Australian Government

BIOREGIONAL ASSESSMENTS

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

Conceptual modelling for the Namoi subregion

Product 2.3 for the Namoi subregion from the Northern Inland Catchments 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 978-1-925315-62-2

Citation

Herr A, Northey J, Mitchell PJ, Aryal SK, Merrin LE and Slatter E (2018) Conceptual modelling for the Namoi subregion. Product 2.3 for the Namoi subregion from the Northern Inland Catchments Bioregional Assessment. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. http://data.bioregionalassessments.gov.au/product/NIC/NAM/2.3.

Authorship is listed in relative order of contribution.

Cover photograph

Gulligal Lagoon, which is located about halfway between Gunnedah and Boggabri on the western side of the Namoi River, NSW, 2005

Credit: Neal Foster

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Bureau of Meteorology

Geoscience Australia

CSIRO

v20180622

Executive summary

This product presents a conceptual model for the Namoi subregion in the Northern Inland Catchments Bioregional Assessment. 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 development with both potential changes to water resources and ecosystems at or near the land surface. Conceptual models are abstractions or simplifications of reality. The essence of how key system components operate and interact is outlined in the conceptual model for the Namoi subregion.

Summary of key system components, processes and interactions

The geology of the Namoi subregion is central in explaining the location of coal mining and coal seam gas (CSG) operations. The coal resources under development in the Namoi subregion are primarily in the geological Gunnedah Basin with the main economic coal seams in the Black Jack Group and the Maules Creek Formation. The Werris Creek Mine is located in the Werrie Basin, adjacent to the eastern side of the Gunnedah Basin. The target coal seams for the Werris Creek Mine are in the Willow Tree Formation.

Coal mining and coal seam gas (CSG) operations can induce changes in groundwater level in the vicinity of operations. This may change the magnitude or direction of flow between groundwater and surface water systems.

The main near-surface aquifers in the Namoi subregion are associated with the alluvial sediments along the Namoi River and its larger tributaries (Mooki and Peel rivers, Coxs and Pian creeks). Other aquifers include porous sedimentary strata in the Great Artesian Basin (GAB) and the Gunnedah Basin.

The main surface water resource of the Namoi subregion is the Namoi River. It drains an area of approximately 42,000 km^2 flowing from east to west from its headwaters in the Great Dividing Range. Except for the Namoi River all Namoi river basin waterways are either ephemeral or intermittent. The Peel River is now permanent because of releases from Chaffey Dam. Prior to regulation it was also temporary.

Ecosystems

In the Namoi subregion the potential impact of hydrological changes due to coal resource development is investigated in ecosystems at the land surface. Dividing the Namoi subregion into landscape classes enables a structured approach for assessing these potential impacts. The landscape classification describes the main ecological and human systems (including agricultural production systems, and industrial and urban uses), and provides a high-level conceptualisation of the subregion at the surface.

In the Namoi subregion, 29 landscape classes were derived and allocated to one of six landscape groups based on broad-scale distinctions in their water dependency and association with floodplain or non-floodplain environments, groundwater-dependent ecosystems (GDEs) and remnant or human-modified habitat types.

The landscape groups are as follows:

- ‘Floodplain or lowland riverine’
- ‘Non-floodplain or upland riverine’
- ‘Dryland remnant vegetation’
- ‘Rainforest’
- ‘Human-modified’
- ‘Springs’.

These landscape groups are expressed as a percentage of the preliminary assessment extent (PAE). The PAE is the geographic area where potential impacts on water-dependent assets due to coal resource development are assessed. Landscape classification shows the following:

- The ‘Human-modified’ landscape group, which includes agricultural, urban and other intensive land uses, comprises 59% of the PAE.
- The ‘Dryland remnant vegetation’ landscape group, which is not considered to be water dependent, comprises 24% of the PAE.
- Approximately 6% of the PAE is covered by the ‘Floodplain or lowland riverine’ landscape group and includes the lowland riverine systems and the adjacent landscape classes associated with the riparian and backplain environments.
- Approximately 10% of the PAE and almost 72% of the watercourses are included in the ‘Non-floodplain or upland riverine’ landscape group, which includes a large extent of vegetation classified as groundwater dependent.

Coal resource development

Potential hydrological changes due to coal resource development are quantified in the Namoi subregion for two potential futures:

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

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

The CRDP for the Namoi subregion consists of six baseline coal mines and ten additional coal resource developments. Under the baseline, there are five open-cut coal mines: Boggabri Coal Mine, Rocglen Mine, Sunnyside Mine, Tarrawonga Mine and Werris Creek Mine; and one longwall mine: Narrabri North. The ten additional coal resource developments are Boggabri Coal Expansion Project, Caroona Coal Project, Gunnedah Precinct, Maules Creek Project, Narrabri South, Tarrawonga Coal Expansion Project, Vickery Coal Project, Vickery South Coal Project, Watermark Coal Project and Narrabri Gas Project. Eight of these additional coal resource developments are modelled for the Namoi subregion, with the remaining two mines, Vickery South Coal Project (open-cut coal mine) and the Gunnedah Precinct (open-cut and underground), not being modelled due to insufficient information. Analysis of the impacts of these two developments will be restricted to commentary in product 3-4 (impact and risk analysis).

BHP's proposed development of the Caroona Coal Mine was discontinued in August 2016. As per companion submethodology M04 the CRDP was not revisited and the timeline described for the project will continue to form the basis for modelling hydrological changes and include Caroona Coal Mine. The CRDP needs to be viewed as an indicative future that highlights potential changes for water resources and water-dependent assets and areas where further investigation may be warranted.

Hazard analysis and causal pathways

A hazard analysis identified the potential hydrological changes due to coal resource development. In the Namoi subregion a hazard analysis workshop was held in May 2015, where participants identified and scored detailed hazards using the Impact Modes and Effects Analysis (IMEA) process to systematically identify coal resource development *hazards* with the potential to change the hydrology. Individual hazards constitute causal pathways and can be aggregated by common impact cause and impact mode into four causal pathway groups:

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

The causal pathway groups under the CRDP are the same for open-cut and underground coal mines and the CSG operations.

The Narrabri Gas Project is targeting the main coal seams in the lower Permian Maules Creek Formation within the Gunnedah Basin. All four causal pathway groups are relevant. Specifically, there is the potential for connectivity between the target coal seams and the surface and near-surface aquifers through the stratigraphic formations. Agricultural bores accessing the alluvial aquifers and the Pilliga Sandstone aquifer in the GAB may have reduced flow if the hydrostatic pressure change from CSG depressurisation propagates vertically through the overlying sequence. Propagation of the depressurisation cone may be impeded or enhanced by faults and the presence or absence of aquitards. If an aquitard is thin or absent, then this may enhance propagation of a depressurisation cone laterally or vertically. To the east of the Narrabri Gas Project area, the Gunnedah Basin strata, including the target coal seams, are in direct contact with the overlying alluvium and associated aquifers. If propagation of the depressurisation cone were to extend this far to the east, then there is the potential for overlying aquifers to have reduced pressure.

The mines in the CRDP located in the Mullaley sub-basin (Narrabri North and South, Watermark, Sunnyside and Gunnedah Precinct) primarily target the Hoskissons Coal in the upper Permian Black Jack Group. These mines are overlain by Surat Basin strata and alluvium. In the south of the Mullaley sub-basin around the Watermark development, the Surat Basin strata are not present.

The Maules Creek, Boggabri (including expansion), Tarrawonga (including expansion), Vickery Project (including Vickery South) and Rocglen mines located in the Maules Creek sub-basin are targeting the coal seams in the Maules Creek Formation. There is the potential for interaction of mine dewatering with the Upper Namoi alluvium and the Namoi River.

The Werris Creek Mine is located in the Werrie Basin targeting the coal seams in the Willow Tree Formation. The Werrie Basin is hydrologically isolated from the Gunnedah Basin as the Hunter-Mooki Thrust Fault System is considered to be an impermeable boundary to regional groundwater flow. For this reason Werris Creek groundwater is not incorporated in the groundwater modelling for the Namoi subregion. The surface waters around the Werris Creek Mine flow into the Namoi River, and so form part of the surface water modelling.

In summary, causal pathways in all four causal pathway groups have the potential to cause hydrological changes due to additional coal resource developments in the Namoi subregion. All four causal pathway groups are relevant for all six major landscape groups.

Gaps

The following knowledge gaps were identified in the development of the conceptual model:

- There are limited long-term, consistent surface water quality and quantity data, which are required for developing models that can predict water quality into the future.
- There is a lack of detailed understanding of the interaction between the surface water and groundwater systems, particularly at the local level.
- The CRDP for the Namoi subregion was confirmed and ‘locked in’ for this BA as of December 2015; therefore, any project-related changes since then have not been reflected in the CRDP presented in this product. For example, BHP’s proposed Caroona Coal Mine is discontinued but still part of the CRDP in this BA. Given the current early stage of the mine developments, the provided mining scheduling and production rates are estimates only.

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Figures

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Contributors to the Technical Programme

The following individuals have contributed to the Technical Programme, the part of the Bioregional Assessment Programme that undertakes bioregional assessments.

Role or team	Contributor(s)
Assistant Secretary	Department of the Environment and Energy: Matthew Whitfort
Programme Director	Department of the Environment and Energy: John Higgins, Anthony Swirepik
Technical Programme Director	Bureau of Meteorology: Julie Burke
Projects Director	CSIRO: David Post
Principal Science Advisor	Department of the Environment and Energy: Peter Baker
Science Directors	CSIRO: Brent Henderson Geoscience Australia: Steven Lewis
Integration	Bureau of Meteorology: Richard Mount (Integration Leader) CSIRO: Becky Schmidt
Programme management	Bureau of Meteorology: Louise Minty CSIRO: Paul Bertsch, Warwick McDonald Geoscience Australia: Stuart Minchin
Project Leaders	CSIRO: Alexander Herr, Kate Holland, Tim McVicar, David Rassam Geoscience Australia: Tim Evans Bureau of Meteorology: Natasha Herron
Assets and receptors	Bureau of Meteorology: Richard Mount (Discipline Leader) Department of the Environment and Energy: Glenn Johnstone, Wasantha Perera, Jin Wang
Bioregional Assessment Information Platform	Bureau of Meteorology: Lakshmi Devanathan (Team Leader), Derek Chen, Trevor Christie-Taylor, Melita Dahl, Angus MacAulay, Christine Price, Paul Sheahan, Kellie Stuart CSIRO: Peter Fitch, Ashley Sommer Geoscience Australia: Neal Evans
Communications	Bureau of Meteorology: Jessica York CSIRO: Clare Brandon Department of the Environment and Energy: John Higgins, Miriam McMillan, Milica Milanja Geoscience Australia: Aliesha Lavers
Coordination	Bureau of Meteorology: Brendan Moran, Eliane Prideaux, Sarah van Rooyen CSIRO: Ruth Palmer Department of the Environment and Energy: Anisa Coric, Lucy Elliott, James Hill, Andrew Stacey, David Thomas, Emily Turner
Ecology	CSIRO: Anthony O'Grady (Discipline Leader), Caroline Bruce, Tanya Doody, Brendan Ebner, Craig MacFarlane, Patrick Mitchell, Justine Murray, Chris Pavey, Jodie Pritchard, Nat Raisbeck-Brown, Ashley Sparrow

Role or team	Contributor(s)
Geology	CSIRO: Deepak Adhikary, Emanuelle Frery, Mike Gresham, Jane Hodgkinson, Zhejun Pan, Matthias Raiber, Regina Sander, Paul Wilkes Geoscience Australia: Steven Lewis (Discipline Leader)
Geographic information systems	CSIRO: Jody Bruce, Debbie Crawford, Dennis Gonzalez, Mike Gresham, Steve Marvanek, Arthur Read Geoscience Australia: Adrian Dehelean
Groundwater modelling	CSIRO: Russell Crosbie (Discipline Leader), Tao Cui, Warrick Dawes, Lei Gao, Sreekanth Janardhanan, Luk Peeters, Praveen Kumar Rachakonda, Wolfgang Schmid, Saeed Torkzaban, Chris Turnadge, Andy Wilkins, Binzhong Zhou
Hydrogeology	Geoscience Australia: Tim Ransley (Discipline Leader), Chris Harris-Pascal, Jessica Northey, Emily Slatter
Information management	Bureau of Meteorology: Brendan Moran (Team Leader), Christine Panton CSIRO: Qifeng Bai, Simon Cox, Phil Davies, Geoff Hodgson, Brad Lane, Ben Leighton, David Lemon, Trevor Pickett, Shane Seaton, Ramneek Singh, Matt Stenson Geoscience Australia: Matti Peljo
Information model and impact analysis	Bureau of Meteorology: Carl Sudholz (Project Manager), Mark Dyall, Michael Lacey, Brett Madsen, Eliane Prideaux Geoscience Australia: Trevor Tracey-Patte
Products	CSIRO: Becky Schmidt (Products Manager), Maryam Ahmad, Helen Beringen, Clare Brandon, Heinz Buettikofer, Sonja Chandler, Siobhan Duffy, Karin Hosking, Allison Johnston, Maryanne McKay, Linda Merrin, Sally Tetreault-Campbell, Catherine Ticehurst Geoscience Australia: Penny Kilgour
Risk and uncertainty	CSIRO: Simon Barry (Discipline Leader), Jeffrey Dambacher, Rob Dunne, Jess Ford, Keith Hayes, Geoff Hosack, Adrien Ickowicz, Warren Jin, Dan Pagendam
Surface water hydrology	CSIRO: Neil Viney and Yongqiang Zhang (Discipline Leaders), Santosh Aryal, Mat Gilfedder, Fazlul Karim, Lingtao Li, Dave McJannet, Jorge Luis Peña-Arancibia, Tom Van Niel, Jai Vaze, Bill Wang, Ang Yang

Acknowledgements

This technical product was reviewed by several groups:

- Senior Science Leaders: David Post (Projects Director), Steven Lewis (Science Director, Geoscience Australia), Brent Henderson (Science Director, CSIRO), Becky Schmidt (Products Manager)
- Technical Assurance Reference Group: Chaired by Peter Baker (Principal Science Advisor, Department of the Environment and Energy), this group comprises officials from the NSW, Queensland, South Australian and Victorian governments.

Currency of scientific results

The modelling results contained in this product were completed in September 2016 using the best available data, models and approaches available at that time. The product content was completed in February 2018.

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 is 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, has undertaken 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.

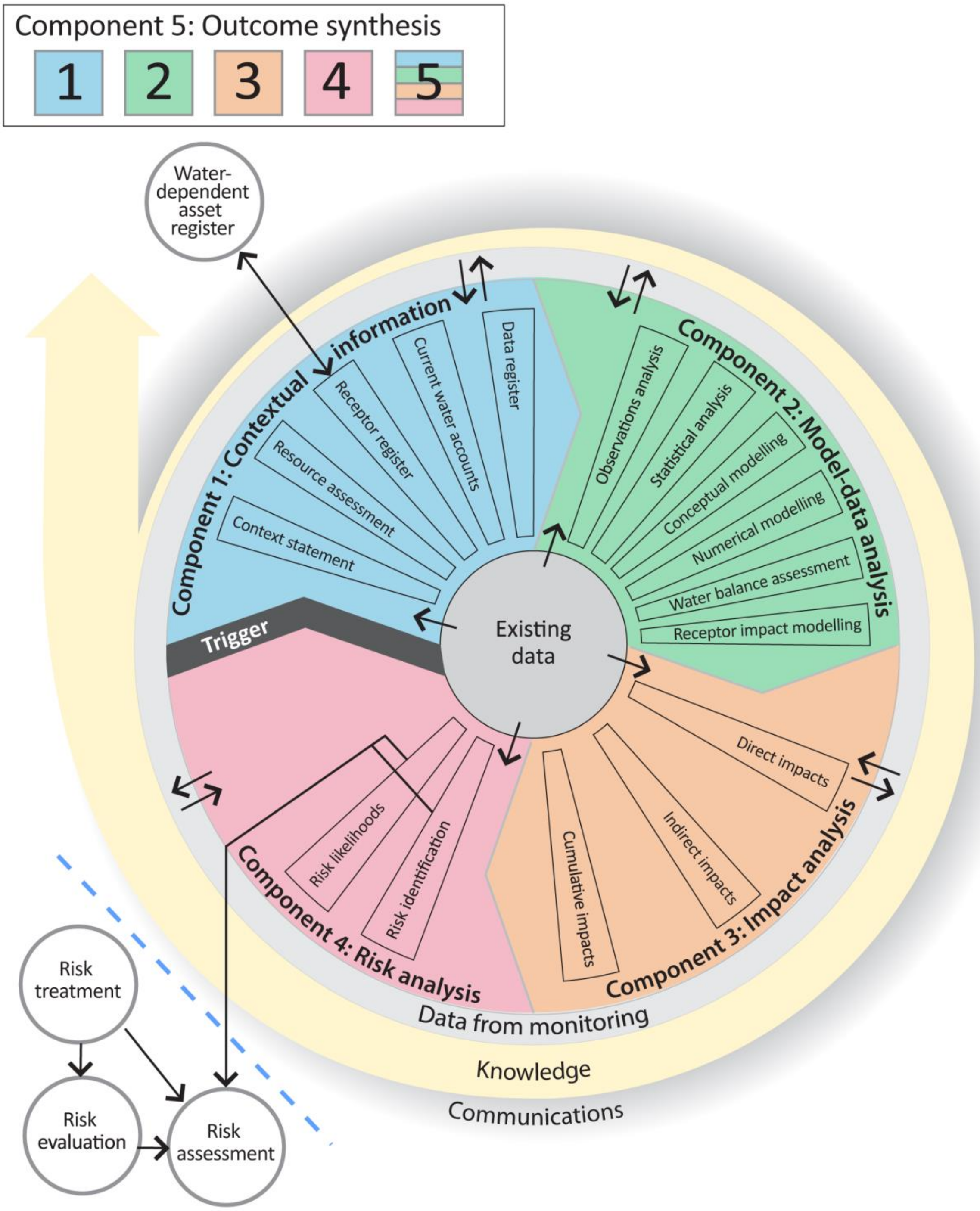

Figure 1 Schematic diagram of the bioregional assessment methodology

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.

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.

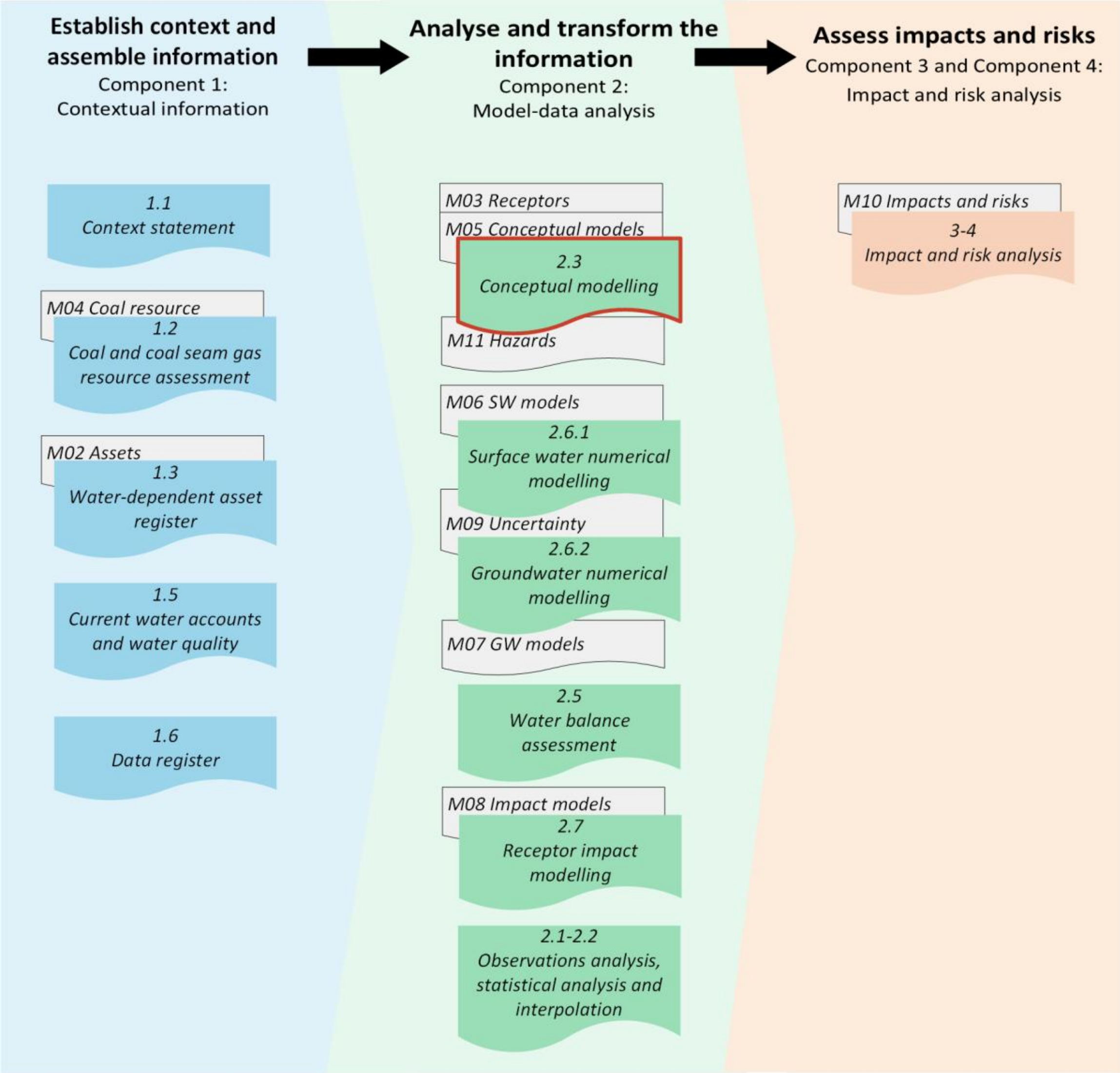

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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 Namoi subregion

For each subregion in the Northern Inland Catchments 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 Namoi 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 Namoi 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 Namoi subregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3	PDF, HTML
Component 5: Outcome synthesis for the Namoi 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 Inland Catchments 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 figure, however, did not grant permission to do so: Figure 10. 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 Inland Catchments bioregion and two standard parallels of –18.0° and –36.0°.
- Visit http://www.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

This product firstly summarises key system components, processes and interactions for the geology, hydrogeology and surface water in the Namoi 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 pathways*, the logical chains of events – either planned or unplanned – that link coal resource development and potential impacts on water resources and water-dependent assets. This section details the specific application to the Namoi subregion of methods described in the companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016).

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

2.3.1.1 Background and context

This product presents information about the conceptual model of causal pathways for the Namoi 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 Namoi 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. Several 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 pathways*, the chains of logic or activities – either planned or unplanned – that link coal resource development and potential impacts on water resources and water-dependent assets. The conceptual model of causal pathways brings together a number of conceptual models developed in a BA, and might be expressed in a variety of ways, with narrative, pictorial graphics and influence diagrams all important.

The causal pathways play a critical role in focusing the BA on the most plausible and important *hazards*, defined as events, or chains of events, that might result in an *effect* (change in the quality and/or quantity of surface water or groundwater). The causal pathways associated with these hazards underpin the construction of groundwater and surface water models, and frame the assessment of the *severity* and *likelihood* of impacts to water-dependent assets. A *water-dependent asset* is an asset potentially impacted, either positively or negatively, by changes in the groundwater and/or surface water regime due to coal resource development. Some assets are solely dependent on 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 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 (e.g. drawdown (Figure 3) or the annual flow volume)
- *receptor impact variables*, the characteristics of the system that, according to the conceptual modelling, potentially change due to changes in hydrological response variables (e.g. condition of the breeding habitat for a given species, or biomass of river red gums).

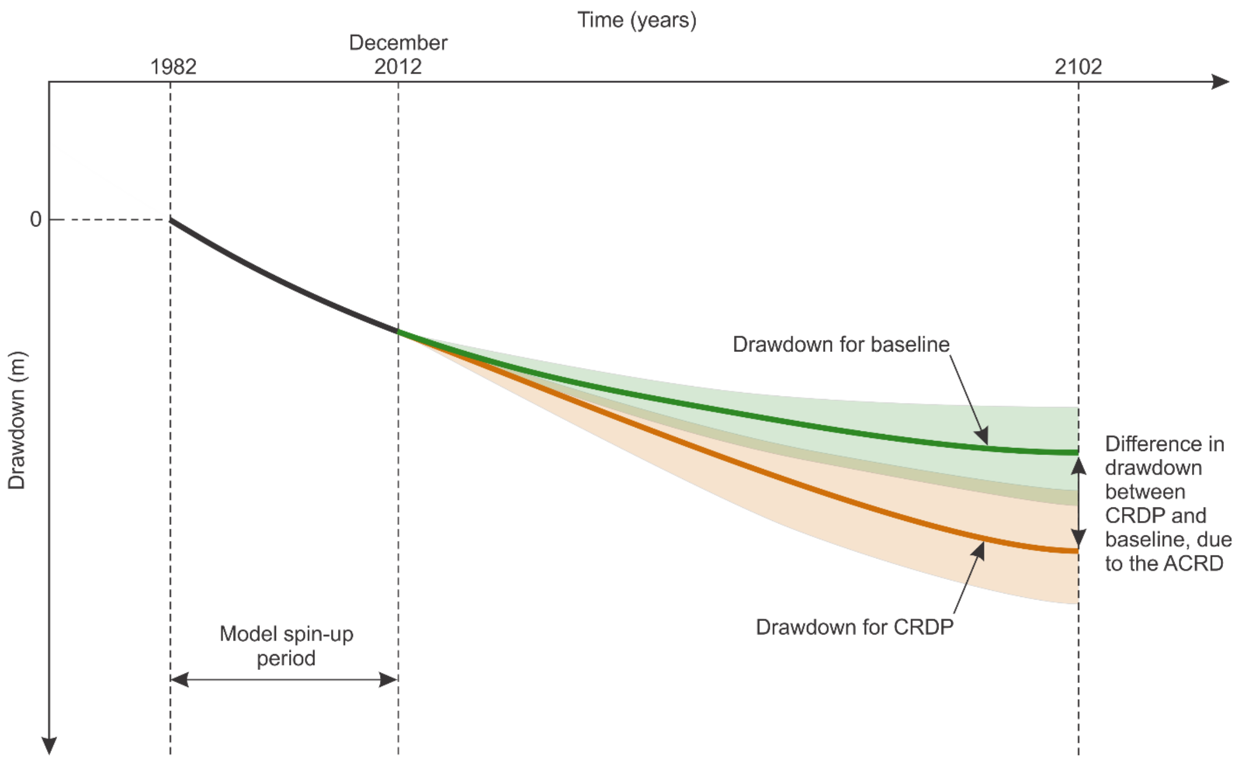

Figure 3 Generic example of drawdown at a specific location over time for the baseline coal resource development (baseline) and coal resource development pathway (CRDP). The difference in drawdown between CRDP and baseline is due to the additional coal resource development (ACRD)

The lighter shades indicate the uncertainty in results. Model spin-up period is a warm-up period for the models.
ACRD = additional coal resource development

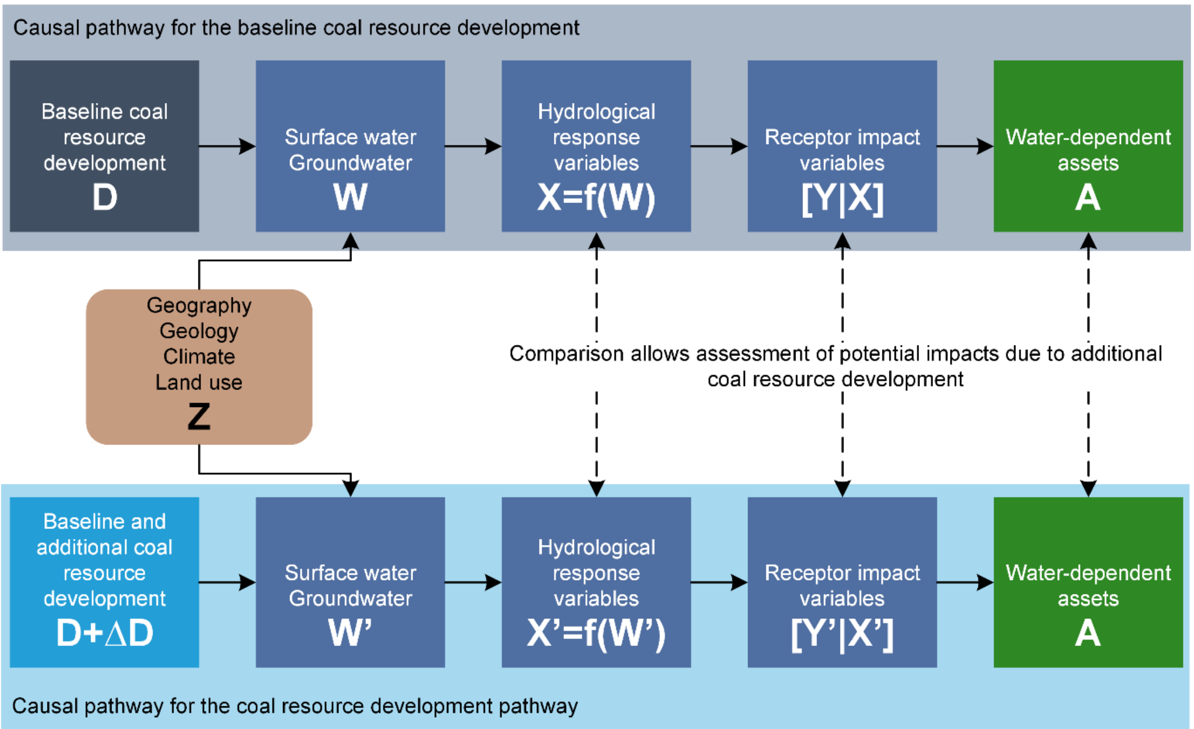

Figure 4 The difference in results under the baseline coal resource development (baseline) and coal resource development pathway (CRDP) provides the potential impacts due to the additional coal resource development (ACRD)

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).

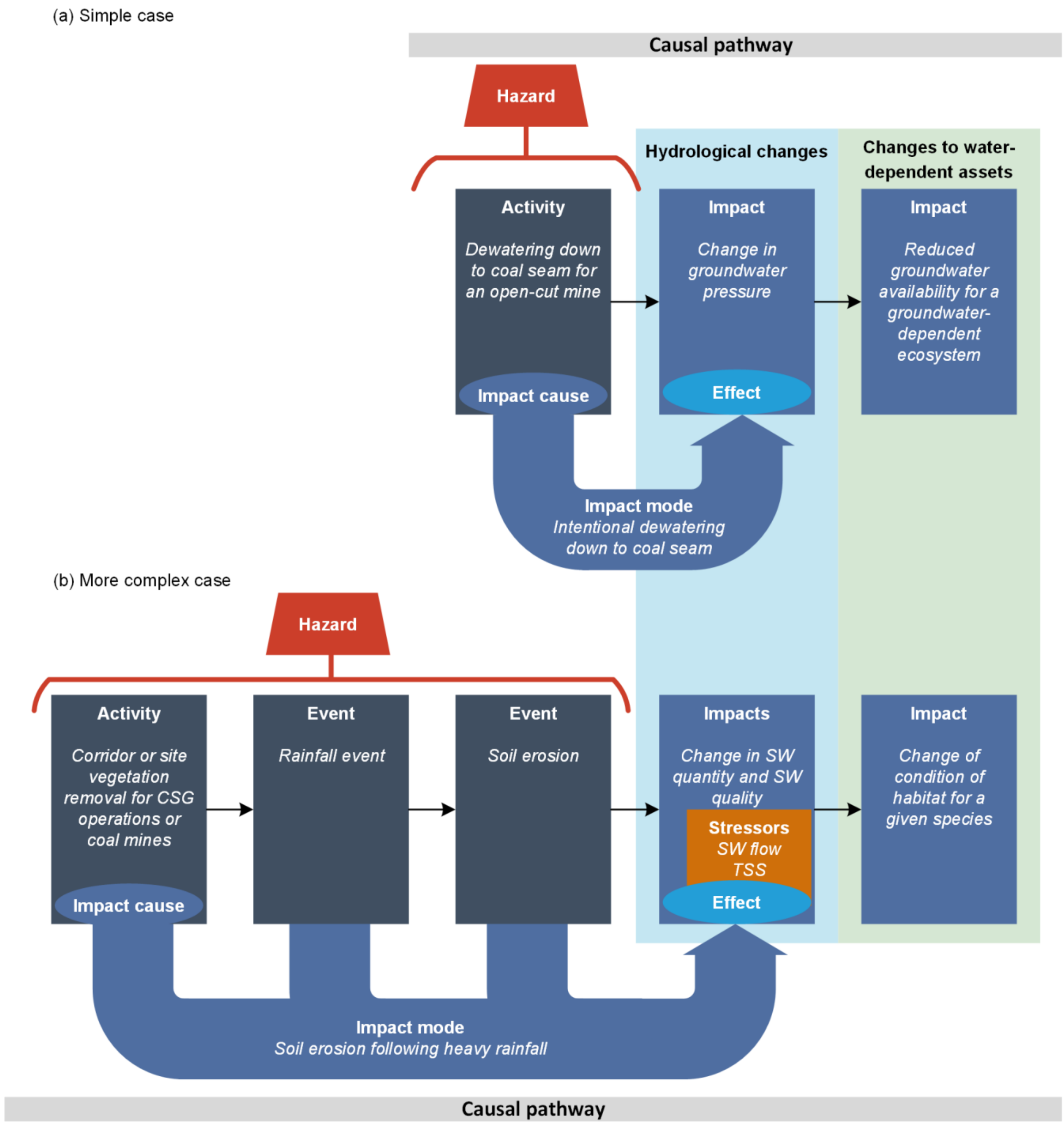

Figure 5 Hazard analysis using the Impact Modes and Effects Analysis

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

This product only specifies the causal pathways from coal resource development to hydrological response variables (see Figure 4). For BAs undertaking receptor impact modelling, the subsequent causal pathways (from hydrological response variables to impacts on landscape classes and water-dependent assets) are reported in companion product 2.7 (receptor impact modelling). These causal pathways are reported for only those landscape classes with potential hydrological changes, as reported in companion product 2.6.1 (Aryal et al., 2018) and companion product 2.6.2 (Janardhanan et al., 2018) for the Namoi subregion.

2.3.1.2 Developing the conceptual model of causal pathways

This product presents the Assessment team's conceptual understanding of how to model the causal pathway of coal resource developments on water-dependent assets in the Namoi subregion. A landscape classification represents the higher level ecosystems within which the water-dependent assets are located. The landscape classification has, through its mutually exclusive landscape classes (i.e. landscape classes do not spatially overlap), a complete spatial coverage of water-dependent assets in the subregion and provides the basis for an automated assessment of impact on these assets. Conceptually, the landscape classes are the impact-receiving surface layer that is connected through the different geological strata with the areas of coal resource development at depth and associated surface facilities.

Multiple lines of evidence form the basis for the conceptual models of causal pathways for the Namoi subregion. This evidence includes the existing information from Component 1: Contextual information on geology, hydrology and ecology of the subregion from the context statement (companion product 1.1 for the Namoi subregion (Welsh et al., 2014)), on the coal and CSG resource assessment (companion product 1.2 for the Namoi subregion (Northey et al., 2014)), and the water-dependent asset register for the Namoi subregion (companion product 1.3 for the Namoi subregion (O'Grady et al., 2015)). They feed into key system components and interactions for the geology, hydrogeology and surface water of the subregion (Section 2.3.2), ecosystems (represented in landscape classes) (Section 2.3.3), and the CRDP (Section 2.3.4). Section 2.3.5 then details the causal pathways for baseline and CRDP based on a hazard analysis.

A detailed hazard analysis determines the level and scope of potential impacts from the coal resource development that may elicit responses in the subregion's surface water and groundwater resources, thus conceptually linking coal resource development activities with potential changes in surface water and groundwater. Linking these coal resource development activities at depth with responses of the hydrology at the land surface (represented as the subregion-specific landscape classification) provides the conceptual understanding of potential causal pathways from coal resource development on water-dependent asset locations. In this context, the conceptual model of causal pathways also considers changes to surface-connected groundwater to incorporate any potential groundwater dependency of the landscape classes. The causal pathways are related to the baseline and CRDP. They provide the Assessment team's current understanding of the potential pathways to impacts that are likely to occur from the existing and future coal resource developments in the Namoi subregion.

This product also provides a broad conceptual understanding of how the Namoi subregion functions in relation to potential future coal resource development impacts on surface water and groundwater. It takes into account existing knowledge on the hydrology of the subregion, and provides the opportunity to reduce the preliminary assessment extent to a 'first cut' footprint of potential coal resource development impacts on water based on the geographic zones of the Namoi subregion (see Section 2.3.5).

The reduced footprint and the causal pathways form the basis for the subsequent product 2.7 (receptor impact modelling). This product incorporates the combination of the Namoi subregion-specific landscape classification and the hydrological estimates from the surface water and groundwater modelling (companion product 2.6.1 (Aryal et al., 2018) and companion product 2.6.2 (Janardhanan et al., 2018) for the Namoi subregion), and uses hydrological response variables and receptor impact variables to identify impacts to landscape classes and water-dependent assets.

Information and knowledge gaps relevant for the developed conceptual models of causal pathways are addressed in Section 2.3.5.

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2.3.2 Summary of key system components, processes and interactions

Summary

This section presents a conceptual understanding of how geology, hydrogeology and surface hydrology link together. Geology is a key driver of landscape formation and is therefore a controlling factor for many hydrological and ecological processes. It is an important control on processes such as groundwater recharge, discharge, flow dynamics and the interaction between different aquifers, and also influences surface water – groundwater interaction.

Coal mining and coal seam gas (CSG) operations can induce changes in groundwater level and pressure in the vicinity of operations. The spatial and temporal changes are controlled by local hydraulic properties, and are complicated by fracturing and faulting of stratigraphic layers and the constituent rock types. Another potential effect of reduced groundwater level is the change in the magnitude or direction of flow between groundwater and surface water systems, for example, by inducing flow away from the alluvial aquifer that would otherwise discharge as baseflow to a stream.

Major streams in the preliminary assessment extent (PAE) of the Namoi subregion are the Namoi and Mooki rivers, and the Coxs, Maules, Bohena and Pian creeks. All streams within the PAE are temporary, with the exception of the Namoi River. The intermittent nature of the surface water systems means that the management, treatment and disposal of water may affect surface water – groundwater interactions.

A conceptual understanding of the system underpins many activities that are reported in this product including the landscape classification (Section 2.3.3) and the identification of causal pathways (Section 2.3.5). It also forms the framework for the numerical surface water modelling and the numerical groundwater modelling. For the bioregional assessment (BA) for the Namoi subregion, existing two-dimensional conceptual models were used together with three-dimensional representations that were developed during the Assessment to identify pathways between the different components of the hydrological cycle.

2.3.2.1 Scope and overview

This section summarises the conceptual understanding of geological and hydrogeological characteristics of the deep and shallow units in the Namoi subregion and how they interact with each other, building on the knowledge reported in companion products 1.1, 1.2, 1.5 and 2.1-2.2 for the Namoi subregion (Welsh et al., 2014; Northey et al., 2014; Peña-Arancibia et al., 2016; and Aryal et al., 2018a, respectively).

This section also describes key system components, processes and interactions – specifically, the connectivity between deep and shallow aquifer systems – and their connectivity to surface water systems, thus identifying potential pathways through which water-dependent assets may be impacted by coal resource development in the Namoi subregion. The conceptual understanding presented here is regional in scope, bringing together current geological components of the Gunnedah and Surat basins, and alluvial groundwater systems.

2.3.2.2 Geology and hydrogeology

A regional geological model of the Namoi subregion was developed for the Assessment, based on the CDM Smith geological model (NTEC, 2013), the Water Resource Assessment for the Great Artesian Basin (Smerdon et al., 2012) and the Hydrogeological Atlas of the Great Artesian Basin (Ransley et al., 2015) (see companion product 2.1-2.2 for the Namoi subregion (Aryal et al., 2018a)).

The model focused on the strata of the Permian – Triassic Gunnedah Basin where the coal seams are present, and the Jurassic – Cretaceous Surat Basin where aquifers of the Great Artesian Basin (GAB) are present. The layering and depth profiles generated in the geological model were a key input into the numerical groundwater modelling (see companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018)).

The geological history of deposition, deformation, uplift and erosion that has occurred in the Namoi subregion has implications for the connectivity between the geological units, coal resource developments and water-dependent assets. Information about the water-dependent assets for the Namoi subregion is presented in companion product 1.3 (O'Grady et al., 2015).

2.3.2.2.1 Geology

The main geological systems of interest for the Assessment, from oldest to youngest, are the Permian – Triassic Gunnedah Basin, the Jurassic – Cretaceous Surat Basin (see Figure 6) and the Cenozoic alluvium. These geological systems overlie the older Paleozoic rocks of the Lachlan Orogen. The stratigraphy column and the surface geology of the Namoi subregion are shown in Figure 7 and Figure 8 in companion product 2.1-2.2 for the Namoi subregion (Aryal et al., 2018a). The Cenozoic alluvium and Pilliga Sandstone in the GAB are the main groundwater sources in the Namoi subregion and do not contain coal. The coal resources under development in the Namoi subregion are primarily in the Gunnedah Basin. The main economic coal seams occur in the Black Jack Group and the Maules Creek Formation.

Coal and CSG are commercially extracted from the northern part of the Surat Basin in Queensland, however, there is no current or planned coal or CSG resource development from the Surat Basin in the Namoi subregion. More detail on the coal resources in the Namoi subregion can be found in companion product 1.2 for the Namoi subregion (Northey et al., 2014).

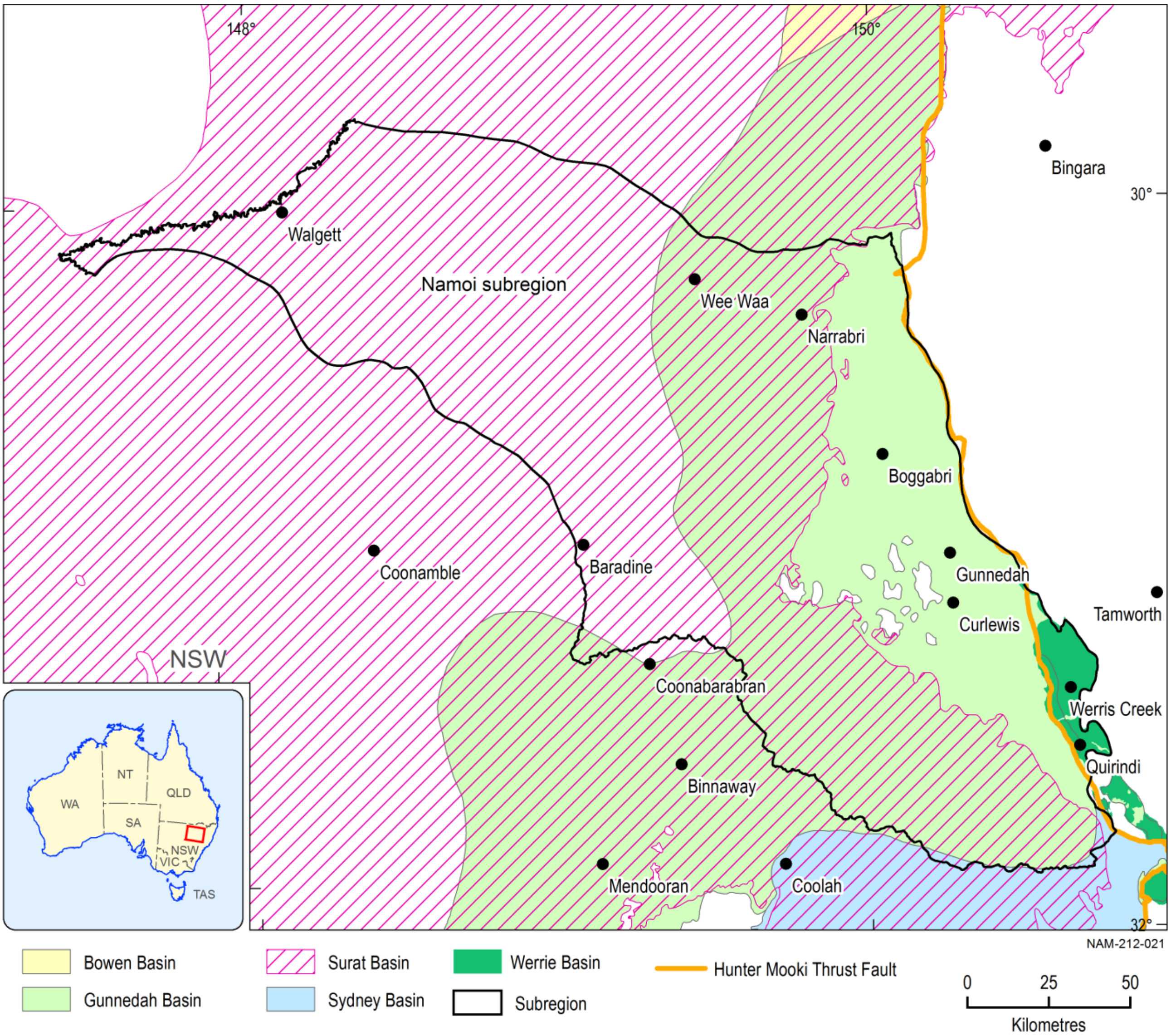

Figure 6 Geological basins of the Namoi subregion, including the Hunter-Mooki Thrust Fault System

Data: Geoscience Australia (Dataset 6, Dataset 7) and FROGTECH (Dataset 8)
Note: The stratigraphic units of the Gunnedah, Bowen, Sydney and Werrie basins are Permo-Triassic and the overlying stratigraphic units of the younger Surat Basin are Jurassic.

