Australian Government

BIOREGIONAL ASSESSMENTS

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

Conceptual modelling for the Gloucester subregion

Product 2.3 for the Gloucester 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.

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ISBN-PDF 978-1-925315-18-9

Citation

Dawes WR, Macfarlane C, McVicar TR, Wilkes PG, Rachakonda PK, Henderson BL, Ford JH, Hayes KR, Holland KL, O'Grady AP, Marvanek SP and Schmidt RK (2018) Conceptual modelling for the Gloucester subregion. Product 2.3 for the Gloucester subregion from the Northern Sydney Basin Bioregional Assessment. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia.
http://data.bioregionalassessments.gov.au/product/NSB/GLO/2.3.

Authorship is listed in relative order of contribution.

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Cover photograph

View of the Gloucester valley NSW with the Barrington River and associated riparian vegetation in the foreground and the township Gloucester in the distance looking south from the Kia Ora Lookout, 2013

Credit: Heinz Buettikofer, CSIRO

Australian Government
Department of the Environment and Energy
Bureau of Meteorology
Geoscience Australia

CSIRO

v20180226

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 bioregional assessments (BAs), conceptual models are developed to describe the *causal pathways*, the logical chain of events – either planned or unplanned – that link coal resource developments to water-dependent assets.

Methods

This product details the conceptual model of causal pathways of the Gloucester subregion, closely following the methods described in companion submethodology M05 for developing a conceptual model of causal pathways. For the subregion it identifies:

- the key system components, processes and interactions, which essentially define pathways over and through which water can move (Section 2.3.2)
- the ecosystems in terms of landscape classes and their dependence on water (Section 2.3.3)
- the potential hydrological changes that may occur due to coal resource development by describing and documenting the baseline coal resource development (baseline) and coal resource development pathway (CRDP) (Section 2.3.4), including a summary of water management for coal resource development (Section 2.3.4.2)
- hazards from coal resource development using an Impact Modes and Effects Analysis (IMEA) hazard analysis approach (Section 2.3.4.3)
- causal pathways from coal resource development through to hydrological changes, both for the *baseline* and the *coal resource development pathway* (CRDP) (Section 2.3.5).

Summary of key system components, processes and interactions

The Gloucester subregion is a small sedimentary geological basin. The groundwater flow processes and interactions in the Gloucester subregion are controlled by the layering, faulting and fracturing of the coal measures and shallow weathered and fractured rock layer. Groundwater recharge mainly occurs at the margins and areas of outcropping lower layers, and discharges in the central valley floor and associated alluvial deposits. Under most natural conditions the streams and rivers in the Gloucester subregion are gaining and connected to local alluvium groundwater systems. Surface water in the subregion is divided into two distinct catchments, with the Avon River flowing to the north and the Karuah River to the south. These rivers draining the subregion are relatively small parts of a larger river system draining surrounding landscapes. According to climatological equilibrium water balance analysis, changes in the surface water volume draining north from the Gloucester River (considering the contribution from the Avon River) will not be reasonably detectable at the confluence with the Manning River, where it supplies only about 3% of the streamflow at that point. Similarly for the Karuah River flowing south, contributions to the total streamflow at Port Stephens are less than 5% from the Gloucester subregion.

Ecosystems

The ecosystems in the Gloucester subregion are classified in terms of landscape classes and their dependence on water. The classifications are based on key landscape properties related to patterns in geology, geomorphology, hydrology, ecology and human-modified land use. The landscape classes were grouped into five broad landscape groups, defined to reflect different connections to surface water and groundwater systems:

- 'Riverine'
- 'Groundwater-dependent ecosystem (GDE)'
- 'Estuarine'
- 'Non-GDE'
- 'Economic land use'.

These landscape groups are expressed as a percentage of the geographic area associated with a subregion or bioregion in which the potential water-related impact of coal resource development on assets is assessed. This geographic area is called the preliminary assessment extent (PAE). Less than 3000 ha (6.4%) of the PAE (46,820 ha in total) was classified in the riverine, estuarine and GDE landscape groups. The majority of the subregion is cleared of native vegetation and supports agricultural uses.

Coal resource development

The CRDP for the Gloucester subregion includes the Duralie, Stratford and Rocky Hill mines. AGL's proposed coal seam gas (CSG) development in the Gloucester Gas Project, stage 1 gas field development area is also included. For numerical modelling purposes the CRDP was finalised in October 2015. Although there may be further stages (beyond Stage 1) of AGL's proposed CSG development in the Gloucester Gas Project, there is no publicly available documentation of these as of October 2015. In December 2015 AGL withdrew from their proposed Gloucester Gas Project and, according to the companion submethodology M04 for developing a coal resource development pathway, once the CRDP is finalised (October 2015) it is not revisited. In the Gloucester subregion, water management plans for existing and proposed coal and CSG resource developments are designed to achieve no overflow from on-site water storages to the neighbouring water bodies. Excess water is disposed through on-site irrigation, on-site reuse for dust suppression, and is evaporated back to the atmosphere from holding dams.

Water management

Information on water management is available for the two existing coal mines with expansion plans (Duralie Coal Mine and Stratford Mining Complex), one proposed coal mine (Rocky Hill, currently on hold as of 15 November 2015) and a CSG project (AGL's proposed CSG development in the Gloucester Gas Project, under development). Each of these developments has a water management plan.

Common elements of these water management plans are: (i) mine areas are isolated from the larger surface water catchment area by diversion drains early in the development process; (ii) surface water, where possible, is diverted around the mine areas; (iii) any water in the mine area is utilised for mining purposes, such as dust suppression and fracture stimulation, including pumped groundwater and (iv) progressive rehabilitation of mined-out areas as mining advances. The surface area that is disconnected from a catchment due to mining may vary during the life of the mine. There may be some provision for each of the mines to discharge off site during surface water high-flow periods.

Hazard analysis

Identification of potential hazards followed the Impact Modes and Effects Analysis (IMEA) method. It is used to systematically identify activities that may initiate hazards, defined as events, or chains of events that might result in an effect (change in the quality or quantity of surface water or groundwater). A large number of hazards are identified; some of these are beyond the scope of an Assessment and others are adequately addressed by site-based risk management processes and regulation.

CSG operations have their immediate impact deep below ground. For CSG operations the highest ranked hazards are: (i) aquifer depressurisation in the coal seams where extraction occurs, (ii) enhanced inter-aquifer connectivity and (iii) the storage and disposal of co-produced water. Open-cut coal mines most directly affect surface water flows and shallow groundwater aquifers; accordingly the highest ranked hazards are: (i) disruption of natural surface drainage, (ii) enhanced inter-aquifer connectivity of shallow aquifers and (iii) the storage and disposal of precipitation.

Causal pathways for coal seam gas

The hazards associated with CSG operations (identified as part of the IMEA) were considered in relation to the scope and were aggregated into four causal pathway groups (refer to Appendix B in companion submethodology M05 for developing a conceptual model of causal pathways).

The ‘Subsurface depressurisation and dewatering’ causal pathway group includes CSG operations that intentionally dewater and depressurise subsurface hydrostratigraphic units (such as coal seams and aquifers) to permit coal resource extraction. The water pathway for this group of hazards depends on the local geological environment of each individual CSG well. Predictions of fault locations by the newly developed three-dimensional geological model for the Gloucester subregion (Figure 13 in companion product 2.1-2.2 for the Gloucester subregion) reconfirm that major faults exist within the Stage 1 gas field development area of AGL’s proposed CSG development in the Gloucester Gas Project.

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. Flow paths may be altered by well construction due to enhanced connection between layers. The water pathway for this group of hazards is a result of drilling the well for CSG operations or for any well that penetrates between distinct geological layers.

The ‘Operational water management’ causal pathway group involves the modification of water management systems and is required for CSG operations due to the use of water during several operational stages. This water may be sourced from either surface water or groundwater systems. Section 2.3.4 details the specific plans for each of the mines in the Gloucester subregion, and water quality ranges for its various uses. Water quality monitoring by Parsons Brinckerhoff (2012) indicate that salinity of water generally increases with depth, and that water in the coal seams and interburden layers is three to four times more saline than water in the shallow alluvial aquifer and up to 50 times more saline than Avon and Gloucester river water.

The ‘Surface water drainage’ causal pathway group is defined by the physical infrastructure of CSG operations, and the associated surface works. Land clearing, land levelling, the construction of hard-packed areas such as roads and tracks, pipelines and plant for collection and transport of gas can all disrupt natural surface flows and pathways by redirecting and concentrating flows. The CSG development approved in the Gloucester subregion is for a maximum of 110 wells in the 50 km^2 stage 1 CSG development area of AGL’s proposed CSG development in the Gloucester Gas Project, and subsequent stages, not yet approved, are estimated as 200 to 300 wells over the full 210 km^2 gas field development area. This may see localised disruption to surface flows, with the changes in water chemistry or flow input location along a reach potentially having effects on water or other assets many kilometres downstream. Soil erosion resulting from changes in runoff pathways may cause damage with an individual storm event, as well as changes to the amount and type of material discharging into the stream over many years.

Causal pathways for open-cut coal mines

The hazards associated with open-cut mines (identified as part of the IMEA) were considered in relation to the scope and were aggregated into three main causal pathway groups.

In the ‘Surface water drainage’ causal pathway group there may be a loss, or redirection, of runoff. The water issue with this group of hazards is that any rain that falls within the limits of the mine operations area must be retained on site. This group of hazards will have a greater impact the closer an open-cut mine is to the first order streams (or headwater streams) of a surface water network. In the Gloucester subregion, the maximum extent of the baseline plus CRDP mine footprints is 16.9 km^2, or approximately 5% of the surface area of the subregion. This should result in a maximum of 5% direct reduction in runoff to the entire stream network, assuming uniform runoff production.

‘Subsurface physical flow paths’ and ‘Subsurface depressurisation and dewatering’ causal pathway groups are combined for open-cut coal mines. Flow paths will be altered by the dewatering of an open-cut coal mine by lowering the local watertable, potentially affecting inter-aquifer connectivity to some degree and thus may potentially lead to a loss of baseflow. Mines must have water removed to allow the safe extraction of coal, and this decrease in local groundwater level creates a gradient toward the pit, and induces flow into it; this is called ‘seepage’. The spatial extent of the influence area of the pit dewatering is a function of the depth of mining, the local hydraulic properties of conductivity and storativity of the geological volume proximal to the mine, and the time elapsed. It is the time elapsed that affects the spatial extent of this impact. For example, a particular water-dependent asset may be so distant from an open-cut mine that within the life of the mine, that drawdown will not affect it, but in the years following, the spread of the drawdown area may have an impact. This can only be quantified with monitoring and modelling.

The ‘Operational water management’ causal pathway group for open-cut mines and CSG operations has similar potential impacts but the volumes of water are likely to be larger as dewatering an open-cut mine, including seepage, usually involves much more water than dewatering a deep coal seam. The future impacts are controlled by the management of site rehabilitation (e.g. refilling the mine void with much looser material will allow seepage to continue toward the old mine void and may interrupt local groundwater flow pathways). Similarly for the disruption of surface drainage, without suitable rehabilitation, the mining lease area may have very different properties in runoff production, vegetation health, infiltration characteristics and local groundwater level long into the future once mining has ceased.

Gaps

In the Gloucester subregion, the greatest knowledge gap for the flow pathways due to coal mines and CSG operations is knowledge of the locations and characteristics of the subterranean faults and fractures of the geological layers. For example, there is not a clear idea of the location of all the largest faults in the geological Gloucester Basin and the nature, location and extent of smaller potential pathways between adjacent layers is only known theoretically. This makes any definitive statement on the spatial extent of a groundwater level decline due to CSG operations difficult, although uncertainty analysis does allow a probabilistic estimate of maximum groundwater level decline. At the regional scale it was shown that drawdown propagation is minimal for a wide range of randomised faults and well locations, however no modelling was done for local effects at specific locations.

In relation to landscape classes, the underlying data are of such a large scale that it only coarsely covers the small Gloucester PAE. To this end, the final classification was greatly generalised to five landscape classes in the 'Groundwater-dependent ecosystem (GDE)' landscape group and seven landscape classes in the 'Riverine' landscape group; at the regional scale of analysis, reach lengths of 1 to 3 km were considered too detailed.

Further work

The causal pathways for the baseline and CRDP 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 in the Gloucester subregion.

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Acknowledgements

This technical product was reviewed by several groups:

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Currency of scientific results

The modelling results contained in this product were completed in July 2015 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.

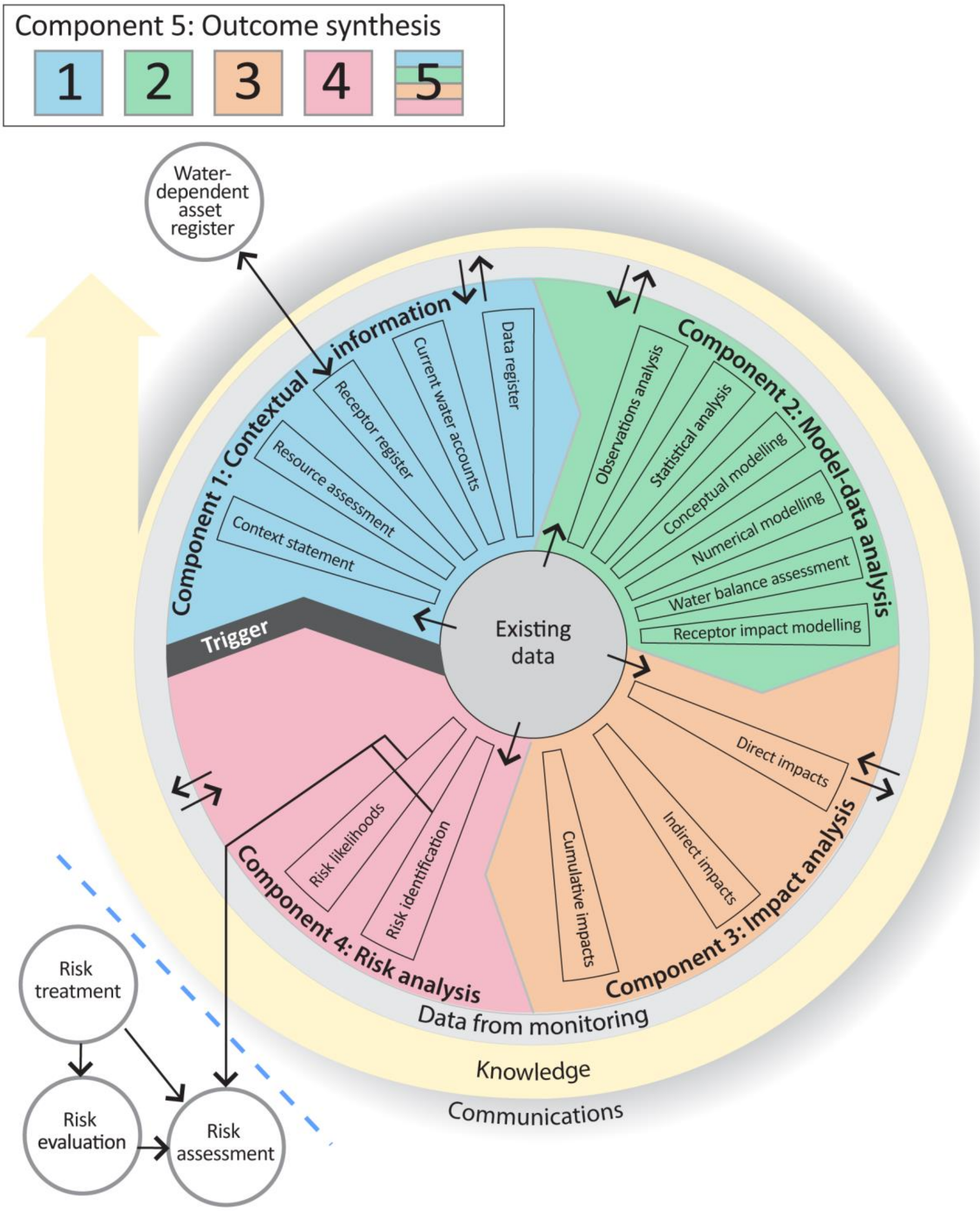

Figure 1 Schematic diagram of the bioregional assessment methodology

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.

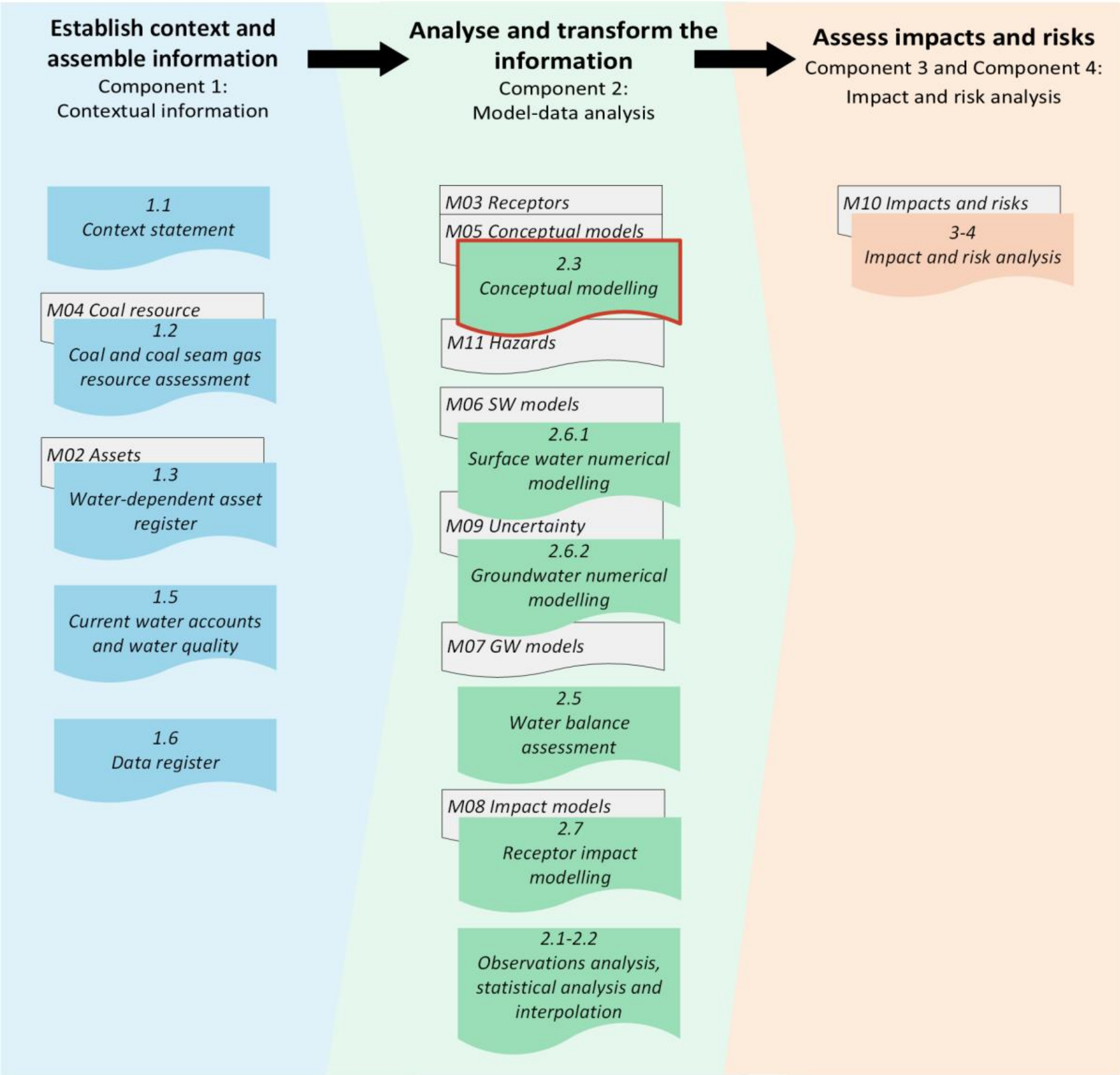

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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 Gloucester 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 Gloucester 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 Gloucester 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 Gloucester subregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3	PDF, HTML
Component 5: Outcome synthesis for the Gloucester 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.

- All reasonable efforts were made to provide all material under a Creative Commons Attribution 3.0 Australia Licence. The copyright owners of the following figures, however, did not grant permission to do so: Figure 6. It should be assumed that third parties are not entitled to use this material without permission from the copyright owner.
- All maps created as part of this BA for inclusion in this product used the Albers equal area projection with a central meridian of 151.0° East for the Northern Sydney Basin bioregion and two standard parallels of –18.0° and –36.0°.
- Visit http://bioregionalassessments.gov.au to access metadata (including copyright, attribution and licensing information) for datasets cited or used to make figures in this product.
- In addition, the datasets are published online if they are unencumbered (able to be published according to conditions in the licence or any applicable legislation). The Bureau of Meteorology archives a copy of all datasets used in the BAs. This archive includes datasets that are too large to be stored online and datasets that are encumbered. The community can request a copy of these archived data at http://www.bioregionalassessments.gov.au.
- The citation details of datasets are correct to the best of the knowledge of the Bioregional Assessment Programme at the publication date of this product. Readers should use the hyperlinks provided to access the most up-to-date information about these data; where there are discrepancies, the information provided online should be considered correct. The dates used to identify Bioregional Assessment Source Datasets are the dataset's published date. Where the published date is not available, the last updated date or created date is used. For Bioregional Assessment Derived Datasets, the created date is used.

References

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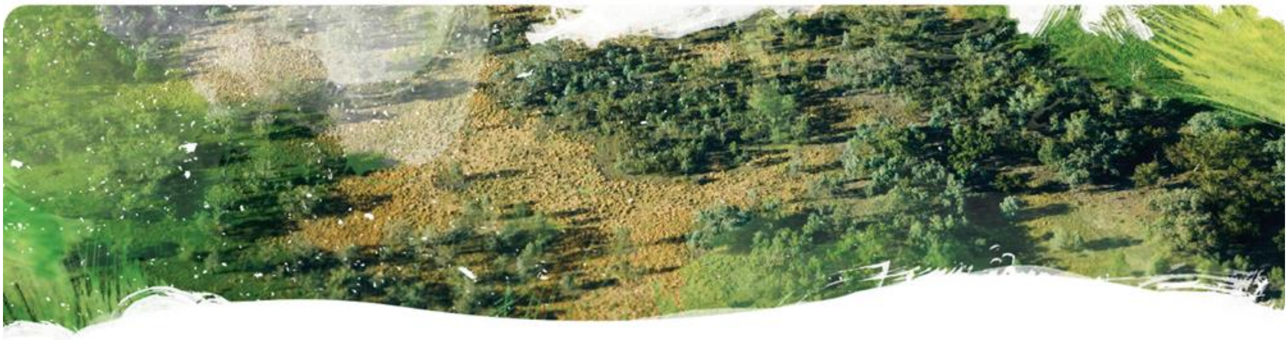

2.3 Conceptual modelling for the Gloucester subregion

This product firstly summarises key system components, processes and interactions for the geology, hydrogeology and surface water in the Gloucester 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 Gloucester 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., 2015).

Key concepts and terminology are also explained, and the overall steps are summarised, including the: (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 baseline coal resource development (baseline), the coal resource development pathway (CRDP) and additional coal resource development; (iv) identification of potential hazards; (v) identification of potential causal pathways from the coal resource development to hydrological changes; and (vi) characterisation of those potential causal pathways for both baseline and CRDP for the Gloucester subregion.

This development of causal pathways 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); however, the understanding of the key system components, processes and interactions was explored through consultation with external stakeholders.

2.3.1.1 Background and context

This product presents information about the conceptual model of causal pathways for the Gloucester 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 Gloucester 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 bioregional assessment (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 logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water resources and water-dependent assets. The conceptual 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 coal seam gas (CSG) fields that are commercially producing as of December 2012
- *coal resource development pathway* (CRDP), a future that includes all coal mines and coal seam gas (CSG) fields that are in the baseline as well as those that are expected to begin commercial production after December 2012.

The difference in results between CRDP and baseline is the change that is primarily reported in a BA. This change 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.

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 impact 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).

