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Department of Agriculture, Water and the Environment

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BIOREGIONAL ASSESSMENTS

CSIRO

Geological and environmental baseline assessment for the Cooper GBA region

Geological and Bioregional Assessment: Stage 2

2020

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

The Geological and Bioregional Assessment Program

The Geological and Bioregional Assessment Program will provide independent scientific advice on the potential impacts from development of selected unconventional hydrocarbon plays on water and the environment. The geological and environmental data and tools produced by the Program will assist governments, industry, landowners and the community to help inform decision making and enhance the coordinated management of potential impacts.

The Program 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 geological and bioregional assessments. For more information, visit http://www.bioregionalassessments.gov.au.

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Authorship is listed alphabetically after first author.

On 1 February 2020 the Department of the Environment and Energy and the Department of Agriculture merged to form the Department of Agriculture, Water and the Environment. Work for this document was carried out under the then Department of the Environment and Energy. Therefore, references to both departments are retained in this report.

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Cover photograph

Cooper Creek in flood, 4 km east of Windorah, March 2018.
Credit: Geological and Bioregional Assessment Program, Russell Crosbie (CSIRO)
Element: GBA-COO-2-343

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At a glance

The $35.4 million Geological and Bioregional Assessment (GBA) Program is assessing the potential environmental impacts of shale and tight gas development to inform regulatory frameworks and management approaches. The geological and environmental baseline assessment for the Cooper GBA region (Stage 2) integrates data, knowledge and conceptual models that are the building blocks for the Stage 3 impact analysis and management. The Cooper GBA region (Figure 1) is in south-west Queensland and in the north-east of SA. Although conventional production has been underway for over 50 years, the region continues to yield new onshore gas discoveries.

Geology and gas resources: Areas of higher prospectivity for shale, tight and deep coal gas plays include the Nappamerri, Patchawarra, Windorah troughs (Figure 1), which is consistent with the location of recent exploration activity.

Groundwater*:* Most (90%) of the 2137 registered bores that access the Eromanga and Lake Eyre basins are less than 300 m deep. The deeper Cooper Basin is not a groundwater source.

Surface water: Cooper Creek supports the Ramsar-listed Coongie Lakes and many waterholes and terminal lakes. Waterholes are sustained by localised freshwater lenses recharged by floods. There is no evidence of connectivity between deeper groundwaters, gas plays and waterholes.

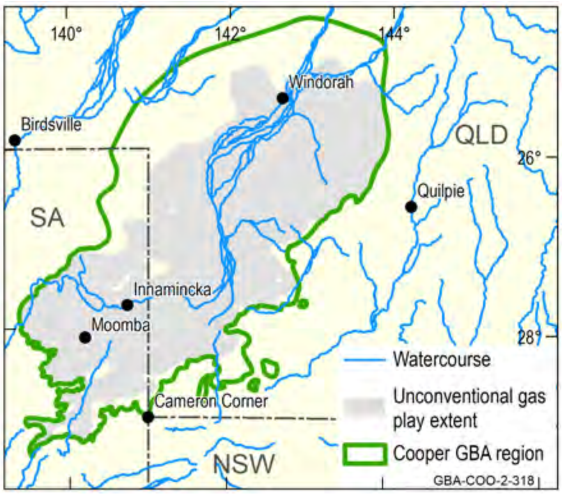

Figure 1 The Cooper GBA region

Element: GBA-COO-2-318

Water availability: Surface water is an unreliable potential water source for a future shale, tight and deep coal gas industry. Groundwater and produced water extracted during conventional oil and gas development are likely water sources.

Potential hydrological connections: Stage 3 will assess potential impacts from possible hydrological connections between deep unconventional gas plays or water source aquifers and environmental assets (including groundwater-dependent ecosystems).

Protected matters: Matters of national and state environmental significance include threatened species (plants, reptiles, birds and mammals) and ecological communities, wetlands, and heritage places.

Most of the Cooper GBA region is classified as floodplain and alluvium, inland dunefields or undulating country on fine-grained sedimentary rocks. Conceptual models for each landscape class will underpin assessments in Stage 3.

In Stage 3, 12 protected species and 18 protected areas will be assessed in greater detail (priority 1). This includes ten threatened species, one threatened ecological community and one Ramsar-listed wetland listed under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth). A further nine protected areas will be assessed at a regional scale using landscape classes (priority 2). Further assessment is not warranted for the remaining 131 protected matters (priority 3).

Potential impacts: Over 200 individual hazards were systematically identified by considering all the possible ways an activity may impact ecological, economic and social values. Hazards were classified into 14 causal pathways – the logical chain of events that link unconventional gas resource development with potential impacts on water and the environment – and then aggregated in three groups.

Stage 3 will assess how each causal pathway might impact on the suite of endpoints – ecological, economic and/or social values to be protected. Seven causal pathways will be assessed in greater detail (priority 1). Important potential impacts to be assessed in Stage 3 are changes to groundwater quality; surface water flows; cultural heritage damage or loss; habitat fragmentation and loss; introduction of invasive species; and contamination of soil, groundwater and/or surface water.

The Geological and Bioregional Assessment Program

The $35.4 million Geological and Bioregional Assessment (GBA) Program is assessing the potential environmental impacts of shale and tight gas development to inform regulatory frameworks and appropriate management approaches. The geological and environmental knowledge, data and tools produced by the Program will assist governments, industry, landowners and the community by informing decision making and enabling the coordinated management of potential impacts.

In consultation with state and territory governments and industry, three geological basins were selected based on prioritisation and ranking in Stage 1: Cooper Basin, Isa Superbasin and Beetaloo Sub-basin. In Stage 2, geological, hydrological and ecological data were used to define 'GBA regions': the Cooper GBA region in Queensland, SA and NSW; the Isa GBA region in Queensland; and the Beetaloo GBA region in NT. In early 2018, deep coal gas was added to the assessment for the Cooper GBA region, as this play is actively being explored by industry.

The Program will assess the potential impacts of selected shale and tight gas development on water and the environment and provide independent scientific advice to governments, landowners, the community, business and investors to inform decision making. Geoscience Australia and CSIRO are conducting the assessments. The Program is managed by the Department of the Environment and Energy and supported by the Bureau of Meteorology.

The Program aims to:

- inform government and industry and encourage exploration to bring new gas supplies to the East Coast Gas Market within five to ten years
- increase understanding of the potential impacts on water and the environment posed by development of shale, tight and deep coal gas resources
- increase the efficiency of assessment and ongoing regulation, particularly through improved reporting and data provision/management approaches
- improve community understanding of the industry.

The Program commenced in July 2017 and comprises three stages:

- **Stage 1 Rapid regional basin prioritisation** identified and prioritised geological basins with the greatest potential to deliver shale and/or tight gas to the East Coast Gas Market within the next five to ten years.
- **Stage 2 Geological and environmental baseline assessments** is compiling and analysing available data for the three selected regions to form a baseline and identify gaps to guide collection of additional baseline data where needed. This analysis includes a geological basin assessment to define structural and stratigraphic characteristics and an environmental data synthesis.
- **Stage 3 Impact analysis and management** will analyse the potential impacts to water resources and matters of environmental significance to inform and support Commonwealth and State management and compliance activities.

The PDF of this report and the supporting technical appendices are available at https://www.bioregionalassessments.gov.au/geological-and-bioregional-assessment-program.

About this report

This report synthesises knowledge about the geology and prospectivity of shale, tight and deep coal gas resources, water resources, protected matters (environmental and cultural) and risks to water (quantity and quality) and the environment in the Cooper GBA region (Figure 2).

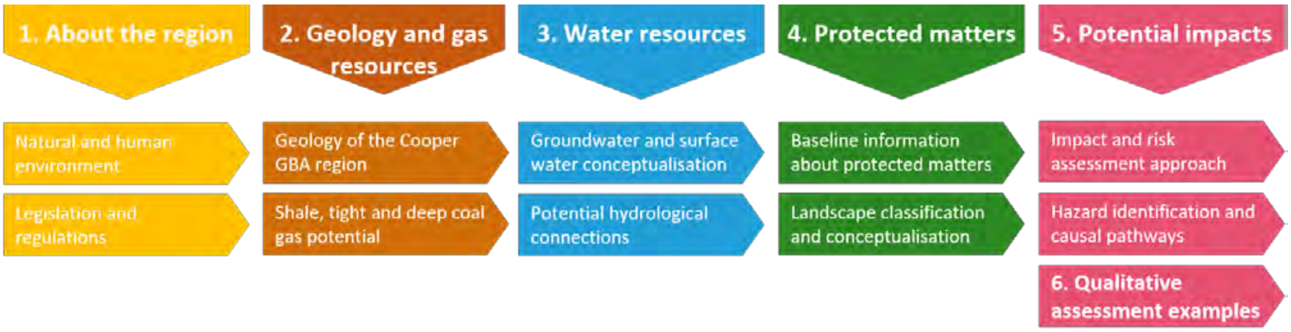

Figure 2 Geological and environmental baseline assessment report structure

Element: GBA-COO-2-105

1. **'About the region'** briefly introduces the natural and human environments of the Cooper GBA region and summarises the legislative and regulatory controls governing water and gas resource development.
2. **'Geology and gas resources'** defines the stratigraphic and structural characteristics that may influence shale, tight and deep coal gas prospectivity, extraction and potential environmental risks. The spatial extent and relative prospectivity of the resources are assessed.
3. **'Water resources'** describes the current conceptual understanding of surface water and groundwater and water quality, and the surface water – groundwater interactions in the region. This section concludes with an assessment of the availability of water resources for future drilling and hydraulic fracturing for shale, tight and deep coal gas development.
4. **'Protected matters'** describes the environmental and cultural knowledge in the region, with an emphasis on Matters of National Environmental Significance and Matters of State Environmental Significance. Landscape classification is used to systematically define geographical areas with similar physical and/or biological and hydrological characteristics.
5. **'Potential impacts'** identified by a systematic hazard analysis of the potential hazards associated with all life-cycle stages of shale, tight and deep coal gas development, definition of a set of causal pathways, which represent the logical chain of events, either planned or unplanned, that may link shale gas development activities with potential impacts on water and the environment (Figure 67) and then aggregated into three causal pathway groups.
6. **'Qualitative assessments'** presents assessments of three important issues to the community, government and industry: screening of drilling and hydraulic fracturing chemicals, hydraulic fracturing and well integrity.

All maps for the Cooper GBA region use the Map Grid of Australia (MGA) projection (zone 54) and the Geocentric Datum of Australia 1994 (GDA94).

User values

The Program is informed by user panels that provide a forum for the discussion and inclusion of user needs in each region. User panels aim to help guide the assessment process, provide a forum to communicate findings and enable the sharing of information on the regions and the assessments. The user panel in the Cooper GBA region consists of representatives from relevant local governments, natural resource management bodies, Queensland and SA governments, Traditional Owner groups, industry and other land user groups.

The user panels encourage inclusive discussions and representation of stakeholder views and expectations about potential opportunities and risks associated with shale and tight gas development in regional centres. In turn, the Program provides stakeholders with scientific information on the potential impacts of future shale and tight gas development in their region, helping to inform environmental decision making and future management approaches.

The user panel for the Cooper GBA region met in March and September 2018 and has:

- identified sources of additional data and knowledge from government, industry and communities and reinforced the cultural, hydrological and ecological uniqueness of the region
- highlighted the importance of Cooper Creek floodplain and groundwaters, including the limited understanding of surface flow characteristics within the Cooper Creek floodplain and shallow groundwater properties (quantity and quality) within the Cooper GBA region
- confirmed broad support for improved understanding of surface water flow characteristics for the Cooper Creek floodplain and shallow groundwater properties in Stage 3, including acquisition of Light Detection and Ranging (LiDAR) data to develop a hydrodynamic flow model for Cooper Creek and development of an environmental accounting approach to support a consistent and transparent approach to environmental data gathering.

Technical appendices

Each assessment is slightly different, due in part to regional differences but also in response to user needs, the availability of data, information, and fit-for-purpose models. This synthesis is supported by the six technical appendices cited in the relevant sections of this report:

- Owens R, Hall L, Smith M, Orr M, Lech M, Evans T, Skeers N, Woods M and Inskeep C (2020) Geology of the Cooper GBA region.
- Lech ME, Wang L, Hall LS, Bailey A, Palu T, Owens R, Skeers N, Woods M, Dehelean A, Orr M, Cathro D and Evenden C (2020) Shale, tight and deep coal gas prospectivity of the Cooper Basin.
- Evans TJ, Martinez J, Lai ÉCS, Raiber M, Radke BM, Sundaram B, Ransley TR, Dehelean A, Skeers N, Woods M, Evenden C and Dunn B (2020) Hydrogeology of the Cooper GBA region.
- O’Grady AP, Herr A, MacFarlane CM, Merrin LE and Pavey C (2020) Protected matters for the Cooper GBA region.
- Kirby JK, Golding L, Williams M, Apte S, Mallants D and Kookana R (2020) Qualitative (screening) environmental risk assessment of drilling and hydraulic fracturing chemicals for the Cooper GBA region.
- Kear J and Kasperczyk D (2020) Hydraulic fracturing and well integrity review for the GBA regions.

Executive summary

About the region *see Section 1, page 1*

The Cooper GBA region (Figure 1) covers approximately 130,000 km^2 – 95,740 km^2 in Queensland, 34,310 km^2 in SA and 8 km^2 in NSW. It is defined by the surface projection of the outline of the Cooper Basin geological province.

The Cooper GBA region is generally flat and surface water availability is unpredictable. Rainfall in the region is highly variable and is supplemented by surface water flowing into the region from the north. Consequently, natural systems are driven by resource pulses and boom–bust ecological dynamics, shaping the high diversity of ecological communities and species. Native vegetation communities have been modified by grazing of sheep and cattle (Section 1.3). A hotter and drier climate is forecast by global climate models (Section 1.2).

The human population is sparse, with a large 'fly-in–fly-out' workforce servicing the oil and gas industry. More than 60% of the region is covered by Indigenous Land Use Agreements and is within the Eyre region for Indigenous language groups (Section 1.3).

The emerging shale, tight and deep coal gas industry is regulated at federal, state and local levels to ensure that industry development is sustainable and responsible and minimises impacts on environmental and social values. Commonwealth, intergovernmental, SA and Queensland regulations that are relevant to the development of shale, tight and deep coal gas resources are summarised (Section 1.4).

Geology and gas resources *see Section 2, page 25*

The Cooper Basin is a Carboniferous to Triassic sedimentary basin that is up to 2500 m thick and occurs at depths between 1000 and 4500 m. It is overlain by the Jurassic–Cretaceous Eromanga and Cenozoic Lake Eyre sedimentary basins, both of which host major confined aquifer systems (Section 2.1).

The Cooper and Eromanga basins form Australia's most developed onshore hydrocarbon province. Although commercial production has been underway for over 50 years, the region continues to yield new discoveries. Between 1969 and 2014, the Cooper Basin and overlying Eromanga Basin produced 6.54 Tcf of gas (AERA, 2018) and contain 256 gas fields and 166 oil fields currently in production. This is a nationally significant provider of gas to the East Coast Gas Market (Section 2.2).

In the Cooper Basin numerous resource development companies are pursuing a range of shale, tight and deep coal gas plays. Key geological properties are evaluated, and the relative prospectivity of each resource type is mapped at a regional scale across the basin (Figure 27, Section 2.2.3). Areas of higher prospectivity include the Nappamerri, Patchawarra, Windorah, Allunga and Wooloo troughs, consistent with recent exploration activity. The mapped depth and extent of these shale, tight and deep coal gas plays inform where the plays are most likely to be present within the basin, which in turn aids assessment of potential connectivity to overlying surface water – groundwater systems and associated assets (Figure 29, Section 2.2.4).

Water resources *see Section 3, page 59*

Groundwater occurs in three major hydrostratigraphic sequences in the Cooper GBA region (Figure 30). The deepest is the Cooper Basin, where the Permian Gidgealpa Group hosts the shale, tight and deep coal gas resources. Due to the depth of burial (generally greater than 1500 m), the Cooper Basin is not directly used as a groundwater source. The Eromanga Basin covers the entire Cooper Basin (Figure 30) and contains a sequence of aquifers and aquitards that are part of the Great Artesian Basin (GAB) (Section 3.1.2). The third sequence – the Cenozoic sediments of the Lake Eyre Basin – encompass several important aquifer systems. Groundwater in the aquifers of the Eromanga and Lake Eyre basins in the Cooper GBA region is generally suitable for stock and domestic use, with 90% of the 2137 registered bores less than 300 m deep, accessing water from the Winton-Mackunda partial aquifer and aquifers in the Cenozoic Lake Eyre Basin.

The surface water system is dominated by Cooper Creek, which receives runoff from outside the Cooper GBA region flowing through the Barcoo and Thomson river systems before becoming Cooper Creek. It supports the Ramsar-listed Coongie Lakes and many waterholes and terminal lakes (Figure 39). When flooded, the floodplain becomes a huge inland 'sea' that contracts in the dry season to channels, lagoons and claypans. Surface water quality is variable in space and over time, with floodwaters in the upper reaches having low salinity and the terminal lakes tending to be saline. Median salinity recorded at three stream gauges on the Cooper, Barcoo and Thomson rivers is approximately 100 mg/L total dissolved solids (TDS), which is suitable for drinking water and for stock watering (Section 3.2.2).

Potential water sources for a future shale, tight and deep coal gas industry in the Cooper GBA region are unlikely to include surface water (Section 3.2.3). Groundwater (from the GAB and above the GAB) and produced water extracted during conventional oil and gas development are both potential water sources (Section 3.1.4). Existing allocations under water-sharing plans, potential competition with existing water users (e.g. stock and domestic users, conventional oil and gas industry) and proximity to produced water supplies affect potential water source availability.

Groundwater levels in shallow aquifers are consistently below streambed levels, indicating that connectivity between the surface water and groundwater in the Cooper GBA region is limited to recharge of small freshwater lenses near waterholes during floods (Section 3.3). The main potential for connectivity between the Eromanga and Cooper basins is where the Gidgealpa Group subcrops beneath the Eromanga Basin, particularly where sandier units in the Nappamerri Group are in direct contact with the Eromanga Basin or where major faults significantly offset aquifer sequences. Between 600 and 2000 m of sedimentary rock typically separates aquifers, such as those in the Cenozoic and Winton-Mackunda formations or deeper GAB aquifers, from shale, tight and deep coal gas plays in the Cooper Basin. This sedimentary rock impedes potential hydrological connectivity between the gas plays and groundwaters (Section 3.4). Hydrochemistry and dissolved gas concentrations provide some evidence of hydrological connectivity that will be investigated further in Stage 3 (Section 3.5).

Protected matters *see Section 4, page 113*

Matters of National Environmental Significance (MNES) in the Cooper GBA region include a Ramsar-listed wetland (Coongie Lakes), eight nationally important wetlands ((i) Bulloo Lake; (ii) Coongie Lakes; (iii) Cooper Creek – Wilson River Junction; (iv) Cooper Creek Overflow swamps – Nappa Merrie; (v) Cooper Creek Overflow swamps – Windorah; (vi) Lake Cuddapan; (vii) Lake Yamma Yamma; and (viii) the Strzelecki Creek Wetland system) (Figure 55) and 26 taxa (plants, reptiles, birds and mammals) listed as threatened (critically endangered, endangered or vulnerable) (Section 4.1.1).

In addition, Matters of State Environmental Significance (MSES) (Section 4.1.2) in Queensland include 28 species listed as endangered, near threatened, vulnerable or special least concern. The region also contains areas of significant environmental value, including protected areas, High Ecological Value Aquatic Ecosystems (HEVAE) and regional ecosystems listed as 'of concern' in Queensland. In SA, 17 species are listed as endangered or vulnerable. Both states contain areas reserved for the region's iconic landforms and biota, important wetlands and groundwater-dependent ecosystems.

Due to its historical significance, the Burke, Wills, King and Yandruwandha National Heritage Place located along the course of Cooper Creek is the one national heritage place listed as a protected matter (Section 4.2). The Register of the National Estate also lists nine Indigenous sites, 12 heritage sites and two recreational areas. Cooper Creek and associated waterholes have a long and enduring cultural significance as part of traditional trade routes (Section 4.2).

The assessment of potential hydrological and environmental impacts due to shale, tight and deep coal gas development in Stage 3 is underpinned by landscape classifications. The key ecological and hydrological features are categorised into seven landscape classes (Figure 58). Three landscape classes cover more than 80% of the region: floodplain and alluvium (known as 'Channel Country', Figure 59), inland dunefields (Figure 61), and undulating country on fine-grained sedimentary rocks. There are smaller areas of loamy and sandy plains, tablelands and duricrusts, clay plains, and springs (Table 19, Section 4.3).

To focus assessment in Stage 3, protected matters are prioritised based on the importance of the region to the matter. The prioritisation identified 30 assets (including MNES and MSES) to be assessed in greater detail (priority 1) and 20 assets (regional ecosystems and protected areas) to be assessed at a regional scale using landscape classes (priority 2). The remaining 131 assets do not warrant further assessment in Stage 3 (priority 3) based on listed conservation status and/or expected occurrence in the region.

Potential impacts due to shale, tight and deep coal gas development

see Section 5, page 139

The risk assessment approach follows the principles for ecological risk assessment outlined by the United States Environmental Protection Agency (US EPA, 1998) and Hayes (2004) with a view to meeting regulatory processes for the Cooper GBA region (Figure 62). The identification of causal pathways in Stage 2 is a key component of the identification and formulation step of the GBA impact and risk assessment approach outlined in Section 5.1, and allows prioritisation of the assessment to be conducted in Stage 3.

Over 200 individual hazards were systematically identified by considering all the possible ways an activity in the life cycle (Section 5.2.2, Figure 64) of shale, tight and deep coal gas development may impact ecological, economic and social values (Section 5.2). The range of severity and likelihood scores for each hazard were agreed by experts from government, industry and members of the assessment team in five meetings.

Each hazard is classified into one of 14 causal pathways – the logical chain of events that link unconventional gas resource development with potential impacts on water and the environment – aggregated into three groups (Section 5.3). Causal pathways play a central role in the assessment (Figure 63), connecting hazards arising from existing activities (Section 1.3) and unconventional gas resource development activities (Section 5.2) with the values to be protected (Sections 4.1 and 4.2) for each landscape class (Section 4.3). Prioritised causal pathways for more detailed assessment in Stage 3 are mostly in the 'landscape management' and 'water and infrastructure management' causal pathway groups, with fewer in the 'subsurface flow paths' causal pathway group. The impact and risk assessment in Stage 3 will assess how each causal pathway might impact on the suite of endpoints, including endemic native species, migratory species, ecological communities, wetland ecosystems, water resources, cultural heritage and agriculture (Section 5.3).

Qualitative assessment examples see Section 6, page 195

Potential impacts from drilling and hydraulic fracturing chemicals and two causal pathways – 'hydraulic fracturing' and 'compromised well integrity' – were assessed in greater detail because of concern from government, the community and industry.

The Tier 1 qualitative screening assessed 116 chemicals used between 2011 and 2016 for drilling and hydraulic fracturing at shale, tight and deep coal gas operations in GBA regions (Section 6.1). About one-third (42 chemicals) were of 'low concern' and pose minimal risk to aquatic ecosystems. A further 33 chemicals were of 'potentially high concern' and 41 were of 'potential concern'. These chemicals would require site-specific quantitative chemical assessments to be undertaken to determine risks from specific operations to aquatic ecosystems.

Natural rock formations contain elements and compounds (geogenic chemicals) that could be mobilised into flowback and produced waters during hydraulic fracturing. Laboratory-based leachate tests were designed to provide an upper-bound estimate of geogenic chemical mobilisation from target formations in the Cooper GBA region and are intended to guide future field-based monitoring, management and treatment options. Laboratory-based leachate tests on powdered rock samples identified several elements and priority organic chemicals that could be mobilised into solutions by hydraulic fracturing fluids (Section 6.1). The independent collection, as well as open and transparent reporting of water quality data at future gas operations before, during and after hydraulic fracturing would improve knowledge of the process and outputs, and inform wastewater management and treatment.

Hydraulic fracturing has been used to stimulate conventional oil and gas and unconventional gas reservoirs in the Cooper Basin for over 50 years (Figure 89). Risks from hydraulic fracturing have been the focus for industry, government and academia for more than a decade. A qualitative review of nine domestic and international inquiries into onshore gas industry operations, historical Cooper Basin data and the hazard scoring for the Cooper GBA region indicated that the likelihood of occurrence of the three impact modes associated with hydraulic fracturing (hydraulic fracture growth into an aquifer, a well or a fault) is low (Table 31). While the three hydraulic fracturing impact modes were not ranked highly in the hazard assessment process, heightened community concern and relative proximity of important aquifers to prospective gas plays (300 to 2,000 m vertical separation) mean that further assessment of the 'hydraulic fracture growth into aquifer' impact mode will be investigated.

Regulated construction of wells for shale, tight and deep coal gas development activities aims to ensure that fluid and gas are prevented from flowing unintentionally from the reservoir into another geological layer or to the surface. In this qualitative review, Cooper GBA region historical data is compared with findings from international and domestic inquiries to present an initial evaluation of five conceptual impact modes (Table 32). These were compared with the prioritisations from Cooper GBA region hazard identification (Section 5.2) and are broadly consistent. Two impact modes – 'migration of fluids along casing between geological layers' and 'migration of fluids along decommissioned or abandoned wells' – have been prioritised for inclusion in Stage 3 analysis (Section 6.2.2).

Conclusion *see Section 7, page 221*

The baseline data, knowledge and conceptual models presented (Section 7.1) are the building blocks for the Stage 3 impact analysis and management for the Cooper GBA region. Plausible development scenarios to test the range of potential impacts will be developed in consultation with industry, state governments and Commonwealth agencies. Fieldwork and modelling will be undertaken, where required, to address stakeholder questions and priority knowledge gaps (Section 7.2). Monitoring and management options will be considered as part of the impact analysis. User panel input will help target the analysis to key issues for regulation and management.

The synthesis report follows the colour guide of this executive summary, with key information summarised in coloured boxes at the start of each section and methods set out in grey boxes.

Contents

Figures

Tables

Contributors to the Program

The following individuals have contributed to the Geological and Bioregional Assessment Program.

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- South Australia – Department for Environment and Water, and Department for Energy and Mining.