2.3.2.2.1.1 Geological history and lithology

The Gunnedah Basin was initiated in a back-arc setting in the early Permian when an extensional event resulted in the deposition of a thick succession of volcanics interlayered with lacustrine sedimentary rocks (Totterdell et al., 2009). In the west, the Gunnedah Basin sits unconformably on older basement rocks of the Lachlan Orogen and in the east it abuts the New England Orogen along the Hunter-Mooki Thrust Fault System (see Figure 15 in companion product 1.1 for the Namoi subregion (Welsh et al., 2014)). The main lithology associated with strata in the Namoi subregion is shown in Table 3 and a stratigraphic column is shown in Figure 7 in companion product 2.1-2.2 for the Namoi subregion (Aryal et al., 2018a). The geological strata relative to coal resource development are shown in Figure 7 and Figure 8.

Table 3 Main lithology of strata in the Namoi subregion

Period	Formations and groups	Host sedimentary basin	Main lithology
Quaternary	Alluvium	na	Clays, sands and gravels
Jurassic and Cretaceous	Rolling Downs Group	Surat Basin	Mudstone, siltstone and fine sandstone
Jurassic	Pilliga Sandstone	Surat Basin	Sandstone and conglomerate with minor mudstone, siltstone and coal
Jurassic	Purlawaugh Formation	Surat Basin	Sandstone thinly interbedded with siltstone, mudstone and thin coal seams
Jurassic	Garrawilla Volcanics	Surat Basin	Flows and intrusions of dolerite, basalt, trachyte, tuff and breccia overlying major depositional unconformity with the Gunnedah Basin.
Triassic	Deriah Formation	Gunnedah Basin	Sandstone with volcanic fragments and mudclasts. Overlain by sandstone and mudstone
Triassic	Napperby Formation	Gunnedah Basin	Sandstone and siltstone interbedded with thick, massive or crossbedded sandstones; minor conglomerate
Triassic	Digby Formation	Gunnedah Basin	Conglomerate at base, overlain by sandstone. Siltstone/claystone at top
Permian	Black Jack Group	Gunnedah Basin	Conglomerateic sandstone, claystone, tuff and pyroclastic detritus. Coal bearing
Permian	Watermark Formation	Gunnedah Basin	Fining-up sequence of silty sandstone to siltstone/claystone, then a coarsening-up sequence
Permian	Porcupine Formation	Gunnedah Basin	Basal conglomerate passing upwards into bioturbated silty sandstones and minor siltstones with dropped pebbles
Permian	Maules Creek Formation	Gunnedah Basin	Basal claystone, sandstone, siltstone, numerous coal seams, conglomerate
Permian	Goonbri and Leard Formations	Gunnedah Basin	Claystones, siltstones and sandstones
Permian	Boggabri Volcanics	Gunnedah Basin	Rhyolitic to dacitic lavas and ashflow tuffs with interbedded shale

Source: Geoscience Australia and Australian Stratigraphy Commission (2017)

The onset of sedimentation in the basin is marked by localised deposition of colluvial and alluvial material of the Leard Formation in paleovalleys on the weathered surface of the basement volcanics. This is overlain by the lacustrine Goonbri Formation (Gurba et al., 2009).

This was followed by an influx of volcanolithic sediments, sourced from the nearby Boggabri Ridge (see Figure 10) and other local highlands by erosion, forming the lower Permian Maules Creek Formation. The Maules Creek Formation was deposited in a variety of fluvial settings ranging from alluvial fans to peat swamps and contains numerous coal seams (Gurba et al., 2009; Totterdell et al., 2009). Thrusting of the Maules Creek sub-basin in the east of the subregion, mainly during a compressional event at the end of the Permian or Early Triassic, resulted in a disparity of several hundred metres in the vertical elevation of the Maules Creek Formation across the Boggabri Ridge (Tadros, 1993).

The lower Permian Porcupine and Watermark formations were deposited under transgressive marine conditions. The contractional event that marks the boundary between the Maules Creek Formation and overlying Porcupine Formation may have resulted in further uplift of the Boggabri Ridge, which then provided the source of sediment for the Porcupine and Watermark formations (Totterdell et al., 2009).

This was followed by marine regression and the deposition of fluvial sediments, including peat swamp deposits, the precursor sediments of the relatively widespread Hoskissons Coal in the Black Jack Group (Totterdell et al., 2009). The upper Black Jack Group, which overlies the Hoskissons Coal, was deposited as part of an alluvial system from which sediments were derived from the New England Orogen to the east of the Namoi subregion. The Hoskissons Coal crops out to the west of the Boggabri Ridge.

A contractional event in the late Permian resulted in deformation of the Gunnedah Basin. Erosion prior to the deposition of Triassic sediments resulted in the formation of an essentially flat plain. The erosion may have removed almost all of the Gunnedah Basin strata above the Maules Creek Formation in the Maules Creek sub-basin, including the Black Jack Group (Geological Survey of NSW, 2002). The Digby and Napperby formations in the Early Triassic were deposited on this erosional surface (Totterdell et al., 2009).

Down-warping during the Late Triassic – Early Jurassic resulted in the accumulation of more alluvial sediments creating the Surat Basin, which unconformably overlies the western part of the Gunnedah Basin in the subregion (see Figure 6).

The Garrawilla Volcanics generally form the base of the Surat Basin (Totterdell et al., 2009) and crop out to the west and south of Gunnedah (refer to Figure 8 in companion product 2.1-2.2 (Aryal et al., 2018a)). The Purlawaugh Formation unconformably overlies the Garrawilla Volcanics and is interpreted to have been deeply eroded prior to the deposition of the overlying Pilliga Sandstone (Totterdell et al., 2009). Erosion of the Pilliga Sandstone prior to the deposition of Cenozoic sediments has resulted in a layer of saprolite that is of variable thickness and extent across the Namoi subregion.

During the Cenozoic more alluvium was deposited over the subregion, forming the Upper and Lower Namoi alluvial aquifers. This period was also marked by volcanic activity and the remains of the resulting volcanic structures are seen today as hills around the margin of the Namoi river basin, including the Liverpool and Nandewar ranges (Wellman and McDougall, 1974). The weathered remnants of these Cenozoic volcanic flows now form the rich and fertile soils of the Liverpool Plains.

More detail on the general geology of the Namoi subregion, including the stratigraphy, is in companion product 1.1 (Welsh et al., 2014) and Section 2.1.2 in companion product 2.1-2.2 (Aryal et al., 2018a) for the Namoi subregion. Other summaries of the sedimentary basins in the subregion include Hawke and Cramsie (1984), Korsch and Totterdell (2009), Tadros (1993) and Totterdell et al. (2009).

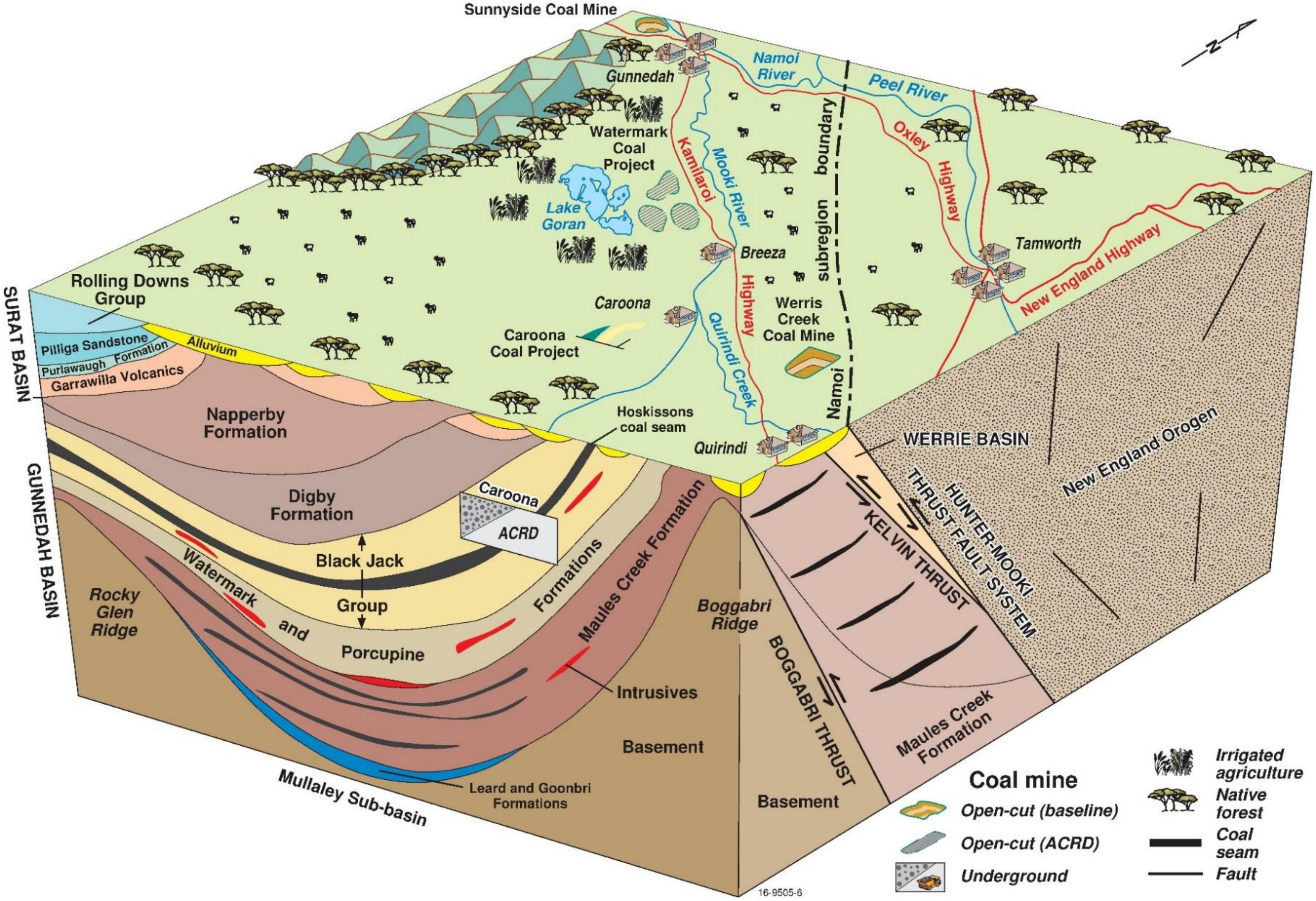

Figure 7 Schematic diagram of the south-east of the Namoi subregion from Quirindi to Gunnedah showing underlying geology relative to coal resource development

The coal resource developments in the coal resource development pathway (CRDP) are the sum of those in the baseline coal resource development (baseline) and the additional coal resource development (ACRD).

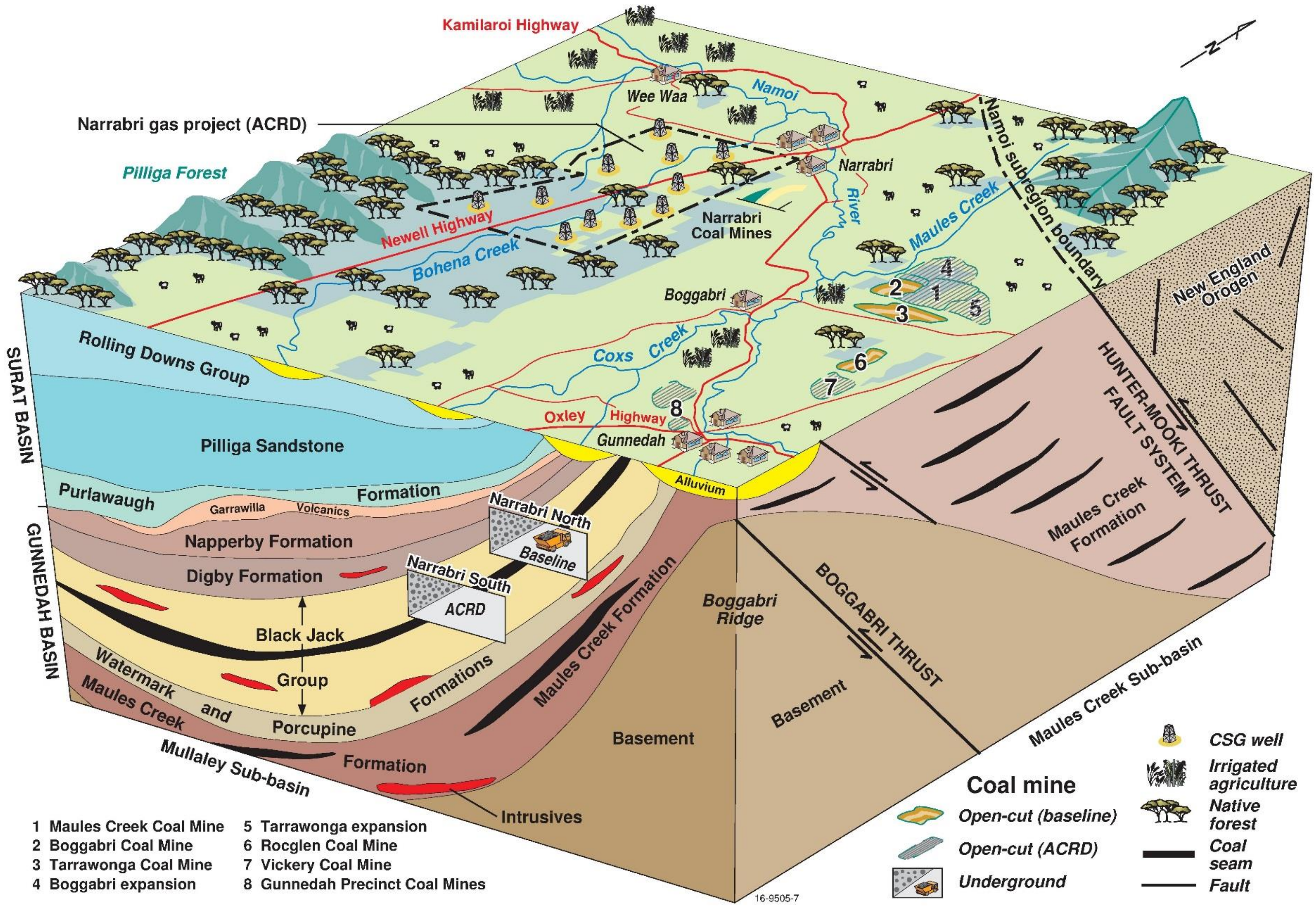

Figure 8 Schematic east–west diagram of the Namoi subregion from Gunnedah to Wee Waa showing underlying geology relative to coal resource development

The coal resource developments in the coal resource development pathway (CRDP) are the sum of those in the baseline coal resource development (baseline) and the additional coal resource development (ACRD).
CSG = coal seam gas

The Werris Creek Mine is located in the Werrie Basin (Figure 6), targeting the coal-bearing Willow Tree Formation (see Figure 9). The Werrie Basin is a north-north-west trending synclinal structure to the east of the Hunter-Mooki Thrust Fault System and is therefore a structurally isolated (non-contiguous part) from the Gunnedah Basin (Figure 9). The Hunter-Mooki Thrust Fault System terminates the basin at each end and as the fault is considered to be an impermeable boundary, the deeper groundwater systems of the Werrie Basin are hydrogeologically isolated from the Gunnedah Basin. While the Werrie Basin is not considered to be part of the Gunnedah Basin, the age and stratigraphic similarities between them suggest a close association and probably a direct physical link during deposition (Geological Survey of NSW, 2002). The coal measures in the Willow Tree Formation were once connected to the early Permian Greta Coal Measures of the Hunter Valley. Since deposition, periods of uplift and erosion have left only the isolated remnants of coal measures at the Werris Creek Mine (Whitehaven Coal, n.d.). The alluvial cover is connected over the Hunter-Mooki Thrust Fault System.

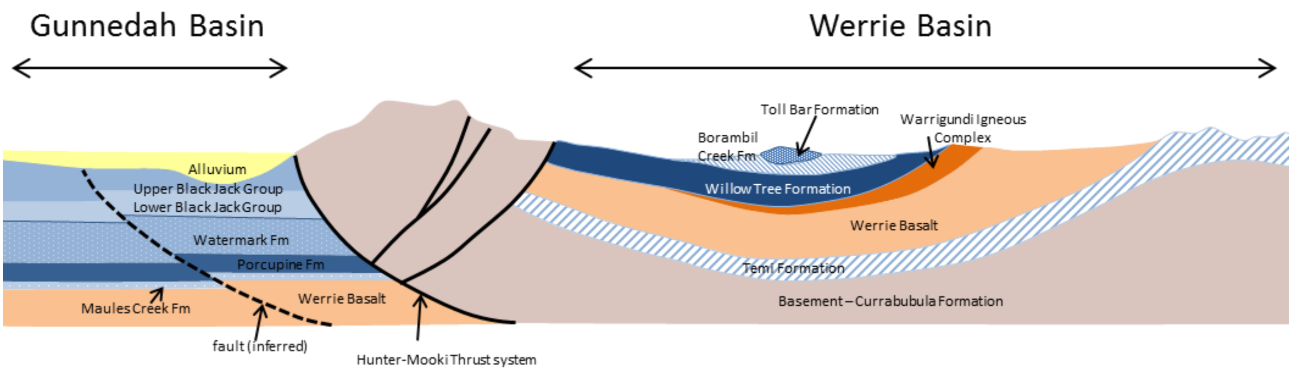

Figure 9 Indicative cross-section of the Werrie Basin

Source: derived from Pratt (1996)
For approximate location of cross-section, please see Figure 10.

2.3.2.2.1.2 Structure and subdivisions of the Gunnedah Basin

This section provides information on the subdivisions and structures of the Gunnedah Basin relative to the coal resource development pathway (CRDP) for the Namoi subregion. The Gunnedah Basin consists of several major structural elements (Figure 10), as initially proposed by Tadros (1988). The architecture of the geological basement underlying the Gunnedah Basin comprises three north-north-westerly oriented sub-basins lying between basement ridges, over which the strata thin. The coal resources of the Gunnedah Basin in the Namoi subregion are located in the Maules Creek and Mullaley sub-basins, as shown in Figure 10 and Table 4. Section 2.3.4 contains more detailed information about the CRDP for the Namoi subregion.

In the east of the Namoi subregion the Boggabri Ridge separates the Maules Creek sub-basin from the central Mullaley sub-basin. To the west of the Mullaley sub-basin is the Rocky Glen Ridge and the Gilgandra sub-basin underlies the western portion of the Namoi subregion (Figure 10) (Tadros, 1993). In the Gunnedah Basin the depositional architecture of the Maules Creek and Mullaley sub-basins were compartmentalised, which also suggests the sub-basin strata may be compartmentalised in some areas with respect to regional groundwater flow systems.

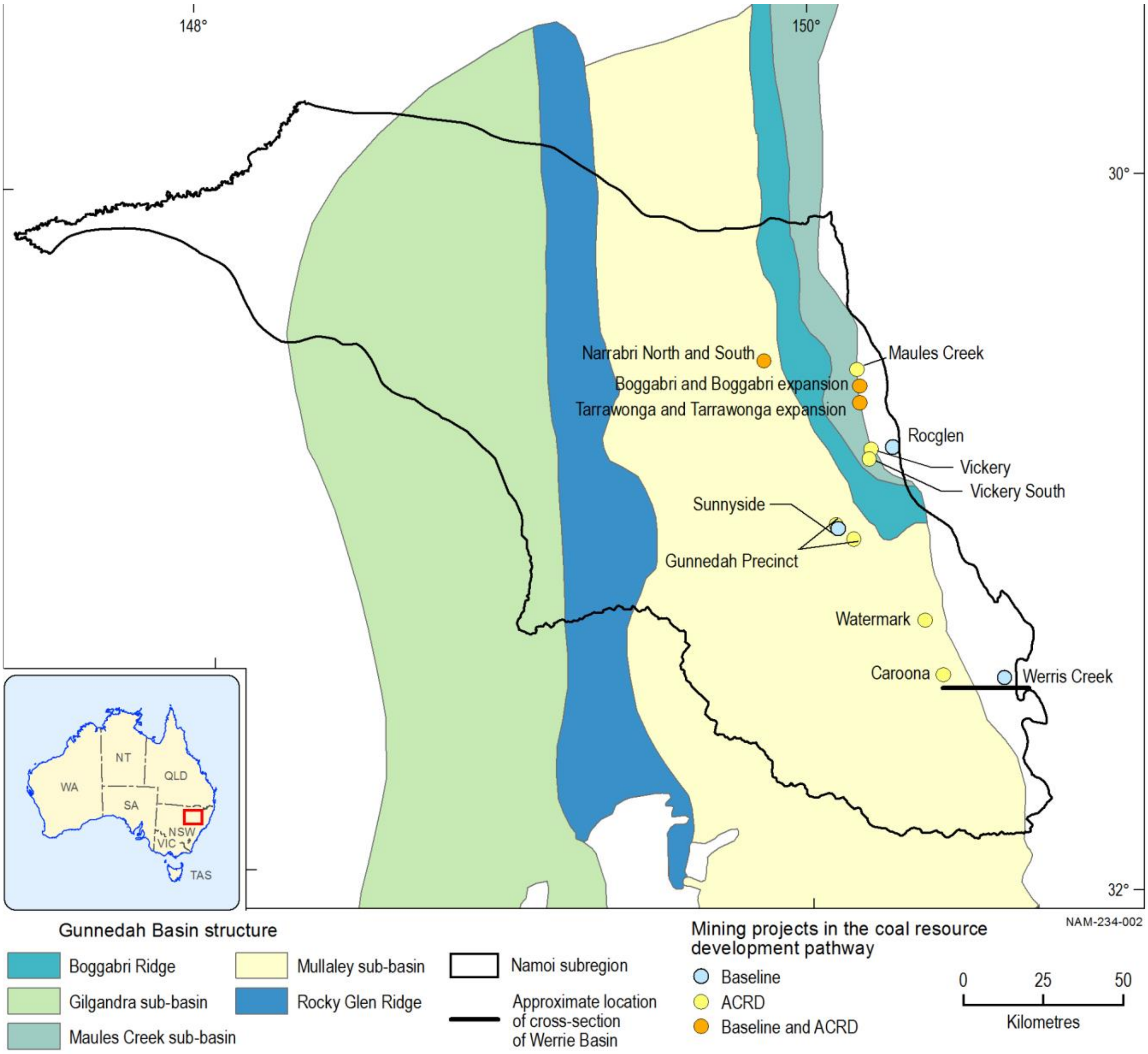

Figure 10 Subdivisions of the Gunnedah Basin in the Namoi subregion showing the locations of mines in the coal resource development pathway

The coal resource developments in the coal resource development pathway (CRDP) are the sum of those in the baseline coal resource development (baseline) and the additional coal resource development (ACRD).
Source: derived from Gurba et al. (2009). This figure is not covered by a Creative Commons Attribution Licence. © CO2CRC Limited
Data: Bioregional Assessment Programme (Dataset 2)

The most easterly subdivision of the Gunnedah Basin is the early Permian Maules Creek sub-basin, which is bound to the east by the Hunter-Mooki Thrust Fault System and to the west by the Boggabri Ridge (Figure 10). East of the Boggabri Ridge the strata dip gently to the east, becoming steeper near the Hunter-Mooki Thrust Fault System. Several coal resource developments in the CRDP are located in the Maules Creek sub-basin, where the target coal seams of the Maules Creek Formation crop out or are close to the surface.

The Boggabri Ridge is oriented generally in a north–south direction and is truncated to the east of Gunnedah by the Hunter-Mooki Thrust Fault System (see Figure 10). West of the Boggabri Ridge the strata dip gently towards the basin axis. Early Permian sediments onlap the eastern and western sides of the Boggabri Ridge and thus the ridge would have separated the eastern half of the Gunnedah Basin into the Maules Creek and the Mullaley sub-basins during the early Permian. The Boggabri Ridge is not a continuous high and gaps exist (Tadros, 1993).

The Mullaley sub-basin, which extends over the entire length of the Gunnedah Basin, is the largest and most prominent of the sub-basins. It is divided by a prominent transverse high, the Walla Walla Ridge, and by several other structural highs into a series of north-north-westerly troughs including the Ballata, Bohena, Bando and Murrurundi troughs (see Figure 9 in companion product 2.1-2.2 for the Namoi subregion (Aryal et al., 2018a)). Coal mine and CSG developments in the Mullaley sub-basin primarily target the Hoskissons Coal, opportunistically mining the coal seams of the Maules Creek Formation where present.

West of the Mullaley sub-basin is another north–south trending ridge: the Rocky Glen Ridge (see Figure 10). This ridge is a prominent basement high partially onlapped by Permian strata. Aeromagnetic and gravity data confirm that it coincides with the western edge of the Werrie Basalt and Boggabri Volcanics in the Gunnedah Basin (Geological Survey of NSW, 2002).

The BA has compiled these features into a composite three-dimensional geological model to form the basis for the groundwater model (companion product 2.6.2 (Janardhanan et al., 2018) for the Namoi subregion).

The subdivision of the Gunnedah Basin into troughs and structural highs has the potential to compartmentalise deeper groundwater flow systems within the basin, thereby possibly compartmentalising potential groundwater impacts from coal resource developments. The Boggabri Ridge is the primary structure that may compartmentalise the Maules Creek and Mullaley sub-basins such that impacts in the Gunnedah Basin strata may not propagate over this structural high. However, as noted by Tadros (1993), the ridge is not continuous and so there may be areas where the groundwater systems may be connected. There is also the potential of flow around the Boggabri Ridge where the Boggabri Volcanics are close to the surface and are weathered or fractured (Schlumberger Water Services, 2012a). Additionally, the alluvial cover over the Boggabri Ridge is connected and so groundwater impacts may propagate via the alluvium.

Table 4 Target coal seams for coal resource developments in the Namoi subregion

Coal resource development	Sub-basin	Target stratigraphic unit	Target coal members
Boggabri Coal Mine and Boggabri Coal Expansion Project	Maules Creek	Maules Creek (minor basal seam from underlying Leard Formation)	Braymont, Merriowen, Jeralong
Caroona Coal Project[a]	Mullaley	Black Jack	Hoskissons Coal
Gunnedah Precinct	Mullaley[b]	Black Jack[b]	Hoskissons Coal[b]
Maules Creek Mine	Maules Creek	Maules Creek	15 members within Maules Creek Formation (i.e. Herndale to Templemore seams)
Narrabri North and South	Mullaley	Black Jack	Hoskissons Coal
Narrabri Gas Project	Mullaley (Bohena trough)	Black Jack Group and Maules Creek	Hoskissons Coal, Bohena
Rocglen Mine	Maules Creek	Maules Creek	Belmont, Upper Glenroc, Lower Glenroc
Sunnyside Mine	Mullaley	Black Jack	Hoskissons Coal, Upper Melville, Lower Melville
Tarrawonga Mine and Tarrawonga Coal Expansion Project	Maules Creek	Maules Creek	Braymont, Bollol Creek, Jeralong
Vickery Coal Project (including Vickery South Coal Project)	Maules Creek	Maules Creek	Gundawarra, Welkeree, Kurrunbede, Shannon Harbour (upper and lower), Stratford, Bluevale (upper and lower), Cranleigh (upper, middle and lower)
Watermark Coal Project	Mullaley	Black Jack	Hoskissons Coal, Melvilles
Werris Creek Mine	Werrie Basin[c]	Willow Tree Formation (early Permian, time-equivalent to Maules Creek Formation)	Willow Tree Formation (time-equivalent to the Maules Creek coals and Greta Coal Measures)

[a]The Caroona Coal Project was discontinued in 2016. However, in accordance with companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis, 2014), the project is included in the Assessment.
[b]No information available. Assumed to be in Mullaley sub-basin targeting the Hoskissons Coal of the Black Jack Group due to proximity to the Sunnyside Mine.
[c]Werris Creek Mine is located in the Werrie Basin and targets the Willow Tree Formation. These coal measures were once connected to the Greta Coal Measures of the Hunter Valley but periods of uplift and erosion have left only the isolated remnant of coal at the Werris Creek Mine.

2.3.2.2.1.3 Overburden thickness of the Permian coal measures

The Permian coal measures are the primary targets for coal mining and CSG development in the Namoi subregion. Overburden thickness is one of several significant factors that affect the degree of connectivity between coal measures and water-dependent assets. The overburden of the Permian coal measures is the combined thickness of the Cenozoic sediments, the Surat Basin stratigraphic sequences where present, and the Triassic Digby and Napperby formations. The

Watermark and Porcupine formations also form the overburden of the coal seams in the Maules Creek Formation.

The overburden thickens rapidly to the west of the Boggabri Ridge in the troughs of the Mullaley sub-basin with overburden thicknesses of between 600 and 1200 m above the coal seams in the Maules Creek Formation and 700 m for the Hoskissons Coal. The Gunnedah Basin sequence is thickest in the Bohena Trough to the west of the Boggabri Ridge. Overburden thickness is considerably less in the Maules Creek sub-basin, with the deepest coal seam targeted at the Maules Creek Mine approximately 400 m from ground surface, indicating a maximum overburden thickness in the Maules Creek sub-basin of approximately 400 m.

2.3.2.2.1.4 Potential for structural connectivity within the Gunnedah Basin

Faults can act as localised barriers to groundwater flow if they juxtapose an aquifer against an aquitard or if the faults are filled with significant amounts of clay. Conversely, they can act as conduits to groundwater flow if there is sufficient fracture connectivity. It is difficult to characterise individual faults as either potential conduits or barriers to groundwater flow as detailed and site-specific geoscientific studies are required. Consequently, the implications for groundwater flow near faults under stress are largely unknown and this uncertainty was the main reason why faults were not specifically modelled in the groundwater numerical modelling for Namoi.

Most structural activity, including faulting in the Namoi subregion, occurred in the lower to middle Permian (Tadros, 1993). Higher in the sequence, the younger Surat Basin strata is less deformed.

Tectonic activity has produced linked thrust faults in the east of the subregion with fewer faults identified in the west of the Namoi subregion. The most significant fault system within the Namoi subregion is the Boggabri Thrust located within the Boggabri Volcanics of the Boggabri Ridge, which approximately underlies the Namoi River between Gunnedah and Narrabri. Activation of this fault raised the Maules Creek sub-basin strata several hundred metres higher than equivalent strata in the Mullaley sub-basin (Geological Survey of NSW, 2002).

Several faults have been interpreted in the Maules Creek and Mullaley sub-basins that generally orientate in a north-north-westerly or south-westerly direction. In many instances, minor faulting appears to be associated with uplifting after the Permian (Geological Survey of NSW, 2002). Closely spaced drilling in the Maules Creek sub-basin east of the Boggabri Ridge identified a number of north-westerly striking normal faults with vertical displacements ranging from 80 to 120 m (Tadros, 1993). These fault structures have the potential to cause a large disconnection across geological units. It is anticipated that some of these faults may have a significant effect on groundwater flow characteristics at a local scale and would need to be assessed in local-scale model simulations (Schlumberger Water Services, 2011).

2.3.2.2.2 Hydrogeology

The Namoi subregion consists of two major aquifer systems – the Namoi Alluvial aquifer (Upper and Lower Namoi) and the Pilliga Sandstone aquifer. The most widely used aquifer in the Namoi subregion is the Namoi alluvium compromising the Quaternary Narrabri and Gunnedah Formations. These units contain significant resources of high-quality groundwater that is heavily utilised for irrigation, town water supply, and stock and domestic use. The Pilliga Sandstone is part of the Surat Basin and is a major regional aquifer consisting of medium- to coarse-grained sandstone and conglomerate with minor interbeds of fine-grained sediments. Minor groundwater resources occur in the Gunnedah Basin, however, these systems are only rarely utilised for stock and domestic purposes where the alluvium is absent. A detailed description of the key aquifers is in Section 1.1.4 of companion product 1.1 for the Namoi subregion (Welsh et al., 2014).

Of primary interest in understanding groundwater movement is the identification of potential connectivity of aquifers between basins (the Gunnedah and Surat basins) and, ultimately, connectivity with alluvial aquifers. Understanding the contact of aquifers and where vertical pressure gradients exist will assist in identifying potential pathways for fluids migrating upwards from underlying basins. The greatest potential for connectivity is through direct physical contact of aquifers either through overlap of their extents or from their juxtaposition along faults.

Cross-formational flow occurs where a vertical pressure gradient exists between two formations and there is sufficient permeability to permit flow between them. The rate of transfer between units is therefore a function of the connectivity in terms of permeability between the two units and the magnitude of the pressure gradient between them. This has been shown to occur in the Pilliga Sandstone, the regional potentiometric surface in the GAB, where hydraulic heads are above the heads in the overlying Narrabri Formation (see companion product 1.1 for the Namoi subregion (Welsh et al., 2014)), potentially resulting in flow from the GAB into the alluvial aquifers. Where formations have lower hydraulic conductivity and act as aquitards, such as the Purlawaugh and Napperby formations, the rate of vertical transfer between formations is slower, even if the pressure gradient is strong.

2.3.2.2.2.1 Alluvial aquifers and watertable groundwater flow systems

The alluvial aquifer systems in the Namoi subregion occur along the river valleys and floodplains and play an important role for agriculture and groundwater-dependent ecosystems. Traditionally the alluvial material has been described as a stacked aquifer system with the uppermost Narrabri Formation (up to 30 to 40 m deep) underlain by the Gunnedah Formation (usually 40 to 100 m deep, 170 m at its deepest) with the Cubbaroo Formation in the Lower Namoi associated with the main paleochannel (Barrett, 2012). Within the alluvial sequence, gravel- and sand-rich layers generally occur near the base, overlain by fine-grained floodplain silts and clays that have been deposited in a lower energy environment. However, Kelly et al. (2007) emphasised that the alluvial sequence as described generally oversimplifies the complexity of the sequence and the interplay between clay, sand and gravel beds. Most groundwater models for the Namoi river basin have split the Namoi alluvium into the Narrabri Formation and the Gunnedah Formation in order to characterise the upward-fining alluvial sediments. However, it is recognised that in some areas there may be no hydraulic separation between the Narrabri and Gunnedah formations, and they act as a single aquifer. This variability in connectivity within the alluvium is the result of deposition in a complex fluvial system and can occur on a very small scale, making it difficult to characterise and incorporate in groundwater models.

The alluvial system is subdivided geographically and for management purposes into the Upper and Lower Namoi alluvium, with the Upper Namoi alluvium referring to the upper catchment where there is generally less alluvial deposition, and the Lower Namoi alluvium which, being the lower part of the catchment, is characterised by extensive and thicker alluvial development. The town of Narrabri marks the boundary between the Upper and Lower Namoi alluvium (Figure 11).

Narrow geological constrictions along the length of the Upper Namoi Valley have had a significant effect on how the alluvial sediment was deposited, which influences groundwater movement in the Upper Namoi alluvium. In certain places, the basement rocks form narrow valleys, which restrict groundwater movement through the alluvial aquifers and may compartmentalise groundwater impacts from mining activities. The main constrictions occur at Gin’s Leap, north of Boggabri (between Zone 4 and Zone 5), Coxs Creek at Mullaley (between Zone 2 and Zone 9) and at Breeza on the Mooki River(between Zone 3 and Zone 8) (Barrett, 2012) (Figure 11).

The alluvial sediments form a continuous unit across the Hunter-Mooki Thrust Fault System, extending beyond the eastern boundary of the Namoi subregion, similar to the surface water catchment. Parts of the Upper Namoi Zone 4 and Zone 12 groundwater management areas extend over the Hunter-Mooki Thrust Fault System, indicating connectivity in the alluvium extends over the fault.

The hydraulic characteristics of the Narrabri and Gunnedah formations are generally well documented, however this is not the case for the deeper strata (see companion product 2.1-2.2 for the Namoi subregion (Aryal et al., 2018a)). The hydraulic properties of the alluvial aquifers are highly variable depending on the presence of sand or clay lenses. However, hydraulic conductivity generally increases with depth and in the paleochannels.

Regionally, groundwater gradients in the alluvial aquifers indicate flow from the east in a north-westerly to westerly direction (see Figure 26 in companion product 1.1 for the Namoi subregion (Welsh et al., 2014)). Groundwater mounds tend to develop around the Namoi River and its anabranch, Pian Creek.

In the northern Namoi paleochannel in the Lower Namoi, groundwater flow is from the Narrabri Formation into the Gunnedah Formation due to groundwater pumping for irrigation mostly from the Gunnedah Formation over the Lower Namoi Valley, but especially in the paleochannel. Groundwater pumping from the Gunnedah Formation induces significant downward leakage from the Narrabri Formation and changes in local groundwater flow direction (Smithson, 2009).

In general, groundwater levels in the alluvial aquifers respond to rainfall variability and the associated variability in groundwater use. At Narrabri, the watertable level is about 4 to 12 m below ground level, becoming progressively deeper towards the west, and is about 25 to 34 m below ground level near Walgett. Long-term groundwater level declines at the western end of the valley, where usage is low, are most likely related to extraction higher in the valley, limiting throughflow (Smithson, 2009).

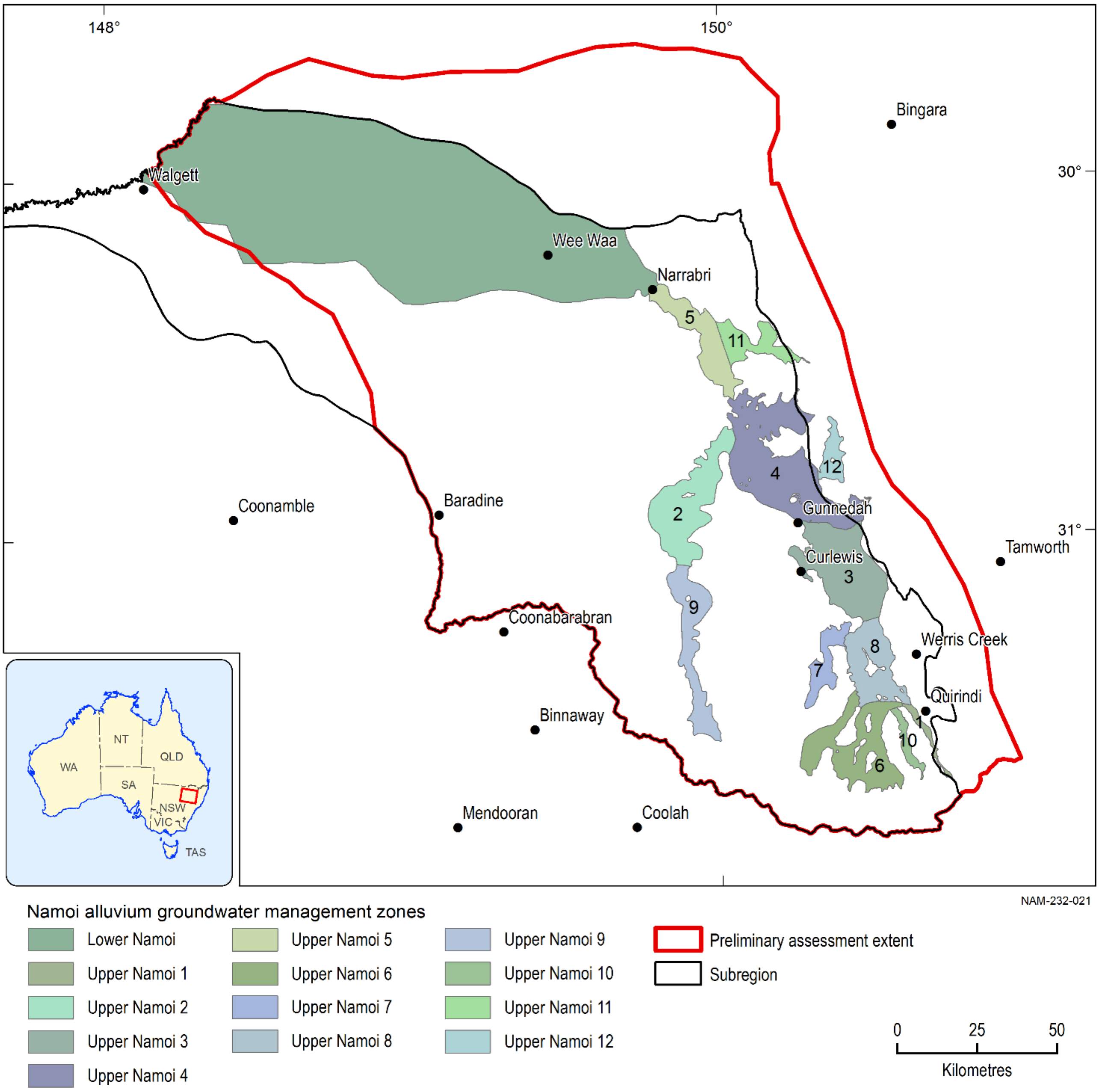

Figure 11 Groundwater management zones of the Upper and Lower Namoi groundwater sources within the preliminary assessment extent of the Namoi subregion

Data: Bioregional Assessment Programme (Dataset 3)

2.3.2.2.2.2 Surat Basin

The central and western parts of the Namoi subregion are underlain by the Coonamble Embayment, the south-eastern extent of the Surat Basin. The main Surat Basin aquifer is the Pilliga Sandstone, which crops out in the central part of the Namoi subregion, marking the eastern boundary of the Surat Basin.

Results from the Great Artesian Basin Water Resource Assessment (CSIRO, 2012) indicated that in the Coonamble Embayment, the Rolling Downs Group is a tight aquitard, the Pilliga Sandstone is an aquifer and the Purlawaugh Formation is an aquiclude. Other documentation describes the Purlawaugh Formation as a negligibly transmissive unit (CH2MHill, 2013) and an aquifer

(Schlumberger Water Services, 2011). These differences may be attributed to there being a limited groundwater monitoring network in the Purlawaugh Formation (Schlumberger Water Services, 2011) and the reported difficulty in picking the boundary between the Purlawaugh Formation and underlying rocks (Hawke and Cramsie, 1984). This may result in the Purlawaugh Formation not always being accurately logged and indicates a better understanding of its hydraulic behaviour may assist in determining the potential for connectivity between the Gunnedah and Surat basins in the Namoi.

Groundwater in the Pilliga Sandstone aquifer flows from south-east to west and north-west (Figure 12). From east to west, the watertable lies in the Pilliga Sandstone then passes into thin bands of Keelindi and Drildool beds and then into undifferentiated Rolling Downs Group to the west, outside of the Namoi subregion (CSIRO, 2012). Hydrographs from bores screened in the GAB show that artesian groundwater levels in the GAB have fallen over time but have been relatively stable since the 1970s (Schlumberger Water Services, 2012b). According to the New South Wales Government (NSW Government), increases in artesian bore pressure are being observed in many areas as a result of the cap and piping program under the GAB Sustainability Initiative (NSW DPI, 2017).

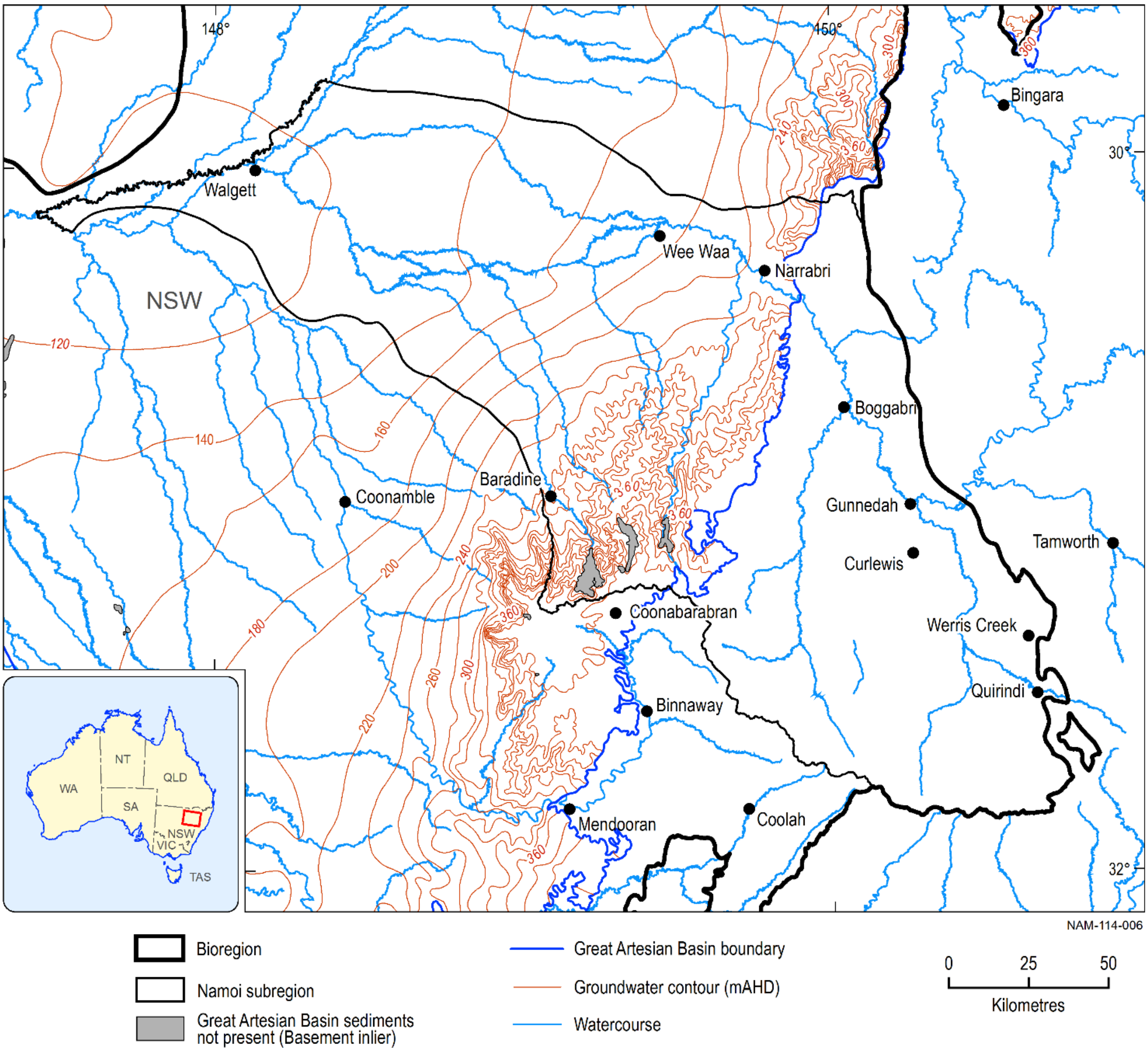

Figure 12 Potentiometric surface of groundwater in the uppermost Great Artesian Basin aquifer

Source: modified from CSIRO (2012)

The Pilliga Sandstone potentiometric heads do not generally show any obvious surface water – groundwater interaction along the Namoi River and its anabranch, Pian Creek. One possible exception is the area just downstream of Narrabri at the confluence with Bohena Creek.