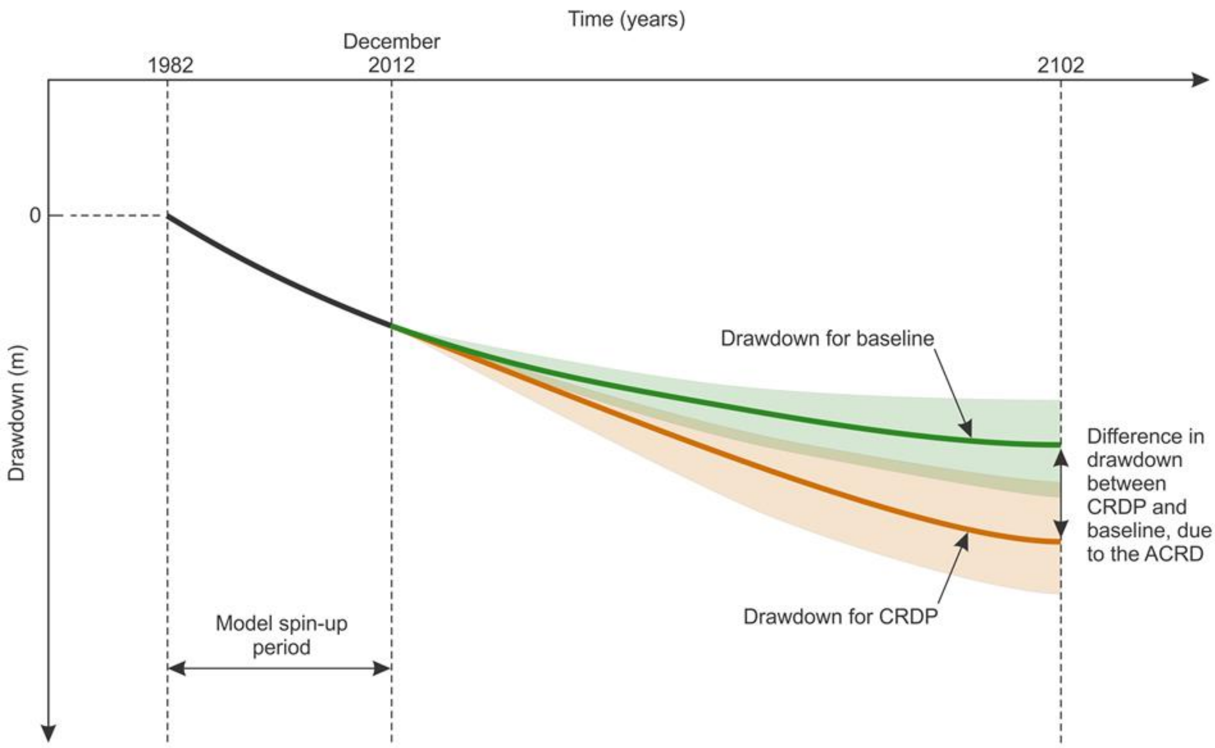

Figure 3 Generic example of drawdown at a specific location over time for the baseline coal resource development (baseline) and coal resource development pathway (CRDP). The difference in drawdown between CRDP and baseline is due to the additional coal resource development (ACRD)

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

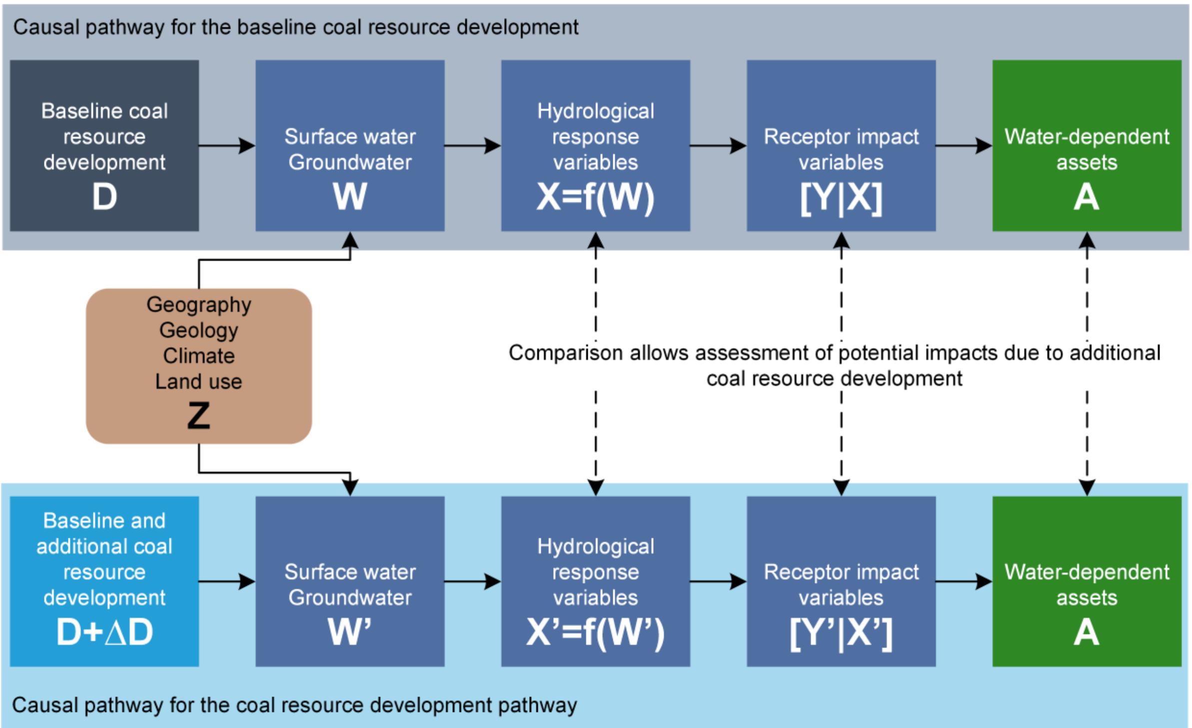

Figure 4 The difference in results under the baseline coal resource development (baseline) and coal resource development pathway (CRDP) provides the potential impacts due to the additional coal resource development

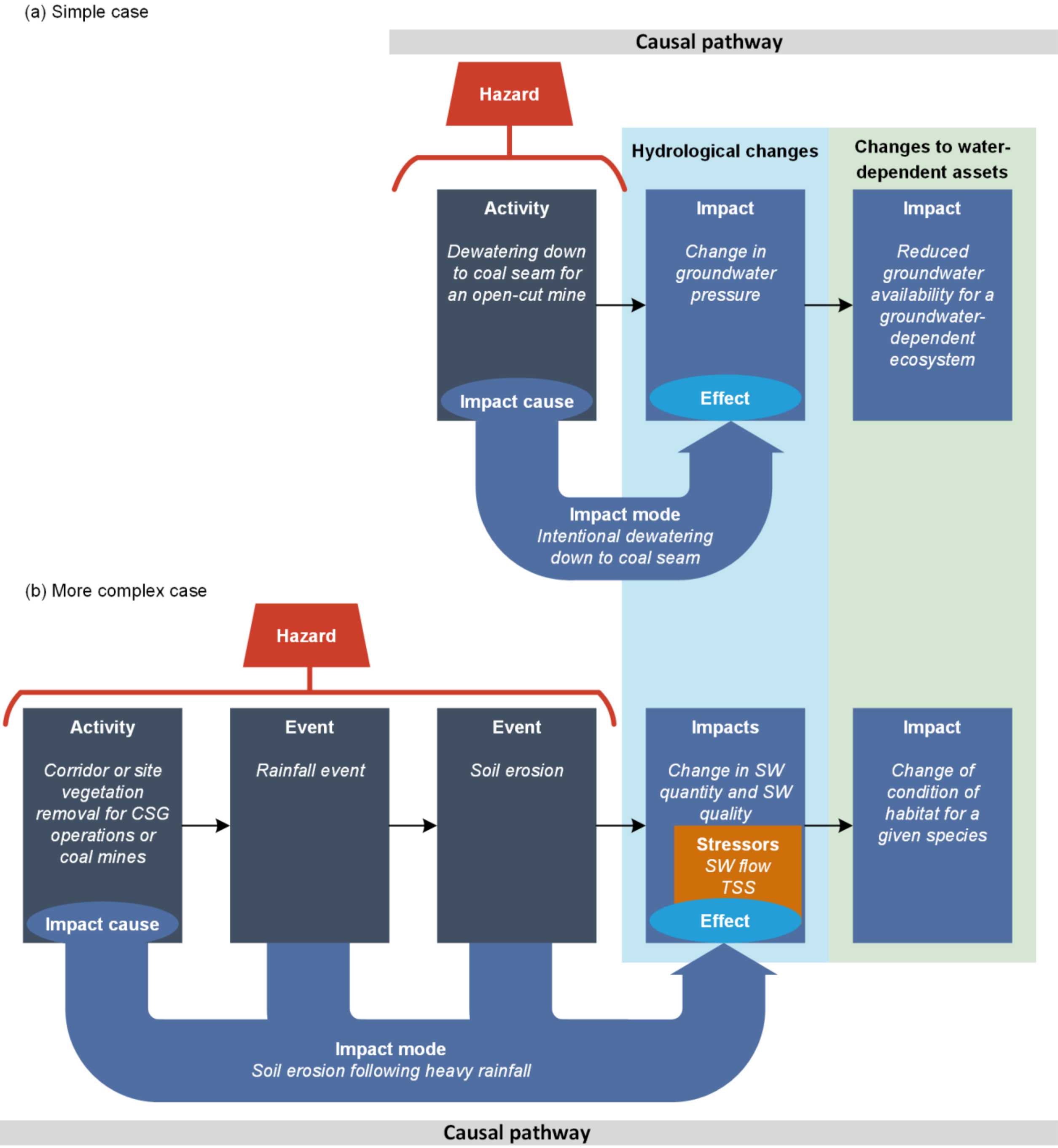

Figure 5 Hazard analysis using the Impact Modes and Effects Analysis. This figure shows how hazards identified using IMEA are linked to changes in hydrology and water-dependent assets via causal pathways

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

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 includes 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 Gloucester 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 Component 1: Contextual information and in conjunction with the development of the companion products for surface water modelling (companion product 2.6.1 for the Gloucester subregion (Zhang et al., 2018)), groundwater modelling (companion product 2.6.2 for the Gloucester subregion (Peeters et al., 2018) and water balance assessment (companion product 2.5 for the Gloucester subregion (Herron et al., 2018)).

The geological synthesis relied on a detailed new geological model developed by the Assessment team that integrated existing knowledge of the relevant geology for the Gloucester subregion (in companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018)). A landscape classification that represents the main biophysical and human ecosystems and that captures the high-level conceptualisation of the subregion was created.

Future coal resource development was discussed with external stakeholders from the subregion at a workshop in December 2013 and was subsequently refined based on external feedback and information.

A hazard analysis for the Gloucester subregion was conducted over five days via workshops with a range of experts present from CSIRO, Geoscience Australia and the Department of the

Environment. The hazards were prioritised and subsequently aggregated by common impact causes to a reduced set of causal pathways for baseline and CRDP.

The causal pathways for the Gloucester subregion were discussed and tested with external stakeholders; this discussion focused on knowledge gaps and uncertainties identified by the Assessment team.

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2.3.2 Summary of key system components, processes and interactions

Summary

The flow processes and interactions in the Gloucester subregion are controlled by the layering, faulting and fracturing of the coal measures and shallow weathered and fractured rock layer. At the scale of the geological Gloucester Basin, groundwater recharge occurs at the margins and areas of outcropping lower layers, and discharges in the central valley floor and associated alluvial deposits. Under most natural conditions the streams and rivers in the Gloucester subregion are gaining and connected to local groundwater.

Coal mine and coal seam gas (CSG) operations can induce changes in groundwater level at any worked or drilled depth in the geological column. The spatial and temporal influence of groundwater level changes is controlled by local hydraulic properties, and complicated by fracturing and faulting of layers. A reduced groundwater level may cause a groundwater level drop in a stock or domestic bore that makes it harder to extract water, or cause the bore to dry out periodically. Another potential effect of reduced groundwater level is to induce flow away from the alluvial aquifer that would otherwise discharge as baseflow to a stream.

Connectivity by direct linkages due to faulting and fracturing enhance the effects of groundwater level changes due to human activities. However, the role of faults and fractures as carriers or barriers of flow, their location in three dimensions particularly local *versus* regional extent, and their propensity to change their nature due to water pressure changes are all poorly known in the Gloucester subregion.

2.3.2.1 Scope and overview

The scope of this section is to collate and summarise the connections in the hydrological cycle of the Gloucester subregion (see companion product 1.1 for the Gloucester subregion (McVicar et al., 2014)), and to describe the flows and pathways that may be affected by coal mining and/or CSG development. The range of both existing and potential flows and pathways for water in the subregion will be summarised, without lengthy discussion of any individual component. Section 2.3.5 discusses specific pathways in the context of coal mining and CSG development, whereas companion product 2.5 for the Gloucester subregion (Herron et al., 2018) details complete water balances of all components.

The spatial extent of the flows and pathways is limited to the preliminary assessment extent (PAE) of the Gloucester subregion as defined in companion product 1.3 for the Gloucester subregion (McVicar et al., 2015). This covers a surface area of about 350 km^2 underlain by the geological Gloucester Basin, a north–south elongated sedimentary basin, along with a 1 km buffer either side of the Gloucester River flowing north to its confluence with the Manning River, and a similar buffer for the Karuah River flowing south to Port Stephens (McVicar et al., 2015, p. 20, Figure 6).

Open-cut coal mine operations in the Gloucester subregion have occurred at the Stratford Mining Complex since 1995, with four pits mined but only two currently (as of June 2015) operational, and at Duralie Coal Mine since 2003 (see companion product 1.2 for the Gloucester subregion (Hodgkinson et al., 2014)). The existing coal mine operations, along with any pits that have ceased production, are considered under the baseline coal resource development (baseline). All descriptions of the current and future coal mine operations are in Section 2.3.4.

From a groundwater perspective there are essentially three hydrogeological units in the Gloucester Basin:

- surface alluvium up to 15 m thick, a semi-confined to unconfined aquifer
- shallow weathered and fractured rocks up to 150 m thick, a confined to semi-confined aquifer
- interburden units alternating with coal seams, only considered as water-bearing strata, to a maximum depth of about 2500 m.

The key to the pathways in the Gloucester subregion is that it is a geologically closed basin, so that any water that enters must be expressed as discharge within the basin. The important layer controlling the surface water – groundwater interactions is the shallow weathered and fractured rock layer (SRL). This layer underlies the alluvium entirely, and outcrops extensively across the rest of the surface of the Gloucester subregion. Groundwater recharge to the SRL is primarily via rainfall and, to a lesser extent, from surface runoff at the margins of the subregion (i.e. the overland surface water flowing towards the basin draining the surrounding mountain ranges). The rivers and streams that are hosted within the alluvial aquifer are typically gaining and connected with local groundwater (McVicar et al., 2014, p. 79, Section 1.1.6). This aquifer is recharged via river leakage during high flow and flood events, by diffuse rainfall infiltration, and upward discharge from the SRL.

For the near-surface system the water pathways centre on hydraulic pressure and open-cut mining. CSG exploration and production reduce the groundwater level locally due to pumping out excess water to allow gas to flow and be collected. Local pressure drops can be transferred to the SRL and then to the alluvium where any diffuse pathway exists, and via fractures and structural features. If the underlying groundwater level of the SRL decreases enough, then it may induce flow downward and reduce stream discharge potentially turning a gaining stream into a losing stream. There may also be the possibility that a leaky well would allow the transfer of water to any layer above it, including to the surface.

For open-cut mine operations, local mine site dewatering is required so that coal can be mined and the mine is not flooded from incoming flows. This will induce water to flow toward the pit locally, and again will have an effect on the SRL, and potentially the alluvium if the proximity and hydraulic properties allow it. In such cases, water that would normally be discharged to the river and support baseflow in the surface water network could be drawn away.

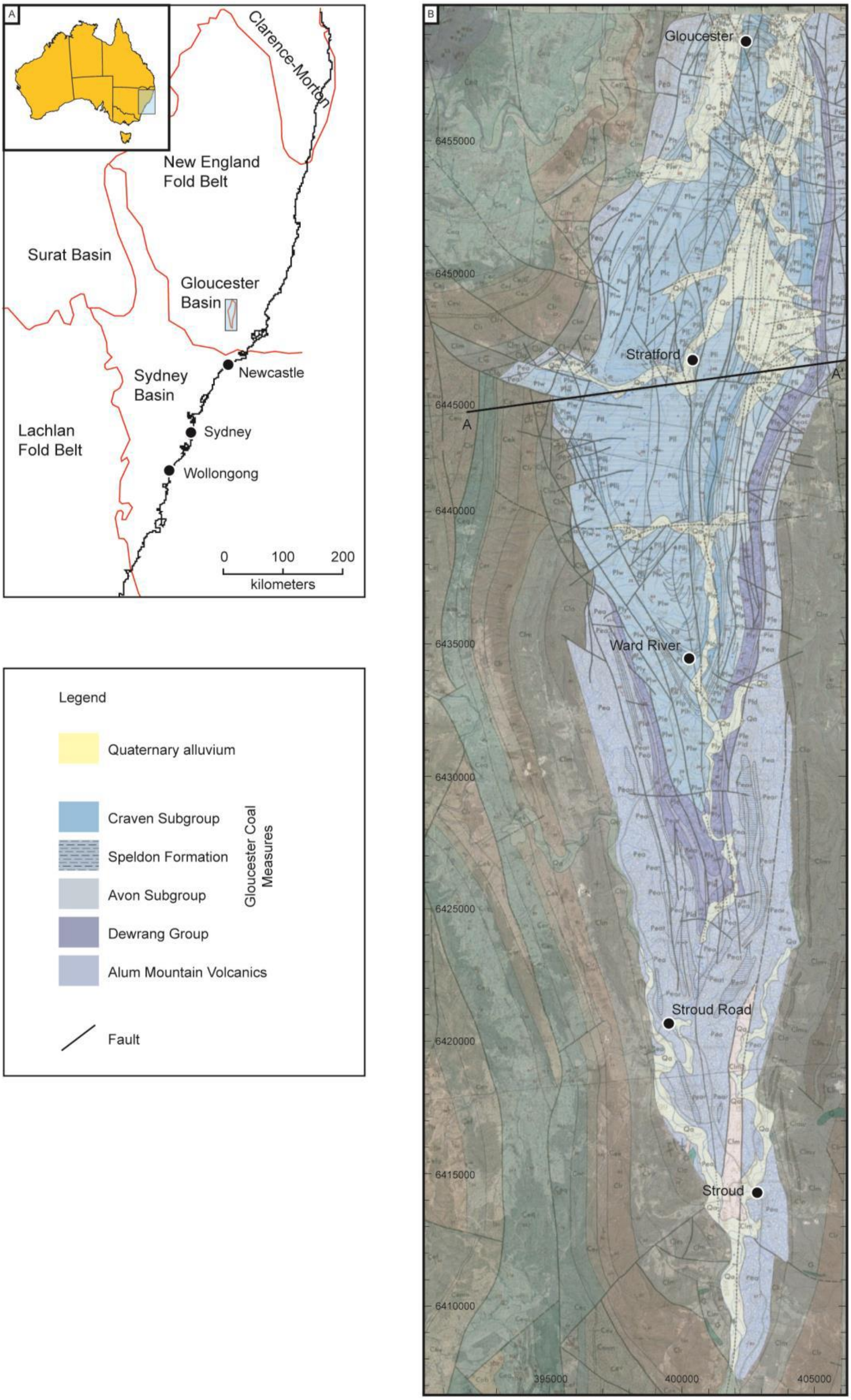
2.3.2.2 Geology and hydrogeology

The coal mine and CSG operations, and the critical water pathways, are contained entirely within the Gloucester PAE (McVicar et al., 2014, p. 17, Section 1.1.2.1; Parsons Brinckerhoff, 2012, p. 30; SRK, 2010, p. 45).

2.3.2.2.1 Geology

The basin is an elongated north-trending sedimentary basin, about 55 km long and up to 15 km wide, containing up to 2500 m of faulted, deformed and eroded coal-bearing Permian sedimentary and volcanic rocks (McVicar et al., 2014, p. 43, Section 1.1.3). The strata in the basin are relatively flat in the central portion, and are steeply dipping and faulted toward the flanks (Figure 6).

The near-surface layers are the Leloma Formation and Crowthers Road Conglomerate within the Craven Subgroup. The upper parts consist of interbedded sandstones, siltstones, claystones and conglomerates that form poor-yielding confined aquifers. However, where they are fractured (from about 100 m and below) they are categorised as water-bearing formations. The other members of the subgroup contain sandstones and conglomerates interbedded with coal seams. Due to faulting and erosion these other members and their coal seams may outcrop where the strata dip steeply enough.


A
Clarence-Morton
New England
Fold Belt
Surat Basin
Gloucester
Basin
Sydney
Basin
Newcastle
Lachlan
Fold Belt
Sydney
Wollongong
0
100
200
kilometers
Legend
Quaternary alluvium
Craven Subgroup
Speldon Formation
Avon Subgroup
Dewrang Group
Alum Mountain Volcanics
Gloucester Coal Measures
Fault
B
Gloucester
Stratford
A
A'
Ward River
Stroud Road
Stroud
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6410000
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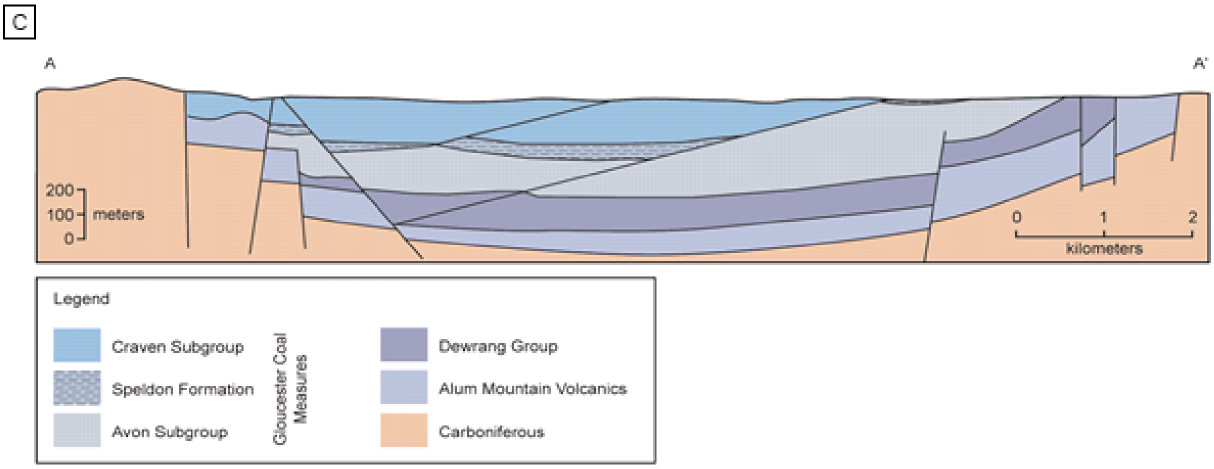

Figure 6 (a) Location of the Gloucester Basin. (b) Geological map of the Gloucester Basin with the Permian coal-bearing units highlighted (note the northern end of the basin is not shown). (c) Simplified regional cross-section A-A' for the Gloucester Basin; the Quaternary alluvium is not shown

Source: Roberts et al. (1991). This figure is not covered by a Creative Commons Attribution licence. It has been reproduced with the permission of NSW Trade & Investment.

The next layers are the Speldon Formation and Avon Subgroup, formed by marine transgressions and coastal plain environments, containing sandstone and siltstone layers with interbedded coal seams. These layers contain the most saline groundwater in the basin, due to their marine origin (see Parsons Brinckerhoff, 2012, p. 96, Table 8-3; p. 100, Table 8-5), about double the salinity of groundwater contained in the SRL. The Dewrang Group has similar origins to the Avon Subgroup but contains coarse-grained sandstones and conglomerates, and contains the Duralie Road and Weismantels formations worked at Duralie Coal Mine. The base unit of Alum Mountain Volcanics contains volcanic and sedimentary rocks, and is considered impermeable to water.

During the review of the geological structure of the Gloucester Basin, it was determined that the existing structural framework dating back to the 1990s was inadequate and led to substantial uncertainty about the location and orientation of faults (see companion product 1.1 for the Gloucester subregion (McVicar et al., 2014)). As part of the work in this subregion, a first-order regional geological model was developed that was based on all available deep borehole lithologies and geophysical data. Major faults were included to account for the basin-scale architecture, while a probabilistic fault population model for sub-seismic faults was developed based on published data from other basins of similar origin. The details of the geological model are found in companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018), and the fault population models are used in numerical modelling in companion product 2.6.2 for the Gloucester subregion (Peeters et al., 2018).

2.3.2.2.2 Hydrogeology

The hydrogeology with respect to water movement was divided into three units: alluvial aquifer, SRL, and alternating units of interburden and coal seams (see companion product 1.1 for the Gloucester subregion (McVicar et al., 2014, Section 1.1.4)).

Within the 7 to 15 m thick alluvial aquifer are the streams and rivers that pass through the subregion. The aquifer consists of gravel, sand, and clay layers and lenses, with a high range of conductivity locally (0.3 to 500 m/day), and is overall the most hydraulically conductive hydrogeological unit in the subregion (see companion product 1.1 for the Gloucester subregion (McVicar et al., 2014, Section 1.1.4 and Section 1.1.6)). The local water levels are shallow and within the first few metres of the land surface adjacent to the watercourses. These water levels are responsive to rainfall events and floods in the surface water catchments. Rivers and streams in the Gloucester subregion are mostly gaining, although the total water volume may be small relative to total streamflow (see companion product 1.1 for the Gloucester subregion (McVicar et al., 2014, Section 1.1.5 and Section 1.1.6)).