Abbreviations and acronyms

Abbreviation/acronym	Definition
ABS	Australian Bureau of Statistics
AERA	Australian Energy Resources Assessment
ANZECC	Australian and New Zealand Environment and Conservation Council
API	American Petroleum Institute
CSG	Coal seam gas
Cth	Commonwealth
DEA	Digital Earth Australia
DEM	Digital elevation model
DNRME	Department of Natural Resources, Mines and Energy
EC	Electrical conductivity
EIR	Environmental Impact Report
EIS	Environmental impact statement
EPBC Act	Commonwealth's Environment Protection and Biodiversity Conservation Act 1999
ERA	Environmental risk assessment
FNPWA	Far North Prescribed Wells Area
GAB	Great Artesian Basin
GABORA	Great Artesian Basin and Other Regional Aquifers
GBA	Geological and Bioregional Assessment
GCM	Global climate model
GDE	Groundwater-dependent ecosystem
IBRA	International Biogeographic Regionalisation for Australia
ILUA	Indigenous Land Use Agreement
IMEA	Impact Modes and Effects Analysis
ISO	International Organization for Standardization
JNP	Jackson–Naccowlah–Pepita
LGA	Local government area
LiDAR	Light detection and ranging
MNES	Matters of National Environmental Significance
MSES	Matters of State Environmental Significance
NORM	Naturally occurring radioactive material
NRM	Natural resource management
NSW	New South Wales

Abbreviation/acronym	Definition
NT	Northern Territory
PAH	Polycyclic aromatic hydrocarbon
PFS	Polygonal fault system
SA	South Australia
scf	Standard cubic feet
SEO	Statements of Environmental Objectives
SWAN	Surface Water Ambient Network
TDS	Total dissolved solids
TEM	Transient electromagnetics
TOC	Total organic carbon
TRH	Total recoverable hydrocarbons
WOfS	Water Observations from Space

Units

Unit	Description
%Ro	Vitrinite reflectance (as a percentage)
µg/g	Microgram per gram
mg/kg	Microgram per kilogram
µg/L	Microgram per litre
µm	Micrometre
µS/cm	Microseimens per centimetre
GL	Gigalitre (1 GL = 1,000,000,000 litre)
GL/year; GL/y	Gigalitre per year
km	Kilometre
km^2	Kilometres squared
kPa	Kilopascals
m	Metre
mAHD	metres above Australian Height Datum
Ma	Millions of years before the present
Mcf	Million cubic feet
mD	MilliDarcy
mg HC/g TOC	Milligrams of hydrocarbons per gram of total organic carbon
mg/L	Milligrams per litre
ML	Megalitre (1 ML = 1,000,000 litre)
ML/day	Megalitre per day
mm/y	Millimetres per year
MPa	Megapascals
MPa/km	Megapascals per kilometre
^{o}C	Degrees Celsius
psi	Pounds per square inch
psi/ft	Pounds per square inch per foot
scc/g	Standard cubic centimetres per gram
Tcf	Trillion cubic feet
wt%	Weight (as a percentage)

1 About the region

1.1 Cooper GBA region

For the Geological and Bioregional Assessment (GBA) Program, the Cooper GBA region is defined by the outline of the Cooper Basin geological province, an Upper Carboniferous – Middle Triassic sedimentary basin that is up to 2500 m thick. The Cooper Basin does not outcrop at the surface, is overlain entirely by the Jurassic–Cretaceous Eromanga Basin and occurs at depths between 1000 and 4500 m. The Cooper GBA region crosses the SA–Queensland border (including a small area of NSW at Cameron Corner), occupying approximately 130,000 km^2, including 95,740 km^2 in Queensland, 34,310 km^2 in SA and 8 km^2 in NSW (Figure 3).

Oil and gas resources were discovered in the region in 1963 and both the Cooper and overlying Eromanga geological basins have been producing conventional oil and gas for 50 years. The first gas flowed by pipeline into Adelaide in 1969, followed by Sydney in 1976 and Brisbane in 1996. Subsequent prospectivity assessments for selected unconventional plays have identified that the Cooper Basin has the potential to produce significant amounts of shale, tight and deep coal gas in the coming years (Section 2.2).

The Cooper GBA region is generally flat, with dunes in the south-west. The topography ranges from –3 to 367 mAHD and is characterised by the braided channels of Cooper Creek and the Barcoo River, with very few freshwater lakes and salt lakes (Figure 3).

The Cooper GBA region is located in the Lake Eyre drainage catchment. Most of the Cooper GBA region (approximately 118,500 km^2) is in the Cooper Creek – Bulloo river catchment, although a small part (approximately 11,500 km^2) in the north-west of the region is in the Diamantina–Georgina river catchment. The region is large in area with a sparse human population (only 783 residents in the 2016 census). Unpredictable surface water availability results in natural and human systems driven by resource pulses and boom–bust dynamics. A ‘boom’ is associated with floods and a ‘bust’ is associated with drier periods, where water is scarce and contracts to fragments across the landscape.

The dominant land use in the region is grazing of sheep and cattle on natural pastures (grazing native vegetation). There is no pasture modification or intensive production within the Cooper GBA region. Extensive grazing has resulted in modification to many of the native vegetation communities, especially the *Eucalyptus* woodlands with grassy understorey, the Mitchell grass (*Astrebla*) and the tussock grass associated with the black cracking clays (Smith et al., 2015). Invasive plants and animals (including cane toads, cats, goats, pigs, rabbits and red foxes) are listed as key threatening processes under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act).

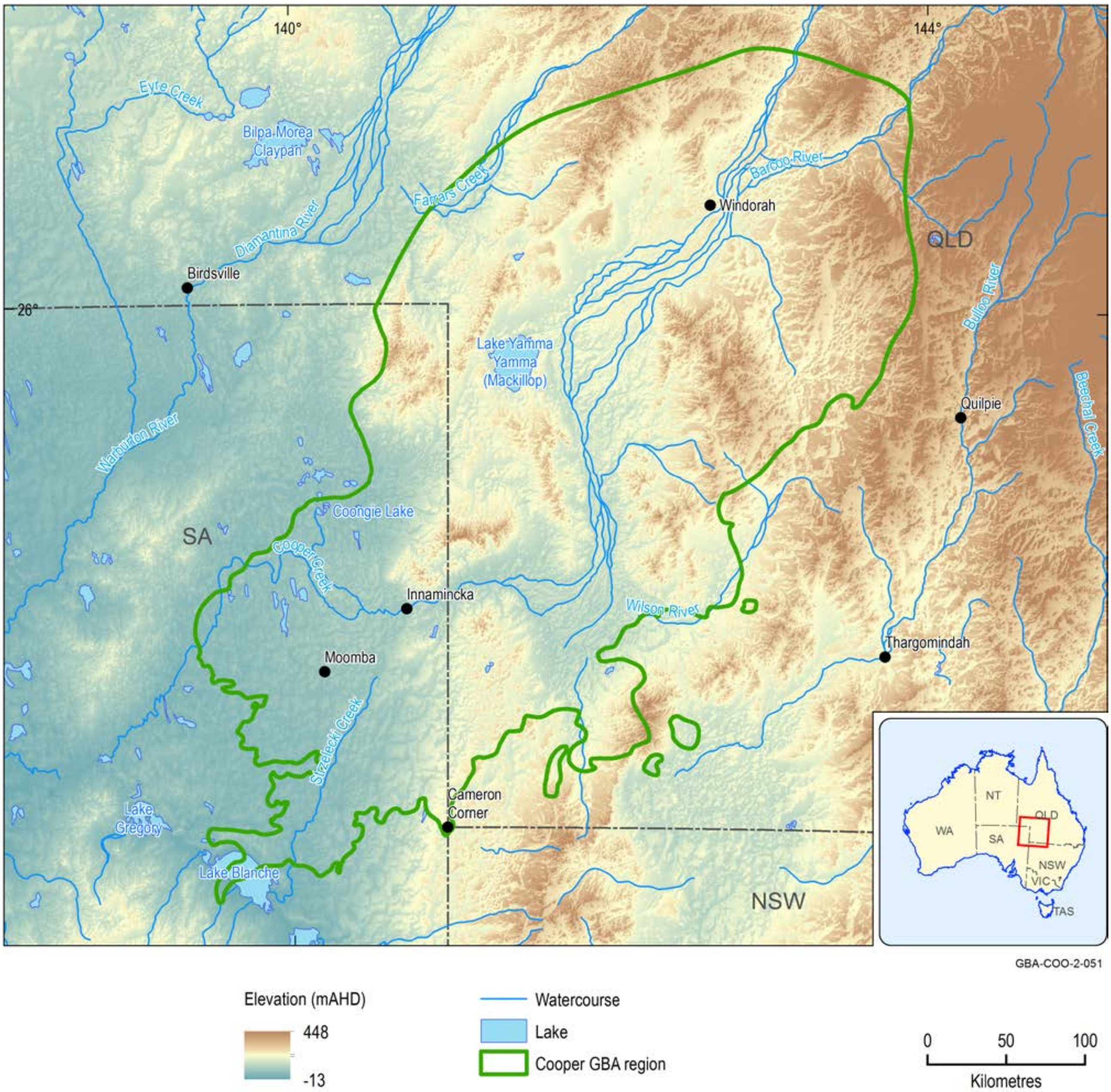

Figure 3 Location and topography of the Cooper GBA region

The patches of the region that are south-east of the main region are areas where sediments from the Gidgealpa Group and Nappamerri Group were once deposited. It is quite possible that these areas were once connected to the Cooper Basin proper, but uplift and subsequent erosion have created isolated patches.
Note: the elevation range shown in this figure is for the map extent, not just the Cooper GBA region.
Data: Geoscience Australia (2008a)
Element: GBA-COO-2-051

The diversity of landforms, geology, soils and ecological communities and species in the Cooper GBA region is characterised by five Interim Biogeographic Regionalisation for Australia (IBRA) regions (Department of the Environment and Energy, 2018a) (Table 1 and Figure 4). Most of the Cooper GBA region occurs in the Channel Country (72%), Mulga Lands (13%) and Simpson Strzelecki Dunefields (13%) IBRA regions. The Mitchell Grass Downs and Stony Plains IBRA regions occupy less than 3% of the Cooper GBA region.

The *Channel Country* IBRA region occupies over 300,000 km² in Queensland, NT, NSW and SA and comprises 'Low hills on Cretaceous sediments; forbfields and Mitchell grass downs, and intervening braided river systems of coolibah (E. coolibah) woodlands and lignum/saltbush Muehlenbeckia sp./Chenopodium sp. shrublands. (Includes small areas of sand plains.)'. Tangled lignum is now *Duma florulenta* (synonym *Muehlenbeckia florulenta*). The *Mulga Lands* IBRA region comprises 'Undulating plains and low hills on Cainozoic sediments; red earths and lithosols; *Acacia aneura* shrublands and low woodlands'. The *Simpson Strzelecki Dunefields* IBRA region comprises 'Arid dunefields and sand plains with sparse shrubland and spinifex hummock grassland, and cane grass on deep sands along dune crests. Large salt lakes, notably Lake Eyre and many clay pans are dispersed amongst the dunes. Several significant arid rivers terminate at Lake Eyre, Cooper Creek and Warburton River. They are fringed with coolibah and redgum woodlands'.

Table 1 Interim Biogeographic Regionalisation for Australia (IBRA) regions and subregions in Cooper GBA region

Parameter	Channel Country	Mulga Lands	Simpson Strzelecki Dunefields
Mean rainfall	130–330 mm/y	220–380 mm/y	130–190 mm/y
Climate	Desert (hot, persistently dry), summer dominant rainfall	Grassland (hot, persistently dry), summer dominant rainfall	Desert (hot, persistently dry), summer dominant to uniform rainfall
Description of IBRA region and key subregions	Low hills on Cretaceous sediments, grasslands, braided river systems and sand plains *Cooper Plains*, braided, flood and alluvial plains surrounded by hummock grassland on sand plains and/or dunefields. *Coongie*, parallel dunes and claypans. *Sturt Stony Desert*, undulating gibber pavement with occasional dunes and small isolated silcrete-capped mesas and hills.	Undulating plains and low hills on Cenozoic sediments; red earths and lithosols *West Bulloo*, dissected tablelands and hills formed by weathered Cretaceous sediments. *Northern Uplands*, scarps, dissected tablelands, sandstone mesas and buttes.	Arid dunefields and sand plains interspersed with large salt lakes and clay pans. *Strzelecki Desert*, extensive dunefields with numerous small claypans, and a chain of interconnected salt lakes with gypsum dunes along the eastern margins. *Bulloo Dunefields*, aeolian sands, alluvial and lake sediments, with bedrock outcrops.
Soils	Grey self-mulching cracking clays, sand plains, dunefields and gibber plains.	Stony plains with silcrete-capped mesas, minor alluvial and sandy tracts.	Red massive earths and red siliceous sands. Yellowish sands and grey self-mulching cracking clays.
Vegetation	Braided river systems of eucalypt (*Eucalyptus coolabah* ssp. *arida*) and lignum (*Duma florulenta*) low woodland with Chenopod shrubland (*Chenopodium* sp.), hummock grassland, Mitchell grass (*Astrebla* spp.) grass/herblands and Gidgee (*Acacia cambagei*) shrublands.	Mulga (*Acacia aneura*) and bendee (*A. catenulata*) shrublands and low woodlands on plateaus with bastard mulga (*A. stowardii*) open shrublands or lancewood (*A. shirleyi*) on shallower soils. River red gum (*Eucalyptus camaldulensis*) open woodlands along drainage lines.	Chenopod shrubland of *Atriplex nummularia*, *Chenopodium auricomum*, *Halosarcia* spp. and *Maireana astrotricha*. Hummock grassland of *Zygochloa paradoxa* and *Triodia basedowii*. Low shrubland and grassland of *Eragrostis australasica* and *Duma florulenta*.

Parameter	Channel Country	Mulga Lands	Simpson Strzelecki Dunefields
Wetlands	Coongie Lakes, Cooper Creek Overflow Swamps, Cooper Creek – Wilson River Junction, Lake Yamma Yamma, Bulloo Lake and Lake Cuddapan	None	Lake Blanche
Land use	Mining, nature conservation, grazing native vegetation, marsh/wetland/lake	Grazing native vegetation	Nature conservation, grazing native vegetation

Two of the five IBRA regions in the Cooper GBA region – Mitchell Grass Downs (2%) and Stony Plains (less than 1%) – are not included in this table, as they cover less than 3% of the Cooper GBA region.
Data: Department of the Environment and Energy (2018a)

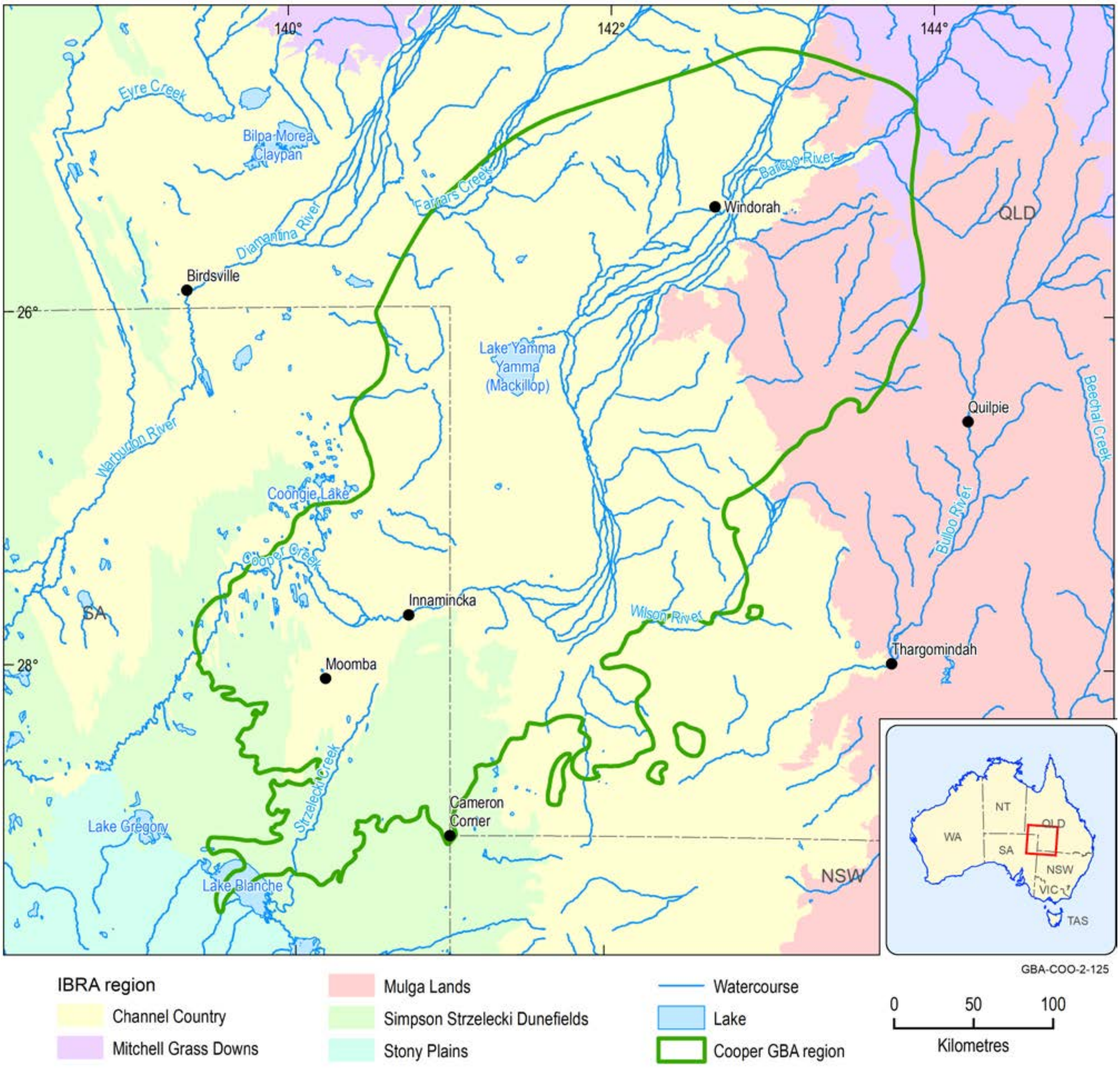

Figure 4 Interim Biogeographic Regionalisation for Australia (IBRA) regions of the Cooper GBA region

Data: Department of the Environment and Energy (2018a)
Element: GBA-COO-2-125

The SA Arid Lands Natural Resource Management (NRM) Board regional NRM plan (South Australian Arid Lands Natural Resources Management Board, 2017) uses a systems approach to provide a coordinated and integrated basis for maintaining and enhancing the region's natural resources. Socio-economic and environmental values in the region are described by six NRM districts and seven major bioregions, including Channel Country and Simpson Strzelecki Dunefields. Figure 5 highlights how 'environmental, cultural, social and economic aspects of the Channel Country system interact and respond to the episodic, irregular, extreme boom and bust periods that are a feature of the region'. 'Channel Country features extensive drainage systems, braided channels, vast floodplains and terminal lakes, with highly variable flow patterns, inundation frequency, salinity and vegetation communities. Gibber plains, low hills and mesas, and vegetated, relatively stable, high sand dunes with swale wetlands separate the major drainage basins/channels' (South Australian Arid Lands Natural Resources Management Board, 2017, p 57).

(a)

(b)

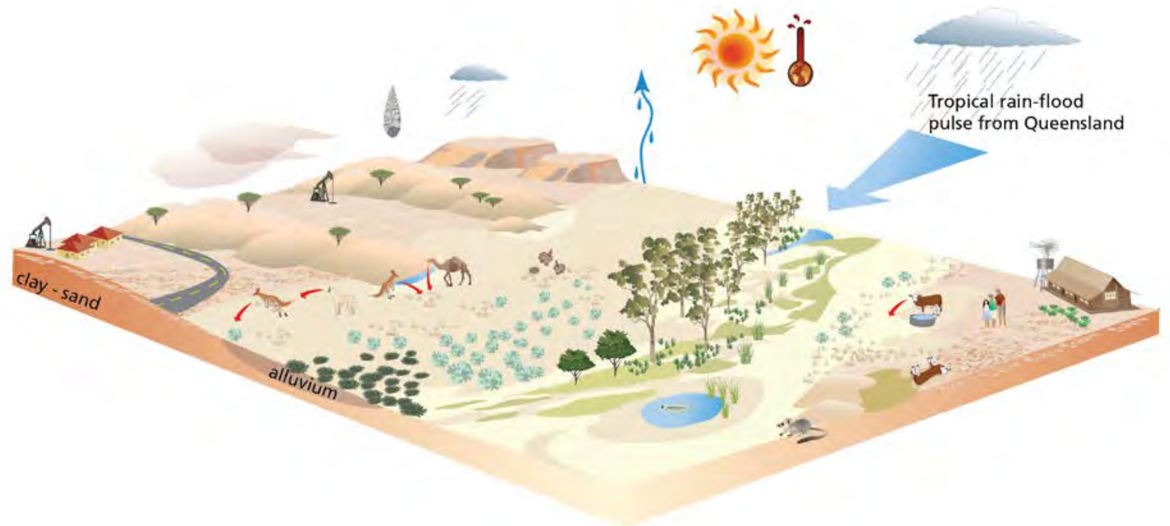

Figure 5 Channel Country characteristics during extreme (a) boom and (b) bust periods

The red arrows in the diagram represent grazing pressure and weed spread.
Source: Figure 4 in South Australian Arid Lands Natural Resources Management Board (2017)

Element: GBA-COO-2-257

1.2 Climate

The Cooper GBA region is characterised by summer-dominated rainfall (December to February), hot summers and warm winters as shown by the monthly distribution of rainfall and air temperatures at three sites: Longreach, Windorah and Innamincka (Figure 6). (Longreach is outside of the Cooper GBA region but is within the Cooper Creek catchment that flows through the Cooper GBA region.) The 30-year period 1976 to 2005 was chosen to present the climate statistics, as this is the baseline climate period used to compare the future climate projections. For the historical period the mean monthly precipitation was at a maximum in summer, with 82 mm at Longreach in February in the north-east and 28 mm in January at Innamincka in the west. The minimum rainfall occurred in the late winter to early spring and was comparable at all three sites, averaging 7 to 10 mm/month in August and September.

The inter-annual variability of rainfall (variation of rainfall from one year to the next) in the Lake Eyre Basin was greater than that observed in arid zones elsewhere in the world (McMahon et al., 2008a). Over the period 1976 to 2005 the maximum annual rainfall was greater than five times the minimum annual rainfall for the three selected locations and ten times greater at the most arid site at Innamincka (Figure 7).

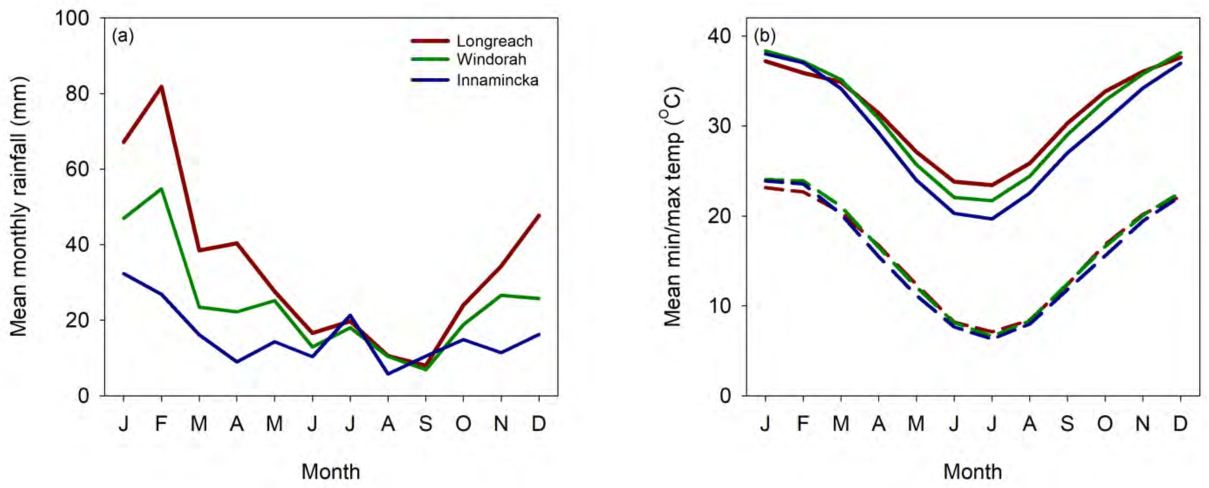

Figure 6 Longreach, Windorah and Innamincka: (a) mean monthly rainfall; and (b) mean monthly maximum and minimum temperature

The locations for Longreach, Windorah and Innamincka are shown in Figure 8.
Data: Department of Environment and Science (Qld) (2018b)
Element: GBA-COO-2-093

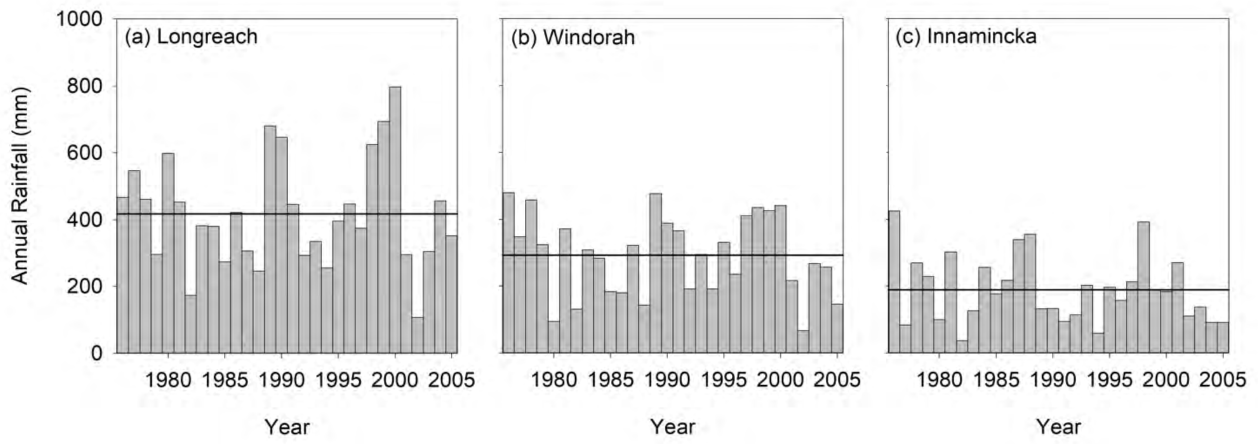

Figure 7 Annual series of rainfall totals for (a) Longreach; (b) Windorah; and (c) Innamincka for 1975–2005

The solid lines represent the mean of annual rainfall for this 30-year period.
Data: Department of Environment and Science (Qld) (2018b)
Element: GBA-COO-2-094

> Future climate projections are typically reported as a percentage change between the period of 1976 to 2005 to the period of 2046 to 2075 for the 10th, 50th and 90th percentiles of the 42 global climate models (GCMs). This report uses the RCP8.5 scenario – a worst-case scenario in which emissions continue to rise throughout the 21st century. The projected median global mean temperature of the 42 GCMs is 2.0 °C higher for RCP8.5 in 2046 to 2075 relative to 1976 to 2005.

Within the Cooper GBA region the mean annual rainfall was 217 mm/year, with a maximum in the north-east of 378 mm/year and a minimum of 127 mm/year in the south-west. Mean annual rainfall was even greater in the headwaters upstream of the GBA region, being up to 662 mm/year along the Great Dividing Range (Figure 8). Mean annual rainfall for the period 2046 to 2075 is projected to decrease by up to 10% in the Cooper GBA region for the 50th percentile. The 10th and 90th percentiles give the range of future projections of mean annual rainfall of between a 30% decrease and a 20% increase (Figure 8).