The weathering of exposed Surat Basin sediments prior to the deposition of overlying Cenozoic alluvium resulted in a basin-wide saprolite layer of low permeability in the basal portion (Kellett and Stewart, 2013). This is considered to reduce connectivity with the alluvium, except in some places where the saprolite has eroded – namely, the paleochannels in the Upper and Lower Namoi alluvium.

Potentiometric heads in the Pilliga Sandstone are above watertable levels in the Narrabri Formation, indicating the potential for upwards leakage in places. This is in contrast to the situation in the early 1990s, when Williams (1997) showed the water levels in the alluvium were generally lying above the regional Surat Basin watertable. This suggests that there has been a reversal in the head differential between the two flow systems due to groundwater pumping for irrigation.

It is likely that water in the Pilliga Sandstone aquifer is providing baseflow to tributaries of the Namoi River at the eastern extent of the outcropping Surat Basin units. These baseflows are fed by rejected recharge, which occurs where water is restricted from entering the aquifer, mainly due to geology, and is discharged at the surface.

2.3.2.2.2.3 Gunnedah Basin

The Gunnedah Basin hosts the porous rock aquifers within the Digby Formation and Clare Sandstone (part of the Black Jack Group), and the Permian coal beds. The Gunnedah Basin strata do not constitute a single aquifer – rather, the sequence consists of many overlapping units that are stacked together and commonly separated by lower-permeability layers. The porous rock aquifers and coal beds within the Gunnedah Basin are considered to have a significantly lower hydraulic conductivity than the alluvial aquifers.

There is very little published information relating to the Gunnedah Basin aquifers, so groundwater levels and flow paths are largely unknown.

2.3.2.2.2.4 Basement

Lower Permian volcanic rocks of the Lachlan Orogen underlie the Gunnedah Basin strata. There is little published information relating to the potential for Lachlan Orogen aquifers.

2.3.2.3 Surface water

The main surface water resource of the Namoi subregion is the Namoi River. It drains an area of 42,000 km^2 flowing from east to west from its headwaters in the Great Dividing Range (CSIRO, 2007a). The major tributaries of the Namoi River within the Namoi subregion are the Mooki River and the Coxs, Pian (anabranch), Gunidgera (anabranch), Baradine and Bohena creeks (Figure 13). There are numerous other minor tributaries. The lowland floodplain downstream of Narrabri supports small lagoons, wetlands and anabranches. Namoi River is a perennial stream whereas Maules Creek at Avoca East (419051) and Mooki River at Breeza (419027) are nearly perennial flowing for 93% and 85% of the days, respectively. The rest of the Namoi river basin waterways within the PAE are temporary intermittent streams. River regulation by weirs and water diversions downstream of Gunnedah is reflected in lower mean daily flows downstream of Gunnedah relative to flows upstream of Gunnedah (see Section 1.1.5.1.4 in companion product 1.1 for the Namoi subregion (Welsh et al., 2014)).

Water quality in most sites in the Namoi river basin did not meet the Australian and New Zealand Environment and Conservation Council (ANZECC) and Agriculture and Resource Management Council of Australian and New Zealand (ARMCANZ) criteria for the protection of aquatic ecosystems during the 2002 to 2007 water quality indicator monitoring survey. Salinity in these areas are thought to be caused by the presence of salt in underlying soil or bedrock released by weathering, salt deposited during past marine inundation of an area, or salt particles being carried over the land surface from the ocean (Mawhinney, 2011). The Coxs Creek and Mooki and Peel rivers were the major contributors of salts to the Namoi River, with releases from Keepit Dam providing dilution flows (Mawhinney, 2011). Turbidity increases with distance from the dam (Olley and Scott, 2002). Phosphorus and nitrogen levels in the Peel River downstream of Tamworth were elevated due to the influence of sewage treatment outflows and urban runoff (Mawhinney, 2011).

The subregional topography is undulating in the west and progressively flattens to the east. This causes surface water drainage channels to be less dense west of Pilliga and flooding is more extensive downstream from Wee Waa. Surface and groundwater are connected in the alluvial material and in the Namoi streams, which are generally losing systems except the Namoi River reach between Boggabri and Narrabri, which contains gaining systems (see companion product 1.1 for the Namoi subregion (Welsh et al., 2014)).

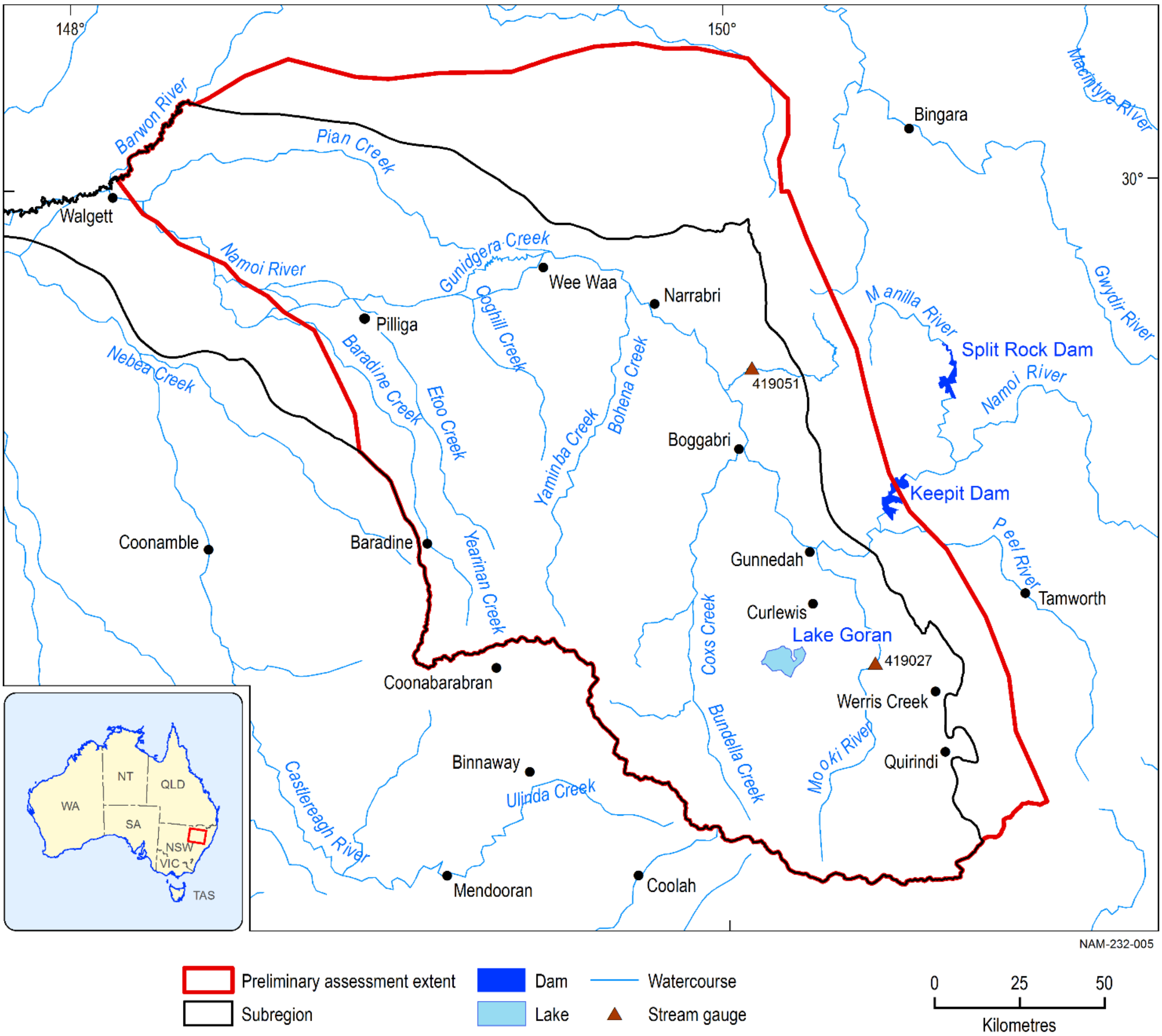

Figure 13 The Namoi River and its tributaries and major dams

2.3.2.4 Water balance

Characterisation of the water balance in the Namoi subregion is complicated by river regulation, the extensive practice of irrigated agriculture, groundwater flow across the subregion boundaries, interaction between the surface water and groundwater systems, and connectivity between aquifers. While it is relatively simple to measure surface water fluxes, quantifying the effect of the aforementioned influences on groundwater flows in the subregion is not possible with the available knowledge, and water managers must rely heavily on estimates and models. This section provides a qualitative discussion of the elements of the water balance, including volumetric estimates of terms where available.

2.3.2.4.1 Surface water balance

The subregion is bounded by the surface water catchment boundaries of the Namoi River along the northern and southern boundaries, and to the east by the Hunter-Mooki Thrust Fault System, which cuts across the Namoi river basin. The long-term surface water inflow at the eastern subregion boundary depends on the yearly dam water release from Keepit Dam and flow in the Peel River. The mean annual flow in the Peel River at Carroll Gap is 248.7 GL (53.3 mm runoff) for 1923 to 2015, while the mean annual release from the Keepit Dam is 215.8 GL (1996 to 2015) (NSW DPI, n.d.a). The sum of flows through these gauges provides an estimate of the surface water inflow to the subregion. The average annual outflow from the subregion, measured at Walgett, is 645.2 GL (1999 to 2014) (NSW DPI, n.d.b).

The long-term mean annual rainfall and potential evapotranspiration across the Namoi subregion varies from 600 to 1100 mm and from 1200 to 1400 mm respectively, indicating a large annual water deficit in the subregion. The long-term mean annual rainfall and modelled runoff of the entire Namoi river basin are 633 mm and 24 mm, respectively (runoff ratio 3.8%, Scenario A) (CSIRO, 2007a). The mean annual flow of the Namoi River upstream of Walgett as given by the Budyko analysis (Budyko, 1974) is 2000 GL (47.8 mm runoff) for 1982 to 2010 (Figure 14), which is almost double the long-term modelled runoff. The mismatch between the Budyko and CSIRO (2007a) rainfall-runoff analyses can be partially explained by losses due to consumptive use, which are accounted for in the rainfall-runoff modelling, whereas the Budyko analysis is based on water balance calculations that take into account only the long-term rainfall and potential/actual evapotranspiration. The difference in calculation period used in the long-term modelling and Budyko analysis may also explain the discrepancy.

Although there are differences between the theoretical Budyko analysis and the modelled and observed flows and in the water balance calculations, the value of the Budyko analysis is the ability to compare the relative contribution of stream sections in a regional sense. The long-term average surface water flows estimated using water balance techniques of Budyko (1974) are presented in Figure 14. The figure shows that streamflow in the main Namoi River is much greater than in the individual tributaries, and provides a much greater dilution (in orders of magnitude) than the tributaries.

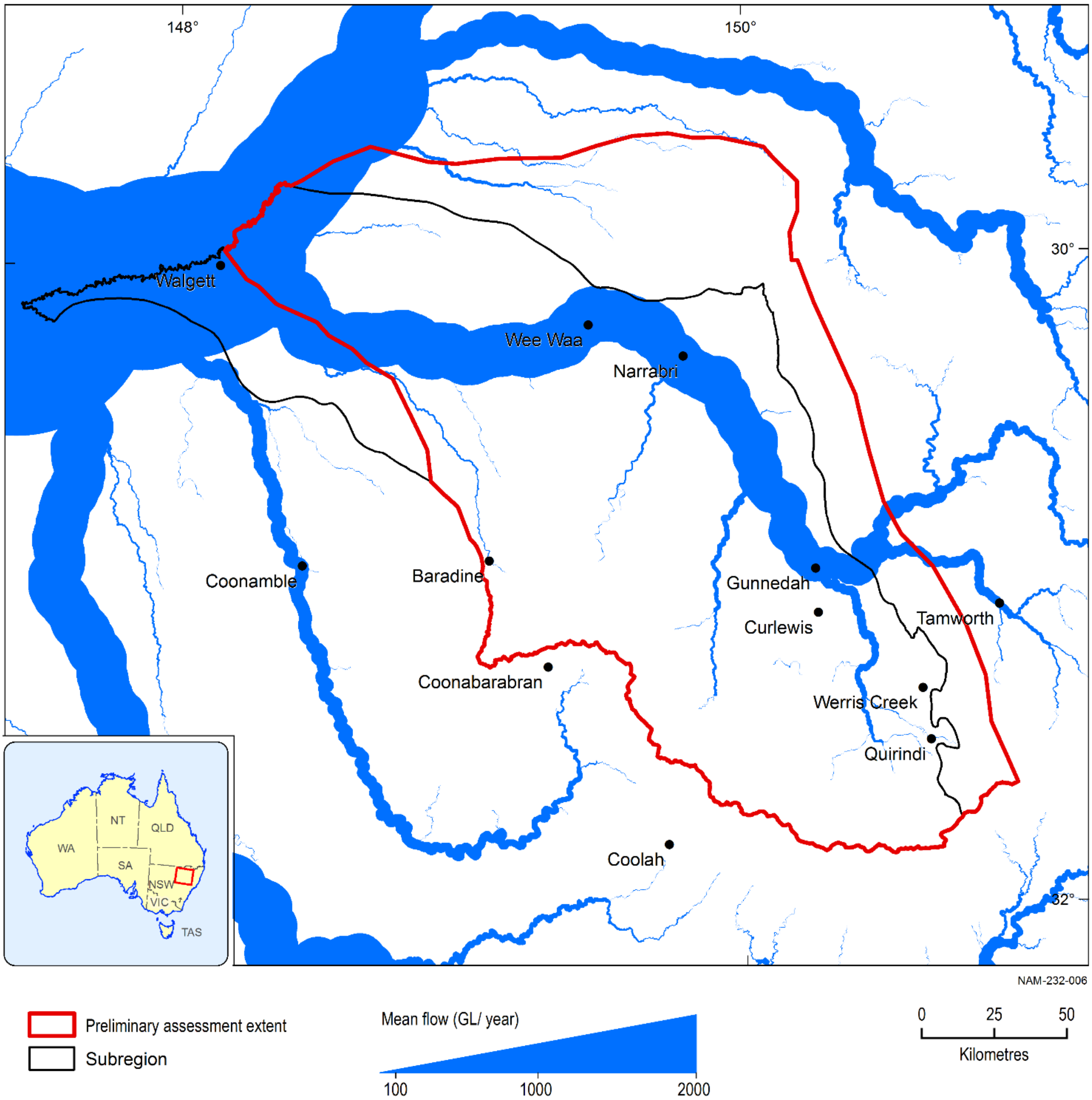

Figure 14 Surface water flows for river basins in the preliminary assessment extent for the Namoi subregion

Long-term annual flow is estimated using the water balance technique of Budyko (1974), which does not consider any impounding or regulation of river flow.
Data: Bioregional Assessment Programme (Dataset 1)

2.3.2.4.2 Groundwater

Figure 15 shows a conceptual water balance diagram for the Upper Namoi alluvium groundwater sources. The diagram represents the modelled water balance for the 2012 to 2013 water year, used by NSW Government water managers (Burrell et al., 2014). The diagram is included here to provide an example of the range of inflows and outflows that need to be characterised to have a comprehensive understanding of the water balance of groundwater systems. All of the flux values must be estimated or modelled; even those terms that have a measureable component rely heavily on estimates. For example, pumped extraction volumes must include both licensed extractions, usually metered, and stock and domestic water extraction, which is generally not metered, and can constitute a significant proportion (between 0.8% and 98%; Peña-Arancibia et al., 2016) of the sustainable diversion limit in each groundwater source.

Figure 15 shows that inflow to groundwater sources is via recharge from rainfall and irrigation. Groundwater outflows include evapotranspiration and pumped extractions. River recharge, or more specifically river/groundwater connections, and inter-aquifer connectivity provide mechanisms for water to flow between systems.

Groundwater outflows include evapotranspiration (discussed earlier in this section) and groundwater extraction. Groundwater extraction is a significant feature of the water balance and is discussed in detail in companion product 1.5 for the Namoi subregion (Peña-Arancibia et al., 2016).

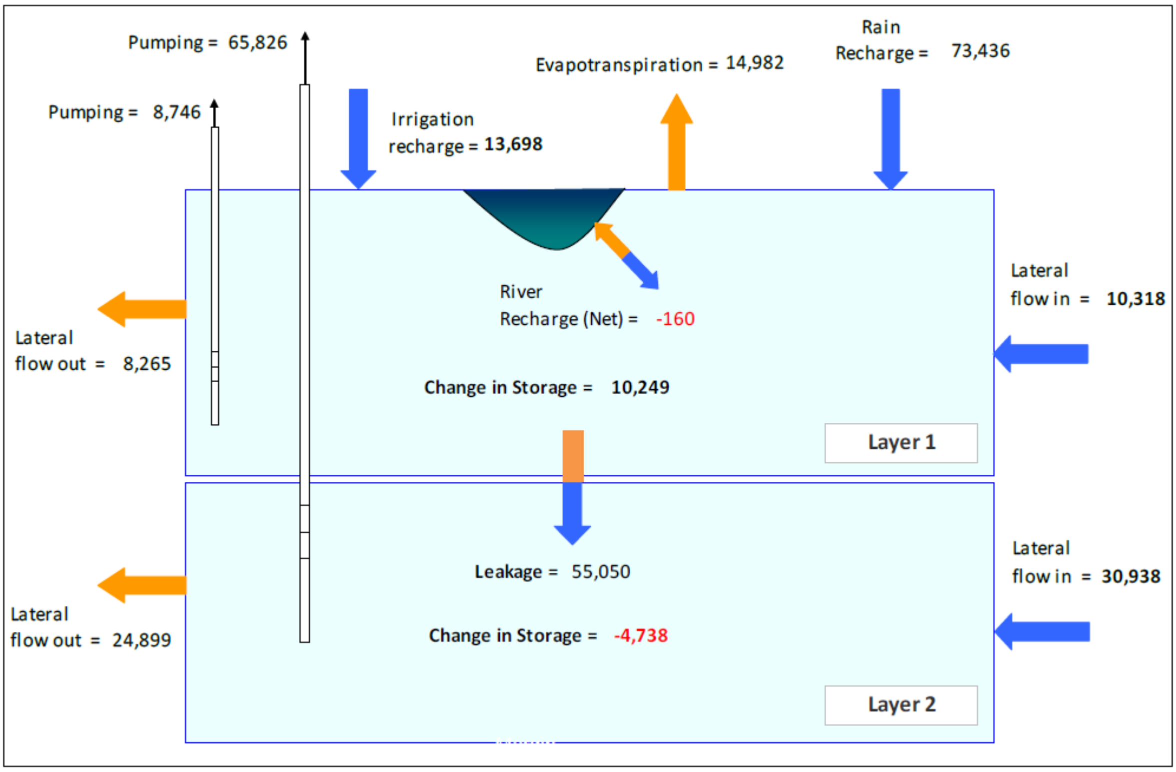

Figure 15 Example of conceptual diagram of water balance for a groundwater source (Upper Namoi alluvium) in the Namoi subregion

Upper Namoi groundwater combined sources physical flow budget 2012 to 2013. Layer 1 and Layer 2 in this diagram refer to modelled layers in the alluvial water source. All figures stated are in megalitres (ML).
Source: Figure 38 in Burrell et al. (2014)

2.3.2.4.3 Rainfall recharge

Rainfall recharge in the western part of the Namoi subregion is considered to be low. The Lower Namoi river basin groundwater model indicates that diffuse recharge from rainfall is a minor recharge source (Merrick, 2001). Groundwater level monitoring data revealed that recharge is less than 0.6% of annual rainfall during very wet years and is limited to localised areas of the plains. Considering the uncertainties involved, recharge is considered very small or negligible in the Lower Namoi (Timms et al., 2012).

In contrast, groundwater levels show a rapid response to rainfall in the Upper Namoi river basin, resulting in elevated groundwater levels that then dissipate during dry periods (Timms et al., 2001; Timms and Acworth, 2005).

Rainfall recharge to deeper groundwater sources generally occurs in areas of geological outcrop. The GAB units in the west of the subregion are recharged primarily through the southern and eastern recharge beds, shown in Figure 16, via direct rainfall infiltration into outcrops or indirect leakage from streams or overlying units.

Groundwater recharge mechanisms are discussed in greater detail in companion product 1.1 for the Namoi subregion (Welsh et al., 2014).

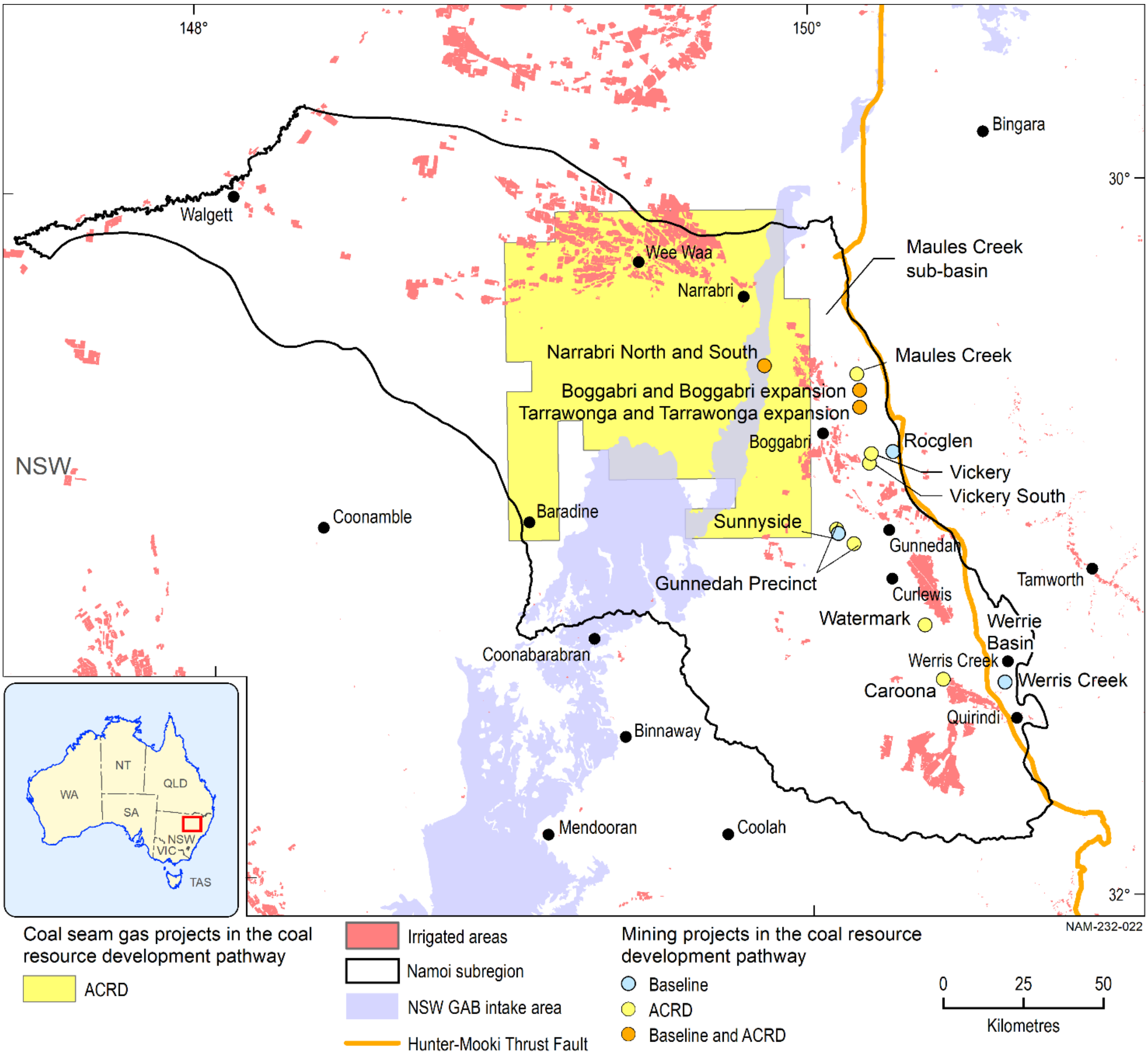

Figure 16 Groundwater recharge area for the Great Artesian Basin in New South Wales and irrigation areas within the Namoi subregion

The coal resource developments in the coal resource development pathway (CRDP) are the sum of those in the baseline coal resource development (baseline) and the additional coal resource development (ACRD).
Data: Bioregional Assessment Programme (Dataset 4), Australian Bureau of Agricultural and Resource Economics and Sciences (Dataset 5)

2.3.2.4.4 Irrigation recharge

Groundwater recharge as a result of irrigation may represent a significant component of recharge in some areas, however estimates of groundwater recharge from irrigation vary considerably. Figure 16 shows the area of irrigated agriculture in the Namoi subregion, based on 2014 land use mapping (Australian Bureau of Agricultural and Resource Economics and Sciences, Dataset 5).

Studies undertaken near Narrabri showed irrigation drainage to groundwater ranged from approximately 30 to 50 mm/year during the cotton irrigation season, was 23 mm/year under fallow conditions and was negligible under non-irrigated wheat (Ringrose-Voase and Nadelko, 2011). Other studies have provided complementary findings, however more work is needed to understand if this water migrates laterally, returns to the surface water flows or moves downwards to recharge deeper aquifers (see companion product 1.1 for the Namoi subregion (Welsh et al., 2014)). The main irrigation areas in the Namoi subregion are given in companion product 2.1-2.2 (Aryal et al., 2018a).

2.3.2.4.5 River connectivity

Shallow aquifers that are highly connected to the river system (defined as a system in which 70% or more of the groundwater extraction volume is derived from streamflow (NSW Office of Water, 2012)) are common in the Upper Namoi and, as a result, groundwater levels are highly dependent on surface water flows (Green et al., 2011). In the Upper Namoi the watertable is shallow, resulting in generally gaining river conditions (groundwater discharges to the river). On the upper alluvial plain, the groundwater levels fall relative to the river and losing conditions persist (river recharges the groundwater).

The streams on the Lower Namoi alluvial plain are in hydraulic connection with the Narrabri Formation, the uppermost alluvial layer. At the eastern and western margins of the plain, the rivers are directly linked with the watertable. An unsaturated zone occurs between these areas, where the watertable lies well below the streams. Surface water recharges the underlying aquifer whenever streamflow persists.

It is highly likely that water in the Pilliga Sandstone aquifer is providing baseflow to the Namoi River at the eastern extent of the outcropping GAB units via the Cenozoic alluvium. The river model of the Lower Namoi used in groundwater management plans has an average inflow of 8.3 GL/year from the GAB (Herczeg, 2008).

As a result of this surface water – groundwater connectivity, historical groundwater use has impacted on streamflow in the Namoi River and its tributaries. The Lower Namoi River has changed from a substantially gaining river prior to agricultural development to a largely losing river. CSIRO (2007b) estimated that the total average impact on tributary streamflow by 2010 would be a loss to groundwater of 19 GL/year more than that included in the river planning models examined.

Surface water – groundwater interactions are analysed further in companion product 2.1-2.2 for the Namoi subregion (Aryal et al., 2018a).

2.3.2.4.6 Inter-aquifer connectivity

The Gunnedah Formation is mainly recharged via infiltration from the overlying Narrabri Formation. In general, there is a downward movement of groundwater from the Narrabri Formation to the Gunnedah Formation in the east, while at the western margin the direction is reversed (CSIRO, 2007b). The aquifers of the Cubbaroo and Gunnedah formations are also recharged in part by upward leakage from the GAB (Ransley et al., 2012a).

Close to the margins of the GAB, paleochannels of overlying alluvium can be incised into aquifers such as the Pilliga Sandstone, resulting in upward leakage where the paleochannel has eroded the low permeability saprolite. The location and extent of contact between the alluvium and the Pilliga Sandstone is poorly understood, but is considered to be highly variable across the region (Ransley et al., 2012b). The contribution of the GAB aquifers to the alluvium in the water balance of the Lower Namoi model has previously been calculated as approximately 3.8 $m^3/day/km^2$ (Herczeg, 2008). It is estimated that there are approximately 400 km^2 of paleochannels.

The hydraulic connectivity between the GAB and underlying Gunnedah Basin appears to be variable but limited across the Namoi subregion, with an area in the northern part of the subregion providing the most likely area of connectivity (CSIRO, 2012).

The degree of connectivity between the alluvium, GAB and Gunnedah Basin aquifers is a key component for determining any impacts on water resources within the subregion due to coal resource development. However, information and data on connectivity are very limited and represent a significant knowledge gap; this issue is addressed further in Section 2.3.2.5.

2.3.2.5 Gaps

The knowledge gaps described in this section relate to limited surface water quality and quantity data that lead to limited modelling ability of surface water processes (see companion product 2.6.1 for the Namoi subregion (Aryal et al., 2018b)). Currently there are no streamflow and water quality gauging stations in any of the lower order streams, thus limiting the ability to model the streamflow and water quality of these streams. Some water quality measuring stations exist in the major rivers and tributaries for limited monitoring of nutrient, electrical conductivities and other constituents, however they do not measure dissolved oxygen and pH, which are critical to the survival of most aquatic species.

There is a lack of understanding of the interaction between the surface water and groundwater systems, particularly at the local level. Important knowledge gaps in this area are:

- quantification of the hydraulic connection between the shallow alluvial aquifers, the GAB and underlying geological basins. While there may be areas of connectivity between basins and between surface and groundwater, the rates of groundwater exchange remain poorly understood on a regional scale
- controlling mechanisms for vertical leakage (cross-formational flow) for the multiple layers of aquifers and aquitards present in the Namoi subregion. Understanding these mechanisms is critical for determining interaction between groundwater systems and also the effect of depressurisation proposed for CSG developments in the region. Permeability and specific

storage can now be measured in situ and these additional data would assist in constraining conceptual and numerical models

- hydraulic properties of aquitards and response to changes in groundwater pressure within adjacent aquifers. Where several layers of aquifers and aquitards are present, pressure changes caused by groundwater extraction will propagate at various rates in various directions, depending on the physical properties unique to each aquifer and aquitard layer (CSIRO, 2012)
- groundwater flow fluxes and compartmentalisation of deep aquifers in the Gunnedah Basin
- influence of geological structures (e.g. the Boggabri Fault, sub-basins, major faults) on regional groundwater flow in the Gunnedah Basin and the extent of compartmentalisation of the aquifers and groundwater flow systems
- extent of hydrologic connectivity between the alluvial aquifers and the deeper groundwater flow systems in the Gunnedah Basin
- magnitude of variability in surface water – groundwater connectivity
- variability of baseflow for the (mostly ungauged) rivers in the Namoi subregion.

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2.3.3 Ecosystems

Summary

The development of a landscape classification was undertaken with the objective of enhancing our understanding of the potential water-related impacts across the subregion. This landscape classification characterises the diverse range of water-dependent assets into a smaller number of classes for further analysis. It is based on key landscape properties related to patterns in geology, geomorphology, hydrology and ecology, as well as the land use patterns associated with human-modified ecosystems. The process of devising and implementing a landscape classification for the preliminary assessment extent (PAE) of the Namoi subregion used existing data associated with surface water network, aquatic and/or groundwater-dependent ecosystems (GDEs), remnant vegetation and land use mapping. Where appropriate, the approach (outlined in this section) has built on and integrated existing classification systems implemented by state and federal government institutions. This section describes the attributes by which landscape features are categorised and their corresponding rule sets for spatial data, which are represented as polygons (e.g. wetlands), polylines (stream network) and points (e.g. springs).

A total of 29 landscape classes, comprising 6 landscape groups, were defined using the rule sets described here. Most of the PAE (59%) is classed under the ‘Human-modified’ landscape group that includes agricultural, urban and other intensive land uses. For the remaining parts of the landscape, most (24% of the PAE) fall into the ‘Dryland remnant vegetation’ landscape group, which is not considered to be water dependent. The ‘Floodplain or lowland riverine’ landscape group covers approximately 6% of the PAE and includes the lowland riverine systems and the adjacent landscape classes associated with the riparian and back plain environments. Approximately 10% of the PAE and almost 72% of the watercourses are included in the ‘Non-floodplain or upland riverine’ landscape group that included a large extent of vegetation classified as groundwater dependent. Aspects of water dependency and the vegetation communities associated with each landscape group are discussed.

The Namoi subregion exhibits environmental gradients in climate and physiognomy that support a variety of ecosystems. These ecosystems form regions of similarity that are described in the Interim Biogeographic Regionalisation for Australia (IBRA; SEWPaC, Dataset 1). These IBRA subregions (Figure 17) define four broad geographic zones relevant for the subsequent assessment of water-related impacts. The surface water flow through these geographic zones is increasing generally from east to west (see schematic in Figure 18). The zones are the Liverpool Plains, the elevated areas between the Nandewar Range and the Merriwa district (termed here the Merriwa-Nandewar uplands, which comprise the Peel, Northern Basalt, Northern Outwash and Kaputar subregions of the Nandewar bioregion), Pilliga, the Pilliga Outwash and the Castlereagh-Barwon. The physical characteristics within each zone are similar. These zones are apparent in the soils, land and soil capability, land cover and land use maps (see Figure 5, Figure 6, Figure 7 and Figure 8 in companion product 1.1 for the Namoi subregion (Welsh et al., 2014)). Their common characteristics are summarised in Table 5.

The above described regions provide a coarse conceptual understanding that is useful in defining and ruling out areas that do not intersect with the zones of potential hydrological change when combined with conceptual understanding developed in Section 2.3.5. However, the development of receptor impact models – that is, the integration of hydrological and ecosystem understanding to analyse the risk to impact on ecosystems – requires a more hydrologically focused understanding of the ecological landscape elements. IBRA regions were developed for the purpose of defining representative conservation reserve systems, so are not fit for the purpose of developing receptor impact models related to changes in water. For this purpose the subsequent part of this section develops a specific landscape classification, which is essential to an understanding of water-related impacts. This classification is designed to reduce the complexity in the receptor impact modelling and aid in the selection and development of appropriate conceptual models for the landscape classes (see companion product 1.3 for the Namoi subregion (O'Grady et al., 2015)).

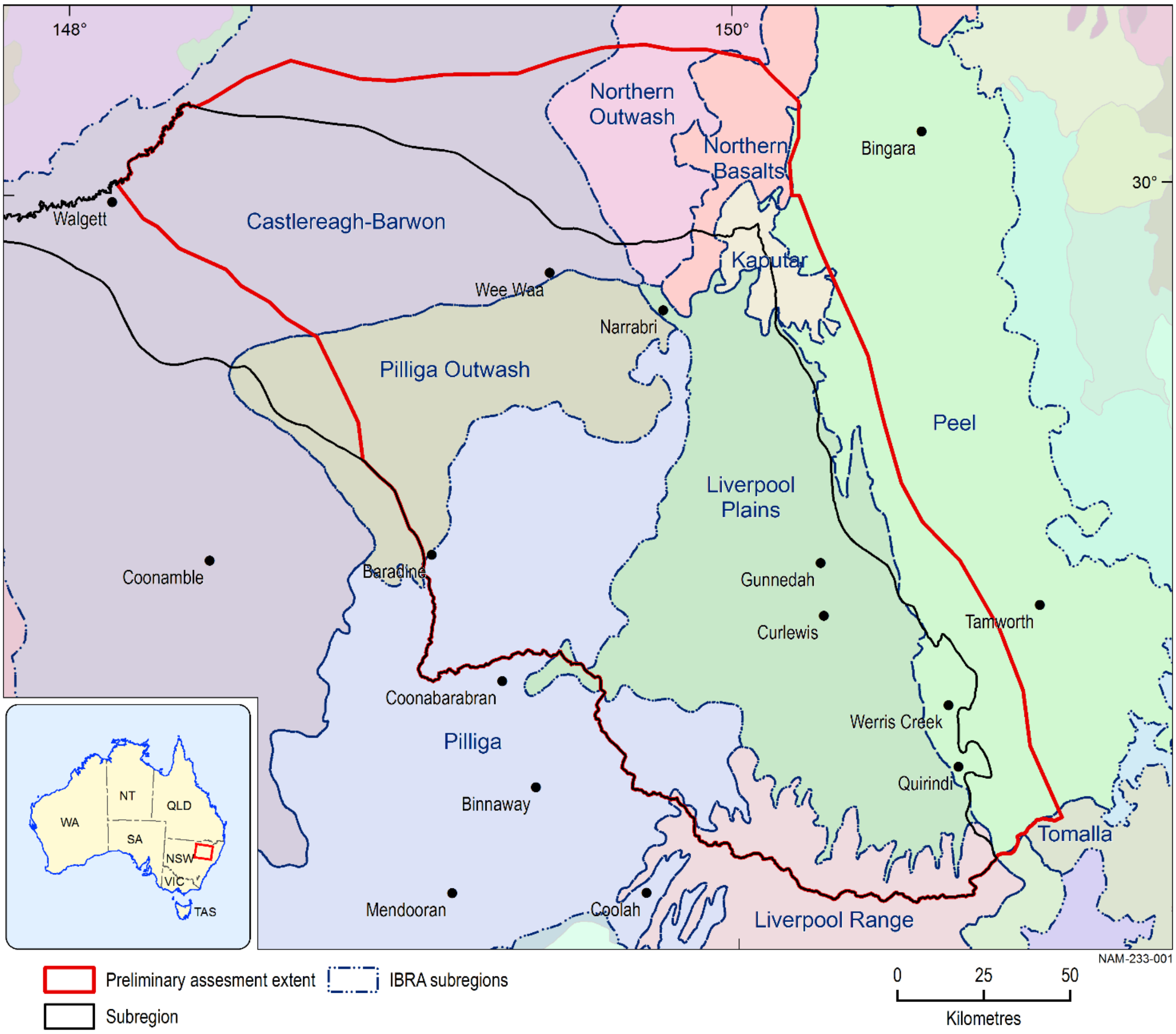

Figure 17 Interim Biogeographic Regionalisation for Australia (IBRA) subregions in the Namoi subregion

Data: SEWPaC (Dataset 1)

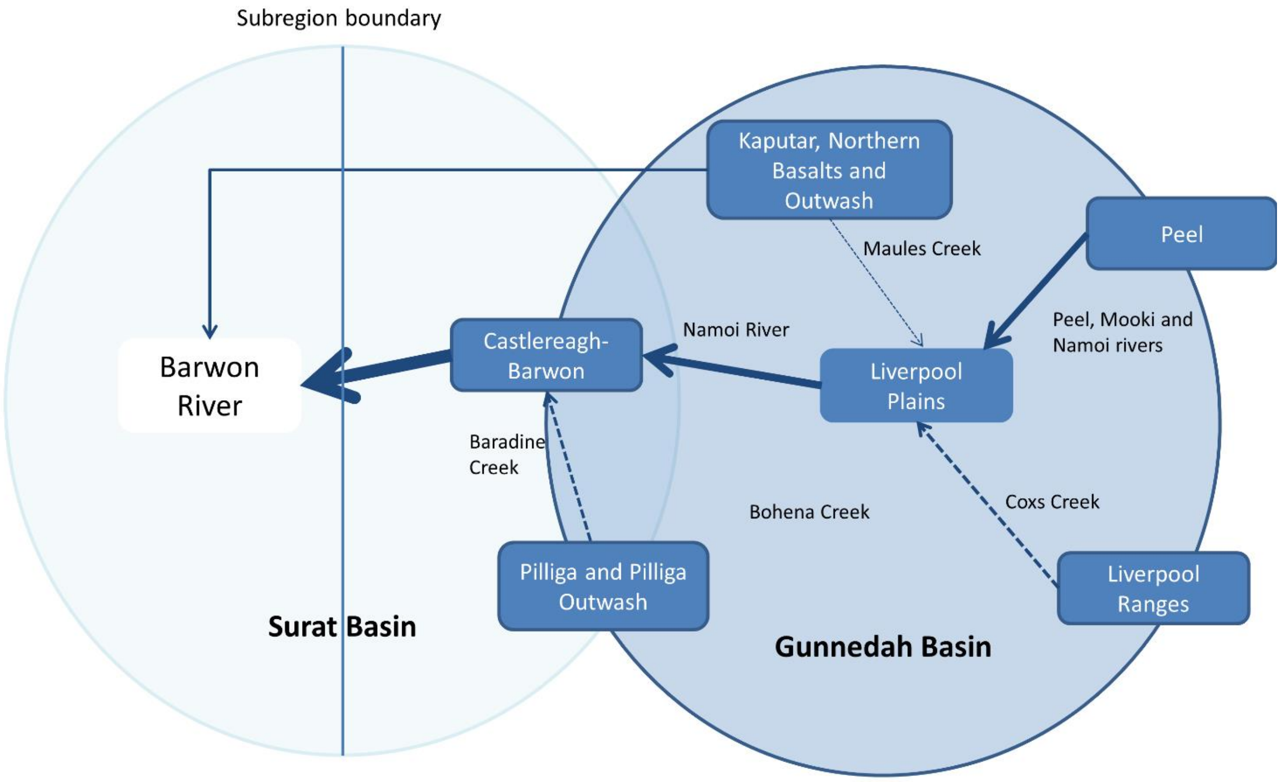

Figure 18 Schematic of the surface water connectivity between geographic zones of the Namoi subregion overlying the sedimentary basins

The flow direction is towards the western subregion boundary into the Barwon River. Dashed arrows represent ephemeral streams and full arrows permanent streams, and the increasing thickness of the lines indicates broadly increase in water volume.

Table 5 Characteristics of the four Interim Biogeographic Regionalisation for Australia (IBRA) subregions in the Namoi subregion

	Castlereagh-Barwon	Pilliga and Pilliga Outwash	Liverpool Plains	Merriwa-Nandewar uplands (Peel, Kaputar, Northern Basalt and Northern Outwash[a])
Mean annual rainfall (mm)	<600	600–750	650–750	>750
Climate	Semi-arid (hot, dry)	Sub-humid; no dry season	Sub-humid; no dry season	Warm, dry, slight summer dominance
Physiography	Overlapping, low-gradient alluvial fans	Quartz sandstone plateau; long gentle outwash slopes	Alluvial fans and outwash slopes	Basalt over sandstone slopes and tablelands
Soil	Clay soils on plains; sandy soils along older streams	Thin stony, sandy soils; texture contrast soils on slopes; deep sands, grey clays and texture contrast soils in valleys	Black earths on low slopes; brown clays, alluvial soils and texture contrast soils	Clay or loam soils; black earths; red or brown, well-structured clays
Land and soil capability	Moderate with areas of few limitations	Severe limitations: erosion, sodicity, salinity, scalding	Moderate with areas of few limitations	Extreme limitations: steep, rocky, erosion
Land cover	Pasture and crops; sparse trees	Sparse – open trees	Crops and pasture	Sparse – closed trees
Vegetation	River red gum (*Eucalyptus camaldulensis*); coolibah-black box (*E. coolabah, E. largiflorens)*; poplar box (*E. populnea*); weeping myall (*Acacia pendula*)	Poplar box, pilliga box (*E. pilligaensis*), narrow-leaved ironbark (*E. crebra*), Blakely's red gum (*E. blakelyi*), cypress pine (*Callitris* spp.) on coarser soils; belah (*Casuarina cristata*), brigalow (*A. harpophylla*); river red gum in creek lines	Plains (*Austrostipa aristiglumis*), panic (*Digitaria brownii*), windmill (*Chloris truncata*) and blue grasses (*Dicanthium sericeum*) on black earths with occasional box woodlands (*E. melliodora*); cypress pine (*Callitris* spp.), occasional belah and mulga (*A. aneura*) on slopes	Open box woodlands (*E. melliodora, E. leucoxylon*); barrow-leaved ironbark/cypress pine woodlands
Wetlands	Namoi River floodplains	Gilgai wetlands	Lake Goran, floodplain wetlands	na
Land use	Dryland cropping; grazing (native pasture); irrigated crops; forestry	Nature conservation; forestry	Dryland cropping; grazing (modified pasture); irrigated crops	Nature conservation; grazing

[a]The Merriwa-Nandewar uplands comprise the Peel, Northern Basalt, Northern Outwash and Kaputar subregions of the Nandewar bioregion.
na = not applicable
Data: SEWPaC (Dataset 1), ABARES (Dataset 2), NSW OEH (Dataset 3)

2.3.3.1 Methodology

The purpose of the landscape classification is to group landscape elements based on common characteristics with a focus on water and to facilitate a conceptual understanding of water dependency. The bioregional assessment (BA) landscape classification capitalises on existing classifications and regionalisation approaches that provide existing conceptual models. This facilitates a conceptual understanding of how hydrological regimes link to system level water requirements.

The classification for the PAE of the Namoi subregion uses broad-scale geomorphological, soil, hydrological and habitat information for a diverse range of landscape features to produce landscape classes that capture key distinctions using one or more of the following classifiers (Table 6):

- broad habitat type (remnant/human-modified/aquatic)
- geomorphology (floodplain/non-floodplain)
- vegetation type (riparian/woodland floodplain/grassy woodland/rainforest)
- water regime (near-permanent/temporary)
- groundwater (groundwater dependent/non-groundwater dependent) or, in the case of springs, groundwater source (Great Artesian Basin (GAB)/non-GAB).

The classification broadly took a hierarchical approach in that certain types of landscape elements were given priority in developing a spatially complete landscape classification across the PAE. Prioritisation was assigned in order of highest to lowest as:

- aquatic ecosystems (e.g. wetlands, streams and lakes)
- remnant vegetation – areas of vegetation that contained relatively intact plant communities
- other landscape elements that are 'non-remnant vegetation' and are typically 'human-modified'.

