscape classes. Hazards associated specifically with CSG development were not covered in the Hunter hazards workshop, as CSG development is not part of the coal resource development pathway (CRDP) for the Hunter subregion.

In a BA, the identification and definition of causal pathways is supported by a formal hazard analysis, known as Impact Modes and Effects Analysis (IMEA) as outlined in companion submethodology M11 (Ford et al., 2016) and illustrated in Figure 5 (Section 2.3.1). The causal pathways are based on the outcomes of this hazard analysis and current understanding of the way ecosystems and landscape classes in the Hunter subregion work and interact. The IMEA rigorously and systematically identifies potential *hazards*, defined as events, or chains of events, that might result in an *effect* (change in the quality and/or quantity of surface water or groundwater). Only hazards identified through the IMEA process are considered further in the BA. Additionally, the IMEA considers all the possible ways in which activities may lead to effects or impacts, before assessing the severity, likelihood and detectability of such impacts under current controls through structured scoring.

Key to the IMEA for the Hunter subregion was identifying *activities*, planned events associated with open-cut and underground mining operations. Activities are grouped into *components*, which are grouped into *life-cycle stages*. It is important to assign activities to their appropriate life-cycle stage because the scale and duration of similar activities can be different for each life-cycle stage, which is reflected in the scores for severity and/or likelihood of the impacts resulting from these activities.

Activities for open-cut and underground coal mines are separated into five life-cycle stages and four components:

- life-cycle stages: (i) exploration and appraisal, (ii) development, (iii) production, (iv) closure, and (v) rehabilitation
- components: (i) open pit, (ii) underground mine layout, (iii) surface facilities, and (iv) infrastructure.

An *impact cause* is an activity (or aspect of an activity) that initiates a hazardous chain of events. An activity can have undesirable effects (such as water extraction that leads to groundwater drawdown, reduction in baseflows, more frequent episodes of inter-pool connectivity and loss of species richness or abundance) and desirable effects (such as water extraction enabling coal extraction to occur and providing water for other on-site uses).

An *impact mode* is the manner in which a hazardous chain of events could result in an effect. There might be multiple impact modes for each activity or chain of events. The impact modes may arise through various mechanisms, including anthropogenic activities that are planned and expected to occur as part of operations; unplanned events due to human error or infrastructure failure; or through combination with external factors (e.g. heavy rainfall or floods).

A simple example for open-cut mines is illustrated in Figure 5(a), initiated by 'dewatering down to coal seam for an open-cut mine', which is the impact cause. The impact mode ('intentional dewatering down to coal seam') leads to the effect ('change in groundwater quantity (drawdown)'), which in turn may result in an ecological impact, 'reduced groundwater availability for a groundwater-dependent ecosystem'.

Participants in the Hunter IMEA workshop were invited to identify all plausible hazards and impact modes on an activity-by-activity basis, together with the potential hydrological effects on groundwater and/or surface water. Each hazard is scored with respect to the severity, likelihood and time to detection. The IMEA elicits an interval (upper and lower score) for each hazard that all workshop participants agree upon:

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

Two overarching hazard ranking scores are calculated:

- *hazard score*, the sum of the severity score and likelihood score
- *hazard priority number*, the sum of severity score, likelihood score and detection score.

It is important to emphasise that despite the use of severity scores and likelihood scores, the hazard ranking scores do not provide an absolute or even relative measure of risk. IMEA provides a relative rank of hazards. The value of this analysis lies in the systematic and thorough identification of hazards and in their ranking relative to each other. Hazards with higher scores do not imply that the risks associated with those potential hazards are in some way significant or apply equally across the Hunter subregion at all times, only that it is important that these hazards (along with many others) are considered for inclusion in the BA.

There is considerable structure and hierarchy within these lists of IMEA hazards (Bioregional Assessment Programme, Dataset 1) with the finer-level hazards aggregating to successively coarser resolutions. For example, there are a range of activities that may require the removal of site vegetation (the impact cause), including site clearance prior to construction of pits, storage ponds, site processing plants, water treatment plants, and the construction of access roads and pipeline or infrastructure networks; these may all potentially result in changes to surface water quality from soil erosion following heavy rainfall (impact mode).

The hazards identified by the IMEA represent a conceptual model of the chain of events that begins with an activity and ends with a potential impact on groundwater or surface water; causal pathways include these chains of events and also extend to resulting ecological impacts (see Figure 5). Causal pathways are considered for open-cut and underground coal mines separately, for both the baseline coal resource development (baseline) and the coal resource development pathway (CRDP). A full suite of generic causal pathways for hazards due to coal mining operations is presented in figures in an appendix in companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016). These figures identify activities, impact causes and impact modes as well as those aspects of surface water and groundwater that might be affected. The causal pathways in the submethodology are generally applicable to all subregions or bioregions; Section 2.3.5.3 presents specific results for the Hunter subregion.

Hazards are grouped for the Hunter subregion if they have the same causal pathways, even if those hazards occur because of different activities, at different life-cycle stages, or at different intensities. This smaller set of causal pathway groups provides a useful starting point for summarising and representing the causal pathways associated with coal resource development (e.g. through influence diagrams) and focusing on those causal pathways that are in scope for BA.

The spatial footprint for the identified hazards and causal pathways identified is a core focus of the conceptual modelling, and is arrived at on the basis of existing knowledge, scientific logic and preliminary hydrological modelling results. An important aspect of that is using those same sources to identify which landscape classes and assets may be affected by a potential hydrological change that arises from those causal pathways, and (equally importantly) which landscape classes and assets will *not* be affected. Throughout the BA, areas that will not be affected are progressively ruled out in order to focus efforts of the Assessment team and ultimately the impact and risk analysis.

### ***2.3.5.2 Hazard analysis***

A hazard analysis was conducted for the Hunter subregion based on the existing and proposed coal mines and their water management outlined in Section 2.3.4.1 and Section 2.3.4.2, respectively. The hazard analysis for the Hunter subregion was undertaken during a one-day workshop on 13 April 2015 with invited representatives from CSIRO, Geoscience Australia, Commonwealth Department of Energy and Environment and the NSW Department of Primary Industries Water (formerly NSW Office of Water), having expertise in coal resource development operations in the subregion or more generally and/or experience from earlier hazard workshops in other regions. The experts worked from a list of hazards that had been compiled during prior hazard workshops in other BA bioregions and subregions, which contributed to the efficiency of the process, ensured consistency with other subregions and assisted in confirming the comprehensiveness of the hazards identified for the Hunter subregion. Hazards associated specifically with coal seam gas development were not covered in the Hunter hazards workshop, as there are no proposals for CSG development in the CRDP for the Hunter subregion.

For the Hunter subregion, 271 hazards were identified and scored as per the IMEA (Ford et al., 2016). Activities were left unscored if they were considered not applicable to the subregion or were not expected to occur at the time of the Assessment. All decisions made during the workshop were recorded.