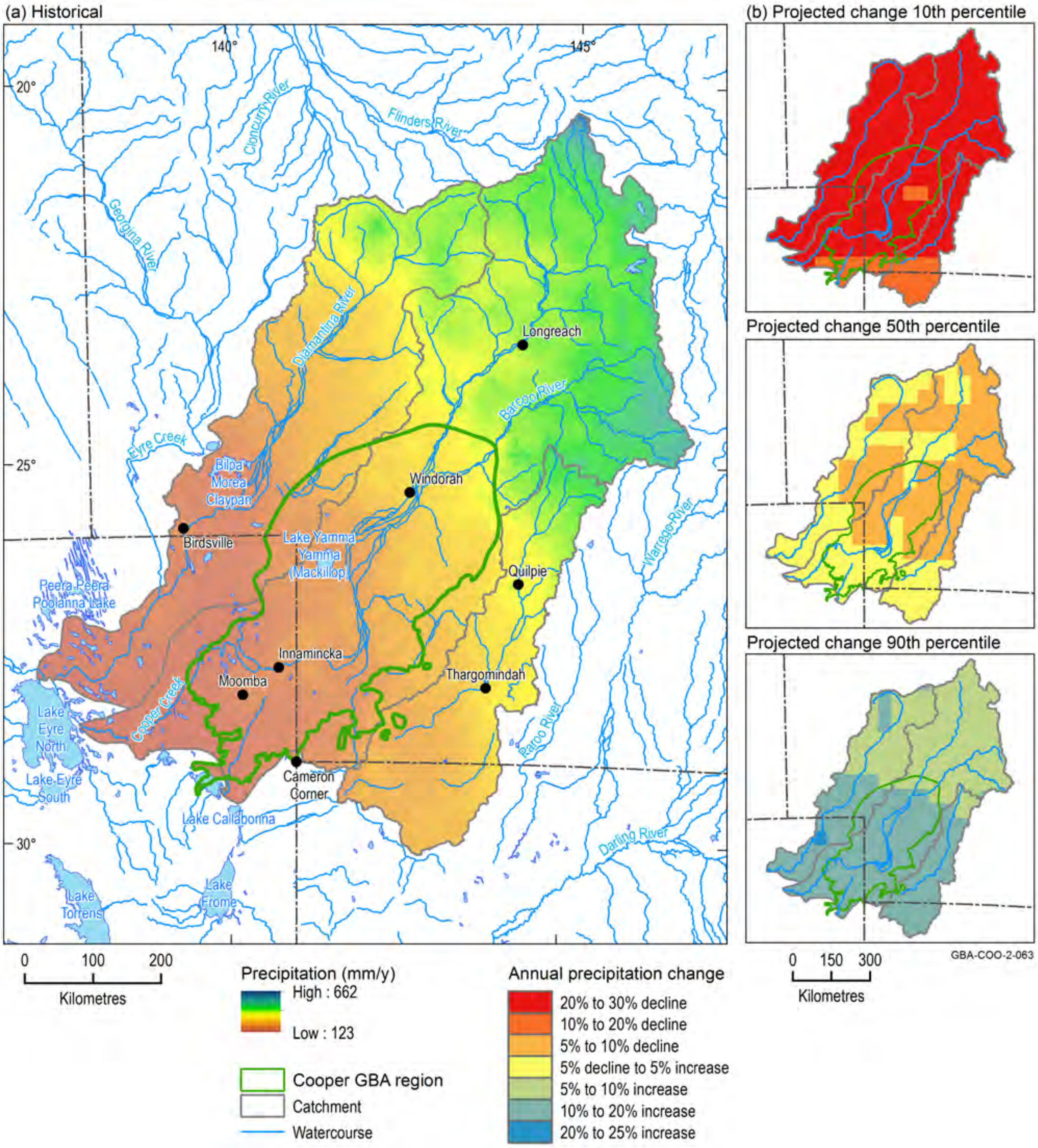

Figure 8 Spatial patterns of mean annual precipitation for the historical period (1976–2005) and 10th, 50th and 90th percentile estimates of projected percentage change in mean annual precipitation for the historical period 1976–2005 to the future period 2046–2075 across the Cooper Creek – Diamantina–Bulloo river catchments

Percentiles of projected scenarios are from 42 CMIP5 global climate models under emission in RCP8.5.
Data: Geological and Bioregional Assessment Program (2018e, 2018f)
Element: GBA-COO-2-063

Mean annual potential evapotranspiration (PET) calculated using the Morton method (Chiew and McMahon, 1991) was high for the period 1976 to 2005, with an average of 1702 mm/year across the Cooper GBA region (Figure 9). The range within the region was from 1620 to 1768 mm/year, with a greater range within the upstream catchments between 1568 mm/year in the north-west to 1859 mm/year in the south. PET was more than seven times greater than precipitation across the region. Mean annual PET for the period 2046 to 2075 is projected to increase for the three percentiles (of the GCM noted above) across the region. Increases vary from 3% to 6% under the 10th percentile, 5% to 10% under the 50th percentile and 8% to 10% under the 90th percentile.

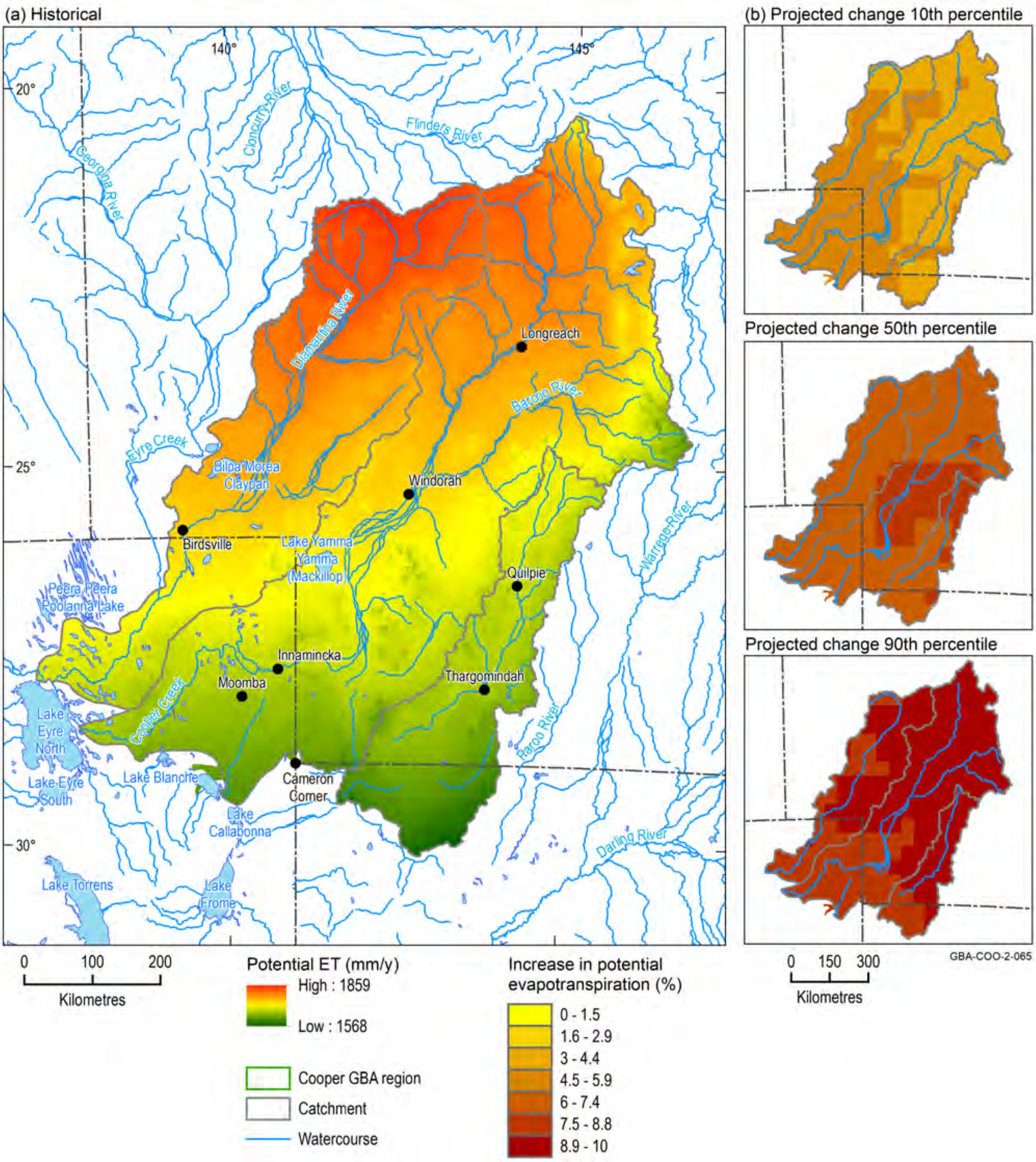

Figure 9 Spatial pattern of mean annual potential evapotranspiration (PET) for the historical period (1976–2005) and 10th, 50th and 90th percentile estimates of projected percentage change in mean annual PET for the historical period 1976–2005 to the future period 2046–2075 across the Cooper Creek – Diamantina–Bulloo river catchments

PET was calculated using the Morton method (Chiew and McMahon, 1991).
Percentiles of projected scenarios are from 42 CMIP5 global climate models under emission in RCP8.5.
Data: Geological and Bioregional Assessment Program (2018e, 2018f)
Element: GBA-COO-2-065

Mean maximum air temperatures for the period 1976 to 2005 ranged from 35 to 40 °C and mean minimum temperatures varied from 20 to 24 °C (Figure 6). Winter was warm with mean maximum temperature above 19 °C and mean minimum temperature above 6 °C. The number of hot days (maximum air temperature >35 °C) for the period 1976 to 2005 across the Cooper GBA region decreased from a maximum of 114 days per year in the north to 84 days per year in the south (Figure 10). Mean number of hot days for the period 2046 to 2075 is projected to increase for the three percentiles across the region. Increases vary from less than 30 days under the 10th percentile and from 30 to 40 days in the south-west to 50 to 60 days in the north-east under the 50th percentile; and from 40 to 60 days in the south-west to 80 to 90 days in the north-east under the 90th percentile.

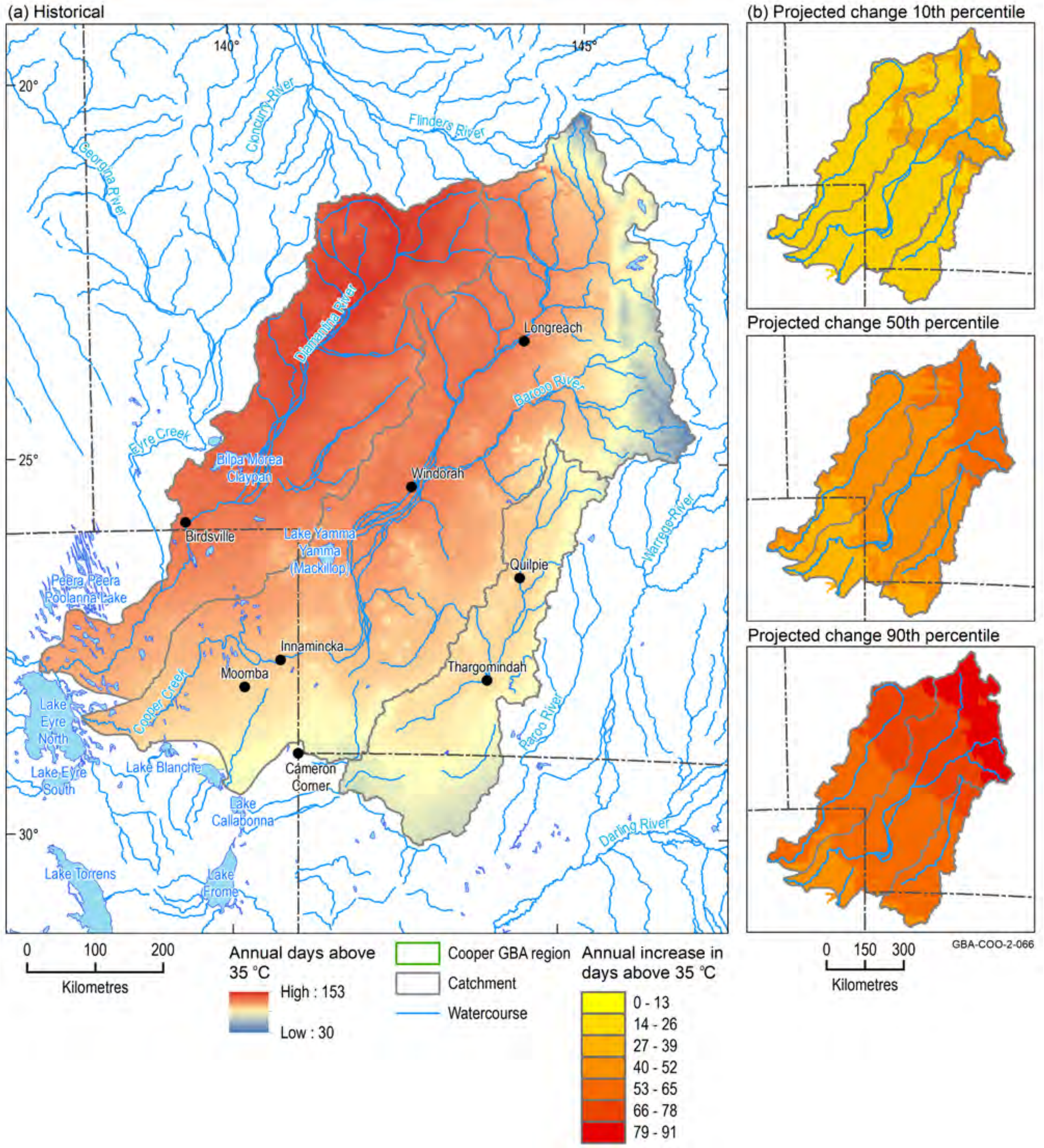

Figure 10 Spatial patterns of mean annual hot days (maximum air temperature >35°C for the historical period 1976–2005) and 10th, 50th and 90th percentile estimates of projected change in hot days (maximum air temperature >35°C) for the historical period 1976–2005 to the future period 2046–2075 across the Cooper Creek – Diamantina–Bulloo river catchments

Percentiles of projected scenarios are from 42 CMIP5 global climate models under emission in RCP8.5.
Data: Geological and Bioregional Assessment Program (2018e, 2018f)
Element: GBA-COO-2-066

1.3 Population and land use

The Cooper GBA region is sparsely populated. The estimated population was 783 persons in the 2016 population census (Australian Bureau of Statistics, 2016a). Approximately 8% of people residing in the Cooper GBA region identified as Indigenous in 2016, compared with 2.8% for Australia. Windorah was the most populous Indigenous community, with approximately 20 Indigenous residents. The combination of agriculture, forestry and fishing is the largest employment industry in the region, with 37% of people employed in agriculture, while 17% were employed in mining. The largest producer of oil and gas in the basin is Santos, with its main production facility at Moomba in SA. Other major producers are Beach Energy, Senex and Strike Energy.

The local government areas (LGAs) in the region are the Barcoo, Quilpie and Bulloo shire councils, with small areas of Diamantina Shire and Longreach Regional Council in Queensland and part of the Outback Areas Community Development Trust in SA (Figure 11). The Unincorporated Far West LGA in NSW covers the 8 km^2 in the Cooper GBA region that has not been included in the employment statistics above.

The Cooper GBA region is within the Eyre region (Horton, 1996) for Indigenous language groups (Australian Institute of Aboriginal Torres Strait Islander Studies, 1994) and has five tribal or language groups: Birria, Wangkumara, Yandruwandha, Yawarrawarrka and Karuwali (Constable et al., 2015). In the Queensland part of the Cooper GBA region, native title claims have been formally determined for the Kullilli, Boonthamurra and Mithaka peoples (Figure 11). In the SA part of the region, three native title claims have been determined for the Dieri and Yandruwandha Yawarrawarrka peoples. Most of the region (71%), including all of the region in SA and 60% in Queensland (Figure 11), is covered by Indigenous Land Use Agreements (ILUAs). ILUAs are negotiated agreements between native title claimants and others about the use and management of lands and waters. They were introduced by amendments in 1998 to the *Native Title Act 1993* (Cth). An ILUA can be negotiated and registered separately from a native title determination. In October 2018, there were 43 ILUAs registered in the Cooper GBA region, six of which relate to the petroleum industry (National Native Title Tribunal, 2013).

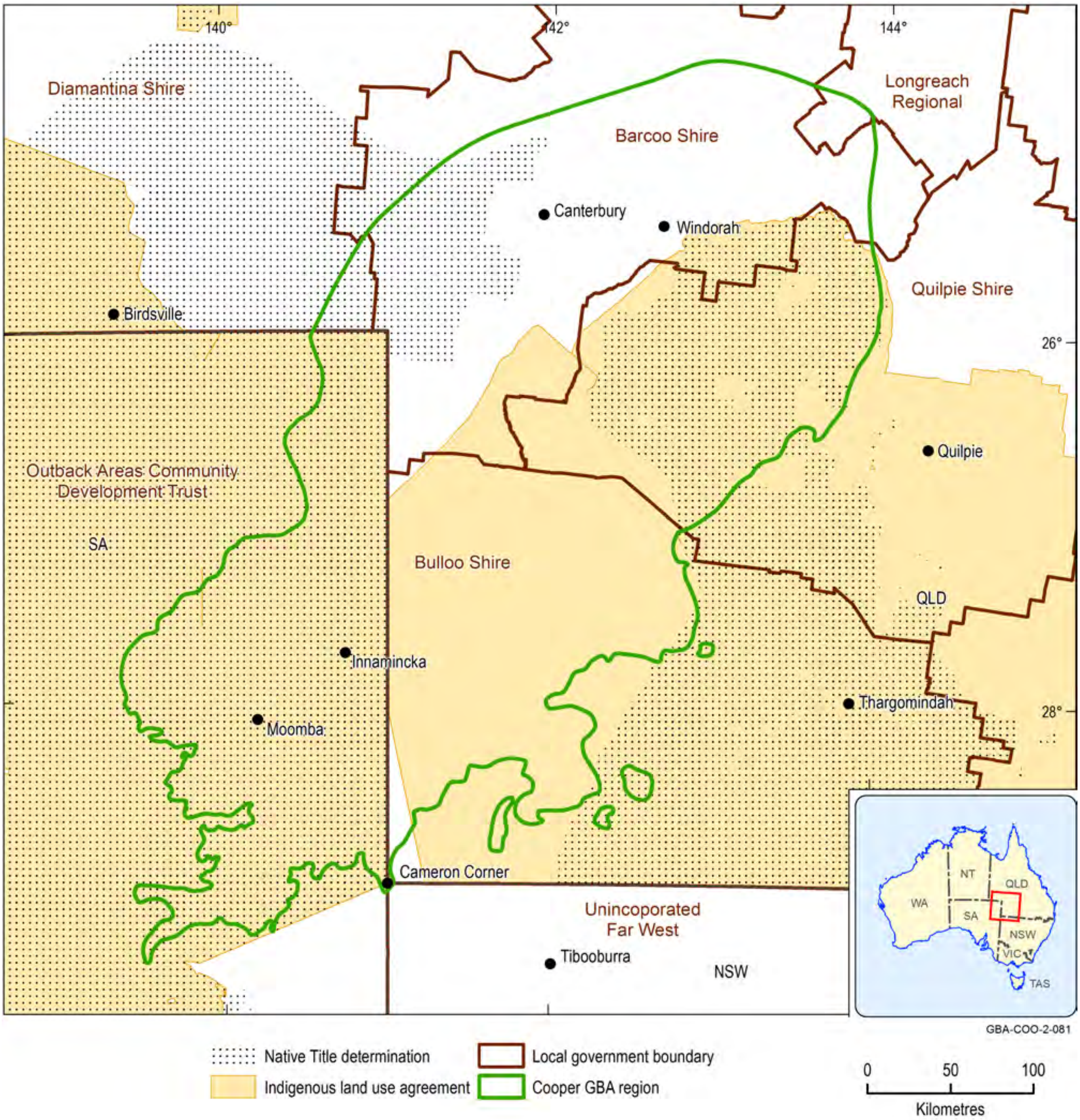

Figure 11 Local government areas and Indigenous Land Use Agreement areas in the Cooper GBA region

Data: Australian Bureau of Statistics (2016b); National Native Title Tribunal (2013, 2019)
Element: GBA-COO-2-081

Most of the land in the region is used for natural vegetation grazing, but there are also significant areas of nature conservation (Figure 12). The region contains an area classified as 'Mining and waste' around Moomba – a gas exploration and processing town with no permanent population, where intensive gas treatment, storage and distribution occurs. Smaller oil and gas treatment plants to the east of Innamincka at Ballera (0.6 km^2) and Jackson (0.3 km^2) in Queensland are not captured in this dataset (Figure 12).

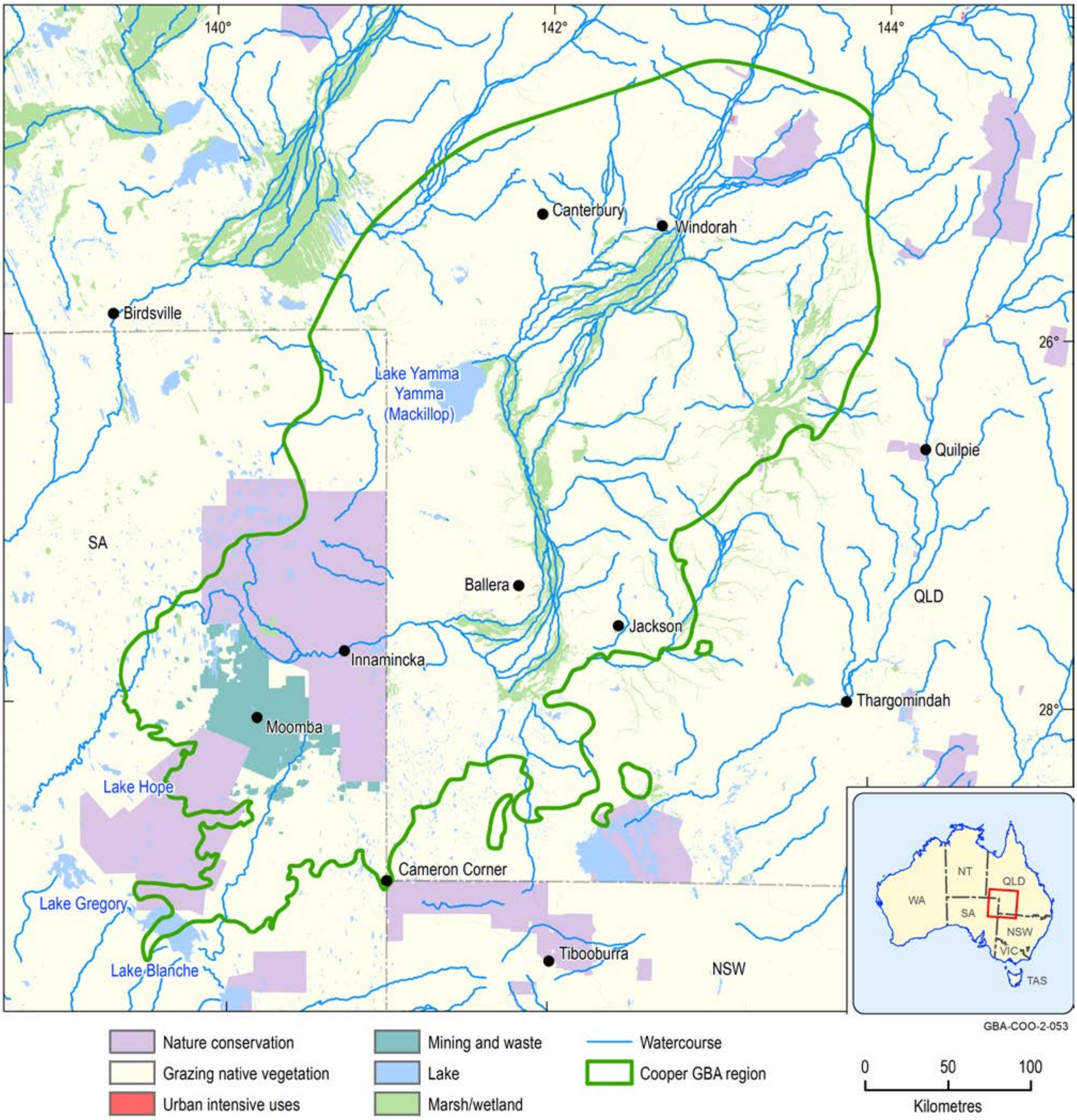

Figure 12 Land use in the Cooper GBA region

Data: Australian Bureau of Agricultural and Resource Economics and Sciences (2016)
Element: GBA-COO-2-053

1.4 *Water and resource development legislation and regulations*

The development of shale, tight and deep coal gas resources is an emerging industry in Australia and has the potential to impact water resources, biodiversity, social and human capital and other non-renewable natural resources such as air quality. As such, the industry is regulated at federal, state and local levels to ensure that industry development is sustainable and responsible and minimises impacts on environmental and social values. The following sections outline the

Commonwealth, intergovernmental, SA and Queensland regulations that are relevant to the development of shale, tight and deep coal gas resources.

1.4.1 Commonwealth and intergovernmental agreements

There are five key Commonwealth agreements and one key intergovernmental agreement that apply to the regulation of the development of the shale, tight and deep coal gas resources (Table 2). The EPBC Act and the *Lake Eyre Basin Intergovernmental Agreement Act 2001* are discussed in more detail in this section.

Table 2 Commonwealth legislation relating to the development of petroleum resources

Legislation	Description	Administering department
Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act)	Protects and manages nationally and internationally important flora, fauna, ecological communities, wetlands (e.g. Ramsar) and heritage places. It is the overarching legislation for strategic assessments and considers water resources as a Matter of National Environmental Significance, in relation to coal seam gas (CSG) and large coal mining development.	Department of the Environment and Energy
Lake Eyre Basin Intergovernmental Agreement Act 2001	Provides for integrated management of surface water, groundwater and natural resources within the Agreement Area.	Department of Agriculture and Water Resources
Native Title Act 1993	Recognises and protects native title and the requirements for Indigenous Land Use Agreements.	Attorney-General's Department, Department of the Prime Minister and Cabinet (Indigenous Affairs)
Aboriginal and Torres Strait Islander Heritage Protection Act 1984	Preserves and protects places, areas and objects of particular significance to Aboriginals, where 'Aboriginal' means a member of the Aboriginal race of Australia and includes a descendant of the Indigenous inhabitants of the Torres Strait Islands.	Attorney-General's Department, Department of the Environment and Energy
Industrial Chemicals (Notification and Assessment) Act 1989	Notification and assessment of the use of industrial chemicals within Australia.	Department of Health (through the National Industrial Chemicals Notification and Assessment Scheme)
Water Act 2007	Manages the water within the Murray–Darling Basin and provides for the collection, collation, analysis and dissemination of information about Australia's water resources; and the use and management of water in Australia – includes water access rights, water delivery rights or irrigation rights.	Australian Government Department of Agriculture and Water Resources Water information – Bureau of Meteorology

Environment Protection and Biodiversity Conservation Act 1999 (Cth)

The EPBC Act is the Australian Government's central piece of environmental legislation, providing the legal framework for environmental and heritage protection and biodiversity conservation — defined in the EPBC Act as Matters of National Environmental Significance (MNES). The objectives of the EPBC Act are to:

- provide for the protection of the environment, especially MNES
- conserve Australian biodiversity
- provide a streamlined national environmental assessment and approvals process
- enhance the protection and management of important natural and cultural places
- control the international movement of plants and animals (wildlife), wildlife specimens and products made or derived from wildlife
- promote ecologically sustainable development through the conservation and ecologically sustainable use of natural resources
- recognise the role of Indigenous people in the conservation and ecologically sustainable use of Australia's biodiversity
- promote the use of Indigenous peoples' knowledge of biodiversity with the involvement of, and in cooperation with, the owners of the knowledge.

The nine MNES are:

- world heritage properties
- national heritage places
- wetlands of international importance (often called 'Ramsar wetlands' after the international treaty under which such wetlands are listed, signed in the Iranian city named Ramsar)
- nationally threatened species and ecological communities
- migratory species
- Commonwealth marine areas
- the Great Barrier Reef Marine Park
- nuclear actions (including uranium mining)
- a water resource, in relation to coal seam gas (CSG) development and large coal mining development.

Generally, proposed activities (e.g. a mine or wellfield development) are individually submitted to the Department of the Environment and Energy for assessment (Parts 7-9 of the EPBC Act). A strategic assessment for an industry type (e.g. CSG industry), however, takes a bigger picture approach over the impacted region. Rather than looking at how a single activity will affect nationally protected matters, a strategic assessment looks at how a group of activities (under a policy, plan or program) will affect these matters regionally. As well as helping to protect Australia's unique biodiversity, this type of assessment also benefits the community, developers, industry and government by increasing regulatory efficiency and providing long-term certainty.

Strategic assessments (Part 10 of the EPBC Act) offer the opportunity to examine and potentially approve a series of new proposals or developments at a much larger scale and time frame than can be achieved using a project-by-project referrals process. Strategic assessments enable the consideration of cumulative impacts on MNES and seek to explore opportunities for conservation and planning outcomes at a scale that could not be addressed via a project-by-project referral process.

In addition to MNES, Part 10 of the EPBC Act provides for assessment of other certain and likely impacts of actions. This occurs if the minister of the state or territory requests the responsible Australian Government Minister to ensure that the assessment deals with those additional impacts to assist the state or territory to make decisions about the actions.

The definition of 'Environment' under section 528 of the EPBC Act is a comprehensive list of ecological and socio-economic values: '(a) ecosystems and their constituent parts, including people and communities; and (b) natural and physical resources; and (c) the qualities and characteristics of locations, places and areas; and (d) Heritage values of places; and (e) the social, economic and cultural aspects of a thing mentioned in paragraph (a), (b), or (c).'