Landscape elements are classed as either 'aquatic', if mapped using wetlands, streams or springs datasets; 'remnant', if they are mapped in the NSW regional native vegetation mapping (NSW OEH, Dataset 3) and do not include 'non-native' or 'candidate native grasses' within the 'Keith Form' classification (Keith, 2004); and 'human-modified' for all remaining landscapes not covered by the aquatic and remnant areas (see Table 6). This classifier delineates between 'human-modified' landscapes and those that are relatively intact. This distinction has important consequences for defining where important habitats and biota may occur when considering assets and their likely distribution.

Vegetation communities are broadly classified based primarily on existing classification within the NSW regional native vegetation mapping (NSW OEH, Dataset 3 and Table 6) (Keith, 2004). Riparian and floodplain woodland vegetation are defined as separate classes based on their importance in riverine and floodplain environments. Rainforest remnants are also defined separately given their high ecological value within the landscape. Riparian remnants on non-floodplain or upland areas are distinguished from other non-floodplain vegetation communities. The remaining non-floodplain woodland, shrubland and grassland communities were aggregated into a 'grassy woodlands' classification.

The aquatic features (wetlands) and remnant vegetation are classified based on whether they occur on floodplain or non-floodplain areas (Table 6). The spatial distribution of wetland elements were derived from the existing Australian National Aquatic Ecosystem (ANAE) classification framework for wetlands (excluding riverine habitats) (SEWPaC, Dataset 4) and the NSW regional native vegetation mapping (NSW OEH, Dataset 3). This distinction was made using the maximum flooding extent using the Namoi Valley floodplain atlas (NSW OEH, Dataset 5). This helps to broadly characterise which landscape features, such as wetlands, might be influenced by flooding regimes that are more likely to support water-dependent vegetation and habitats.

Riverine or instream landscape elements were classified according to topography using upland *versus* lowland distinctions and the water regime (temporary or permanent). The distribution and persistence of riverine ecosystems is influenced largely by water regime and is a key attribute for differentiating and characterising habitats and ecosystems. In this case the existing ANAE classification framework of streams (SEWPaC, Dataset 4) was aggregated to produce four separate riverine categories that were subsequently classified according to association with GDEs (Table 6). The association of riverine landscape features with GDEs was assessed using the *National atlas of groundwater dependent ecosystems* (GDE Atlas; Bureau of Meteorology, 2012; Bioregional Assessment Programme, Dataset 7). This dataset was used because the NSW GDE mapping and classification does not cover streams and riverine habitat. The spatial overlap between stream segments and those GDE elements that were defined as ecosystems dependent on the surface expression of groundwater in the GDE Atlas was used to classify the riverine ecosystems (Table 6). The potential for different wetland or vegetation elements to access or interact with groundwater is based on their spatial overlap with those areas identified as high potential GDEs in the NSW GDE mapping and classification (NSW Office of Water, Dataset 6). This dataset was used over the GDE Atlas because it has been mapped at a finer spatial resolution and uses the NSW native vegetation mapping as a basis for the delineation of landscape elements (NSW OEH, Dataset 3). The NSW Department of Primary Industries Water methodology (Kuginis et al., 2016) 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 Keith's (2004) classification of vegetation communities. The landscape classification approach uses Keith's (2004) classification of 'formations' and 'classes' to vegetation types associated with these GDEs. Data on the distribution of GDEs within the PAE of the Namoi subregion were based on multiple lines of evidence that included remote sensing of vegetation condition, watertable data, vegetation community and landscape information (Kuginis et al., 2016).

Land use mapping data (ABARES, Dataset 2) were used to classify all landscape elements identified as 'non-remnant' into six land use types (Table 6) that comprise the human-modified group of landscape classes:

- conservation and natural environments
- intensive uses

- modified water bodies
- production from dryland agriculture and plantations
- production from irrigated agriculture and plantations
- production from relatively natural environments.

The logic of the landscape classification rule sets used in the landscape classification for the Namoi subregion is shown in Figure 19.

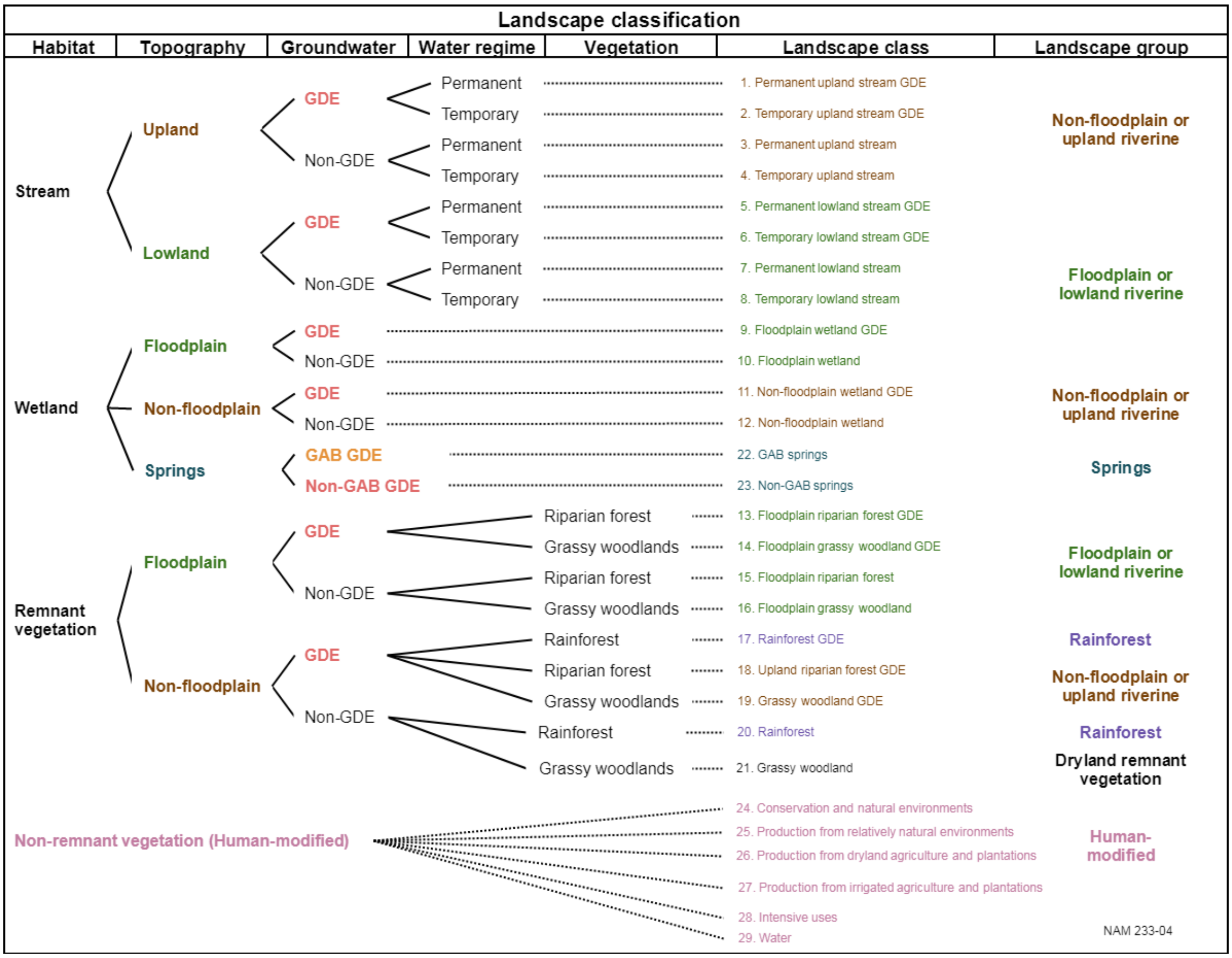

Figure 19 Landscape classification for the Namoi subregion based on five key criteria: habitat, topography, groundwater, water regime and vegetation

GAB = Great Artesian Basin, GDE = groundwater-dependent ecosystem

Table 6 Relevant datasets and key rule sets used for the landscape elements

Relevant datasets	Broad habitat type	Geomorphology	Vegetation type	Water regime	Groundwater
Water-dependent asset register and asset list for the Namoi subregion (Bioregional Assessment Programme, Dataset 8)	**Springs (points):** spatial intersect with [asset name] contains 'Spring GDE' (Bioregional Assessment Programme, Dataset 8)	na	na	na	**GAB:** [GMA_DS] = 'Great Artesian Basin' (Bioregional Assessment Programme, Dataset 8)
		na	na	na	**Non-GAB:** Not [GMA_DS] = 'Great Artesian Basin' (Bioregional Assessment Programme, Dataset 8)
ANAE streams (SEWPaC, Dataset 4); GDE Atlas – GDE surface layer (Bioregional Assessment Programme, Dataset 7)	**Streams (lines and polygons):** spatial intersect with 'ANAE streams' (SEWPaC, Dataset 4)	**Upland:** If [ANAEstT] contains 'upland' OR 'transitional' (SEWPaC, Dataset 4)	na	**Permanent:** If [ANAEstT] contains 'permanent' (SEWPaC, Dataset 4)	**GDE:** Spatial intersect with 'GDE_sur' (Bioregional Assessment Programme, Dataset 7)
		Lowland: If [ANAEstT] contains 'lowland' (SEWPaC, Dataset 4)	na	**Temporary:** If [ANAEstT] contains 'temporary' (SEWPaC, Dataset 4)	**Non-GDE:** No spatial intersect with 'GDE_sur' data layer (Bioregional Assessment Programme, Dataset 7)
ANAE wetlands (SEWPaC, Dataset 4); Namoi Valley floodplain atlas 1979 (NSW OEH, Dataset 5), NSW groundwater-dependent ecosystem mapping (NSW Office of Water, Dataset 6); NSW regional vegetation (NSW OEH, Dataset 3)	**Wetlands (polygons):** spatial intersect with 'ANAE wetlands' (SEWPaC, Dataset 4) OR 'NSW regional vegetation'[Keith_form] = 'freshwater wetlands' (NSW OEH, Dataset 3)	**Floodplain:** Spatial intersect with 'floodplain atlas' layer (NSW OEH, Dataset 5)	na	na	**GDE:** Spatial intersect with 'NSW_GDE' data layer (NSW Office of Water, Dataset 6)
		Non-floodplain: No spatial intersect with 'floodplain atlas' layer (NSW OEH, Dataset 5)	na	na	**Non-GDE:** No spatial intersect with 'NSW_GDE' data layer (NSW Office of Water, Dataset 6)

Relevant datasets	Broad habitat type	Geomorphology	Vegetation type	Water regime	Groundwater
NSW regional vegetation (NSW OEH, Dataset 3); NSW groundwater-dependent ecosystem mapping (NSW Office of Water, Dataset 6)	**Remnant vegetation (polygons):** spatial intersect with 'NSW regional vegetation'; excluding [Keith_form] = 'non-native' OR 'candidate native grasses' OR 'freshwater wetlands' AND 'ANAE wetlands' layer (NSW OEH, Dataset 3; SEWPaC, Dataset 4)	**Floodplain:** If [Keith_class] contains 'floodplain' OR 'inland riverine forests' (NSW OEH, Dataset 3)	**Floodplain riparian forest:** If [Keith_class] = 'inland riverine forests' (NSW OEH, Dataset 3)	na	**GDE:** spatial intersect with 'NSW_GDE' data layer (NSW Office of Water, Dataset 6)
			Floodplain grassy woodland: [Keith_class] = 'floodplain' OR 'riverine' AND NOT [Keith_form] = 'forested wetlands (NSW OEH, Dataset 3)	Na	**Non-GDE:** no spatial intersect with 'NSW_GDE' data layer (NSW Office of Water, Dataset 6)
		Non-floodplain: NOT [Keith_class] contains 'floodplain' OR 'inland riverine forests' (NSW OEH, Dataset 3)	**Rainforest:** [Keith_form] = 'rainforests' OR 'wet sclerophyll forests' (NSW OEH, Dataset 3)	na	**GDE:** spatial intersect with 'NSW_GDE' data layer (NSW Office of Water, Dataset 6)
					Non-GDE: no spatial intersect with 'NSW_GDE' data layer (NSW Office of Water, Dataset 6)
			Grassy woodland: NOT [Keith_form] = 'rainforests' OR 'wet sclerophyll forests' (NSW OEH, Dataset 3)	na	**GDE:** spatial intersect with 'NSW_GDE' data layer (NSW Office of Water, Dataset 6)
					Non-GDE: no spatial intersect with 'NSW_GDE' data layer (NSW Office of Water, Dataset 6)
			Riparian forest: [Keith_class] = 'eastern riverine forests' (NSW OEH, Dataset 3)	na	na

Relevant datasets	Broad habitat type	Geomorphology	Vegetation type	Water regime	Groundwater
Australian land use mapping (ABARES, Dataset 2); NSW regional vegetation (NSW OEH, Dataset 3)	**Human-modified landscapes (polygons):** spatial intersect with [Keith_form] = 'non-native' OR 'candidate native grasses' (NSW OEH, Dataset 3)	**'Human-modified' landscape class:** [Primary_v7] (ABARES, Dataset 2)			

ANAE = Australian National Aquatic Ecosystems, GAB = Great Artesian Basin, GDE = groundwater-dependent ecosystem, na = not applicable

2.3.3.2 Landscape classification

Twenty-nine landscape classes were derived using the approach detailed in Section 2.3.3.1. These 29 landscape classes were allocated to one of six landscape groups based on broad-scale distinctions in their water dependency and association with floodplain/non-floodplain environments, GDEs and remnant/human-modified habitat types (Table 6). The 29 landscape classes are presented in Table 7, Table 8 and Table 9 and are based on their spatial attribution as either polygons, lines or points as defined in Table 5.

Most of the PAE (59.3%) is classified in the ‘Human-modified’ landscape group, which includes agricultural, urban and other intensive land uses (Table 7). Among those areas classified as remnant vegetation, the majority (24.2% of the PAE) fell into the ‘Grassy woodland’ landscape class (‘Dryland remnant vegetation’ landscape group) (Table 7 and Figure 20); they are assumed to be non-water dependent because they do not intersect floodplain, wetland or GDE features. The ‘Floodplain or lowland riverine’ landscape group covers 6.2% of the PAE. Of the remaining non-floodplain landscapes, GDEs cover 9.1% of the PAE, with ‘Grassy woodland GDE’ making up the vast majority of these. A very small portion of this non-floodplain environment (0.5% of the PAE) contains ‘Rainforest’ or ‘Rainforest GDE’ landscape classes (Table 7 and Figure 20).

Table 7 Land area and proportion of polygon landscape classes in the Namoi preliminary assessment extent

Landscape group[a]	Landscape class number	Landscape class[a]	Landscape class area (ha)	Percentage of total PAE (%)
Floodplain or lowland riverine	10	Floodplain wetland	3,008	<0.1%
	9	Floodplain wetland GDE	15,179	0.4%
	16	Floodplain grassy woodland	40,024	1.1%
	14	Floodplain grassy woodland GDE	144,544	4.1%
	15	Floodplain riparian forest	150	<0.1%
	13	Floodplain riparian forest GDE	14,868	0.4%
	7	Permanent lowland stream[b]	1,730	<0.1%
	5	Permanent lowland stream GDE[b]	1	<0.1%
	8	Temporary lowland stream[b]	151	<0.1%
	6	Temporary lowland stream GDE[b]	833	<0.1%
		Total	**220,488**	**6.2%**
Non-floodplain or upland riverine	12	Non-floodplain wetland	13,025	0.4%
	11	Non-floodplain wetland GDE	2,349	<0.1%
	19	Grassy woodland GDE	324,762	9.1%
	3	Permanent upland stream[b]	7	<0.01%
	1	Permanent upland stream GDE[b]	113	<0.01%
	4	Temporary upland stream[b]	2	<0.01%
	2	Temporary upland stream GDE[b]	8	<0.01%
	18	Upland riparian forest GDE	8,742	0.3%
		Total	**349,009**	**9.8%**
Dryland remnant vegetation	21	Grassy woodland	862,371	24.2%
		Total	**862,371**	**24.2%**

Landscape group[a]	Landscape class number	Landscape class[a]	Landscape class area (ha)	Percentage of total PAE (%)
Rainforest	20	Rainforest	15,310	0.4%
	17	Rainforest GDE	4,349	0.1%
		Total	**19,659**	**0.5%**
Human-modified	24	Conservation and natural environments	40,072	1.1%
	25	Intensive uses	27,599	0.8%
	26	Production from dryland agriculture and plantations	1,607,492	45.1%
	27	Production from irrigated agriculture and plantations	185,478	5.2%
	28	Production from relatively natural environments	235,620	6.6%
	29	Water	18,215	0.5%
		Total	**2,114,480**	**59.3%**
Total			**3,566,007**	**100.0%**

[a]Punctuation and typography appear as generated by the landscape classification.
[b]These riverine features were mapped as polygons in the source datasets.
GDE = groundwater-dependent ecosystem, PAE = preliminary assessment extent
Data: Bioregional Assessment Programme (Dataset 9)

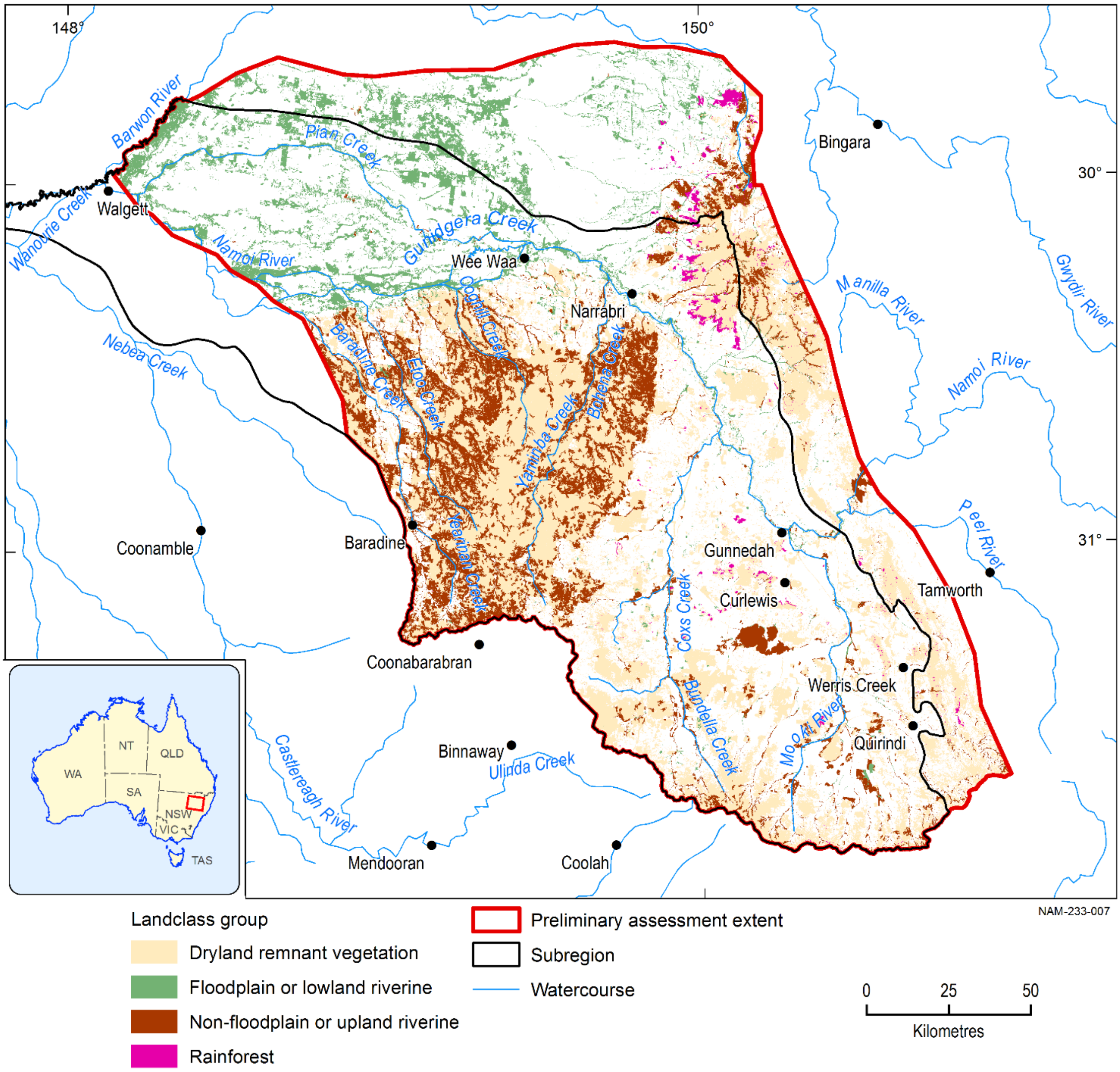

Figure 20 Landscape groups (excluding the 'Human-modified' and 'Springs' landscape groups) across the Namoi preliminary assessment extent

Data: Bioregional Assessment Programme (Dataset 9), Bureau of Meteorology (Dataset 10)

The 'Non-floodplain or upland riverine' landscape group made up the largest proportion of the stream network (63.8%) (Table 7, Table 8 and Figure 21). Among the landscape classes within the 'Non-floodplain or upland riverine' landscape group, most belong to the 'Temporary upland stream' landscape class (Table 8). The lowland riverine streams are also predominantly classified as 'temporary' and only approximately 5% of these streams are associated with GDEs (Table 8).

Of the 22 springs classified within the Namoi PAE, 7 are associated with the GAB aquifers (Table 9 and Figure 22).

Table 8 Length of stream network classes in the Namoi preliminary assessment extent

Landscape group[a]	Landscape class number	Landscape class[a]	Total length (km)	Percentage of total stream network length (%)
Floodplain or lowland riverine	7	Permanent lowland stream	1,688	5.7%
	5	Permanent lowland stream GDE	457	1.5%
	8	Temporary lowland stream	8051	27.3%
	6	Temporary lowland stream GDE	509	1.7%
		Total	**10,705**	**36.2%**
Non-floodplain or upland riverine	3	Permanent upland stream	1,644	5.6%
	1	Permanent upland stream GDE	227	0.8%
	2	Temporary upland stream GDE	16,499	55.9%
	4	Temporary upland stream	464	1.6%
		Total	**18,834**	**63.8%**
Total			**29,539**	**100%**

[a]Punctuation and typography appear as generated by the landscape classification.
GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 9)

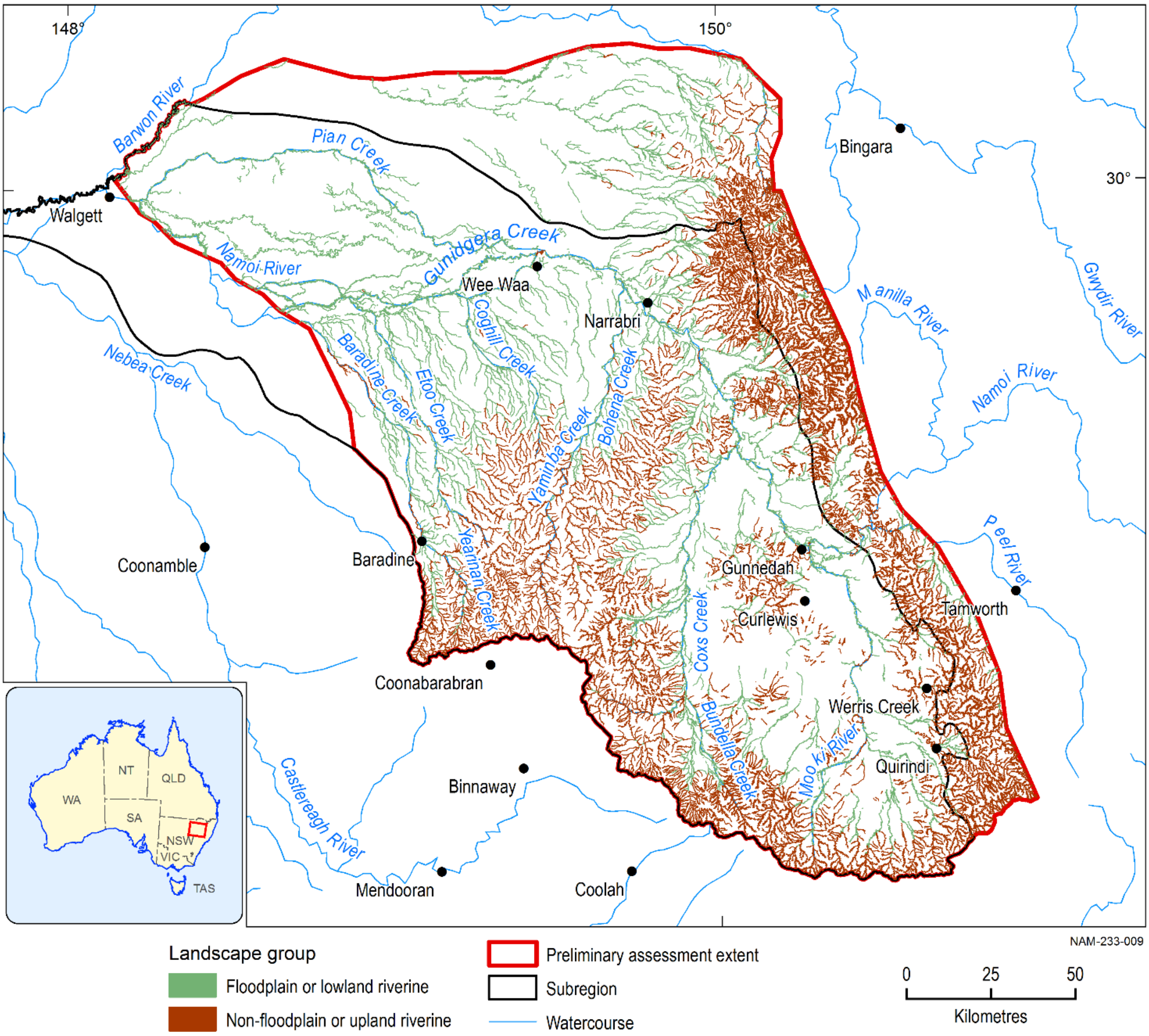

Figure 21 Stream network classified as 'upland' or 'lowland' in the landscape classification for the Namoi subregion

Data: Bioregional Assessment Programme (Dataset 9), Bureau of Meteorology (Dataset 10)

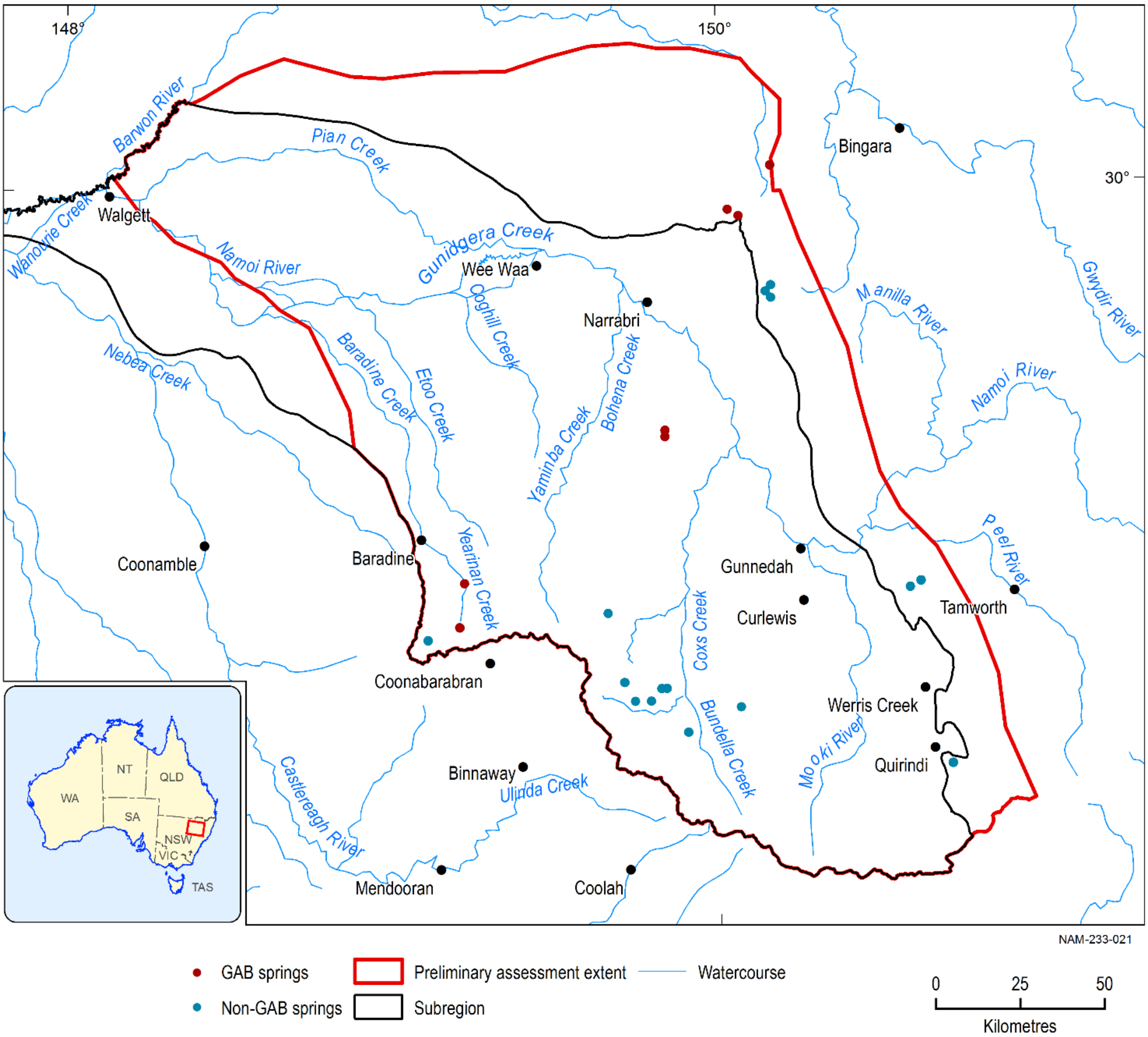

Figure 22 'Springs' landscape group across the Namoi preliminary assessment extent

GAB = Great Artesian Basin

Data: Bioregional Assessment Programme (Dataset 9), Bureau of Meteorology (Dataset 10)

Table 9 Landscape classes in the 'Springs' landscape group in the Namoi preliminary assessment extent

Landscape group[a]	Landscape class number	Landscape class[a]	Total count
Springs	21	GAB springs	7
	22	Non-GAB springs	15
Total			**22**

[a]Punctuation and typography appear as generated by the landscape classification.

GAB = Great Artesian Basin

Data: Bioregional Assessment Programme (Dataset 9)

Table 10 Location, associated communities, threatened ecological communities, water dependency and nature of water dependency for each landscape group

	Location	Associated communities	Listed ecological communities (EPBC Act)	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Floodplain or lowland riverine	Quaternary alluvial systems	• Riparian forests dominated by river red gum • *Casuarina cunninghamiana* is also common • Floodplain woodlands including coolibah, black box and poplar box	• Coolibah - Black Box Woodlands of the Darling Riverine Plains and the Brigalow Belt South Bioregions • Natural grasslands on basalt and fine-textured alluvial plains of northern New South Wales and southern Queensland • Grey Box (*Eucalyptus microcarpa*) Grassy Woodlands and Derived Native Grasslands of South-eastern Australia • White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland • Weeping Myall Woodlands	• Associated with 'near-permanent' and 'temporary lowland' streams • Floodplain wetlands are characterised by size, water regime and emergent vegetation • Flooding pulses enable growth and recruitment • River red gum flooding required every 1–4 years • Black box/coolibah/river cooba – flooding required every 3–7 years (Roberts and Marston, 2011) • Streamside water not critical water source (Thorburn and Walker, 1994) • Groundwater – intermittent and aseasonal and where salinity levels are tolerable (Roberts and Marston, 2011)	Surface water (regional, episodic) and groundwater (landscape, aseasonal/intermittent)

	Location	Associated communities	Listed ecological communities (EPBC Act)	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Non-floodplain or upland riverine	• Pilliga Forest • Basaltic and sedimentary slopes	• Pilliga 'gilgai' and other ephemeral wetlands and associated communities • Grassy woodlands containing white box, yellow box and grey box, *Callitris* spp. and other eucalypt species • Non-woody wetland ground cover such as nardoo and lignum	• Natural Grasslands on basalt and fine-textured alluvial plains of northern New South Wales and southern Queensland • Grey Box (*Eucalyptus microcarpa*) Grassy Woodlands and Derived Native Grasslands of South-eastern Australia • White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland	• Ephemeral wetlands dependent on local runoff • Rejected recharge can also contribute to subsurface soil water (Bell et al., 2012) • In the case of Lake Goran, large internal drainage basin with little regional connectivity (Environment Australia, 2001)	• Dependent on region and landscape position • Groundwater dependency tends to be local-regional and temporary. Surface water (local, temporary)
Human-modified	Irrigated agriculture concentrated around the Narrabri and Gunnedah formations and other floodplain systems	• Herbaceous pasture and crop species. Plantation tree species. Some small areas of remnant native vegetation	na	• Variable ranging from incident rainfall – dryland cropping and grazing to irrigated agriculture reliant on shallow and deep aquifers • Potential for groundwater dependency of plantations and deep-rooted perennial crops • Flooding may help to replenish subsoil moisture for farm systems on floodplains	Rainfall (local, intermittent); surface water (local-regional, temporary-near-permanent); groundwater (local-regional, temporary-near-permanent)
Rainforest	Small isolated pockets along creek lines and at higher elevations in east of the preliminary assessment extent	• 'Western dry rainforest' communities including 'semi-evergreen vine thicket' on basaltic soils and along creek lines • Wet sclerophyll forests at high elevations/high rainfalls	Semi-evergreen vine thickets of the Brigalow Belt (North and South) and Nandewar Bioregions	• Limited dependency on surface water • Potential for groundwater dependency along depressions and riparian areas (Kuginis et al., 2016)	Rainfall (local, intermittent); surface water (local-regional, temporary-near-permanent); groundwater (local-regional, temporary-near-permanent)

	Location	Associated communities	Listed ecological communities (EPBC Act)	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Dryland remnant vegetation	Upland areas (excluding floodplains and areas mapped as GDEs)	• Ironbark and bloodwood *Eucalyptus* dominated shrubby woodlands on sandstone and acid volcanic substrates • Large expanses of basalt-derived soils support grassy box woodland and native grasslands including those on the Liverpool Plains	• Brigalow (*Acacia harpophylla* dominant and co-dominant) • Grey Box (*Eucalyptus microcarpa*) Grassy Woodlands and Derived Native Grasslands of South-eastern Australia • Natural grasslands on basalt and fine-textured alluvial plains of northern New South Wales and southern Queensland	Reliant on locally stored soil water	Rainfall and runoff, (localised, temporary)
Springs	Occur across different landscapes including break of slopes, dissected volcanic formations, tablelands and alluvial plains	• Largely agricultural land with some springs occurring on remnant native vegetation	na	Maintained and defined by groundwater flow patterns from several different hydrogeologies including sandstones and volcanic basalts	Groundwater (ranging from localised to regional, both temporary and permanent)

[a]Spatial scale refers to the flow system and its predominant pattern at local (10^0 to 10^4 m^2), landscape (10^4 to 10^8 m^2) or regional (10^8 to 10^{10} m^2).
[b]Temporal scale of the water regime refers to the timing and frequency of the reliance on a particular water source.
EPBC Act = Commonwealth's *Environment Protection and Biodiversity Conservation 1999*, GDE = groundwater-dependent ecosystem, na = not applicable

2.3.3.2.1 ‘Floodplain or lowland riverine’ landscape group

Floodplains can be defined broadly as a collection of landscape and ecological elements exposed to inundation or flooding along a river system (Rogers, 2011). The floodplain landscapes of the Namoi PAE are predominantly lowland-dryland systems incorporating a range of wetland types such as riparian forests, marshes, billabongs, tree swamps, anabranches and overflows (Rogers, 2011). Landscape classes in the ‘Floodplain or lowland riverine’ landscape group occupy a land area of approximately 6% of the Namoi PAE, and make up around a quarter of the entire length of the stream network (Table 7 and Table 8). Figure 23 is an example of the distribution of landscape classes along typical floodplain areas along the Namoi River.

A riparian zone that fringes the river channel typifies floodplain landscapes along major rivers in the PAE such as the Namoi River. This riparian environment is represented by the ‘Floodplain riparian forest’ and ‘Floodplain riparian forest GDE’ landscape classes and is dominated by tree species such as river red gum (*Eucalyptus camaldulensis*) and river oak (*Casuarina cunninghamiana*; Figure 25) (Benson et al., 2010). The methodology used to ascertain groundwater dependency in the NSW GDE dataset (NSW Office of Water, Dataset 6) assumes that all riparian areas are groundwater dependent, thus most of these riparian landscapes were classified as ‘Floodplain riparian forest GDE’ (Table 7) (NSW DPI, 2016).

Adjacent to the riparian zone is the back plain environment, representing the transition between the frequently flooded river channel and the upland environment. This back plain environment contains floodplain woodlands and various types of wetlands with varying degrees of groundwater dependency (Figure 24 and Table 10) (Holloway et al., 2013). The back plain environment tends to be dominated by woodland species such as poplar box (*Eucalyptus populnea*), black box (*Eucalyptus largiflorens*), coolibah (*Eucalyptus coolabah*), river coobah (*Acacia stenophylla*) and other *Eucalyptus* spp., shrubs and grasses (most commonly plains grass – *Austrostipa aristiglumis)* (see Figure 25 for an example) (Eco Logical, 2009). Landscape classes occurring in the back plain environment include ‘Floodplain grassy woodland’ and ‘Floodplain grassy woodland GDE’. Flooding frequency, duration and depth tend to be reduced for the floodplain wetland landscape classes that tend to have a ‘temporary’ water regime (Figure 24 and Table 10).

Elements of the ‘Floodplain grassy woodland GDE’ landscape class tend to be interspersed along the riparian and back plain environments and groundwater use is influenced by access (depth to groundwater) and salinity (Table 10). Alluvial aquifers form in deposited sediments such as gravel, sand, silt and/or clay within the river channels or on the floodplain. Water is stored and transmitted to varying degrees through inter-granular voids; this means that aquifers are generally unconfined and shallow, and have localised flow systems (DSITI, 2015). Groundwater expressed at the surface supports ecosystems occupying drainage lines, riverine water bodies, lacustrine and palustrine wetlands.

Several listed ecological communities are found in the ‘Floodplain or lowland riverine’ landscape group areas including the ‘Coolibah - Black Box Woodlands of the Darling Riverine Plains and the Brigalow Belt South Bioregions’ (Table 10), listed under the Commonwealth’s *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act).

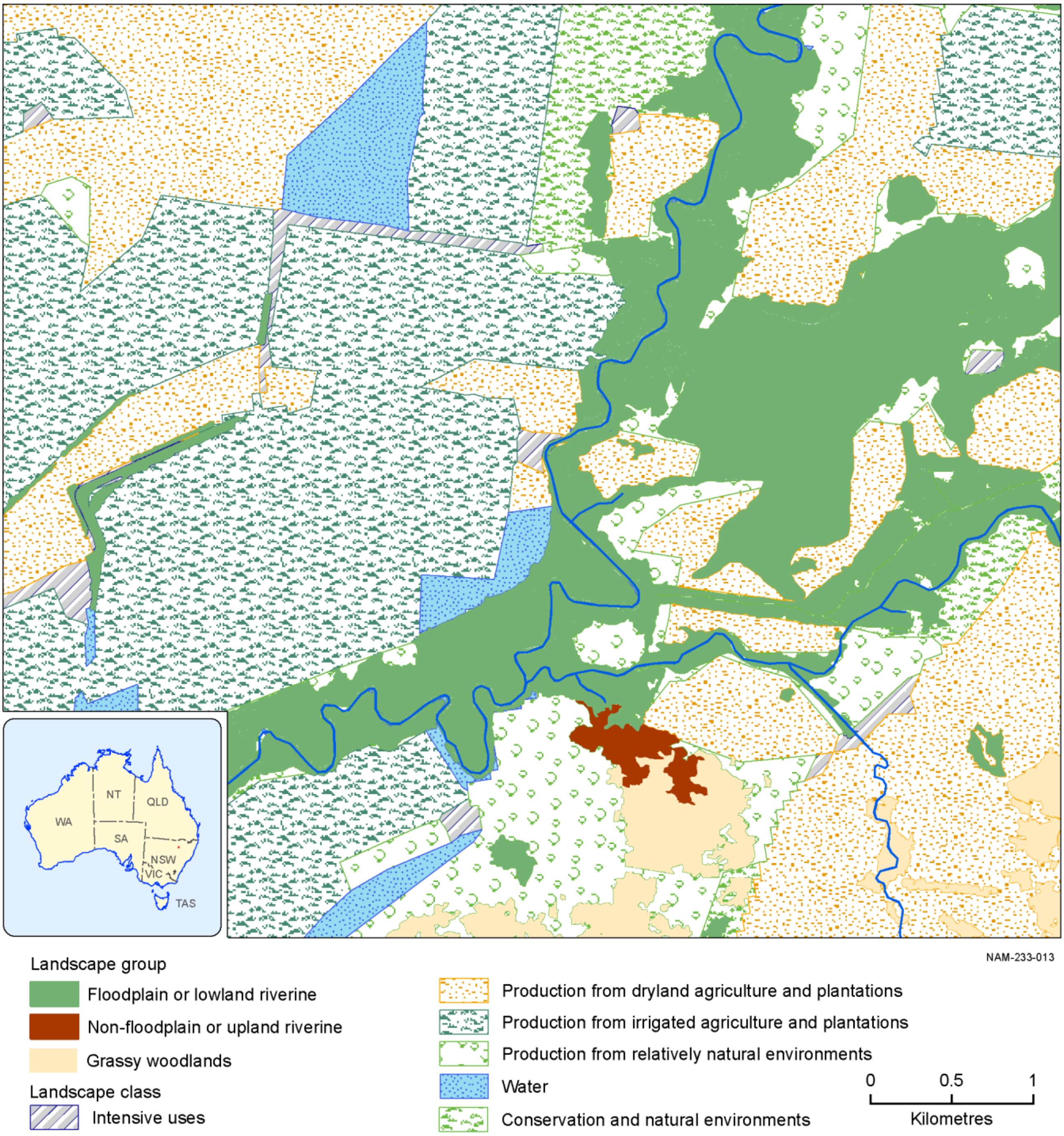

Figure 23 Landscapes along the Namoi River approximately 50 km west of Narrabri showing the 'Floodplain or lowland riverine' and 'Non-floodplain or upland riverine' landscape groups and landscape classes in the 'Human-modified' landscape group

Data: Bioregional Assessment Programme (Dataset 9)

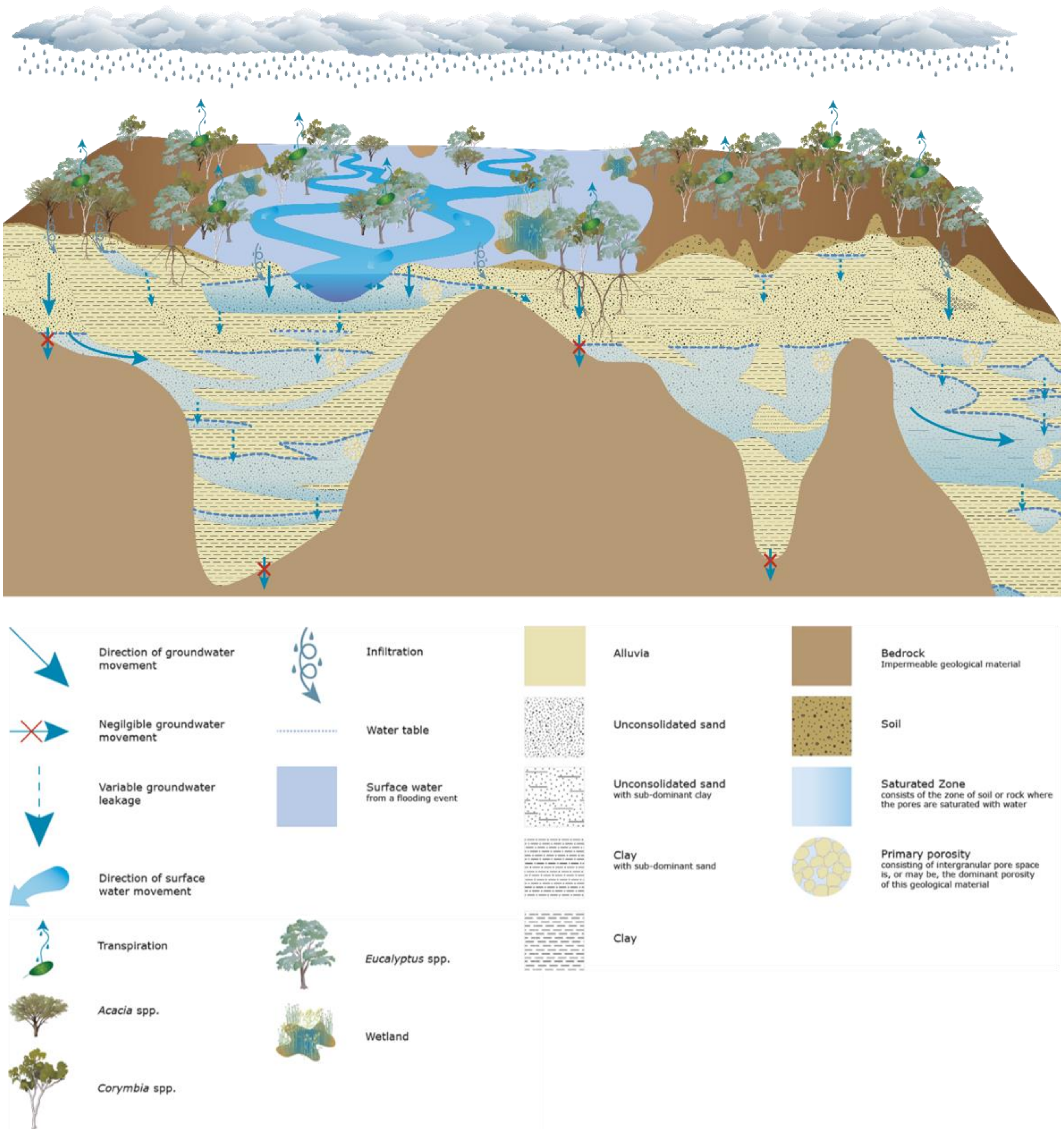

Figure 24 Pictorial conceptual model of a typical floodplain landscape with substantial alluvial development

The arrows indicate the direction of water movement, with the dashed arrow line indicating variable groundwater leakage and the crossed (red) arrow line indicating negligible groundwater movement. The blue dashed horizontal line indicates the position of the watertable within the cross-section.
Source: DEHP (2015a)
This figure has been optimised for printing on A3 paper (297 mm x 420 mm).