### 2.3.5.2.1 Open-cut and underground coal mines

Results from the IMEA for the Hunter subregion suggest that the majority of activities associated with open-cut and underground mines could potentially impact the quality of surface water and groundwater through changes in total suspended solids, pollutants (e.g. metals, trace elements, sulfides, phosphorus), total dissolved solids (e.g. salt) and hydrocarbon loads. Some of these water quality impacts could result from the addition (e.g. spillage of contaminants) and/or release of pollutants (e.g. from erosion following vegetation removal; from leaching of mine waste) into the landscape, but many would simply arise from changes in the quantity, timing, pathways and interactions of surface water and groundwater flows. It is these hydrological changes that are the focus of modelling in the BAs. Changes in water quality are not modelled directly, but can potentially be inferred from the hydrological changes.

The hazard scores and hazard priority numbers for each hazard provide indicators of the key hazards in the Hunter subregion, as they reflect the severity and likelihood of a negative impact. Figure 21 lists the top 30 hazards in the Hunter subregion ranked by the mid-point of the hazard priority number range that resulted from the workshop, and then by the mid-point for the hazard score range. The same hazard can be associated with different mine components (e.g. open-cut and underground mines), life-cycle stages (development, production, closure) and/or different effects, where effects are specific hydrological characteristics of surface water and groundwater, including quality, quantity, timing, flow direction and connectivity. The hazards can be broadly grouped according to whether their main effect is to modify surface water drainage, cause leaching of contaminants from waste sites, change the flow paths between aquifers, cause dewatering of aquifers or change discharges to the river.

Excavation of topsoil and mine pits, subsidence above longwall mines, pit backfill and construction of on-site water storages and diversion channels modify surface water drainage and are in the top 30 hazards shown in Figure 21. Other activities with a lower hazard score that modify surface water drainage include removal of vegetation, construction of roads and other mine-site facilities and re-contouring the landscape during site rehabilitation.

Leaching occurs when water extracts certain materials from the medium through which it flows; it may lower the quality of the water and has implications for environmental and agricultural uses that depend on a certain quality of water. Leaching from waste rock dumps, run-of-mine (ROM) plants, coal stockpiles and tailings dams were identified in the highest ranked hazards in the Hunter subregion.

Creating new or enhancing existing connections between aquifers can cause aquifer depressurisation, changes in flow gradients and mixing of different quality waters. It can occur through increased fracturing caused by longwall coal extraction and associated subsidence, mine expansions into alluvial aquifers, installation of groundwater bores and creation of artificial recharge points (e.g. from open-cut mine pits). Five of the highest ranking hazards in the Hunter subregion relate to changes in subsurface flow paths. The full list of hazards (Bioregional Assessment Programme, Dataset 1) includes other hazards that potentially enhance links between aquifers as a result of drilling, coring, pit and shaft excavations and bore leakage.

Deliberate groundwater dewatering undertaken as part of longwall panel construction, longwall coal extraction and open-cut pit wall stabilisation were identified in the top 30 hazards. Unplanned mine water increases from old workings was also identified as an important hazard.

Discharges of treated mine water to the river are hazards as the quality of the water and the timing of releases can differ from the quality and natural flow regime of the receiving water.

Details of the full hazard analysis are available at Bioregional Assessment Programme (Dataset 1). Not all the hazards identified in the IMEA are addressed in the BA for the Hunter subregion. Section 2.3.5.2.2 identifies the hazards that are in scope for the BA for the Hunter subregion and how they are handled, particularly for the purposes of hydrological modelling.

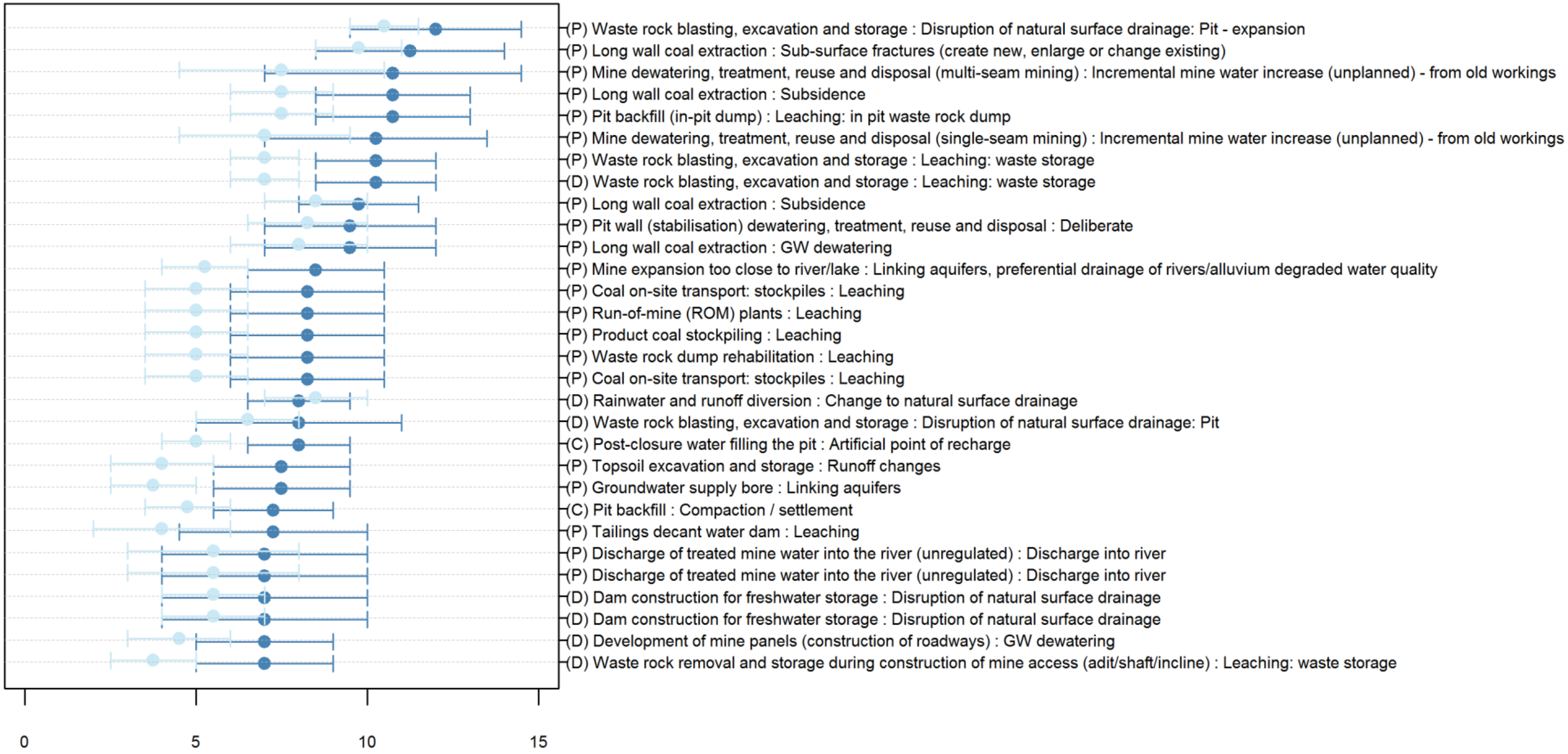

**Figure 21 Highest ranked hazards (and their associated activities and impact modes) for open-cut and underground mines, ranked by midpoint of the hazard priority number**

The x-axis shows the hazard priority number and hazard score for potential hazards. The intervals between the highest and lowest hazard priority number are shown in dark blue; the intervals for hazard score are shown in light blue. The same hazard may appear multiple times, as it may apply to different life-cycle stages (e.g. Waste rock blasting, excavation and storage), or to both open-cut and underground operations (e.g. Discharge of treated mine water into the river; Dam construction for freshwater storage) or be associated with different effects (e.g. Longwall coal extraction: Subsidence). Hazards are listed with the syntax [Life-cycle stage][Activity]:[Impact mode], where life-cycle stages are indicated by (D) for development, (P) for production and (C) for closure.