Within this context, the GBA Program is designed to provide the underpinning science to facilitate an assessment of future development of shale, tight and deep coal gas resources in the Cooper Basin and to streamline compliance with the EPBC Act.

Lake Eyre Basin Intergovernmental Agreement

The Lake Eyre Basin is one of the last unaltered, unregulated, arid water systems in the world (Kingsford et al., 1999). The Lake Eyre Basin Intergovernmental Agreement, which was signed by the Australian, Queensland and SA governments in 2000 and by the NT Government in 2004, provides for the establishment of arrangements for the sustainable management of water and related natural resources in the Lake Eyre Basin Agreement Area. The second review of the Lake Eyre Basin Intergovernmental Agreement specifically identifies the potential impacts on water resources associated with gas development and climate change. This review signalled the need for integrated surface water and groundwater management and improved governance of both these resources. Six policies have been prepared to support the agreement:

- River Flows Policy
- Water Quality Policy
- Water and Related Natural Resources Policy
- Existing Entitlements and Water Resource Development Policy
- Research and Monitoring Policy
- Whole-of-Basin Approach Policy.

Under the agreement, the condition of all watercourses and catchments within the Lake Eyre Basin Agreement Area is reviewed and reported on at least once every ten years. The first assessment took place in 2008, with a second assessment commissioned in 2016 and finalised in 2017. This latest State of the Basin Condition Assessment (Lake Eyre Basin Ministerial Forum, 2017) documents the current status of the hydrology, water quality, and fish and waterbird populations of the Lake Eyre Basin and on the current and emerging threats to the basin. It reveals an internationally significant river catchment in good condition, which is a rarity around the globe.

1.4.2 Queensland

Shale, tight and deep coal gas developments are subject to the same regulatory environments that govern the exploration and development of coal, oil and gas resources in Queensland. These requirements are reviewed by Queensland Competition Authority (2014) and Huddlestone-Holmes et al. (2018) and summarised here. Regulation is achieved via primary legislation, subordinate regulation, administrative decisions or discretions and quasi-regulation (Figure 13).

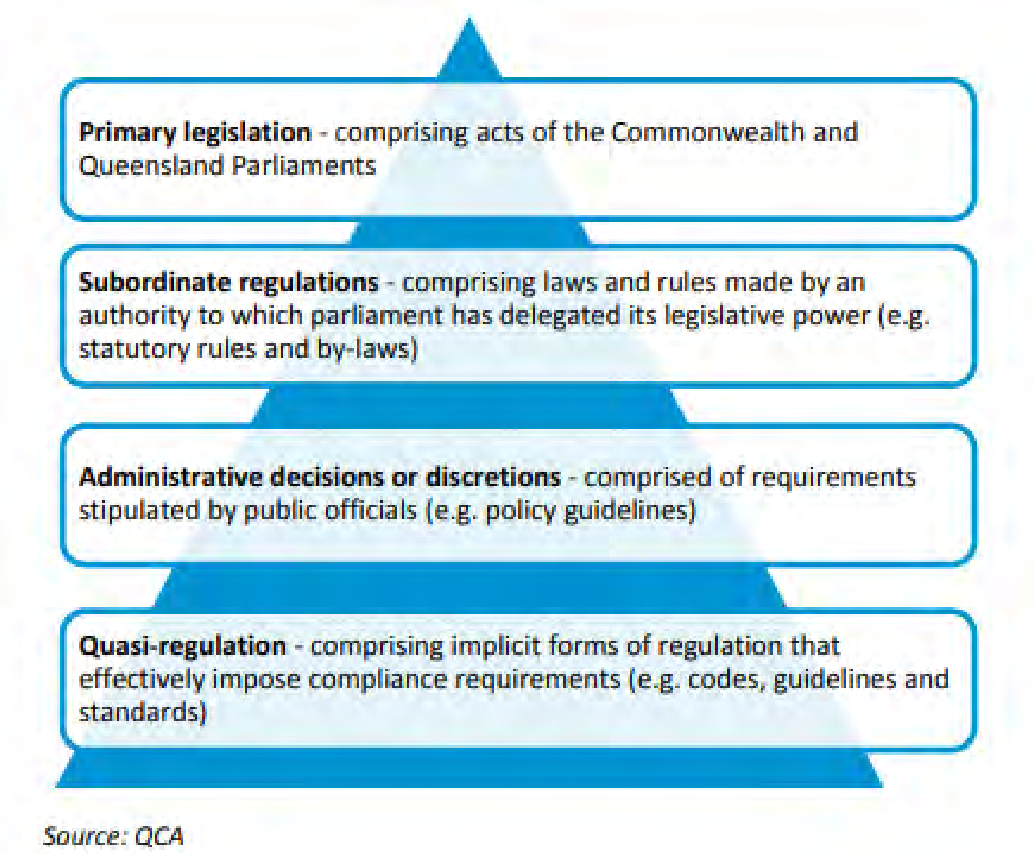

Figure 13 Regulation hierarchy showing how subordinate regulations, policies and codes are nested

Source: Queensland Competition Authority (2014).
Element: GBA-COO-2-112

In addition to the Commonwealth and intergovernmental agreements that provide the overarching regulatory environment for the development of unconventional gas resources in Queensland, including shale, tight and deep coal gas, there are six primary pieces of Queensland legislation applying to the petroleum and gas industries (Table 3). Additional Acts that are relevant to the development of unconventional gas resources are listed in Table 4.

Table 3 Primary Queensland legislation relating to the development of petroleum resources in Queensland

Legislation	Description	Administering department
Petroleum Act 1923	Regulates certain petroleum and natural gas activities. The *Petroleum and Gas (Production and Safety) Act 2004* supersedes this act, but an amended version of the *Petroleum Act 1923* was retained so that the rights of existing permit holders were not lost.	Department of Natural Resources, Mines and Energy
Petroleum and Gas (Production and Safety) Act 2004	Regulates petroleum and gas exploration tenure, safety, production and pipelines.	Department of Natural Resources, Mines and Energy
Environmental Protection Act 1994 (EP Act)	Regulates activities to avoid, minimise or mitigate impacts on the environment.	Department of Environment and Science
Water Act 2000	Regulates the sustainable management of Queensland's water resources, water supply and the impacts on groundwater caused by the extraction of groundwater by the resources sector.	Department of Natural Resources, Mines and Energy; Department of Environment and Science
Water Supply (Safety and Reliability) Act 2008	Regulates interactions and direct impacts associated with drinking water supply.	Department of Natural Resources, Mines and Energy; Department of Health
Gasfields Commission Act 2013	Established the Gasfields Commission – an independent statutory body with powers to review legislation and regulation; obtain and disseminate factual information; advise on coexistence issues; convene parties to resolve issues; and make recommendations to government and industry.	The commission is independent, but administrative matters are handled by the Department of State Development, Manufacturing, Infrastructure and Planning.

Data: Queensland Competition Authority (2014)

Table 4 Additional Queensland legislation relevant to the development of petroleum resources in Queensland

Legislation	Description	Administering department
Aboriginal Cultural Heritage Act 2003	Regulates activities to protect Queensland's Indigenous cultural heritage values.	Department of Aboriginal and Torres Strait Islander Partnerships
Biosecurity Act 2014	Manages and contains weeds and pest animals	Department of Agriculture and Fisheries (Biosecurity Queensland)
Environmental Offsets Act 2014	Regulates the requirements and management of environmental offsets in response to activities that cause a significant residual impact on prescribed environmental matters.	Department of Environment and Science
Fisheries Act 1994	Regulates the use of waterway barriers that may impact on fish movement along a waterway.	Department of Agriculture and Fisheries
Forestry Act 1959	Regulates activities involving the clearing of forest products and access to quarry material on state land.	Department of Agriculture and Fisheries
Heritage Act (1992)	Provides for the protection of Queensland's Cultural Heritage.	Department of Environment and Science

Legislation	Description	Administering department
Mineral and Energy Resources (Common Provisions) Act 2014	Regulates land access for mineral and energy resource authority holders. Commenced on 27 September 2016.	Department of Natural Resources, Mines and Energy
Nature Conservation Act 1992	Regulates the protection of flora and fauna as well and enables offset conditions to be imposed on certain authorities.	Department of Environment and Science
Planning Act 2014	Establishes integrated land use planning and development to achieve ecological sustainability. Provides standards and requirements for bore construction, especially artesian bores.	Department of State Development, Manufacturing, Infrastructure and Planning
Public Health Act 2005 (PH Act)	Protects and promotes the health of the Queensland public. Allows for public health orders to be issued that require the removal or reduction of the risk to public health from a public health risk or to prevent that risk from recurring. It also allows for investigating health complaints.	Department of Health
Queensland Heritage Act 1992	Regulates activities to protect Queensland's heritage places.	Department of Environment and Science
Regional Planning Interests Act 2014 (RPI Act)	Identifies and protects areas of Queensland that are of regional interest and resolves potential land use conflicts. Protects living areas in regional communities, high-quality agricultural areas from dislocation, strategic cropping land, and regionally important environmental areas.	Department of State Development, Manufacturing, Infrastructure and Planning
State Development and Public Works Organisation Act 1971	Provides ability for Queensland's Coordinator-General to declare a project a 'coordinated project'. Coordinated projects require an environmental impact statement and a higher level of public input.	Department of State Development, Manufacturing, Infrastructure and Planning
Transport Operations (Road Use Management) Act 1995	Regulates the transportation of dangerous goods by road, manages road use impacts and issues directions on road use, including payment of compensation.	Department of Transport and Main Roads
Waste Reduction and Recycling Act 2011	Promotes waste avoidance and reduction, reduce consumption of natural resources, minimise the impact of waste generation and ensure shared responsibility between government, business and the community.	Department of Environment and Science
Work Health and Safety Act 2011	Provides a framework to protect the health, safety and welfare of all workers at work. It also protects the health and safety of all other people who might be affected by the work.	Office of Industrial Relations, which resides in the Queensland Department of Education

Source: Huddlestone-Holmes et al. (2018)

For Queensland, the regulatory pathway that all petroleum resource projects must follow is consistent, although additional requirements may be required in areas of regional interest. In addition to legislation and regulations, codes and policies, including the following, must also be adhered to:

- The project proponent applies for an Authority to Prospect (ATP). An ATP allows a proponent to explore for petroleum, test for petroleum production, evaluate the feasibility of petroleum production and evaluate or test natural underground reservoirs for the storage of petroleum or a prescribed storage gas. The process is conducted through tender and regulated through the *Petroleum and Gas (Production and Safety) Act 2004* (Qld). The financial and technical capability of proponents (authority holder) is assessed along with an initial work program. An ATP must also obtain an Environmental Authority (EA) from the Queensland Department of Environment and Science (DES). The requirements of the EA are regulated by the *Environmental Protection Act 1994* (EP Act). Queensland waters, including water in rivers, streams, wetlands, lakes, groundwater aquifers, estuaries and coastal areas, are protected by the Environmental Protection (Water) Policy 2009. The policy sets values (cultural, spiritual and environmental) and water quality objectives for Queensland waters.
- The holder of an ATP must comply with all conditions and any other permits and authorities that may be needed – for example, avoiding disturbance of sites of cultural significance in accordance with the *Aboriginal Cultural Heritage Act 2003* (Qld).
- The holder of an ATP can apply to have the ATP declared as a potential commercial area to continue evaluation of production and market potential. The holder will be bound by the EA or would need to have the EA amended to reflect any planned activities.
- Once the ATP holder confirms the potential of the commercial viability of the project, the applicant can apply for a petroleum lease, also regulated through the *Petroleum and Gas (Production and Safety) Act 2004* (Qld). The applicant must submit an initial development program as part of their application. Applicants for a petroleum lease must obtain an EA or amend an existing one for the development program. At this point consideration should be given to potential impacts on MNES that may trigger a referral under the EPBC Act. The Queensland Government's DES may require an environmental impact statement (EIS) to be prepared, according to the requirements of the EP Act. If the lease is considered to be commercially viable, it must be developed within 15 years.
- If the project is deemed a 'coordinated project' (i.e. one deemed by the Queensland Coordinator-General as requiring rigorous impact assessment involving whole-of-government coordination), an EIS would need to be prepared under the requirements of the *State Development and Public Works Organisation Act 1971* (Qld). Regardless, environmental assessments are still required for projects that are not deemed a 'coordinated project'.
- The operator must operate in accordance with the conditions of their petroleum lease (PL) and EA and meet all other legislative requirements relevant to their activities (Huddlestone-Holmes et al., 2018).
- In an area of regional interest, such as a Strategic Environmental Area, a proponent will also have to obtain a regional interests development approval under the *Regional Planning Interests Act 2014* (Qld).

1.4.3 South Australia

The Department for Energy and Mining is responsible for the regulation of petroleum licensing in SA and the Department for Environment and Water is responsible for the licensing of groundwater use by the industry. The primary legislation and regulations governing the development of petroleum resources are the *Petroleum and Geothermal Energy Act 2000* (SA); and the *Petroleum and Geothermal Energy Regulations 2013* made under the Act. The key objectives of the Act are to:

- create effective, efficient and flexible regulatory requirements for industries involved in the exploration, recovery or commercial utilisation of petroleum and other resources
- encourage and maintain an appropriate level of competition in exploration for and production of petroleum and other resources
- provide stakeholders with information on industry performance and government decision making through effective reporting
- create effective and efficient and flexible regulation for the construction and operation of transmission pipelines
- minimise environmental damage from the activities involved in exploration, recovery and commercial utilisation of petroleum and other resources and the construction and operations of transmission pipelines for petroleum and other resources
- establish an appropriate consultation processes involving people directly affected by regulated activities
- as far as is practicable, ensure security of production and supply for users of natural gas
- protect the environment and public from risks inherent in regulated activities (Department for Energy and Mining (SA), 2018b; Santos, 2015).

Licensing and approvals under the *Petroleum and Geothermal Energy Act 2000* (SA) are carried out in three stages:

- licensing
- environmental assessment and approval of environmental objectives
- activity notification and approval.

The steps involved in each of the three stages of the activity approval process depend on the proposed activity. The activity approval process is divided into two types: (i) the general activities approvals process, which includes exploration retention, production and associated activities; and (ii) the pipeline activity approvals process, which includes transmission pipeline projects (Department for Energy and Mining (SA), 2018a). A workflow for the approval process for each of these activity types is available at Department for Energy and Mining (SA) (2018a).

Additional primary pieces of legislation are summarised in Table 5.

Table 5 Key South Australian legislation relating to the development of petroleum resources in South Australia

Legislation	Description	Relevant minister or department
Petroleum and Geothermal Energy Act 2000	Regulates exploration for, recovery of and commercial utilisation of petroleum and certain other resources.	Department for Energy and Mining
Planning, Development and Infrastructure Act 2016	Provides for the use, development and management of land and buildings, including by providing a planning system to regulate development within the state, to facilitate the development of infrastructure, facilities and environments that will benefit the community.	Department of Planning, Transport and Infrastructure
Natural Resources Management Act 2004	Promotes sustainable and integrated management of the state's natural resources and to make provision for the protection of the state's natural resources.	Department for Environment and Water
National Parks and Wildlife Act 1972	Provides for the establishment and management of reserves for public benefit and enjoyment; to provide for the conservation of wildlife in a natural environment.	Department for Environment and Water
Native Vegetation Act 1991	Provides incentives and assistance to landowners in relation to the preservation and enhancement of native vegetation; to control the clearance of native vegetation.	Department for Environment and Water
Heritage Places Act 1993	Makes provision for the identification, recording and conservation of places and objects of non-Aboriginal heritage significance. Established the South Australian Heritage Council.	Department for Environment and Water
Crown Lands Management Act 2009	Provides for the disposal, management and conservation of Crown Land.	Department for Environment and Water
Environment Protection Act 1993	Provides for the protection of the environment. Established the Environmental Protection Authority and defined its functions and powers.	Department for Environment and Water
Native Title (South Australia) Act 1994	Provides for recognition of the communal, group or individual rights of Aboriginal people in relation to lands and waters.	Attorney-General's Department
Aboriginal Heritage Act 1988	Provides for the protection and preservation of Aboriginal heritage.	Department of Premier and Cabinet
Fire and Emergency Services Act 2005	Provides for the establishment of the South Australia Fire and Emergency Services Commission; continuation of a metropolitan fire and emergency service – a state emergency service; prevention, control and suppression of fires and handling of certain emergency situations.	Minister for Police, Emergency Services and Correctional Services
South Australian Public Health Act 2011	Provides for the protection of the health of the public of SA and to reduce the incidence of preventable illness, injury and disability.	Minister for Health and Wellbeing
Work Health and Safety Act 2012	Provides for the health, safety and welfare of persons at work.	Treasurer
Dangerous Substances Act 1979	Regulates the keeping, handling, transporting, conveyance, use, disposal and quality of dangerous substances.	Treasurer
Explosives Act 1936	Consolidates and amends the law relating to explosives.	Treasurer

Source: Adapted from Santos (2015)

2 Geology and gas resources

2.1 Regional geological architecture

The Cooper Basin is a Carboniferous to Triassic sedimentary basin that is prospective for both conventional and unconventional petroleum resources. It covers an area of approximately 130,000 km^2, is up to 2500 m thick and occurs at depths between 1000 and 4500 m below sea level. It is overlain by the Jurassic–Cretaceous Eromanga and Cenozoic Lake Eyre basins, which host major aquifer systems.

This review of the regional structure and stratigraphic architecture of the Cooper Basin provides the geological framework required to better understand the distribution and properties of stratigraphic sequences hosting both petroleum and water resources.

This section summaries the architecture and evolution of the Cooper Basin and overlying geological Eromanga and Lake Eyre basins. A more detailed review of the region's geological architecture can be found in the accompanying geology technical appendix (Owens et al., 2020).

2.1.1 Geological setting

The Cooper Basin is a Carboniferous to Triassic sedimentary basin (Figure 14 and Figure 15). It covers an area of approximately 130,000 km^2, is up to 2500 m thick and occurs at depths between 1000 and 4500 m below sea level.

The south-western Cooper Basin overlies lower Paleozoic sediments of the Warburton Basin; however, the north-eastern part of the basin also overlies Devonian sediments associated with the Adavale Basin (Gravestock and Jensen-Schmidt, 1998; Draper, 2002; Radke, 2009; Raymond et al., 2018; Hall et al., 2015b).

The Cooper Basin does not outcrop at the surface and is overlain entirely by the Jurassic–Cretaceous Eromanga Basin (Raymond et al., 2018; Gravestock and Jensen-Schmidt, 1998; Cook et al., 2013a). In the Cooper GBA region, the Eromanga Basin sedimentary sequence exceeds 2500 m in thickness.

The Eromanga Basin is in turn overlain by Cenozoic sediments of the Lake Eyre Basin, which cover parts of north-eastern SA, south-eastern NT, western Queensland and north-western NSW (Raymond et al., 2018). The Lake Eyre Basin is less than 300 m thick over the Cooper Basin (Ransley et al., 2012b).

2.1.2 Structural elements

The Cooper Basin is divided into north-eastern and south-western areas that have different structural and sedimentary histories. These regional areas are separated by a series of north-west to south-east trending ridges known as the Jackson–Naccowlah–Pepita (JNP) Trend (Figure 14 and Figure 15) (McKellar, 2013; Gravestock et al., 1998).

The south-west of the Cooper Basin is dominated by north-east to south-west trending basement highs, including the Gidgealpa–Merrimelia–Innamincka and Murteree ridges (Gravestock and Jensen-Schmidt, 1998). These ridges separate the south-western basin's three major depocentres: the Patchawarra, Nappamerri and Tenappera troughs, which reach depths of over 3650 m, 4500 m and 3000 m, respectively (Hall et al., 2015b) (Figure 14 and Figure 16).

In contrast, the north-east of the basin is dominated by north-west to north trending structures (Figure 14). In this region the Permian sediments are thinner than in the south-west, and the major depocentres (Figure 14), including the Windorah Trough and Ullenbury Depression, are generally less well defined (Draper and McKellar, 2002; McKellar, 2013).

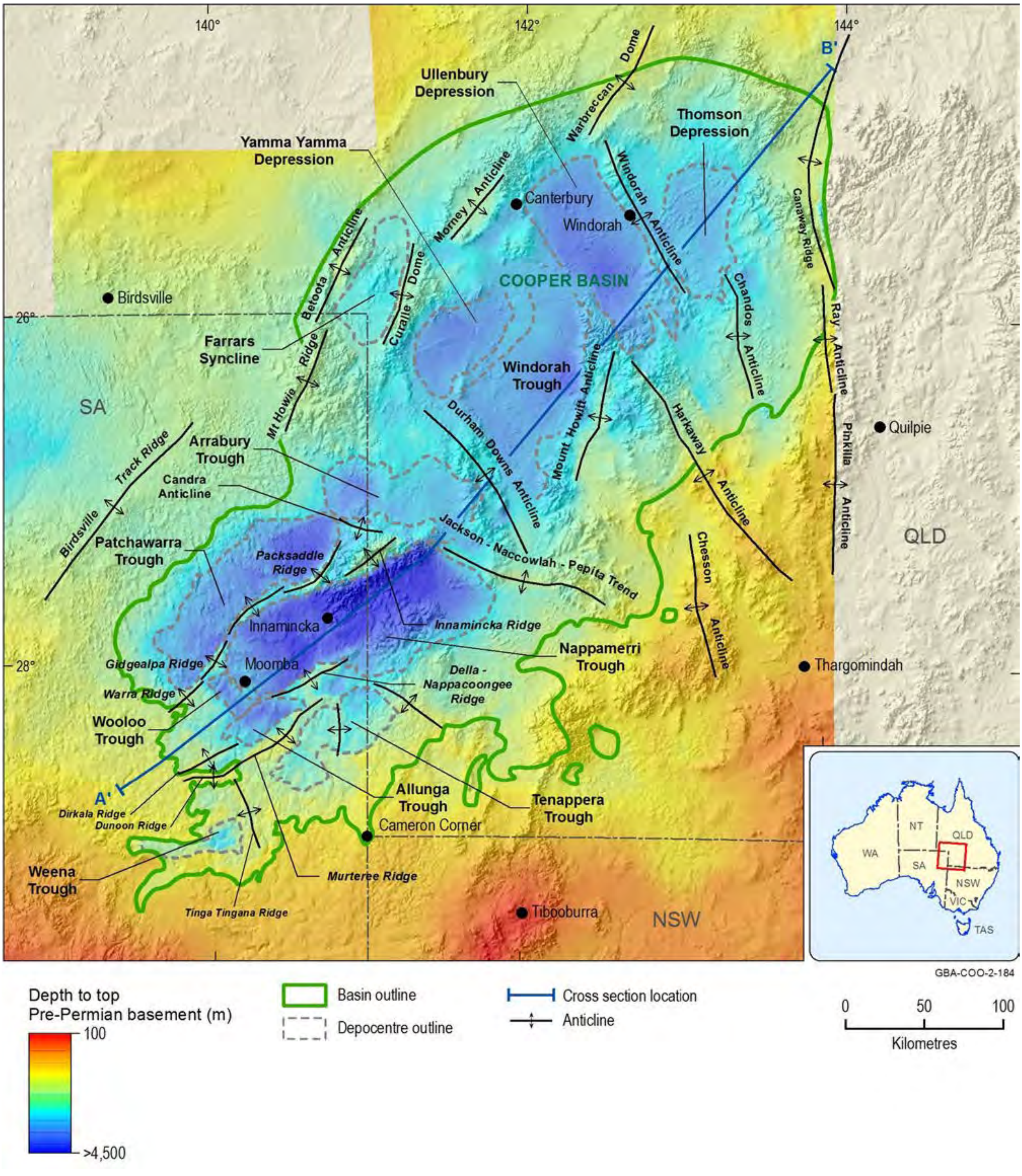

Figure 14 Cooper Basin structural elements overlain on the top of the pre-Permian basement depth horizon

Source: After Hall et al. (2015b); Carr et al. (2016)

Structural elements after Draper (2002); (Gravestock and Jensen-Schmidt, 1998); McKellar (2013); and Ransley et al. (2012b); see also Owens et al. (2020)

Data: Cooper Basin outline from Raymond et al. (2018); hill-shade derived from 9-second DEM (Geoscience Australia, 2008a), depth to Pre-Permian basement from Bioregional Assessment Programme (2015); structural elements from Hall et al. (2015b)

Element: GBA-COO-2-184

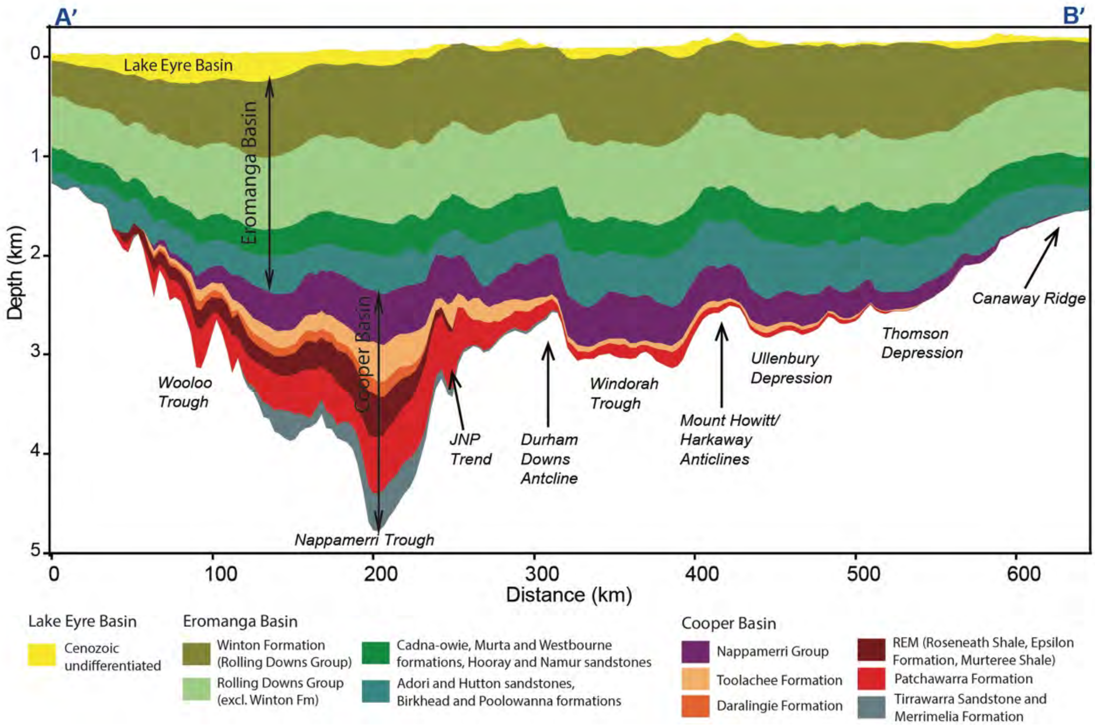

Figure 15 Regional cross-section through the Cooper Basin extracted from the regional three-dimensional geological model. Location of the cross-section is shown in Figure 14

Cooper Basin sediments incorporate the Nappamerri and Gidgealpa groups below and including the purple-filled unit. Eromanga Basin sediments (including the Lake Eyre Basin) incorporate all stratigraphy from the yellow to the blue. Refer to Figure 17 for more detailed stratigraphy. Names of structural elements, including troughs and ridges, are from top of the Cooper Basin level. Faults were not interpreted in the three-dimensional model; thus they are absent from this cross-section.