The SRL is locally confined and of lower hydraulic conductivity than the alluvial aquifer. The conductivity can be modelled as decreasing exponentially with depth (Parsons Brinckerhoff, 2013b, Figure 4-9). The water levels in the SRL have only limited response to rainfall seasonally, and there is only occasional response to individual rainfall events (see Parsons Brinckerhoff 2013a, p. 10–22, Figure A-6 to Figure A-30), although in some areas there may be greater connectivity and groundwater response (SKM, 2012). These conclusions indicate that recharge naturally occurs in the SRL and potentially to deeper layers. The hydraulic conductivity of the entire weathered zone is heterogeneous, with higher and lower conductivity domains associated with fault and fracture zones. The known aquifer zones occur to a maximum depth of 150 m but are mostly present in the upper 100 m.

The deeper interburden and coal seam layers are referred to as ‘water bearing’ rather than ‘aquifers’, which implies they are strata that yields a low amount of water. The reduction in hydraulic conductivity of both layer types is considered as exponentially decaying (SRK, 2010; Australasian Groundwater and Environmental, 2013; Heritage Computing, 2009), although the conductivity of the interburden layer is one or two orders of magnitude less than for a coal seam layer at the same depth.

As a closed basin, any rainfall recharge that occurs must result in storage within the geological basin or discharge to the surface via evaporation or to the stream via the alluvial aquifer. Recharge occurs to the alluvial aquifer and outcropping of shallow strata within the valley floor, and to deeper water-bearing zones around the flanks of the geological Gloucester Basin. Fluxes between layers are generally low with the greatest being from the SRL to alluvial aquifer in the valley floor. However, there is no consistent observed upward trend between layers in nested bores (see companion product 1.1 for the Gloucester subregion (McVicar et al. 2014, Section 1.1.4)).

Faulting and fracturing potentially play a major role in the groundwater flow paths from deeper to shallower layers. However, the role of faults and fracture zones is not consistent or well understood in the subregion as they have been reported to be both impediments to flow (URS, 2007; Parsons Brinckerhoff, 2012), and to have enhanced hydraulic conductivity (Parsons Brinckerhoff, 2013b; SRK, 2010) with chemical signatures indicative of upward flow of deep groundwater under natural conditions. Section 1.1.3 of companion product 1.1 of the Gloucester subregion (McVicar et al., 2014) states:

> The present definition of the structural framework for the Gloucester Basin relies on: (i) sparse two-dimensional seismic reflection data, (ii) interpolation of surface geological mapping, (iii) correlation of coal seams from borehole data, (iv) observations in open-cut mines, and (v) geophysical surveys. The low density and poor resolution of the seismic data, the limited number of outcropping structures and the high degree of lateral

stratigraphic variation in the basin result in significant uncertainty about the location and orientation of subsurface structural features.

Probabilistic modelling of inferred fractures shows that on a regional scale there is limited propagation of drawdown at the regional scale (companion product 2.6.2 of the Gloucester subregion (Peeters et al., 2018)); however, no actual well locations were specified at the time of this work and any local effects could not be addressed.

2.3.2.3 Surface water

Surface water in the Gloucester subregion is topographically split into a northern and southern part, with the divide just south of the township of Stratford (see companion product 1.1 for the Gloucester subregion (McVicar et al., 2014, p. 68, Figure 26)). The watercourses of the Gloucester subregion are within subcatchments of the Manning river basin in the northern part, and the Karuah river basin in the southern part. The main rivers in the northern part are the Avon River and Gloucester River, both within the Gloucester river basin that makes up about 20% of the Manning river basin and produces about 22% of the annual flow. The PAE includes the Gloucester River downstream from the geological basin to the surface confluence with the Manning River (see companion product 1.3 for the Gloucester subregion (McVicar et al., 2015)). The main rivers in the southern part are the Mammy Johnsons River and Karuah River, both within the Karuah river basin. These comprise about 49% of the basin area and contribute about 46% of the annual flow to Port Stephens. Long-term average surface water flows have been visualised according to the techniques of McVicar et al. (2015) and are shown in Figure 7 and Figure 8 being, respectively, the broader area considering all relevant surface water connectivity with the subregion and the area zoomed to the subregion.

It is perhaps clearer in Figure 8 that in the northern part of the Gloucester subregion the streamflow contribution of the Barrington River far exceeds that of the Gloucester and Avon rivers. In the southern part, however, the upper Karuah River and Mammy Johnsons River are much more equal contributors to the streamflow further south out of the geological basin.

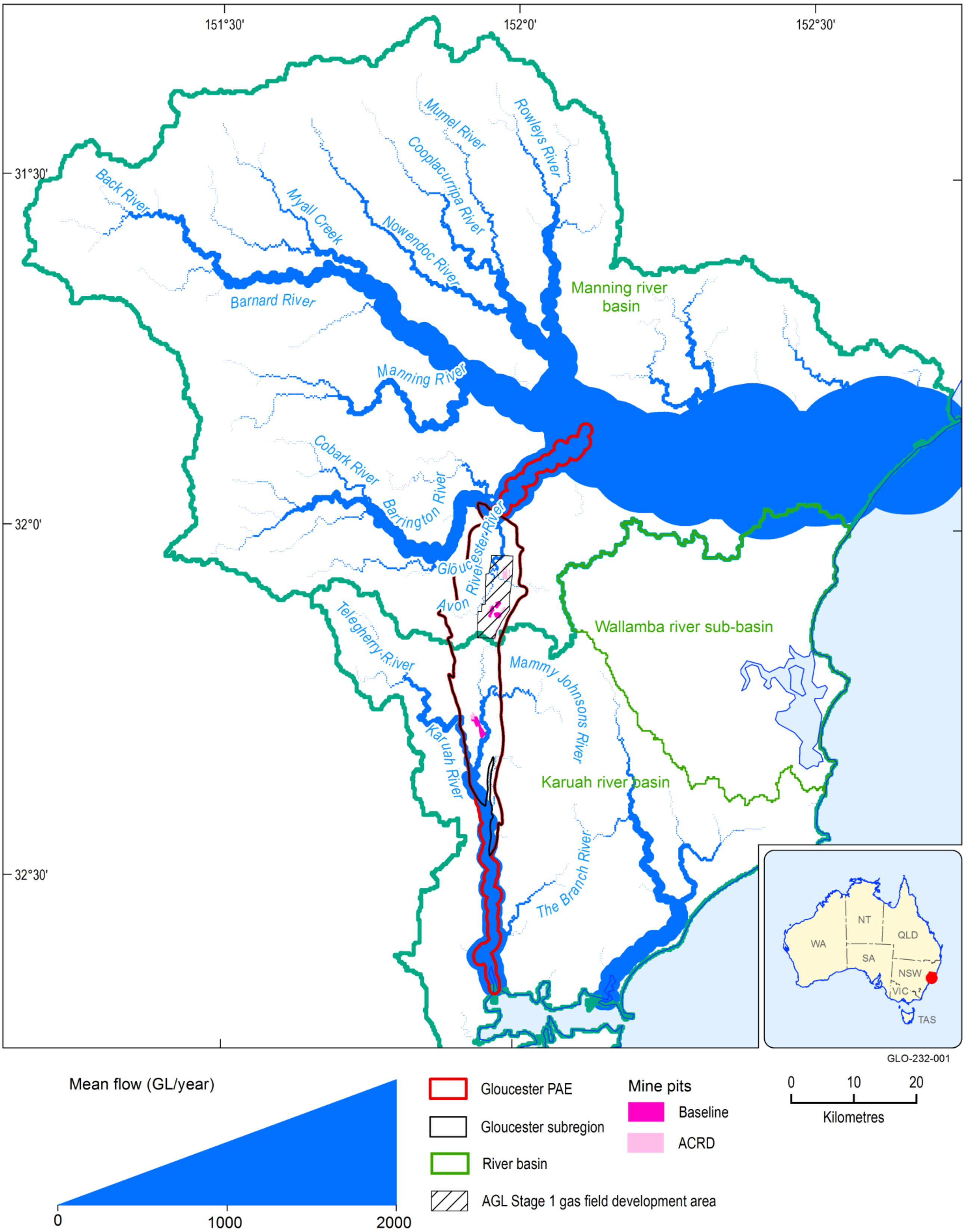

Figure 7 Surface water flows for river basins that interact with those originating in, or passing through, the Gloucester subregion

Long-term annual flow is estimated using water balance technique of Budyko (1974), as described by McVicar et al. (2015). The extent of the mines in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD). PAE = preliminary assessment extent

Data: PAE: Bioregional Assessment Programme (Dataset 1); surface water boundaries: Bioregional Assessment Programme (Dataset 2); mine pits: Bioregional Assessment Programme (Dataset 3; Dataset 4; Dataset 5) and AGL Stage 1 gas field development area: AGL Energy Ltd. (Dataset 6); flow volume: Bioregional Assessment Programme (Dataset 7)

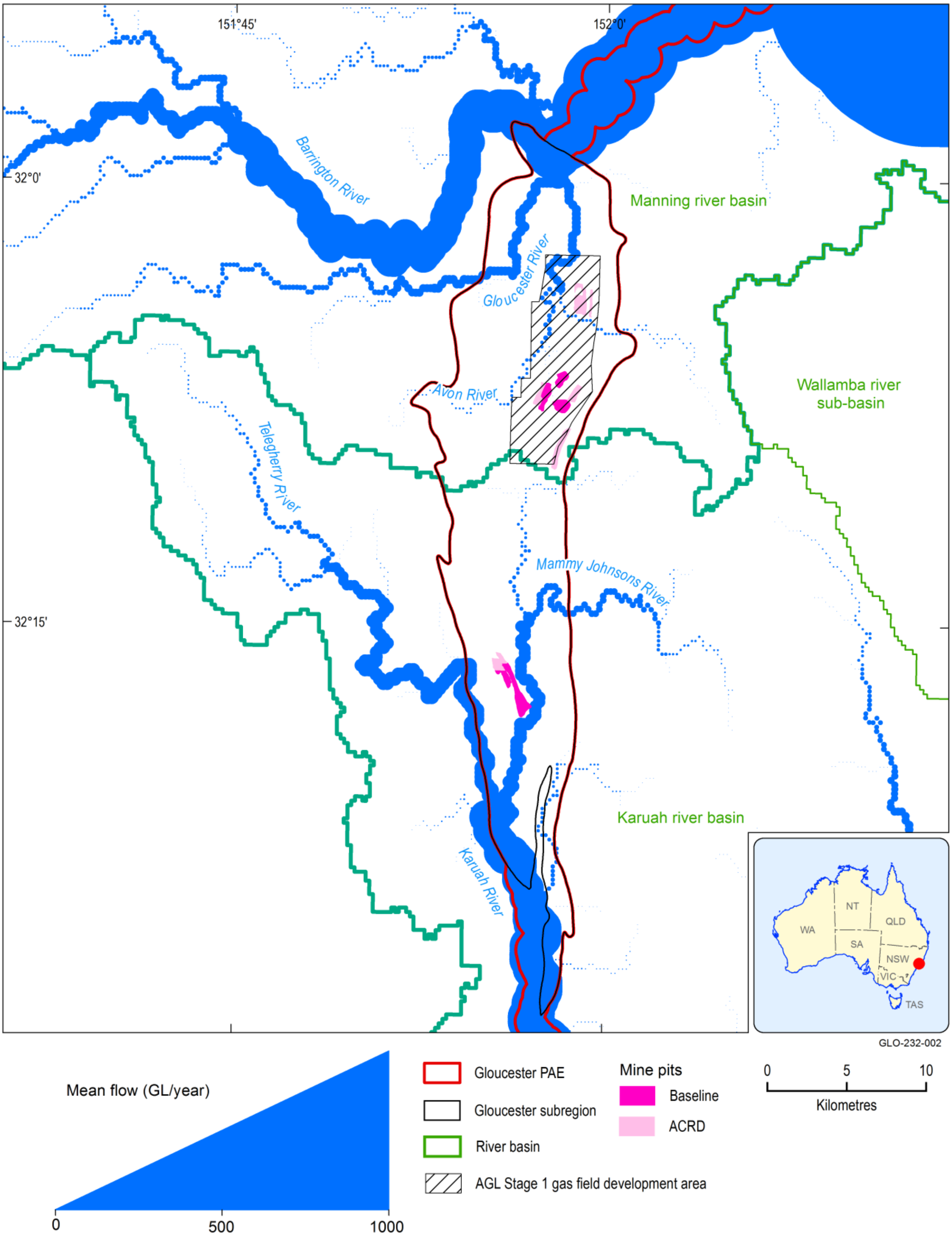

Figure 8 Surface water flows for river basins that interact with those originating in, or passing through, the Gloucester subregion, zoomed in to the subregion area

Long-term annual flow is estimated using water balance technique of Budyko (1974), as described by McVicar et al. (2015). The extent of the mines in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD). PAE = preliminary assessment extent

Data: PAE: Bioregional Assessment Programme (Dataset 1); surface water boundaries: Bioregional Assessment Programme (Dataset 2); mine pits: Bioregional Assessment Programme Data (Dataset 3; Dataset 4; Dataset 5) and AGL Stage 1 gas field development area: AGL Energy Ltd. (Dataset 6); flow volume: Bioregional Assessment Programme (Dataset 7)

2.3.2.4 Water balance

The long-term water balance of a closed groundwater system such as the Gloucester subregion can be simplified greatly such that annual rainfall is equal to evapotranspiration plus streamflow. As the streams are all apparently net gaining under most natural conditions (see companion product 1.1 for the Gloucester subregion (McVicar et al., 2014)), then streamflow is surface runoff plus groundwater discharge, or baseflow. In a closed geological system such as the Gloucester subregion, and assuming steady state, rainfall recharge is equal to groundwater discharge. At the regional scale the amount of groundwater discharge that is apportioned to deep-rooted vegetation is not significant, as the current vegetation cover is overwhelmingly cleared for grazing (see companion product 1.1 for the Gloucester subregion (McVicar et al., 2014, p. 25, Figure 11; p. 32, Figure 16)), with tall vegetation, associated with deep roots, restricted to small remnant plots at the edges of the PAE. Also considered not significant is groundwater pumping, with only about 0.2 GL/year in known usage (see companion product 1.1 for the Gloucester subregion (McVicar et al., 2014, p. 61)) representing about 0.1% of the subregion's annual mean rainfall.

There are no groundwater inputs or outflows from the geological basin, and there is no hydrogeological connectivity between the geological Gloucester Basin and the surrounding areas.

Recharge has been estimated to occur across the entire Gloucester subregion; the values range spatially from zero to 23% of rainfall. The highest values occur in the alluvium and the flanks of the geological basin where deep strata outcrop (see companion product 1.1 for the Gloucester subregion (McVicar et al., 2014, p. 63, Table 5)).

Hydrological analyses indicate that the long-term (1900 to 2012) mean rainfall across the Gloucester subregion is 1100 mm/year, and the mean streamflow in the Gloucester and Avon rivers (2003 to 2013) is 326 mm/year, or 177 GL/year. The area of the northern part of the Gloucester subregion included in the surface catchments of these two rivers is 181 km^2, or 33.4% of the contributing area. Using the simplified two-component annual water balance, rainfall of 199 GL is partitioned into 59 GL of streamflow and 140 GL of evapotranspiration. Using computer models, Parsons Brinckerhoff (2013b) estimated that 1.7 GL/year was transferred upward from the SRL. Using this as a first order estimate of groundwater discharge to the stream, or baseflow, the streamflow is therefore 57.3 GL runoff (97.1%) and 1.7 GL baseflow (2.9%). If the baseflow is equal to mean catchment recharge, then this equates to 0.8% of rainfall, or 9.4 mm/year. As the mapped alluvium associated with the Gloucester and Avon rivers is only 8% of the northern surface catchment area within the subregion, the effective rate over a smaller area would be much larger.

Using baseflow separation based on digital filtering, estimates of baseflow from stream records are 27% for Avon River at Waukivory and 57% for Gloucester River at Gloucester (see companion product 1.1 for the Gloucester subregion (McVicar et al., 2014, p. 74, Section 1.1.5.3.2)). Using a simplified system based on minimum monthly flows, Parsons Brinckerhoff (2014) estimated baseflow of 6% for Avon River at Waukivory and 29% for Gloucester River at Gloucester. Using the ratio of stream and alluvium water salinity as a baseflow proportion, Frery et al. (2018, Section 2.1.6) estimated baseflow is 3% for Gloucester River at Gloucester, and about 13% for Avon River but with less than 40 data points.

For the southern part of the Gloucester subregion including the Mammy Johnsons and Karuah rivers, a similar simplified water balance can be constructed. The catchment area within the subregion is 166 km^2 and the water balance calculations continues to use only long-term mean rainfall value and assume uniform runoff production. The 1968 to 2013 mean flow of the Karuah River at Booral is 270 GL/year, which is the gauge at the southernmost tip of the Gloucester Basin. Within the subregion is 17% of the Karuah river basin area, yielding 183 GL of rainfall partitioned into 46 GL of streamflow and 137 GL of evapotranspiration. Using the range of stream salinity at this gauge of 100 to 350 µS/m (see companion product 1.1 for the Gloucester subregion (McVicar et al., 2014, Section 1.1.5)) and assuming the same alluvial salinity as for the northern part of 3000 µS/m, the ratio of salinities yields 3.3 to 11.7% as a first order baseflow estimate. The volume this represents is 1.5 to 5.4 GL, leaving runoff as 44.5 to 40.6 GL, respectively. Baseflow separation by digital filtering estimates baseflow at 34% for Mammy Johnsons River and 40% for Karuah River at Booral (see McVicar et al., 2014, Section 1.1.5.3.2).

2.3.2.5 Gaps

The major gap describing groundwater processes in the Gloucester subregion is the lack of knowledge of geological structures, particularly faults, including (i) their nature as carriers or barriers to flow, (ii) their location spatially and (iii) their extent vertically throughout the coal seam and shallower layers. Within the Assessment efforts have been made to understand the faulting and layering of the subregion using existing deep well and geophysical datasets. This work is summarised in Section 2.1.3 of companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018).

The major faults and sub-seismic fault distribution estimates are used in numerical modelling of the deep strata with 10,000 random realisations of faults. The results are described in companion product 2.6.2 for the Gloucester subregion (Peeters et al., 2018). That work was done in a probabilistic manner and showed that at the regional scale there was a low chance of propagation of drawdown from mining and CSG operations (random well locations). No modelling was performed for specific locations with known or proposed wells for local effects only.

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2.3.3 Ecosystems

Summary

To deal with the complexity of a large number of diverse assets, a landscape classification was developed to group assets with similar hydrological function. Landscape classes were identified within five broad groups: ‘Riverine’, ‘Groundwater-dependent ecosystems (GDEs)’, ‘Estuarine’, ‘Non-GDE vegetation’ and ‘Economic land use’. Less than 3000 ha of the preliminary assessment extent (PAE; 46,820 ha in total) fell into the ‘Riverine’, ‘Estuarine’ and ‘Groundwater-dependent ecosystem (GDE)’ landscape groups. Seven landscape classes in the ‘Riverine’ landscape group were defined based on hydrology and river bed substrate. The dominant ecohydrology was perennial streams and lowly intermittent streams, and the dominant river substrate was gravel/cobble. Both types of streams are expected to have significant groundwater dependence in addition to surface water dependence. Five landscape classes in the terrestrial ‘Groundwater-dependent ecosystem (GDE)’ landscape group were defined based on vegetation formations: ‘Rainforest’, ‘Forested wetlands’, ‘Freshwater wetlands’, ‘Wet sclerophyll forests’ and ‘Dry sclerophyll forests’. Both the mapping of vegetation and the nature of the water dependence of some identified GDEs are significant sources of uncertainty. Possible water-dependencies of each landscape class in the ‘Groundwater-dependent ecosystem (GDE)’ landscape group are suggested based on vegetation descriptions and expert advice. Two landscape classes in the ‘Estuarine’ landscape group are defined: the Karuah River estuary is classified as a ‘Barrier river’ while the fringing vegetation of the estuary is defined as ‘Saline wetlands’. Both are likely to have tidal influences in addition to possible groundwater and surface water dependencies. Of the remainder of the PAE, there are 13,000 ha of non-GDE native vegetation and 31,000 ha of cleared land that is mainly dryland agriculture (28,000 ha) and intensive uses (2,000 ha).

2.3.3.1 Landscape classification

2.3.3.1.1 Methodology

Bioregions often contain a large number and diverse range of assets. To deal with this complexity, a landscape classification was developed to group assets that function similarly with respect to hydrology. This section describes the methodology and datasets used to arrive at the landscape classification for ecological assets within the Gloucester PAE. Landscape classes were defined within five broad groups:

- *‘Riverine’ landscape group*. Landscape classes in the riverine landscape group are based on ecohydrology and substrate layers supplied by the NSW Office of Water (Dataset 1) and derived from the River Styles® Framework (River Styles) in NSW (Brierley and Fryirs, 2000). The use of the River Styles offers significant advantages over frameworks such as the Geofabric (Bureau of Meteorology, Dataset 2) as ecologically relevant information is associated with River Styles via the application of the River Condition Index (RCI; Healey et al., 2012) by relevant NSW state agencies. The RCI was developed to combine multiple indices into a single condition score for monitoring, evaluating and reporting on river condition. The RCI is based on the Framework for Assessing River and Wetland Health (FARWH) (Norris et al., 2007). In addition to the RCI, the indices that contribute to the RCI and the ecological datasets that underpin these indices are available for River Styles and can be used within a BA, as required, for modelling impacts of coal seam gas (CSG) and/or large coal mining development on riverine classes.

- *'Groundwater-dependent ecosystem (GDE)' landscape group*. Landscape classes in the GDE landscape group were based on the NSW Office of Water mapping of GDEs (NSW Department of Primary Industries, Dataset 3). The NSW Office of Water's methodology combines vegetation mapping, optical remote sensing (from the Landsat and MODIS instruments), 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 NSW Office of Environment and Heritage's (NSW OEH) mapping of wetlands (NSW Office of Environment and Heritage, Dataset 4) and 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 1 (NSW Office of Water) allowed the classification of landscape classes to reflect the underlying function of the wetlands with which they are associated. By contrast, the NSW OEH (NSW Office of Environment and Heritage, Dataset 4) mapping of wetlands was largely restricted to coastal areas, was last updated in 2004 and does not report underlying wetland function.
- *'Estuarine' landscape group*. Landscape classes in the estuarine landscape group were based on both the ecohydrology and substrate layers described above (NSW Office of Water, Dataset 1) for estuarine river reaches, and the mapping of saline wetlands provided by the NSW OEH (Department of Primary Industries, Dataset 6).
- *'Non-GDE' landscape group*. Native vegetation that was not identified as being groundwater dependent was classified as 'native vegetation' based on the Hunter Native Vegetation Mapping (Bioregional Assessment Programme, Dataset 7).
- *'Economic land use' landscape group*. Remaining areas of the Gloucester PAE that were still unclassified were assigned a landscape classification based on the Australian Land Use and Management (ALUM) Classification of Australia (for catchment-scale land use classification in Australia), Update 14 (Australian Bureau of Agricultural and Resource Economics Bureau of Rural Sciences, Dataset 8).

The landscape classification for the Gloucester subregion is shown in Figure 9 and in Table 3 and explained in detail in Section 2.3.3.1.2.