### 2.3.5.2.2 Hazard handling and scope

Although a long list of hazards has been generated for open-cut and underground coal mining operations as part of BA, not all of the identified hazards are addressed through the BA process. From a BA perspective, the hazards of primary focus are those where impacts may extend beyond the development site and may accumulate with impacts from other mines. This is consistent with the regional focus of BA and is where a BA can add value beyond site-specific environmental impact statements (EIS). However, for every identified hazard, BAs need to be able to define whether it is within scope (i.e. likely to have or contribute to an off-site impact), whether its effects can be quantified using numerical models and/or whether other literature or narratives can be drawn upon to infer an impact. In this way, the BA can identify where science gaps may exist and provide guidance on how they might be overcome.

BAs are constrained by considering only impacts that can happen via water, and so hazards such as dust, fire or noise are deemed out of scope and are addressed by site-based risk management, unless there is a water-mediated pathway.

The BAs are also largely constrained to considering the impacts on water quantity, and not water quality. Site-based risk management procedures are in place to minimise off-site impacts on stream water quality. While stream salinity is not modelled in BAs, it is a significant issue in some subregions, including the Hunter subregion. A qualitative assessment of the potential effects of the modelled hydrological changes on stream salinity is included in the impact and risk analysis (companion product 3-4 for the Hunter subregion (as listed in Table 2)).

In general, leading practice is assumed and accidents are deemed to be covered adequately by site-based risk management procedures and are beyond the scope of BA; for example, the failure of a pipeline is covered by site-based risk management.

Hazards that pertain to the development site but have no off-site impacts are important to acknowledge but will typically be addressed by site-based risk management procedures.

For open-cut and underground coal mines, the following hazards were identified as being out of scope in the Hunter subregion, because they are deemed to be covered by site-based risk management and regulation and contained to the mine site:

- equipment/infrastructure failure (e.g. pipeline failures, plant failures)
- impacts of ground support staff
- leaching/leaking from storage ponds and stockpiles
- loss of containment (due to construction or design, slope failure)
- bore and well construction (integrity, leakage)
- spillages and disposals (diesel, mud, cuttings, fluid recovery)
- vegetation clearance and subsequent soil erosion following heavy rainfall.

Applying these filters to the 271 hazards resulted in 178 of the Hunter subregion hazards being deemed out of scope. This does not mean that they do not impact the water balance, but their impacts can generally be assumed to be contained to the mine site. Section 2.3.4.2 describes mine water management practices in the Hunter subregion, including the various regulatory instruments that define the obligations on mines in relation to minimising off-site impacts from coal resource development. In BAs, it is assumed that the existing regulatory measures are adequate and that mines are adopting best practice.

Of the 93 hazards that were deemed to be in scope because they potentially impact the hydrology off site, 46 can be addressed by the BA numerical modelling. For the remaining 47 hazards that are in scope, which include some that relate to water quality, it will only be possible within this BA to qualify their impacts through a more qualitative assessment.

The hazard priority number or hazard scores indicate the relative importance of the hazard. Hazards with low scores are of lower priority. Hazards have been grouped into the three scope classes identified above: 'out of scope' (assumed to be covered by site-based risk management and regulation), 'model' (can be addressed by numerical modelling within the BA) and 'narrative' (can be addressed qualitatively within the BA). In Figure 22, the hazards within the three scope classes have been classified into hazard priority number classes to show what level of risk based on hazards identified through IMEA process for the Hunter subregion is addressed by the BA and what level of risk has been deemed out of scope, but handled through other control mechanisms. The median hazard priority number for the 'out of scope' hazards is 3, with 147 of these hazards having hazard priority numbers of 5 or less. For the in scope hazards, the median hazard priority number for the 'model' hazards is 5.1 (mean 5.5), while the median hazard priority number for the 'narrative' hazards, which can be assessed through narrative, is 5.5 (mean 5.1). This indicates that the hazards addressed by the BA tend to be higher priority than many of the hazards that are deemed out of scope.

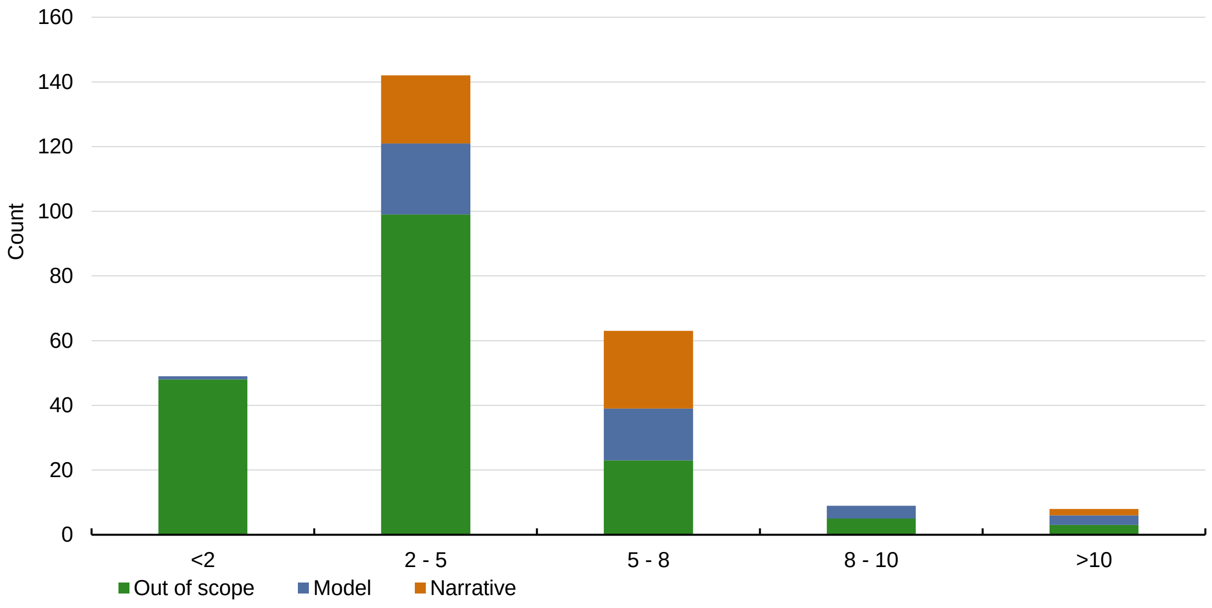

**Figure 22 Hazards classified by hazard priority number class and scope**

Data: Bioregional Assessment Programme (Dataset 1)