Source: Hall et al. (2016c)

Data: Hall et al. (2016b); Hall and Palu (2016)

Element: GBA-COO-2-170

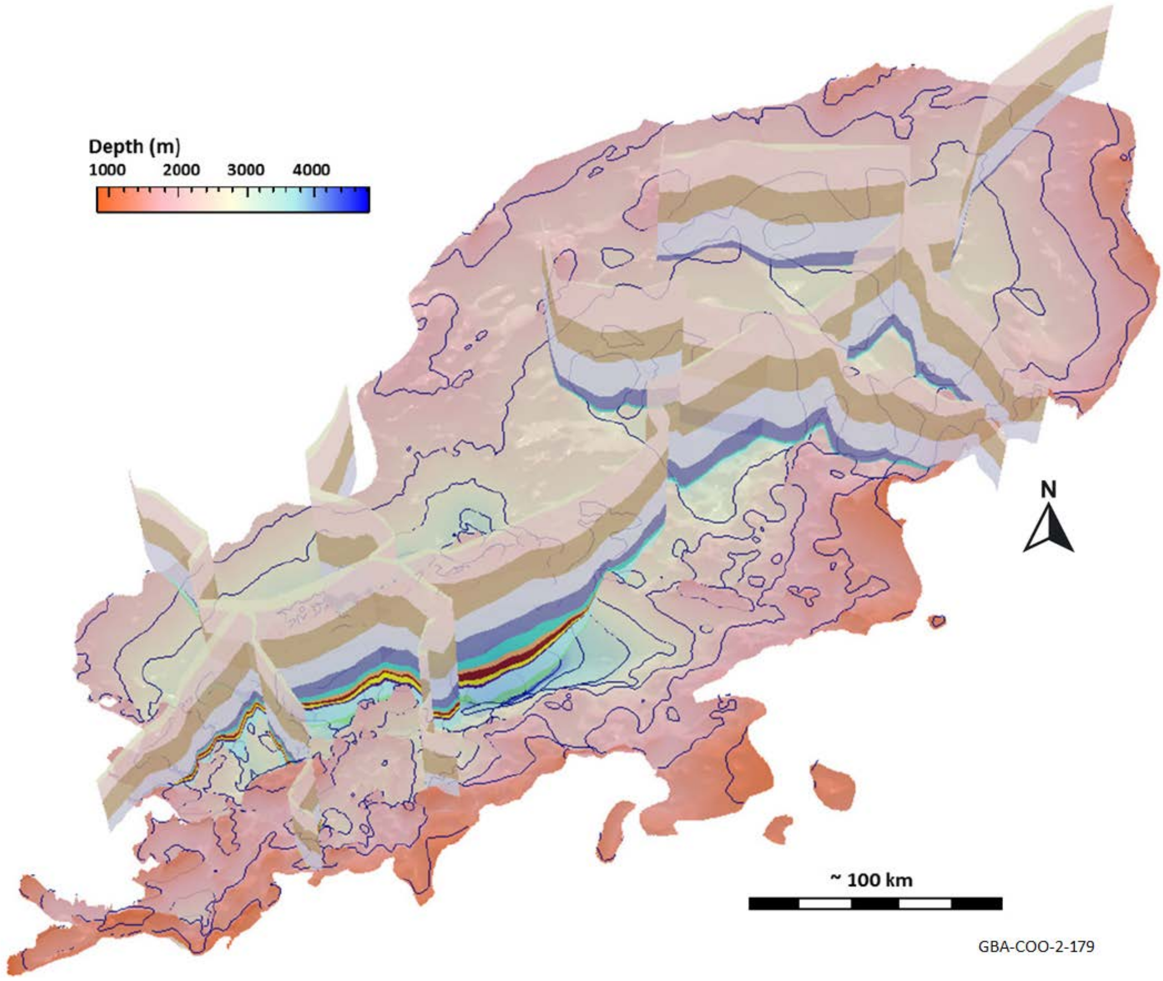

Figure 16 Oblique view of the regional three-dimensional geological model of the Cooper Basin, looking north

The structural surface shown is the top 'pre-Permian' basement clipped to the Cooper Basin outline (Raymond et al., 2018). Cross-sections running north-east–south-west through the basin and broadly east–west across the basin help to show the thickness and distribution of the sedimentary units within the basin. Faults were not interpreted for the three-dimensional model.
Source: Hall et al. (2015b)
Data: Hall et al. (2016b)
Element: GBA-COO-2-179

2.1.3 Basin evolution

2.1.3.1 Carboniferous to Triassic Cooper Basin

The Cooper Basin sediments were deposited over a time span of nearly 100 million years, from the late Carboniferous to the Triassic. The basin formed in the centre of the Australian continent, well inboard of the convergent plate margin affecting eastern Australia. Despite being relatively well studied, the tectonic history of the Cooper Basin is complex and debate continues regarding the basin's origin and geological history (McKellar, 2013; Draper and McKellar, 2002; AWT International, 2013).

The stratigraphy of the Cooper Basin (Figure 17) is divided into two groups: (i) the late Carboniferous to Permian Gidgealpa Group; and (ii) the Early to Middle Triassic Nappamerri Group. It is the Gidgealpa Group which hosts the primary shale, tight and deep coal gas resources in the basin.

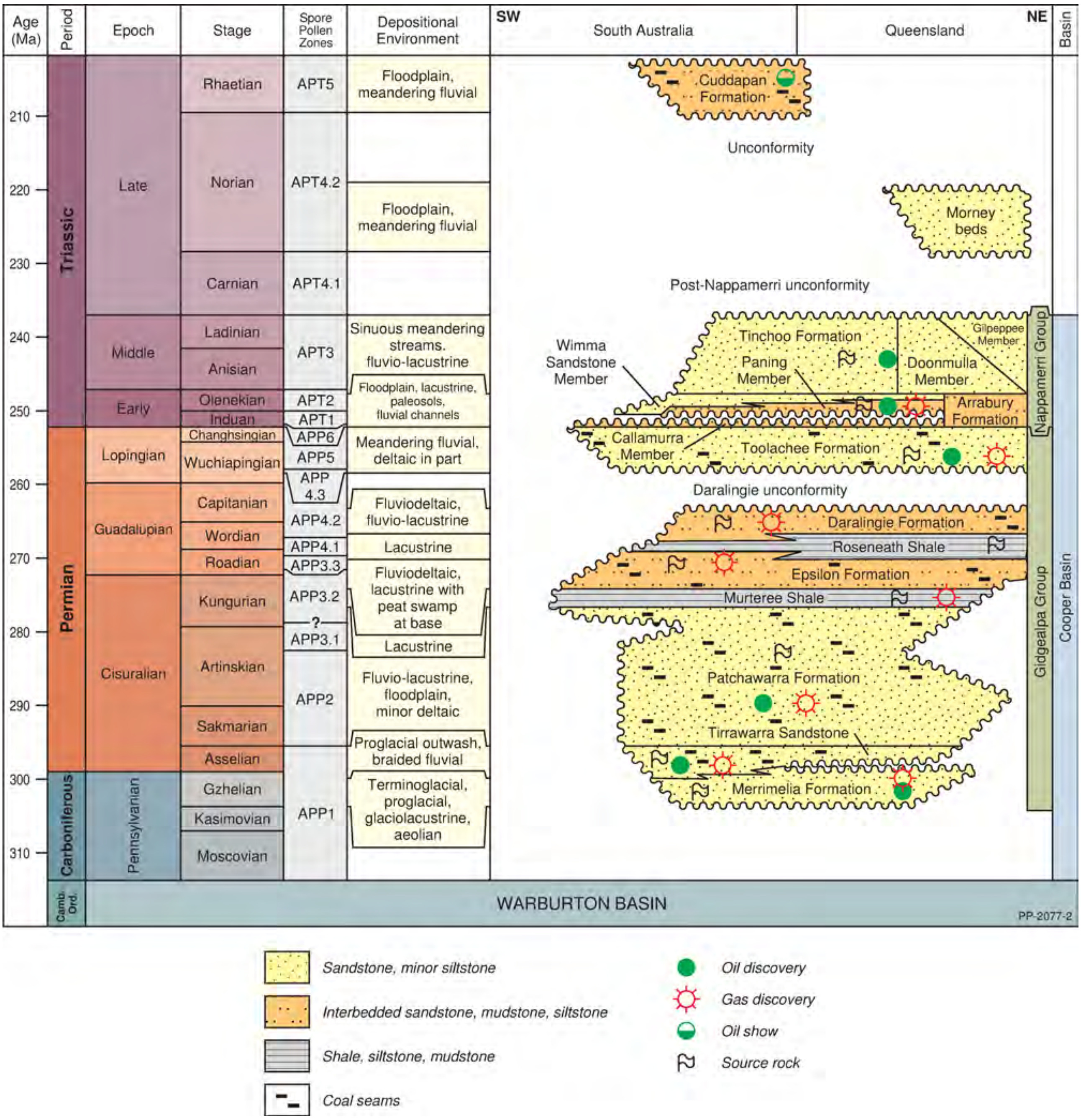

Figure 17 Stratigraphy of the Cooper Basin showing depositional facies, conventional petroleum occurrences and identified source rocks

Source: from Hall et al. (2015b); see also the geology technical appendix (Owens et al., 2020)
Element: GBA-COO-2-173

The lowermost units recognised within the Cooper Basin are the Carboniferous to Early Permian Merrimelia Formation and the Tirrawarra Sandstone (Figure 17 and Table 6). These were deposited in a glacial environment and consist of a mixture of rock types, including sandstone, mudstone and conglomerate (Alexander et al., 1998; Veevers, 1984).

The Permian Patchawarra Formation is broadly distributed across both the northern and southern Cooper Basin and reaches a maximum thickness of 680 m in the Nappamerri Trough. It comprises a heterogeneous mixture of sandstone, siltstone, shale and coal, deposited by complex lake and braided river systems. Patchawarra Formation coal seams average 2.1 m thick but can be up to 22 to 30 m, and 30% of seams exceed 2 m in thickness.

The Permian Murteree Shale, Epsilon Formation, Roseneath Shale and Daralingie Formation are primarily located in the southern part of the Cooper Basin. The Murteree and Roseneath shales are composed of siltstones and shale, while the Epsilon and Daralingie formations also contain coals and sandstones. These formations were deposited in alternating lake to river-delta environments. Although coal seams are extensive in both the Epsilon and Daralingie formations, individual seams rarely exceed 3 m and are commonly <0.3 m thick (Alexander et al., 1998). At the top of the Daralingie Formation is a major unconformity, which resulted from uplift due to tectonic activity along the eastern margin of Australia (Gravestock and Jensen-Schmidt, 1998).

The Triassic Toolachee Formation was deposited extensively across both the northern and southern Cooper Basin, reaching a maximum thickness of approximately 400 m in the Nappamerri Trough. Similar to the Patchawarra Formation, the Toolachee Formation comprises a mixture of sandstone, siltstone, shale and coal, deposited in dominantly meandering river to floodplain and peat swamp environments. The average coal seam thickness in the Toolachee Formation is 4.3 m (less in Queensland), but individual seams can reach 22 m (Alexander et al., 1998).

The overlying Early to Middle Triassic Nappamerri Group was deposited in braided to meandering river and floodplain environments (Alexander et al., 1998). Overall, the Nappamerri Group contains much less organic material that the Gidgealpa Group and therefore does not contain any unconventional plays.

Following deposition of the Nappamerri Group, a basin-wide erosional unconformity developed, marking the top of the Cooper Basin and the end of this Permo-Triassic depositional phase. This unconformity developed at the same time as cessation of sedimentation in the Galilee, Bowen, Gunnedah and Sydney basins in eastern Australia (Wiltshire, 1982; Gravestock and Jensen-Schmidt, 1998) and marks the end of the Hunter-Bowen Orogeny (Korsch et al., 2009). Overlying the Nappamerri Group there is a thin layer of Late Triassic sediments, less than 30 m thick, considered transitional between the Cooper and Eromanga basins.

Table 6 Stratigraphy of the Cooper Basin

Group	Formation	Age	Lithological description	Thickness	Depositional environments
Nappamerri Group	Tinchoo Formation	Middle Triassic	Siltstone, sandstone, minor coal	Maximum 263 m	Meandering fluvial
	Arrabury Formation	Early Triassic	Mudstone, siltstone, sandstone	Maximum 390 m	Fluvial, floodplain and ephemeral lakes
Gidgealpa Group	Toolachee Formation	Lopingian	Sandstone, shale and minor coal	Average 61 m; maximum ~400 m	Meandering fluvial, floodplain, deltaic in part
	Daralingie Formation	Guadalupian	Sandstone, shale and minor coal	Average 50 m; maximum 150 m	Deltaic, fluvio-lacustrine
	Roseneath Shale	Guadalupian	Siltstone, shale and minor sandstone	Average 57 m; maximum 240 m	Lacustrine, fluvio deltaic
	Epsilon Formation	late Cisuralian – early Guadalupian	Sandstone, siltstone, shale and coal	Average 50 m; maximum 225 m	Fluvio-deltaic, lacustrine with basal peat swamp
	Murteree Shale	late Cisuralian	Siltstone and sandstone	Average. 33 m; maximum 190 m	Lacustrine
	Patchawarra Formation	Cisuralian	Sandstone, siltstone, shale and coal	Average 130 m; maximum ~680 m	Fluvio-lacustrine, floodplain, minor deltaic
	Tirrawarra Sandstone	Cisuralian	Sandstone, conglomerates, minor shale interbeds and rare coal	Maximum 75 m	Fluvio-glacial, braided fluvial, proglacial outwash
	Merrimelia Formation	Cisuralian	Conglomerate, diamictite, sandstone, conglomeratic mudstone, siltstone and shale	Maximum 80 m	Glacio-lacustrine, aeolian, terminoglacial, proglacial

Source: Gatehouse (1972); Kapel (1972); Morton and Gatehouse (1985); Powis (1989); Price (1997); Alexander et al. (1998); (Draper, 2002); Gray and McKellar (2002); Hall et al. (2015b); see also geology technical appendix (Owens et al., 2020)

2.1.3.2 Early Jurassic to Late Cretaceous Eromanga Basin

The Cooper Basin is entirely overlain by the Early Jurassic to Late Cretaceous Eromanga Basin. The Eromanga Basin extends laterally over an area of approximately 1,000,000 km² – well beyond the extent of the Cooper Basin (Figure 18) (Raymond et al., 2018; Gravestock and Jensen-Schmidt, 1998; Cook et al., 2013a). Deposition within the Eromanga Basin was relatively continuous and widespread during its formation and was controlled by subsidence rates driven by tectonic activity along the margins of the Australian Plate.

The Eromanga Basin varies in thickness from around 1500 m near the margins to 2800 m in the middle of the basin and is thickest where it overlies the Cooper Basin. The structural features of the Eromanga Basin coinciding with the Cooper GBA region are shown in Figure 19.

The early part of the Eromanga Basin succession is Early Jurassic to Early Cretaceous in age and comprises large sand-dominated terrestrial sedimentary rocks. These were deposited by braided river systems which drained into lowland lakes and swamps. These units are overlain by a marine succession, which is dominated by shales interspersed with sandstone. In the Late Cretaceous, the Eromanga Basin returned to a non-marine environment in which meandering river systems were dominated by coal swamps and lakes .

The stratigraphy and depositional environments of the Eromanga Basin are summarised in Figure 18 and Table 7. Due to proximity, three units (Algebuckina Sandstone and the Mount Anna and Trinity Well sandstone members) found adjacent to the Cooper GBA region are included.

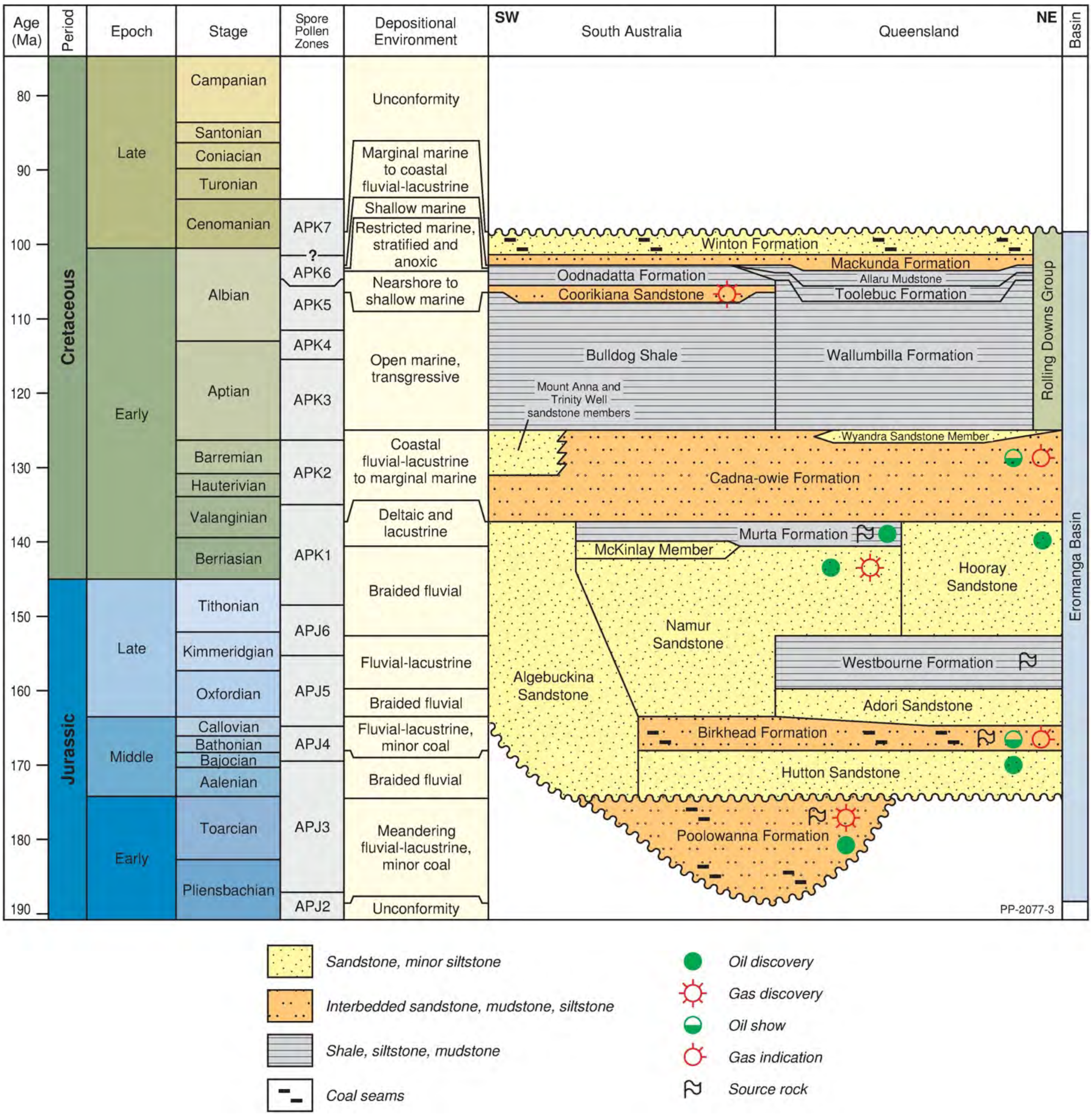

Figure 18 Eromanga Basin stratigraphy, depositional environments and petroleum occurrences

Source: after Smith et al. (2016); see also the geology technical appendix (Owens et al., 2020)
Element: GBA-COO-2-171

Table 7 Stratigraphy of the Eromanga Basin in the Cooper GBA region

Group	Formation	Age	Simplified lithological description	Thickness	Depositional environments
Rolling Downs Group	Winton Formation	Early to Late Cretaceous	Sandstone, shale, siltstone, coal	More than 400 m, maximum 1100 m	Fluvial, lacustrine
	Mackunda Formation	Early Cretaceous	Sandstone, siltstone, shale	60–120 m	Deep-marine, shoreface
	Allaru Mudstone	Early Cretaceous	Mudstone, siltstone, minor limestone and sandstone	100–240 m, maximum ~600 m	Shallow marine
	Toolebuc Formation	Early Cretaceous	Shale, limestone, minor sandstone	20–45 m	Restricted marine at maximum high stand
	Oodnadatta Formation	Early Cretaceous	Claystone, siltstone, sandstone, limestone	Up to 300 m	Shallow marine
	Coorikiana Sandstone	Early Cretaceous	Sandstone, minor conglomerate. Siltstone and mudstone at base	20 m	Near-shore
	Wallumbilla Formation	Early Cretaceous	Mudstone, siltstone, sandstone and minor limestone	200–375 m, maximum 596 m	High latitude marine shelf
	Bulldog Shale	Early Cretaceous	Mudstone, minor siltstone and very fine-grained sandstone interbeds	Generally 200 m, maximum >340 m	High latitude marine shelf
No group assigned	Cadna-owie Formation (inc Mount Anna[a], Trinity Well[a] and Wyandra sandstone members)	Early Cretaceous	Silty mudstone, siltstone sandstone, rare coal	60–115 m	Fluvial, lagoonal, shoreface, beach, marine, lacustrine
	Murta Formation (inc McKinlay Member)	Late Jurassic	Shale, sandstone, minor siltstone	30–60 m, maximum 90 m	Lacustrine, possible marine
	Namur and Hooray sandstone	Late Jurassic	Sandstone, minor siltstone and mudstone	40–240 m	Fluvial
	Westbourne Formation	Late Jurassic	Shale, siltstone, minor sandstone	30–140 m, maximum 166 m	Fluvial, lacustrine, lake-shore
	Adori Sandstone	Late Jurassic	Sandstone with minor siltstone and conglomerate	20–130 m	Braided fluvial
	Birkhead Formation	Middle Jurassic	Siltstone, mudstone, sandstone, thin coal seams	40–100 m, maximum 150 m	Lacustrine and swamp, deltaic

Group	Formation	Age	Simplified lithological description	Thickness	Depositional environments
	Hutton Sandstone	Middle Jurassic	Sandstone, minor siltstone	40–360 m	Braided fluvial
	Algebuckina Sandstone[a]	Middle Jurassic to Early Cretaceous	Sandstone, minor shale, siltstone	Up to 800 m	Braided fluvial
	Poolowanna Formation	Early Jurassic	Siltstone, sandstone, rare coal	Up to 205 m	Fluvial floodplain, minor swamps, lacustrine

[a] These stratigraphic units occur just to the west of the Cooper GBA region, toward the margin of the Eromanga Basin in SA.
na = not applicable
Source: Smith et al. (2015); see also geology technical appendix (Owens et al., 2020)

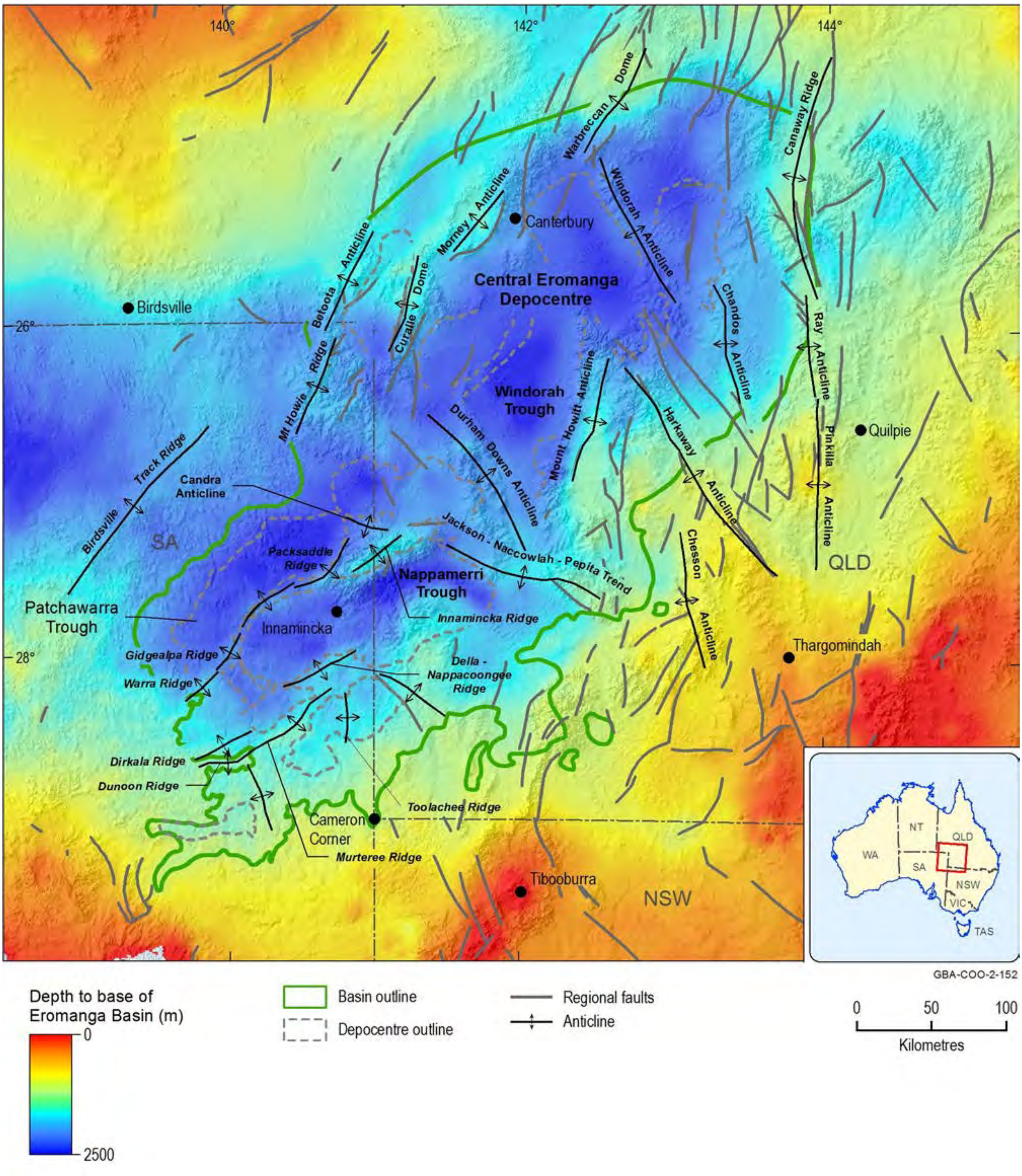

Figure 19 Structural elements map of the Eromanga Basin in the Cooper GBA region overlain on the depth to base Eromanga Basin

Anticlines depicted are regional trends and therefore to be used as a guide only.
Data: depth to base Eromanga Basin and regional faults from Smerdon et al. (2012). Anticlines from (Hall et al., 2015b)
Element: GBA-COO-2-152

2.1.3.3 Cenozoic Lake Eyre Basin

The Lake Eyre Basin covers parts of northern and eastern SA, south-eastern NT, western Queensland and north-western NSW. It is composed of Cenozoic aged terrestrial sedimentary rocks, which unconformably overlie the Eromanga Basin. In the Cooper GBA region, the Lake Eyre Basin has a maximum thickness of 300 m and was deposited following an extended period of erosion and deep weathering across the region. This was formed due to Cenozoic subsidence in north-eastern SA and south-western Queensland, which produced a large shallow depression in which river and lacustrine sediments were deposited.

The Lake Eyre Basin is divided into the Tirari and Callabonna sub-basins (Figure 20). Only the latter overlies the Eromanga Basin in the Cooper GBA region (Callen et al., 1995), so the former is not discussed further herein. Sub-division of the Lake Eyre Basin into internally draining sub-basins occurred as a result of Early Oligocene deformation (Wopfner, 1974; Moore and Pitt, 1984) followed by Miocene uplift of the northern Flinders Ranges (Foster et al., 1994). Subsequently, renewed uplift of the Eastern Highlands generated a regional south-westward tilt that greatly increased drainage (Ransley et al., 2012b).