Table 3 Summary of landscape classes in the Gloucester preliminary assessment extent

Landscape group	Landscape class
Riverine	Intermittent – gravel/cobble streams
	Intermittent – high gradient bedrock confined streams
	Intermittent – lowland fine streams
	Perennial – gravel/cobble streams
	Perennial – high gradient bedrock confined streams
	Perennial – lowland fine streams
	Perennial – transitional fine streams
Groundwater-dependent ecosystem (GDE)	Dry sclerophyll forests
	Forested wetlands
	Freshwater wetlands
	Rainforests
	Wet sclerophyll forests
Estuarine	Barrier river
	Saline wetlands
Non-GDE	Native vegetation
Economic land use	Dryland agriculture
	Intensive uses
	Irrigated agriculture
	Plantation or production forestry
	Water

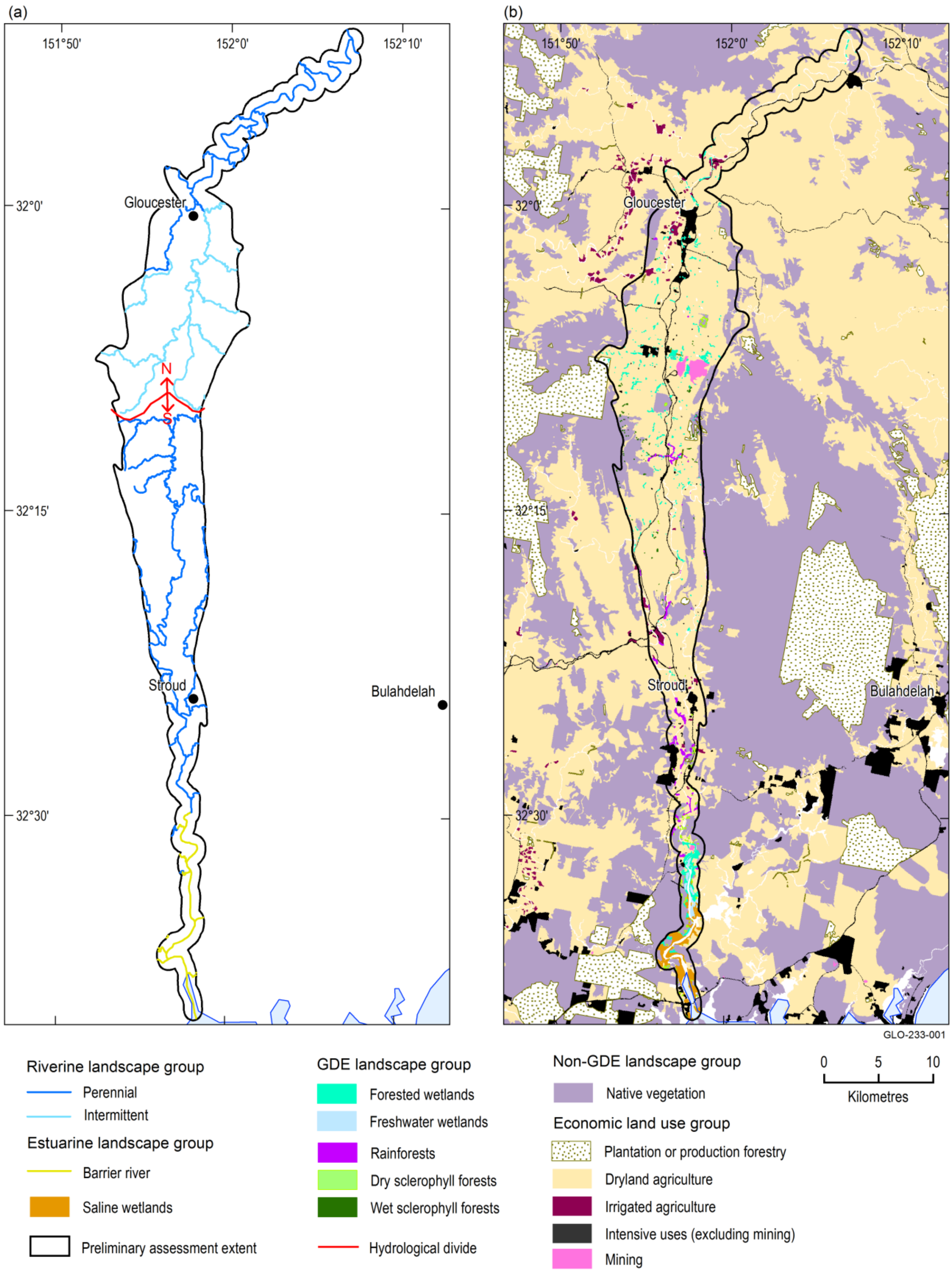

Figure 9 Map of landscape classes in the Gloucester subregion

For clarity, only the hydrology component of the landscape classification is illustrated (perennial, intermittent or estuarine) and the 'Water' landscape class in the economic land use group is omitted. GDE = groundwater-dependent ecosystem. The Australian Land Use and Management (ALUM) land use data used for (b) are current for this area as at 1999 and hence the Duralie Coal Mine, which commenced after then, is not shown.
Data: Australian Bureau of Agricultural Resource Economics Bureau of Rural Sciences (Dataset 8, Dataset 9); NSW Office of Water (Dataset 10)

2.3.3.1.2 Landscape classification

2.3.3.1.2.1 Landscape classes in the 'Riverine' landscape group

The River Styles classification of rivers is widely used in NSW but is largely based on river geomorphology, which primarily focuses on the physical structure of a river (Brierley and Fryirs, 2000). Factors such as shape, cross-section and substrate, the extent of channel confinement, and the presence or absence of pools and riffles are all factors in the designation of a river style (Brierley et al., 2010). A geomorphological approach is appropriate for river management activities such as rehabilitation that 'manipulate the physical structure of a river (its geomorphology) in attempts to improve water quality and enhance ecological values' (Brierley et al., 2010), especially at local scales. However, for a regional-scale assessment it is not possible to model individual pools and riffles, nor is it possible to deal with the complexity of many tens of river styles. The focus of the BAs is on changes to flow volumes and regimes, which logically suggests a more hydrologically-oriented classification such as the Australian National Aquatic Ecosystem (ANAE) Classification Framework (Brooks et al., 2014), in which rivers are classified firstly on flow regime and then on relevant aspects of landform (e.g. landscape position of riverbed substrate). The hydrological classification is important because it reflects the underlying water dependence of the different rivers.

A classification for rivers in the Gloucester PAE was provided by The NSW Office of Water (Dataset 1) that combined hydrological information with a key aspect of geomorphology: substrate. Substrate has a general relationship with river geomorphology. For example, bedrock confined streams are frequently high-energy upland streams while finer substrate streams and gravel or cobble substrate streams are frequently on lowlands (Boulton et al., 2014, p. 101). In the Gloucester PAE this classification scheme yielded seven landscape classes in the riverine landscape group and one landscape class in the estuarine landscape group. This initial classification was further amalgamated to underpin the BA (Table 4). The NSW Office of Water classification identifies four ecohydrological classes, broadly based on Kennard et al. (2008): perennial (strong baseflow contribution), lowly intermittent (rarely cease to flow; moderate baseflow contribution), moderately intermittent (regularly cease to flow; runoff dominated) and highly intermittent or ephemeral (rarely flow; runoff dominated). Only perennial and lowly intermittent streams are present in the Gloucester PAE and these are likely to have some groundwater dependence, whereas moderately and strongly intermittent streams are strongly surface water (runoff) dependent.

Table 4 Landscape classes in the 'Riverine' and 'Estuarine' landscape groups derived from river types supplied by the NSW Office of Water for the Gloucester preliminary assessment extent

River type	Percentage of stream length (%)	Bioregional assessment landscape class
Perennial flow, permanent pools – high-gradient bed rock confined	18%	Perennial – high gradient bedrock confined streams
Perennial flow, permanent pools – transitional fine	3%	Perennial – transitional fine streams
Perennial flow, permanent pools – lowland fine	<1%	Perennial – lowland fine streams
Perennial flow, permanent pools – gravel and cobble with pools	47%	Perennial – gravel/cobble streams
Lowly intermittent flow, permanent pools – high gradient bed rock confined	3%	Intermittent – high gradient bedrock confined streams
Lowly intermittent flow, permanent pools – lowland fine	<1%	Intermittent – lowland fine streams
Lowly intermittent flow, no pools – valley fill no pools	1%	Intermittent – lowland fine streams
Lowly intermittent flow, permanent pools – gravel and cobble with pools	16%	Intermittent – gravel/cobble streams
Lowly intermittent flow, limited pools – entrenched	2%	Intermittent – gravel/cobble streams
Tidal flow, permanent pools – tidal	9%	Estuarine – barrier river

Data: NSW Office of Water (Dataset 1)

River reaches within the Gloucester PAE are dominated (47% of total stream length) by perennial streams with gravel or cobble substrate; these are mainly in the south of the PAE but also included the Gloucester River in the north. In the north of the PAE, intermittent streams with gravel or cobble substrate are more common. High-gradient perennial and intermittent streams with confined bedrock substrate comprise 21% of the total stream length and are located on the fringes of the PAE. Streams with fine substrate are uncommon (less than 6% of total stream length). For reference, the River Styles in Gloucester PAE are predominantly of the 'Partly confined valley setting' type (66%), with significant 'Confined valley setting' (21%) and 'Laterally unconfined valley setting' (12%).

Note that some river types have been amalgamated to create landscape classes in the riverine landscape group for convenience. The 'Lowly intermittent flow, no pools – valley fill no pools' river type deserves special mention. This river type comprises less than 1% of all streams in the Gloucester subregion and these have been combined with other river reaches with fine-textured substrate to create the 'Intermittent – lowland fine streams' landscape class in the riverine landscape group. 'Valley fill' river reaches are highly fragile and can be of great ecological significance when not degraded by catchment clearing and other land uses because this was the natural state of many small- and medium-sized streams (Rutherford et al., 2000). In the area managed by the former Hunter-Central Rivers Catchment Management Authority (which entirely covers the Gloucester PAE), reaches with this geomorphology are frequently in poor condition as a result of livestock grazing (Cook and Schneider, 2006). This can result in loss of native vegetation, incision and transport of sediment downstream. Incision may lead to draining of alluvial aquifers present in these systems resulting in the discharge of salt from surrounding sediments (Cook and Schneider, 2006). The high ecological significance of this river type lies primarily in its vegetation rather than its in-channel habitat (it typically contains no permanent pools) and its GDE values are captured in the landscape classes in the 'Groundwater-dependent ecosystem (GDE)' landscape group (see Section 2.3.3.1.2.2). In addition to its very limited extent within the Gloucester PAE, it was determined that this was reason to combine it with another river type to construct a landscape class for the BA. In other subregions where this river type is both more prevalent and contains very high ecological value ecosystems such as upland swamps, it may be considered as a separate landscape class. The 'Lowly intermittent flow, limited pools – entrenched' river type comprised only 2% of the total stream length in the Gloucester PAE and is a degraded river type with little ecological value. It has a gravel or cobble substrate, resulting from channel instability, incision and sediment release (Cook and Schneider, 2006), possibly of former 'Valley fill' river reaches. For convenience it has been amalgamated with the dominant substrate type cobble/gravel.

Landscape classes in the riverine landscape group provide potential in-channel habitat for several species whose potential distributions form part of the register of water-dependent assets (Bioregional Assessment Programme, Dataset 11). These include fish and frogs (including the Stuttering and Giant Barred frogs, listed in the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act)), and the community-nominated platypus, as well as freshwater oyster-growing regions of the Karuah River. Whilst the riverine landscape group is intended to capture in-channel habitats, rivers are necessarily connected to GDE vegetation that supports a range of terrestrial species, via the riparian zone. Hence, it is anticipated that conceptual models of the riverine landscape group would include riparian vegetation elements and that there would be some overlap between riverine and some GDE conceptual models, although GDE vegetation is primarily dealt with through the 'Groundwater-dependent ecosystem (GDE)' landscape group (described in Section 2.3.3.1.2.1).

2.3.3.1.2.2 Landscape classes in the 'Groundwater-dependent ecosystem (GDEs)' landscape group

The NSW Office of Water methodology (Dabovic et al., *in prep*) defines GDEs as ecosystems 'which have their species composition and natural ecological processes wholly or partially determined by groundwater'. 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 vadose 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). Of the twelve vegetation formations used across NSW, six have been identified in the Gloucester PAE (Table 5), and all were identified in the GDE mapping. The areas of each within the PAE, along with their BA landscape class names, are given in Table 6.

Table 5 Description of Keith's (2004) vegetation formations

Vegetation formation	Description
Rainforests	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 forests	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 forests	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 wetlands	Freshwater wetlands occur on areas where 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 wetlands	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.
Saline wetlands	Saline wetlands occur 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.

Source: Somerville (2009)

The 'Saline wetlands' landscape class accounted for 35% of the GDE area within the PAE and is restricted to the far south of the PAE along with 'Freshwater wetlands' landscape class (Table 7); the latter accounts for only 7% of GDEs in the PAE. 'Forested wetlands' landscape class accounts for the majority of non-estuarine GDEs in the Gloucester PAE (33%; Table 6) and are overwhelmingly in the 'Coastal floodplain wetland' Keith vegetation class. The 'Rainforests' landscape class is overwhelmingly composed of the 'Northern warm temperate rainforests' Keith vegetation class (Table 6). The 'Subtropical rainforests' Keith vegetation class includes 'Lowland Subtropical Rainforest on Basalt Alluvium in NE NSW and SE Qld', a threatened ecological community listed in the register of water-dependent assets (Bioregional Assessment Programme, Dataset 11), makes up a very small fraction of all the 'Rainforests' landscape class. Rainforests are also predominantly in the southern part of the PAE. Similarly the 'Dry sclerophyll forests' landscape class is concentrated in the southern part of the PAE; this landscape class is dominated by the 'Hunter-Macleay dry sclerophyll forests' Keith vegetation class. The 'Wet sclerophyll forests' landscape class has a very scattered distribution and is mainly in the north of the PAE; this landscape class is overwhelmingly dominated by the 'North Coast wet sclerophyll forests' Keith vegetation class. Only forested wetlands and rainforests occur above the alluvium to any significant extent. All other GDE types occur away from the alluvium.

Table 6 Area of landscape classes in the 'Groundwater-dependent ecosystem (GDE)' landscape group, and the 'Estuarine – saline wetlands' landscape class, within the preliminary assessment extent of the Gloucester subregion

Bioregional assessment landscape class	Keith[a] vegetation formation	Keith[a] vegetation class	Total area (ha)	Percentage of total GDE area (%)	Percentage of total PAE area (%)	Percentage of GDE area located on the alluvium (%)
Rainforests	Rainforests		220	14%	0.5%	47.9%
		Dry rainforests	9.2	1%	0.0%	1.6%
		Northern warm temperate rainforests	210	13%	0.4%	50.2%
		Subtropical rainforests	0.8	0%	0.0%	0.0%
Wet sclerophyll forests	Wet sclerophyll forests		36	2%	0.1%	0.0%
		North Coast wet sclerophyll forests	36	2%	0.1%	0.0%
		Northern hinterland wet sclerophyll forests	0.7	0%	0.0%	0.0%
Dry sclerophyll forests	Dry sclerophyll forests		139	9%	0.3%	1.0%
		Coastal dune dry sclerophyll forests	27.8	2%	0.1%	0.0%
		Hunter-Macleay dry sclerophyll forests	89	6%	0.2%	1.5%
		Sydney coastal dry sclerophyll forests	22	1%	0.0%	0.0%
Freshwater wetlands	Freshwater wetlands		112	7%	0.2%	0.0%
		Coastal freshwater lagoons	112	7%	0.2%	0.0%
Forested wetlands	Forested wetlands		519	33%	1.1%	16.7%
		Coastal swamp forests	15.1	1%	0.0%	17.1%
		Coastal floodplain wetlands	504	32%	1.1%	0.0%
		Eastern riverine forests	2.9	0%	0.0%	10.2%
Saline wetlands	Saline wetlands		541	35%	1.2%	0.0%
		Mangrove swamps	482	31%	1.0%	0.0%
		Saltmarshes	59	4%	0.1%	0.0%

PAE = preliminary assessment extent
The PAE of the Gloucester subregion covers 46,820 ha.
[a]Keith's (2004) classification of vegetation communities into 'formations' and 'classes'
Data: NSW Department of Primary Industries (Dataset 3)

GDEs provide habitat for many of the species whose potential distributions form part of the register of water-dependent assets (Bioregional Assessment Programme, Dataset 11). For example, animals such as koalas, birds of prey, honeyeaters and flying foxes may live, roost or nest in trees within GDEs. Some state and nationally listed plant species, such as the leafless tongue orchid, may be associated with GDE vegetation. GDEs along river banks (i.e. riparian vegetation) 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. Riparian vegetation affects both the physical and chemical properties of river channel habitats by providing shade, as well as large woody debris and fine litter. This provides in-channel habitats as well as energy for instream biota, and can maintain or alter stream geomorphology.

The nature of groundwater and/or surface water dependence of much GDE vegetation is 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 to access (Cole et al., 1997). The dependence of terrestrial vegetation on groundwater is difficult to predict or quantify (Eamus et al., 2006). Riparian and near-riparian vegetation may have an absolute dependency on groundwater (obligate phreatophyte) while vegetation further 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, individuals within a community may require flooding events for seedling recruitment and survival during early life stages, but be reliant on groundwater in later 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 abstraction have been shown to result in morbidity and death of GDE vegetation (Groom et al., 2000).

The following water dependencies associated with landscape classes were identified:

- *Local rainfall*. These vegetation communities are dependent on local rainfall only and will not be affected by abstraction of regional groundwater or changed surface water flows, but could be impacted by local development such as clearing associated with CSG and/or coal mine establishment and operation.
- *Local groundwater*. These vegetation communities may rely on local aquifers that are unconnected to regional groundwater aquifers (e.g. perched aquifers above basement rock). They will also 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 transmittance of the alluvial system).
- *Surface water*. These vegetation communities are dependent on surface flows from flooding events for their maintenance.

- *Regional groundwater*. These vegetation communities 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.

The water dependencies of the Keith vegetation formations and associated Keith vegetation classes in the Gloucester PAE are presented in Table 7. These are based on general information about the location of the classes within the landscape, their characteristics and associated species from Keith (2004), lists of known GDEs and expert advice from the NSW OEH. Although some vegetation formations have been judged as unlikely to be water dependent for the purposes of the BA, they are nonetheless present in the NSW Office of Water mapping of GDEs (NSW Department of Primary Industries, 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 2.3.3.1.3). This uncertainty is a key reason why vegetation formation, rather than vegetation class, was adopted as the landscape class for the 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 (receptor impact modelling) for the Gloucester subregion). Where a landscape class contains Keith vegetation classes that are heterogeneous with regard to their water dependencies (e.g. 'Coastal swamp forests' Keith vegetation class and 'Eastern riverine forests' Keith vegetation class within the 'Forested wetlands' landscape class) it may be necessary to develop more than one detailed receptor impact model for that landscape class within a region. In the Gloucester subregion, the 'Forested wetlands' landscape class is represented almost exclusively by the 'Coastal floodplain wetlands' Keith vegetation class.

Table 7 Water dependence of landscape classes in the 'Groundwater-dependent ecosystem (GDE)' landscape group and the 'Estuarine – saline wetlands' landscape class and their associated Keith (2004) vegetation classes

Bioregional assessment landscape class	Keith[a] (2004) vegetation class	Water dependence
Rainforests	Dry rainforests	Regional groundwater
	Northern warm temperate rainforests	Local and regional groundwater
	Subtropical rainforests	Regional groundwater; surface water
Wet sclerophyll forests	North Coast wet sclerophyll forests	Local and regional groundwater
	Northern hinterland wet sclerophyll forests	Local groundwater
Dry sclerophyll forests	Coastal dune dry sclerophyll forests	Local groundwater
	Hunter-Macleay dry sclerophyll forests	Local groundwater
	Sydney coastal dry sclerophyll forests	Local groundwater
Freshwater wetlands	Coastal freshwater lagoons	Regional groundwater
Forested wetlands	Coastal swamp forests	Regional groundwater
	Coastal floodplain wetlands	Regional groundwater; surface water
	Eastern riverine forests	Regional groundwater; surface water
Saline wetlands	Mangrove swamps	Regional groundwater; surface water; tidal
	Saltmarshes	Regional groundwater; surface water; tidal

[a]Keith's (2004) classification of vegetation communities into 'formations' and 'classes'

2.3.3.1.2.3 Landscape classes in the 'Estuarine' landscape group

The estuarine reaches of the Karuah River are classified as 'Barrier river' landscape class (Table 4), consistent with the classification system used by the NSW OEH (Roper, 2004). As described in Section 2.3.3.1.2.2 for GDEs, the 'Saline wetlands' landscape class (Table 5) is defined based on mapping of GDEs to Keith's (2004) vegetation formations. Saline wetlands are all in the estuarine reaches of the Karuah River and are mainly mangroves with some saltmarshes (Table 6). Saline wetlands are habitats for animals such as waterbirds and migratory birds, as well as fish and a diverse assemblage of invertebrates. Reduced freshwater pulses and flooding, and groundwater abstraction, may impact on a variety of freshwater habitats and in-channel biological processes, and result in the spread of saline wetlands further upstream.

2.3.3.1.2.4 Landscape classes in the 'Non-GDE' landscape group

Over 13,000 ha of native vegetation within the Gloucester PAE is not classified as GDE. All the native vegetation outside that mapped in the riverine, GDE and estuarine landscape groups is considered not to be dependent on surface or groundwater. Of this 13,000 ha, over 10,000 ha was classified as dry sclerophyll forest or wet sclerophyll forest. A further 1500 ha was classified as rainforest, 1700 ha classified as forested wetland, and 118 ha classified as saline wetland. No native vegetation was classified as freshwater wetland. The fact that the 1700 ha of native vegetation classified as forested wetland was not classified as GDE reflects the large uncertainties (see Section 2.3.3.1.3) associated with the remote classification of both vegetation formation (Hunter, 2015) and groundwater dependency (Eamus et al., 2015).

2.3.3.1.2.5 Landscape classes in the 'Economic land use' landscape group

Over 31,000 ha of the Gloucester PAE did not overlap with any of the landscape classes defined in Section 2.3.3.1.2.1, Section 2.3.3.1.2.2 and Section 2.3.3.1.2.4. These areas were classified using 'ALUM' (for catchment-scale land use management classification in Australia), Update 14 (ABARES-BRS, Dataset 8) as follows:

- *Plantation or production forestry*. This corresponds to ALUM classes 2.1 (Grazing native vegetation), 2.2 (Production forestry), 3.1 (Plantation forestry) and 4.1 (Irrigated plantation forestry).
- *Dryland agriculture*. This corresponds 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*. This corresponds 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 uses*. Land is subject to substantial modification, generally in association with closer residential settlement, commercial or industrial uses. This class includes mining.
- *Water*. Mainly reservoirs and dams.

Most (nearly 28,000 ha) of the remaining unclassified area is classified as 'Dryland agriculture '. Nearly 2000 ha is classified as 'Intensive uses' (mainly urban and mining) and nearly 1000 ha is classified as 'Water' (reservoirs, etc.).

2.3.3.1.3 Gaps

Bioregional assessments 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 (CSIRO Land and Water, Dataset 7) on which the mapping of GDEs is based (NSW Department of Primary Industries, 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.

This uncertainty adds to the overall uncertainty regarding the impact, if any, of 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 in 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 for subregions that 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 (1–3 km river lengths) used within River Styles is already quite detailed for a regional-scale analysis. Individual hillslope processes are not being quantitatively modelled. As mentioned in Section 2.3.3.1.2, changes in geomorphology that might result from development activities or remedial activities to improve geomorphology of degraded river sections are not within scope of the BA. This would require detailed cross-sections for river reaches in proximity to development and remediation activities and more detailed modelling than is possible within the current round of the BA. 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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2.3.4 Baseline and coal resource development pathway

The existing and most likely coal and coal seam gas (CSG) resource developments within the Gloucester subregion are summarised in this section. This section builds on information provided in Section 1.2.3 and Section 1.2.4 of companion product 1.2 for the Gloucester subregion (Hodgkinson, 2014) and companion product 2.6.1 (Zhang et al., 2018) and companion product 2.6.2 (Peeters et al., 2018) about locations, resource figures and development status relative to environmental impact statements (EISs). In some cases, the current status is prior to an EIS being submitted and its inclusion in Table 8 does not imply that development will necessarily occur. The area of AGL Energy Limited's (AGL) proposed Stage 1 gas field development area is also included in Figure 10. Coal mine expansion is planned at Yancoal Australia Ltd's (Yancoal) Stratford and Duralie mines and a new coal mine is planned by Gloucester Resources Limited (GRL) at Rocky Hill. For numerical modelling purposes the coal resource development pathway (CRDP) was finalised in October 2015, and while AGL withdrew from their proposed Gloucester Gas Project in December 2015, as per the companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis et al., 2014), the CRDP was not revisited.

Water management information for three coal mines and a gas project is also summarised. In the Gloucester subregion, water management plans for existing and proposed coal and CSG resource developments are designed to achieve no overflow from on-site water storages to the neighbouring water bodies. Excess water is disposed through on-site irrigation.

2.3.4.1 Developing the coal resource development pathway

The information summarised here was obtained from companion product 1.2 for the Gloucester subregion (Hodgkinson et al., 2014). The baseline coal resource development (baseline) comprises Duralie and Stratford mines. The coal resource development pathway also includes the Duralie and Stratford mines and their expansions post December 2012 as well as Rocky Hill Mine and Stage 1 gas field development area of AGL's proposed CSG development in the Gloucester Gas Project. The CRDP was confirmed in October 2015. There may be further stages (beyond Stage 1) of AGL's proposed CSG development in the Gloucester Gas Project but there is no publicly available documentation of these as at October 2015. While AGL withdrew from their proposed Gloucester Gas Project in December 2015, as per the companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis et al., 2014), the CRDP was not revisited.

Figure 10 shows the location of coal mines and CSG deposits in the Gloucester subregion and the area proposed for AGL's Stage 1 gas field development area. Table 8 lists potential developments with locations, resource figures and development status. CSG resources are reported as proved plus probable reserves (2P) using the Petroleum Resource Management System (PRMS). Figure 11 shows timelines for coal resource developments in the Gloucester subregion.

The locations of Rocky Hill coal deposit and AGL's Stage 1 gas field development area have been added from publicly available company documents. Coal resource figures presented in Table 8 are from the OZMIN database (Geoscience Australia, Dataset 1), with more recent updates added using information available from Yancoal Australian Stock Exchange 2013 (Yancoal, 2014) releases and from the Gloucester Resources Limited (2013) EIS for its proposed Rocky Hill coal development. CSG resource numbers in Table 8 are from AGL (AGL Energy Limited, 2013).