The models used to quantify the hydrological impacts of coal mining hazards in the BA do not necessarily model the hazards themselves. Some can be modelled directly. For example, mine dewatering can be represented in terms of a times series of water extracted from a groundwater store at some specified location. Other hazards, for example the subsidence that can result from longwall mining, are not modelled directly. Instead assumptions must be made about the likely impact of the hazard on hydrology, which means identifying what causal pathway group or causal pathway groups are affected by the hazardous activity. For the subsidence example, it is known that subsidence can lead to fracturing of the rock strata above (and/or around) the longwall panels and that this can enhance the hydrological connectivity between aquifers, leading to greater rates of water movement between them (e.g. Tammetta, 2015; Hua et al., 2008; Liu and Elsworth, 1997). The fracturing can be represented as a change in the hydraulic conductivities of the affected strata and the impact of this change on water levels and water fluxes can be quantified by the model. Because the level of fracturing is not known, uncertainty analyses are undertaken to define a range of possible outcomes from varying the hydraulic conductivities of the rock strata. To assess the impacts of the hazards arising from coal resource development on water-dependent assets, they need to be mapped to a causal pathway group that connects the hazard to other parts of the subregion. Section 2.3.4 and companion product 2.6.1 (surface water numerical modelling; Zhang et al., 2018) and companion product 2.6.2 (groundwater numerical modelling; Herron et al., 2018) for the Hunter subregion provide more detail of how the hydrologic impacts of coal mining operations are represented in the numerical modelling.

### *2.3.5.3 Causal pathways*

Four main causal pathway groups have been defined in the Assessment for grouping the hazards from coal resource development. For changes to surface water the causal pathway groups are:

- ‘Surface water drainage’
- ‘Operational water management’.

For changes to groundwater flows the causal pathway groups are:

- ‘Subsurface depressurisation and dewatering’
- ‘Subsurface physical flow paths’.

Table 14 provides a summary for each causal pathway.

**Table 14 Causal pathway groups and the associated hazards for the Hunter subregion**

| Causal pathway group | Types of coal resource development activities that affect the causal pathway | Hazards from Impact Mode and Effects Analysis (IMEA) |
|---|---|---|
| Surface water drainage | • diversion walls, drains, and interception of runoff by site operations<br>• realigned streams etc.<br>• subsidence of land surface due to underground coal extraction (creates artificial dams at surface where surface water (SW) may pool and reduce inflow to natural waterways)<br>• creation of new mine-site infrastructure. | • water management structures (dams, levee bunds and diversions)<br>• rainwater and runoff diversion<br>• waste rock blasting, excavation and storage administration, workshop, service facilities (construction phase)<br>• topsoil excavation and storage<br>• mine access construction<br>• longwall coal extraction<br>• bord-and-pillar coal extraction<br>• construct own quarry for road base etc.<br>• off-lease and on-lease roadways<br>• rail easement construction<br>• recontoured landforms (slopes, gradients, etc.)<br>• topsoil and waste rock dump site preparation<br>• ventilation shaft construction. |
| Operational water management | • sourcing water for on-site operations (e.g. extraction from river system)<br>• discharging of mine water into a surface water system (under specific conditions or rules)<br>• storing co-produced water in dams/ponds<br>• processing or using the produced water. | • discharge of treated mine water into the river (regulated)<br>• discharge of treated mine water into the river (unregulated). |

| Causal pathway group | Types of coal resource development activities that affect the causal pathway | Hazards from Impact Mode and Effects Analysis (IMEA) |
|---|---|---|
| Subsurface depressurisation and dewatering | • changes to groundwater pressure in target coal seams for coal extraction<br>• groundwater pressure changes in non-target aquifers with hydraulic connection to coal seams<br>• groundwater pumping of target coal resource layer to allow underground mining. | • longwall coal extraction<br>• bord-and-pillar coal extraction<br>• pit wall (stabilisation) dewatering, treatment, reuse and disposal<br>• development of mine panels (construction of roadways)<br>• mine access (shaft / incline) construction<br>• mine access (adit / incline) construction<br>• gas post-drainage, surface to goaf: drilling<br>• ventilation shaft construction<br>• drilling and coring<br>• gas post-drainage, surface to goaf: drilling<br>• gas pre-drainage, surface to inseam: drilling<br>• gas pre-drainage, underground: drilling<br>• inseam gas pre-drainage, underground: drilling<br>• mine dewatering drilling: drilling. |
| Subsurface physical flow paths | • well integrity, well failure creating direct fluid pathway between target zone and overlying aquifers<br>• subsurface cracking and fracturing in rock units directly overlying underground longwalls (deformation zone)<br>• reducing aquifer volume through digging it up (e.g. if overlying coal seams). | • longwall coal extraction<br>• bord-and-pillar coal extraction<br>• post-closure water filling the pit<br>• groundwater supply bore<br>• mine access (adit / incline) construction<br>• mine access (shaft / incline) construction<br>• ventilation shaft construction<br>• mine expansion too close to river/lake. |

Data: Bioregional Assessment Programme (Dataset 1)

Water near, and at, the land surface most often occurs in very thin flows. The direction and velocity of surface flows is controlled primarily by local land gradient, and for river flows a combination of the water surface gradient and flow depth. Surface roughness also affects flow velocity (e.g. vegetation cover density and size, material at the surface, presence of other debris). Any natural or anthropogenic activity that changes the roughness, local slope, local flow direction, vegetation or surface material can affect surface flow direction and velocity. Groundwater flows are primarily controlled by differences in local groundwater elevation, as the saturated thickness becomes large. The flow velocity and direction is locally controlled by hydraulic conductivity of rocks and strata, and its anisotropic properties, and on a larger scale by heads and flows at boundaries (e.g. rivers and surface water bodies, oceans, geological barriers and facies changes, diffuse rainfall recharge and evaporation). Anthropogenic activities, such as point recharge from irrigation or point extraction by pumping, change gradients locally and affect the direction and velocity of flows within a groundwater system.

Most water fluxes occur at the surface and in near-surface rock layers. In general, the groundwater flow paths follow the subregion’s topographic directions from the uplands toward the central valley and then to the ocean, with the Goulburn and Hunter river valleys being regional flow discharge zones. Surface porous and fractured rock layers contain the local groundwater flow paths, and many provide baseflow to streams, rivers and springs (McVicar et al., 2015). Inflow from saline streams and groundwater discharge strongly influence the quality of the Hunter River in medium-to-low flows (Kellett et al., 1989). Under high-flow conditions industrial discharge from coal mining and power generation activities, as controlled by the Hunter River Salinity Trading Scheme (HRSTS), may increase river salinity within legislated bounds (McVicar et al., 2015, p. 103).