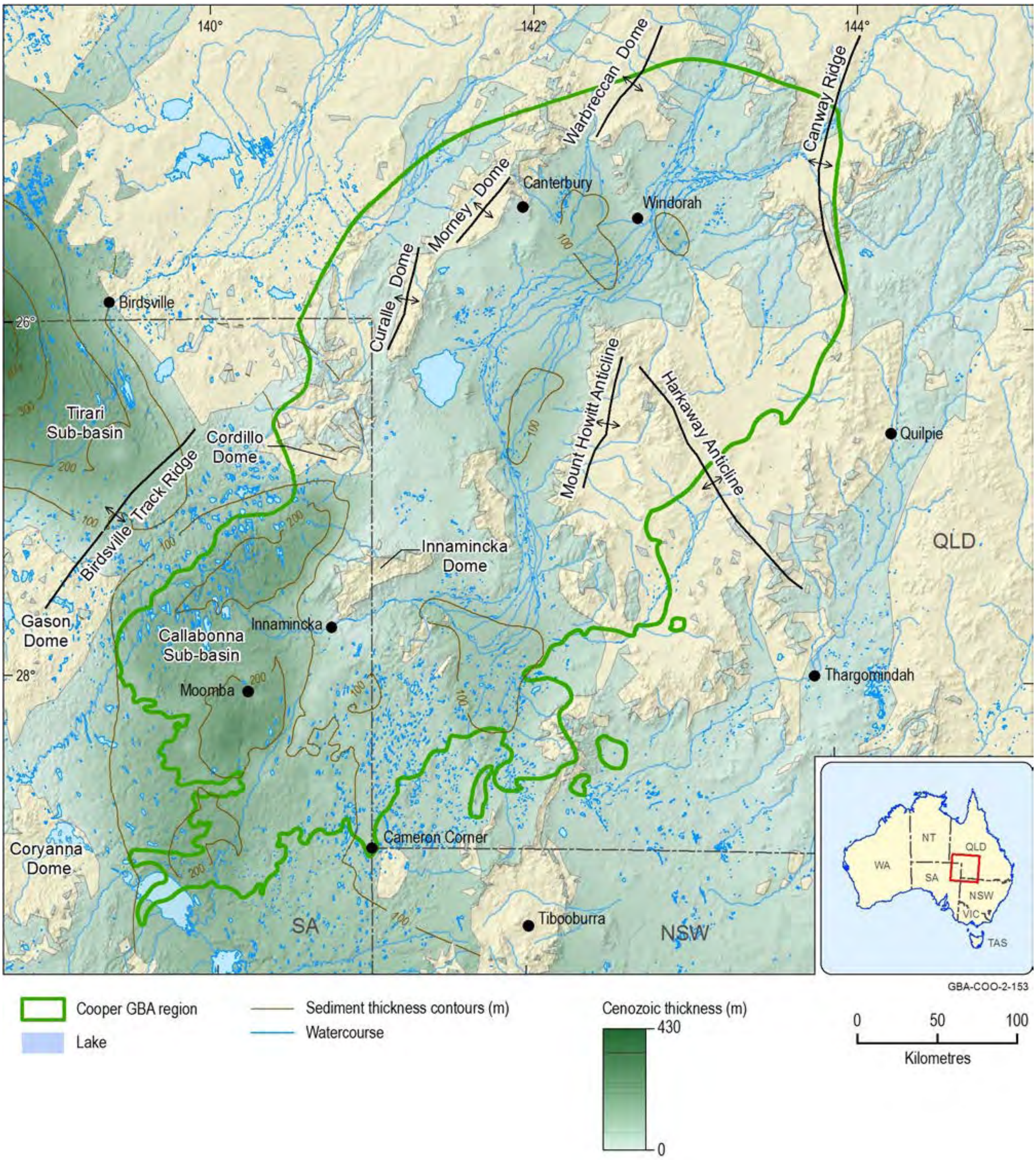

Figure 20 Thickness of the Cenozoic Lake Eyre Basin sediments and regional structures

Cream-coloured areas represent outcrop of rocks that are older than the Cenozoic sediments. In the Cooper GBA region these areas represent outcrop of Winton Formation. Anticlines depicted are regional trends and therefore to be used as a guide only.
Data: Cenozoic thickness from Ransley et al. (2012b); Cooper Basin outline from Raymond et al. (2018); hill-shade derived from 9-second DEM (Geoscience Australia, 2008b); major watercourses, lakes and salt lakes from Bureau of Meteorology (2014)
Element: GBA-COO-2-153

Deposition within the Lake Eyre Basin occurred in three phases punctuated by periods of tectonic activity and deep weathering. The first phase, from the late Paleocene to the middle Eocene, is represented by the Eyre, Glendower and Marion formations. The second phase, from the end of the Oligocene to the Miocene, is represented by the Namba, Whitula and Doonbarra formations and the Cadelga Limestone. The third and youngest phase, from the latest Pliocene to the Quaternary (Callen et al., 1995; Alley, 1998), is represented by undifferentiated surficial sediments that developed as a result of extensive aeolian dunes, fluvial systems, saline lakes, gibber plains and gypsum and carbonate paleosols.

The stratigraphy and depositional environments of the Lake Eyre Basin are summarised in Figure 21 and Table 8.

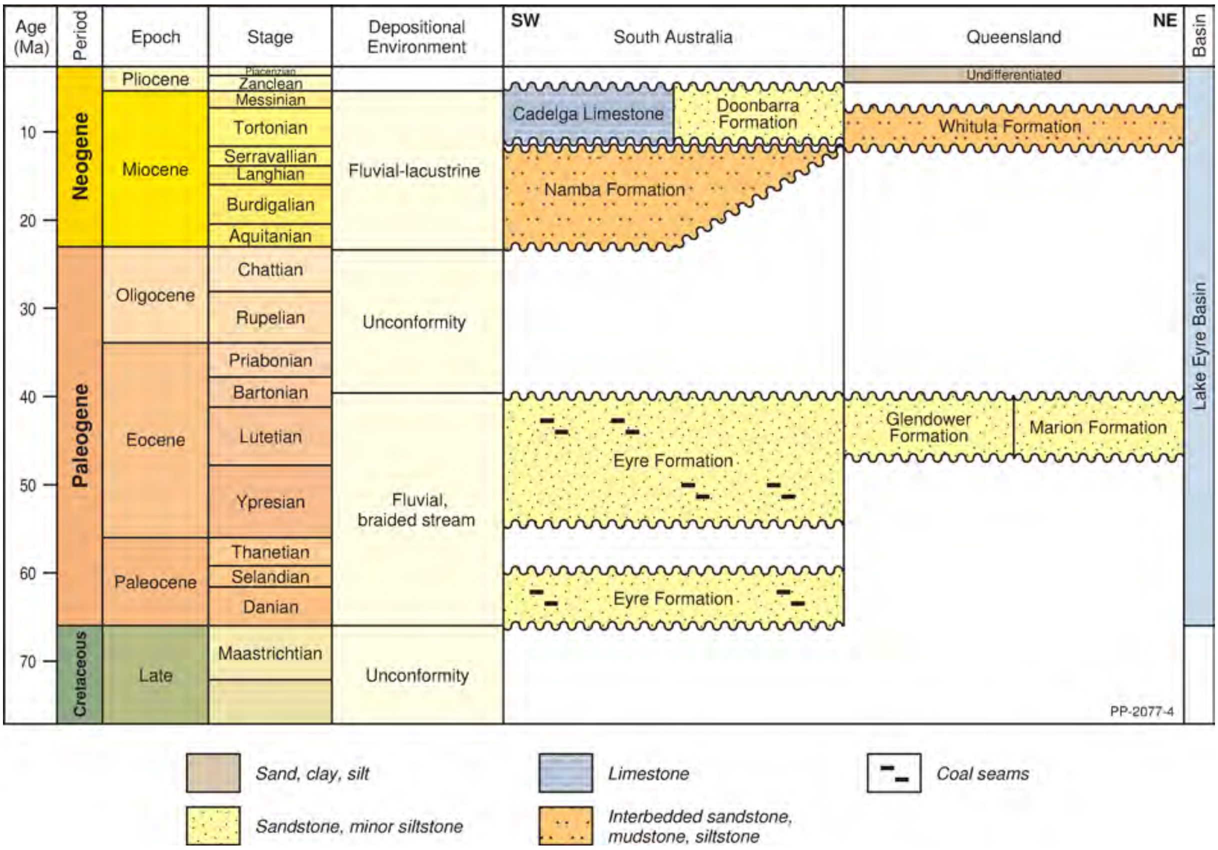

Figure 21 Lake Eyre Basin stratigraphy and depositional environment

Source: redrawn and modified from Smith et al. (2016); see also the geology technical appendix (Owens et al., 2020)
Element: GBA-COO-2-259

Table 8 Stratigraphy of the Lake Eyre Basin in the Cooper GBA region

Formation	Age	Simplified lithological description	Thickness	Depositional environments
Undifferentiated	Latest Pliocene to Quaternary	Sandstone, siltstone, claystone, evaporates and paleosols	Up to 60 m	Aeolian dunes, fluvial systems, lacustrine and gibber plains
Doonbarra Formation	Miocene	Sandstone and conglomerate	Generally 7–10 m, maximum 40 m	Fluvial-lacustrine
Cadelga Limestone	Miocene	Cherty dolomitic limestone	5 m	Lacustrine
Whitula Formation	Miocene	Sandstone, siltstone, mudstone and claystone with minor conglomerate, lignite and gypsum	Up to 160 m	Fluvial-lacustrine
Namba Formation	Miocene	Claystone, sandstone, carbonate, with minor conglomerate and dolomite	Up to 210 m	Fluvial-lacustrine
Marion Formation	Eocene	Sandstone and conglomerate	Up to 8 m	Fluvial, braided stream
Glendower Formation	Eocene	Sandstone, conglomerate and minor siltstone	Generally 70 m	Fluvial, braided stream
Eyre Formation	Paleocene to Eocene	Sandstone, siltstones and gravel with minor lignite and clay beds	0–100 m	Fluvial, braided stream

Source: Smith et al. (2015); see also geology technical appendix (Owens et al., 2020)

2.2 Shale, tight and deep coal gas

The Cooper and Eromanga basins form Australia's most developed onshore oil and gas province. Commercial production has been underway for over 50 years and the region continues to yield new discoveries. Resource development companies are currently pursuing a range of unconventional gas plays in the Cooper Basin, focused on shale, tight and deep coal gas hosted within the Permian succession. Given the basin's existing conventional production, and its processing and pipeline infrastructure, these plays are well placed to be rapidly commercialised pending further exploration success.

The regional prospectivity of shale, tight and deep coal gas plays in the Cooper Basin was assessed to underpin further work on understanding likely development scenarios. Key geological properties were evaluated and the relative prospectivity of each resource type was mapped at a regional scale across the basin. Areas of higher prospectivity were identified within most depocentres, including the Nappamerri, Patchawarra, Windorah, Allunga and Wooloo troughs, consistent with recent exploration activity. The mapped depth and extent of these shale, tight and deep coal gas plays inform where the plays are most likely to be present within the basin. This in turn aids assessment of potential connectivity to overlying surface water – groundwater systems and associated assets.

2.2.1 Conventional versus unconventional petroleum resources

Conventional natural gas (and oil) occurs in discrete accumulations trapped by a geological structure and/or stratigraphic feature, typically bounded by a down-dip contact with water and capped by impermeable rock. Conventional petroleum was not formed in-situ; it migrated from the deeper source rocks into a trap containing porous and permeable reservoir rocks (Schmoker, 2002; Schmoker et al., 1995) (Figure 22).

Unconventional gas is found in a range of geological settings and includes shale gas, tight gas and deep coal gas. Unlike conventional reservoirs, unconventional reservoirs have low permeabilities and require innovative technological solutions to move the trapped hydrocarbons to the surface (Figure 22).

The main types of unconventional gas resources found in the Cooper Basin include shale gas, tight gas, deep coal gas and coal seam gas (Table 9). Shale, tight and deep coal gas resources are included in the Cooper GBA region baseline assessment (Hall et al., 2018); however, development of coal seam gas (which requires dewatering as part of the gas extraction process) is not, as this was previously investigated as part of the Bioregional Assessment Program (Smith et al., 2015).

Gas may be referred to as dry gas or wet gas depending on its composition. Dry gas is natural gas that is dominated by methane (greater than 92% by volume) with little or no condensate or liquid hydrocarbons. Wet gas (also known as liquids-rich gas) contains less methane than dry gas and more ethane and other more complex hydrocarbons (propane, butane, pentane, hexane and heptane). The composition of the gas is important for understanding future development scenarios in the Cooper Basin, as wet gas resources are currently more favourable to develop from an economic perspective.

A more detailed description of each play type can be found in the petroleum prospectivity technical appendix (Lech et al., 2020).

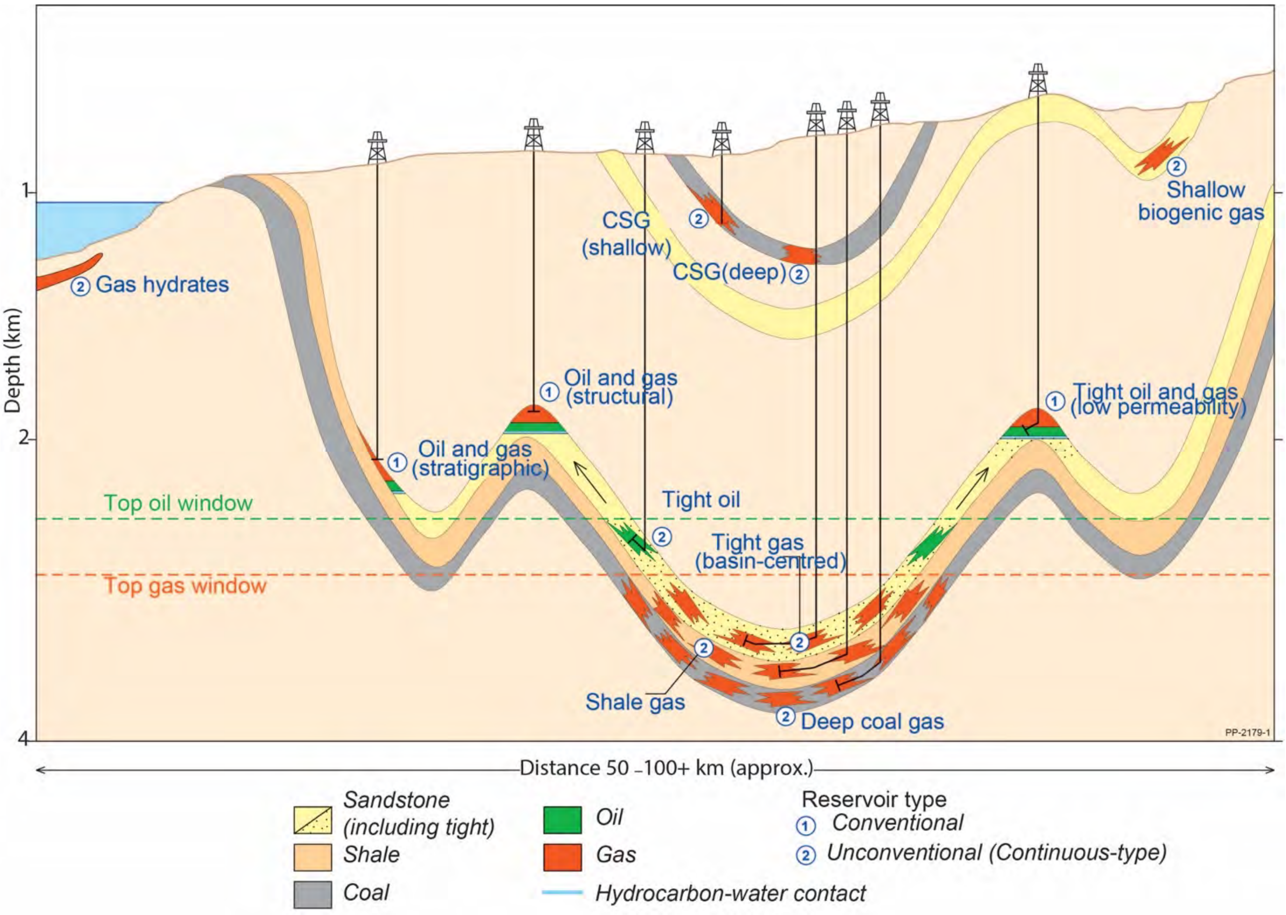

Figure 22 Schematic showing some of the typical types of oil and gas accumulations

Except for gas hydrates, which are located below the sea floor in deep water, these are common conventional and unconventional hydrocarbon accumulations observed in the Cooper Basin. The 'oil window' refers to the maturity range in which oil is generated from oil-prone organic matter. Below is the 'gas window', which refers to the maturity range in which gas is generated from organic matter.

Source: after Schenk and Pollastro (2002); Cook et al. (2013b); Schmoker et al. (1995)

Element: GBA-COO-2-172

Table 9 Types of unconventional gas resource in the Cooper Basin

Play type	Description
Tight gas	Tight gas is natural gas trapped in reservoirs characterised by low porosity (<8–10%) and permeability (<0.1 mD). There are a range of trapping mechanics for tight gas. Tight gas may occur in pervasive, distributed, basin-centred gas accumulations, where gas is hosted in low-permeability reservoirs which are commonly abnormally overpressured, apparently lack a down-dip water contact and are continuously saturated with gas (Fall et al., 2002; Law and Curtis, 2002). Tight gas may also occur in discrete reservoirs, where migrated gas accumulates in rocks with very low porosity and permeability, in a similar manner to conventional accumulations (e.g. Shanley and Robinson, 2004).
Shale gas	Shale gas is natural gas hosted in sedimentary rock with low to moderate porosity (with a pore size of 0.005–0.1 µm) and very low permeability. Shales are a common petroleum source rock and may retain more petroleum than they expel during the thermal maturation process of organic matter. The gas remains trapped in the shale and is either absorbed on to the organic matter or is held in a free state in the pores and fractures of the rock. Shale reservoirs occur with significant (10–100 km) lateral continuity and can be of considerable thickness (>100 m). Where shales act as both the petroleum source and reservoir rock, they are sometimes referred to as 'self-sourcing reservoirs'. Shale gas plays usually occur at depths greater than 1000–1500 m.

Play type	Description
Deep coal gas	Deep coal gas is natural gas hosted in coals at depths typically greater than 2000 m below the land surface that do not require dewatering as part of gas extraction process. At these greater depths, the lack of well-developed cleats and the decrease in fracture permeability mean than hydraulic stimulation is often required to release the free gas held within the organic porosity and fracture system within the coal seam (Dunlop et al., 2017).
Coal seam gas	Coal seam gas is natural gas extracted from coal seams found at depths typically less than 1000 m below the land surface and is predominantly (>95%) methane. The gas is transiently held in place either in the fractures or adsorbed onto the coal's surface by the pressure of formation water in the coal. The large surface area to volume ratio of coals makes them very high capacity reservoirs. Coal seam gas plays require dewatering as part of gas extraction process. This is in contrast to shale, tight and deep coal gas, which do not. Coal seam gas can be either thermogenic or biogenic. Biogenic gas is produced by microorganisms under the surface of the Earth, whereas thermogenic natural gas results from chemical reactions that occur as organic material in the rock is heated as it is buried.

mD = millidarcies
Source: after Schenk and Pollastro (2002); Cook et al. (2013b); Schmoker et al. (1995)
See the petroleum prospectivity technical appendix (Lech et al., 2020) for further information.

2.2.2 Petroleum in the Cooper Basin

The Cooper and Eromanga basins contain 256 gas fields and 166 oil fields currently in production (Figure 23) (Hall et al., 2015b) and, between 1969 and 2014, these basins produced 6.54 Tcf of gas (AERA, 2018). Gas is predominantly reservoired in the Cooper Basin, whereas the overlying Eromanga Basin hosts mainly oil. The regional petroleum systems are summarised in Table 10, with further details provided in the petroleum prospectivity technical appendix (Lech et al., 2020).

Table 10 Regional petroleum systems summary

Component of regional petroleum system	Description
Play types – conventional	Sandstone reservoirs within structural traps and pinch out plays along the basin margins.
Play types – unconventional	Pervasive basin-centred tight gas, discrete tight gas, shale gas, deep coal gas and coal seam gas.
Reservoirs	Conventional and tight gas reservoirs are found within sandier intervals of the Toolachee, Daralingie, Epsilon and Patchawarra formations, in the basal glacial sediments of the Tirrawarra Sandstone and sandier intervals within Nappamerri Group. Shale gas reservoirs are present within Patchawarra Formation, Roseneath and Murteree shales, and deep coal gas reservoirs in the Patchawarra, Toolachee, Epsilon and Daralingie formations.
Seals	The Nappamerri Group forms a regional seal. Intraformational seals include the Roseneath and Murteree shales, as well as finer grained siltstone and shale intervals within all reservoir units except the Tirrawarra Sandstone. The overlying Eromanga Basin sediments also act as a seal across much of the basin.
Source rocks	The main hydrocarbon source rocks of the Cooper Basin are the organic-rich shales and coals found within most formations of the Permian Gidgealpa Group.
Hydrocarbon shows	Shows are found within most of the formations associated with major reservoir units.

Source: after Carr et al. (2016); see also petroleum prospectivity technical appendix (Lech et al., 2020)

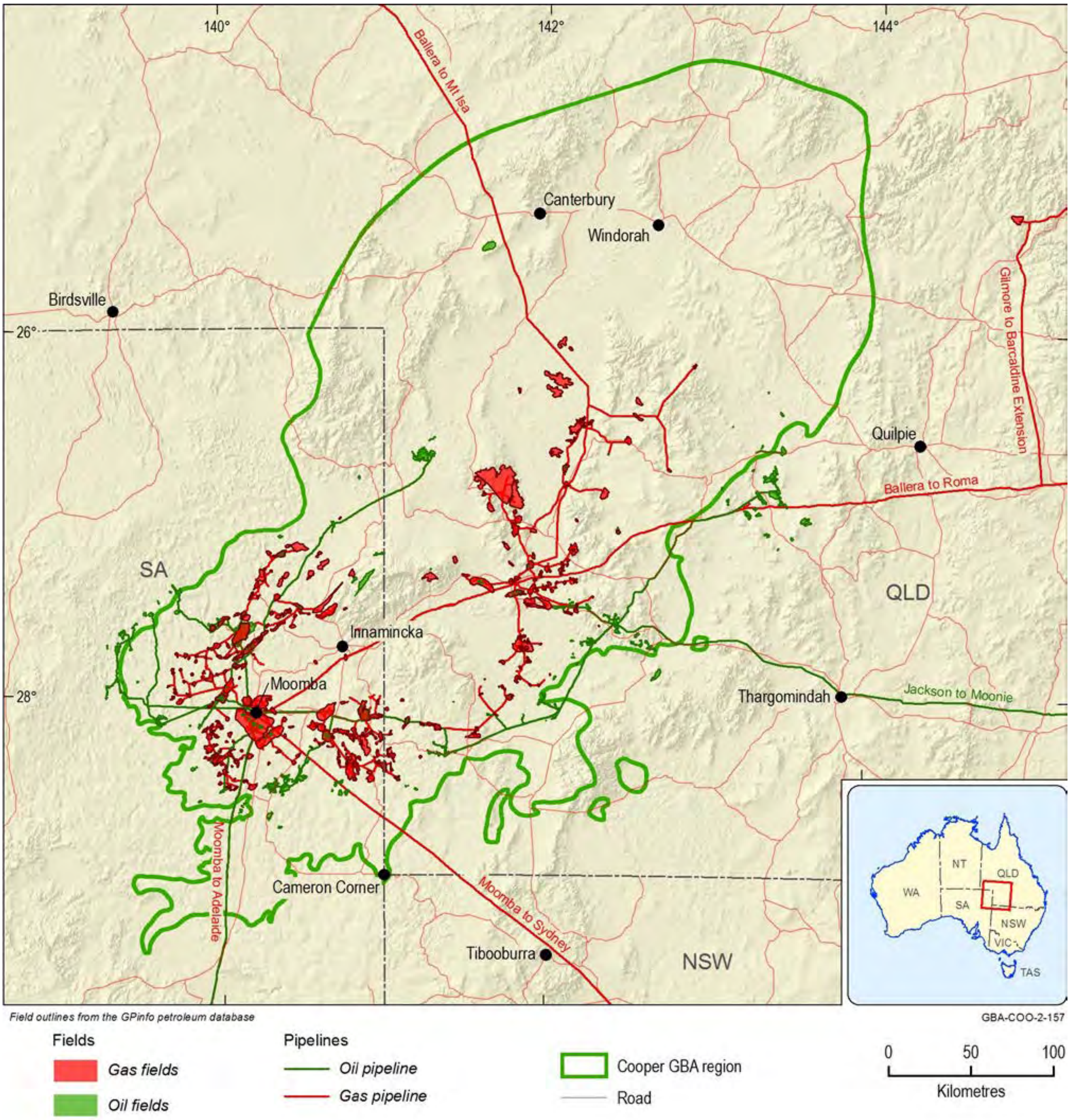

Figure 23 Fields and pipelines in the Cooper Basin as of November 2018

Data: oil and gas field outlines and pipeline routes from the GPinfo petroleum database – a Petrosys Pty Ltd product (Petrosys Pty Ltd, 2019)
Element: GBA-COO-2-157

2.2.2.1 Exploration history

Exploration in the Cooper Basin by Santos began in 1954 and resulted in the basin's first commercial gas discovery in 1963 at Gidgealpa 2 (Santos, 2018; O'Neil, 1998). The discovery of natural gas in the Moomba 1 well by Delhi–Santos in 1966 was followed by further exploration wells, proving the existence of large widespread gas reserves and paving the way for the commercial development of the Cooper Basin (O'Neil, 1998). Initial gas sales to Adelaide began in 1969, followed by Sydney in 1976 and Brisbane 20 years later (Santos, 2018; O'Neil, 1998).

The first Permian oil discovery was announced in 1970, when light crude oil flowed from the Tirrawarra Sandstone in the Tirrawarra 1 well, while the first Jurassic-hosted oil was discovered in Strzelecki 3 (1978) in the Hutton Sandstone of the overlying Eromanga Basin (O'Neil, 1998).

Between 2009 and 2014, there was a revival in exploration activity in the Cooper Basin driven by high resource prices; and an increased interest in newly identified unconventional hydrocarbon plays in the basin. In 2014, 119 petroleum wells were drilled in the SA part of the basin, coupled with major three-dimensional seismic acquisition.

Over the last ten years, numerous companies have also pursued a range of unconventional resources within the Cooper Basin. In December 2011, Santos drilled Moomba 191 – the first dedicated vertical shale gas well – which flowed gas at 2.7 Mcf per day from shales in the Roseneath–Epsilon–Murteree (REM) section (Santos, 2018; Goldstein et al., 2012). Following completion, this was connected to the Moomba processing facilities in October 2012, bringing the first shale gas production to the East Coast Gas Market (Santos, 2018; Goldstein et al., 2012).

Although the presence of a pervasive tight gas accumulation in the Nappamerri Trough had been suspected for over two decades, in 2011 this was confirmed by the intersection of gas-saturated sands outside of structural closure in the Encounter 1 and Holdfast 1 wells (Goldstein et al., 2012). Since this time extensive exploration for tight and shale gas has resulted in the drilling of over 30 wells in the Nappamerri Trough (Department for Energy and Mining (SA), 2018e; Business Queensland – Queensland Government, 2018).

The productivity of the deep Permian coals was initially proven by Santos at the Moomba 77 well, which flowed gas to surface at 100,000 scf per day from a fracture-stimulated deep Patchawarra Formation (Department of the Premier and Cabinet (SA), 2018; Goldstein et al., 2012; Greenstreet, 2015; Menpes and Hill, 2012). The Cooper Basin’s first stand-alone deep coal producer, Tirrawarra South 1 in the Patchawarra Trough, flowed wet gas and was successfully brought online in 2015 (Santos, 2018).

The active exploration for and development of both conventional and unconventional gas resources in the Cooper Basin and overlying Eromanga Basin continues today. Most of the region is covered by exploration permits, retention licences and production licences. To date, over 3000 petroleum wells have been drilled and more than 81,000 line km of two-dimensional seismic data and 10,000 km2 of three-dimensional seismic data have been acquired (Figure 24; Figure 25).