Figure 25 Floodplain landscape along the Namoi River typical of the 'Floodplain or lowland riverine' landscape group

(a) 'Permanent lowland stream' landscape class and adjacent 'Floodplain riparian forest' landscape class, (b) 'Floodplain grassy woodland' landscape class approximately 100 m from the river
Credit: Bioregional Assessment Programme, Patrick Mitchell (CSIRO), January 2016

2.3.3.2.2 'Non-floodplain or upland riverine' landscape group

The landscape classes in the 'Non-floodplain or upland riverine' landscape group include upland streams and wetlands that are not associated with floodplains. 'Non-floodplain wetland' and 'Non-floodplain wetland GDE' landscape classes on shrink-swell cracking clays of low permeability sometimes form 'tank gilgai' (meaning 'small waterhole' wetlands) and are common within the Pilliga Nature Reserve (Bell et al., 2012). These temporary wetlands are essentially small depressions within the Cenozoic clay deposits that are interspersed with mounds and depressions over relatively small distances (approximately 2 m; Chertkov, 2005). Spatial variation in infiltration occurs as these clays swell when wet, causing cracks to close and water to pool on the surface (Chertkov, 2005). The wetlands tend to occur within a mosaic of woodlands and shrublands largely dominated by buloke (*Allocasuarina luehmannii*), *Eucalyptus chloroclada, Eucalyptus pilligaensis, Eucalyptus sideroxylon* and *Melaleuca densispicata* (Benson et al., 2010). They are commonly fringed by buloke and various sedge, rush and other herbaceous plant communities (Bell et al., 2012). The nature of wet and dry phases within these wetlands is determined by localised runoff from rainfall, which means that their dependency on flow systems at larger scales is likely to be negligible (Table 10).

Figure 26 A dry gilgai wetland near the Pilliga Scrub in the Namoi subregion

Credit: Bioregional Assessment Programme, Patrick Mitchell (CSIRO), January 2016

Goran Lake is a different type of non-floodplain wetland in the southern part of the PAE and is listed in *A directory of important wetlands* (Environment Australia, 2001) and the asset register for the BA of the Namoi subregion (Bioregional Assessment Programme, Dataset 8). This wetland is characterised as having a large internal drainage basin (>6000 ha) and historically has been an ephemeral system (filled once in 20 years) until recent diversions of two creek systems have shifted the lake towards semi-permanence (Environment Australia, 2001). The lake supports several ground cover species including nardoo (*Marsilea drummondii*), narrow-leaved cumbungi (*Typha domingensis*) and lignum (*Muehlenbeckia florulenta*), and a narrow band of riparian woodland species (e.g. river red gum) (Environment Australia, 2001).

Terrestrial GDEs (those that rely on the subsurface presence of groundwater) and surface GDEs (those that rely on the surface expression of groundwater) across the non-floodplain areas of the PAE are diverse and are represented by ‘Non-floodplain wetland GDE’, ‘Grassy woodland GDE’, ‘Upland riparian forest GDE’, ‘Temporary upland stream GDE’, and ‘Permanent upland stream GDE’ landscape classes. For example, the ‘Grassy woodland GDE’ landscape class is found along the eastern portion of the Namoi PAE and may be associated with basalt or permeable rock types where groundwater is transmitted and stored through fractures, inter-granular spaces or weathered zones, and is typically discharged to the surface at contact zones between two rock types (Figure 28 and Figure 29) (DSITI, 2015). The other significant expanse of the ‘Grassy woodland GDE’ landscape class is found in the Pilliga Nature Reserve. This large remnant of vegetation was once grazed and selectively harvested for timber (ironbark sleepers and cypress pine sawlogs) until being a reserve in the latter 20th century (Norris, 1996). The underlying geology is dominated by the Pilliga Sandstone and other sedimentary outcrop areas (Rolling Downs and Blythesdale formations). Although NSW Office of Water (NSW Office of Water, Dataset 6) and GDE Atlas (Bioregional Assessment Programme, Dataset 7) mapping show a significant extent of this landscape class, limited ground-validated information exists on the nature of the vegetation’s relationship with groundwater across the landscape. The most likely areas where there is a high likelihood of groundwater dependency would be along drainage lines and riverine landscapes (i.e. Bohena Creek, Figure 27) and where groundwater might be expressed at the surface from zones of rejected recharge (see Table 10).

Figure 27 Bohena Creek and riparian vegetation in the Pilliga Nature Reserve

Credit: Bioregional Assessment Programme, Patrick Mitchell (CSIRO), January 2016

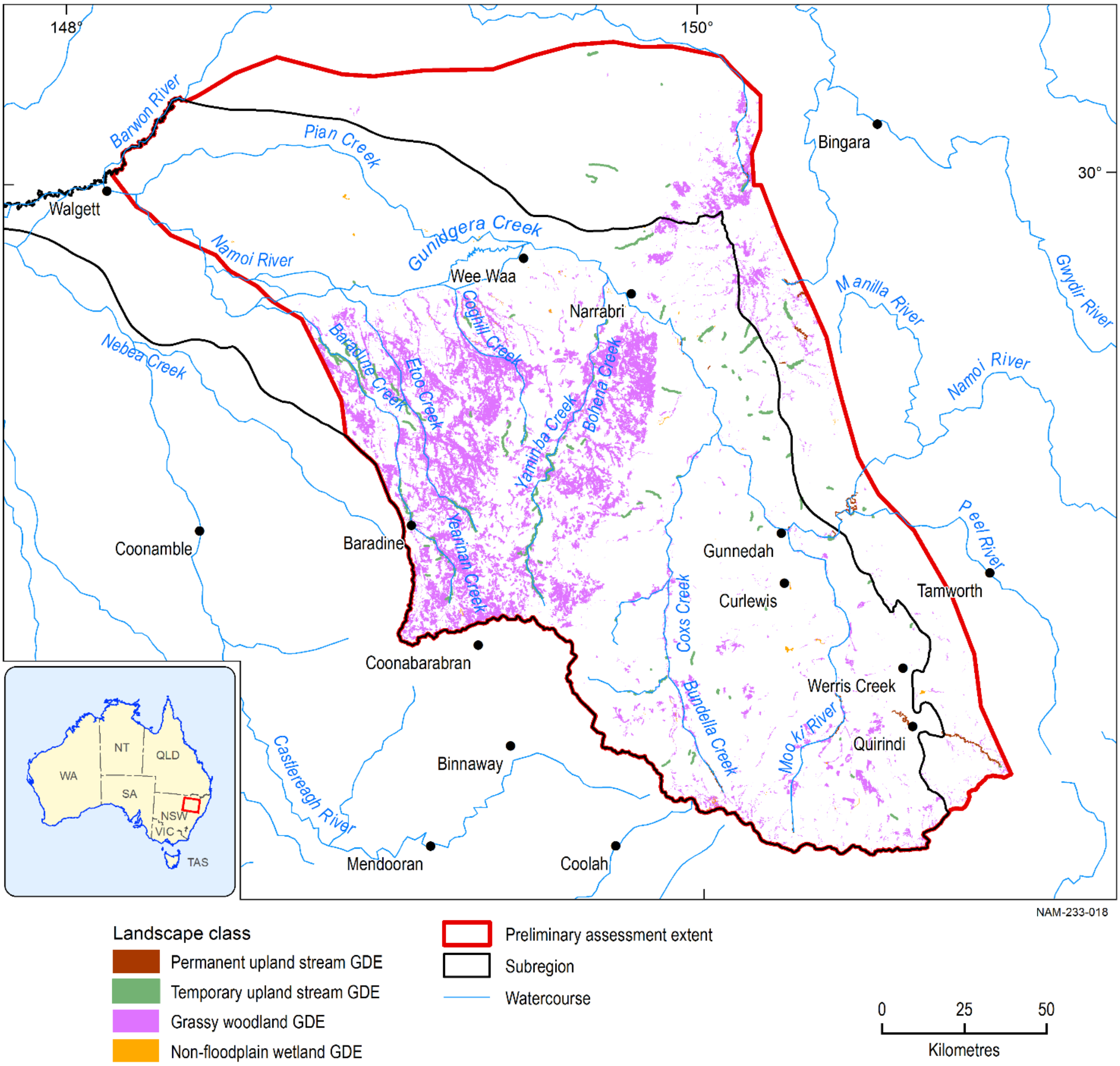

Figure 28 Non-floodplain groundwater-dependent ecosystems in the Namoi preliminary assessment extent

Non-floodplain groundwater-dependent ecosystems (GDEs) include remnant vegetation ('Grassy woodland GDE' landscape class), wetland ('Non-floodplain wetland GDE' landscape class) and riverine GDEs ('Permanent upland stream GDE' and 'Temporary upland stream GDE' landscape classes).
Data: Bioregional Assessment Programme (Dataset 9)

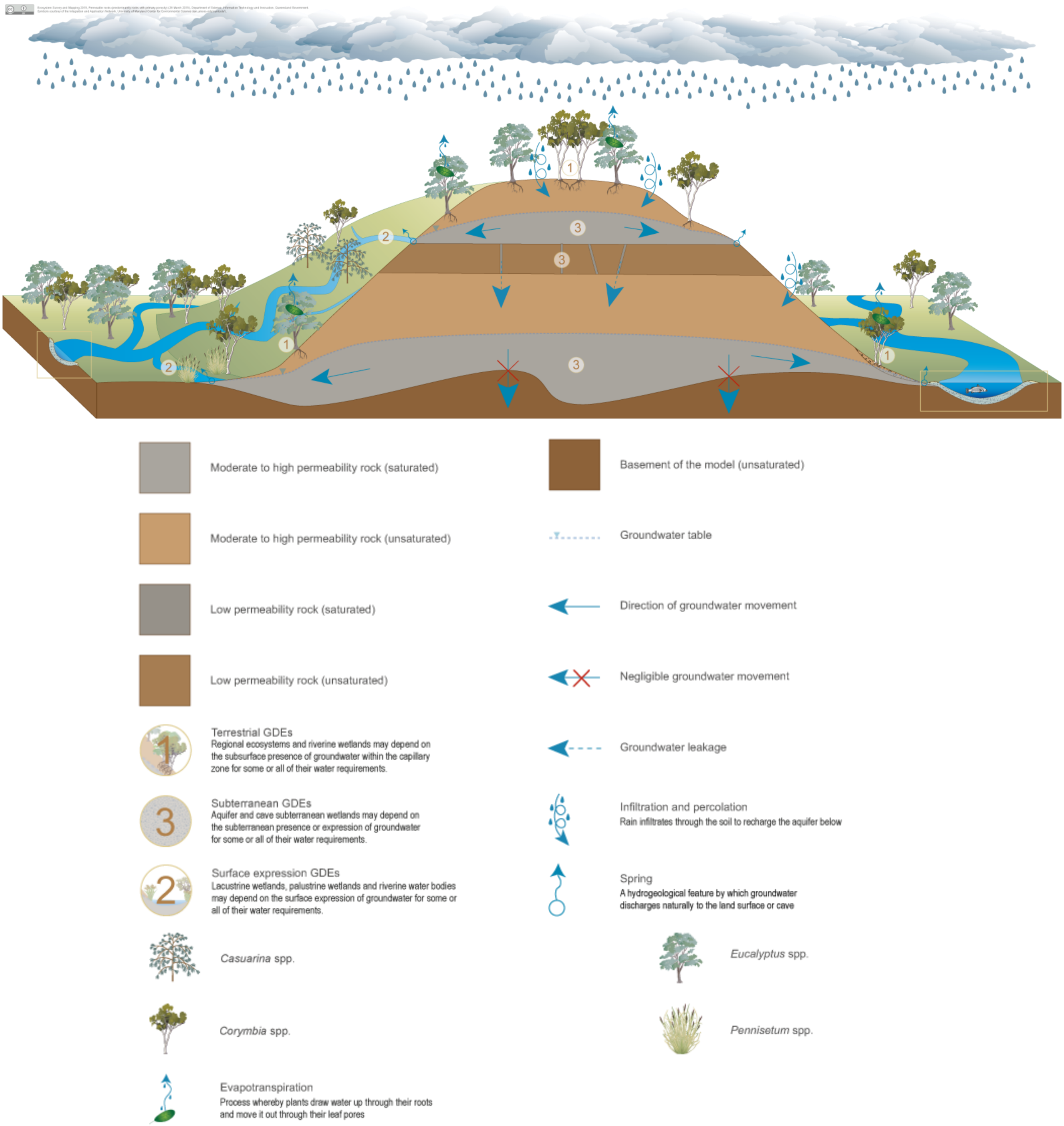

Figure 29 Pictorial conceptual models of groundwater-dependent ecosystems associated with permeable rock (basalt) types

These systems are typical of those landscapes that form on basaltic (volcanic) rocks in the east of the Namoi subregion.
GDE = groundwater-dependent ecosystem
Source: DEHP (2015b)

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

2.3.3.2.3 'Springs' landscape group

GAB springs in the Namoi subregion are surface expressions of groundwater sourced from aquifers contained in the Jurassic and Cretaceous sedimentary sequences associated with the GAB (Habermehl, 1982). Spring ecosystems contain many locally endemic species and plant communities and have significant ecological, economic and cultural values (Fensham and Fairfax, 2003). In the Namoi PAE there are no artesian spring communities listed under the EPBC Act, but there is one artesian spring community listed under NSW's *Threatened Species Conservation Act 1995* known to occur on the Liverpool Plains. Several of the springs identified in the 'GAB springs' landscape class are likely to be 'recharge' springs. Recharge springs form where the sediments that make up the aquifers of the GAB have surface expressions and tend to be situated within the recharge zones of the eastern margin of the GAB (Figure 30) (Fensham and Fairfax, 2003), such as the sandstone layers underlying the Pilliga Scrub (NSW Department of Water and Energy, 2009).

Springs in the 'Non-GAB springs' landscape class occur in the groundwater management area outside of the GAB (Figure 22). These springs are located in groundwater aquifers located within the Oxley Basin, New England Fold Belt, Peel Valley Fractured Rock and Warrumbungle Basalt.

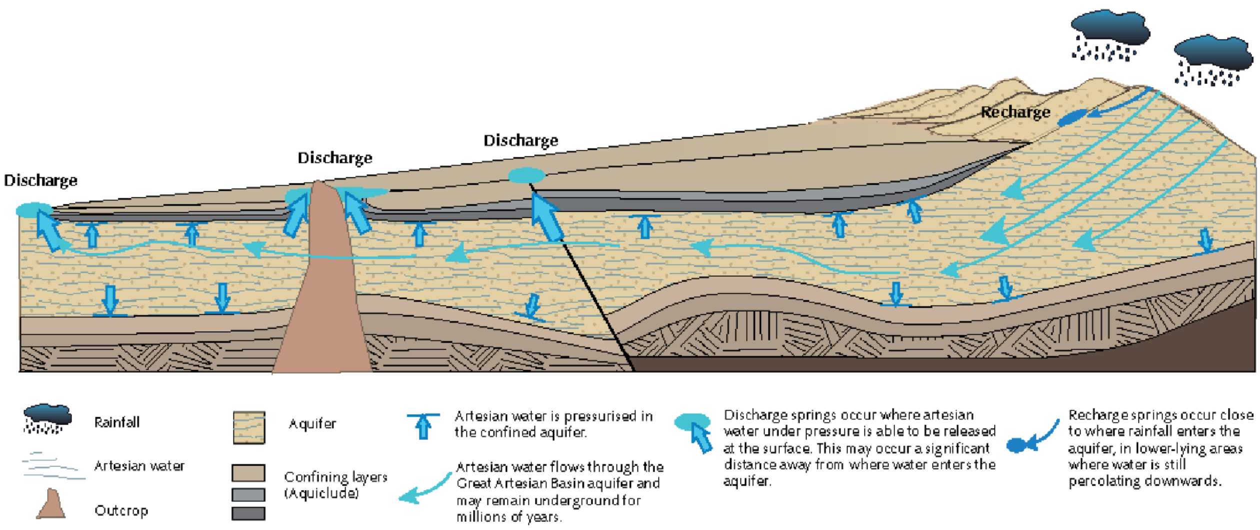

Figure 30 Pictorial representation of the hydrogeological characteristics of recharge and discharge springs associated with the Great Artesian Basin aquifers

Source: DEHP (2013)

2.3.3.2.4 'Rainforest' landscape group

The 'Rainforest' landscape group is distinguished primarily by its vegetation structure and composition. Rainforests were identified based on Keith's vegetation classification system, where 'vegetation formation' is the top level of the hierarchy, and included the 'rainforest' and 'wet sclerophyll' vegetation formations (Keith, 2004). The 'wet sclerophyll' vegetation formation makes up less than 300 ha of the Namoi PAE, whereas most of the 'Rainforest' landscape group comprises the 'rainforest' vegetation formation making up approximately 20,000 ha of the Namoi PAE. 'Rainforests' are defined as forests with a closed canopy generally dominated by non-eucalypt species with soft, horizontal leaves, however various eucalypt species may be present as emergents (Keith, 2004). The ‘Rainforest’ landscape group is predominately ‘Dry rainforest’ or ‘Western vine thickets’ (both threatened vegetation classes in NSW). They tend to occupy upland riparian habitats and higher elevations in the eastern and southern regions of the Namoi PAE within sheltered positions areas such as Mount Kaputar (Figure 20) (Benson et al., 2010). They are predominately associated with basaltic substrates, but also riverine alluvium, sandstones and granites. The water dependency of the ‘Rainforest’ landscape group is likely to be mostly from localised surface runoff, and in the case of ‘Rainforest GDE’ landscape class, from groundwater sourced from localised discharge from fractured or porous substrates (see Figure 29 for a conceptual overview).

2.3.3.2.5 ‘Human-modified’ landscape group

Most of the PAE (59%) is dominated by human-modified landscapes used for agricultural production, mining and urban development (Table 7). The water dependency of the landscape classes derived from this landscape group ranges from a heavy dependence on groundwater and surface water extracted from nearby aquifers and streams (e.g. ‘Intensive uses’ and ‘Production from irrigated agriculture and plantations’ landscape classes), through to dryland cropping and grazing reliant on incident rainfall and local surface water runoff (e.g. ‘Production from dryland agriculture and plantations’ landscape class) (Table 10). Deep-rooted vegetation, such as tree plantations, may tap into groundwater within certain landscapes. Intensive areas, such as townships, often have a strong reliance on groundwater and surface water via bores and river offtakes.

Figure 31 A typical human-modified landscape: 'Production from irrigated agriculture and plantations' landscape class near the Mooki River in the southern part of the Namoi preliminary assessment extent

Credit: Bioregional Assessment Programme, Patrick Mitchell (CSIRO), January 2016

2.3.3.2.6 'Dryland remnant vegetation' landscape group

The 'Dryland remnant vegetation' landscape group represents a large component of those landscapes classified as 'remnant' in the NSW regional native vegetation mapping (SEWPaC, Dataset 4). The associated communities are highly variable and cover many different types of woodland, shrubland and grassland (Table 10, Figure 32). The 'White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland' threatened ecological community listed under the EPBC Act occurs across a large part of the Namoi PAE (excluding eastern regions and Pilliga Nature Reserve) and is largely classified as 'Grassy woodlands' as well as being distributed across those landscape classes thought to be water dependent (e.g. occurring on floodplains and groundwater dependent). The term 'dryland' implies that this landscape group is reliant on incident rainfall and local runoff and does not include features in the landscape that have potential hydrological connectivity to surface or groundwater features.

(a) (b)

Figure 32 Two examples of remnant vegetation communities classified in the 'Dryland remnant vegetation' landscape group in the Namoi preliminary assessment extent

(a) white cypress pine – white box woodland ('Grassy woodland' landscape class) in the Doona State Forest, (b) narrow-leaved ironbark – forest oak – white cypress pine woodland in the Pilliga Nature Reserve
Credit: Bioregional Assessment Programme, Patrick Mitchell (CSIRO), January 2016

2.3.3.3 Gaps

A pertinent issue for the landscape classification component of the BA is formulating a topology that adequately reflects both the functional and structural complexity of the ecosystems, while delivering a succinct and consistent representation of the system that is 'fit for purpose'. The systematic classification of the Namoi subregion undertaken here imposes discrete boundaries among landscape elements that may not adequately capture gradients within and across landscape classes. This approach tends to simplify important components of landscapes such as 'transition' zones or edges between landscape classes where key ecosystem processes and/or biodiversity are likely to peak. If landscape classes are treated purely as 'closed' ecosystems, the role of biotic interactions and energy exchange between adjacent systems may be poorly captured in our impact assessment. These conceptual challenges may not be readily overcome given the scope and scale of this assessment, but are important considerations for the subsequent stages of the risk analysis.

There are several technical issues that constitute important gaps in the landscape classification. Two different approaches to define GDEs were employed because the NSW Office of Water mapping (NSW Office of Water, Dataset 6) only included terrestrial vegetation and did not include riverine systems mapped within the stream network. Hence, the GDE Atlas (Bioregional Assessment Programme, Dataset 7) was used to classify the stream network as being potentially dependent on groundwater. The other obvious gap is that all GDE mapping and classification approaches lack systematic ground-truthing. This is especially true in areas with extensive intact native remnants, such as the Pilliga Forest, where large areas of 'Grass woodland GDE' landscape class were identified but the lack of published studies on vegetation – groundwater interactions limits the Assessment team's ability to define the nature of this interaction.

Close inspection of the ANAE wetland mapping (ABARES, Dataset 2) and the NSW regional native vegetation mapping (NSW OEH, Dataset 3) revealed some mismatches, therefore data were combined where appropriate.

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2.3.4 Coal resource development pathway

Summary

The coal resource development pathway (CRDP) for the Namoi subregion consists of six baseline coal mines and ten additional coal resource developments. There are five baseline open-cut coal mines: Boggabri Coal Mine, Rocglen Mine, Sunnyside Mine, Tarrawonga Mine and Werris Creek Mine, and one underground, longwall coal mine, Narrabri North. The ten additional coal resource developments are Boggabri Coal Expansion Project, Caroona Coal Project, Gunnedah Precinct, Maules Creek Mine, Narrabri South, Tarrawonga Coal Expansion Project, Vickery Coal Project, Vickery South Coal Project, Watermark Coal Project and Narrabri Gas Project. Eight of these additional coal resource developments are being modelled under the CRDP for the Namoi subregion: the open-cut Boggabri Coal Expansion Project, Tarrawonga Coal Expansion Project, Maules Creek Mine, Vickery Coal Project and Watermark Coal Project; the underground coal mines Caroona Coal Project and Narrabri South; and the Narrabri Gas Project. The remaining two mines, Vickery South Coal Project (open-cut coal mine) and the Gunnedah Precinct (open-cut and underground), are not being modelled due to insufficient information regarding the location and depth of mining. The Caroona Coal Project was discontinued in 2016. However, in accordance with companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis, 2014), the project is included in the Assessment.

Detailed information on water management was only available for four of the baseline coal mines and six of the additional coal resource developments. The water management plans for these coal resource developments shared common elements such as diversion of surface water around the mine site where possible, and any water retained in the mine area will be used for mining or related operational purposes (this includes groundwater pumped to dewater mine). Progressive rehabilitation of mined-out areas is also commonly occurring as mining advances. Thus, the amount of surface water that is disconnected from a catchment and groundwater that is extracted from the system will vary during the life of the mine.

2.3.4.1 Developing the coal resource development pathway

The *coal resource development pathway* (CRDP) is a fundamental concept in bioregional assessments (BAs), and an important initial step in the model-data analysis component of any BA. It defines the most likely future that includes all coal mines and coal seam gas (CSG) fields commercially producing as of December 2012 (known as the *baseline*), as well as those expected to commence production in the foreseeable future. The difference in results between the baseline and the CRDP is the change that is primarily reported in a BA, and this is due to the *additional coal resource development*. The additional coal resource development is defined as all coal mines and CSG fields, including expansions of baseline operations, that are expected to begin commercial production after December 2012.

The general input data and analysis required to develop the CRDP are outlined in companion submethodology M04 (as listed in Table 1) for developing a CRDP (Lewis, 2014). This section explains the specific application of this BA submethodology to the Namoi subregion, and builds upon the coal and CSG resource assessment provided in companion product 1.2 for the Namoi subregion (Northey et al., 2014). The CRDP for the Namoi subregion consists of 16 baseline and additional coal resource developments (Table 11). The locations of these baseline and additional new development projects are shown in Figure 33.

There are six baseline coal mines in the Namoi subregion, five of which are operational coal mines: Boggabri Coal Mine, Narrabri North Mine, Rocglen Mine, Tarrawonga Mine and Werris Creek Mine. The Sunnyside Mine is no longer operational and was placed in care and maintenance in October 2012. The future time frame for this mine to become operational again (if at all) is currently unknown.

Ten additional coal resource developments are included in the CRDP for the Namoi subregion. Of these, nine are new coal mine developments or expansion projects in the Namoi subregion: the Boggabri Coal Expansion Project, Caroona Coal Project, Gunnedah Precinct, Maules Creek Mine, Narrabri South, the Tarrawonga Coal Expansion Project, Vickery Coal Project, Vickery South Coal Project and Watermark Coal Project (Table 11). The Vickery Coal Mine originally operated from 1986 to 1991 as an underground mine and from 1991 to 1998 as an open-cut mine. The site was reopened in 2008 for exploration, environmental monitoring and rehabilitation and put into care and maintenance in 2012. However, the mine was recently given approval by the New South Wales Government (NSW Government) to be reopened. The Vickery Coal Mine is therefore considered to be an additional coal resource development. There is one CSG project, the Narrabri Gas Project (Table 11), that is included in the CRDP as an additional coal resource development. Summary information about each coal resource development included in the baseline and the additional coal resource development is provided in Table 11, including company name, total identified resources, and expected start year and duration of mining. Further details about each of these coal resource developments, including plans of several mine sites, are available in companion product 1.2 for the Namoi subregion (Northey et al., 2014).

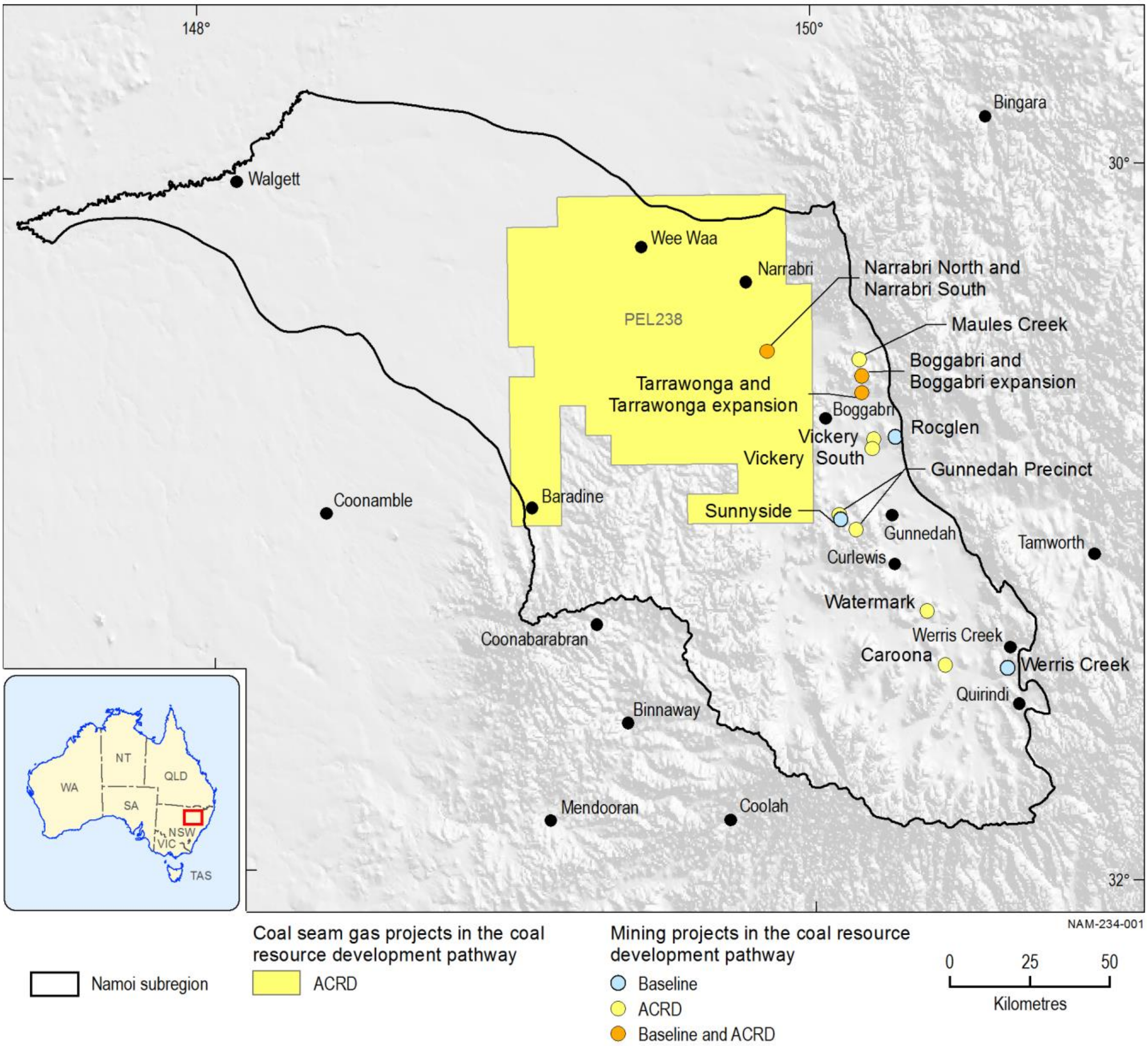

Figure 33 Coal and coal seam gas developments in the coal resource development pathway for the Namoi subregion

There are three developments that are both baseline mines and additional coal resource developments on this map: Boggabri, Tarrawonga and Narrabri North are the baseline mines. Boggabri expansion, Tarrawonga expansion and Narrabri South are the additional coal resource developments. The coal resource developments in the CRDP are the sum of those in the baseline coal resource development (baseline) and the additional coal resource development.

ACRD = additional coal resource development, CRDP coal resource development pathway

Refer to Table 11 for a list of all baseline and additional coal resource developments in the CRDP.

The coal seam gas projects extent includes the exploration lease area.

Data: Geoscience Australia (Dataset 1), NSW Trade and Investment (Dataset 2)

Table 11 Summary of baseline and additional coal resource developments included in the coal resource development pathway as of December 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 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.

Name of coal resource development	Coal mine or coal seam gas (CSG) operation	Company	Included in baseline?	Included in CRDP? (modelled or commentary)	Start of mining operations or estimated project start	Expected end date of commercial operations	Tenement(s)	Total coal resources (Mt)[a] (for coal mining) or 2P gas reserves (PJ)[b] (for CSG)	Comments
Boggabri Coal Mine	Open-cut coal mine	Idemitsu Australia Resources, Chugoku Electric Power Australia Resources, NS Boggabri	Yes	Yes – modelled	2006	2012	CL 368	NA – resource estimate provided for expansion project[c]	Operational mine as of December 2015, merged with expansion project.
Narrabri North Mine	Underground coal mine (longwall mining)	Whitehaven Coal, J Power, EDF Trading, Upper Horn Investments, Daewoo International and Korea Resources Corporation	Yes	Yes – modelled	2010	2035	ML 1609, EL 6243	730 Mt[d]	Operational mine as of December 2015. Total coal resource for Narrabri North and South is 160 Mt measured, 390 Mt indicated and 180 Mt inferred. Coal information in Whitehaven Coal (2015).

Name of coal resource development	Coal mine or coal seam gas (CSG) operation	Company	Included in baseline?	Included in CRDP? (modelled or commentary)	Start of mining operations or estimated project start	Expected end date of commercial operations	Tenement(s)	Total coal resources (Mt)[a] (for coal mining) or 2P gas reserves (PJ)[b] (for CSG)	Comments
Rocglen Mine	Open-cut coal mine	Whitehaven Coal	Yes	Yes – modelled	2009	2019	ML 1620	15 Mt[e]	Operational mine as of December 2015. Total coal resource for Rocglen resource is 7 Mt measured, 7 Mt indicated and 1 Mt inferred, however this includes both open-cut and underground resources. There is no further information regarding the underground coal resource, so development of this resource is not included in the CRDP and will not be modelled. Coal information in Whitehaven Coal (2015).
Sunnyside Mine	Open-cut coal mine	Whitehaven Coal	Yes	Yes – modelled	2008	2012	ML 1624	na – mine closed	Mine is under care and maintenance as of October 2012. No plans for an extension or re-opening of the mine have been made.
Tarrawonga Mine	Open-cut coal mine	Whitehaven Coal	Yes	Yes – modelled	2006	2012	ML 1579	NA – resource estimate provided for expansion project	Operational mine as of December 2015, merged with expansion project.

Name of coal resource development	Coal mine or coal seam gas (CSG) operation	Company	Included in baseline?	Included in CRDP? (modelled or commentary)	Start of mining operations or estimated project start	Expected end date of commercial operations	Tenement(s)	Total coal resources (Mt)[a] (for coal mining) or 2P gas reserves (PJ)[b] (for CSG)	Comments
Werris Creek Mine	Open-cut coal mine	Werris Creek Coal (subsidiary of Whitehaven Coal)	Yes	Yes – modelled (SW)/ commentary (GW)	2005	2020	ML 1563, ML 1672	22 Mt	Operational mine as of December 2015. Total coal resource is 18 Mt measured and 4 Mt indicated. The Werris Creek Mine is located in the Werrie Basin, to the east of the Hunter-Mooki Thrust Fault System, and consequently the mine is not included in the geological or hydrogeological model. However, the alluvium and the surface water system are connected over the Hunter-Mooki Thrust Fault System, so the mine is able to be modelled in the surface water model. Coal information in Whitehaven Coal (2015).
Boggabri Coal Expansion Project	Open-cut coal mine	Idemitsu Australia Resources, Chugoku Electric Power Australia Resources, NS Boggabri	No	Yes – modelled	2013	2033	CL 368	576 Mt	Approval for expansion finalised in February 2013, preliminary construction works started November 2014. Total coal resource for Boggabri is 576 Mt (Geoscience Australia, Dataset 1).

Name of coal resource development	Coal mine or coal seam gas (CSG) operation	Company	Included in baseline?	Included in CRDP? (modelled or commentary)	Start of mining operations or estimated project start	Expected end date of commercial operations	Tenement(s)	Total coal resources (Mt)[a] (for coal mining) or 2P gas reserves (PJ)[b] (for CSG)	Comments
Caroona Coal Project	Underground coal mine (longwall mining)	NSW Energy Coal (BHP Billiton)	No	Yes – modelled	2020	2045	ELA 6505	260 Mt[f]	In August 2016, BHP decided to discontinue its proposed development of the Caroona Coal Mine and sell the exploration licence back to the NSW Government. However, as per the companion submethodology (as listed in Table 1) for developing a CRDP (Lewis, 2014), once the CRDP is determined, it is not changed in this iteration of the BA. This means that the timeline described for the project will continue to form the basis for the groundwater modelling.
Gunnedah Precinct	Open-cut and underground coal mine	Whitehaven Coal	No	Yes – commentary	Unknown	Unknown	CCL 701, ML 1624, EL 5183	307 Mt	Total coal resource for Gunnedah Precinct resource (includes open-cut and underground) is 9 Mt measured, 185 Mt indicated and 113 Mt inferred. Not able to be modelled in this iteration of the BA for the Namoi subregion as there are no development plans or information available. Coal information in Whitehaven Coal (2015).
Maules Creek Mine	Open-cut coal mine	Whitehaven Coal, ICRA MC, J Power Australia	No	Yes – modelled	2015	2035	CL 375, AUTH 346, EL 8072	650 Mt	Total coal resource is 330 Mt measured, 270 Mt indicated and 50 Mt inferred. Coal information in Whitehaven Coal (2015).

Name of coal resource development	Coal mine or coal seam gas (CSG) operation	Company	Included in baseline?	Included in CRDP? (modelled or commentary)	Start of mining operations or estimated project start	Expected end date of commercial operations	Tenement(s)	Total coal resources (Mt)[a] (for coal mining) or 2P gas reserves (PJ)[b] (for CSG)	Comments
Narrabri South	Underground coal mine (longwall mining)	Whitehaven Coal	No	Yes – modelled	2030[g]	2054	EL 6243	NA – see estimate for Narrabri North	Total coal resource for Narrabri North and South is 160 Mt measured, 390 Mt indicated and 180 Mt inferred. Coal information in Whitehaven Coal (2015).
Tarrawonga Coal Expansion Project	Open-cut coal mine	Whitehaven Coal for Tarrawonga Joint Venture	No	Yes – modelled	2015	2031	ML 1579, EL 5967, ML 1685, ML 1693	118 Mt[h]	Total coal resource (for Tarrawonga plus expansion) is 58 Mt measured, 33 Mt indicated and 27 Mt inferred. Coal information in Whitehaven Coal (2015).
Vickery Coal Project	Open-cut coal mine	Whitehaven Coal	No	Yes – modelled	2018[i]	2047	CL 316, AUTH 406 ML 1464, ML 1471, ML 1620	735 Mt[j]	Total coal resource for Vickery is 230 Mt measured, 260 Mt indicated and 245 Mt inferred. Coal information in Whitehaven Coal (2015).
Vickery South Coal Project (also known as Vickery expansion)	Open-cut coal mine	Whitehaven Coal	No	Yes – commentary	Unknown	Unknown	EL 7407, ML 1718	111.2 Mt	Not able to be modelled in this iteration of the BA for the Namoi subregion – insufficient information available. Resource likely to be combined with the Vickery Project. Total coal resource for Vickery South is 91 Mt measured, 0.2 Mt indicated and 20 Mt inferred (Geoscience Australia, Dataset 1).
Watermark Coal Project	Open-cut coal mine	Shenhua Watermark	No	Yes – modelled	2018	2047	EL 7223	291.5 Mt[k]	Project approved in 2015.

Name of coal resource development	Coal mine or coal seam gas (CSG) operation	Company	Included in baseline?	Included in CRDP? (modelled or commentary)	Start of mining operations or estimated project start	Expected end date of commercial operations	Tenement(s)	Total coal resources (Mt)[a] (for coal mining) or 2P gas reserves (PJ)[b] (for CSG)	Comments
Narrabri Gas Project	CSG	Santos Ltd	No	Yes – modelled	2017	2042 (25 year life span)	PEL 238, PAL 2, PPL 3	186 PJ[l]	EIS in preparation.

[a]This is the most recent economically demonstrated resource estimate (measured, indicated, inferred) reported as being compliant with the Joint Ore Reserve Committee (JORC) Code, unless otherwise stated.
[b]This is based on the Petroleum Resource Management System of the Society of Petroleum Engineers code 2P, which refers to estimated quantities of proved reserves plus probable reserves.
[c]A JORC compliant estimate was not available for this project. An updated estimate is provided for the Boggabri expansion.
[d]This resource estimate is for Narrabri North and South, defined by Whitehaven Coal as Narrabri underground.
[e]This resource assessment includes Rocglen open-cut and Rocglen underground.
[f]JORC compliant estimate is not available for Caroona. This is an estimate of the production of run-of-mine coal over the life of the mine (BHP Billiton, 2014).
[g]Narrabri South is presumed to start once Narrabri North has been mined out and mined at the same rate as Narrabri North.
[h]This resource assessment is listed as including Tarrawonga open-cut and Tarrawonga underground.
[i]Whitehaven Coal have indicated it will start the Vickery Project when the Maules Creek Mine is at full production, which is predicted to be in 2018.
[j]This is reported as the total resource for Vickery open-cut and Vickery underground.
[k]GHD and Hansen Bailey (2013).
[l]Santos (2014).
AUTH = authorisation, BA = bioregional assessment, CCL = consolidated coal lease, CL = coal lease, CRDP = coal resource development pathway, CSG = coal seam gas, EIS = environmental impact statement, EL = exploration licence, ELA = exploration licence application, GW = groundwater, ML = mining lease, NA = not available, na = not applicable, PAL = petroleum assessment lease, PEL = petroleum exploration licence, PPL = petroleum production lease, SW = surface water
Full company names are: Chugoku Electric Power Australia Resources Pty Ltd (Chugoku Electric Power Australia Resources), EDF Trading Limited (EDF Trading), Idemitsu Australia Resources Pty Ltd (Idemitsu), J Power Electric Power Development Co., Ltd (J Power), NS Boggabri Pty Ltd (NS Boggabri), Shenua Watermark Coal Pty Limited (Shenhua Watermark), Upper Horn Investments Pty Ltd (Upper Horn Investments), Werris Creek Coal Pty Ltd (Werris Creek Coal), Whitehaven Coal Limited (Whitehaven Coal).

2.3.4.1.1 Quantitative assessment of hydrological changes under the coal resource development pathway

The CRDP for the Namoi subregion describes the most likely future for coal resource development, based on the Assessment team's analysis of publicly available information and expert consultation undertaken in early 2015. This CRDP forms the basis for the subsequent hydrological modelling for the BA (of both surface water and groundwater), which attempts to quantify the hydrological changes of the expected coal resource development. However, in order to undertake the numerical hydrological modelling specified for the BAs (see companion submethodology M06 for surface water modelling (Viney, 2016) and companion submethodology M07 for groundwater modelling (Crosbie et al., 2016)), there are minimum levels of data and information required for each coal resource development in the CRDP.

The data requirements for both surface water and groundwater modelling in BAs are outlined in companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (refer to Table 9 in Lewis (2014)). Information required for hydrological modelling in BAs includes details of the type of coal resource extraction operation (e.g. open-cut, underground or combined development mine), time series of the progression of mining and associated infrastructure areas (both in area and with depth), and the nature of the mine-site stratigraphy and depth to watertable.

Of the 16 coal resource developments in the CRDP, 13 coal mines and one CSG project are considered by the Assessment team to have sufficient information available to be quantitatively assessed through numerical modelling. The coal resource developments being modelled are Boggabri Coal Mine and Boggabri Coal Expansion Project, Caroona Coal Project, Maules Creek Mine, Narrabri Gas Project, Narrabri North Mine, Narrabri South, Rocglen Mine, Sunnyside Mine, Tarrawonga Mine and Tarrawonga Coal Expansion Project, Vickery Coal Project, Watermark Coal Project, and Werris Creek Mine (surface water modelling only). The scheduling of these coal mines and the CSG project is shown in Figure 34. These coal resource developments are the most advanced in the Namoi subregion in terms of progressing through the various environmental and mining-related approvals processes that apply under relevant NSW and Australian Government legislation. Most of these mines have previously undertaken detailed planning and development studies to determine optimal mining and production methods. Importantly, much of the required information for BA modelling purposes has been made publicly available as part of environmental impact statements (EISs), or similar documents, for the individual coal resource developments.

A decision by the NSW Government (11 August 2016) to buy back the Caroona mining exploration licence from BHP Billiton effectively means that future development of coal mining in this lease area near the township of Caroona (Exploration Licence 6505) is highly unlikely. However, it is important to state that, as per companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis, 2014), once the CRDP is determined, it is not changed for this iteration of the BA, even in cases such as this where BHP Billiton have now discontinued their exploration operations in the Namoi subregion.

2.3.4.1.2 Qualitative assessment of hydrological changes under the coal resource development pathway

Of the ten additional coal resource developments in the CRDP, two coal mines are currently much less advanced in their mine development planning and assessment studies under the relevant regulatory approvals processes; these are the Gunnedah Precinct and the Vickery South Coal Project. They have been included in the CRDP, consistent with the methods outlined in companion submethodology M04 (as listed in Table 1) for developing the coal resource development pathway (Lewis, 2014). However, as there is scant information publicly available about the nature and time frame of future development plans for these additional coal resource developments, these two mines have been excluded from the hydrological modelling for the BA. The assessment of the impacts of the Gunnedah Precinct and Vickery South Coal Project will be limited to qualitative assessment in companion product 3-4 (impact and risk analysis) for the Namoi subregion.

Finally, it is worthwhile to note that not all projects listed in the catalogue of potential coal resource developments (see Table 6 and Table 7 in Section 1.2.4 of companion product 1.2 for the Namoi subregion (Northey et al., 2014)) have been included in the CRDP. For some coal resource developments in the Namoi subregion, development planning may not yet have been undertaken, and there remains a high level of uncertainty around the likelihood, scope and nature of any future operations. This may be due to various reasons, such as the coal resource having only been recently discovered and thus requiring significant further appraisal of the magnitude, quality and suitability for mining. In other cases, there may be compelling economic or company-specific evidence that supported the Assessment team's rationale for not including the project in the CRDP.

In these cases, the Assessment team has considered that, on the basis of available information, it is not likely that future commercial production from these potential coal resource developments will occur within the next 10 to 15 years. Of course, this does not imply that these resources will not be mined at some stage in the future, particularly if further assessment studies are undertaken to better understand the geology of the deposit and the economic feasibility of extraction. Table 12 provides a summary of salient information used by the Assessment team to develop and justify the CRDP for the Namoi subregion. This table provides information that was used to exclude some additional coal resource developments from the CRDP, as well as information relevant to decisions to include these projects in hydrological modelling for the BA.

The expected timelines for the coal resource developments that will be modelled in the BA are shown in Figure 34. It should be noted that some of the timelines for the coal resource developments are dependent on market conditions and, in the case of some developments owned and/or operated by Whitehaven Coal, other developments occurring in the subregion. These coal resource developments will be the focus for the later-stage numerical modelling of the BA including surface water modelling (product 2.6.1), groundwater modelling (product 2.6.2), receptor impact modelling (product 2.7), and impact and risk analysis (product 3-4).