Open-cut mines operate extensively at the land surface, but may extract coal from depths of tens or hundreds of metres, and may require digging through multiple geological layers, some of which may be part of an aquifer or aquitard. From the surface water perspective, rain that falls within the working area is considered produced water, and must therefore be retained on site. Water that flows through the working area must be redirected, or retained on site as produced water. These surface water causal pathways result in hazards that disrupt natural drainage, which may lead to reductions in surface water flows feeding streams or water-dependent ecosystems, or increase erosion of surface soils.

Associated with open-cut pits is the requirement for dewatering to allow removal of overburden and coal. The amount of water requiring removal will vary by the size of the mine pit, the specific aquifer layers that have been cut through, and the hydraulic properties of the material in those layers and in the base of the pit. Removing water from these layers results in a reduction of head in the layer, which may change groundwater gradients and induce flow away from rivers and streams, and other surface water features.

Mine operations may require the removal of water from surface streams or bodies for processing or general mine-site operations. To compensate for this, mines are required to obtain equivalent credits from water licences. A hazard will arise if there is sufficient gradient induced that water in the stream is drawn towards a mine operation, and it affects the flow duration in the watercourse. A hazard is also generated with mine-water disposal to streams that may contain a high level of salt or other chemicals. From the view of river salinity, such discharges are controlled by the

HRSTS and not in the scope of the hydrological modelling for this BA, but will be part of the narrative.

Underground mines have the same causal pathway groups as open-cut mines (i.e. ‘Subsurface depressurisation and dewatering’ and ‘Subsurface physical flow paths’), although they may differ in their severity. In addition, underground mines may cause subsidence, with changes to the physical structure and properties of rocks and sediments between the mining plane and some distance up to, and including, the land surface. Where land subsidence coincides with a natural stream or river, water may be lost from the stream temporarily or permanently.

### 2.3.5.3.1 Open-cut and underground coal mines

Figure 23 illustrates some of the mine activities for the causal pathway groups associated with open-cut and underground coal mines, which are discussed in the following sub-sections.

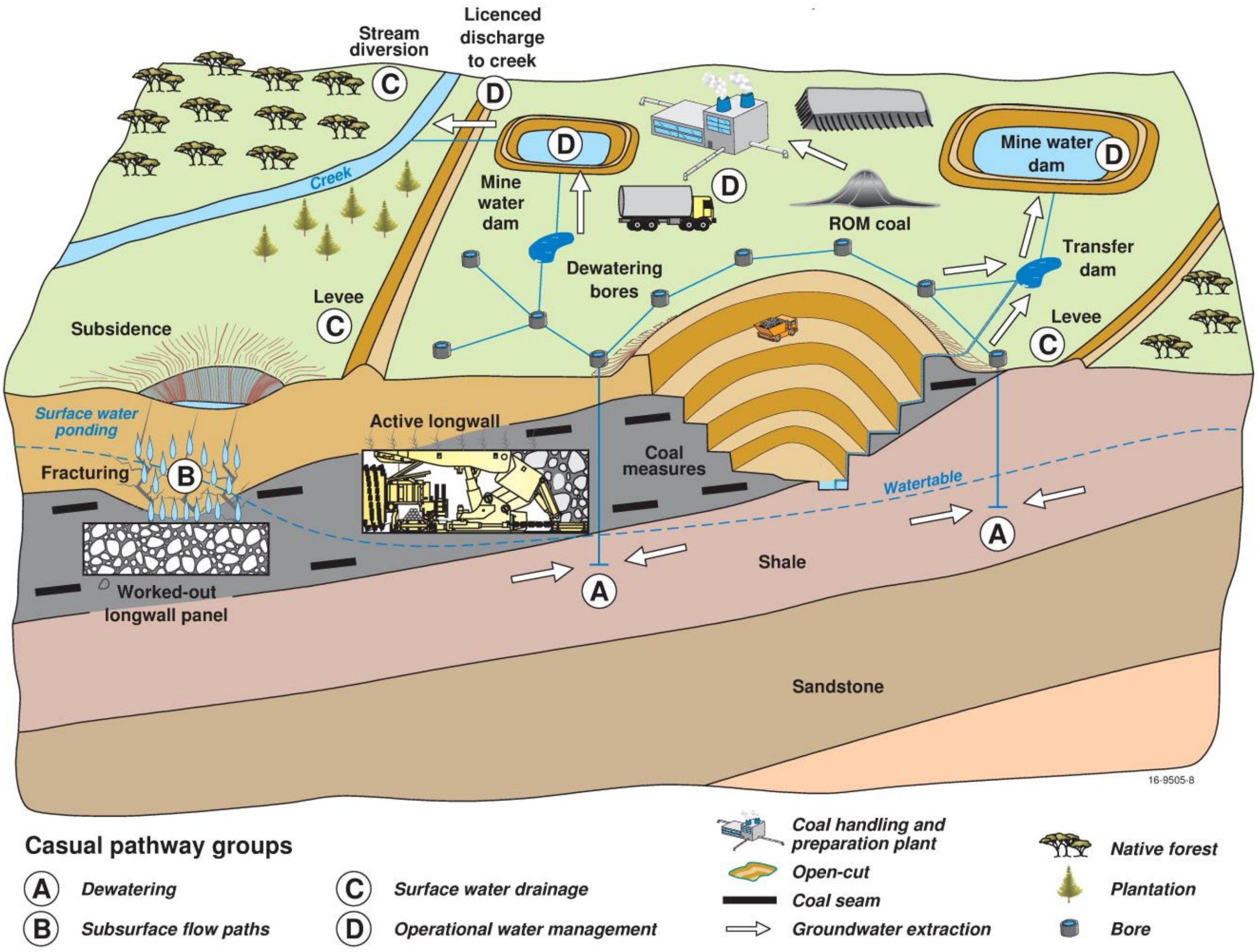

Figure 23 Causal pathways associated with open-cut and underground coal mining

ROM = run of mine

***‘Surface water drainage’ causal pathway group***

The ‘Surface water drainage’ causal pathway group pertains to mine hazards that physically disrupt the surface topography and thereby alter the flow of surface water within and from the mine site. Figure 23 illustrates some of the mining activities that can affect surface water drainage, including excavation of pits; diversion of water around mine-site operation areas with drains or walls (C in Figure 23); and construction of dams to store tailings, mine water and catchment runoff as part of 'Operational water management' causal pathway group (D in Figure 23). Figure 24 summarises the key hydrological changes. Changes to surface water drainage can occur not just from altering the surface topography but also through changing the infiltration properties at the land surface, causing changes in diffuse recharge and potentially changes in streamflow elsewhere in the catchment. Disruptions can cause changes to the quality and total amount of water flowing over the land surface.