In late 2012, the NSW Government introduced its Strategic Regional Land Use Policy to protect valuable residential and agricultural land across NSW from the impacts of mining and CSG activity (NSW Government, 2014). Information was released in January 2014, identifying the areas of Biophysical Strategic Agricultural Land – land of high quality soil and water resources capable of supporting high levels of agricultural production – across NSW, which are deemed necessary to support the state's $12 billion per year agricultural industry. CSG exclusion zones were identified by Strategic Agricultural Lands in 2013 (NSW Government, 2013) and are shown in Figure 12.

Table 8 Existing operations and proposed developments in the baseline coal resource development, additional coal resource development and coal resource development pathway as at October 2015

The primary activity in bioregional assessments (BAs) is the comparison of two potential futures: (i) the 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; and (ii) the coal resource development pathway (CRDP), a future that includes all coal mines and CSG fields that are in the baseline as well as those that are expected to begin commercial production after December 2012. The difference between CRDP and baseline (known as the additional coal resource development) is the change that is primarily reported in a BA.

Name of existing operation or proposed development	Coal mine or coal seam gas (CSG) operation	Company	Included in baseline?	Included in coal resource development pathway (CRDP)?	Start of mining operations or estimated project start	Projected mine life or estimated project life	Tenement(s)	Total coal resources (Mt)[a] (for coal mining) or 2P[b] gas reserves (for CSG) (PJ)	Comments
Duralie Coal Mine	Open-cut coal mine	Yancoal Australia Ltd	Yes	Yes – model	2003	2017	ML 1427	148[c]	None needed
Duralie Coal Mine expansion	Open-cut coal mine	Yancoal Australia Ltd	No	Yes – model	2013	2024	ML 1427,ML A1	8.9[c]	Expansion approved by NSW Land and Environment Court, November 2011
Stratford Mining Complex	Open-cut coal mine	Yancoal Australia Ltd	Yes	Yes – model	1995	2026	ML 1360, ML 1409, ML 1447, ML 1521,ML 1538, ML 1577, ML 1528	98[c]	None needed
Stratford Mining Complex expansion	Open-cut coal mine	Yancoal Australia Ltd	No	Yes – model	2015	2026	ML 1360, ML 1409, ML1447, ML 1521, ML 1528, ML 1538, ML 1577, EL 6904, EL 311, EL 315	24.15[c]	Extension approved by NSW Planning Assessment Commission, May 2015
Rocky Hill Coal Project	Open-cut coal mine	Gloucester Resources	No	Yes – model	2016? If approval granted	2037	EL 6523, EL 6524, EL 6563	25[c]	On hold by NSW Government, as at June 2015
Gloucester Gas Project stage 1	CSG	AGL	No	Yes – model	2016	15–25 years (depending on the extent of the CSG resources)	PEL 285	454[b] for Gloucester Basin exploration to December 2013	Waukivory Pilot Project approved by NSW Government August 2014. AGL final investment decision expected late 2015

Name of existing operation or proposed development	Coal mine or coal seam gas (CSG) operation	Company	Included in baseline?	Included in coal resource development pathway (CRDP)?	Start of mining operations or estimated project start	Projected mine life or estimated project life	Tenement(s)	Total coal resources (Mt)[a] (for coal mining) or 2P[b] gas reserves (for CSG) (PJ)	Comments
Gloucester Gas Project stage 2 and beyond	CSG	AGL	No	Yes – commentary	Unknown (as at June 2015)	Unknown (as at June 2015)	PEL 285	Included in 454[c] for Gloucester Basin exploration to December 2013	Conceptual only as at June 2015. Mainly west and south of stage 1

[a]Indicates the different resource classes that may combine to form the total resource tonnage – typically these are reported in accordance with the Joint Ore Reserves Committee (JORC) Code. For example, the different JORC resource classes of measured, indicated and inferred resources could be shown (or whichever combination of resource classes is applicable for each project).
[b]proved plus probable reserves
[c]Resource figure is for the entire life of the project.
EL = exploration licence; PEL = petroleum exploration licence; ML = mining lease

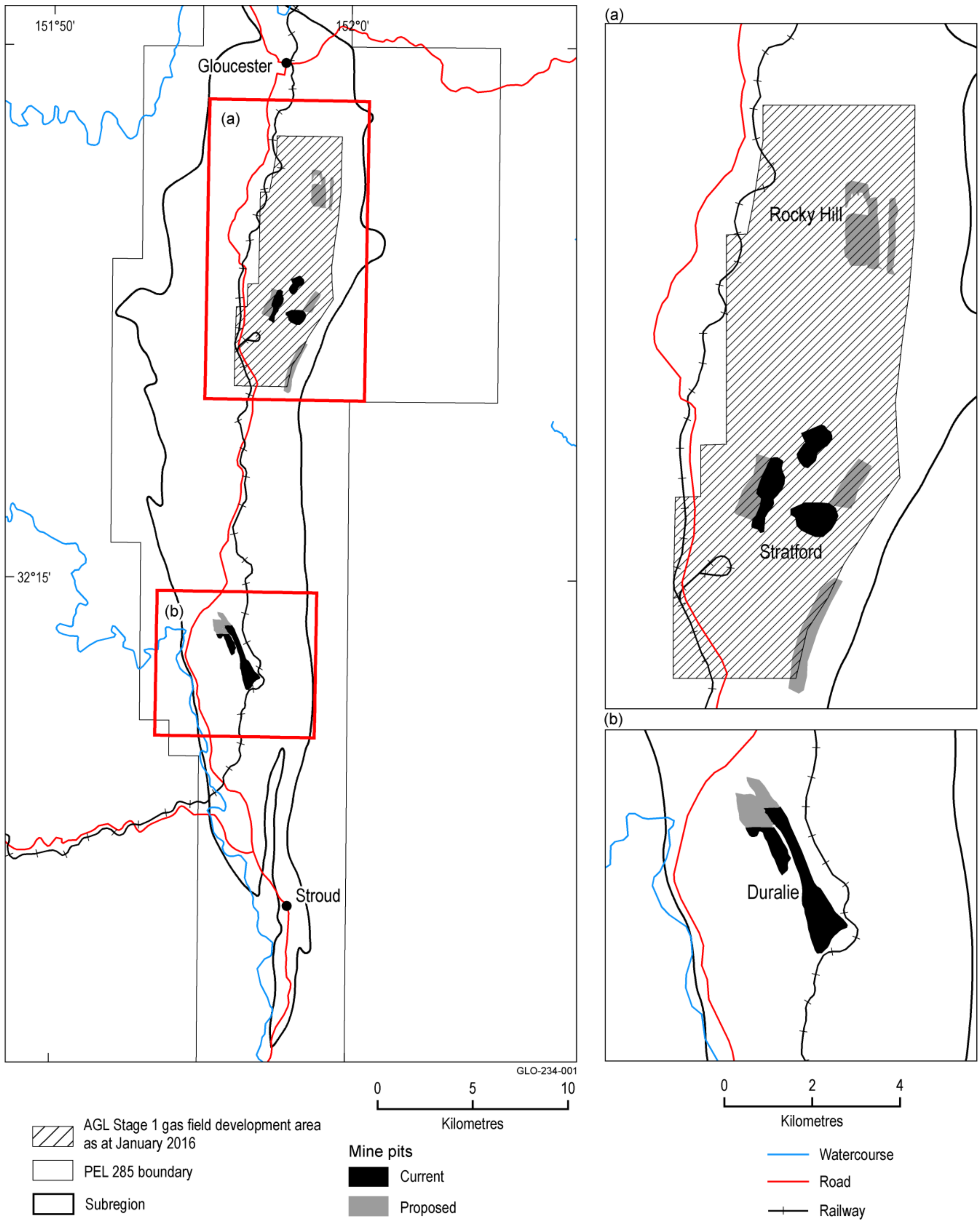

Figure 10 Current and proposed coal mines and coal seam gas development areas in the Gloucester subregion

CSG = coal seam gas

Locations for the Stratford and Duralie operating mines were extracted from the OZMIN database (Geoscience Australia, Dataset 1). The location of Rocky Hill coal deposit and AGL's Stage 1 gas field development area were obtained from publicly available company documents.

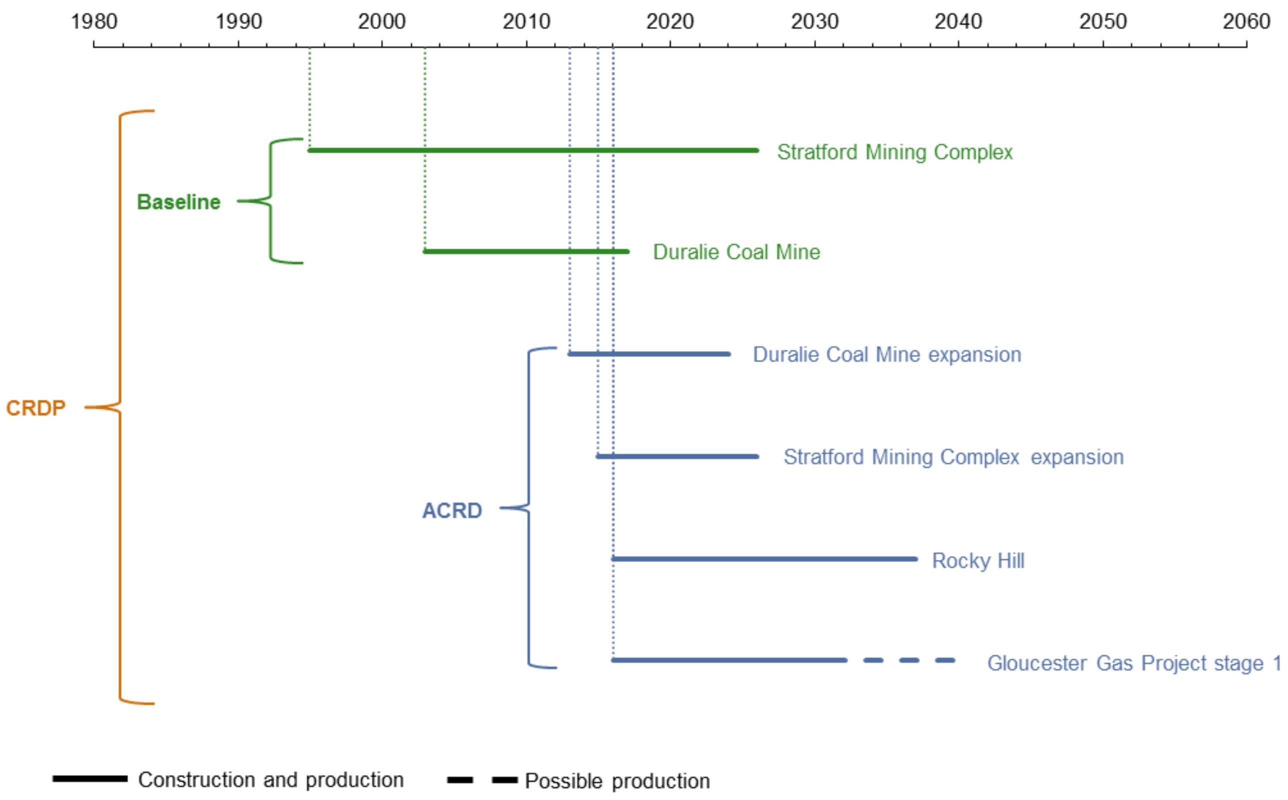

Figure 11 Timelines for coal resource developments in the coal resource development pathway in the Gloucester subregion

These timelines have been used in the bioregional assessment hydrological modelling for the Gloucester subregion in 2015.
It should be noted that as at November 2015, the Rocky Hill development is on hold with the NSW Government and AGL's Stage 1 gas field development area awaits final investment decision by AGL. While AGL withdrew from their proposed Gloucester Gas Project in December 2015, as per the companion submethodology M04, the CRDP was not re-visited.
The coal resource developments in the CRDP are equal to the sum of those in the baseline and ACRD.
Baseline = baseline coal resource development, a future that includes all coal mines and coal seam gas (CSG) fields that were commercially producing under an operations plan approved as of December 2012
CRDP = 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
ACRD = additional coal resource development, all coal mines and coal seam gas fields, including expansion of baseline operations, that are expected to begin commercial production after December 2012

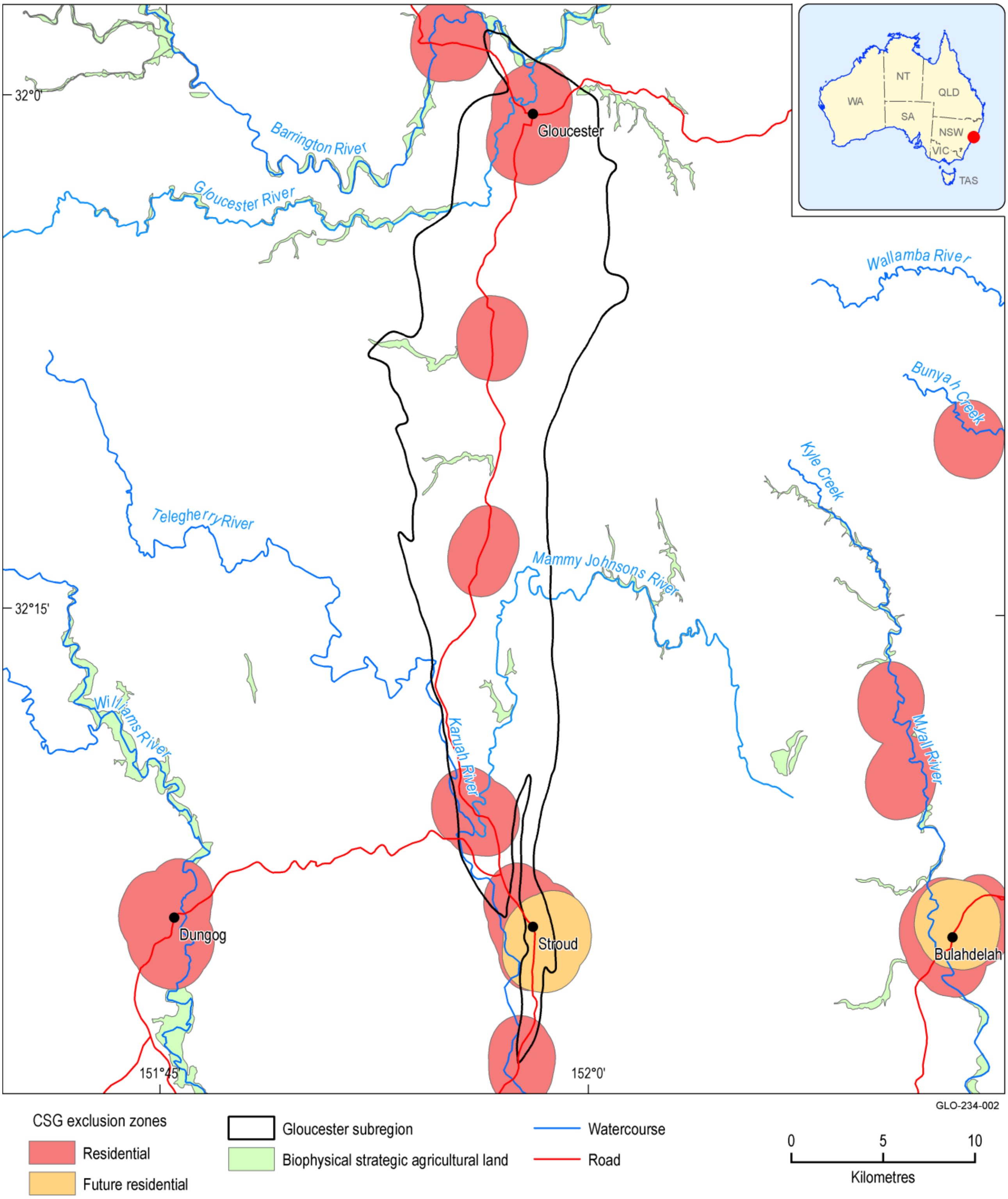

Figure 12 Coal seam gas exclusion zones in the Gloucester subregion

CSG = coal seam gas
Data: Strategic Agricultural Lands (NSW Government, 2013)

2.3.4.2 Water management for coal resource development

In the Gloucester subregion there are two existing coal mines with expansion plans (Duralie Coal Mine and Stratford Mining Complex), one proposed coal mine (Rocky Hill, currently on hold as of 15 November 2015) and a CSG project (AGL's Gloucester Gas Project, under development).

2.3.4.2.1 Duralie Coal Mine

The information summarised in this section was obtained from Duralie Coal Mine Water Management Plan (Duralie Coal Mine, 2013) and Heritage Computing (2009).

Duralie Coal Mine (DCM) water management is designed and operates to control water generated from surface development areas via on-site water permanent and temporary storage structures. The other objective of the DCM Water Management Plan is to prevent overflow of dirty water generated within the mine workings, waste rock emplacements, water storage areas and runoff from areas where coal is handled, to the neighbouring water bodies Coal Shaft Creek or Mammy Johnsons River. The total on-site water storage capacity is about 4609 ML with approved capacity up to 4805 ML. Once mining in the Weismantel Extension open pit is complete (as of 30 June 2015, progressive backfilling with waste rock is occurring and water is allowed to accumulate in the pit (Yancoal, 2015a)), the remaining void will be used as a water storage. The storage capacity is estimated to be 1900 ML. The stored dirty water is used on site for dust mitigation and irrigation of a mixture of pasture, woodland and cropping within the approved irrigation areas. On average, DCM operates in surplus yielding more water from the mine and mine infrastructure catchments than needed for the mining and processing operations. Excess water is disposed through on-site irrigation.

2.3.4.2.2 Stratford Mining Complex

The information summarised in this section was obtained from Stratford Coal Mine Water Management Plan (Stratford Coal Mine, 2012) and Heritage Computing (2012).

Stratford Mining Complex (SCM) water management is designed and operated to achieve no overflow from on-site water storages (Stratford East Dam, Stratford Main Pit, Return Water Dam) to the downstream watercourses including Avondale Creek, Dog Trap Creek and the Avon River. Total on-site storage water capacity of existing dam is about 40,350 ML. Once mine operations are completed in the Bowen Road North Open Cut (BRNOC) (where, as of 30 June 2015, mining ceased (Yancoal, 2015b)) and in the Avon North Open Cut (where, as of 30 June 2015, no activities had commenced in the Avon North Pit, part of the Stratford Extension Project (Yancoal, 2015b)), the voids will also be used as contained water storages.

Run-of-mine (ROM) coal from the DCM is transported by rail to the SCM, where it is processed along with ROM coal from the SCM and BRNOC. The majority of water used on site is for the coal handling processing plant (CHPP) and for dust suppression. On average the site has operated in surplus yielding more water from the mine and mine infrastructure catchments than has been needed to supply the mining and processing operations. This excess has been managed by containment in the Stratford East Dam, storage in Stratford Main Pit and historically controlled release to Avondale Creek under Environment Protection Licence No. 5161. Irrigation of water from the Stratford East Dam over approximately 23 ha of a rehabilitated portion of the Stratford

Waste Emplacement area will occur to reduce stored water on site and to assist the current pasture cropping programme on the rehabilitated emplacement.

2.3.4.2.3 Rocky Hill Coal Project

As of November 2015, the NSW Department of Planning and Environment placed the Rocky Hill Coal Project on hold. The information summarised in this section was obtained from the Rocky Hill Coal Project Environmental Impact Statement (RW Corkery & Co Pty Ltd, 2012a; 2012b) and the Rocky Hill Coal Project Groundwater Assessment (Australasian Groundwater and Environmental Pty Ltd, 2013).

As of June 2015, there was no water management plan for the Rocky Hill Coal Project. Gloucester Resources Limited (GRL) is planning to manage the dirty water through on-site storage areas with no outflow to the downstream watercourses. On-site water storage includes three environmental dams with a total storage capacity of approximately 2300 ML and refilled mining pits. The majority of water used on site is for the CHPP and for dust suppression. According to the site water balance estimated by WRM Water and Environment Pty Ltd (2013), there would be occasional excess quantities of saline water throughout the proposed 21-year life of the project.

2.3.4.2.4 Gloucester Gas Project

The information summarised in this section was obtained from various AGL water management plans (AGL Energy Limited, 2012; 2014b; 2014c; 2014d), produced water factsheets (AGL Energy Limited, 2014a) and AGL's Review of Environmental Factors – Waukivory Pilot Project (AGL Upstream Investments Pty Limited, 2014).

During the fracture stimulation of a CSG well, the volume of water required for fracture treatment is estimated to be between 0.9 ML and 2.4 ML per well (AGL Upstream Investments Pty Limited, 2014). It is expected that all flowback water (i.e. 0.9 ML and 2.4 ML per well) and 0.04 ML/day per well of produced water to be maximum at the commencement of fracturing/testing but quickly diminishing to much lesser volumes (typically an order of magnitude lower) (AGL Energy Limited, 2014b; 2014c).

According to AGL's Produced Water Management Plan (2014c), the produced water strategy is:

- storage of produced water from AGL's offsite operations and transport of this water within the Tiedman property
- blending of produced water with freshwater for irrigation reuse, subject to the water quality meeting relevant Australian and New Zealand Environment Conservation Council (ANZECC) criteria
- storage for blending and/or direct reuse for stock use, subject to the water quality meeting the relevant ANZECC criteria
- storage for blending and/or direct reuse for industrial uses such as fracture stimulation, dust suppression and firefighting, subject to water quality meeting the relevant ANZECC criteria
- storage for future drilling and hydraulic fracture stimulation purposes.

Produced water, flowback water and natural groundwater generated during the fracture stimulation of CSG wells will be stored on the site in above ground tanks (75,000 L capacity) or open top tanks (40,000 L capacity) and then transferred by road tanker to the Tiedman dams for either industrial use or blended water irrigation. As part of the Gloucester Gas Project, AGL is planning to treat produced water using reverse osmosis, a desalination technology to reduce the amount of salt in the produced water and to be used for irrigation or returned to the environment (AGL Energy Limited, 2014a). Salt produced during the reverse osmosis process is crystallised to a mixed solid salt, bagged and removed to suitably licensed landfill sites (AGL Energy Limited, 2014a).

2.3.4.3 Gaps

No knowledge gaps and uncertainties were identified at the time of writing.

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2.3.5 Conceptual modelling of causal pathways

Summary

This section discusses the causal pathways for open-cut coal mines and coal seam gas (CSG) operations to impact water quantity and quality, and to affect water-dependent assets in the Gloucester preliminary assessment extent (PAE).

A hazard analysis was used to systematically identify activities that occur as part of coal resource development in the Gloucester subregion and which may initiate *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). A large number of hazards were identified; some of these are beyond the scope of bioregional assessments (BAs), such as accidents, and others are adequately addressed by site-based risk management processes and regulation. While individual hazards constitute causal pathways, many of these hazards can be grouped by common impact cause and impact mode and represented by a smaller number of aggregated causal pathways for consideration in the BA.

CSG operations have their immediate impact deep below ground. Aquifer depressurisation, enhanced inter-aquifer connectivity, and the storage and disposal of co-produced water are the main impact modes. Open-cut mines most directly affect surface water flows and aquifers, with disruption of natural surface drainage, inter-aquifer connectivity, and the storage and disposal of rainfall the main impact modes.

The baseline coal resource development (baseline) includes only open-cut mines (as of December 2012), while the coal resource development pathway (CRDP) includes the baseline as well as expansions to the open-cut mines (as of December 2012), a new open-cut mine, and a CSG project.

Linkages between impact modes and affected landscape classes are inferred, with most of the landscape cleared for agriculture. Both the perennial streams of Mammy Johnsons River and the intermittent streams of Avon River are potentially impacted by coal mines and CSG operations. The spatial and temporal scale of impacts are summarised, with most effects only local but with unknown fault and fracture zone behaviour making this speculative. Time scales of impact include the full life of mine plus potentially decades into the future as drawdown cones spread slowly and mine-site rehabilitation is established.

2.3.5.1 Methodology

Conceptual models of causal pathways are a specific type of conceptual model that 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 impacts 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 Gloucester subregion has leveraged existing state-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 and these were refined through individual consultation with external stakeholders. The focus of the workshop was to improve the landscape classification (described in Section 2.3.3) and description of the conceptual model of causal pathways. Discussion with representatives at the workshop focused on knowledge gaps and uncertainties identified by the Assessment team.

In a BA, the identification and definition of causal pathways are supported by a formal hazard analysis, known as Impact Modes and Effects Analysis (IMEA) as outlined in companion submethodology M11 (as listed in Table 1) for hazard analysis (Ford et al., 2016) and illustrated in Figure 5 (Section 2.3.1). IMEA is a variant of the established hazard analysis tool, Failure Modes and Effects Analysis (FMEA). The causal pathways are based on the outcomes of this hazard analysis and current understanding of the way ecosystems and landscape classes in the subregion work and interact. The IMEA rigorously and systematically identifies the 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 changes or impacts, before assessing the severity, likelihood and detectability of such impacts under current controls through structured scoring.

Key to an IMEA is identifying *activities*, planned events associated with a CSG operation or coal mine. 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 CSG operations are separated into five life-cycle stages and four components:

- life-cycle stages: (i) exploration and appraisal, (ii) construction, (iii) production, (iv) decommissioning, and (v) work-over
- components: (i) wells, (ii) processing facilities, (iii) pipelines, and (iv) roads and infrastructure.