Table 12 Coal resource developments considered for the coal resource development pathway (CRDP) for the Namoi subregion

Coal resource development	Company	Included in CRDP?	Reasons for including or not including in CRDP
Bibblewindi and Dewhurst Gas Exploration Pilot wells	Santos Ltd	No	Any proposal to convert the pilot wells into production wells will be included in the Narrabri Gas Project.
Boggabri Coal Mine	Idemitsu, Chugoku Electric Power Australia Resources, NS Boggabri	Yes – modelled	The Boggabri Coal Mine has been in operation since 2006. Sufficient information is available about the development to enable inclusion in the CRDP and numerical modelling for the BA for the Namoi subregion. Mine development plans and scheduling information for the Boggabri Coal Mine are available to the Assessment team from information and datasets publicly released as part of the environmental assessment (EA) documentation, as well as data gathered for annual reporting requirements.
Boggabri Coal Expansion Project	Idemitsu, Chugoku Electric Power Australia Resources, NS Boggabri	Yes – modelled	The Boggabri Coal Mine received NSW and Australian Government approval to expand operations in 2013. This expansion is now operational. Sufficient information is available about the development to enable inclusion in the CRDP and numerical modelling. Mine development plans and scheduling information for the Boggabri Coal Expansion Project are available to the Assessment team from information and datasets publicly released as part of the EA documentation, as well as data gathered for annual reporting requirements.
Caroona Coal Project	NSW Energy Coal (BHP Billiton)	Yes – modelled	BHP Billiton submitted an application to the NSW Mining and Petroleum Gateway Panel for the Caroona Coal Project in 2014 and received a conditional certificate, allowing BHP Billiton to proceed with the development application (BHP Billiton, 2014). BHP Billiton was at the stage of compiling information for the environmental impact assessment. However, in August 2016 BHP decided to sell the Caroona exploration licence back to the NSW Government so it is highly unlikely that mining will occur in this area in the foreseeable future. As previously stated, once the CRDP is determined, it is not changed in this iteration of the BA, as per companion submethodology M04 (as listed in Table 1) for developing a CRDP (Lewis, 2014). Therefore, given there is sufficient information available for the Caroona Coal Project, it is included in the CRDP and numerical modelling of the BA for the Namoi subregion.
CCL 711	Curlewis Coal and Coke	No	Curlewis Coal and Coke is seeking renewal of this consolidated coal lease, which is part of the Preston Extended deposit. There is no publically available information for this lease and no coal resource is yet defined in accordance with the JORC Code for the Preston Extended deposit. Consequently, due to lack of current geological understanding about the deposit economics and geology, it is considered unlikely that CCL711 will be developed within a 10–15 year time frame.

Coal resource development	Company	Included in CRDP?	Reasons for including or not including in CRDP
Goonbri Exploration Lease Area	Goonbri Coal	No	The Goonbri Exploration Lease Area is approximately 1000 ha and is located immediately to the east of the Tarrawonga Mine. There is no publicly available information available for the area under the Goonbri exploration licence (EL). No coal resource is yet defined in accordance with the JORC Code and there is no documentation available for the site. Consequently, due to lack of current geological understanding about the deposit economics and geology, it is considered unlikely that Goonbri will be developed within a 10–15 year time frame. There is also no information available on the Goonbri Coal Company Pty Ltd who holds the Goonbri Exploration Lease Area (EL 7435).
Gunnedah Precinct	Whitehaven Coal	Yes – commentary	The 'Gunnedah Precinct' lease areas are held by Whitehaven Coal and have a total coal resource of 307 Mt (includes open-cut and underground resources), however only 9 Mt of this is measured, with 185 Mt indicated and 113 Mt inferred, indicating the deposit needs considerable further work to improve geological understanding and determine the potential for economic development. The project area largely sits within an area previously mined (the Gunnedah Colliery). Future development of this area is possible at some stage, however there is currently insufficient information available about how the resource would be developed, and the timing/schedule/life span etc. of any possible development, for it to be included with any appropriate degree of certainty or confidence in this iteration of the numerical modelling process.
Kahlua and Glasserton Pilot tests	Santos Ltd	No	Santos has undertaken pilot well testing near Kahlua and Glasserton in the south of the subregion, however it has indicated there are no further activities proposed for these exploration areas.
Maules Creek Mine	Whitehaven Coal, ICRA MC, J Power Australia	Yes – modelled	The Maules Creek Mine received NSW and Australian Government development approval in 2013 and the mine is now operational, ramping up to full production. The Assessment team considers sufficient information to be available about the development for inclusion in the CRDP and numerical modelling for the Namoi subregion. Mine development plans and scheduling information for the Maules Creek Mine are available to the Assessment team from information and datasets publicly released as part of the EA documentation, as well as data gathered for annual reporting requirements.
ML 1662	Whitehaven Coal	No	This mining lease is held by Whitehaven Coal and is part of the Rocglen Mine.
ML 1671	Werris Creek Coal	No	This mining lease is held by Werris Creek Coal (a subsidiary of Whitehaven Coal) and so forms part of the Werris Creek deposit.

Coal resource development	Company	Included in CRDP?	Reasons for including or not including in CRDP
Narrabri Gas Project	Santos Ltd	Yes – modelled	Santos is currently at the stage of compiling information for EIS assessment after having submitted a Preliminary Environmental Assessment to the NSW Government and a Referral under the EPBC Act to the Australian Government in 2014. There is a good understanding of the CSG resource and well-advanced plans for the proposed operations. Consequently, the Narrabri Gas Project will be part of the CRDP and numerical modelling for the BA for the Namoi subregion.
Narrabri North Mine	Whitehaven Coal, J Power, EDF Trading, Upper Horn Investments, Daewoo International and Korea Resources Corporation	Yes – modelled	The Narrabri North underground mine has been operational since 2010. The combined project (Narrabri North and South) has a listed probable recoverable coal reserve of 94 Mt and a probable marketable reserve of 75 Mt, indicating the resource is likely to be exploited in the future. The Assessment team considers there is sufficient information for the Narrabri North underground mine to be included in the CRDP and numerical modelling for the BA for the Namoi subregion.
Narrabri South	Whitehaven Coal	Yes – modelled	The Narrabri South exploration tenement (EL 6243) is directly south of the Narrabri North Mine. Narrabri South is included in the CRDP for the Namoi subregion as it has an economic demonstrated resource (EDR) and is part of a larger resource position held by Whitehaven Coal Limited (Whitehaven Coal) in the Namoi subregion – suggesting likely future development at some stage. The combined project (Narrabri North and South) has a listed probable recoverable coal reserve of 94 Mt and a probable marketable reserve of 75 Mt, indicating the resource is likely to be exploited in the future. The Assessment team has assumed that the Narrabri South project would go ahead once the Narrabri North resource is exhausted, predicted to be in about 2030. The Assessment team has obtained a longwall design concept plan for the Narrabri South exploration lease and has assumed that the rate of mining at Narrabri South would be similar to that at Narrabri North, approximately one longwall panel per year. The Assessment team considers there is sufficient information for Narrabri South to be included in the CRDP and numerical modelling for the BA for the Namoi subregion.
Rocglen Mine	Whitehaven Coal	Yes – modelled	The Rocglen Mine has been operational since 2009 and is classified as a baseline mine. Mine development plans and scheduling information for the Rocglen Mine are available to the Assessment team from information and datasets publicly released as part of the EA documentation and annual updates provided by Whitehaven Coal, who owns the mine. Consequently, the mine is included in the CRDP and the numerical modelling.
Sunnyside Mine	Whitehaven Coal	Yes – modelled	The Sunnyside Mine was given approval to commence production in 2008. In October 2012, mining operations at the site were suspended indefinitely and the mine is currently under ‘care and maintenance’. The mine had approval to operate until September 2015. The Sunnyside Mine is classified as a baseline mine and can be included in the CRDP and numerical modelling using historical information about the mine development, phases and closure procedure.

Coal resource development	Company	Included in CRDP?	Reasons for including or not including in CRDP
Tarrawonga Mine	Whitehaven Coal	Yes – modelled	The Tarrawonga Mine has been in operation since 2006. The Assessment team considers sufficient information to be available about the development for inclusion in the CRDP and numerical modelling for the Namoi subregion. Mine development plans and scheduling information for the Tarrawonga Mine are available to the Assessment team from information and datasets publicly released as part of the EA documentation, as well as data gathered for annual reporting requirements.
Tarrawonga Coal Expansion Project	Whitehaven Coal	Yes – modelled	The Tarrawonga Coal Expansion Project received NSW and Australian Government approval to expand operations in 2013. This expansion is now operational. The Assessment team considers sufficient information to be available about the project for inclusion in the CRDP for the Namoi subregion and numerical modelling. Mine development plans and scheduling information for the Tarrawonga Coal Expansion Project are available to the Assessment team from information and datasets publicly released as part of the EA documentation, as well as data gathered for annual reporting requirements.
Vickery Coal Project	Whitehaven Coal	Yes – modelled	The Vickery Coal Project received NSW approval in 2014; Australian Government approval was not required. The Assessment team considers sufficient information to be available about the development for inclusion in the CRDP and numerical modelling for the Namoi subregion. Mine development plans for the Vickery Coal Project are available to the Assessment team from information and datasets publicly released as part of the Preliminary Environmental Assessment and EIS documentation, as well as data gathered for annual reporting requirements. Whitehaven Coal has indicated that the start-up for the Vickery Coal Mine will depend on the market but will not commence prior to the Maules Creek Mine ramping to 13 Mt. The Assessment team has therefore inferred the scheduling of the Vickery Coal Project in accordance with this.
Vickery South Coal Project	Whitehaven Coal	Yes – commentary	Vickery South Coal Project is included in the CRDP for the Namoi subregion as it has an EDR and is part of a larger resource position held by Whitehaven Coal in the Namoi subregion – suggesting likely future development at some stage. However, there is currently insufficient information available about how the Vickery South coal resource would be developed, and the timing/schedule/life span etc. of any possible development, for it to be included with any appropriate degree of certainty or confidence in the numerical modelling for the BA for the Namoi subregion.
Watermark Coal Project	Shenhua Watermark	Yes – modelled	The Watermark Coal Project has passed EIS and EPBC Act approvals process[a], and (from an approvals process view) now only needs its mining lease to be granted and final NSW environmental authority for construction to commence. The Assessment team considers sufficient data and information to be available about the mining development to allow for its inclusion in the CRDP and numerical modelling. Required mine development plans and scheduling data for the Watermark Coal Project are available to the Assessment team.

Coal resource development	Company	Included in CRDP?	Reasons for including or not including in CRDP
Werris Creek Mine	Werris Creek Coal (subsidiary of Whitehaven Coal)	Yes – modelled (SW only)/ commentary (GW only)	The Werris Creek Mine has been operational since 2005 and received approval to extend operations in 2011, allowing for an increase in production and an extension for 20 years to 2031. The Assessment team considers sufficient information to be available about the development for inclusion in the CRDP for the Namoi subregion. Mine development plans and scheduling information for the Werris Creek Mine are available, however the mine lies in the Werrie Basin to the east of the Hunter-Mooki Thrust Fault System, and is hydrogeologically isolated from the groundwater flow systems in the Gunnedah Basin strata. However, it will be included in surface water modelling as the Werrie Basin is part of a larger catchment within the surface water model.

[a]indicate 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).
BA = bioregional assessment, CRDP = coal resource development pathway, CSG = coal seam gas, EA = environmental assessment, EDR = economic demonstrated resources, EIS = environmental impact statement, EL = exploration licence, EPBC Act = Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999*, GW = groundwater, ML = mining lease, SW = surface water
Full company names are: Chugoku Electric Power Australia Resources Pty Ltd (Chugoku Electric Power Australia Resources), EDF Trading Limited (EDF Trading), Goonbri Coal Company Pty Ltd (Goonbri Coal), Idemitsu Australia Resources Pty Ltd (Idemitsu), J Power Electric Power Development Co., Ltd (J Power), NS Boggabri Pty Ltd (NS Boggabri), Shenua Watermark Coal Pty Limited (Shenhua Watermark), Upper Horn Investments Pty Ltd (Upper Horn Investments), Werris Creek Coal Pty Ltd (Werris Creek Coal), Whitehaven Coal Limited (Whitehaven Coal).

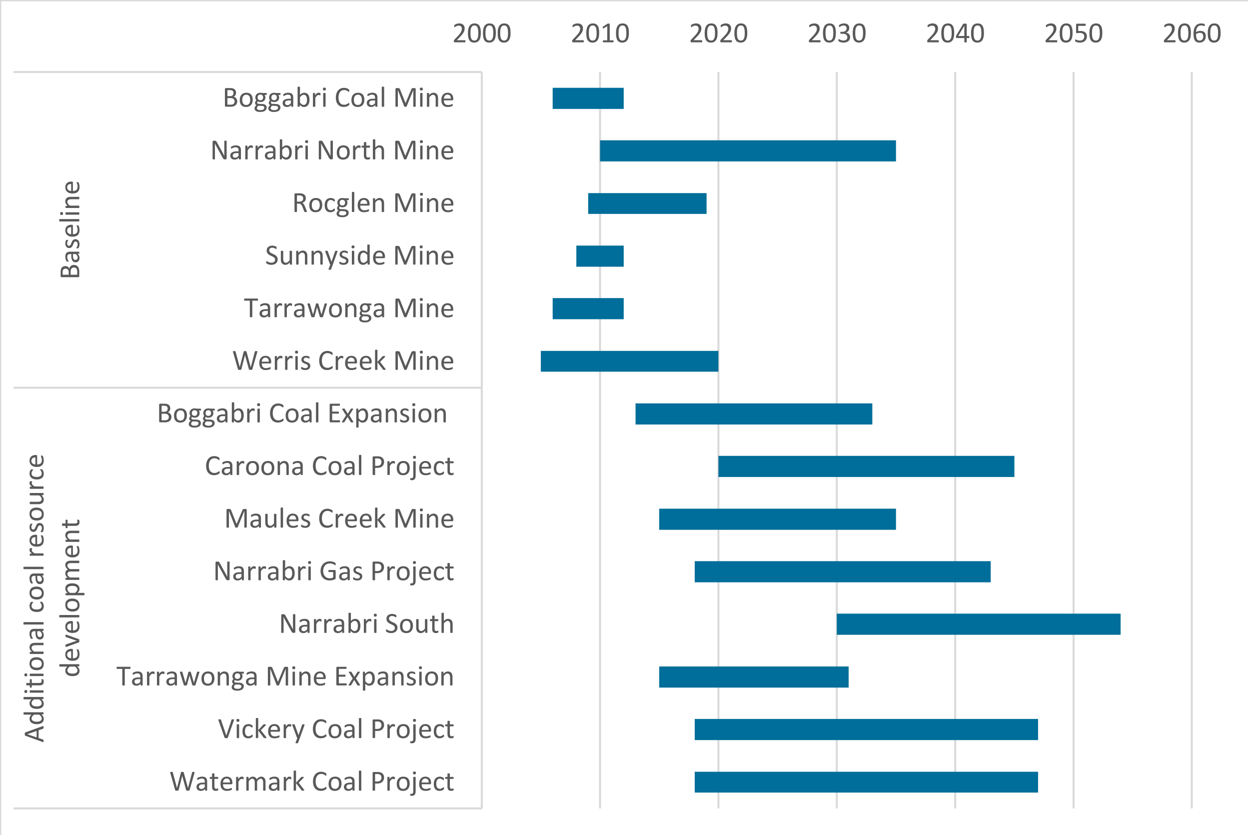

Figure 34 Timelines for coal resource developments included in the numerical modelling for the coal resource development pathway of the Namoi subregion

These timelines have been used in the bioregional assessment numerical modelling for the Namoi subregion in 2016.
The coal resource developments in the coal resource development pathway (CRDP) are the sum of those in the baseline coal resource development (baseline) and the additional coal resource development.
Baseline = 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 = 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
Additional coal resource development = all coal mines and CSG fields, including expansion of baseline operations, that are expected to begin commercial production after December 2012
There are two additional coal resource developments (Vickery South and Gunnedah Precinct) that cannot be modelled due to insufficient data, hence they are not shown on this timeline.

2.3.4.2 Water management for the coal resource developments

This section summarises the general characteristics of mine water management in the Namoi subregion in the context of the existing regulatory framework. Common elements important to informing the representation of mine impacts on water resources are identified.

Mine-specific data used in the groundwater and surface water modelling such as resource extraction start and end dates, mine footprints, flow rates, pumping depths, discharge rules and surface water extractions are provided in companion product 2.1-2.2 for the Namoi subregion (Aryal et al., 2018a).

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

Since coal mining commenced in NSW, policies, legislation and practices have developed to manage the impacts of mining developments both on and off the mine site. Mine and CSG operators are required to prepare mine water management plans detailing how they will ensure their activities avoid or minimise any negative consequences on the environment from the extraction and use of water, both in terms of the quantity and quality of water. It is assumed that the plans are adhered to and that some generalisations about mine water management can be made that apply to all mines, whether a plan for a particular development has been drafted or not.

The key legislation and policies that govern the management of water in relation to mining in NSW are outlined in Table 13. They are listed in the order in which they came into effect, although they typically have had amendments since they were first enacted.

Table 13 NSW legislation and policies governing mine water management in the Namoi subregion

Legislation or policy	Agency	Purpose and relevance to mine water management
NSW *Environmental Planning and Assessment Act 1979* (EP&A Act)	Department of Planning and Environment	Mining developments classified as 'State significant development' (SSD) require preparation of environmental impact statements (EIS) as part of obtaining development consent. An EIS should include assessment for water-related impacts. Extraction plans (formerly subsidence management plans) are required for underground mines that describe how subsidence impacts will be managed to minimise impacts.
NSW *Mining Act 1992*	Department of Industry, Resources and Energy	Part 11 of this Act specifies the various requirements as well as conditions required for conservation and protection of the natural environment (flora, fauna, fish, fisheries, scenic attractions, and features of Indigenous, architectural, archaeological, historic and geological interest) to be specified as part of development consent. The Act also specifies the conditions and requirements for rehabilitation of the mine sites.
NSW *Protection of the Environment Operations Act 1997* (POEO Act)	Environment Protection Authority (EPA)	Mining operations can produce polluted water and require an environment protection licence (EPL) under Schedule 1 of the POEO Act. An EPL authorises discharges to both surface waters and groundwater, and to land, and contains conditions relating to the concentration limits of those discharges, operating practices, discharge and ambient monitoring and reporting. The EPL may also specify requirements for pollution reduction programs (e.g. for site stormwater management).
NSW *Water Management Act 2000*	DPI Water	Under this Act, a licence or an approval is required by the mine to take water from water sources where a statutory water sharing plan is in place.
NSW Aquifer Interference Policy (DPI Water, 2012)	DPI Water	Defines the regime for protecting and managing the impacts of aquifer interference activities on NSW's water resources.
NSW Strategic Land Use Policy (2012)	Department of Industry, Resources and Energy	The Strategic Land Use Policy seeks to better manage potential conflicts arising from the proximity of mining and CSG activity to high-quality agricultural land. This policy has identified CSG exclusion zones and introduced a 'gateway' process which is an early scientific assessment of State significant mining and coal seam gas proposals on the State's strategic agricultural land.

CSG = coal seam gas, DPI Water = Department of Primary Industries – Water, EPL = environment protection licence
Data: adapted from Water Regulations Overview (DPE, 2015)

NSW's *Mining Act 1992* makes provision for the protection of the environment in the course of mining. The definition of environment encompasses ecological and sociocultural assets, which are in or on the land over which authority or claim is sought (Part 11, section 237(1)). Under this Act, the NSW Government Minister may require environmental impact studies to be carried out.

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

A typical mine water management plan provides details of expected pumping rates from the open-cut or underground workings, runoff diversions and on-site water storage, discharge locations to the river network, on-site water treatment, requirements for clean water, and post-mining hydrology following rehabilitation.

The following generalisations, which are reflected in site-scale mine water management plans as a consequence of the regulatory framework, are used to inform numerical modelling of the Namoi subregion:

- Mine working areas are largely isolated from the wider surface water drainage network early on in the development process through construction of diversion drains.
- Rain that falls on the mining area is retained on site.
- Groundwater pumped from mine workings is retained on site, unless the mine has a licence that entitles it to discharge groundwater from site. Managing mine water to minimise pollution of surface water and groundwater resources is a key aspect of site water management. Retained water is used on site for mine and coal processing water requirements. It may need to be treated for other uses. Ultimately it is lost to evaporation.

The amount of runoff retained on site will vary significantly between open-cut and underground mine operations. Generally, a larger surface area is disturbed during open-cut mining than for underground mining, thus there will be bigger impacts on surface water hydrology from open-cut mines than on underground mines. However, underground mines can cause subsidence at the land surface and changes in the hydraulic properties of subsurface layers, leading to increased interception of runoff in the area of subsidence.

In NSW, surface water extracted from rivers and used on site has to be licensed under NSW's *Water Management Act 2000*. The annual volumes of water licensed to be extracted from the stream network for uses on site, which are modelled in the Australian Water Resources Assessment river model (AWRA-R) and reported in companion product 2.6.1 for the Namoi subregion (Aryal et al., 2018b), are provided in companion product 2.1-2.2 for the Namoi subregion (Aryal et al., 2018a).

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

Groundwater pumped from the mine workings is often of lower quality than surface water. Discharges of low-quality water from mining operations need to be disposed of carefully. One of the objectives of NSW's *Protection of the Environment Operations Act 1997* (POEO Act) is to protect the quality of the environment in NSW from pollution. Mining, coal working and coking are scheduled activities under this Act and require an environmental protection licence (EPL) to discharge offsite. The Environment Protection Authority, who administers this Act, can stipulate the conditions relating to pollution prevention and monitoring on mine sites as part of their EPL, including:

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

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

2.3.4.3 Gaps

The CRDP for the Namoi subregion was confirmed and 'locked in' for this BA as of December 2015, therefore any significant project-related changes since then have not been reflected in the CRDP presented in this product.

As many of the most advanced mining proposals in the Namoi subregion may still be undertaking pre-mine planning and optimisation studies, mine scheduling and production rates provided in this product are estimates only. Even mines past the EIS approvals stage may require further environmental and mining-related authorisations, so the estimated commencement dates reported may vary from actual start-up time.

Other current knowledge gaps relating to mining operations include the likelihood that actual mine production rates will vary over the life of operations due to various factors, including changes in mine sequencing rates and schedules, variability in ground conditions encountered during mining, or other unforeseen events such as those caused by inclement weather or natural hazards. Mine lifetimes will depend on a number of factors not immediately known before mining commences, including fluctuations in commodity markets.

Water management strategies need to be finalised and conditions need to be set as part of the approvals process for each additional coal resource development. Thus, there may be variations in water management plans from what is reported in this product and in companion product 2.1-2.2 for the Namoi subregion (Aryal et al., 2018a).

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2.3.5 Conceptual modelling of causal pathways

Summary

This section describes the causal pathways in the preliminary assessment extent (PAE) for the Namoi subregion. Causal pathways are the logical chains of events – either planned or unplanned – that link coal resource development and potential impacts on water resources and water-dependent assets.

A hazard analysis systematically identified activities that occur as part of coal resource development and may lead to potential changes in surface water or groundwater. Some of these hazards are beyond the scope of the bioregional assessments (BAs), such as accidents, and others are assumed to be adequately addressed by site-based risk management. Although individual hazards constitute causal pathways, these hazards can be aggregated by common impact cause and impact mode into four causal pathway groups:

- ‘Subsurface depressurisation and dewatering’. This causal pathway group has the potential to directly affect the regional groundwater system and the surface water – groundwater interactions in the near-surface groundwater areas of the Namoi River and associated streams. Open-cut coal mines may cause changes to hydraulic gradients due to mine pit dewatering, which may also affect surface water – groundwater interactions.
- ‘Subsurface physical flow paths’. Hydraulic fracturing, well integrity failure, and surface water – groundwater interactions associated with coal resource development affect this causal pathway group. Hydraulic fracturing may potentially alter inter-aquifer connectivity and introduce preferential flow paths, whereas poor well integrity may lead to enhanced connection between aquifer layers.
- ‘Surface water drainage’. Disruption of the surface water drainage may lead to a redirection in runoff with possible long-term cumulative effects on quantity and quality of the downstream surface water. It may also result from surface infrastructure associated with mining and coal seam gas (CSG) operations, including diversion of drain lines and on-site water retention.
- ‘Operational water management’. This causal pathway group includes the extraction of water for site management and operations, discharge of co-produced water to surface waters, usage for irrigation, and reinjection to depleted aquifers. It can have a cumulative effect on surface water conditions, stream networks, surface water – groundwater interactions and groundwater conditions.

The causal pathway groups relevant for the coal resource development pathway (CRDP) are the same for open-cut and underground coal mines and the CSG operations though the emphases within these potential causal pathways may differ.

The expected area of potential groundwater change is confined to the Liverpool Plains and the Pilliga and Pilliga Outwash. Surface water – groundwater interactions and potential

surface water responses may occur in the streams of these geographic zones and those of the Castlereagh-Barwon geographic zone.

A landscape classification identified six major landscape groups. These are: 'Dryland remnant vegetation', 'Floodplain or lowland riverine', 'Non-floodplain or upland riverine', 'Human modified', 'Springs' and 'Rainforest'. The causal pathway groups are all relevant to these six groups.

2.3.5.1 Methodology

Conceptual models of causal pathways are a specific type of conceptual model which characterises the *causal pathways*, the logical chains 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 and risks to water resources and water-dependent assets. The approach taken in the Namoi 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 at the 'Conceptual modelling of causal pathways' workshop held in Canberra in August 2015. The focus of the workshop was to improve the description of the conceptual model of causal pathways. Discussion with representatives, who included BA experts in geology, mining and hydrology, at the workshop focused on clarifying causal pathways for coal resource developments exploiting the same coal basins and developing initial conceptual models.

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 Namoi subregion function 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, IMEA considers all the possible ways in which activities may lead to effects or impacts, before assessing the severity, likelihood and detectability of such impacts under current controls through structured scoring.

Key to 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*. In the Namoi subregion, these attributes were assessed by participants during a hazard analysis workshop. It is important to allocate 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 impact modes associated with 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 associated infrastructure.

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

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

An *impact cause* is an activity (or aspect of an activity) that initiates a hazardous chain of events. An activity can have undesirable effects (such as water 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 floods).

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 the IMEA workshop endeavoured 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 was scored with respect to the severity, likelihood and time to detection. The IMEA elicited 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 Namoi subregion at all times, only that it is important that these hazards (along with many others) are considered for inclusion in the BA. Hence, in this Assessment, all in-scope hazards identified in the IMEA workshop are addressed.

There is considerable structure and hierarchy within these lists of IMEA hazards (Bioregional Assessment Programme, Dataset 4) with the finer-level hazards aggregating to successively coarser resolutions. For example, there are various 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 and 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 change in groundwater or surface water; causal pathways include these chains of events and also extend to resulting ecological impacts (see Figure 5). Causal pathways are considered for CSG operations and 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 Namoi subregion.

Hazards are grouped for the Namoi 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 hazards that are in scope for BA.

The potential spatial footprint for the identified hazards and causal pathways is a core focus of the conceptual modelling, and is arrived at on the basis of existing knowledge, scientific logic and (where available) preliminary hydrological modelling results. An important aspect of this is using those same sources to identify which landscape classes and assets may be affected by a potential hydrological change that arises from those causal pathways and, equally importantly, which landscape classes and assets will *not* be affected. Throughout the BA, areas 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

The hazard analysis for the Namoi subregion was based on the existing and proposed CSG operations and coal mines and their water management outlined in Section 2.3.4.1 and Section 2.3.4.2, respectively. The analysis occurred during a one-day hazard workshop (held in May 2015) with experts from CSIRO, Geoscience Australia and the Department of the Environment and considered *activities* – planned events associated with a CSG operation or coal mine – of the different coal mining and CSG life-cycle stages. Specific coal resource expertise from these agencies beyond the Assessment team was included. Hazard analysis workshops for other subregions, some of which had stronger external representation, have assisted in confirming the comprehensiveness of the hazards identified for the Namoi subregion.

Participants of this Namoi hazard workshop identified and scored detailed hazards using the IMEA, aligned with the companion product M11 (as listed in Table 1) for hazard analysis (Ford et al., 2016). Further details are available in the hazard analysis dataset (Bioregional Assessment Programme, Dataset 4). The following sections provide a description of these identified hazards.

2.3.5.2.1 Hazard handling and scope

A long list of hazards has been generated for both coal mines and CSG operations with no particular consideration given to whether coal resource developments are part of the baseline or are additional coal resource developments. The hazards of primary focus from a BA perspective are those that extend beyond the coal resource development site and that may have cumulative impacts, as these are consistent with the regional focus of a BA, and are where BAs will add greatest 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.

In general, leading practice is assumed and accidents are deemed to be covered adequately by site-based risk management procedures and are considered beyond the scope of BAs; for example, the failure of a pipeline is covered by site-based risk management. Hazards that pertain to the coal resource development site and with no off-site impacts are important to acknowledge but will typically be addressed by site-based risk management procedures.

The hazard analysis generated a list of all potential hazards for the different life-cycle stages of the coal resource developments. Life-cycle stages have different scale and duration, which is reflected in the scores for consequence and/or likelihood of the hazards associated with these activities. Hazards that are in scope are addressed in the BA modelling; where modelling is not possible, a qualitative assessment (narrative) is provided (see companion submethodology M11 (as listed in Table 1) for hazard analysis (Ford et al., 2016)).

The relationship between individual hazards and the hydrological effects (groundwater properties, surface water properties) falls into causal pathways, which are combined into pathway groups: ‘Subsurface depressurisation and dewatering’, ‘Subsurface physical flow paths’, ‘Surface water drainage’ and ‘Operational water management’. The associated hydrological effects for the quality, quantity and pressure of surface and groundwater are shown in Table 14. More details on the causal pathways are available in companion submethodology M05 (as listed in Table 1) for developing a coal resource development pathway (Henderson et al., 2016). Section 2.3.5.3 provides further details on these causal pathway groups with focus on the Namoi subregion.

Table 14 Causal pathway groups and associated hydrological effects for the Namoi subregion

Causal pathway group	Hydrological effect
Subsurface depressurisation and dewatering	Groundwater flow or pressure and/or quality changes, and surface and/or subsurface water quality and/or quantity changes
Subsurface physical flow paths	Groundwater flow or pressure and/or quality changes, and surface and/or subsurface water quality and/or quantity changes
Surface water drainage	Direction, volume and quality of surface flow over the landscape
Operational water management	Surface or subsurface water quality and/or quantity changes (including increase in flow quantity and timing of ephemeral streams)

Subsurface water refers to the water in interstitial spaces below surface water expressions.

2.3.5.2.2 Coal seam gas operations

The components for CSG operations that are in scope are CSG wells, roads and infrastructure, and CSG processing. All hazard priority numbers overlap in their range associated with their respective modelling or narrative category, so no priority hazards were selected. Instead, *all* hazards were addressed.

There are 166 CSG hazards associated with CSG operations in the Namoi subregion. These hazards were grouped into hazard groups which link though individual causal pathways (as outlined in companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016)) to causal pathway groups (Table 15). Details of the hazards and their associated hazard groups, as well as their grouping according to the scope of assessment within the BA, are available in the hazard analysis for the Namoi subregion (Bioregional Assessment Programme, Dataset 4). Six hazards are addressed through groundwater quantity and surface water flow modelling and there is a wide overlap in the range of their hazard priority numbers (Figure 35). These fall under the hazard groups:

- 'discharge of co-produced water to stream'
- 'depressurisation of coal seam and non-target aquifers from water and gas extraction'.

Another 37 hazards are qualitatively assessed through narrative (Figure 36). These fall under the hazard groups:

- 'unregulated or forced release of water due to dam/containment failure'
- 'changes to water quality associated with depressurisation and connecting aquifers'
- 'subsidence'
- 'hydraulic fracturing and potential of contamination of aquifers'
- 'disruption of surface drainage network'
- 'bore and well construction'.

There are 123 hazards that are deemed out of scope for this BA because they are considered to be managed through site-based risk management; these hazards are not considered further in the BA. Details of these out-of-scope hazards are available from Dataset 4 (Bioregional Assessment Programme).

Table 15 Hazard groups for coal seam gas operations that are deemed in scope (addressed through modelling or narrative) and out of scope (site-based risk management) for the Namoi subregion

Modelling, narrative or site-based risk management	Hazard groups
Modelling	Depressurisation of coal seam and non-target aquifers from water and gas extraction
	Discharge of co-produced water to stream
Narrative	Bore and well construction
	Changes to water quality associated with depressurisation and connecting aquifers
	Disruption of surface drainage network
	Hydraulic fracturing and potential of contamination of aquifers
	Subsidence
	Unregulated or forced release of water due to dam / containment failure
Site-based risk management	Containment failure due to construction or design
	Disruption of surface drainage network site based
	Drill control issue
	Equipment/Infrastructure failure
	Ground staff impacts
	Leaching/leaking from storage ponds and stockpiles
	Spillages and disposals
	Vegetation clearance and subsequent soil erosion

'Modelling' refers to hazards that are expected to be modelled in surface water and groundwater models. 'Narrative' refers to hazards that are not modelled but are important to provide comment on. 'Site-based risk management' refers to hazards that are believed important to be acknowledged but are handled by site-based risk management procedures.
For further information, see companion submethodology M11 (as listed in Table 1) for hazard analysis (Ford et al., 2016).
Typography and punctuation are consistent with the hazard analysis dataset (Bioregional Assessment Programme, Dataset 4).
Data: Bioregional Assessment Programme (Dataset 4)

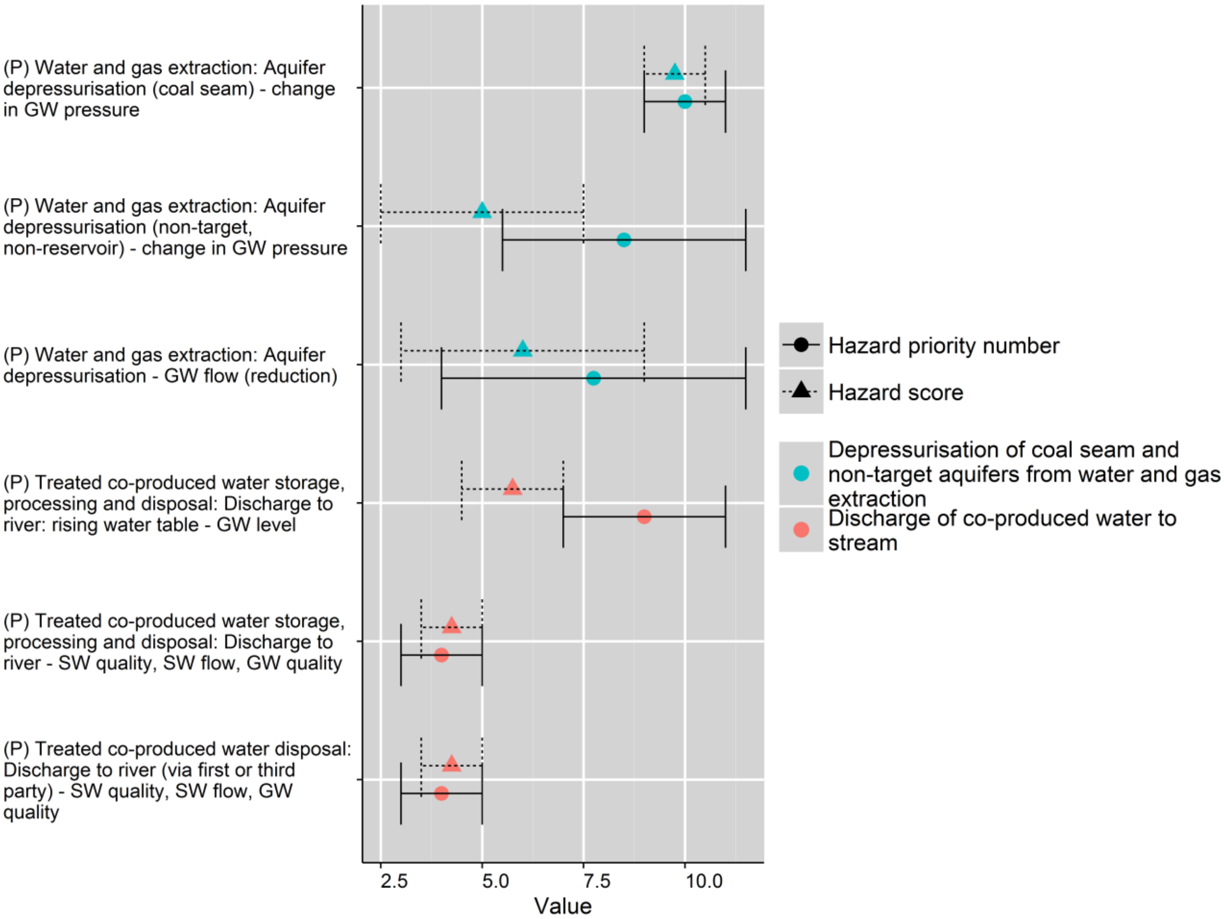

Figure 35 Hazards for coal seam gas operations that are addressed through the hydrological modelling, ranked by midpoint of hazard priority number and hazard score

The x-axis shows the hazard priority number and hazard score for potential hazards as scored by experts. The same hazard may appear multiple times, as it may arise from a number of different life-cycle stages and activities. Hazards and their associated hydrology effects are listed with the syntax (Life-cycle stage) [Activity]: [Impact mode] – Effects, where life-cycle stage is (P) – production.

GW = groundwater, SW = surface water

Data: Bioregional Assessment Programme (Dataset 4)

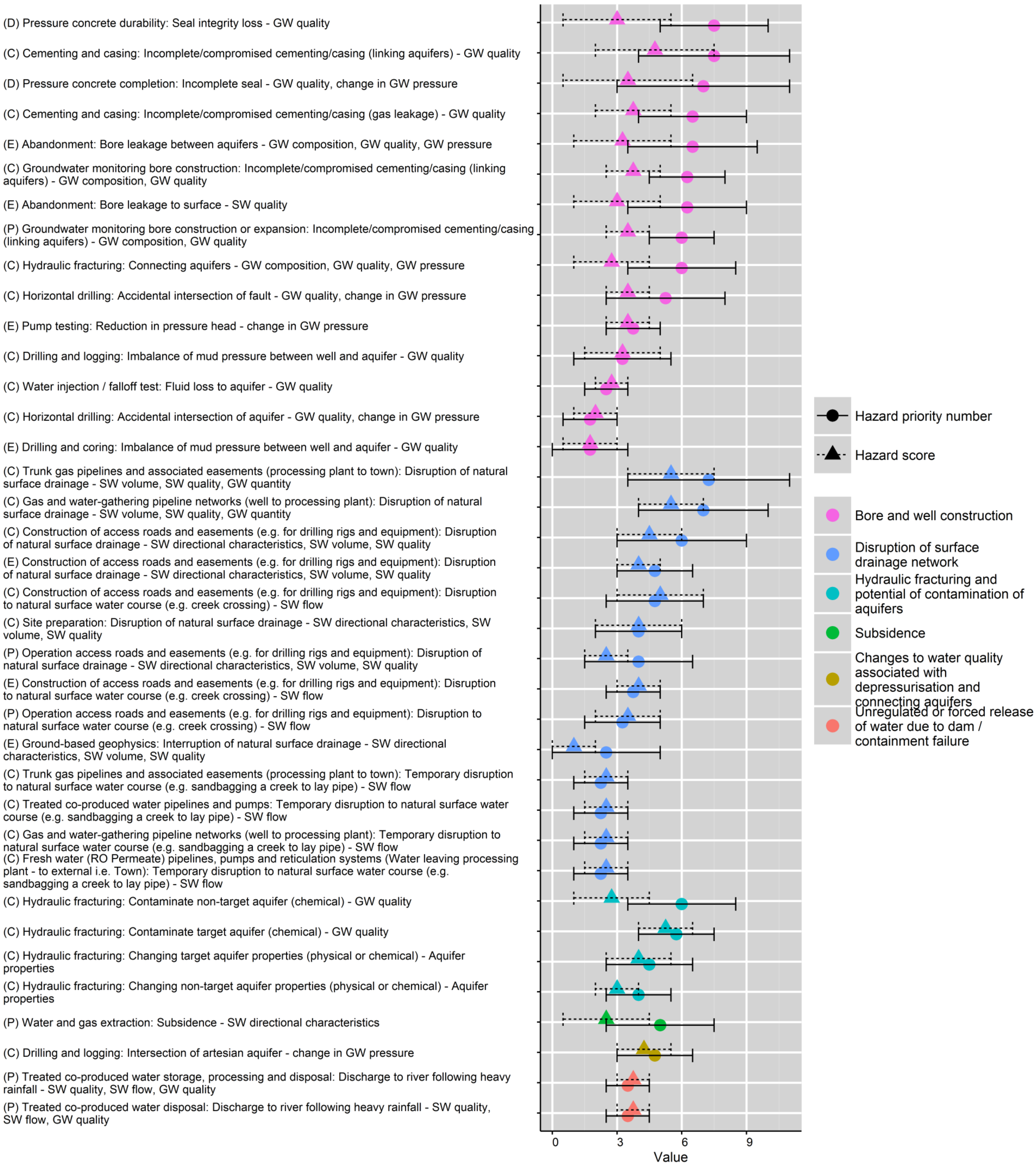

Figure 36 Hazards for coal seam gas operations that are addressed through narrative, ranked by midpoint of hazard priority number and hazard score

The x-axis shows the hazard priority number and hazard score for potential hazards. The same hazard may appear multiple times, as it may arise from a number of different life-cycle stages and activities. Hazards and associated hydrological effects are listed with the syntax (Life-cycle stage) [Activity]: [Impact mode] – Effects, where life-cycle stages are indicated by (C) – closure, (D) – development, (E) – exploration and appraisal, or (P) – production.
GW = groundwater, SW = surface water, TDS = total dissolved solids, TSS = total suspended solids
Data: Bioregional Assessment Programme (Dataset 4)

This figure has been optimised for printing on A3 paper (297 mm x 400 mm).

2.3.5.2.3 Open-cut and underground coal mines

All hazard priority numbers for in-scope hazards overlap in their range associated with their respective modelling or narrative category, so no priority hazards were selected. Instead, *all* hazards are addressed. Underground coal mining is distinctly different from open-cut mining and more akin to CSG in terms of water impact at depth. Surface facilities and infrastructure are similar for both underground and open-cut coal mines. There are 239 coal mine hazards in the Namoi subregion that are related to underground and open-cut mining, and associated infrastructure and surface facilities. Details of the hazard analysis are available from the hazard analysis for the Namoi subregion (Bioregional Assessment Programme, Dataset 4). The hazard groups for these hazards are listed in Table 16.

There are 24 hazards (Figure 37) that are in scope and addressed by the groundwater and surface water modelling. These hazards are related to:

- ‘post mining − creation of groundwater sink, artificial point of recharge’
- ‘disruption of natural surface drainage and change in run-off (interception of run-off by pit)’
- ‘groundwater dewatering of target seam (underground) and layers to coal seam (open-cut)’
- ‘subsidence due to underground mining’.

An additional seven hazards (Figure 38) are covered through narrative and these are related to:

- ‘disruption of natural surface drainage (beyond site, e.g. rail)’
- ‘unregulated or forced release of water due to dam/containment failure’
- ‘changes to water quality associated with depressurisation and connecting aquifers’.

There are 208 hazards that are out of scope as they were deemed to be adequately managed through site-based risk management. These hazards are not considered further in the BA. Details of these out-of-scope hazards are available from Dataset 4 (Bioregional Assessment Programme).