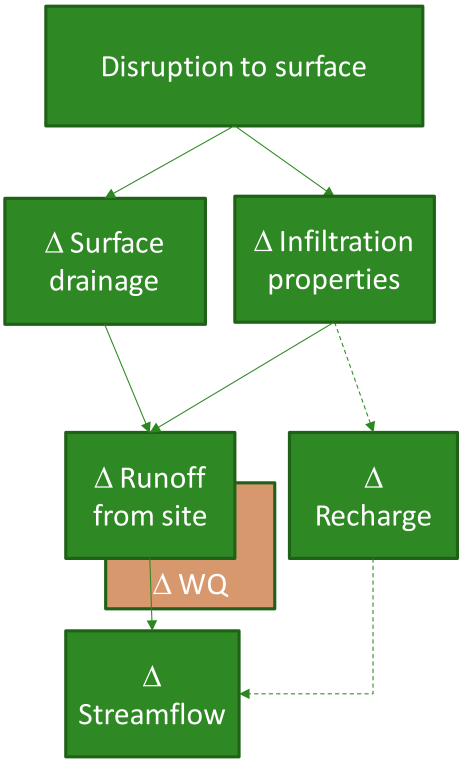

**Figure 24 'Surface water drainage' causal pathway group**

The Δ symbol indicates a change in the quantity, but not a direction of change.
WQ = water quality

Direct rainfall and runoff generated on a mine site are retained on site. This water that would naturally contribute to surface water drainage networks represents a loss to the river system. While the volume of water may be relatively small if it occurs adjacent to a major stream or river, on smaller upland creeks the volumes may become significant. Any secondary value this runoff may provide, such as infiltration further downslope, will be lost.

Intercepting runoff or streamflow into a mine area will remove a volume of water from the larger surface water drainage system. Both the quantity and quality of water downstream may be affected; quality may improve if the runoff or flow was naturally saline or highly turbid, or decrease if the inflow was fresher than the main stream. Surface water that is diverted around a mining operation may lead to concentration of surface flows that may negatively affect water quality due to increased erosion and turbidity.

The subsidence that results from underground mining can affect both surface drainage and infiltration properties. The process of subsidence is a lowering of the land surface due to collapse of the regolith above an underground mine (Holla and Barclay, 2000). It occurs in two phases: active and residual. The active phase comprises about 90% of total subsidence and follows the advance of the mining front, occurring almost immediately with roof collapse. The residual phase takes more time, and occurs as the rocks compress and adjust in the collapsed zone above the mining void.

The collapsed zone (B in Figure 23) is highly fractured and often has enhanced hydraulic conductivity and storage to a thickness of about five times the thickness of the extracted seam, although cracking and some increased hydraulic conductivity can occur over a thickness of 20 to 30 times the extracted seam height depending on the strength of overlying strata (ACARP, 2002). At the surface, longwall mining creates long closed rectangular basins that extend beyond the physical boundaries of the mined area. Depending on depression depth, orientation, gradient of depression and connectivity to drainage lines, these depressions will retain more runoff than pre-disturbance and can be associated with local waterlogging. Under irrigated cropping lands, these changes have been identified as potentially impacting crop yields and disrupting water supply channels (Cotton Australia, 2013). In the Hunter subregion, potential loss of streamflow from fracturing of stream beds appears to be a bigger concern. Shallow longwall mining (e.g. less than 100 m below surface) can result in total loss of flow in smaller streams, while a deeper mine may cause only limited or temporary losses (OEH, 2013). In the Hunter Valley, Eui Creek, Wambo Creek, Bowmans Creek, Fishery Creek and Black Creek have all been affected by subsidence due to underground coal mining. Damage has occurred in the form of increased streambed erosion leading to degraded water quality, loss of streamflow and death of riparian vegetation. Extraction plans, prepared as part of the development consent process for longwall mines in NSW, must identify water resources at risk from the proposed mining and detail how mining will be undertaken to minimise impacts.

Longwall mining occurs adjacent to and under Lake Macquarie and has contributed to localised lowering of the lake bed and foreshore. Mining operations in the vicinity of the lake are controlled by NSW Department of Industry Resources and Energy to limit the maximum vertical subsidence within a high water mark subsidence barrier to 20 mm, which is the effective limit of measureable subsidence. This limit has been imposed to protect the shores of Lake Macquarie from inundation in response to past mining induced damage to the shoreline and adjacent waterfront homes, such as occurred at Chain Valley Bay in 1986. In addition, a habitat protection plan has been developed under the NSW *Fisheries Management Act 1994* to protect seagrasses in NSW. Seagrass beds occur in shallow subtidal waters of Lake Macquarie and are sensitive to base-level changes from mine subsidence. Their density and health are tied to light penetration, which decreases exponentially with increasing water depth (Baird et al., 2003). Extraction plans for mines going under the lake are required to limit the impact of subsidence within the Lake Macquarie seagrass protection barrier.

### *'Operational water management' causal pathway group*

This causal pathway group relates to the creation or modification of water management systems that facilitate sourcing, storing, reuse and release or disposal of water within the mine site (D in

Figure 23). This water may be derived from rainfall, runoff, streamflow, pit dewatering or any other operation or process within the mine site. Figure 25 summarises the pathways in the ‘Operational water management’ causal pathway group that have off-site effects, but do not include intra-site water flows that might be a part of site water management (e.g. mine water make held in dams on site).

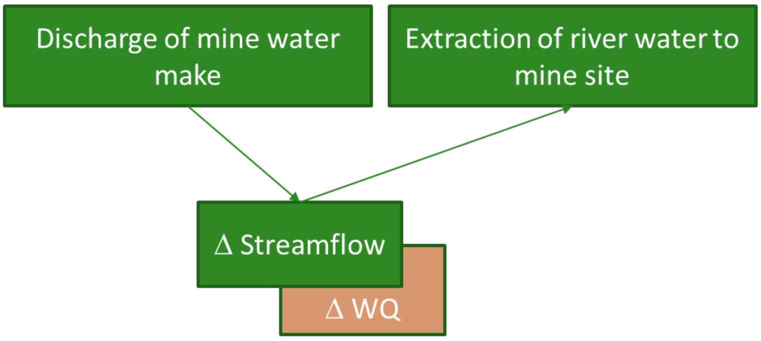

**Figure 25 ‘Operational water management’ causal pathway group**

The Δ symbol indicates a change in the quantity, but not a direction of change.
WQ = water quality

Clearly any release of water to the surface water drainage network, or a surface water feature, will increase the total amount of water and may affect the water quality (see Figure 25). For salt concentrations related to mine water releases in the regulated Hunter River alluvium, the process is covered by the HRSTS and is not in the scope of this BA. Monitoring the water quality for other contaminants, such as heavy metals or BTEX (benzene, toluene, ethylbenzene and xylene), and their removal or disposal is the responsibility of individual mining companies under their mine water management agreements. Any release of contaminated water to the surface water system, for example by leakage or overflow from a storage dam, may negatively affect downstream water quality.

***‘Subsurface depressurisation and dewatering’ causal pathway group***

Mine dewatering is an operation that lowers groundwater levels so that extractive mining can proceed (A in Figure 23). This can change groundwater pressure gradients due to head changes, or other gradients such as temperature, density and chemical composition. The largest pressure gradient changes will occur in the coal seams that are targeted for mining, either near the surface or in longwall panels.