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

- life-cycle stages: (i) exploration and appraisal, (ii) development, (iii) production, (iv) closure, and (v) rehabilitation
- components: (i) open pit, (ii) surface facilities, and (iii) 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 and gas extraction that unintentionally reduces groundwater pressure to unacceptable levels) or desirable effects (such as reinjection of co-produced water to restore groundwater pressure in a heavily utilised aquifer).

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 flood events).

Examples are illustrated in Figure 5 (Section 2.3.1):

- An example for open-cut coal mines (Figure 5(a)) is initiated with the activity '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'.
- An example for CSG operations (Figure 5(b)) is initiated with the activity 'corridor or site vegetation removal for CSG operations or coal mine', which is the impact cause. Subsequent events ('rainfall event' and 'soil erosion') then combine to form the impact mode ('soil erosion following heavy rainfall') that leads to multiple effects ('change in surface water quantity and surface water quality') and associated stressors ('surface water flow' and 'total suspended solids (TSS)'). In turn, this may cause an ecological impact, 'change of condition of habitat for a given species'.

Participants in IMEA workshops 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 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 as part of CSG operations that may require the removal of site vegetation (the impact cause), including the creation of pipeline networks, storage ponds, site processing plants, water treatment plants, ground-based geophysics and the construction of access roads; 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 in Section 2.3.1). Causal pathways are considered for CSG operations and open-cut 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 mines and CSG 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; this section presents specific results for the Gloucester subregion.

Hazards are grouped for the Gloucester 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 this is using those same sources to identify which landscape classes (and receptors) may be affected by a potential hydrological change that arises from those causal pathways, and (equally importantly), which classes of receptors will *not* be affected. Throughout the BA, areas of the PAE 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 Gloucester subregion based on the existing and proposed coal mines and CSG operations and their water management outlined in Section 2.3.4.1 and Section 2.3.4.2, respectively. The hazard analysis for the Gloucester subregion was conducted over five days via workshops with a range of experts present from CSIRO, Geoscience Australia and the Department of the Environment. Specific coal resource expertise within these agencies was included beyond the BA Assessment teams, and subsequent hazard analysis workshops for other subregions, which had stronger external representation, have assisted in confirming the comprehensiveness of the hazards identified for the Gloucester subregion.

A total of 261 activities were identified for CSG operations and 351 activities for open-cut coal mines. These activities were all identified during the IMEA; however, the results are based on a subset of activities with complete scores. All decisions were recorded; however, some activities were left unscored if they were considered not applicable to the Gloucester subregion or if that activity was not expected to occur at the time of the assessment.

2.3.5.2.1 Coal seam gas operations

The hazard analysis identifies impacts on aquifers as the highest ranked potential hazard associated with CSG operations in the Gloucester subregion. The hazard analysis identifies the following ways in which aquifer impacts may occur including:

- hydrostatic depressurisation of the target coal seam
- fault-mediated depressurisation and pressurisation caused by faults opening or closing due to CSG operations
- aquitard-mediated depressurisation (i.e. an aquitard is absent or the integrity of the aquitard is compromised in some parts of the subregion)
- connection of previously disconnected aquifers by hydraulic fracturing or incomplete casing of wells.

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

Figure 13 plots the 30 highest ranked potential hazards (and associated activities and impact modes), ranked by midpoint of the hazard priority number. This figure shows the range of hazard scores and hazard priority numbers for each of these potential hazards.

Disruption to natural surface drainage was the most common impact mode in the top 30 highest ranked potential hazards. This impact mode appears 24 times in the IMEA for CSG operations in the Gloucester subregion, and 8 times in the top 30 hazards, because many of the activities associated with CSG operations (such as site vegetation removal and diverting site drain lines) lead to this impact mode. This impact mode is identified as hazardous as it may lead to impacts on surface water volume, direction and quality; in extreme cases, impacts on groundwater quantity were identified as a possible outcome.

The following complete the list of high-priority hazards that might potentially impact on water-dependent assets in the Gloucester subregion for CSG operations:

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

Details of the full hazard analysis are available at Bioregional Assessment Programme (Dataset 1).

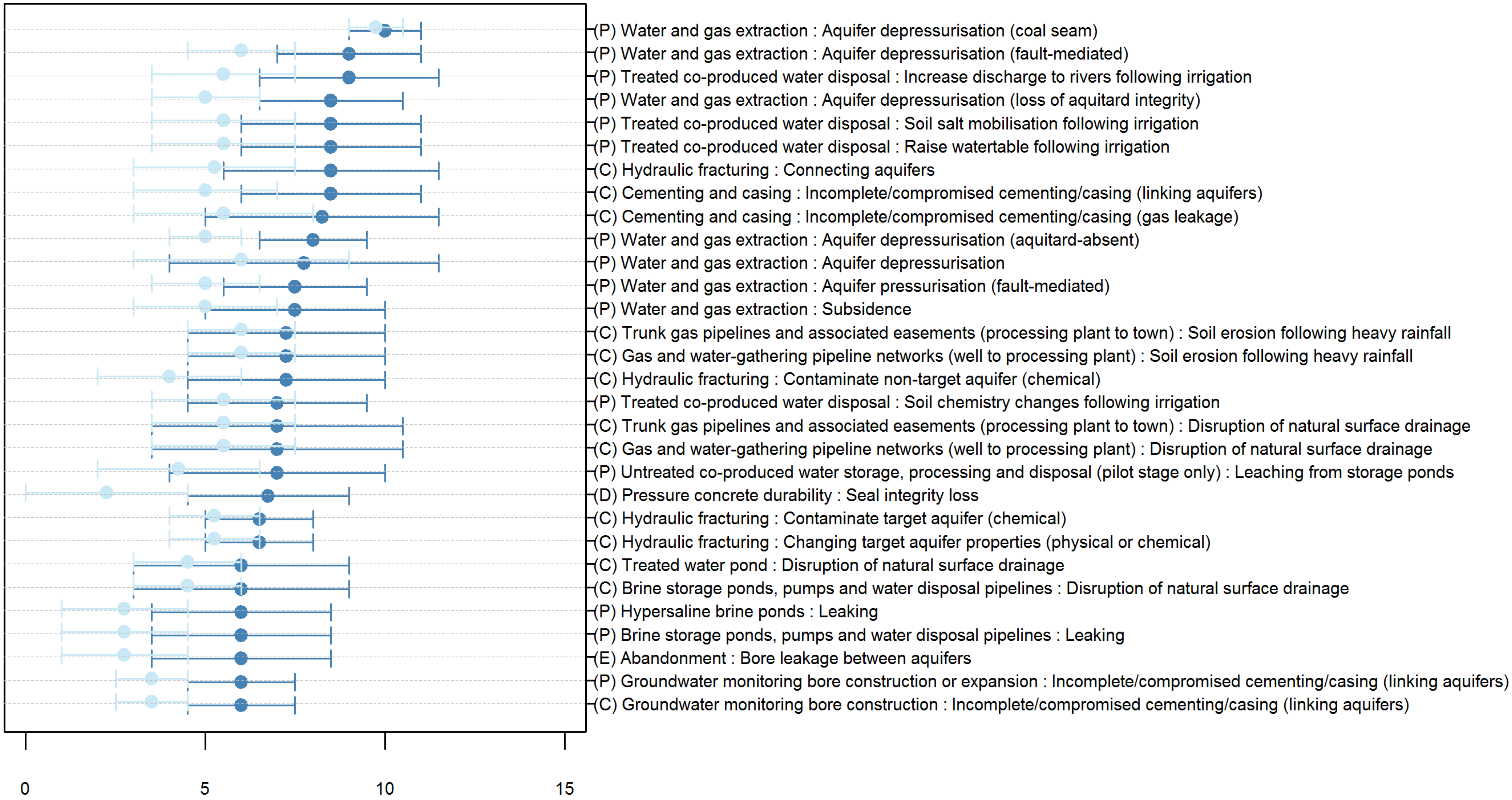

Figure 13 Highest ranked potential hazards (and their associated activities and impact modes) for coal seam gas operations, ranked by midpoint of the hazard priority number

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 arise from a number of different life cycles and activities. Hazards are listed with the syntax [Life-cycle stage][Activity]:[Impact mode], where life-cycle stages are indicated by (E) for exploration and appraisal, (C) for construction, (P) for production, (D) for decommissioning and (W) for work-over.
Data: Bioregional Assessment Program (Dataset 1)

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

2.3.5.2.2 Open-cut coal mines

Activities that lead to disruption of, and changes to, natural surface drainage and runoff associated with open-cut mines in the Gloucester subregion are associated with six of the 30 highest ranked potential hazards. These potential impacts occur because open-cut coal mines may potentially divert rivers and creeks, and divert the natural direction of rainfall-runoff by the construction, or expansion of, the pit and associated mine infrastructure and work areas, and by re-contouring landforms and discharges.

The potential impact of leaching is associated with 7 of the 30 highest ranked potential hazards, including leaching from:

- in-pit waste rock dumps
- waste rock dumps outside of the pit
- coal stockpiles (in and out of the pit)
- run-of-mine (ROM) plants.

The following were identified as having the potential to link, or cause leakage between, aquifers:

- incomplete or compromised cementing casing of groundwater monitoring bores
- supply bores
- mine dewatering bores
- abandoned exploration and appraisal bores.

These – together with deliberate pit wall dewatering, subsidence and enhanced aquifer interconnectivity caused by post-closure water filling the pit – were identified as potentially important hazards. The remaining 30 highest ranked potential hazards include:

- soil erosion caused by heavy rainfall or failure to successfully rehabilitate abandoned mines
- artificial groundwater recharge (following pit abandonment)
- groundwater and surface water contamination via drill cutting disposal
- negligent decontamination of mines post closure.

Figure 14 plots the 30 highest ranked potential hazards (and their associated activities and impact modes), ranked by midpoint of their hazard priority number. The figure shows the range of hazard scores and hazard priority numbers for each of these hazards.

Details of the full hazard analysis are available at Bioregional Assessment Programme (Dataset 1).

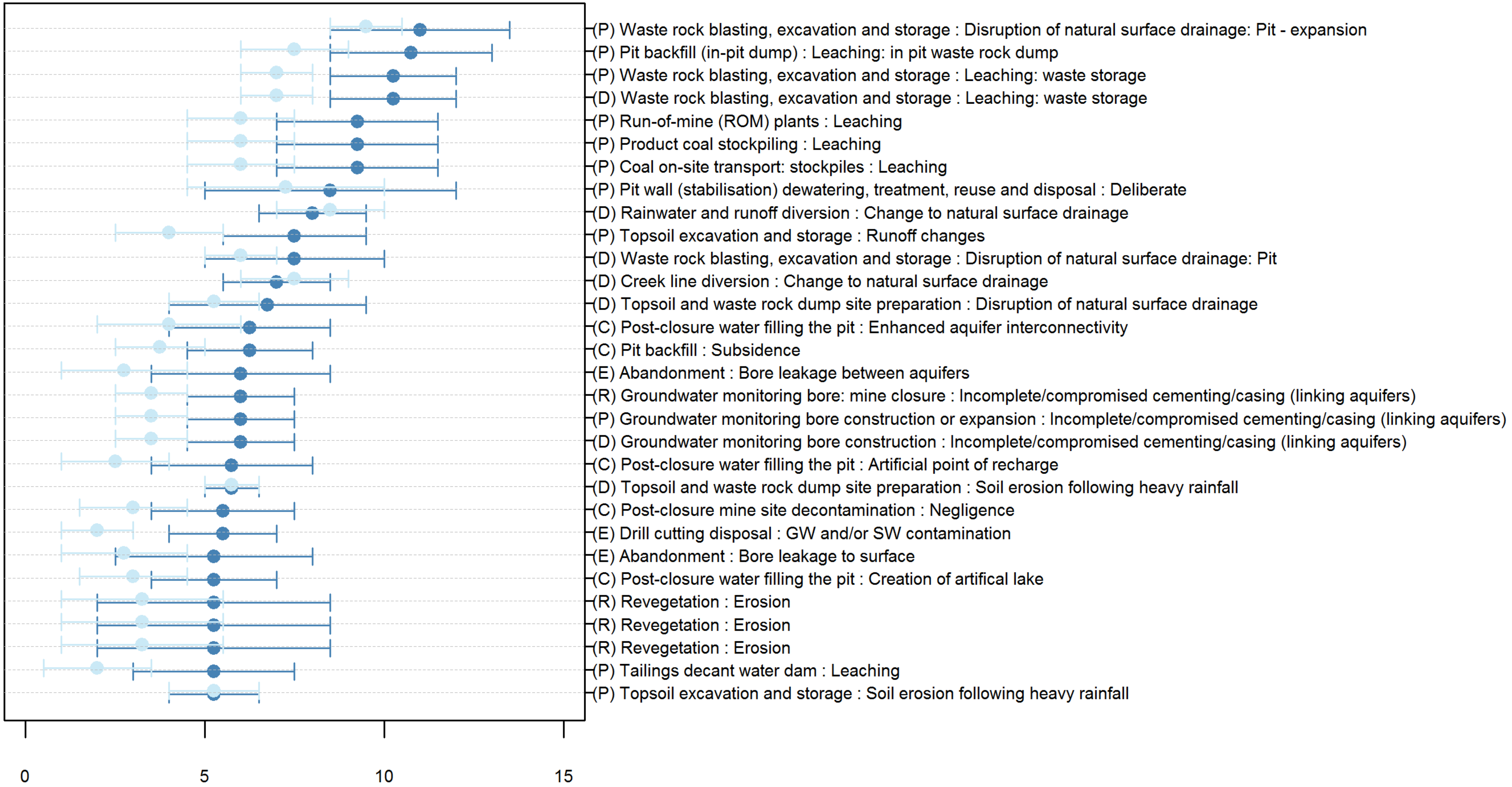

Figure 14 Highest ranked potential hazards (and their associated activities and impact modes) for open-cut coal mines, ranked by midpoint of the risk priority number

The x-axis shows the hazard priority number and hazard score for potential hazards. The intervals between the highest and lowest hazard priority number are shown in dark blue; the intervals for hazard score are shown in light blue. The same hazard may appear multiple times, as it may arise from a number of different life cycles and activities. Hazards are listed with the syntax [Life-cycle stage][Activity]:[Impact mode], where life-cycle stages are indicated by (E) for exploration and appraisal, (D) for development, (P) for production, (C) for closure and (R) for rehabilitation.
Data: Bioregional Assessment Program (Dataset 1)

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

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

2.3.5.2.3 Hazard handling and scope

A full list of hazards has been generated for both coal mines and CSG operations. The hazards of primary focus from a BA perspective are those that extend beyond the development site and that may have cumulative impacts, as these are consistent with the regional focus of BA, and are where BA will add value beyond site-specific environmental impact statements (EIS). Ultimately, however, BAs need to be able to address all identified hazards by considering the scope, modelling, other literature or narratives, and specifying where science gaps may exist.

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.

Best 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 and with no off-site impacts are important to acknowledge but will typically be addressed by site-based risk management procedures.

For CSG operations, the following hazards are considered out of scope for further analysis as part of the bioregional assessment of the Gloucester subregion, because they are deemed to be covered by site-based risk management and regulation:

- abandonment practice
- hazards addressed by site management, no water-mediated pathway (dust, fire or noise)
- containment failure due to construction or design
- disruption of surface drainage network for site-based infrastructure, plant and facilities, roads, creek crossings
- equipment/infrastructure failure (e.g. pipeline failures)
- leaching/leaking from storage ponds and stockpiles
- spillages and disposals (diesel, mud, cuttings, fluid recovery)
- vegetation clearance and subsequent soil erosion following heavy rainfall.

Figure 15 and Table 9 describe all hazards associated with CSG operations that are considered to be in scope in the Gloucester subregion. The hydrological effect of an activity such as ‘water and gas extraction’ depends on the impact cause and impact mode. For example, ‘depressurisation’ (impact cause) that causes ‘subsidence’ (impact mode) affects ‘surface water direction’ (hydrological effect) and ‘aquitard leaks’ (impact cause) that cause ‘non-target, non-reservoir aquifer depressurisation' (impact mode) affects 'groundwater pressure' (hydrological effect) (Figure 15).

Hydrological effects associated with CSG operations that are considered to be in scope in the Gloucester subregion are shown in Figure 15 and listed below:

- surface water quality
- surface water direction
- surface water flow
- surface water quantity/volume
- soil quality
- groundwater quality
- aquifer properties
- groundwater composition
- groundwater flow (reduction)
- groundwater level
- groundwater pressure
- groundwater quantity/volume.

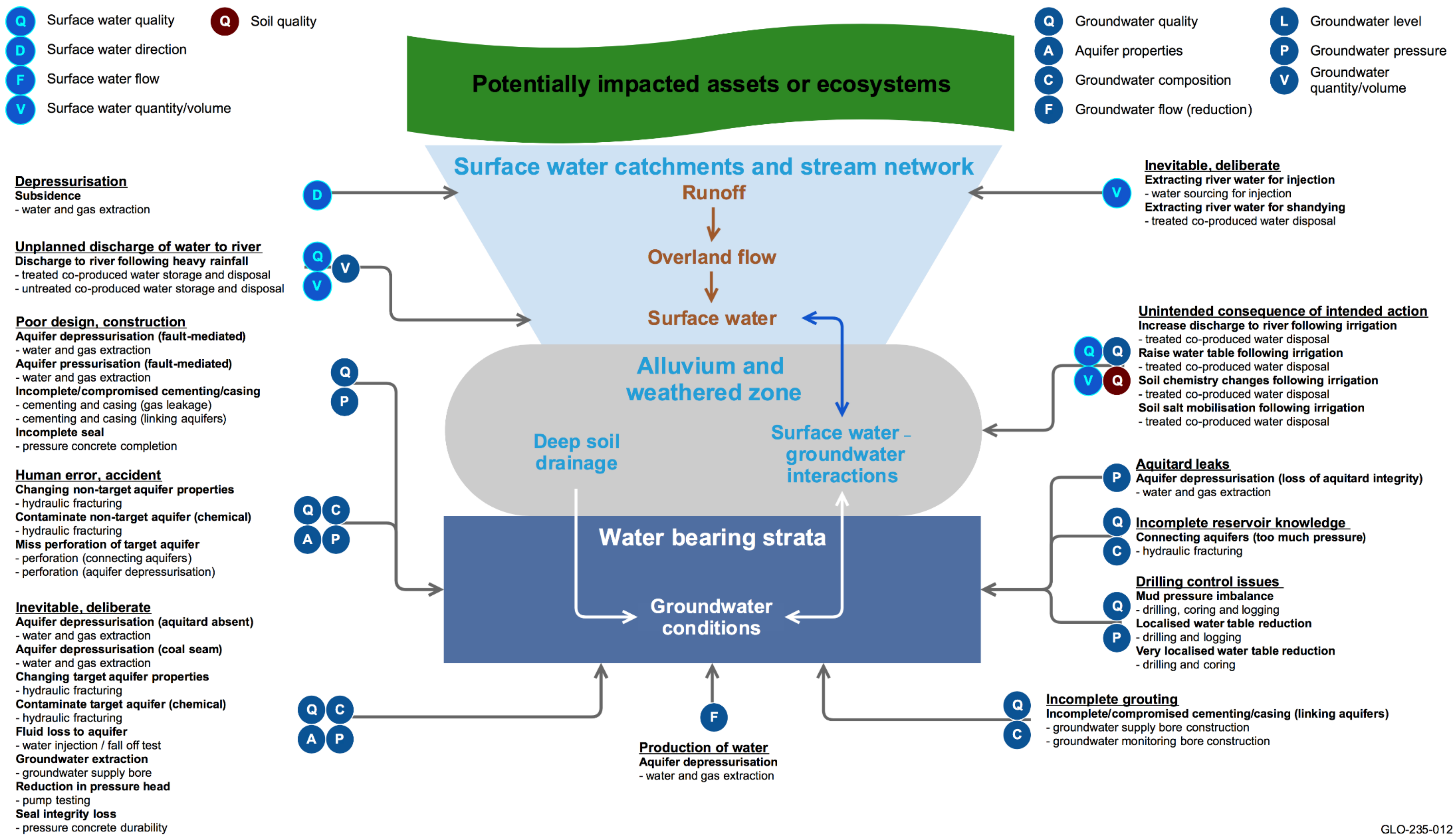

Figure 15 Hazards (impact causes, impact modes and activities) and associated effects identified for the life-cycle stages of coal seam gas operations that are considered to be in scope in the Gloucester subregion

Impact causes are underlined, impact modes are bold and activities are bullet points. Arrows indicate the spatial context for each hazard: aquifers, aquifer outcrop areas, watercourses, catchments.
GDEs = groundwater-dependent ecosystems; groundwater composition = mixing groundwater of different composition (in terms of natural dissolved solids)
Typology and punctuation are consistent with the hazard analysis (Bioregional Assessment Programme, Dataset 1).

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

Table 9 Hazards identified for the life-cycle stages of coal seam gas operations that are considered to be in scope in the Gloucester subregion and their associated hydrological effects, spatial context, temporal context, and potentially impacted assets or ecosystems

This table lists each hazard (with its spatial and temporal context) in a chain of logic from hydrological effects to potentially impacted assets or ecosystems. The spatial context includes target and non-target aquifers, aquifer outcrop areas, coal resource development areas and watercourses. Within the relevant spatial and temporal context, assets and ecosystems are described using landscape classification rule sets, landscape class group (e.g. 'Floodplain or lowland riverine') or asset type (e.g. economic = economic groundwater asset).