Table 16 Hazards for open-cut and underground coal mines that are deemed in scope (addressed through hydrological modelling or narrative) and out of scope (site-based risk management)

Modelling, narrative or site-based risk management	Hazard group
Modelling	Disruption of natural surface drainage and change in run-off (interception of run-off by pit)
	Groundwater dewatering of target seam (underground) and layers to coal seam (open cut)
	Post mining - creation of groundwater sink, artificial point of recharge
	Subsidence due to underground mining
Narrative	Changes to water quality associated with depressurisation and connecting aquifers
	Unregulated or forced release of water due to dam/containment failure
	Disruption of natural surface drainage (beyond site, e.g. rail)
Site-based risk management	Disruption of natural surface drainage and change in run-off (interception of run-off by pit)
	Disruption of surface drainage network (site-based infrastructure, plant and facilities, roads, creek crossings)
	Disruption of surface drainage network (site-based)
	Equipment/infrastructure failure
	Fire
	Ground staff impacts, spillage, dust suppression
	Inter aquifer connectivity - Shaft construction, bore construction
	Leaching/leaking from storage ponds and stockpiles
	Loss of containment (due to construction or design, slope failure)
	Mine rehabilitation issues
	Re-contouring, compaction and settlement following backfill
	Spillages and disposals
	Vegetation clearance and subsequent soil erosion following heavy rainfall

‘Modelling’ refers to hazards that are expected to be modelled in surface water and groundwater models. ‘Narrative’ refers to hazards that are not modelled but are important to provide comment on. ‘Site-based risk management’ refers to hazards that are believed important to be acknowledged but are handled by site-based risk management procedures.
For further information, see companion submethodology M11 (as listed in Table 1) for hazard analysis (Ford et al., 2016).
Typography and punctuation are consistent with the hazard analysis dataset (Bioregional Assessment Programme, Dataset 4).
Data: Bioregional Assessment Programme (Dataset 4)

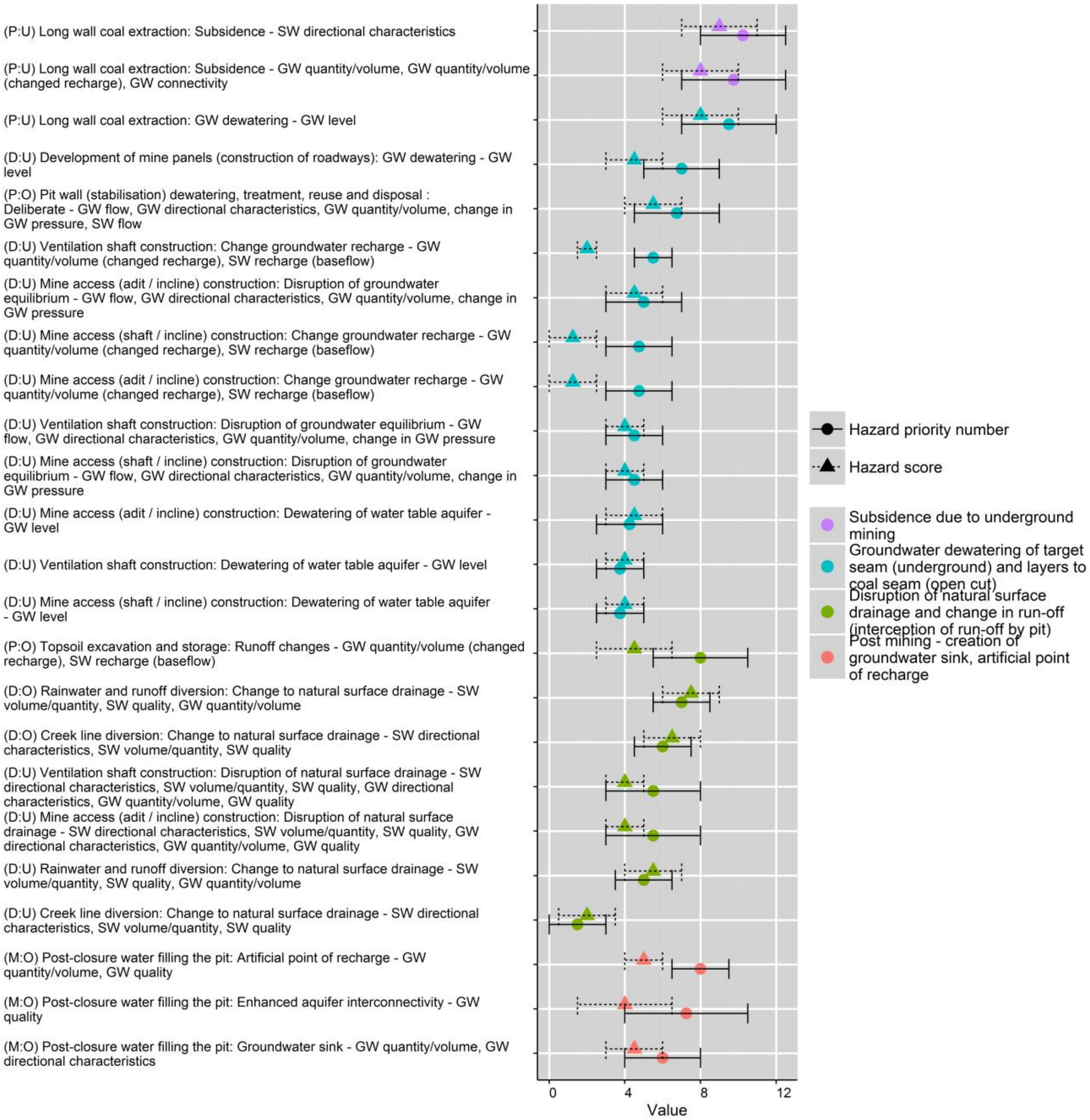

Figure 37 Hazards for coal mines that are addressed in the hydrological modelling, ranked by midpoint of the hazard priority number and hazard score

The x-axis shows the hazard priority number and hazard scores for potential hazards. The same hazard may appear multiple times, as it may arise from a number of different life-cycle stages and activities. Hazards and associated hydrological effects are listed with the syntax (Life-cycle stage) [Activity]: [Impact mode] – Effects, where life-cycle stages are indicated by (D) – development or (P) – production for open pit (O) and underground mining (U) components.
Typography and punctuation are consistent with the hazard analysis dataset (Bioregional Assessment Programme, Dataset 4).
GW = groundwater, SW = surface water, TDS = total dissolved solids, TSS = total suspended solids
Data: Bioregional Assessment Programme (Dataset 4)

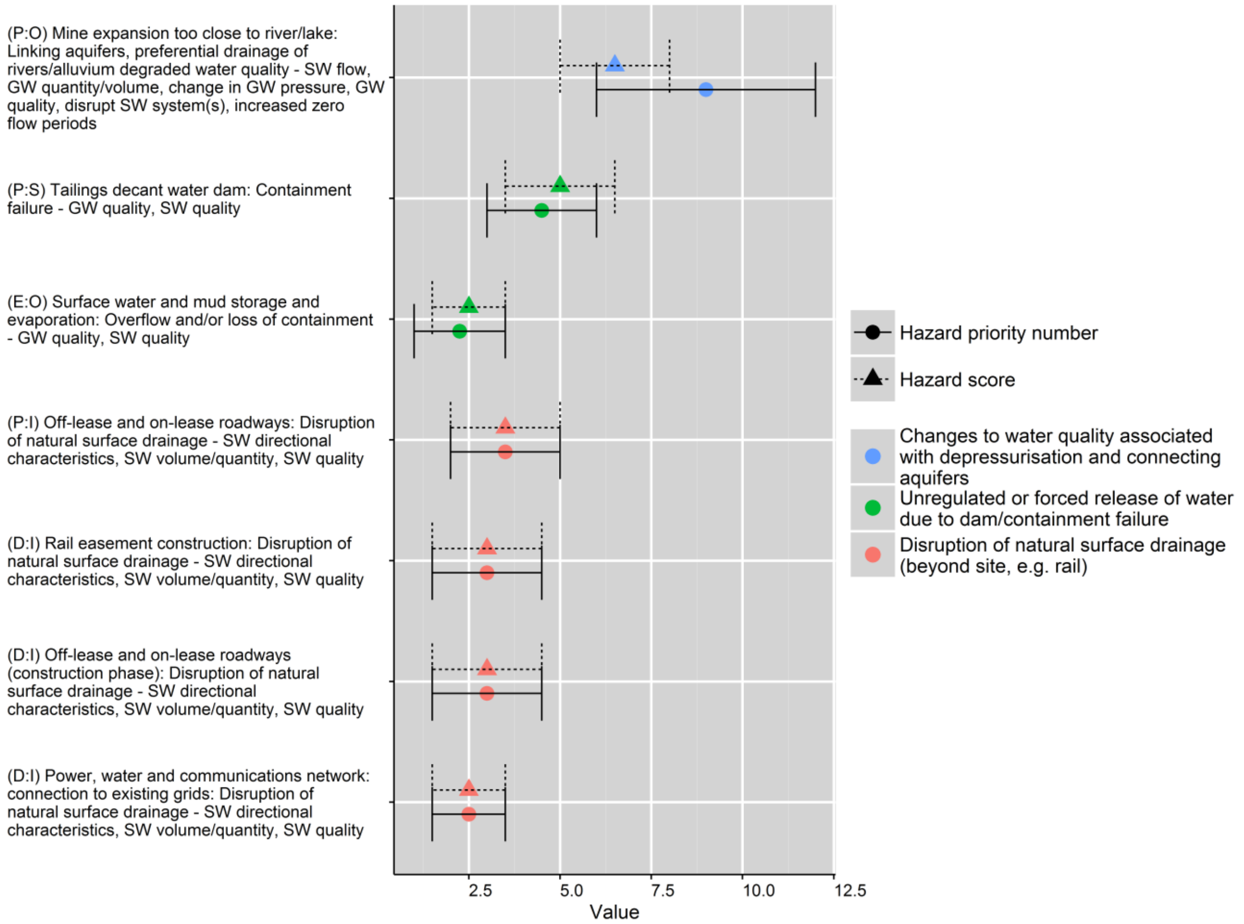

Figure 38 Hazards for coal mines that are addressed in the narrative, ranked by midpoint of the hazard priority number and hazard score

The x-axis shows the hazard priority number and hazard score for potential hazards. The same hazard may appear multiple times, as it may arise from a number of different life-cycle stages and activities. Hazards and associated hydrological effects are listed with the syntax [Life-cycle stage][Activity]:[Impact mode] – Effects, where life-cycle stages are indicated by (D) – development, (P) – production or (E) – exploration for components open pit (O), infrastructure (I) or surface facility (S).
Typography and punctuation are consistent with the hazard analysis dataset (Bioregional Assessment Programme, Dataset 4).
GW = groundwater, SW = surface water, TDS = total dissolved solids, TSS = total suspended solids
Data: Bioregional Assessment Programme (Dataset 4)

2.3.5.3 Causal pathways

This section describes the causal pathways that are relevant to the Namoi subregion for both coal mines and CSG operations (Table 14). These causal pathways describe the potential for impact of coal resource developments on water resources and water-dependent assets in the Namoi subregion. This does not mean, however, that these causal pathways are realised for each coal resource development. Many conditions need to be satisfied in order to assess impacts and these will be addressed in more detail through further work in surface water and groundwater modelling (companion product 2.6.1 (Aryal et al., 2018a) and companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018), respectively) and assessment of knowledge gaps related to geological, groundwater and surface water connections between depth at coal resource exploitation and the surface (represented as landscape classes in the BA; see Section 2.3.3).

The coal resource development activities occur in the eastern and central parts of the subregion (Figure 39) within the Liverpool Plains, Pilliga and Pilliga Outwash geographic zones (see Table 5, Section 2.3.3). These activities are discussed in detail subsequently. This section firstly describes the four causal pathway groups that are relevant for the Namoi subregion more generally. Then it explains the coal resource development specific causal pathways for the subregion (Section 2.3.5.3.6). Finally, it provides a summary of the causal pathways for the subregion (Section 2.3.5.3.7).

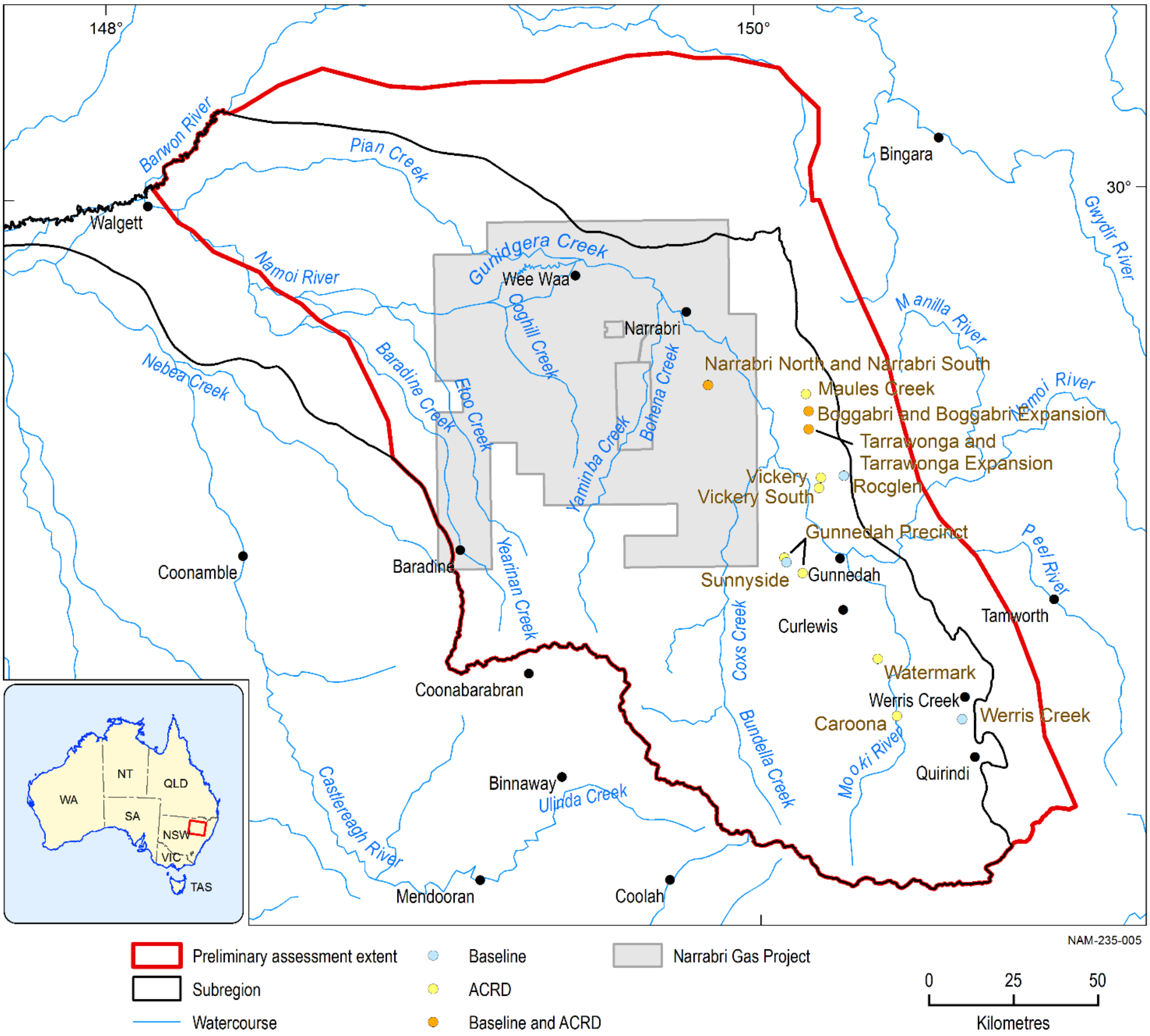

Figure 39 Coal mines and coal seam gas tenements in the coal resource development pathway in relation to the major streams that are addressed by hydrological modelling

There are three developments that are both baseline mines and additional coal resource developments (ACRD) on this map: Boggabri, Tarrawonga and Narrabri North are the baseline mines. Boggabri expansion, Tarrawonga expansion and Narrabri South are the additional coal resource developments. The coal resource developments in the coal resource development pathway (CRDP) are the sum of those in the baseline coal resource development (baseline) and the additional coal resource development.
The Narrabri Gas Project extent includes the exploration lease area.
Data: NSW Trade and Investment (Dataset 1), Bioregional Assessment Programme (Dataset 6, Dataset 7)

2.3.5.3.1 'Subsurface depressurisation and dewatering' causal pathway group

Groundwater extraction associated with coal mines or CSG operations leads to depressurisation of the target coal seam and potentially any connected aquifer layers. Hydrological effects resulting from this causal pathway group depend on the local environment of the individual well (groundwater supply bore or CSG well) or open-cut or underground coal mines. The head changes caused by depressurisation of a coal seam may be passed to other strata, depending on the inherent hydraulic properties of the targeted seams as well as those of the adjacent and nearby rock strata. These affect the magnitude of head change, the spatial extent of head change and the time it takes for maximum head change to occur. There is no general rule for how depressurisation of the target aquifer will affect depressurisation of the target coal seam. In areas where a fault or fracture does exist, pressure changes may transmit more readily. However, this depends on whether the structures act as barriers or conduits to flow. Furthermore, it may be possible that prolonged depressurisation will reactivate a fault causal pathway, and thus create a connection that was not active prior to the aquifer depressurisation. Although conceptual modelling is able to identify that a change in groundwater pressure is possible, only field-verified fault locations and hydrological conductivity data with hydrological modelling will provide an opportunity to accurately quantify the extent of such a change.

Open-cut and underground coal mines must be dewatered to allow the safe extraction of coal, and this decrease in local groundwater level creates a gradient towards the drained coal seam, and induces flow into it. For open-cut coal mines, the primary sources of this water are the geological layers in which the mine is situated, down to the base of the pit. 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. For example, a particular asset may be so distant from an open-cut coal mine that, within the life of the mine, drawdown will not affect it. However, in the years following mine closure, the spread of the drawdown area may expose it to change. Quantification of this is only possible through predictive numerical groundwater modelling and targeted monitoring. It also requires the iterative incorporation of the monitoring information into the numerical modelling to improve precision of the model predictions. Mine pit dewatering may also affect alluvial aquifers, which in turn may affect the volume and timing of groundwater that is discharged as baseflow to connected watercourses. If the dewatering of an open-cut coal mine allows a drawdown cone to intersect with an alluvial aquifer supporting a stream, then some of the water that would naturally discharge to the stream is instead drawn away from the alluvium towards the open-cut coal mine.

Open-cut and underground coal mines require groundwater bores for monitoring, dewatering and water supply. They also have the potential to enhance connection between aquifers where well integrity is compromised. Connections from the surface to the target coal seam can also occur through ventilation and access shafts, although during the extraction phase, maintenance of these ventilation and access shafts aims to avoid a breach of their seals. In addition, underground mining may lead to subsidence at the land surface, with changes to the physical structure and properties of rocks and sediments occurring between the target coal seams and some distance up to, and including, the land surface. Where land subsidence coincides with a natural stream or river, water may be lost from the stream temporarily or permanently. Subsidence is discussed further in Section 2.3.5.3.3 ('Surface water drainage' causal pathway group).

Aquifer depressurisation associated with CSG operations and dewatering associated with coal mine development may affect target and non-target aquifers, at both local and regionally relevant scales, potentially leading to a hydrological effect in connected aquifers and both surface water and groundwater systems. Companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018) describes the cumulative effects of aquifer depressurisation and dewatering. Companion product 2.6.1 for the Namoi subregion (Aryal et al., 2018a) details analogous hydrological changes to the surface water arising from the same coal resource developments.

Figure 40 summarises the causal pathway group ‘Subsurface depressurisation and dewatering’ associated with groundwater extraction and reduction in groundwater pressure in the surrounding and deeper aquifers. This can reduce the groundwater level if there is a connection to the surface aquifer and in turn results in groundwater property changes and may cause subsidence. ‘Change in groundwater flow’ is a summary term incorporating changes to the magnitude, direction and rate of groundwater flow. The disposal of the extracted groundwater is discussed in the ‘Operational water management and disposal’ pathway group (Section 2.3.5.3.4).

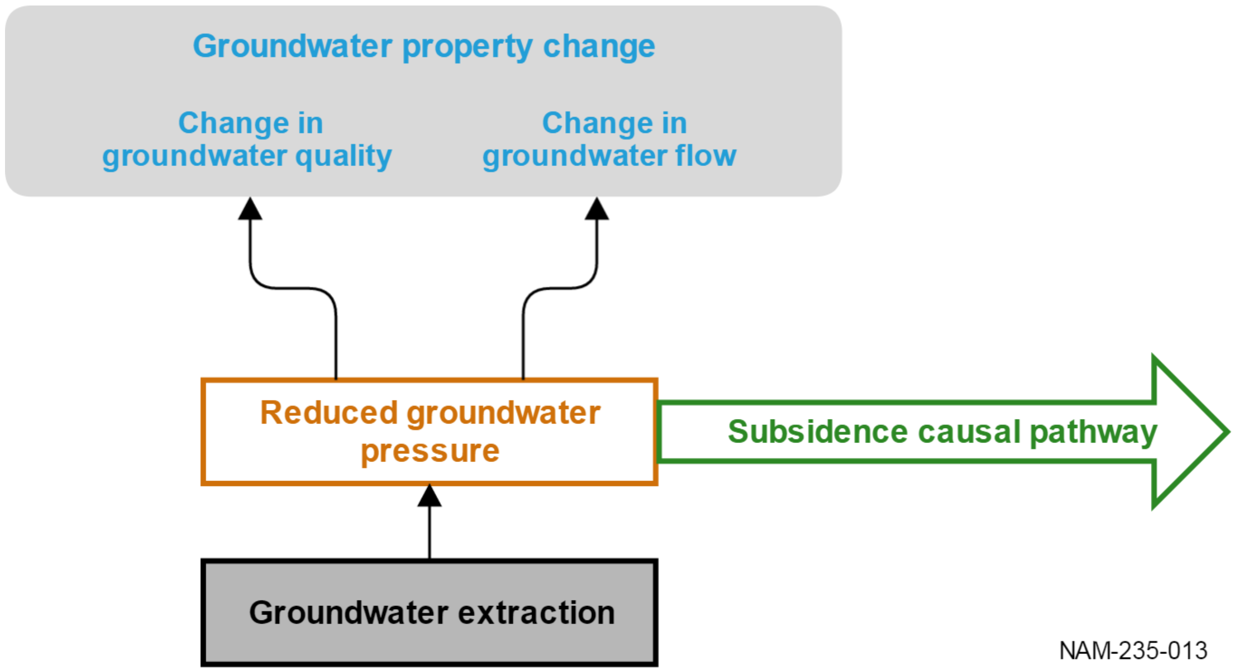

Figure 40 Groundwater extraction in the ‘Subsurface depressurisation and dewatering’ causal pathway group

Groundwater extraction can cause changes to groundwater properties and also links to subsidence. Where there are connections of groundwater to surface water, there is a causal linkage between groundwater property changes and surface water property changes (see Figure 42). Subsidence is presented in Figure 44.
The colours in the diagram represent the following: white box with green writing = causal pathway, grey box with blue writing = hydrological effect, white box with orange writing = an event that forms part of the causal pathway chain, grey box with black writing = an activity.

2.3.5.3.2 ‘Subsurface physical flow paths’ causal pathway group

Preferential flow paths can be introduced between strata by hydraulic fracturing (including deviated drilling and changes to non-target aquifers) and compromised well integrity (including incomplete and/or compromised cementing or casing, miss perforation of target aquifers), and can impact on surface water – groundwater interactions (including changes to aquifer interconnectivity, mine expansion too close to a river or lake, preferential drainage and recharge associated with post-closure water filling the pit).

Potential effects are likely to be localised, but will continue until remedial actions are taken. Potential effects include the release of gas from the coal seams to the overlying geological layers and ultimately to the atmosphere. Inter-aquifer mixing can potentially compromise aquifer water quality. Effects on surface water systems are thought to be minimal and limited to reaches of surface water that receive baseflow from the groundwater system.

Hydraulic fracturing is designed to alter connectivity within target layers but may potentially alter inter-aquifer connectivity and introduce preferential flow paths. Hydraulic fracturing involves high-pressure injection of water (and other materials including chemical compounds and sand) to induce changes in coal seam properties to aid the release and flow of gas from the coal seams towards the well (Department of the Environment, 2014). The intended impact of changing aquifer properties is expected to be limited to the coal seams with a smaller risk of impacting neighbouring aquifers or aquitards. The lateral extent to which aquifer properties are changed is dependent on the physical properties of the coal, and diminishes with distance from the well. It is therefore also influenced by the number of wells and their spatial layout where this process is implemented. The water quality of the fractured coal seams and neighbouring aquifers can be compromised. While hydraulic fracturing is subject to management controls and monitoring, and Santos currently has no plans to use hydraulic fracturing as part of the Narrabri Gas Project (Santos, 2014), some of the chemicals in the compounds used for hydraulic fracturing or mobilised from the coal seam may seriously impair groundwater quality and could be difficult to decontaminate. At the end of hydraulic fracturing, water is pumped out, which is discussed as part of the 'Subsurface depressurisation and dewatering' causal pathway group (see Section 2.3.5.3.1 and also Figure 40). Potential effects of disposal of co-produced water removed after hydraulic fracturing are discussed as part of the 'Operational water management' causal pathway group (see Section 2.3.5.3.4).

Well construction may lead to enhanced connection between aquifer layers (Stuckey and Mulvey, 2013). It allows the mixing of waters from previously disconnected layers of different quality and chemical properties or of any fluid introduced down the well. CSG wells are drilled vertically from the surface to the coal seam and can be drilled within the coal seam by directional or deviated drilling. Maintaining well integrity throughout construction, operation and decommissioning phases is crucial to ensuring sustainable gas production and avoiding adverse environmental impacts. Incomplete and/or compromised casing and seals could introduce preferential flow paths. Miss perforation of the target aquifer can create a connection between previously disconnected aquifers. Preferential flow paths have the potential to connect any two or more consecutive or non-consecutive geological layers up to the land surface.

Open-cut coal mines can have a localised effect on preferential flow paths in surrounding aquifers and affect surface water – groundwater interactions. This includes changes to hydraulic gradients in the alluvial aquifer and connected aquifers associated with mine pit dewatering and preferential drainage and recharge associated with water filling any pit that remains below the watertable post-closure and rehabilitation. An important component of streamflow is baseflow, where groundwater discharges to the stream from the adjacent aquifer. Changes to hydraulic gradients can change the timing and volume of baseflow contributions to streams, which can affect the stream ecosystem within and downstream of tenements.

Void collapse as a result of underground mining can alter the hydraulic properties of overlying rock layers and may lead to subsidence at the surface. Subsidence is discussed as part of the 'Surface water drainage' causal pathway group below.

Figure 41 shows the major gaining and losing streams in the Namoi subregion that groundwater discharge changes are likely to influence. In losing streams, groundwater is not contributing to baseflow, whereas in gaining streams baseflow benefits from groundwater. All coal mines between the Coxs Creek – Namoi confluence and Narrabri have the potential to affect baseflow in the Namoi River and its tributaries in their sphere of hydraulic gradient change. However, this does not mean that a decrease in hydraulic gradient has no influence on other streams outside this area. The gaining and losing stream calculations are based on flow averages, and a stream can be a gaining stream at some stage of the hydrograph. The findings in companion product 2.1-2.2 for the Namoi region (Aryal et al., 2018b) support this in that hydraulic connection between the river and the alluvium shows changes in flux directions that respond to natural and human factors.

For smaller streams, which are gaining during some of the time, the reduction in the surrounding hydraulic gradient could result in an increase in low-flow or cease-to-flow times. As a consequence, responses by streams to changes in hydraulic gradient from mining are also likely in other areas of the subregion. Figure 42 shows a schematic of the causal relationship between groundwater property changes associated with the 'Subsurface physical flow paths' causal pathway group and surface water property changes.

The surface water and groundwater modelling reported in companion product 2.6.1 (Aryal et al., 2018a) and companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018) will further provide the numeric information and spatial context of hydrological changes associated with coal resource developments in the baseline and CRDP.

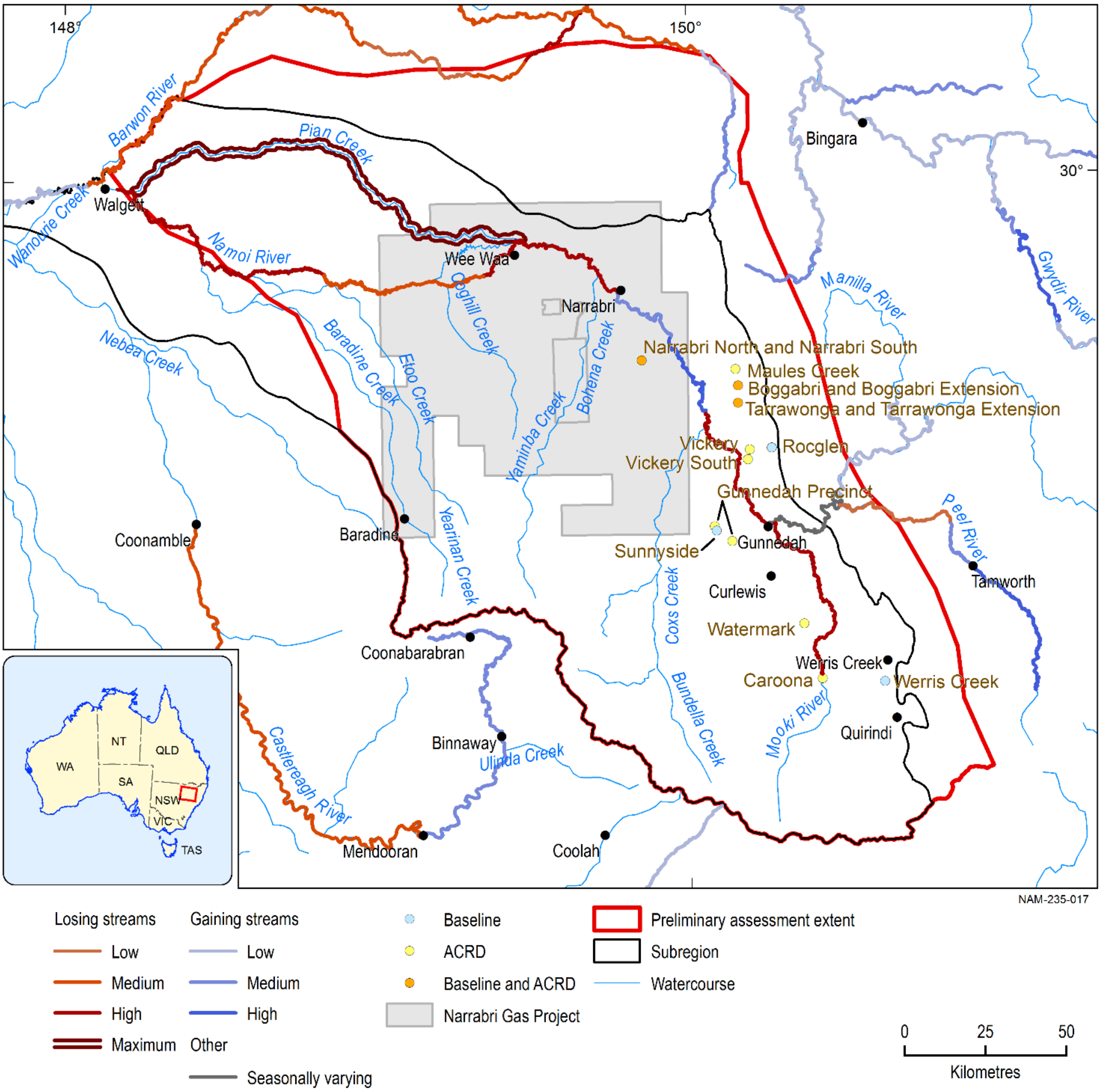

Figure 41 Losing and gaining sections of the major streams in the context of coal resource development in the Namoi subregion

There are three developments that are both baseline mines and additional coal resource developments (ACRD) on this map: Boggabri, Tarrawonga and Narrabri North are the baseline mines. Boggabri expansion, Tarrawonga expansion and Narrabri South are the additional coal resource developments. The coal resource developments in the coal resource development pathway (CRDP) are the sum of those in the baseline coal resource development (baseline) and the additional coal resource development.
The Narrabri Gas Project extent includes the exploration lease area.
Data: NSW Trade and Investment (Dataset 1), CSIRO (Dataset 5)

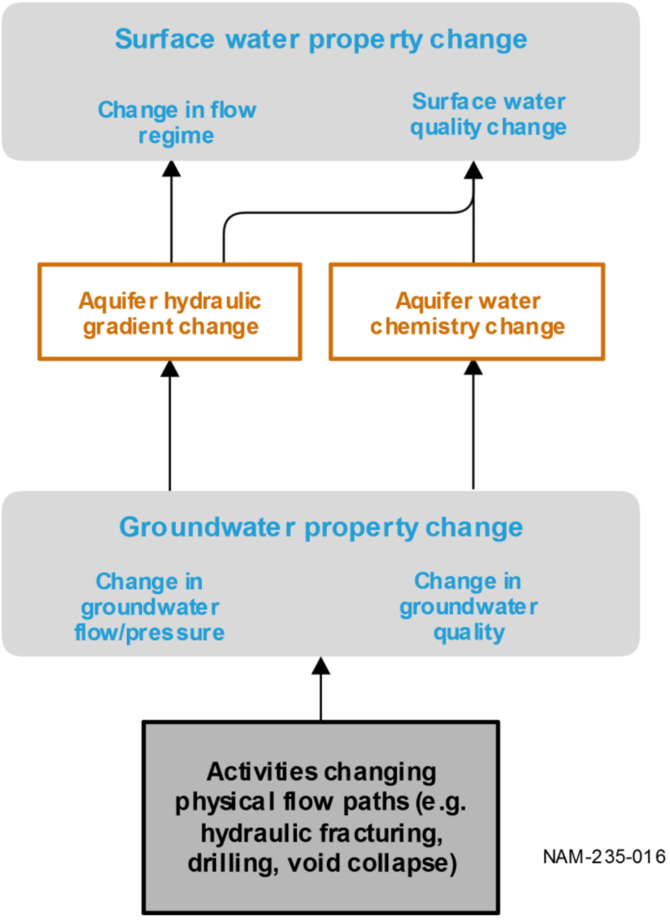

Figure 42 The relationship between groundwater property changes in the 'Subsurface physical flow paths' causal pathway group and surface water property changes

The colours in the diagram represent the following: grey box with blue writing = hydrological effect, white box with orange writing = an event that forms part of the causal pathway chain.

2.3.5.3.3 'Surface water drainage' causal pathway group

Disruption of the surface drainage network may lead to a loss, or redirection, of runoff that can have long-term cumulative effects on downstream watercourses. The physical infrastructure of CSG operations and surface infrastructure of open-cut and underground coal mines, including land clearing, land levelling, the construction of roads and railway tracks, and pipelines and plant facilities for collection and transport of gas, can all disrupt natural surface water flows and pathways by redirecting and concentrating surface water runoff flows (Figure 43). Changes in flow regime and catastrophic events can alter flows and pathways either temporarily before returning to the previous state, or semi-permanently until the next event. This may lead to erosion of the land surface, stream banks or streambeds, and alter water quality in streams if new material is mobilised and washed into them. Geomorphological changes may create chemical or flow barriers to migration of aquatic organisms that can affect upstream watercourses (Figure 44). The interstitial spaces in the streambed – the hyporheic zone that connects surface water and groundwater – are ecologically important refuges for organisms and primary production (for a review see Boulton et al. (2010)). This section conceptually includes these spaces when discussing surface water related causal pathways.

Open-cut coal mines may also alter the surface water flows and pathways, through diverting site drain lines and on-site water retention. Intercepting runoff or streamflow into a mine area will remove a volume of water from the larger surface water drainage system. Both the quantity and quality of water downstream may be affected; quality may improve if the runoff or flow was naturally saline or highly turbid, or decrease if the inflow was fresher than the main stream. Surface water that is diverted around a mining operation may lead to concentration of surface flows that may alter water quality due to increased erosion and turbidity.

Although the total amount of runoff in a surface water catchment might be reduced by only a few percent, creek line diversions change where water enters the stream network. For example, a mine may alter runoff and drainage such that a single upland stream that contributes only a few percent of overall catchment streamflow is diverted around the mine to a watercourse further downstream. This has implications for the local stream environment and downstream reaches where the contribution at this point may be more significant. It can lead to flow being more concentrated, so that erosion risk is greater, or reduce the flow contributions to a water-dependent asset. The relative effect will be greater the closer an open-cut coal mine is to the stream. On-site water retention minimises the chances of any runoff from the mining operations or infrastructure being contaminated and released to the surface water catchment or watercourse. Therefore, any runoff that is naturally generated within the mining operations area is not available to streamflow and the environment. After mining ceases and if mine-site rehabilitation occurs, at some stage following this activity, some proportion of the rehabilitated land area will again become connected to the wider surface water catchment.

Subsidence is a lowering of the land surface due to collapse of the regolith and rock strata above an underground mine. It occurs when underground voids or cavities collapse, or when soil or geological formations (including coal seams, sandstone and other sedimentary strata) compact due to reduction in moisture content and pressure within the ground (Holla and Barclay, 2000; IESC, 2014). Subsidence occurs in two phases: active and residual. The active phase comprises about 90% of total subsidence and follows the advance of the mining front, occurring almost immediately with roof collapse. The residual phase takes more time, and occurs as the rocks compress and adjust in the collapsed zone above the mining void. The maximum vertical surface subsidence associated with underground coal mining is typically 1 to 2 m, but can be 2 to 3 m for a thick coal seam at shallow depth (Commonwealth of Australia, 2014b).The maximum subsidence predicted for the Stage 2 Narrabri underground coal mine is 2.17 m and 2.44 m

Depressurisation associated with CSG development also has the potential to compact the coal seam, which may result in subsidence of the land surface (IESC, 2014). There is currently very limited evidence of subsidence available for Australian CSG developments, however modelled predictions of coal seam subsidence for CSG fields in Queensland are up to 300 mm but would not be expected to result in subsidence at the ground surface (Commonwealth of Australia, 2014a).

The collapsed zone is highly fractured and commonly has enhanced hydraulic conductivity and storage to a thickness of about five times the thickness of extracted seam, although cracking and some increased hydraulic conductivity can occur over a thickness of 20 to 30 times the extracted seam height, depending on the strength of overlying strata (Waddington and Kay, 2002). At the surface, longwall mining creates long, closed rectangular basins that may extend beyond the physical boundaries of the mined area. Depending on depression depth, orientation, gradient of depression and connectivity to drainage lines, these depressions will retain more runoff than pre-disturbance and can be associated with local waterlogging. Extraction plans, prepared as part of the development consent process for longwall mines in NSW, must identify water resources at risk from the proposed mining and detail how mining will be undertaken to minimise impacts. In the Namoi subregion, subsidence from future coal mine development has the potential to only occur from the Narrabri South development, as the Caroona coal mine development is unlikely to proceed because of the NSW Government exploration licence buyback in 2016.

Subsidence may lead to a change in surface flow, enhanced erosion of the land surface and stream channels and in some instances loss of surface water through drainage into underground cavities. Figure 45 describes the impacts of subsidence caused by the removal of a coal seam in underground mining and, to a lesser extent, by depressurisation of an aquifer in the 'Surface water drainage' causal pathway group and the 'Subsurface depressurisation and dewatering' causal pathway group (Figure 43). NSW's *Environmental Planning and Assessment Act 1979* regulates underground mine subsidence via extraction plans (formerly subsidence management plans) that describe how a mine operator will manage and minimise subsidence impacts. Since mining consent in NSW is contingent on minimising the negative impacts of subsidence, as specified through an approved extraction plan, for BA modelling purposes the reduction in surface runoff from areas above longwall mines is assumed to be negligible. Details are reported in companion product 2.6.1 for the Namoi subregion (Aryal et al., 2018a).

The cumulative effects on natural surface drainage in the subregion may have medium- to long-term cumulative effects on watercourses within, upstream of and downstream of tenements.

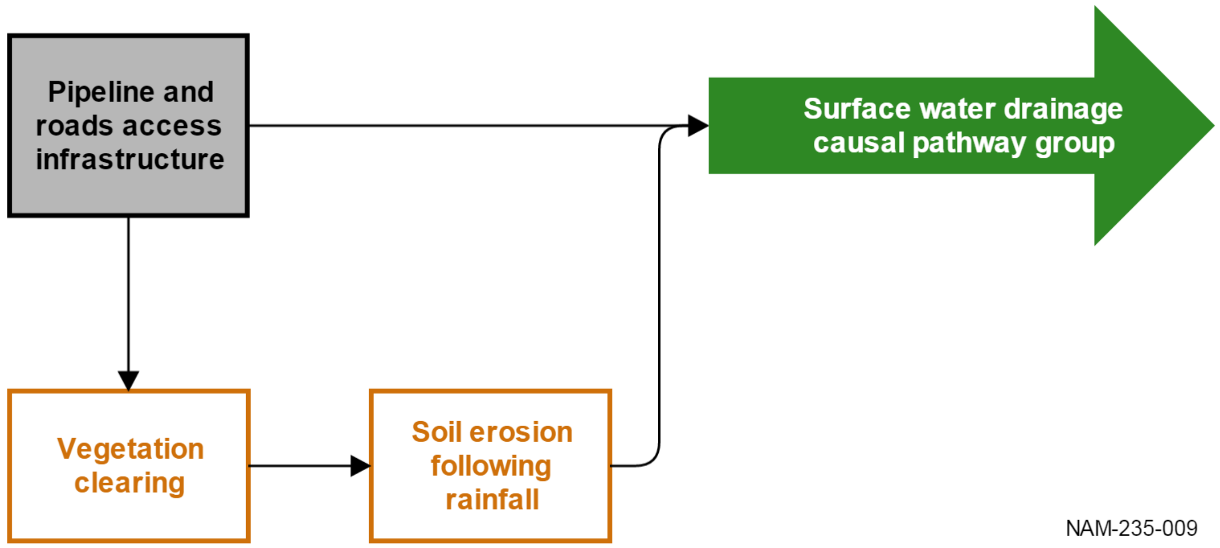

Figure 43 Disruption of the surface water drainage network due to pipeline and roads access infrastructure leads to causal pathways in the 'Surface water drainage' causal pathway group

The colours in the diagram represent the following: green box with white writing = causal pathway group, white box with orange writing = an event that forms part of the causal pathway chain, grey box with black writing = an activity.

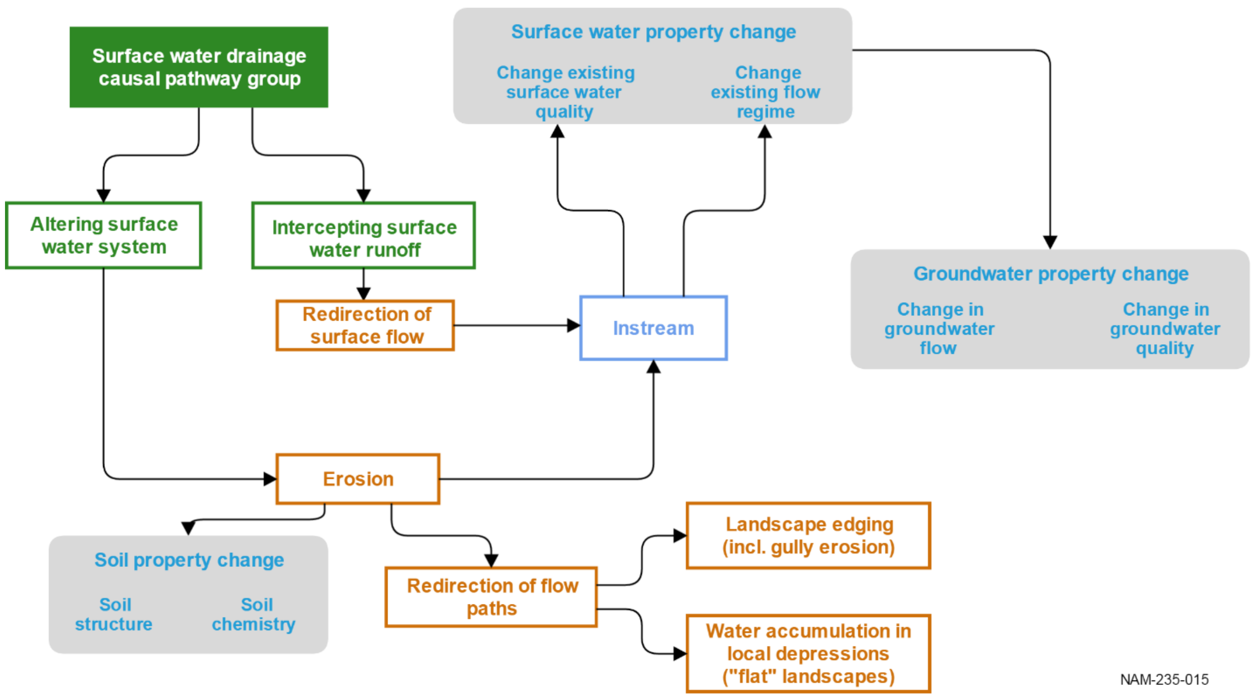

Figure 44 Surface water drainage disruption causes hydrological changes to surface water, groundwater and soil property changes as part of the 'Surface water drainage' causal pathway group

Groundwater properties can be influenced where there are interactions between surface water and groundwater (see Figure 42). The colours in the diagram represent the following: green box with white writing = causal pathway group, white box with green writing = causal pathway, grey box with blue writing = hydrological effect, white box with orange writing = an event that forms part of the causal pathway chain, white box with blue writing = the specific environment where an event takes place.

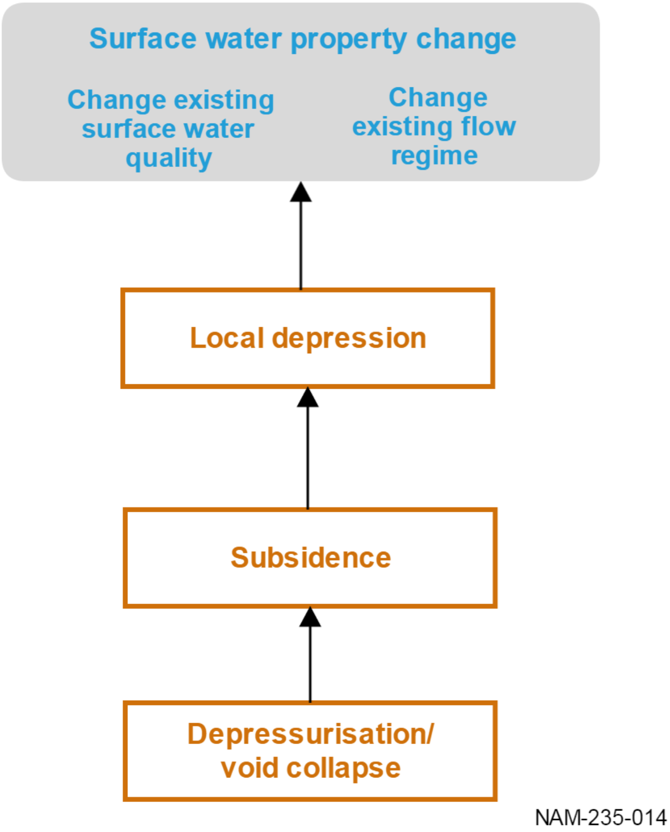

Figure 45 Subsidence caused by depressurisation and coal extraction creates a causal relationship between the 'Subsurface depressurisation and dewatering' causal pathway group and the 'Surface water drainage' causal pathway group (see Figure 44)

The colours in the diagram represent the following: grey box with blue writing = hydrological effect, white box with orange writing = an event that forms part of the causal pathway chain.

2.3.5.3.4 'Operational water management' causal pathway group

CSG operations remove water from the coal seam to release gas during the production stage. If the produced water is of poor quality, it may require dilution with fresh water or treatment to remove salts, gas and other contaminants sourced from the coal seam.

Beneficial uses include water for site management such as dust suppression or washing, discharge to rivers for conveyance to beneficial uses, and reinjection to depleted aquifers. Co-produced water that is treated and disposed of locally via irrigation or release to rivers can affect water quality and quantity. Discharge of treated co-produced water to rivers and for irrigation can affect watertable levels and soil salt mobilisation along watercourses and near irrigation areas. Instream disposal leads to changes in surface water. Reinjection causes groundwater property changes and treatment or amendment of the groundwater for irrigation purposes, which may result in soil property changes (Figure 46).