This causal pathway group leads to a hazard that is a degradation of the water resource in terms of availability or quality in the surface water system, and conjunctively in the river/alluvial aquifer. In the case of direct extraction from streams it is necessary for mine operations to obtain credits to extract this water, and conditions may be placed on such extraction at times of low flow, for example. Where water can be extracted from an alluvial aquifer and the stream is well connected with local groundwater, then prolonged extraction from the aquifer may result in enhanced leakage from the stream, and therefore affect total streamflow (see Figure 26a). Under the Hunter Water Sharing Plan for the Hunter Unregulated and Alluvial Water Sources (DWE, 2009) there are specific rules under low- and no-flow conditions to prevent pumping that may stress the alluvial aquifer under drying conditions.

Similarly, lowering the groundwater level in surface layers that are being dewatered or mined, can induce a gradient away from a connected alluvial aquifer. If water levels are maintained in the alluvial aquifer then water must be sourced from the river (see Figure 26b). If that source is unable to maintain the required flux, then water levels in the alluvial aquifer will ultimately be reduced. The water quality and groundwater levels in the alluvial aquifer will be resolved by the complexities of the pathways and interactions between the potential source (e.g. the river), and the sink (e.g. the depressurised local rock layer). AGEC (2013) provides an example at Mount Arthur Coal Mine of changing the direction of the groundwater gradient toward Permian rocks and away from the Hunter River alluvial aquifer through depressurisation, but without a change to water levels in the alluvial aquifer.

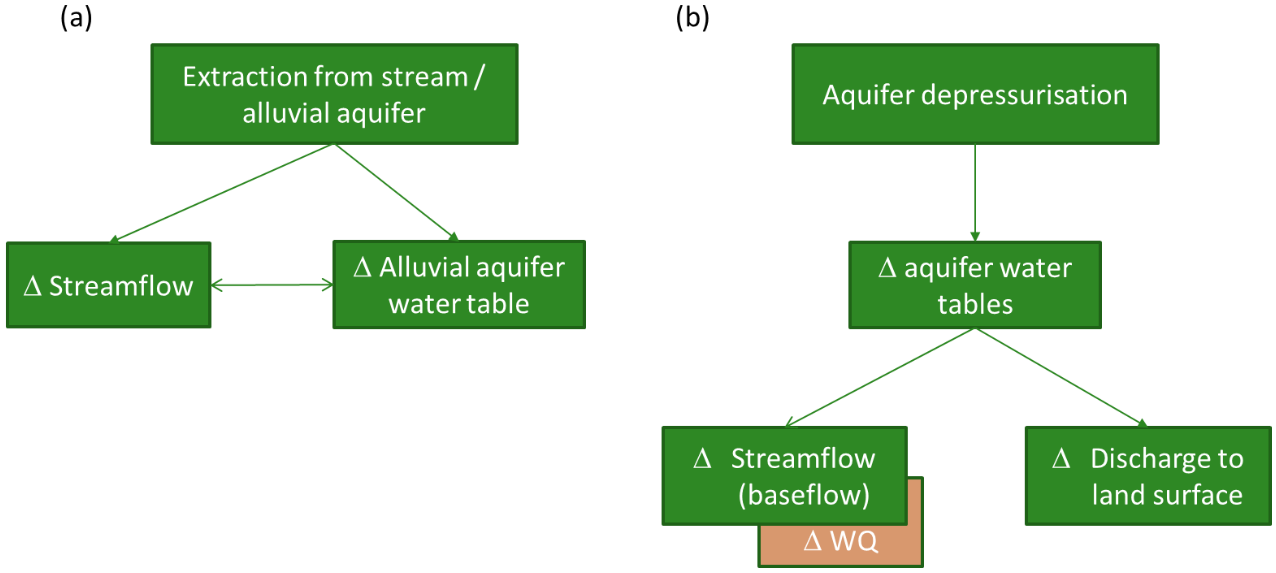

**Figure 26 'Subsurface depressurisation and dewatering' causal pathway group, by (a) direct extraction of water from streams, and (b) extraction of water from aquifers**

The Δ symbol indicates a change in the quantity, but not a direction of change.
WQ = water quality

### *'Subsurface physical flow paths' causal pathway group*

This causal pathway group shares many similarities with the 'Subsurface depressurisation and dewatering' causal pathway group, as can be seen by comparing Figure 26b and Figure 27. While the former applies to water losses or gains within the stream plus alluvial aquifer system, this causal pathway group relates to water transfer between any layers. This causal pathway group involves physical modification of the structure of the rock strata that leads to new, or changes to existing, pathways that water can potentially move through (such as at B in Figure 23). Note that the creation of a pathway does not necessarily mean water will flow through it; fluxes are governed by the pressure gradients. Off-site effects can result due to changes in baseflow to nearby streams or changes in discharge to the land surface, such as via springs or wetlands (Figure 27).

Where aquifer layers, or indeed the land surface, are separated by aquitards or other low-conductivity barriers, the water within each aquifer may have different chemical properties and constituents. Mixing of water between layers may be undesirable due to contamination of a resource by lower quality water, or by drainage to another layer leading to reduced availability, or loss, of a resource. Reduced resource availability due to water removed by a newly connected aquifer or pathway is analogous to the previously described ‘Subsurface depressurisation and dewatering’ causal pathway group.

Hazards in this causal pathway group can be generated by drilled holes for exploration, monitoring or dewatering (A in Figure 23) and by excavation of open-cut and underground mines. This hazard may be generated by wells due to inadequate design or completion of a hole, mechanical failure of the well casing or sealants, or by failure induced by movement of the layers the well is drilled through. Department of the Environment (2014) provides a thorough review of the leakage issues and best practices associated with bore construction in Australia. Physical flow paths created or enhanced through well construction are not represented in the BA numerical modelling: the connections are point scale, and are unlikely to result in significant changes in groundwater flows, and therefore will not affect regional watertables.

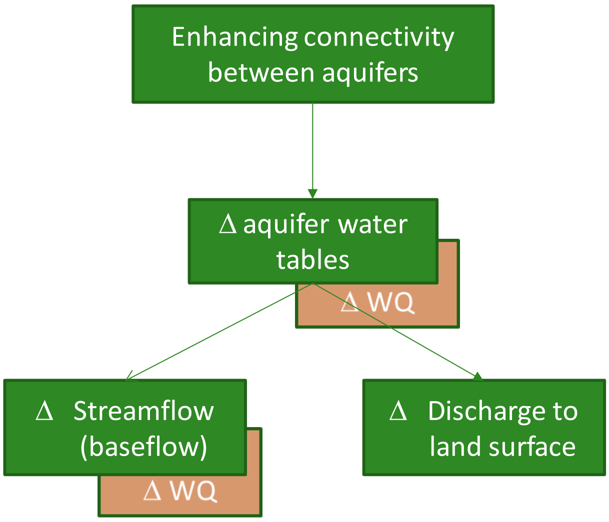

**Figure 27 ‘Subsurface physical flow paths’ causal pathway group**

The Δ symbol indicates a change in the quantity, but not a direction of change.
WQ = water quality

Through the excavation of open-cut and underground mines, physical pathways can be created between aquifers that were previously separated. In longwall mining, the inevitable collapse of overburden layers into the mine void following coal extraction leads to subsidence. The collapsed zone is characterised by fracturing and hydraulic enhancement from changes in horizontal and vertical compression and tension. The hydraulic enhancement varies with depth, with large increases in permeability associated with the caved and fractured zones immediately above the worked area, diminishing through the constrained and surface zones. It also varies between the goaf area (above the worked area) and the rib area, which extends out from the worked area. As already discussed, where fracturing coincides with drainage lines at the surface, streamflow losses can occur. Thus longwall mining leads to creation and enhancement of subsurface physical pathways, aquifer depressurisation and modifications to surface water drainage.