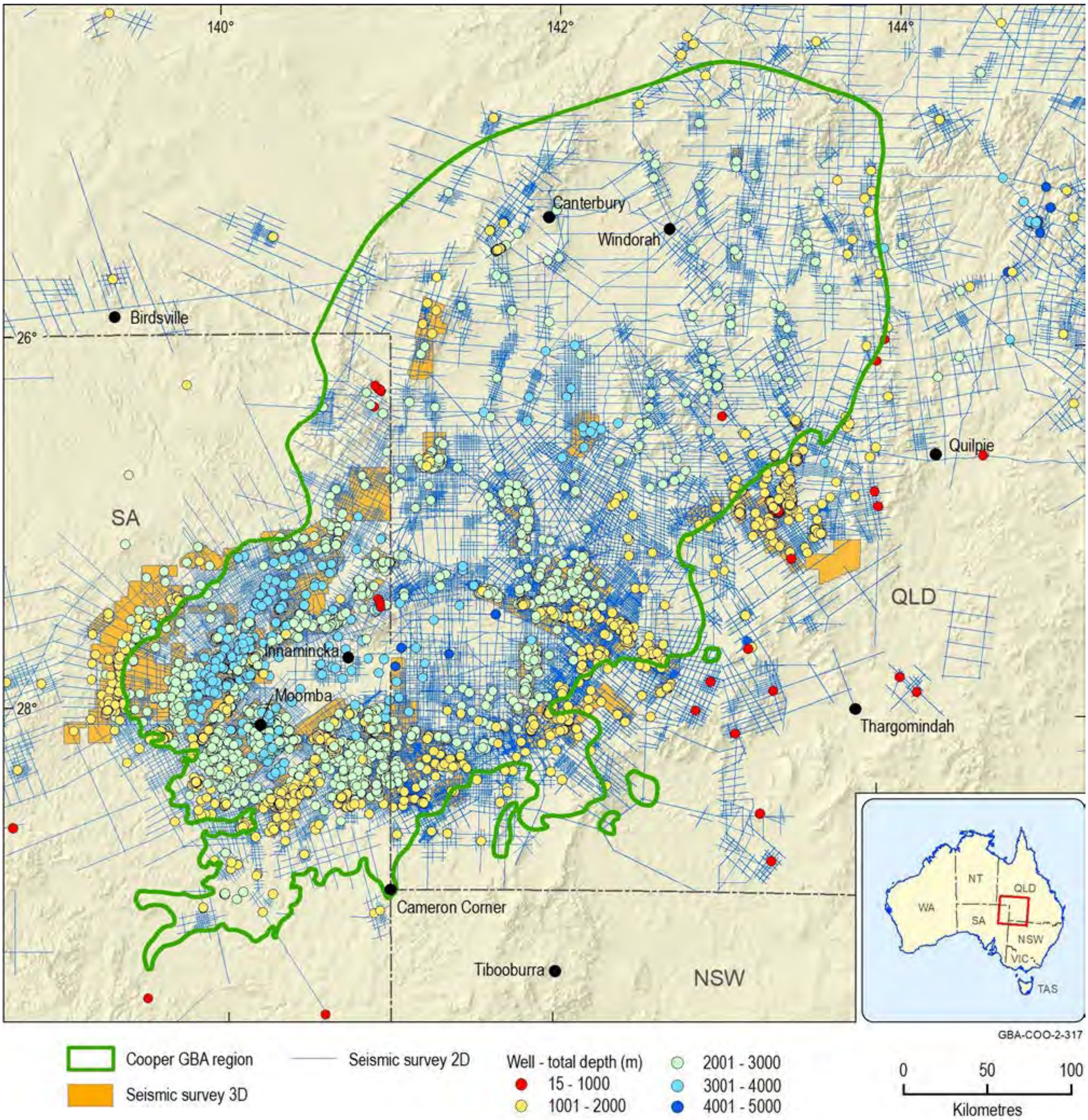

Figure 24 Cooper Basin well and seismic data coverage (two-dimensional and three-dimensional)

Data: basin boundary from Raymond et al. (2018); wells from Department of Natural Resources, Mines and Energy (Qld) (2018b) and Department of State Development (SA) (2018); seismic data from Department for Energy and Mining (SA) (2019a, 2019b); Department of Natural Resources, Mines and Energy (Qld) (2017, 2019b, 2019c)
Element: GBA-COO-2-317

Figure 25 Seismic lines in the Cooper Basin, including two well pads

Credit: Geological and Bioregional Assessment Program, Russell Crosbie (CSIRO), September, 2018
Element: GBA-COO-2-220

2.2.2.2 Unconventional gas plays

In geology, a petroleum play, or simply a play, is a group of petroleum accumulations that occur in the same region and are controlled by the same set of geological circumstances.

In the Cooper Basin, the main unconventional gas plays lie within the Permian sediments of the Gidgealpa Group. These include shale gas associated with the Patchawarra Formation and the Roseneath and Murteree shales; deep coal gas accumulations within the Toolachee, Epsilon and Patchawarra formations; and basin-centred tight gas within the Permian Gidgealpa Group (Figure 26) (Goldstein et al., 2012; Hillis et al., 2001; Menpes et al., 2013; Menpes and Hill, 2012; Hall et al., 2015b; Greenstreet, 2015).

The principal shale gas play is the Roseneath-Epsilon-Murteree play comprising Permian Murteree and Roseneath shales separated by tight sands of the Epsilon Formation (Department of the Premier and Cabinet (SA), 2018; Goldstein et al., 2012; Greenstreet, 2015; Menpes and Hill, 2012). These formations are generally restricted in extent to the southern part of the basin (Hall et al., 2015b; Hall et al., 2015a). Well data suggest these shales have a lower porosity than producing shale gas plays in the United States, highlighting the requirement for thicker and overpressured shale sections to commercialise the resource (Department of the Premier and Cabinet (SA), 2018).

Tight gas plays are present in multiple depocentres across the Cooper Basin (Department of the Premier and Cabinet (SA), 2018; Goldstein et al., 2012; Greenstreet, 2015; Menpes and Hill, 2012). The most extensive of these is located in the distributed basin-centred gas play in the Nappamerri Trough, where the Permian Gidgealpa Group reaches a maximum thickness of 1.7 km and contains thermally mature, gas-prone source rocks (Department of the Premier and Cabinet (SA), 2018).

In addition to basin-centred tight gas, discrete tight gas sources are also present in the basin. These are located within and surrounding conventional fields; for example, the tight gas sands of the Patchawarra Formation in the Moomba and Big Lake fields on the southern end of the Nappamerri Trough.

Deep coal gas is a relatively new and under-explored resource in the Cooper Basin. Since the viability of this play was demonstrated by Santos Limited in 2007 (Dunlop et al., 2017), gas-saturated deep coal plays in the Permian Toolachee, Epsilon and Patchawarra formations (that do not require dewatering as part of the gas extraction process) have become additional exploration targets (Department of the Premier and Cabinet (SA), 2018; Goldstein et al., 2012; Greenstreet, 2015; Menpes and Hill, 2012).

Exploration for coal seam gas (which requires dewatering to extract) is primarily restricted to the Weena Trough in SA, where thermal maturities are low (<0.75 %Ro) at the base of the Patchawarra Formation (Department of the Premier and Cabinet (SA), 2018). These plays were previously assessed in the Bioregional Assessment Program (Smith et al., 2015).

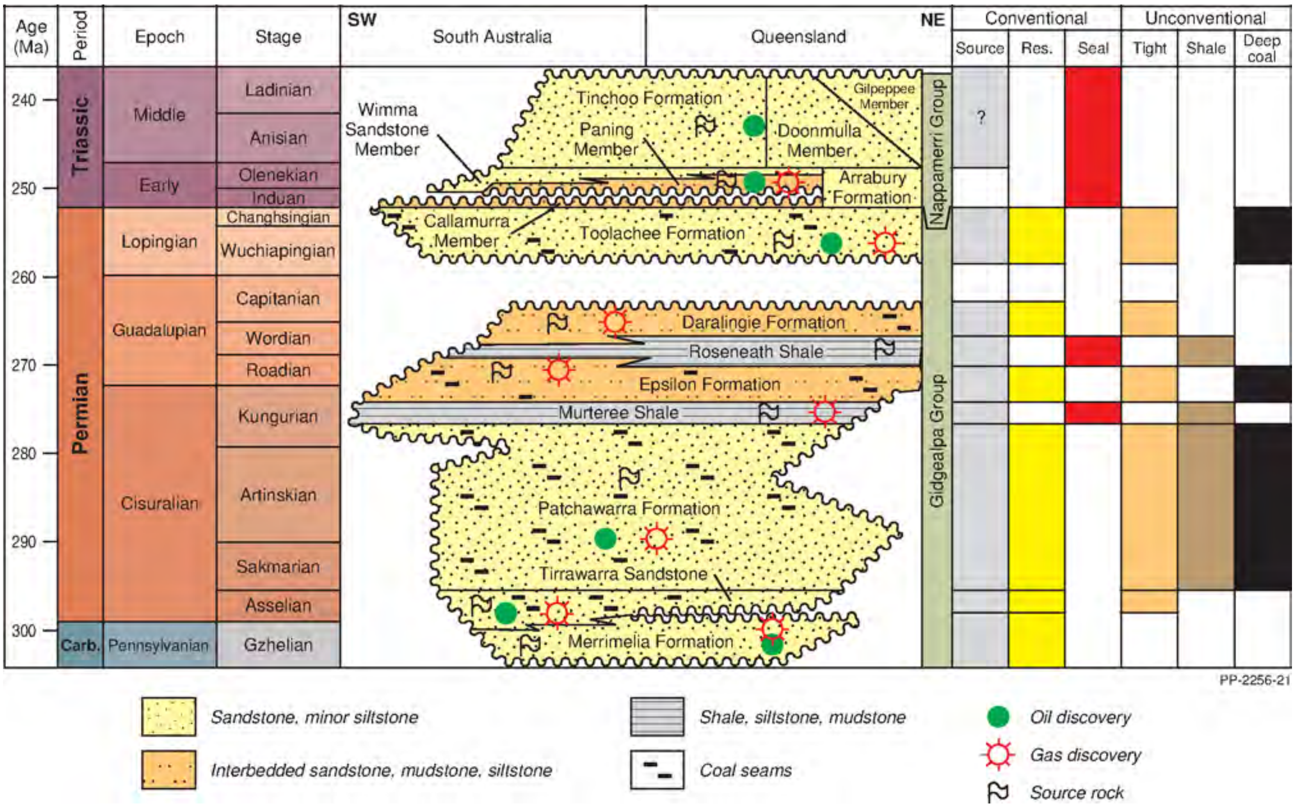

Figure 26 Schematic diagram showing key conventional and unconventional (shale, tight and deep coal) hydrocarbon plays in the Cooper Basin

Source: stratigraphy after Hall et al. (2015b); hydrocarbon plays after Hall et al. (2015b); see also petroleum prospectivity technical appendix (Lech et al., 2020)
Element: GBA-COO-2-175

2.2.3 Formation characterisation

The amount of gas (and oil) present within a petroleum accumulation depends on the geological characteristics of both the petroleum source rock and the reservoir rock in which the petroleum is trapped.

To underpin further work on understanding likely development scenarios and recovery factors, the geological properties of all formations hosting shale, tight and deep coal plays were characterised, based all available open file domain data. These formations evaluated included the Toolachee, Daralingie, Epsilon and Patchawarra formations; Roseneath and Murteree shales; and Tirrawarra Sandstone. The geological properties evaluated for each formation were:

- formation depth and extent.
- source rock properties, including net coal and shale thickness, total organic carbon (TOC) content, the type of organic matter (kerogen type) and the quality of the source rock (hydrogen index).
- source rock thermal maturity. This represents the degree to which a source rock has been heated under the Earth's surface and influences whether the generated petroleum is oil, wet gas or dry gas.
- reservoir characteristics, including porosity, permeability, gas saturation, mineralogy and brittleness.

- regional stress regime and pressure gradient.

Results are summarised in Table 11 and Figure 27, and a full descriptions of this assessment is provided in the petroleum prospectivity technical appendix (Lech et al., 2020).

Table 11 Characteristics of formations hosting shale, tight and deep coal gas plays in the Cooper Basin

Source rock properties	• Abundant petroleum source rocks that are mature for gas are present in the Permian Gidgealpa Group across the Cooper Basin. • The thickest and most extensive source rocks are coals (TOC >50 wt%) and carbonaceous shales (TOC 2–50 wt%) in the Toolachee and Patchawarra formations. Net coal thickness in the Patchawarra Formation reaches nearly 200 m in the Weena Trough and over 40 m in the Wooloo and southern Patchawarra troughs. Net coal thickness in the Toolachee Formation reaches approximately 40 m in the northern Patchawarra Trough and 25 m in the Arrabury Depression. The net shale thickness in the Patchawarra and Toolachee formations is greatest in the Nappamerri Trough, where it reaches 250 m and 180 m respectively. • Additional source rocks include carbonaceous shales in the Roseneath and Murteree shales; and coals and carbonaceous shales in the Daralinigie and Epsilon formations. • Source rocks comprise a mixture of oil and gas-prone Type II/III and gas-prone Type III kerogen.
Reservoir rock properties	• Net sand thicknesses demonstrate an abundance of potential tight gas reservoir units in the Gidgealpa Group across the basin. These range in thickness from 75 m for the proglacial to braided fluvial Tirrawarra Sandstone to 680 m for the largely fluvio-lacustrine to floodplain Patchawarra Formation, with the thickest successions deposited in the Nappamerri and Patchawarra troughs. The predominantly fluvial Toolachee Formation is thickest in the Windorah Trough and Ullenbury Depression. The average effective sandstone porosities and permeabilities range from 7.2% and 0.1 mD in the Patchawarra Formation to 7.8% and 0.6 mD in the Toolachee Formation. • The coal and carbonaceous shale units within the Toolachee, Daralingie, Epsilon and Patchawarra formations (described above) also represent the reservoir intervals for the shale and deep coal gas plays. • The average effective porosities and permeabilities for shale reservoirs are 2.5% and 3.3×10^{-3} mD for the Roseneath Shale, 2.7% and 6.7×10^{-3} mD for the Murteree Shale and 2.3% and 3.7×10^{-3} mD for the Patchawarra Formation. • Based on an assessment of shale brittleness, the Patchawarra Formation is the most favourable for fracture stimulation, with an average Brittleness Index of 0.695, indicative of brittle rocks. The Roseneath and Murteree shales are less brittle, with Brittleness Indices of 0.343 and 0.374, respectively. • As-received total gas content is favourable, with averages ranging from 1.3 scc/g in the Patchawarra Formation to 1.6 scc/g for the Murteree Formation.
Regional stress regime	• The mean maximum horizontal stress azimuth trends approximately east–west. Although the stress regime is variable, it is predominantly transitional strike-slip to reverse. • Stress magnitudes vary between lithologies. Stress variations are a likely impediment to fracture propagation, where intraformational variations contain fractures within formational zones. The Nappamerri Group forms a natural barrier to induced fracture propagation between gas-saturated Permian sediments and the overlying Eromanga Basin.
Pressure gradient	• Pressure gradients are significantly greater than lithostatic (>10.2 MPa/km) at depths >2800 m, although this varies by structural setting.

MPa/km = megapascals per kilometre; scc/g = standard cubic centimetres per gram; TOC = total organic carbon; wt% = weight (as a percentage)
Source: See the petroleum prospectivity technical appendix (Lech et al., 2020) for full formation descriptions and associated references

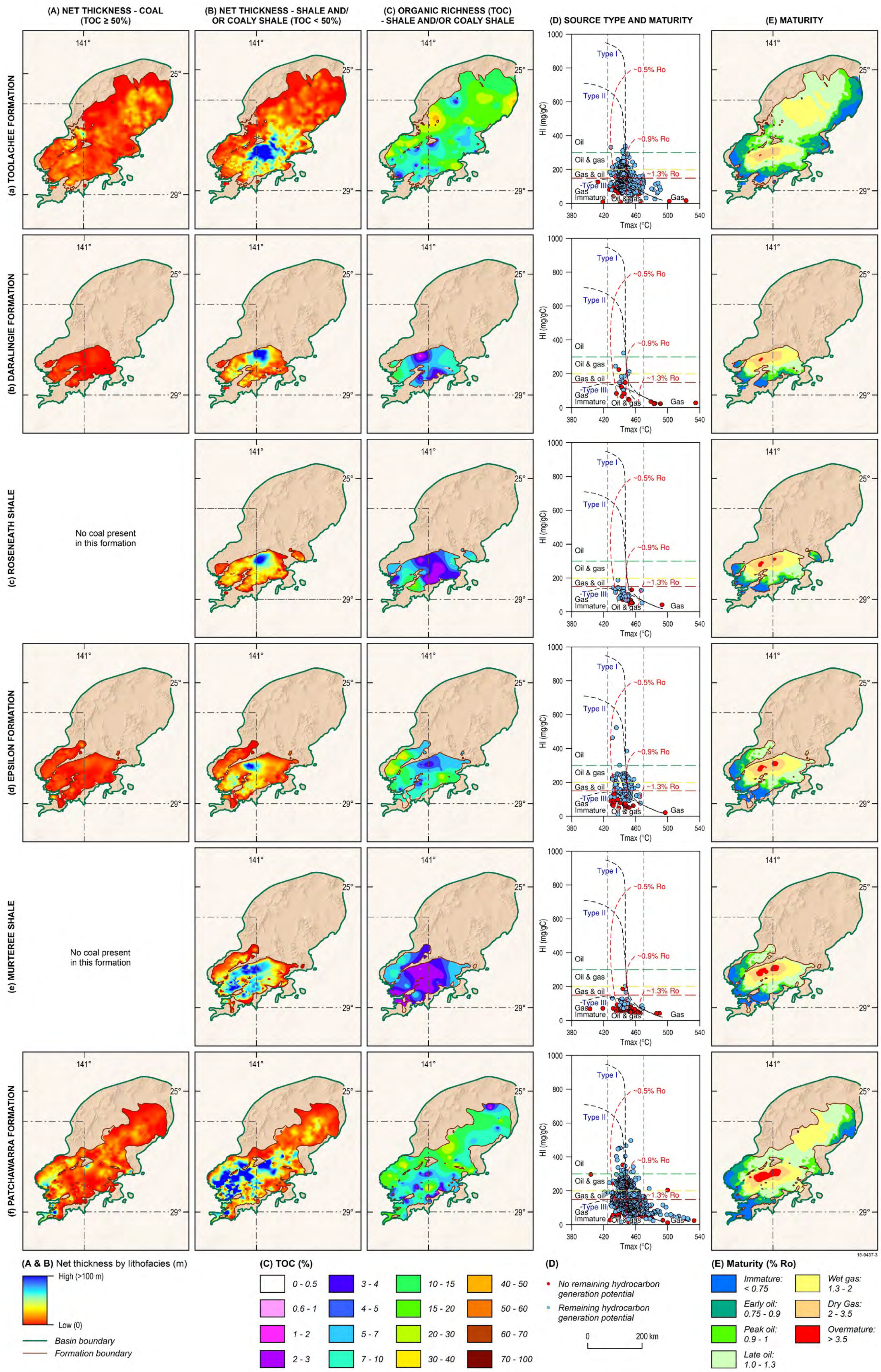

Figure 27 Key characteristics of formations hosting shale, tight and deep coal gas plays

(a) Toolachee Formation; (b) Daralingie Formation; (c) Roseneath Shale; (d) Epsilon Formation; (e) Murteree Shale; and (f) Patchawarra Formation. Column A (the left-most column): net coal thickness maps. Column B (second from left): net shale and/or coaly shale thickness maps. Column C (middle column): present-day maps of total organic carbon (TOC) for coals and coaly shale source units. Note that coals (TOC >50%) are excluded, as these are represented in Column A. Column D (second from right): hydrogen index (HI) versus maturity (Tmax) plots showing the variation in source rock quality and kerogen type by formation. Column E (the right-most column): source rock maturity.

Source: Hall et al. (2015b); Hall et al. (2016c); Hall et al. (2016a)

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

2.2.4 Shale, tight and deep coal gas prospectivity maps

The distribution of the different shale, tight and deep coal gas plays were mapped across the Cooper Basin at a regional scale. These maps inform where the gas resources are more likely to be present within basin. This in turn aids assessment of potential connectivity to overlying surface water–groundwater systems and associated assets.

The following plays were mapped for this assessment:

- shale gas plays within the Patchawarra Formation and the Roseneath and Murteree shales.
- wet and dry gas deep coal gas plays within the Toolachee, Epsilon and Patchawarra formations (which do not require dewatering as part of the gas extraction process).
- basin-centred tight gas hosted within sandstones of the Permian Gidgealpa Group.

Exploration and development of discrete tight gas plays primarily occurs in conjunction with the conventional gas field development (Figure 23), so this play type has not been mapped separately for this study.

The potential extent of petroleum resources in Cooper Basin were evaluated for each play using a process called play fairway analysis. This analysis assessed the relative variation in prospectivity of each play across the basin based on the geological characteristics described in the previous section. The play fairway analysis workflow is summarised below and is documented in full in the accompanying petroleum prospectivity technical appendix (Lech et al., 2020).

Methods snapshot: play fairway analysis

Prospectivity mapping – sometimes referred to as ‘chance of success’, ‘play fairway’ or ‘common risk segment’ mapping (Royal Dutch Shell, 2017; Salter et al., 2014) – was used to determine the likely prospective area of the Cooper Basin shale gas, tight gas and deep coal gas plays.

The geological properties required for each play to be considered important were identified in collaboration with state agencies (Department of the Premier and Cabinet, SA and Geological Survey of Queensland) and industry. For each geological property, criteria were applied to categorise relative risk. Relative risks associated with each parameter were then multiplied together to construct a composite map, highlighting the relative prospectivity across the basin (Figure 28).

The resulting classified maps were multiplied together to produce an overall relative prospectivity map, which highlights regions with the most favourable geological conditions for this play type (Figure 29). These areas of moderate to high prospectivity form the extent of the play (or ‘play fairway’) and highlight where additional work on a finer scale is warranted to further develop understanding of a prospect.

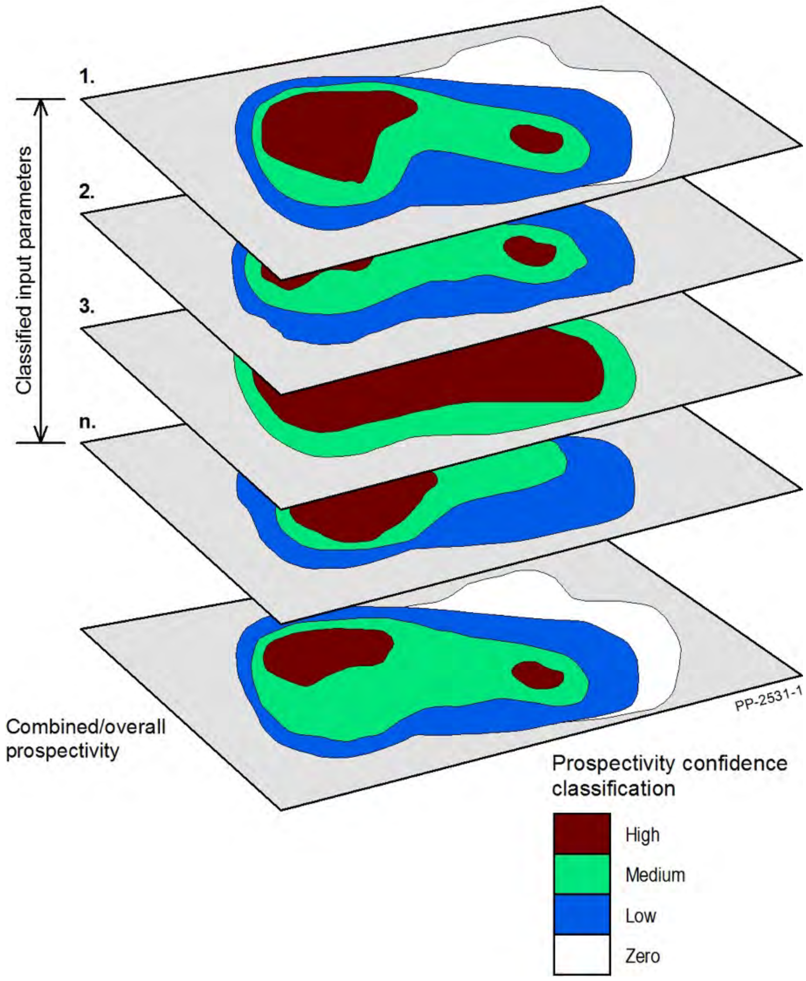

Figure 28 Schematic workflow for combining classified input parameter maps to obtain the relative prospectivity of a formation or play

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For shale gas plays, the Murteree and Roseneath shales and the Patchawarra Formation were chosen for assessment primarily based on formation thickness and spatial extent, source rock volume, quality and thermal maturity, and pressure regime. The areas of highest shale gas relative prospectivity are defined where net shale thickness exceeds 30 m thickness, the total organic carbon content is greater than 2% and the formation is overpressured (defined by a pressure gradient >0.45 psi/ft) (Table 12).

The Gidgealpa Group basin-centred tight gas play is defined where there is a significant sandstone thickness (>100 m) within the Gidgealpa Group (Table 13) (including the Patchawarra, Epsilon, Daralingie and Toolachee formations and the Tirrawarra Sandstone) in the zone of major overpressure (defined by a pressure gradient >0.45 psi/ft at depths >2800 m).

The area considered to be most prospective for deep coal gas is defined where net cumulative coal thickness exceeds 25 m and the formation is thermally mature (Table 14). Both wet and dry gas play extents were mapped, reflecting the significance of gas condensate production as an economic driver for deep coal play development. The criteria for deep coal gas was based on industry advice specific to the Cooper Basin, further details of which can be found in petroleum prospectivity technical appendix (Lech et al., 2020).

Table 12 Shale play criteria input parameter thresholds

Parameter	Absent (0)	Low (0.25)	Medium (0.5)	High (1)
Net shale thickness (m)	<15	na	≥15 – <30	≥30
Pressure regime (Patchawarra) (m)[a]	na	na	<2800	≥2800
Pressure regime (Roseneath, Murteree) (psi/ft)	na	<0.433	≥0.433 – <0.55	≥0.55
Total organic carbon (wt%)	<1	na	≥1 – <2	≥2
Thermal maturity (%Ro)	<0.75; >3.5	na	≥0.75 – <1.2	≥1.2 – ≤3.5
Original hydrogen index (mg HC/g TOC)	<50	≥50 – <150	≥150 – <250	≥250

na = not applicable

mg HC/ g TOC = milligrams of hydrocarbons per gram of total organic carbon; psi/ft = pounds per square inch per foot; %Ro = vitrinite reflectance; TOC = total organic carbon; wt% = weight (as a percentage)

[a] A pressure gradient map was not available for the Patchawarra Formation. Instead, a depth of 2800 m was used as a proxy for the zone of major overpressure based on the observed pressure–depth relationship in the basin.

Source: petroleum prospectivity technical appendix (Lech et al., 2020). Please refer to Lech et al. (2020) for further details on input assumptions.

Table 13 Gidgealpa Group tight gas thresholds

Parameter	None (0)	Low (0.25)	Medium (0.5)	High (1)
Gidgealpa Group cumulative net sand thickness in major overpressure zone (m)	<10	10 – <50	≥50 – <100	≥100

Source: petroleum prospectivity technical appendix (Lech et al., 2020). Please refer to Lech et al. (2020) for further details on input assumptions.

Table 14 Deep coal gas criteria input parameter thresholds for (a) wet gas and (b) dry gas

(a)

Parameter	None (0)	Low (0.25)	Medium (0.5)	High (1)
Net coal thickness (m)	<10	na	≥10 – <25	≥25
Thermal maturity (%Ro)	<0.75 or ≥1.4	na	≥0.75–0.9	≥0.9 –1.4

(b)

Parameter	None (0)	Low (0.25)	Medium (0.5)	High (1)
Net coal thickness (m)	<10	na	≥10 – <25	≥25
Thermal maturity (%Ro)	<1.4 or ≥2.5	≥2.5–3.5	≥2–2.5	≥1.4–2

na = not applicable; %Ro = vitrinite reflectance

Source: petroleum prospectivity technical appendix (Lech et al., 2020). Criteria for deep coal gas in the Cooper Basin was based on advice provided by Santos. Please refer to Lech et al. (2020) for further details on input assumptions.