Hazard (with syntax 'Impact cause: (life-cycle stage[a]) impact mode – activity')	Hydrological effects	Spatial context	Temporal context[b]	Potentially impacted assets or ecosystems
Aquitard leaks: (P) Aquifer depressurisation (loss of aquitard integrity) – water and gas extraction	Change in GW pressure	Aquifers intersected by CSG wells within operations area	Long term	GDEs and economic
Depressurisation: (P) Subsidence – water and gas extraction	SW direction	Watercourses within and downstream of operations area	Long term	All
Drilling control issues: (C) Mud pressure imbalance – drilling, coring and logging	GW quality	Aquifers intersected by CSG wells within operations area	Short term	GDEs and economic
Drilling control issues: (C) Localised watertable reduction – drilling and logging	GW level	Aquifers intersected by CSG wells within operations area	Short term	GDEs and economic
Drilling control issues: (E, C) Very localised watertable reduction – drilling and coring	GW level	Aquifers intersected by CSG wells within operations area	Short term	GDEs and economic
Human error, accident: (C) Changing non-target aquifer properties – hydraulic fracturing	Aquifer properties	Aquifers within operations area	Long term	GDEs and economic
Human error, accident: (C) Contaminate non-target aquifer (chemical) – hydraulic fracturing	GW quality	Aquifers within operations area	Long term	GDEs and economic
Human error, accident: (C) Miss perforation of target aquifer – perforation (connecting aquifers)	GW composition, GW quality	Aquifers within operations area	Long term	GDEs and economic

Hazard (with syntax 'Impact cause: (life-cycle stage[a]) impact mode – activity')	Hydrological effects	Spatial context	Temporal context[b]	Potentially impacted assets or ecosystems
Human error, accident: (C) Miss perforation of target aquifer – perforation (aquifer depressurisation)	GW pressure, GW quality	Target aquifer	Long term	GDEs and economic
Incomplete grouting: (C) Incomplete/compromised cementing/casing (linking aquifers) – groundwater monitoring bore construction	GW composition, GW quality	Aquifers within operations area	Long term	GDEs and economic
Incomplete grouting: (C) Incomplete/compromised cementing/casing (linking aquifers) – groundwater supply bore construction	GW composition, GW quality	Aquifers within operations area	Long term	GDEs and economic
Incomplete reservoir knowledge: (C) Connecting aquifers (too much pressure) – hydraulic fracturing	GW composition, GW quality	Aquifers within operations area	Long term	GDEs and economic
Inevitable, deliberate: (P) Aquifer depressurisation (aquitard absent) – water and gas extraction	GW pressure	Target aquifer	Long term	GDEs and economic
Inevitable, deliberate: (P) Aquifer depressurisation (coal seam) – water and gas extraction	GW pressure	Target aquifer	Long term	GDEs and economic
Inevitable, deliberate: (C) Changing target aquifer properties – hydraulic fracturing	Aquifer properties	Target aquifer within operations area	Long term	GDEs and economic
Inevitable, deliberate: (C) Contaminate target aquifer (chemical) – hydraulic fracturing	GW quality	Target aquifer within operations area	Long term	GDEs and economic
Inevitable, deliberate: (C) Fluid loss to aquifer – water injection / fall off test	GW quality	Aquifers within operations area	Long term	GDEs and economic

Hazard (with syntax 'Impact cause: (life-cycle stage[a]) impact mode – activity')	Hydrological effects	Spatial context	Temporal context[b]	Potentially impacted assets or ecosystems
Inevitable, deliberate: (E) Reduction in pressure head – pump testing	GW pressure	Aquifers within operations area	Long term	GDEs and economic
Inevitable, deliberate: (D) Seal integrity loss – pressure concrete durability	GW quality	Aquifers intersected by CSG wells within operations area	Long term	GDEs and economic
Inevitable, deliberate: (P) Groundwater extraction – groundwater supply bore	GW pressure	Aquifers within operations area	Long term	GDEs and economic
Inevitable, deliberate: (W) Extracting river water for injection – water sourcing for injection	SW volume	Aquifers within operations area	Long term	GDEs and economic
Inevitable, deliberate: (P) Extracting river water for shandying – water sourcing for injection	SW volume	Aquifers within operations area	Long term	GDEs and economic
Poor design, construction: (P) Aquifer depressurisation (fault-mediated) – water and gas extraction	GW pressure	Aquifers intersected by CSG wells and faults	Long term	GDEs and economic
Poor design, construction: (P) Aquifer pressurisation (fault-mediated) – water and gas extraction	GW pressure	Aquifers intersected by CSG wells and faults	Long term	GDEs and economic
Poor design, construction: (C) Incomplete/compromised cementing/casing – cementing and casing (gas leakage)	GW quality	Aquifers intersected by CSG wells within operations area	Long term	GDEs and economic
Poor design, construction: (C) Incomplete/compromised cementing/casing – cementing and casing (linking aquifers)	GW quality	Aquifers intersected by CSG wells within operations area	Long term	GDEs and economic

Hazard (with syntax 'Impact cause: (life-cycle stage[a]) impact mode – activity')	Hydrological effects	Spatial context	Temporal context[b]	Potentially impacted assets or ecosystems
Poor design, construction: (D) Incomplete seal – pressure concrete completion	GW quality	Aquifers within operations area	Long term	GDEs and economic
Production of water: (P) Aquifer depressurisation – water and gas extraction	GW flow (reduction)	Aquifers intersected by CSG wells	Long term	GDEs and economic
Unintended consequence of intended action: (P) Increase discharge to rivers following irrigation – treated co-produced water disposal	SW volume, SW quality, GW quantity	Watercourses	Short term	Lowly intermittent – gravel/cobble streams
Unintended consequence of intended action: (P) Raise watertable following irrigation – treated co-produced water disposal	SW quality, GW quality	Alluvium and watercourses in aquifer outcrop areas within operations area	Short term	Lowly intermittent – gravel/cobble streams
Unintended consequence of intended action: (P) Soil chemistry changes following irrigation – treated co-produced water disposal	Soil quality	Alluvium and watercourses in aquifer outcrop areas within operations area	Short term	Lowly intermittent – gravel/cobble streams
Unintended consequence of intended action: (P) Soil salt mobilisation following irrigation – treated co-produced water storage and disposal	SW quality, GW quality	Alluvium and watercourses in aquifer outcrop areas within operations area	Short term	Lowly intermittent – gravel/cobble streams
Unplanned discharge of water to river: (P) Discharge to river following heavy rainfall – treated co-produced water storage and disposal	SW quality, SW volume, GW quality	Alluvium and watercourses in aquifer outcrop areas within operations area	Short term	Lowly intermittent – gravel/cobble streams

Hazard (with syntax 'Impact cause: (life-cycle stage[a]) impact mode – activity')	Hydrological effects	Spatial context	Temporal context[b]	Potentially impacted assets or ecosystems
Unplanned discharge of water to river: (P) Discharge to river following heavy rainfall – untreated co-produced water storage and disposal	SW quality, SW volume, GW quality	Alluvium and watercourses in aquifer outcrop areas within operations area	Short term	Lowly intermittent – gravel/cobble streams

[a]life-cycle stage of coal seam gas operations, where C = construction; D = decommissioning; E = exploration and appraisal; P = production; W = work-over
[b]short term = less than 5 years; medium term = 5 to 10 years; long term = 10 to 100 years
CSG = coal seam gas; GDEs = groundwater-dependent ecosystems; GW = groundwater; SW = surface water; GW composition = mixing groundwater of different composition (in terms of natural dissolved solids)
Typology and punctuation are consistent with the hazard analysis (Bioregional Assessment Programme, Dataset 1).
Data: Bioregional Assessment Programme (Dataset 1)

For open-cut coal mines, the following hazards are considered out of scope in the Gloucester subregion because they are deemed to be covered by site-based risk management and regulation and do not have cumulative effects on water in the subregion:

- hazards addressed by site management, no water-mediated pathway (dust, fire or noise)
- bore and well construction (integrity, leakage)
- disruption of surface drainage network for site-based infrastructure, plant and facilities, roads, creek crossings
- equipment/infrastructure failure (e.g. pipeline failures, plant failures)
- leaching/leaking from storage ponds and stockpiles
- loss of containment (due to construction or design, slope failure)
- re-contouring, compaction and settlement following backfill
- spillages and disposals (diesel, mud, cuttings, fluid recovery)
- vegetation clearance and subsequent soil erosion following heavy rainfall.

Of those hazards that are in scope, some will be addressed by the BA numerical modelling, while others (e.g. water quality hazards) will be assessed qualitatively, using the logic and rule-sets described in the conceptual model of causal pathways. The hazard priority number or hazard scores indicate the relative importance of the hazard. Hazards with low scores are of lower priority.

Figure 16 and Table 10 describe all hazards associated with coal mining developments that are considered to be in scope in the Gloucester subregion. The hydrological effect of an activity such as 'water management structures' depends on the impact cause and impact mode. For example, the hydrological effect of 'poor handling/management' (impact cause) can cause 'excessive runoff during closure' (impact mode) that affects 'surface water quality and groundwater quality' (hydrological effects) and 'diverting site drain line' (impact cause) can cause 'disruption of natural surface drainage' (impact mode) that affects 'surface water volume/quantity, surface water quality and groundwater quantity/volume' (hydrological effect). Hydrological effects associated with coal mines that are considered to be in scope in the Gloucester subregion are shown on Figure 16 and listed below:

- surface water quality
- surface water direction
- surface water flow
- surface water volume
- groundwater quality
- groundwater direction
- groundwater flow (reduction)
- groundwater quantity/volume
- groundwater pressure.

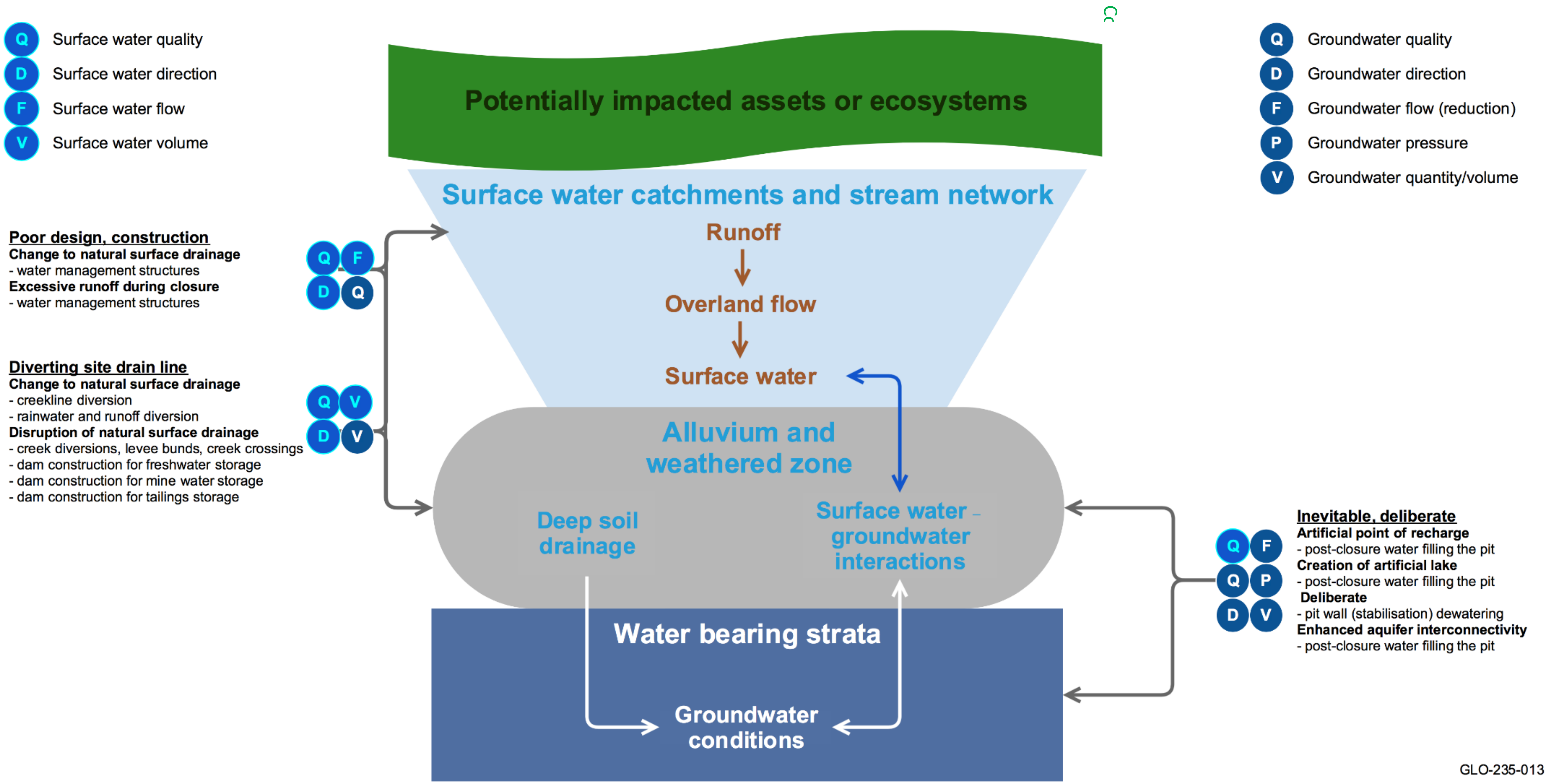

Figure 16 Hazards (impact causes, impact modes and activities) and associated effects identified for the life-cycle stages of open-cut coal mines that are considered to be in scope in the Gloucester subregion

Impact causes are underlined, impact modes are bold and activities are bullet points. Arrows indicate the spatial context for each hazard: aquifers, aquifer outcrop areas, watercourses, catchments.
GDEs = groundwater-dependent ecosystems
Typology and punctuation are consistent with the hazard analysis (Bioregional Assessment Programme, Dataset 1).

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

Table 10 Hazards identified for the life-cycle stages of open-cut coal mines that are considered to be in scope in the Gloucester subregion and their associated hydrological effects, spatial context, temporal context, and potentially impacted assets or ecosystems

This table lists each hazard (with its spatial and temporal context) in a chain of logic from hydrological effects to potentially impacted assets or ecosystems. The spatial context includes target and non-target aquifers, aquifer outcrop areas, coal resource development areas and watercourses. Within the relevant spatial and temporal context, assets and ecosystems are described using landscape classification rule sets, landscape class group (e.g. 'Floodplain or lowland riverine') or asset type (e.g. economic = economic groundwater asset).

Hazard (with syntax 'Impact cause: (life-cycle stage[a]) impact mode – activity')	Hydrological effects	Spatial context	Temporal context[b]	Potentially impacted assets or ecosystems
Diverting site drain line: (D) Change to natural surface drainage – creekline diversion	SW directional characteristics, SW volume/quantity, SW quality	Watercourses within and downstream of operations area	Medium to long term	All watercourses
Diverting site drain line: (D) Change to natural surface drainage – rainwater and runoff diversion	SW volume/quantity, SW quality, GW quantity/volume	Watercourses within and downstream of operations area	Medium to long term	All watercourses
Diverting site drain line: (D) Disruption of natural surface drainage – creek diversions, levee bunds, creek crossings	SW directional characteristics, SW volume/quantity, SW quality	Watercourses within and downstream of operations area	Medium to long term	All watercourses
Diverting site drain line: (D) Disruption of natural surface drainage – dam construction for freshwater storage	SW volume/quantity, SW quality, GW quantity/volume	Alluvium and watercourses in aquifer outcrop areas within and downstream of operations area	Medium to long term	Intermittent and perennial – gravel/cobble streams
Diverting site drain line: (D) Disruption of natural surface drainage – dam construction for mine water storage	SW volume/quantity, SW quality, GW quantity/volume	Alluvium and watercourses in aquifer outcrop areas within and downstream of operations area	Medium to long term	Intermittent and perennial – gravel/cobble streams
Diverting site drain line: (D) Disruption of natural surface drainage – dam construction for tailings storage	SW volume/quantity, SW quality, GW quantity/volume	Alluvium and watercourses in aquifer outcrop areas within and downstream of operations area	Medium to long term	Intermittent and perennial – gravel/cobble streams
Inevitable, deliberate: (C) Artificial point of recharge – post-closure water filling the pit	GW quantity/volume	Alluvium aquifer within operations area	Long term	GDEs and economic

Hazard (with syntax 'Impact cause: (life-cycle stage[a]) impact mode – activity')	Hydrological effects	Spatial context	Temporal context[b]	Potentially impacted assets or ecosystems
Inevitable, deliberate: (P) Deliberate – pit wall (stabilisation) dewatering	GW flow, GW direction, GW quantity/volume, GW pressure, SW flow	Alluvium and watercourses in aquifer outcrop areas within and downstream of operations area	Medium to long term	Intermittent and perennial – gravel/cobble streams
Inevitable, deliberate: (C) Enhanced aquifer interconnectivity – post-closure water filling the pit	GW quality	Alluvium aquifer within operations area	Medium to long term	GDEs and economic
Inevitable, deliberate: (C) Creation of artificial lake – post-closure water filling the pit	SW quality	Alluvium aquifer within operations area	Medium to long term	GDEs and economic
Poor design, construction: (C) Change to natural surface drainage – water management structures	SW directional characteristics, SW flow, SW quality	Watercourses within and downstream of operations area	Medium to long term	All watercourses
Poor design, construction: (C) Excessive runoff during closure – water management structures	GW quality, SW quality	Alluvium and watercourses in aquifer outcrop areas within and downstream of operations area	Medium to long term	Intermittent and perennial – gravel/cobble streams

[a]life-cycle stage of coal mine where C = mine closure; D = development; E = exploration and appraisal; P = production; R = rehabilitation
[b]medium term = 5 to 10 years; long term = 10 to 100 years
GDEs = groundwater-dependent ecosystems; GW =groundwater; SW = surface water
Typology and punctuation are consistent with the hazard analysis (Bioregional Assessment Programme, Dataset 1).
Data: Bioregional Assessment Programme (Dataset 1)

2.3.5.3 Causal pathways

Causal pathways are considered for CSG operations and coal mines separately, for both the baseline coal resource development (baseline) and CRDP. Many of the causal pathways that exist are common to both baseline and the CRDP because the latter includes extensions of Stratford and Duralie mines beyond December 2012.

Water flow paths are controlled primarily by changes in total head. For surface water flows, the water depth is small relative to land-surface elevation changes, so that surface topography and slope are the main drivers of both direction and velocity. For groundwater flows, the thickness of saturated material (i.e. the aquifer) is often larger than changes in the base elevation of the layer, so absolute groundwater elevation is the main driver of flow direction. Flow velocity is a function of the aquifer material and geological connections, so horizontal and vertical hydraulic conductivity are the main drivers of groundwater flow velocity. With groundwater flows, however, the presence of faults and discontinuities can alter both direction and velocity. These are present in the geological Gloucester Basin.

There are three hydrogeological units in the Gloucester Basin:

- surface alluvium up to 15 m thick; this has limited spatial extent
- shallow weathered and fractured rock layer (SRL) up to 150 m thick
- alternating layers of interburden and coal seams to a maximum depth of 2500 m.

The natural cycle for water within the Gloucester Basin is for rainfall to recharge outcropping layers at the margins of the basin causing upward pressure in these layers that discharges to the alluvial aquifer and valley floor. Streams and rivers hosted in the alluvial aquifer are gaining and connected under natural conditions. Diffuse rainfall recharge occurs to the alluvial aquifer and supports baseflow.

The main controls for groundwater interactions with the surface are in the SRL, with its connectivity between the coal layers and the alluvium, and the fracture and fault networks within it. A necessary part of CSG exploration and production is depressurisation of individual gas-bearing layers. Target seams in the Gloucester Basin are between 150 and 600 m depth with dry ash-free gas content of 10 to 25 m^3/t, increasing with depth (Hodgkinson et al., 2014, p. 13). While layers at these depths are considered to be water-bearing strata rather than aquifers, the weathered and fractured rock zone extends as far as 150 m depth, so the uppermost target coal seams may be just below this upper aquifer. As water volumes extracted as part of CSG operations are likely to be relatively small, changes would be propagated to the surface via SRL through lowering the hydrostatic pressure in coal seams, rather than direct water transfer.

Coal seams outcrop on the land surface within the Gloucester Basin and are open-cut mined, but these seams have lost their gas content long ago and are not targets for CSG. Localised groundwater pressure drops can be transferred to the SRL by natural diffuse pathways and vertical conductance, and via fractures and structural features where present. If the underlying groundwater level within the SRL decreases enough, then it may induce flow away from the alluvial aquifer, reducing natural stream discharge.

A potential impact of CSG operations occurs if a CSG well leaks. If this occurs then it may create a connection between the targeted coal seam and any other layer(s) above it, including the land surface. The results include localised groundwater level reduction, and the induced transfer of water and any introduced material between geological layers. If such a leak occurred within the alluvial aquifer, then stock and domestic bores that draw water from it may be affected. There is no evidence of any leakage from the four gas test wells drilled and fracture stimulated as part of the Waukivory Pilot Project.

Open-cut coal mines in the Gloucester subregion are focused at the land surface. The pit must be dewatered so that coal can be removed, and this causes a groundwater level gradient toward the pit, which induces more groundwater seepage that needs to be removed. This groundwater level gradient is induced within the geological layers the mine occupies, and the area of drawdown is controlled by the local hydraulic conductivity. If there is connectivity between other outcropping layers and hydraulic properties allow it, then water could be drawn from these layers. If water flows are induced away from the alluvial aquifer, then natural discharge to streams may be reduced.

Open-cut coal mines also affect surface flows. Typically, all rain falling within the active mining operations area must be retained on site. This means that any runoff produced in that area does not contribute to normal surface flows to streams, wetlands and any other surface water features.

In general, negative effects of changes in groundwater level gradient hinge on the presence of a connection between an asset and CSG or coal mining operations via direct or diffuse pathways, or the creation of a new connection due to changes in the rocks and layers as a result of drilling and/or other operations. The scale of change depends on rates of hydraulic conductivity, and the behaviour of faults and discontinuities as either carriers of, or barriers to, groundwater movement.

2.3.5.3.1 Coal seam gas operations

The hazards associated with CSG operations (identified as part of the IMEA) were considered in relation to the scope (Section 2.3.5.2.3) and were aggregated into four main causal pathway groups:

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

‘Subsurface depressurisation and dewatering’ causal pathway group

Groundwater extraction for CSG production can lead to hydrostatic depressurisation of aquifer layers. The water pathway for this hazard depends on the local environment of an individual CSG well (Figure 17). If there are no faults or fractures nearby then the head changes caused by depressurisation must be passed to other layers diffusively according to conductivity, layer structure and the presence of aquitards. These affect the magnitude of head change, the spatial extent of head change, and the time it takes for maximum change to occur. Therefore, there is no hard and fast rule for how depressurisation of a particular CSG target layer will affect surrounding layers or the SRL or alluvial aquifer, if at all. Where a fault or fracture does exist then pressure change may potentially be transmitted much quicker and much further. However, this depends on the geometry of the geological compartments defined by the faults or fractures and their properties. Furthermore, it may be possible that prolonged depressurisation will reactivate a fault pathway, and thus create a pathway that was not active prior to the extractive activity. Predictions of fault locations by the revised geological model for Gloucester subregion (Figure 13 in companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018)) indicate that major faults exist within the Stage 1 gas field development area of AGL's proposed CSG development in the Gloucester Gas Project.

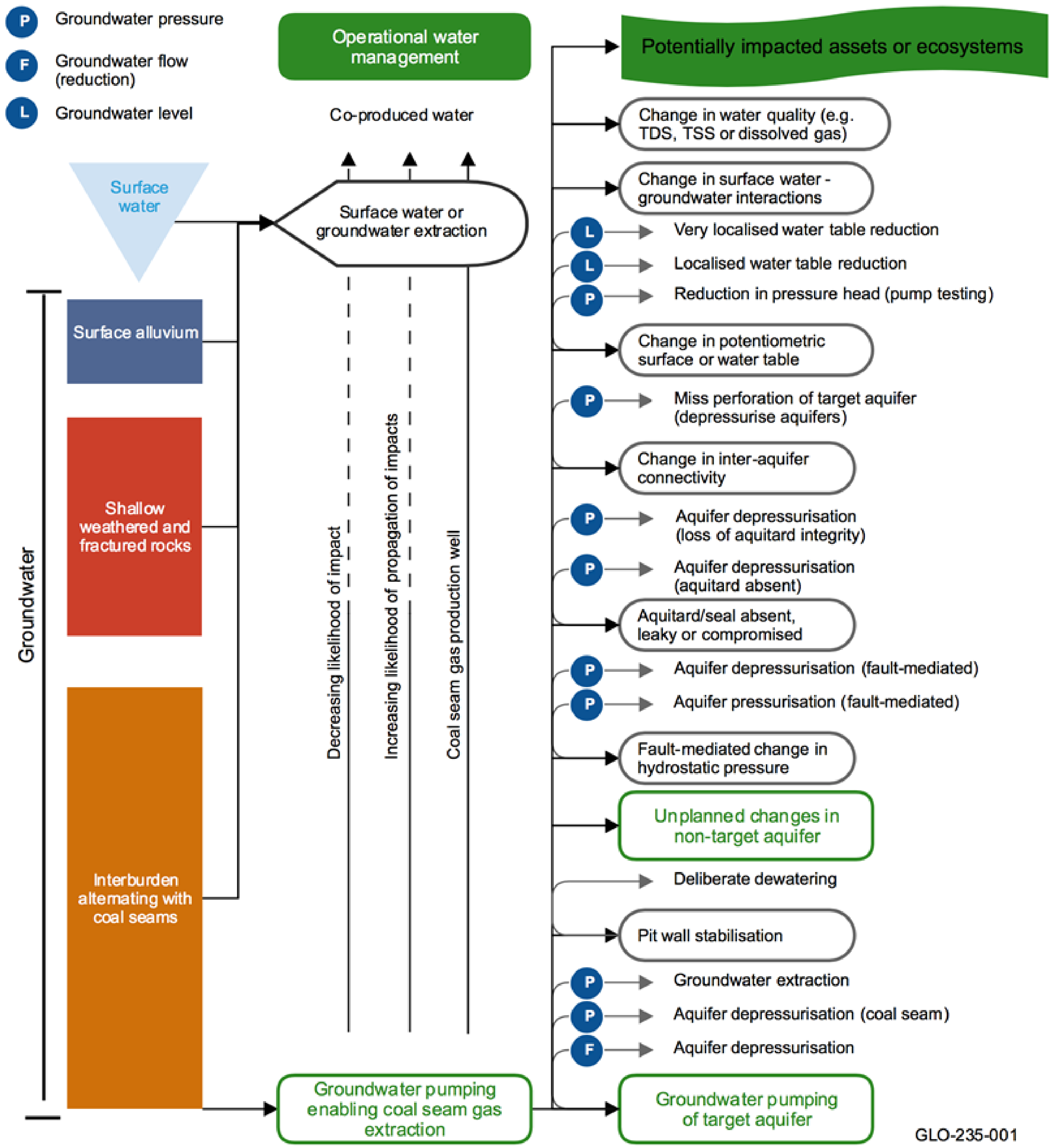

Figure 17 'Subsurface depressurisation and dewatering' causal pathway group arising from coal seam gas operations

'TDS' (total dissolved solids) and 'TSS' (total suspended solids) are examples only of a range of metrics that could be assessed for water quality.

'Subsurface physical flow paths' causal pathway group

Well construction may lead to enhanced connection between layers. The water pathway for this hazard is a result of drilling the well for CSG operations (Figure 18) or for any well that penetrates between distinct geological layers. A well that is not completely sealed against the surrounding material may provide a direct conduit for water to any other layer it is drilled through, including to the land surface. This may be as a result of well construction methods, degradation of the well sealing materials over time, or changes in the aquifer material or structure over time. Hydraulic fracturing is designed to alter connectivity within target layers but may potentially alter inter-aquifer connectivity and introduce additional preferential pathways. Well construction may increase local connectivity (Stuckey and Mulvey, 2013), and allow the mixing of waters from previously disconnected layers of different quality and chemical properties, or of any fluid introduced down the well.