Furthermore, enhancing connectivity means greater potential for water-borne pollutants to move through and between aquifers and can also mean enhanced weathering. Sulfide-bearing minerals that are exposed to both oxygen and water can create sulfuric acid, and the resulting drainage water is termed 'acid rock drainage' (Blodau, 2006). This water may contaminate surface water bodies by escaping storage dams overland or via newly connected underground pathways, or form on the face of mine walls and acidify water in mining voids. There are several inactive mine sites in the lower Hunter that are leaking, or have leaked, acid rock drainage to surface watercourses at Aberdare East, Testers Hollow, Neath, Dagworth, Greta and Rothbury (SMH, 2013).

The spatial and temporal extents of hydrological changes from open-cut and underground mining are summarised by causal pathway group in Table 15. The temporal extent of, for example, discharge to streams and extraction from streams as part of the 'Operational Water Management' causal pathway group is measured in years, but likely only over the life of the mine, as these activities are most closely associated with a producing mine. Life of mine and post-mining hydrological effects of land modification due to hazards in the 'Surface water drainage' causal pathway group will depend on land management and mine rehabilitation. The surface water characteristics post-rehabilitation may be altered with respect to infiltration, runoff production and vegetation health. The effects of subsidence on surface water drainage can be permanent. Groundwater modelling has indicated that filled-in mining voids and lake pits can be a groundwater sink for decades or centuries (Vandenburg, 2011; McCullough et al., 2012), and that mine closure is a whole-of-landscape development.

'Vertical' is included in the 'Spatial extent' column for some causal pathway groups in Table 15. It indicates that effects propagate both laterally, as aquifer properties and connectivity allow, and vertically, potentially through several different strata and potentially to the land surface for underground mining.

Table 15 Spatial and temporal extent of open-cut and underground mining by causal pathway groups

| Causal pathway group | Spatial extent | Temporal extent |
|---|---|---|
| Surface water drainage | Local, stream network | Storm event to decades |
| Surface water drainage | Local, vertical | Years to permanent |
| Operational water management | Local, stream network | Years |
| Subsurface depressurisation and dewatering | Local, vertical | Years |
| Subsurface physical flow paths | Local, vertical | Years to decades |

### *2.3.5.4 Gaps*

Coal mine operations in the Hunter subregion are mature, and have been ongoing for more than 100 years. Many of the hazards from mining have been observed in the subregion (e.g. subsidence, changes to aquifer connectivity, depressurisation of aquifers and disruption of natural drainage) and their potential effects on water resources and water-dependent assets are recognised. The local experience of coal mining hazards and their effects is supported by international experience, and the risks from many hazards are managed through existing regulatory controls on mine planning and operations management.

One hazard that has occurred, but is not well documented, is subsidence in and around the subregion's coastal lakes due to underground mining. Depth of longwall mining and properties of the interburden influence the extent of subsidence at the surface and magnitude of changes in hydraulic properties due to fracturing. The latter is hard to predict, but is explored through the wide range of hydraulic properties in the groundwater modelling. The extent to which flora and fauna within coastal lakes (e.g. seagrass beds) have been impacted by subsidence historically is not well known. To manage the risks from subsidence, NSW regulations require additional conditions and approvals from proponents for mines that will operate close to, or beneath, lakes and estuaries.

The causal pathway groups link hazards to subregion assets but do not predict the impact. Numerical modelling is needed to determine whether the magnitude of change from mining activities and strength of connection to each subregion asset, as mediated by existing regulatory controls, are sufficient to impact each asset. This is a gap being addressed through the quantitative modelling within the BAs. However, while there is a good conceptual understanding of the potential for subsidence to impact coastal lake habitats, the groundwater modelling does not represent base-level changes in lake beds from subsidence.

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## *Datasets*

Dataset 1 Bioregional Assessment Programme (2016) Impact Modes and Effects Analysis for the HUN subregion. Bioregional Assessment Source Dataset. Viewed 23 August 2016, http://data.bioregionalassessments.gov.au/dataset/57404bd8-7be8-4800-bc94-ee7544a11673.

# Glossary

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

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

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

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

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

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

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

basement: the crust below the rocks of interest. In hydrogeology it means non-prospective rocks below accessible groundwater. Commonly refers to igneous and metamorphic rocks which are unconformably overlain by sedimentary beds or cover material, and sometimes used to indicate 'bedrock' (i.e. underlying or encasing palaeovalley sediments).

bioregion: a geographic land area within which coal seam gas (CSG) and/or coal mining developments are taking place, or could take place, and for which bioregional assessments (BAs) are conducted bioregional assessment: a scientific analysis of the ecology, hydrology, geology and hydrogeology of a bioregion, with explicit assessment of the potential direct, indirect and cumulative impacts of coal seam gas and coal mining development on water resources. The central purpose of bioregional assessments is to analyse the impacts and risks associated with changes to water-dependent assets that arise in response to current and future pathways of coal seam gas and coal mining development.

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

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

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

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

conceptual model: abstraction or simplification of reality

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

consequence: synonym of impact

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

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

dataset: a collection of data in files, in databases or delivered by services that comprise a related set of information. Datasets may be spatial (e.g. a shape file or geodatabase or a Web Feature Service) or aspatial (e.g. an Access database, a list of people or a model configuration file).

detection score: for the purposes of Impact Modes and Effects Analysis (IMEA), the expected time to discover a hazard, scored in such a way that a one-unit increase (or decrease) in score indicates a ten-fold increase (or decrease) in the expected time (measured in days) to discover it

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

diversion: see extraction

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

impact mode: the manner in which a hazardous chain of events (initiated by an impact cause) could result in an effect (change in the quality and/or quantity of surface water or groundwater). There might be multiple impact modes for each activity or chain of events.

Impact Modes and Effects Analysis: a systematic hazard identification and prioritisation technique based on Failure Modes and Effects Analysis

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

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

landscape group: for the purposes of bioregional assessments (BAs), a set of landscape classes grouped together based on common ecohydrological characteristics that are relevant for analysis purposes

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

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

marine transgression: the landward spreading of the sea over a large area within relatively short space of geological time (a few million years or less). The reverse of transgression is regression.

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

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

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

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

recharge: see groundwater recharge

risk: the effect of uncertainty on objectives

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

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.

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

severity: magnitude of an impact

severity score: for the purposes of Impact Modes and Effects Analysis (IMEA), the magnitude of the impact resulting from a hazard, which is scored so that an increase (or decrease) in score indicates an increase (or decrease) in the magnitude of the impact

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

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

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

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

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

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

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

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

water make: the groundwater extracted for dewatering mines

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)

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

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