Discharge of co-produced water from CSG operations for the Narrabri Gas Project is estimated to peak at 8 ML/day in the early stages of production, and is forecast to stabilise at around 4 ML/day on average approximately 10 years after production commences (Santos, 2012). Current options for disposal of co-produced water include use on site for dust suppression and operational requirements and the potential for irrigation or release as environmental flows of (reverse osmosis) treated water.

Water from open-cut and underground coal mines in the Namoi subregion is mostly used for operational purposes including dust suppression and coal processing. Discharge to rivers is limited to times of high flow and/or when water is a suitable quality. More detailed information on mine water management for each baseline mine and additional coal resource development in the Namoi is discussed in Section 2.1.6 in companion product 2.1-2.2 for the Namoi subregion (Aryal et al., 2018b).

Water management structures (dams, levee bunds and diversions) associated with open-cut coal mines can change natural surface drainage or cause excessive runoff during closure that has a cumulative effect on surface water and groundwater systems in the subregion. Upstream impacts that change watercourse geomorphology or create barriers to the migration of aquatic organisms are also possible.

Water management structures are likely to have medium- to long-term effects on surface water quality, direction and flow. Activities that involve discharge to rivers are likely to have episodic- to short-term effects on surface water flow and quality in watercourses in the aquifers in the subregion.

The effects are akin to the disposal of extracted groundwater (Figure 44), albeit being dependent on the water chemistry, temperature and discharge amount of the water source. One major effect of continual discharge is the increase in (base) flow, which can result in major shifts to the aquatic and riparian ecosystem as the stream is buffered against climatic low-flow or cease-to-flow events, however continual discharge is not currently allowed for mines in the Namoi subregion.

Changes to groundwater level and quality and surface water quality associated with discharge to rivers and irrigation that raises the watertable and mobilises salt are likely to be episodic to short term and localised. Other effects, including local reduction in species numbers, are likely to be in the medium to long term and include watercourses with aquifer connectivity that are within, upstream of and downstream of tenements.

The state regulations (as listed in Table 13, Section 2.3.4) and approval conditions for the individual mines regulate water take and discharges of water in the Namoi river basin. Monitoring groundwater and surface water quality – such as for heavy metals or BTEX (benzene, toluene, ethylbenzene and xylene), and the removal or disposal of these – is the responsibility of individual mining companies under their mine water management agreements. Any release of contaminated water to the surface water system, for example by leakage or overflow from a storage dam, will negatively affect downstream water quality. Mines will have monitoring strategies in-place as part of their approval conditions to monitor for any overflow or leaks from on-site storage dams.

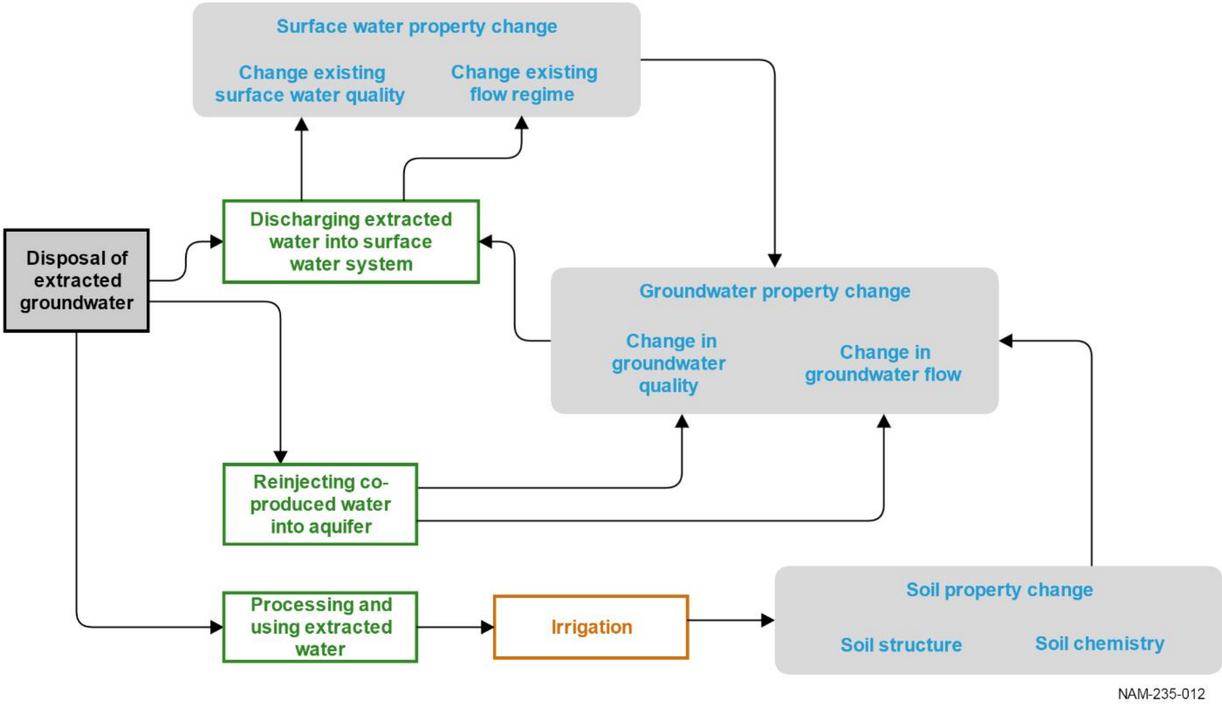

Figure 46 Hydrological changes as a result of disposal of extracted groundwater in the 'Operational water management' causal pathway group

The colours in the diagram represent the following: white box with green writing = causal pathway, grey box with blue writing = hydrological effect, white box with orange writing = an event that forms part of the causal pathway chain, grey box with black writing = an activity.

2.3.5.3.5 Summary of causal pathways

The four causal pathway groups are intrinsically connected through the activities that result in changes to groundwater and surface water. These changes are coal resource development activity specific in the case of pipeline and roads access infrastructure, redirection of surface flow, and groundwater extraction and disposal or the changes are a combination of a range of activities that lead to establishing preferential flow paths transcending stratigraphic units. The previous sections provided the details of the individual causal pathways, and in doing so had to trade off readability with showing all causal pathways and their connectivity. Figure 47 provides this overview of the causal pathway connectivity.

Future coal resource development activities (identified as grey boxes with black writing in Figure 47) and the mechanisms in which these changes affect surface water and the groundwater in the alluvium at the regional level are the main concern of a BA. In this section, the Assessment team outlined the conceptual understanding of these mechanisms – termed causal pathways – and including their linkages. There is one central causal pathway group, 'Subsurface physical flow path'. It embeds these surface water and groundwater property changes, which are the result of linkages (identified through arrows in Figure 47) with all the other causal pathways.

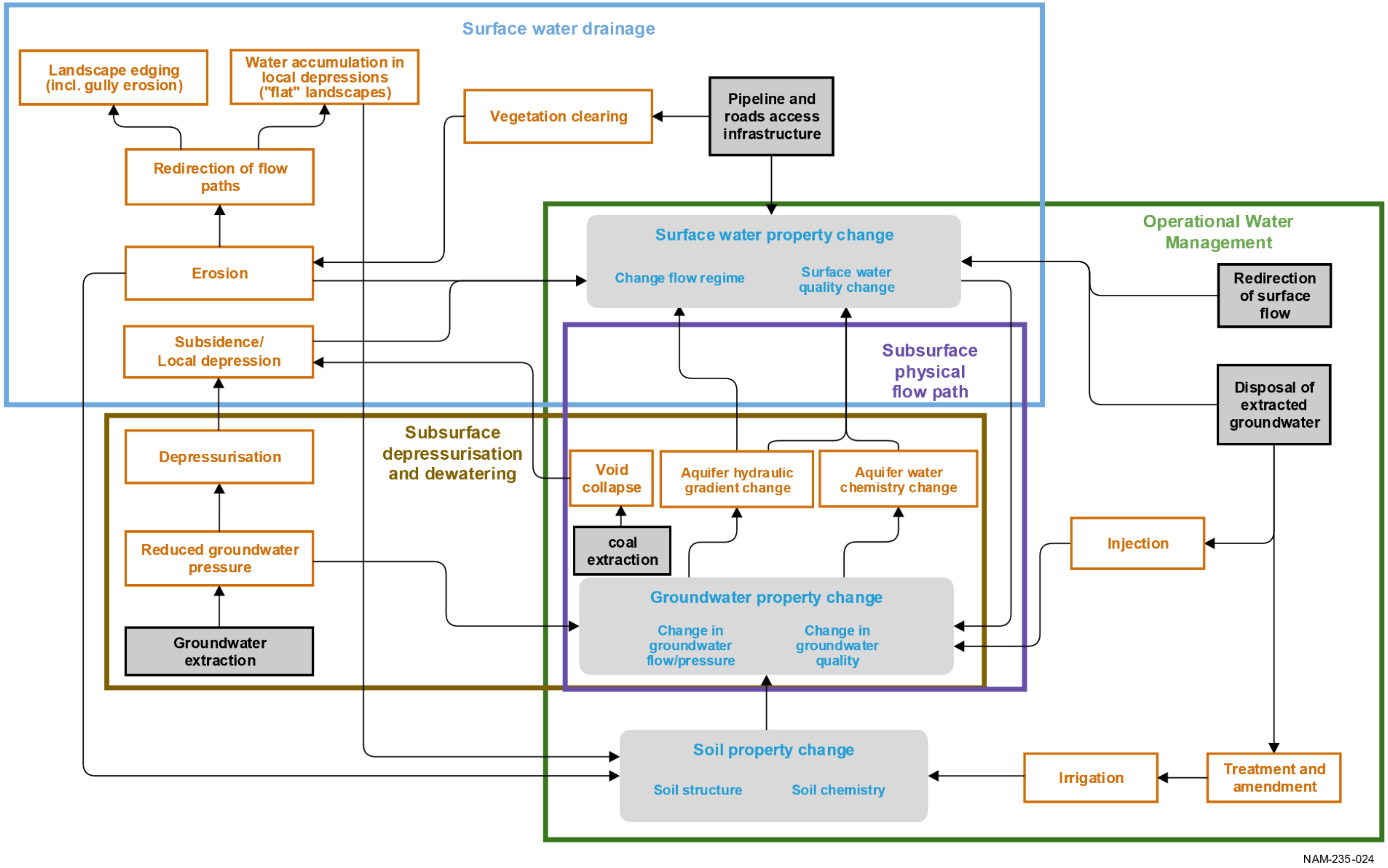

Figure 47 Causal pathway connectivity

The colours in the diagram represent the following: grey box with blue writing = hydrological effect, white box with orange writing = an event that forms part of the causal pathway chain, grey box with black writing = an activity.

2.3.5.3.6 Causal pathways for the coal resource development pathway

This section explains the coal resource development specific causal pathways for the Namoi subregion, which were developed in the 'Conceptual modelling of causal pathways' workshop (held in Canberra in August 2015) and links these to the generic causal pathway groups described in the previous sections.

2.3.5.3.6.1 Coal seam gas operations

The Narrabri Gas Project is the only CSG development in the CRDP for the Namoi subregion. The Narrabri Gas Project is targeting the main coal seams in the lower Permian Maules Creek Formation. There is the potential for connectivity between the target coal seams and the surface and near-surface aquifers through the stratigraphic units outlined in Figure 48, which leads to causal pathways that are related to subsidence and groundwater extraction ('Subsurface depressurisation and dewatering' and 'Subsurface physical flow paths' causal pathway groups, respectively). Detailed descriptions of the causal pathways are in Section 2.3.5.3.1 and Section 2.3.5.3.2 and they relate specifically to the causal pathways outlined in Figure 40 and Figure 44. Agricultural bores accessing the alluvial aquifers and the Pilliga Sandstone aquifer in the Great Artesian Basin (GAB) may have reduced flow if the induced pressure change from CSG depressurisation propagates vertically through the overlying sequence, potentially leading to a drop in water levels and bores drying up. This may also result in any of the GAB bores that are artesian ceasing to flow naturally, requiring pumping to extract water. Propagation of the depressurisation cone may be impeded or enhanced by faults and the presence or absence of aquitards.

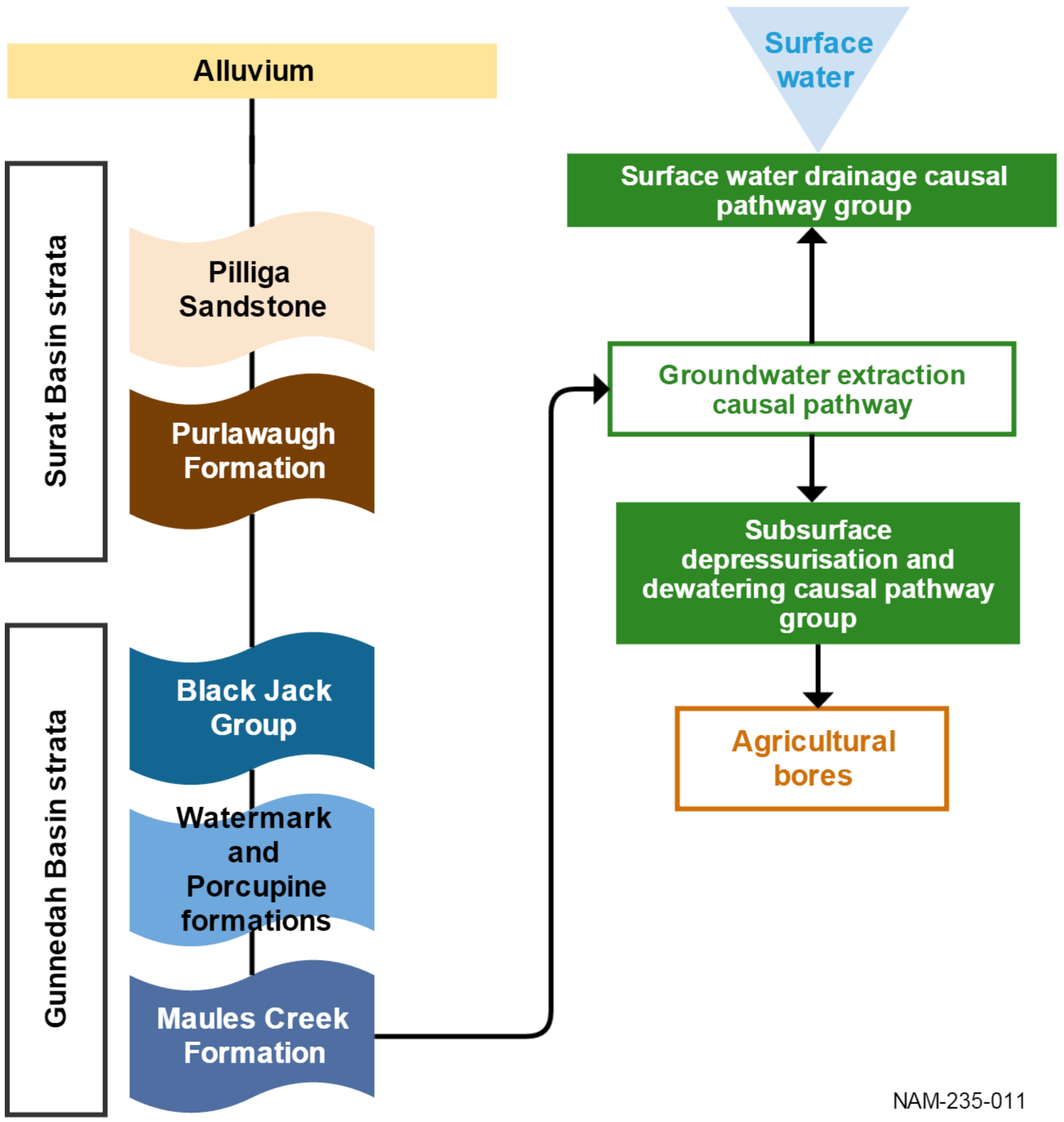

Figure 48 Causal pathways resulting from changes in groundwater and surface water for the Narrabri Gas Project targeting the Maules Creek Formation

Causal pathways are discussed in Section 2.3.5.3 (see Figure 40, Figure 42, Figure 43, Figure 44, Figure 45 and Figure 46).

2.3.5.3.6.2 Open-cut and underground coal mines

There are 15 open-cut and underground coal mines in the CRDP for the Namoi subregion. For the purposes of assessing potential causal pathways, the coal mines in the CRDP for the Namoi subregion have been grouped according to the target coal seams and the geology. The mines in the CRDP located in the Mullaley sub-basin (Narrabri North Mine, Narrabri South, Watermark Coal Project, Caroona Coal Project, Sunnyside Mine and Gunnedah Precinct) primarily target the Hoskissons Coal in the upper Permian Black Jack Group. These mines are overlain by Surat Basin strata (with thickness on average about 300 m) and alluvium. The remaining mines: Maules Creek Mine, Boggabri Coal Mine, Tarrawonga Mine, Vickery Coal Project and Rocglen Mine are located in the Maules Creek sub-basin and target coal seams in the Maules Creek Formation. Only Gunnedah Basin strata and alluvial sediments are present at these mine sites, as the Surat Basin strata have been completely removed by uplift and erosion.

There is the potential for connectivity between the target coal seams and the surface and near-surface aquifers through the Gunnedah Basin strata, which can lead to hydrological changes related to subsidence and groundwater extraction. Detailed descriptions of the causal pathways are in Section 2.3.5.3.1 (‘Subsurface depressurisation and dewatering’ causal pathway group) and Section 2.3.5.3.2 (‘Subsurface physical flow paths’ causal pathway group) and they relate specifically to the causal pathways outlined in Figure 40 and Figure 44.

Coal mines in the Mullaley sub-basin

The coal resource developments in the Mullaley sub-basin include the Narrabri North Mine, Narrabri South and the Caroona Coal Project (all underground mines), and the open-cut Watermark Coal Project, Sunnyside Mine and Gunnedah Precinct (see Figure 7, Figure 8 and Figure 9). These mines target the coal seams in the upper Permian Black Jack Group, primarily the Hoskissons Coal. The Narrabri North Mine and Narrabri South project area is partly overlain by the Pilliga Sandstone and Purlawaugh Formation (see pink line in Figure 49) of the Surat Basin. In the south of the Mullaley sub-basin around the Watermark and Caroona coal projects, only the Garrawilla Volcanics are present. Consequently, causal pathways for the Watermark Coal Project and Caroona Coal Project will not include the Pilliga Sandstone and Purlawaugh Formation.

Activities relevant to open-cut developments involve aquifer dewatering of the target seam, which will potentially reduce water pressures in the coal seams and lower the regional watertable, with some potential for transmission of these water level reductions to other aquifers (depending on hydraulic parameters and thickness of aquitards etc.). Activities relevant to the three underground coal mines involve the extraction of coal from underground longwall panels which results in the collapse of strata above the mined-out panels, leading to subsidence. There is the potential to impact surface physical flow paths. The mine infrastructure interferes with and disrupts the natural surface drainage. Management, storage and disposal of mine water may also create localised impacts. Figure 49 provides a schematic of the causal pathways through the stratigraphic layers.

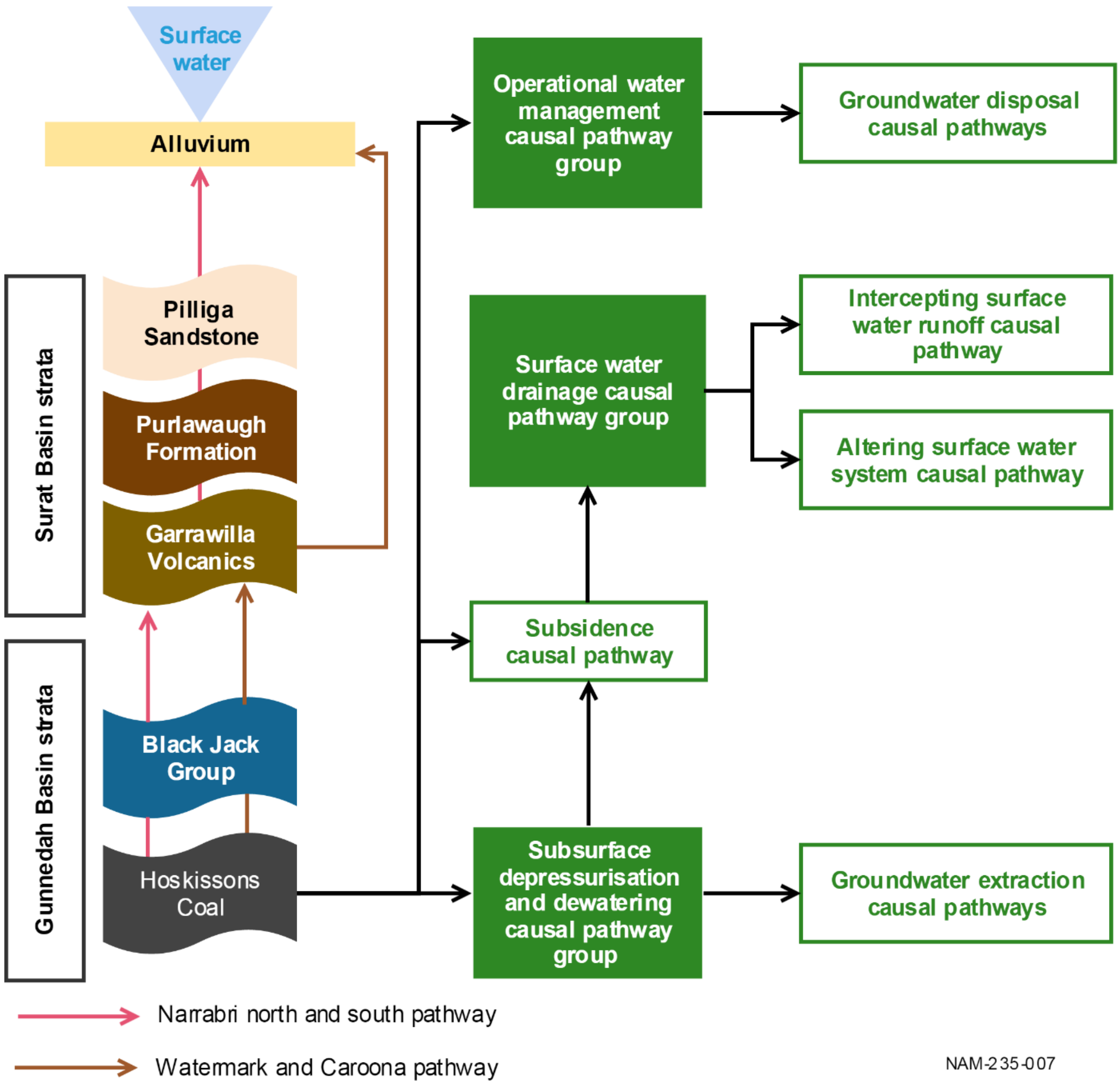

Figure 49 Causal pathway for the open-cut and underground coal mines in the Mullaley sub-basin targeting the Black Jack Group in the Permian stratigraphy

Causal pathways are discussed in Section 2.3.5.3 (see Figure 40, Figure 42, Figure 43, Figure 44, Figure 45 and Figure 46).

Coal mines in the Maules Creek sub-basin

The Maules Creek Mine, Boggabri (including expansion) Coal Mine, Tarrawonga (including expansion) Mine, Vickery Coal Project (including Vickery South) and Rocglen Mine are located in the Maules Creek sub-basin to the east of the Boggabri Ridge (see Figure 8 and Figure 9) and are targeting the coal seams in the Maules Creek Formation. There are no Surat Basin units in this part of the Namoi subregion, nor are there any units from the Black Jack Group due to erosion of Gunnedah Basin strata above the Maules Creek Formation in the Maules Creek sub-basin (Geological Survey of NSW, 2002) (see Figure 8). Consequently there is the potential for a lowering of the regional watertable in the Upper Namoi alluvium if mining activities occur close to the alluvium. Figure 50 provides a schematic of the causal pathway to impact through the stratigraphic layers. There is potential for interaction between the Namoi River alluvium and associated waters flowing into the Namoi River if mining results in a decrease in baseflow to the river, as this is an area of gaining streams (Figure 41).

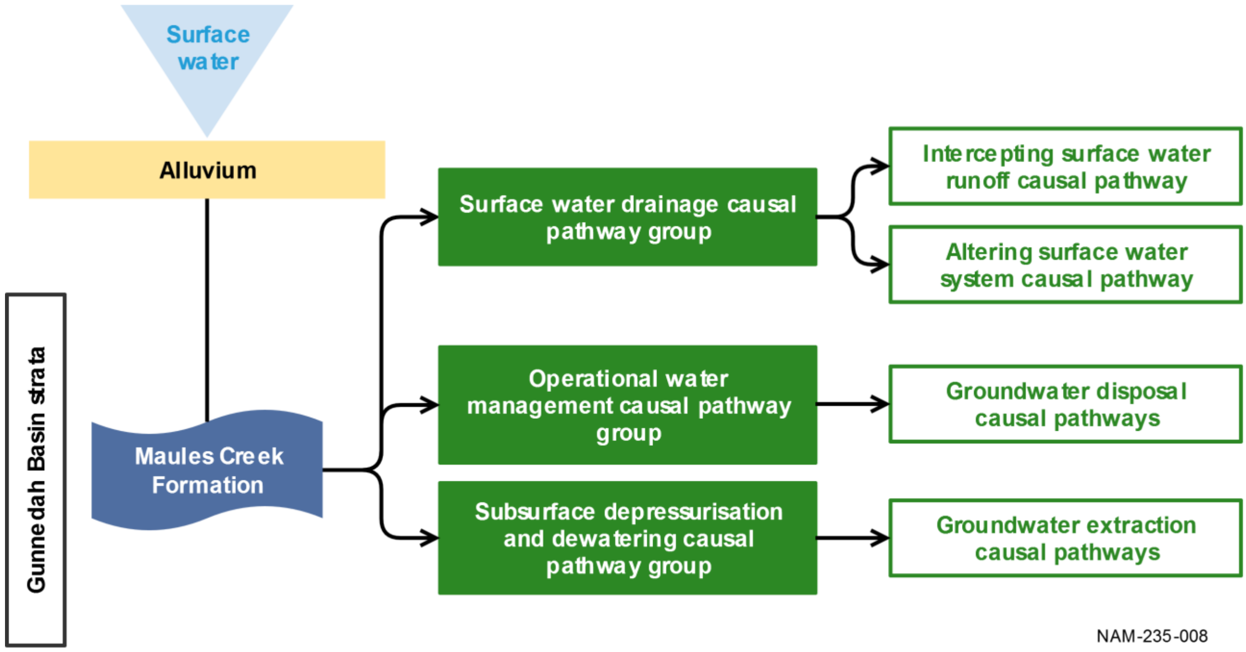

Figure 50 'Subsurface depressurisation and dewatering' and 'Surface water drainage' causal pathway groups for open-cut mines in the Maules Creek sub-basin targeting the Maules Creek Formation in the Permian stratigraphy

Causal pathways are discussed in Section 2.3.5.3 (see Figure 40, Figure 42, Figure 43, Figure 44 and Figure 45).

Werris Creek Mine

The Werris Creek Mine is located in the Werrie Basin (see Section 2.3.2 for more detail). The target coal seams for the Werris Creek Mine are in the Willow Tree Formation (see Figure 6 in Section 2.3.2). The Werrie Basin is a structurally isolated (non-contiguous) part of the Gunnedah Basin. The very low permeability basement rocks of the New England Orogen underlying the Werrie Basin essentially form a natural hydrogeological barrier that isolates the regional groundwater flow system of the Werrie Basin from the Gunnedah Basin. Consequently, the Werris Creek Mine is not included in the Namoi groundwater modelling. The surface waters around the Werris Creek Mine flow into the Namoi River, and so form part of the surface water modelling. Figure 51 provides a schematic of the causal pathways through the stratigraphic layers in the Werrie Basin.

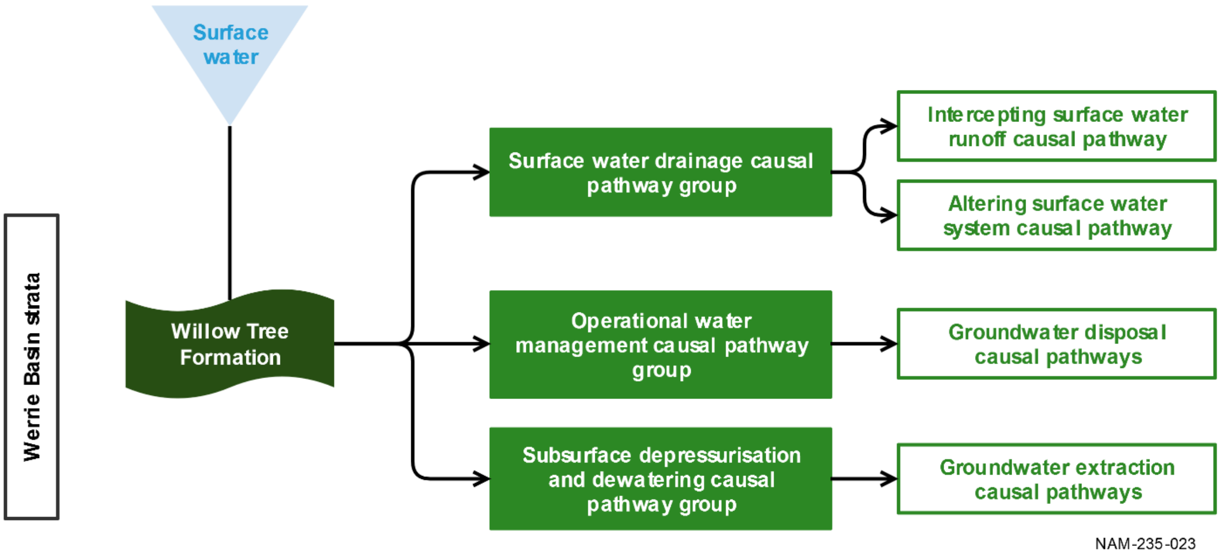

Figure 51 Schematic of causal pathways for the Werris Creek Mine in the Werrie Basin

2.3.5.3.7 Summary of the causal pathways for the coal resource development pathway

This section describes the potential cumulative effects of the CRDP in the Namoi subregion, which includes one additional CSG operation, four baseline open-cut coal mines, one baseline underground coal mine and nine additional open-cut coal mines or mine expansions and two additional underground coal mines (see Table 11 in Section 2.3.4). The cumulative hydrological effects of multiple coal resource developments in the Namoi subregion, which overlap in both time and space, have the potential to affect aquifers, catchments and watercourses via the four main causal pathway groups (Table 14).

The four causal pathway groups associated with the baseline coal mining operations, and the additional CSG and coal mining operations have the potential to directly affect the local and regional groundwater system, and the surface water – groundwater interactions in aquifer areas of the Namoi River and associated streams.

Based on Figure 18 in Section 2.3.3 and the locations of the additional coal resource development (Figure 39), the expected area of potential groundwater change is confined to the Liverpool Plains and the Pilliga and Pilliga Outwash. Surface water – groundwater interactions and potential surface water responses may occur in the streams of these geographic zones and those in the Castlereagh-Barwon geographic zones (as per Table 5 in Section 2.3.3).

Figure 52 shows the coal resource developments overlain with the landscape groups in the PAE. It shows that all landscape groups are potentially affected – namely, ‘Dryland remnant vegetation’, ‘Floodplain or lowland riverine’, ‘Non-floodplain or upland riverine’, ‘Human modified’, ‘Springs’ and ‘Rainforest’. While this assessment is helpful in identifying the broad spatial extent of the hydrological responses to coal resource development and the potentially impacted landscape groups in the subregion, it is only a starting point that enables a coarse identification of zones (as outlined in Figure 18), where impacts are very unlikely. A quantitative assessment of these hydrological changes will delineate the areas where impacts to ecosystems may potentially occur. Hydrological modelling outputs (detailed in companion product 2.6.1 for the Namoi subregion (Aryal et al., 2018a)) will provide the numeric values and the detailed spatial context of the hydrological responses to coal resource development in the Namoi subregion. A result of this modelling is the refinement of the expected zone of potential hydrological change, which will enable a more precise identification of landscape classes potentially impacted.

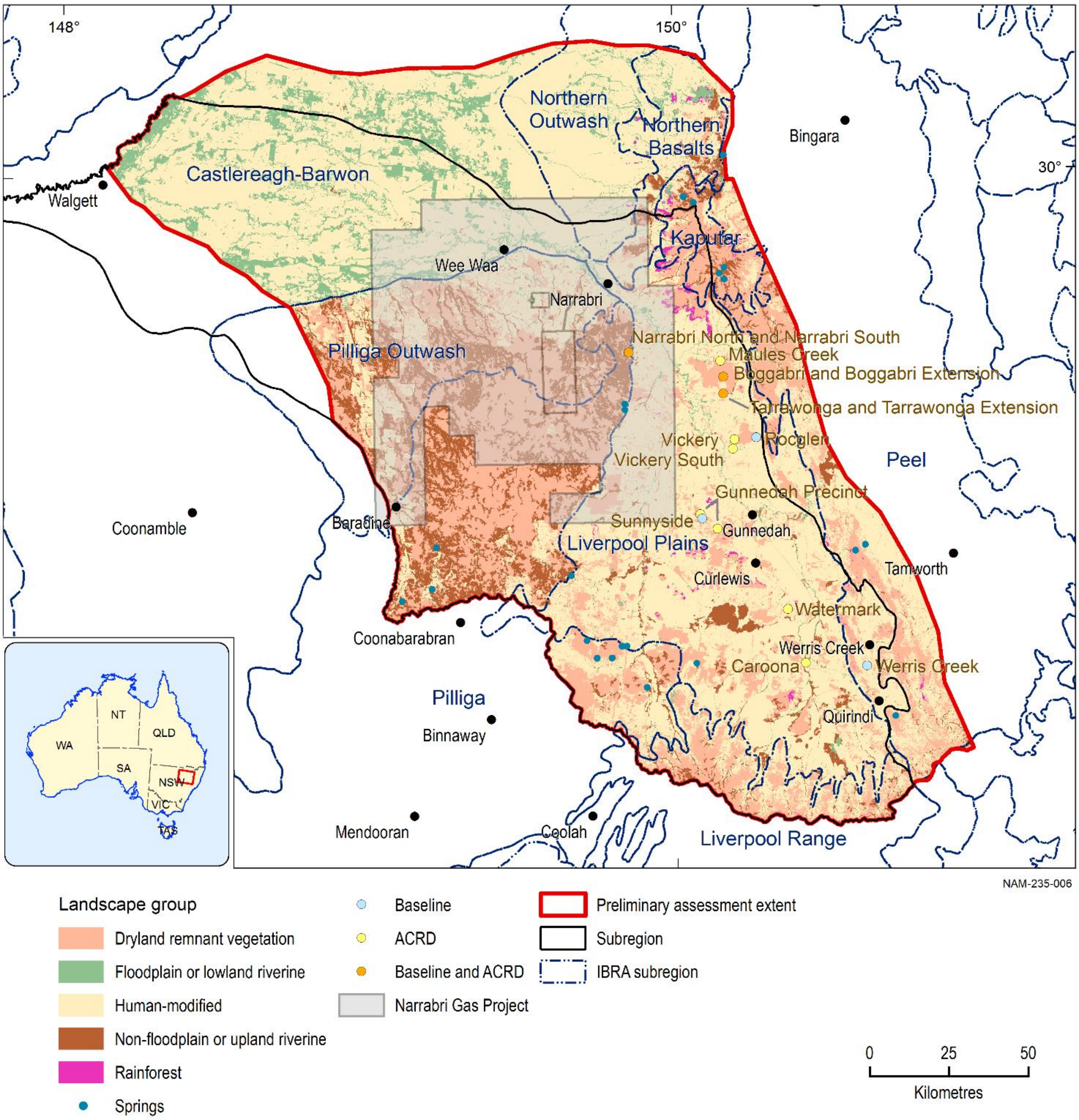

Figure 52 Landscape groups overlain with Interim Biogeographic Regionalisation for Australia (IBRA) subregions in the Namoi preliminary assessment extent (PAE)

There are three developments that are both baseline mines and additional coal resource developments (ACRD) on this map: Boggabri, Tarrawonga and Narrabri North are the baseline mines. Boggabri expansion, Tarrawonga expansion and Narrabri South are the additional coal resource developments. The coal resource developments in the coal resource development pathway (CRDP) are the sum of those in the baseline coal resource development (baseline) and the additional coal resource development.
Mining developments are likely to impact Liverpool Plains, Pilliga and Pilliga Outwash. Although the coal seam gas (CSG) petroleum exploration lease covers the Castlereagh-Barwon, Northern Outwash, the Santos environmental impact statement indicates that CSG developments are unlikely to occur in these additional regions (Chubb, 2017).
The Narrabri Gas Project extent includes the exploration lease area.
Data: NSW Trade and Investment (Dataset 1), SEWPaC (Dataset 2), Bioregional Assessment Programme (Dataset 3, Dataset 6, Dataset 7)

Three mines in the baseline (Boggabri, Narrabri North and Tarrawonga) have expansions that are modelled in the CRDP. The baseline defines the effects of the mines on groundwater and surface water and is modelled into the future. Modelling the additional coal resource developments, which include coal mining and CSG, defines the future changes in water. All four causal pathways are relevant to these coal resource developments. The causal pathway groups are the same for both open-cut and underground coal mines and CSG operations in the CRDP (Table 17).

Table 17 Causal pathway groups arising from coal mines and coal seam gas operations for coal resource developments in the baseline and coal resource development pathway (CRDP)

Type of coal resource development	Causal pathway group	In baseline?	In CRDP?	Spatial context
Coal mines	Subsurface depressurisation and dewatering	Yes	Yes	Alluvial and consolidated sedimentary rock aquifers
	Subsurface physical flow paths	Yes	Yes	Aquifers within tenements Watercourses in aquifer outcrop areas within and downstream of tenements
	Surface water drainage	Yes	Yes	Watercourses within and downstream of tenements
	Operational water management	Yes	Yes	Watercourses in aquifer outcrop areas within and downstream of tenements
Coal seam gas operations	Subsurface depressurisation and dewatering	No	Yes	Alluvial and consolidated sedimentary rock aquifers
	Subsurface physical flow paths	No	Yes	Aquifers within tenements Watercourses in aquifer outcrop areas within and downstream of tenements
	Surface water drainage	No	Yes	Watercourses within and downstream of tenements
	Operational water management	No	Yes	Watercourses in aquifer outcrop areas within and downstream of tenements

2.3.5.4 Gaps

While the Namoi subregion has a long history of coal mining, the subregion is experiencing an increase in the intensity of mining and CSG activities with the expansion of existing mines and new coal resource developments commencing or in the pipeline. Many of the hazards expected from mining are expected to be observed locally in the subregion (e.g. subsidence, depressurisation of aquifers and disruption of natural drainage) and their potential effects on water resources and water-dependent assets are recognised. The local experience of coal mining hazards and their effects is supported by international experience, and the risks from many hazards are managed through existing regulatory controls on mine planning and operations management.

The extent to which the development of CSG in the subregion, coupled with an expansion in mining activities, will impact on water-dependent assets is hard to predict. This means that uncertainty exists in the precise spatial extent of groundwater level decline and surface water changes due to coal mines and CSG operations. For example, the uncertainty analysis undertaken for the numerical groundwater modelling does allow a probabilistic estimate of maximum groundwater level decline, as described in companion product 2.6.2 for the Namoi subregion

(Janardhanan et al., 2018). Surface water modelling and associated uncertainties are also restricted as a result of the inability to model streams with limited or non-existing gauging information.

The Assessment team considers that faults are unlikely to be a major influence on modelling groundwater flow at the regional scale. The model developed for the BA of the Namoi subregion is regional in scale and does not incorporate faults directly. It uses a statistical approach that is stochastically evaluating a very wide range of uniform parameter values, which accounts for the regional impacts of faults. The high end of the parameter range can be thought of as the hydraulic properties that are equivalent to an aquitard locally compromised by faults. Companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018) provides the results of this, and from it we can take that faults are unlikely to have a major impact in the regional groundwater model. Faults do, however, have the potential to have a major influence on groundwater flow at a local scale, and addressing the potential influence of faults at the local scale would require investigation in local scale assessments.

Subterranean faults and fractures also affect the flow paths for methane. In areas where faults and fractures connect the coal seam with surface water, hydraulic fracturing could increase methane leakage to aquifers and connected surface waters. Analyses of petroleum well completion reports (where gas content logs exist) and gas absorption tests of cores may assist in addressing this. Some of this information may be available from the Digital Imaging of Geological System website (NSW Government, 2017).

The lack of information with regards to the interactions of the causal pathways with surface and groundwater quality is a major gap. The lack of long-term, consistent water quality measurements of surface water and groundwater systems limits the value of developing a water quality focused coupled surface water – groundwater model in the Namoi subregion.

The causal pathway groups link hazards to subregion assets but do not predict the impact. Numerical modelling is needed to determine whether the magnitude of change from mining activities and strength of connection to each subregion asset, as mediated by existing regulatory controls, are sufficient to impact each asset. This is a gap being addressed through the quantitative modelling within the BAs.

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Dataset 7 Bioregional Assessment Programme (2014) GEODATA TOPO 250K Series 3, File Geodatabase format (.gdb). Bioregional Assessment Derived Dataset. Viewed 02 May 2016, http://data.bioregionalassessments.gov.au/dataset/96ebf889-f726-4967-9964-714fb57d679b.

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

annual flow: the volume of water that discharges past a specific point in a stream in a year, commonly measured in GL/year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).

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

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

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

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. The assessment extent is created by revising the preliminary assessment extent on the basis of information from Component 1: Contextual information and Component 2: Model-data analysis.

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.

baseflow: the portion of streamflow that comes from shallow and deep subsurface flow, and is an important part of the groundwater system baseline coal resource development: a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012

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

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

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

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

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

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

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

conceptual model: abstraction or simplification of reality

confined aquifer: an aquifer saturated with confining layers of low-permeability rock or sediment both above and below it. It is under pressure so that when the aquifer is penetrated by a bore, the water will rise above the top of the aquifer.

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

consequence: synonym of impact

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

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

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

depressurisation: in the context of coal seam gas operations, depressurisation is the process whereby the hydrostatic (water) pressure within a coal seam is reduced (through pumping) such that natural gas desorbs from within the coal matrix, enabling the gas (and associated water) to flow to surface

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

dewatering: the process of controlling groundwater flow within and around mining operations that occur below the watertable. In such operations, mine dewatering plans are important to provide more efficient work conditions, improve stability and safety, and enhance economic viability of operations. There are various dewatering methods, such as direct pumping of water from within a mine, installation of dewatering wells around the mine perimeter, and pit slope drains.

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

diversion: see extraction

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

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

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

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

geological formation: stratigraphic unit with distinct rock types, which is able to mapped at surface or in the subsurface, and which formed at a specific period of geological time

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

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

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

groundwater system: see water system

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.

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

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

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

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

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

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

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

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

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

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

likelihood: probability that something might happen

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

lithic: sediment or sedimentary rock that contains a significant proportion of detrital rock fragments (10 to 50%) derived by erosion from older, pre-existing rock outcrop

Namoi subregion: The Namoi subregion is located within the Murray–Darling Basin in central New South Wales. The subregion lies within the Namoi river basin, which includes the Namoi, Peel and Manilla rivers. However, the subregion being assessed is smaller than the Namoi river basin because the eastern part of the river basin does not overlie a coal-bearing geological basin. The largest towns in the subregion are Gunnedah, Narrabri and Walgett. The main surface water resource of the Namoi subregion is the Namoi River. There are three large dams that supply water to the subregion, of which Keepit Dam is the main water storage. More than half of the water released from Keepit Dam and river inflow may be extracted for use for agriculture, towns and households. Of this, the great majority is used for agricultural irrigation. The landscape has been considerably altered since European settlement for agriculture. Significant volumes of groundwater are also used for agriculture (cropping). Across the subregion there are a number of water-dependent ecological communities, and plant and animal species that are listed as threatened under either Commonwealth or New South Wales legislation. The subregion also contains Lake Goran, a wetland of national importance, and sites of international importance for bird conservation.

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

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

preliminary assessment extent: the geographic area associated with a subregion or bioregion in which the potential water-related impact of coal resource development on assets is assessed. The PAE is estimated at the beginning of a bioregional assessment, and is updated to the ‘assessment extent’ on the basis of information from Component 1: Contextual information and Component 2: Model-data analysis.

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

receptor impact model: a function that translates hydrological changes into the distribution or range of potential ecosystem outcomes that may arise from those changes. Within bioregional assessments, hydrological changes are described by hydrological response variables, ecosystem outcomes are described by receptor impact variables, and a receptor impact model determines the relationship between a particular receptor impact variable and one or more hydrological response variables. Receptor impact models are relevant to specific landscape classes, and play a crucial role in quantifying potential impacts for ecological water-dependent assets that are within the landscape class. In the broader scientific literature receptor impact models are often known as ‘ecological response functions’.

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

recharge: see groundwater recharge

riparian: An area or zone within or along the banks of a stream or adjacent to a watercourse or wetland; relating to a riverbank and its environment, particularly to the vegetation.

risk: the effect of uncertainty on objectives

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

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

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

stratigraphy: stratified (layered) rocks

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

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

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

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

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

tenement: a defined area of land granted by a relevant government authority under prescribed legislative conditions to permit various activities associated with the exploration, development and mining of a specific mineral or energy resource, such as coal. Administration and granting of tenements is usually undertaken by state and territory governments, with various types related to the expected level and style of exploration and mining. Tenements are important mechanisms to maintain standards and safeguards relating to environmental factors and other land uses, including native title.

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

unconfined aquifer: an aquifer whose upper water surface (watertable) is at atmospheric pressure and does not have a confining layer of low-permeability rock or sediment above it

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

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

water-dependent asset register: a simple and authoritative listing of the assets within the preliminary assessment extent (PAE) that are potentially subject to water-related impacts water system: a system that is hydrologically connected and described at the level desired for management purposes (e.g. subcatchment, catchment, basin or drainage division, or groundwater management unit, subaquifer, aquifer, groundwater basin)

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

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

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

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