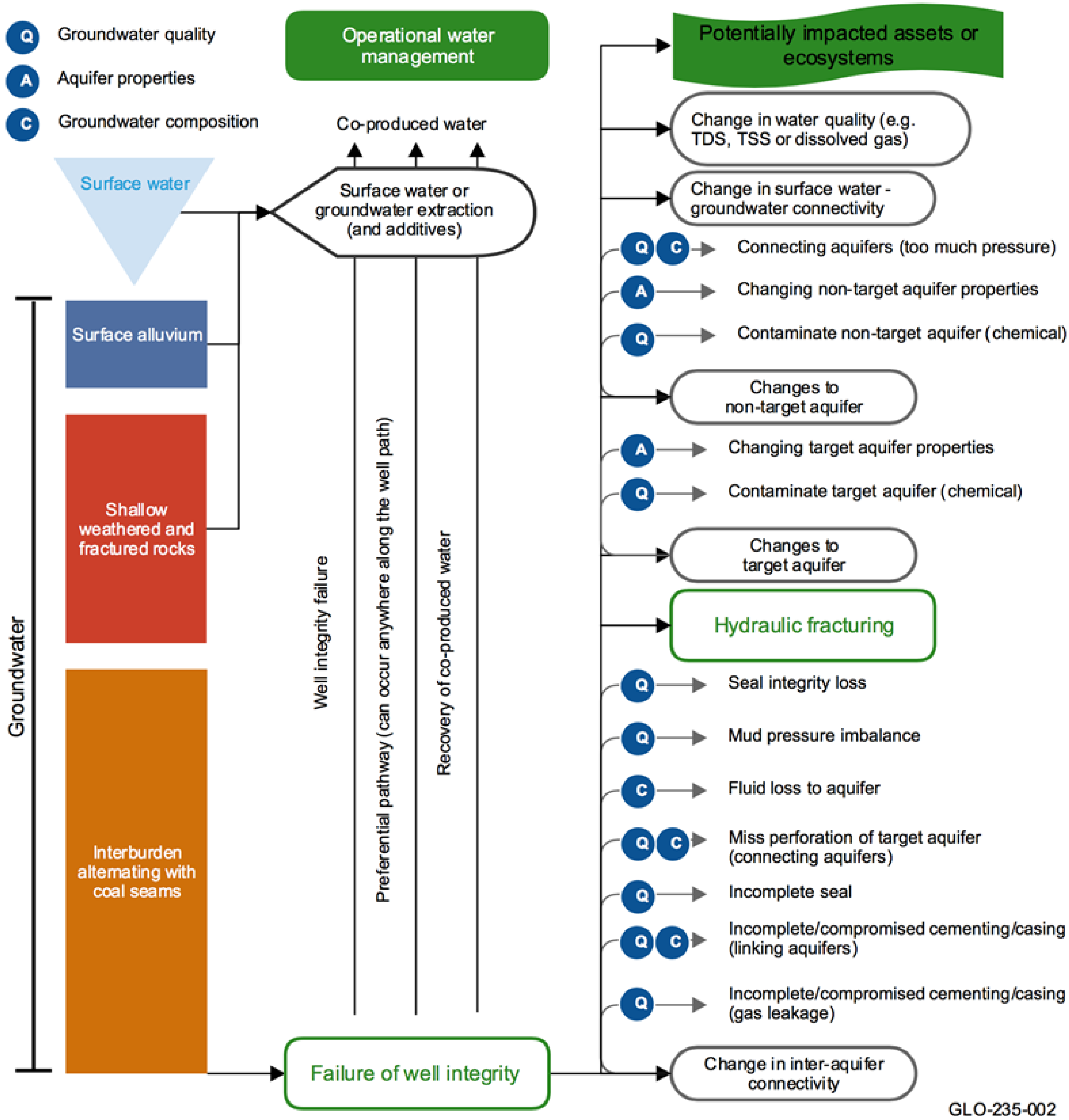

Figure 18 'Subsurface physical flow paths' causal pathway group arising from coal seam gas operations

'TDS' (total dissolved solids) and 'TSS' (total suspended solids) are examples only of a range of metrics that could be assessed for water quality.

'Operational water management' causal pathway group

This causal pathway group is less about the impact of water removal from the system, and more what happens after it is removed and collected (Figure 19). The water produced from CSG operations will contain the products added to water pumped into the well, along with the salt (and may also contain other naturally occurring dissolved components that occur in the coal seam groundwater system) in the water removed from the coal seam to release gas. If the water is transported off site, then the problem may no longer exist in the subregion. Other options include use for mine site management, such as dust suppression, irrigation of land locally, or release into local stream and rivers during flow events. If the produced water is of poor quality it may require dilution with fresh water, which introduces an issue of gathering fresh water either from the local environment or from outside the area. Any produced water that is disposed of locally via irrigation or released to rivers can affect water quality and quantity. Section 2.3.4 details the specific plans for each of the mines in the Gloucester subregion, and water quality ranges for its various uses. Water quality monitoring by Parsons Brinckerhoff (2012) indicates that salinity of water generally increases with depth, and that water in the coal seams and interburden layers is three to four times more saline than water in the alluvial aquifer and up to 50 times more saline than Avon and Gloucester river water.

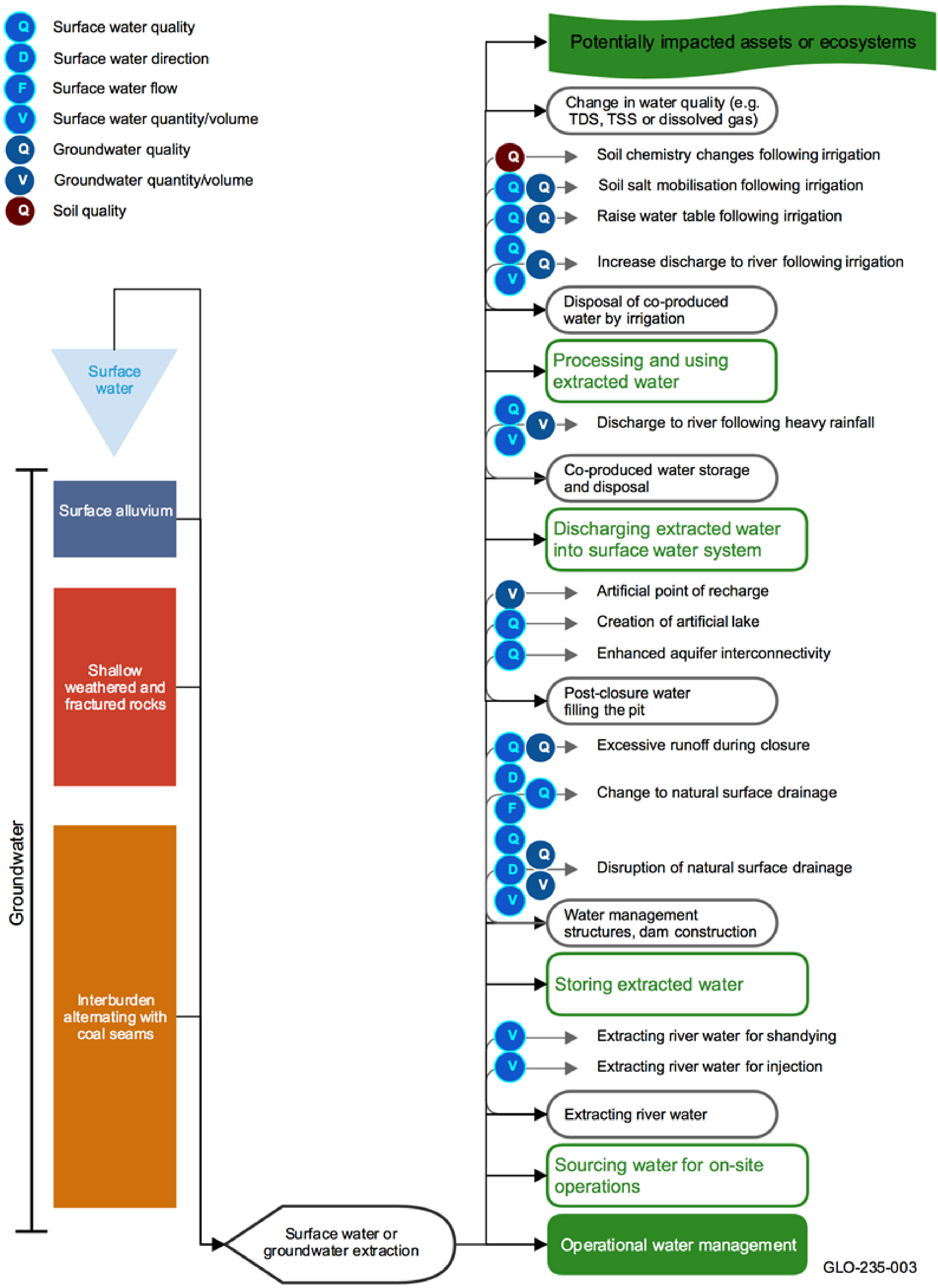

Figure 19 'Operational water management' causal pathway group arising from coal seam gas operations

'TDS' (total dissolved solids) and 'TSS' (total suspended solids) are examples only of a range of metrics that could be assessed for water quality.

'Surface water drainage' causal pathway group

This impact mode is defined by the physical infrastructure of CSG operations, and the associated surface works. Land clearing, land levelling, the construction of hard packed areas such as roads and tracks, pipelines and plant for collection and transport of gas can all disrupt natural surface flows and pathways by redirecting and concentrating flows (Figure 20). In many natural systems water flow and landscape topography co-evolve so that in a stable system the areas of most concentrated flow are the most resistant to erosion. Changes in flow regime and catastrophic events can alter flows and pathways either temporarily before returning to the previous state, or semi-permanently until another such event. In the same way, engineered structures and earth works associated with CSG exploration and production may divert and concentrate surface flow. This may lead to erosion of the land surface, stream banks or stream beds, and alter water quality in streams if new material is mobilised and washed into them. As noted in Hodgkinson et al. (2014, pp. 27–29) the CSG development approved in the Gloucester subregion is for 110 wells in the 50 km^2 stage 1 CSG development area of AGL's proposed CSG development in the Gloucester Gas Project, and subsequent stages estimated as 200 to 300 wells over the full 210 km^2 gas field development area. This allows for what the NSW Department of Planning (2011, p. 5) calls:

> ... construction, operation, decommissioning and rehabilitation of gas wells and associated infrastructure including gas and water gathering lines and temporary construction facilities ....

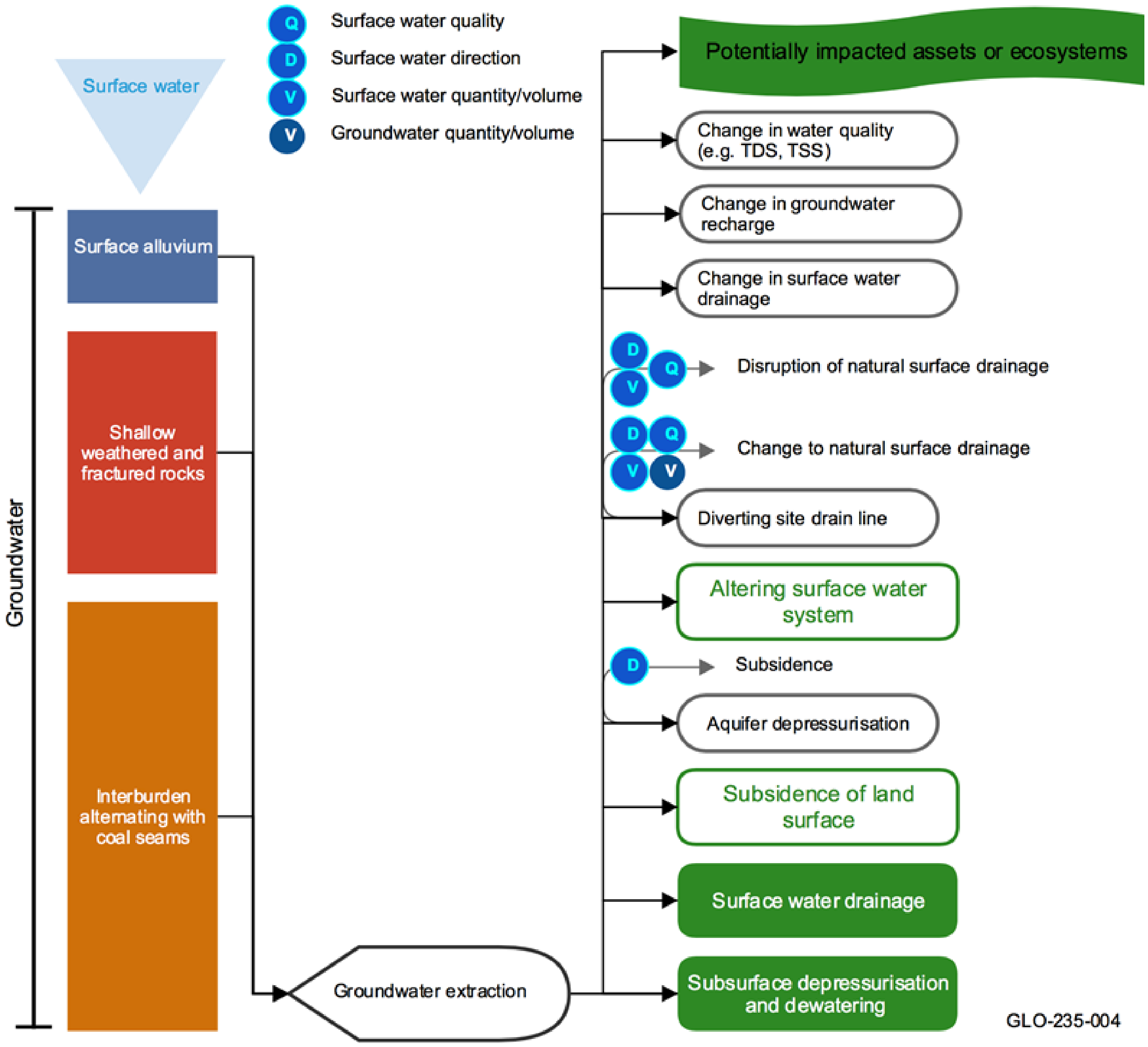

Figure 20 'Surface water drainage' causal pathway group arising from coal seam gas operations

'TDS' (total dissolved solids) and 'TSS' (total suspended solids) are examples only of a range of metrics that could be assessed for water quality.
SW = surface water

The influence of the various impact modes is described in Table 9. While all of the effects are generally local to the CSG operation, for example, less than 1 km from the site, both aquifer depressurisation and inter-aquifer connectivity are affected by the local geological environment. The spread of drawdown or water mixing is controlled by the presence and nature of faults and fractures, and local hydraulic properties. Drawdown cones from pumping wells will take decades to reach maximum effect in both groundwater level drop and diameter, while water mixing from a leaky well may be recognised in less than a year. Similarly, disruption to surface flows is generally localised, but the changes in water chemistry or flow input location along a reach may have effects on water or other assets many kilometres downstream. Soil erosion resulting from changes in runoff pathways may cause damage with an individual storm event, and changes to the amount and type of material discharging into the stream over many years.

2.3.5.3.2 Open-cut coal mines

The hazards associated with open-cut coal mines (identified as part of the IMEA) were considered in relation to the scope (Section 2.3.5.2.3) and were aggregated into four main causal pathway groups:

- 'Surface water drainage'
- 'Subsurface physical flow paths' grouped with 'Subsurface depressurisation and dewatering'
- 'Operational water management'.

'Surface water drainage' causal pathway group

Disruption of surface drainage network may lead to a loss, or redirection, of runoff. The water issue with this hazard is that any rain that falls within the limits of the mining operations area must be retained on site (Figure 20). This on-site water retention minimises the chances of any runoff from the mining operations or infrastructure being contaminated and then exported to the rest of the surface catchment or watercourse. Due to this requirement, however, any runoff that would naturally be generated from the mining operations area is lost to streamflow and the environment. After mining ceases mine-site rehabilitation occurs and, at some stage following this activity, some proportion of the rehabilitated land area will again become connected to the wider surface water catchment.

Open-cut mining area may also alter the surface water pathways. While the total amount of runoff in a surface water catchment might be reduced by only a few percent, the locations that water enters within a stream network may be altered. For example, a mining site may alter runoff pathways such that a single upland stream that contributes only a few percent of overall streamflow contributes none of its normal surface water volumes at the confluence with the network at lower elevations. This has implications for the local stream environment and the next downstream reach where the contribution at this point may be much more significant. It can lead to a greater concentration of flow, so that erosion risk is greater, or a lack of contribution to a water dependent asset. This hazard will have a greater impact the closer an open-cut mine is to the first order streams (or headwater streams) of a surface water network. In the Gloucester subregion the maximum extent of the CRDP mining footprints is 16.9 km^2, or 5.5% of the surface area of the subregion. This should result in a maximum of 5.5% direct reduction in runoff to the entire stream network, assuming uniform runoff production.

'Subsurface physical flow paths' and 'Subsurface depressurisation and dewatering' causal pathway groups

The dewatering of an open-cut coal mine will lower the watertable, affect inter-aquifer connectivity and may potentially lead to a loss of baseflow (Figure 18). Mines must have water removed to allow the safe removal of coal, and this decrease in local groundwater level creates a gradient toward the pit, and induces flow into it. The primary sources of this water are the layers in which the mine is sited, down to the layer being mined. The spatial extent of the influence area of the pit dewatering is a function of the depth of mining, the local hydraulic properties of conductivity and storativity, and the time elapsed. It is the time elapsed that affects the spatial extent of this impact. For example, a particular asset may be so distant from an open-cut coal mine that within the life of mining that drawdown will not affect it, but in the years following the spread of the drawdown area may affect it. This can only be quantified with monitoring and estimated with modelling. Streams exist in an alluvial aquifer and recharge within this aquifer discharges to the stream as baseflow. If the dewatering of an open-cut coal mine allows a drawdown cone to intersect with an alluvial aquifer supporting a stream, then potentially that water that would naturally discharge to the stream is instead drawn away from the alluvium toward an open-cut mining pit.

On a much more local scale exploration and monitoring bores may alter inter-aquifer connectivity through well integrity issues creating preferential pathways. This may be as a result of well construction methods, degradation of the well casing or sealing materials over time, or changes in the aquifer material or structure over time due to operations or natural events.

'Operational water management' causal pathway group

The pathways for open-cut coal mines are the same as those for co-produced water from CSG operations (Figure 19) but the volumes of water are likely to be larger, as dewatering an open-cut coal mine including seepage involves much more water than dewatering a deep coal seam. The hazard identification workshop also indicated leaching of water within the mine site from waste rock dumps, coal stockpiles and storage dams of produced water. The pathway here is direct contamination of the aquifer the mine is sited on, or if water escapes over the surface then contamination of local streams.

The spatial and temporal extents of impact modes associated with open-cut mines are shown in Table 10, while the water volumes and water management plans for specific mines are discussed in Section 2.3.4. The inter-aquifer connectivity impact is related to mine pit dewatering, and this must occur over the full life of the mine plus some time into the future. The future impacts are controlled by the management of site rehabilitation (e.g. refilling the mine void with much looser material will allow seepage to continue toward the old mine void and may interrupt local groundwater flow pathways). Similarly, for the disruption of surface drainage, without suitable rehabilitation the mining lease area may have very different properties in runoff production, vegetation health, infiltration characteristics and local groundwater level long into the future.

2.3.5.3.3 Causal pathways for baseline and coal resource development pathway

Baseline coal resource development

There is no coal seam gas development in the baseline for the Gloucester subregion and therefore no associated potential causal pathways.

The causal pathways from open-cut coal mines in the baseline in the Gloucester subregion (see Table 7 in Section 2.3.4) are all those associated with the current Stratford and Duralie mines:

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

Activities at the Stratford site may affect the 'Intermittent – gravel/cobble streams' landscape class in the 'Riverine' landscape group of the upper Avon River and the 'Forested wetlands' landscape class in the 'Groundwater-dependent ecosystem (GDE)' landscape group (see Figure 6 in Section 2.3.3). The mine is otherwise within an area classified as cleared for dryland agriculture with some proximity to native vegetation. The 'Forested wetlands' landscape class is associated with the alluvium containing the Avon River locally, and will respond to changes in groundwater quality and level, stream baseflow quantity and variability (see Figure 6 and Table 3 in Section 2.3.3). At the Duralie site the 'Perennial – gravel/cobble streams' landscape class (in the 'Riverine' landscape group) of Mammy Johnsons River is affected, while the mine is located in land cleared for dryland agriculture.

Coal resource development pathway

AGL's proposed Gloucester Gas Project introduces the following causal pathway groups related to CSG operations for the CRDP:

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

The Gloucester Gas Project site will be located within land cleared for dryland agriculture with scattered native vegetation, and these causal pathways may affect reaches of the Avon River in the 'Intermittent – gravel/cobble streams' landscape class in the 'Riverine' landscape group.

The causal pathways for the CRDP include those for Yancoal Australia Ltd's (Yancoal) existing Stratford and Duralie mines and are supplemented by expansions at both Stratford and Duralie, and new open-cut mining at Rocky Hill. At the Stratford and Duralie sites no additional causal pathways due to open-cut mines are introduced, and it is expected the same landscape and GDE classes will continue to be affected in the same manner as for the baseline. The Rocky Hill open-cut mining sites are located within land cleared for dryland agriculture with scattered native vegetation, and may affect reaches of the Avon River in the 'Intermittent – gravel/cobble streams' landscape class in the riverine landscape group

Summary

Table 11 summarises the causal pathways linking coal resource development to potentially impacted landscape classes in the Gloucester subregion.

Table 11 Causal pathways arising from open-cut mines and coal seam gas operations

Type of coal resource development	Causal pathway group	Baseline coal resource development	Coal resource development pathway	Potentially impacted landscape class
Open-cut coal mines	Subsurface depressurisation and dewatering	Yes	Yes	Intermittent – gravel/cobble streams Forested wetlands (Groundwater-dependent ecosystem (GDE) landscape group) Perennial – gravel/cobble streams
	Subsurface physical flow paths	Yes	Yes	
	Operational water management	Yes	Yes	
	Surface water drainage	Yes	Yes	
Coal seam gas operations	Subsurface depressurisation and dewatering		Yes	Lowly intermittent – gravel/cobble streams
	Subsurface physical flow paths		Yes	
	Operational water management		Yes	
	Surface water drainage		Yes	

2.3.5.4 Gaps

This section draws together all the elements up to specifying causal pathways for baseline and CRDP, and includes the gaps in each of the individual components.

The level of specification in the potential causal pathways represented reflects the current state of knowledge. In general, data limitations in the Gloucester subregion contribute importantly to gaps in the Assessment team's conceptualisation of the potential causal pathways. For instance, limited geological datasets, sparse data on surface water – groundwater interactions and the lack of current specification on some of the operational water management all affect the conceptualisation of potential causal pathways. The specific nature of these data limitations are typically explored in more detail through the development of surface water and groundwater models (refer to the companion products 2.6.1 and 2.6.2 for the Gloucester subregion (Zhang et al. (2018) and Peeters et al. (2018)) respectively).

For the flow pathways due to coal mines and CSG operations the greatest gap is knowledge of the faults and fractures of the geological layers. For example, there is not a clear idea of the location of all the largest faults in the geological Gloucester Basin, and both the nature, location, regional *versus* local extent, hydraulic properties and extent of smaller potential pathways between adjacent layers is only known theoretically. This makes any absolute statement on the spatial extent of a groundwater level decline due to CSG operations difficult. Uncertainty analysis does allow a probabilistic estimate of maximum groundwater level decline at the regional scale and the drawdown propagation is minimal (refer to Section 2.6.2.8 in companion product 2.6.2 for the Gloucester subregion (Peeters et al., 2018)). Because these realisations were random and modelled at the regional scale, no general comment can be made about potential local impacts of any single future well.

When placing each project in baseline and CRDP in its spatial context with landscape classes and GDEs, the underlying data is of such a large scale that it only coarsely covers the small Gloucester

PAE. To this end the final classification was greatly generalised to five landscape classes in the 'Groundwater-dependent ecosystem (GDE)' landscape group and seven landscape classes in the 'Riverine' landscape group; at the regional scale of analysis, reach lengths of 1 to 3 km were considered too detailed (Section 2.3.3).

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Glossary

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

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

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

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

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

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

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

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

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

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

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

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

dataset: a collection of data in files, 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). In the BA Repository, datasets are guaranteed to have a metadata record in the Metadata Catalogue and to have their components (files, database interface) delivered via the Data Store. In semantic web terms, a BA dataset is defined as a subclass of DCAT Dataset and PROMS Entity and is described in the BA Ontology as a scope note in term record.

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)

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 (i.e. humans are regarded as part of nature).

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

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

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

groundwater-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.

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

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 the groundwater and/or surface water due to coal resource development. They are present on the landscape across the entire BA subregion or bioregion and their spatial coverage is exhaustive and non-overlapping. Conceptually, landscape classes can be considered as types of ecosystem assets.

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

likelihood: probability that something might happen

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

material: pertinent or relevant

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

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

receptor impact variable: 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)

recharge: see groundwater recharge

risk: the effect of uncertainty on objectives

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

severity: magnitude of an impact

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

source dataset: a pre-existing dataset sourced from outside the Bioregional Assessment Programme. This includes data sourced from the Programme partner organisations.

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

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

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

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

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

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

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