To obtain relative prospectivity maps for the shale, tight and deep coal gas plays, the maximum value at any given location was assigned to create a final composite map by play type (Figure 29). The following observations based on the maps were made:

- The Nappamerri, Patchawarra and Windorah troughs contain areas of high relative prospectivity for basin-centred tight gas, consistent with recent exploration activity.
- The Patchawarra Trough contains areas of high relative prospectivity for wet deep coal gas, consistent with the recent exploration activity in this region. Areas of high relative prospectivity for wet deep coal gas are also mapped along the eastern margin of the Windorah Trough.
- The Nappamerri Trough has high relative prospectivity for dry deep coal gas.
- There are no areas of high relative prospectivity for shale gas, while the Nappamerri and Windorah troughs have a medium relative prospectivity for shale gas.
- In most depocentres, there is at least partial overlap between the medium-high prospectivity areas defined for each play, highlighting the possibility of stacked play targets in these regions.
- Pressure and thermal maturity input parameters have the greatest influence on the shale and tight gas prospectivity, while thickness of the formations and thermal maturity are the principal drivers for deep coal gas prospectivity.
- Discrete tight gas plays are primarily associated with conventional gas field development.

In order to inform hazard and development scenario analysis and assess the impact that the exploration and development of shale, tight and deep coal gas resources might have on water and the environment, an area of interest for each play type was developed (Lech et al., 2020). This represents the maximum possible area within which each play type may be present based on regional geological criteria alone.

Shale, tight and deep coal gas exploration to date has primarily focused on SA; consequently, there is higher confidence in the resultant maps in the southern Cooper Basin, as more data was available there. Further investigation in the less well explored Queensland portion of the plays is warranted, particularly for deep coal gas.

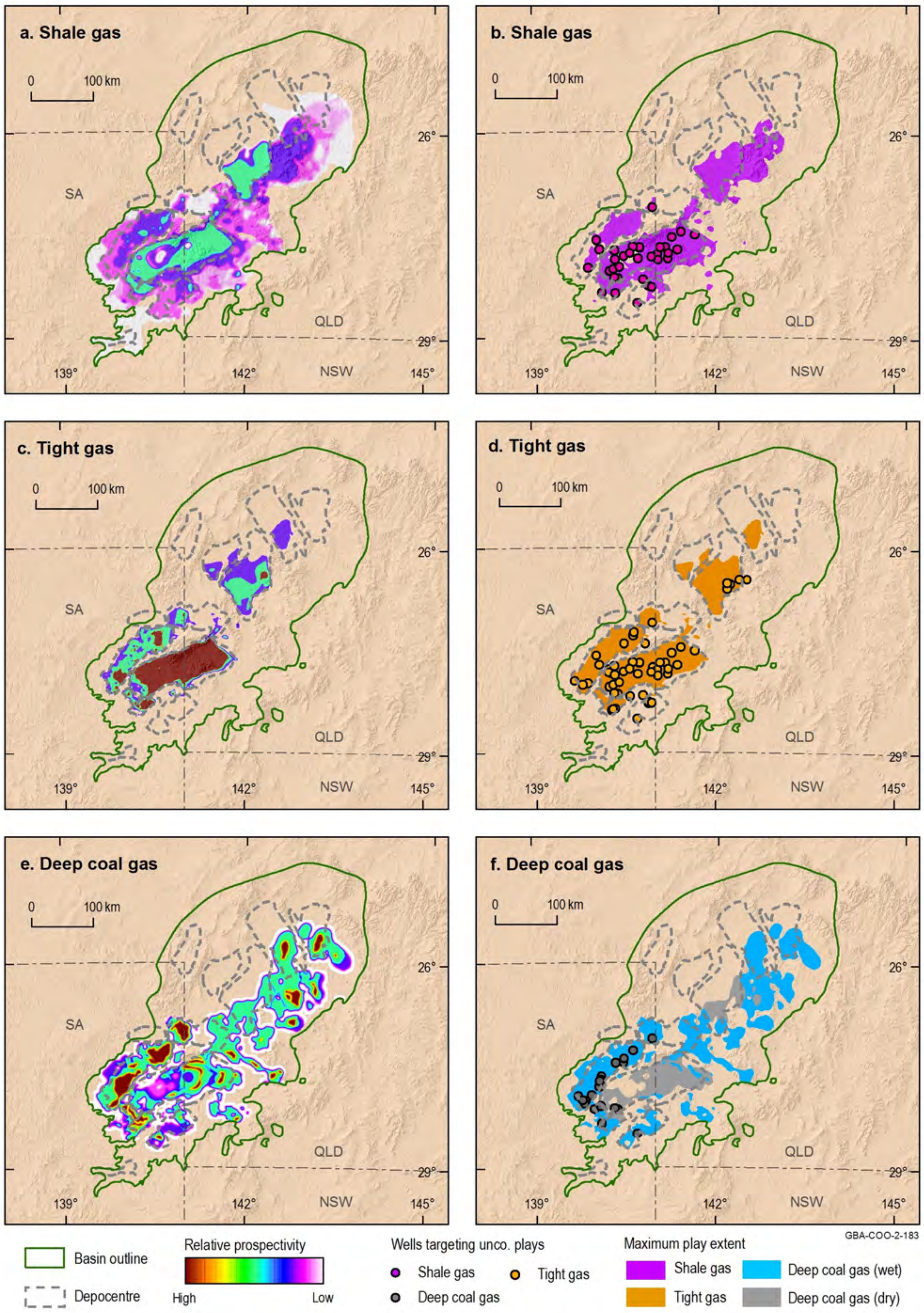

Figure 29 Combined relative prospectivity maps by play type

(a) Shale gas relative prospectivity map; (b) maximum extent of shale gas plays with location of key wells targeting shale gas; (c) basin-centred tight gas relative prospectivity map; (d) maximum extent of basin-centred tight gas plays with location of key wells targeting tight gas; (e) deep coal gas (dry and wet) relative prospectivity map; and (f) maximum extent of deep coal gas play with location of key wells targeting deep coal gas play. The maximum area in which each play type may be present was derived from the relative prospectivity maps using a cut-off value of 0.2.
Well coverage is not exhaustive, as there are inconsistencies in how wells have been classified depending on the information source. Only key wells used in shale, tight and deep coal gas characterisation are shown.
This figure has been optimised for printing on A3 paper (420 mm x 297 mm).
Data: Geological and Bioregional Assessment Program (2019b)
Source: petroleum prospectivity technical appendix (Lech et al., 2020)
Element: GBA-COO-2-183

2.3 Knowledge gaps

The prospectivity analysis uses the regional-scale geological conceptualisation described in the geology technical appendix (Owens et al., 2020). Results identify areas where further data acquisition and geological modelling can be undertaken; however, this regional analysis is not suitable for individual play or prospect-scale evaluations. The rocks of the Cooper Basin are very heterogeneous and, as a result, both rock type and associated geological properties are highly variable at a local scale (<10 km). In most regions, these local differences will not be captured by the regional input datasets, so not all the areas identified as having a high relative prospectivity will result in gas discoveries. Further data limitations are described in the petroleum prospectivity technical appendix (Lech et al., 2020).

Due to the large capital expenditure required to extract unconventional resources, if and how an unconventional play is developed will be dependent on its economic viability, along with other cultural and environmental considerations. Therefore, to inform future development profiles, and determine associated hazards and impacts, it is important to consider development of each play in the context of likely economic outcomes.

The prospectivity maps presented here are based solely on the geological factors required for a viable petroleum play to be present. While these results inform where the plays are most likely to be located with respect to overlying assets, they do not provide any economic context and, hence, are insufficient to effectively inform future development profiles alone. To place this work in an economic context, the following additional work is required:

- resource assessments to estimate total volume of gas-in-place for priority play types, based on the geological understanding of the plays outlined in this report
- estimation of the proportion of gas-in-place that is technically recoverable
- economic analysis to understand what would be economic to produce, based on market conditions.

Any additional work should seek to understand the costs of any cultural and environmental impacts.

3 Water resources

The hydrogeological conceptualisation and understanding of groundwater, surface water and surface water – groundwater interactions in the region are used to identify (i) water sources for future drilling and hydraulic fracturing; (ii) potential hydrological connections between stressors and assets; and (iii) risks from the development of shale, tight and deep coal gas resources to water and the environment.

3.1 *Hydrogeological and groundwater system conceptualisation*

There are three major hydrostratigraphic sequences in the Cooper GBA region: the Cooper Basin, the Eromanga Basin and Cenozoic sediments of the Lake Eyre Basin. In the Cooper Basin, the Permian Gidgealpa Group hosts the shale, tight and deep coal gas resources and is overlain by the Nappamerri Group, which is considered a regional seal to petroleum systems in the Gidgealpa Group. Due to depth of burial (generally greater than 1500 m), the Cooper Basin is not directly used as a groundwater source.

The Eromanga Basin covers the entirety of the Cooper Basin and contains a sequence of aquifers and aquitards that comprise part of the Great Artesian Basin. The Cenozoic Lake Eyre Basin includes several locally important aquifer systems. Most of the existing groundwater bores (779 of 1566) in the region access the Cenozoic Lake Eyre Basin aquifers from a mean depth of 55 m. Groundwater in the aquifers of the Eromanga and Lake Eyre basins in the Cooper GBA region is generally suitable for stock and domestic use, with 90% of the 2137 registered bores less than 300 m deep.

Groundwater (from the Great Artesian Basin (GAB) and aquifers above the GAB) and produced water extracted during conventional oil and gas development are both potential water sources for a future shale, tight and deep coal gas industry in the Cooper GBA region. Existing allocations under water-sharing plans, potential competition with existing water users (e.g. stock and domestic users; conventional oil and gas industry) and proximity to produced water supplies are likely to affect the future availability.

The regional hydrogeological conceptualisation of the Cooper GBA region is informed by a review of the (i) configuration of aquifers and aquitards; (ii) recharge and discharge processes; (iii) groundwater flow dynamics and hydrochemistry; and (iv) potential inter-basin connectivity. Full details are provided in the hydrogeology technical appendix (Evans et al., 2020). Key reports include the *Context statement for the Cooper subregion* from the Lake Eyre Basin Bioregional Assessment (Smith et al., 2015), the *Hydrogeological atlas of the Great Artesian Basin* (Ransley et al., 2015b) and *Allocating water and maintaining springs in the Great Artesian Basin* (Keppel et al., 2013).

The hydrostratigraphic cross-section for the Cooper GBA region (Figure 30), showing the configuration of aquifers and aquitards, is detailed in the hydrogeology technical appendix (Evans et al., 2020). It distinguishes on a regional scale between formations with different hydraulic properties and varying lithological compositions, from aquifers (sandstone dominated) to partial aquifers to leaky aquitards (variable lithological compositions) and aquitards (mudstone–siltstone dominated). It also identifies formations with variable hydrostratigraphic status due to issues such as presence of hydrocarbons.

The three major hydrostratigraphic sequences in the Cooper GBA region are the Cooper Basin (Figure 17), the Eromanga Basin (Figure 18) and Lake Eyre Basin (Figure 21). The Eromanga Basin includes parts of the GAB aquifer system. A brief summary of key aspects of the hydrostratigraphy of the Cooper GBA region is included in the following sections.

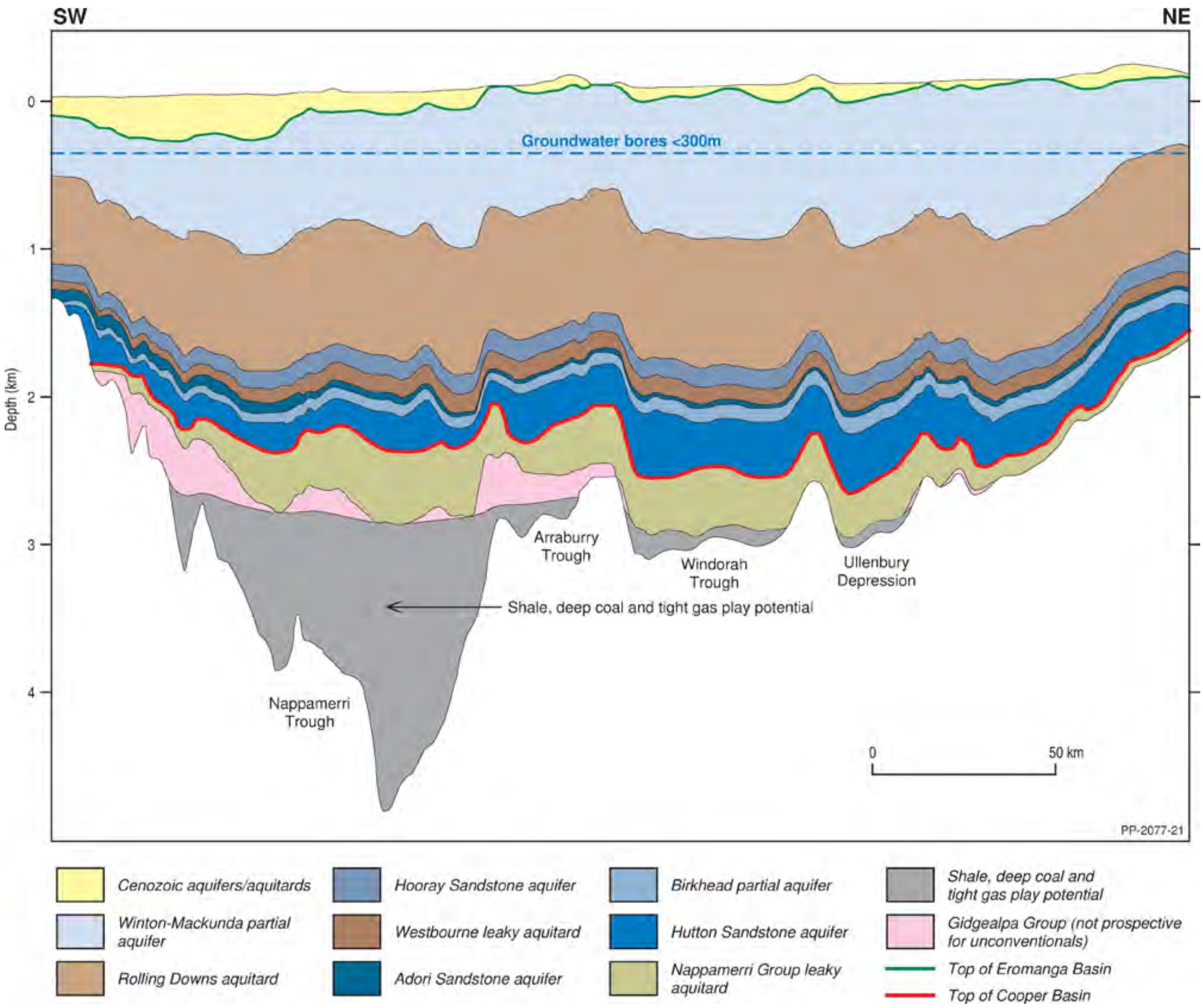

Figure 30 Hydrostratigraphic cross-section for the Cooper GBA region

Location of the cross-section line is shown in Figure 14. Dashed blue line represents depth of most groundwater bores in the region (i.e. 90% of bores are less than 300 m deep (Evans et al., 2020)).
Source: Geoscience Australia (2016)
Element: GBA-COO-2-177

3.1.1 Cooper Basin

Due to the depth of burial (generally greater than 1500 m), the Cooper Basin is not directly used as a groundwater source. Furthermore, its hydrogeology is complicated by the occurrence of extensive petroleum accumulations. The Cooper Basin comprises two hydrostratigraphic groups: the Gidgealpa Group and the Nappamerri Group (Section 2.1, Figure 17 and Table 6). Conventional petroleum resources occur in both Gidgealpa and Nappamerri groups, whereas shale, tight and deep coal gas resources are only found in the Gidgealpa Group below about 2800 m (Lech et al., 2020).

The Nappamerri Group forms a regional seal to petroleum systems in the underlying Gidgealpa Group (Section 2.2) and is classed a leaky aquitard (Evans et al., 2020), separating the Gidgealpa Group from artesian GAB aquifers in the overlying Eromanga Basin (Section 3.4). However, the occurrence of sandier units (e.g. the Wimma Sandstone Member – see Figure 17 and Table 6) may mean that local partial aquifers of limited extent could be present in the Nappamerri Group.

Potential connectivity between the Eromanga and Cooper basins could occur where the Gidgealpa Group subcrops directly beneath the Eromanga Basin, where sandy facies in the Nappamerri Group are in contact with the Eromanga Basin or where major faults significantly offset aquifer sequences (Section 3.4).

Two predominantly shaly formations in the Gidgealpa Group – the Roseneath Shale and Murteree Shale – are classed as aquitards due to their fine-grained lithology (Evans et al., 2020). These units also act as regional seals to underlying petroleum systems as well as source rocks and reservoirs for shale gas plays.

Pressure in the Gidgealpa Group units show considerable variation with depth (Figure 31). Hydrostatic pressure (Figure 31) is the pressure a static column of fluid exerts at a given depth. Pressures that fall below expected hydrostatic pressure are termed 'underpressured' while those greater than the expected hydrostatic pressure are classed as 'overpressured'. Overpressuring becomes increasingly evident from about 2000 m below surface. This may be due to higher gas saturations that increasingly occur with depth, which would have the effect of driving out groundwater. Measurements that indicate underpressured conditions (Figure 31) could be attributable to past or ongoing production of hydrocarbons or, alternatively, an indication that the rock has low permeability. Low permeability can inhibit pressure recovery during tests by restricting the flow of fluids and pressure recovery, which can result in a measured reservoir pressure that is lower than expected due to the time taken to recover in-situ reservoir pressure.

Within deeper portions of Gidgealpa Group, overpressuring and gas generation is likely to have expelled much of the groundwater, forming gas-charged units on an extensive scale (Evans et al., 2020). This situation may negate consideration of inter- and intra-aquifer hydrological connectivity within much of the Cooper Basin sequence below about 2500 m (Figure 30). Where shale, tight and deep coal gas hydrocarbon plays do not dominate at shallower depths (e.g. above about 2500 m) then aquifer/aquitard concepts could apply in the Cooper Basin.

Pressures in Nappamerri Group follow a more normally pressured trend (Figure 31), which suggests it may be largely water-saturated. Also, the Nappamerri Group pressure profiles appear to have more in common with those in the overlying Eromanga Basin than the underlying Gidgealpa Group. These differences in pressure regime support the interpretation that the Nappamerri Group has potential to inhibit natural flow through it from the Gidgealpa Group to overlying aquifers at shallower levels, such as to the aquifers of the GAB (Evans et al., 2020).

To investigate pressure distributions spatially for a given hydrostratigraphic unit in the Cooper Basin, Evans et al. (2020) converted pressures to an equivalent water level (hydraulic head). It was found that on a regional scale it was difficult to spatially discern specific trends, other than some of the low water levels (which are an equivalent to underpressure) occurring in the vicinity of petroleum production fields.

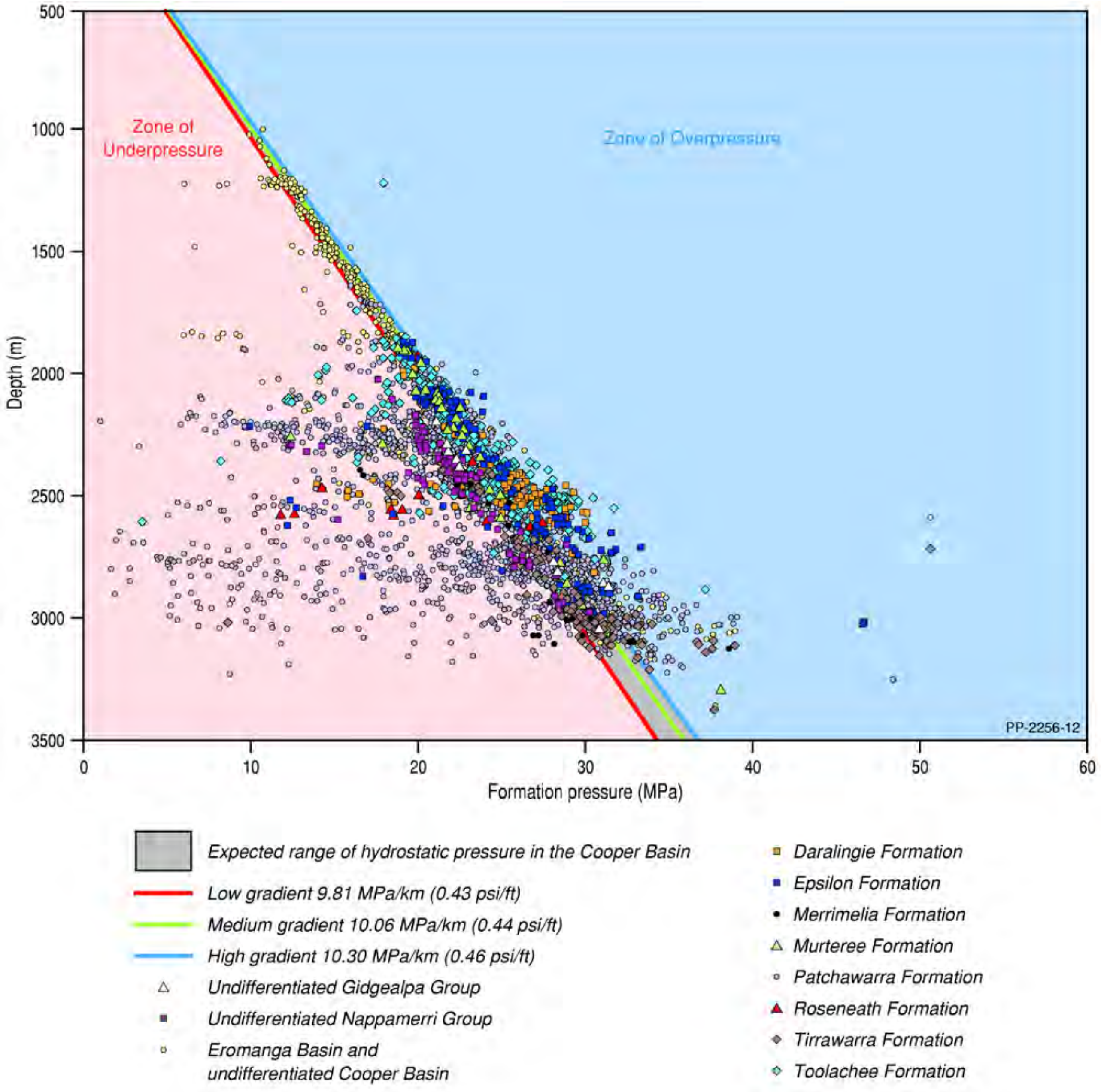

Figure 31 Pressure data for Cooper and Eromanga basins in the Cooper GBA region

Hydrostatic gradients are calculated using equivalent densities of freshwater (low), 2500 mg/L salinity (medium) and 5000 mg/L salinity (high). Evans et al. (2020) includes spatial distributions of formation pressure data, reported as equivalent water level.
Source: Kulikowski et al. (2016)
Element: GBA-COO-2-187

3.1.2 Eromanga Basin

The Eromanga Basin covers the entire extent of the Cooper Basin, which can reach over 2800 m thick in the Central Eromanga depocentre (see petroleum prospectivity technical appendix (Lech et al. (2020), Figure 25). Its stratigraphy is complex (Table 7, Figure 18) consisting of a series of stacked aquifers separated by aquitards that comprise part of the GAB (Evans et al., 2020; Smerdon et al., 2012; Ransley et al., 2015b).

The major hydrostratigraphic units for the Eromanga Basin in the Cooper GBA region are (from bottom to top):

- Lower Eromanga aquifers: these are deeper sequences that lie stratigraphically below the Cadna-owie – Hooray Aquifer (Figure 18, Figure 30). It includes the Westbourne Formation (leaky aquitard); Adori Sandstone (Adori–Springbok Aquifer in Ransley et al. (2015b)); Birkhead Formation (partial aquifer, as it includes thin sandy units); and Hutton Sandstone and Poolowanna Formation (aquifers). These underlying aquifers all merge westwards into the Algebuckina Sandstone, toward the western Eromanga Basin margin in SA.
- The Cadna-owie – Hooray Aquifer: in the Cooper GBA region, the Cadna-owie – Hooray Aquifer includes the Cadna-owie Formation (includes the Wyandra, Mount Anna and Trinity Well sandstone members), Murta Formation (including the McKinlay Member), and Hooray and Namur sandstones (Figure 18, Figure 30). All these units constitute the uppermost, predominantly artesian, GAB aquifer sequence and have been the focus of significant study (e.g. Keppel et al., 2013; Smerdon et al., 2012; Ransley et al., 2015b). As outlined in (Evans et al., 2020), due to depth, the Cadna-owie – Hooray Aquifer is predominantly the only artesian GAB aquifer sequence used in the Cooper GBA region. Although it contains only 43 of 1566 existing groundwater artesian GAB aquifers in the region, it is an important aquifer due to its lateral continuity, artesian pressures and relatively good water quality (Evans et al., 2020). However, average bore depths for these aquifers are around 1700 m, whereas 90% of bores in the Cooper GBA region are less than 300 m deep (Figure 30). Like the lower Eromanga Basin sequence, the Cadna-owie – Hooray Aquifer sequence merges into the Algebuckina Sandstone to the west of the Cooper GBA region.
- The Rolling Downs Group: comprises a thick basal aquitard and upper unconfined partial aquifer (Evans et al., 2020). It has a variable thickness between 300 and 700 m in the Central Eromanga depocentre (Ransley et al., 2015b) and comprises lithostratigraphic units ranging from tight aquitards (Bulldog Shale, Oodnadatta Formation, Toolebuc Formation and Allaru Mudstone) to leaky aquitards (Wallumbilla Formation and the Doncaster Member) and contained partial aquifers (Coorikiana Sandstone and Coreena Member of the Wallumbilla Formation).
- Winton and Mackunda formations (Figure 28): this widespread sub-artesian aquifer is called the Winton-Mackunda partial aquifer (Evans et al., 2020; Smith et al., 2015; Smerdon et al., 2012). The majority of bores in Cooper GBA region that source groundwater from the Eromanga Basin tap into this aquifer due to relatively shallow depth of drilling when compared with deeper artesian GAB aquifers (Evans et al., 2020). The basal parts of the Winton Formation and the Mackunda Formation tend to have higher yields (Smerdon et al., 2012; Ransley et al., 2015a). It has a minimum thickness of 450 m, reaching up to 1200 m

thick along the axis of the Central Eromanga depocentre. While it outcrops within Cooper GBA region (Figure 19), it may be confined where overlain by significant thicknesses of Lake Eyre Basin sediments.

Across the Eromanga Basin, including the Cooper GBA region, groundwater from artesian GAB aquifers are primarily managed to maintain aquifer pressure rather than to limit a volumetric withdrawal (Lai et al., 2016; Klohn Crippen Berger, 2016b) (see Section 3.1.4). GAB aquifers receive recharge through rainfall, intra-aquifer leakage and aquifer throughflow from outside the Cooper GBA region, as well as contributions through upward leakage from underlying basins, such as the Cooper Basin. Direct recharge from rainfall occurs where the GAB aquifers outcrop (Evans et al., 2020).

Only the Winton Formation outcrops within the Cooper GBA region. Outcrop of the artesian GAB aquifers (the 'recharge beds') is situated outside the Cooper GBA region, along the margins of the Eromanga Basin. Along the western margin, (Love et al., 2013) identified three recharge pathways for the artesian GAB aquifers: diffuse recharge, ephemeral river recharge and mountain system recharge. Outcrop along the eastern margin coincides in part with the Great Dividing Range (Ransley et al., 2015b), located 300 km east of the Cooper GBA region. Using chloride mass balance, Kellett et al. (2003) established that diffuse recharge rates for artesian GAB aquifers ranged from 0.03 to 2.4 mm/year. However, subsequent investigations calculated using rainfall chloride accession rates and groundwater chloride concentrations (e.g. Evans et al., 2018) suggest that overlying Lake Eyre Basin sediments as well as presence of a clay-rich deep-weathering profile and upward hydraulic gradients may substantially impede recharge. As a result, earlier calculations over estimated diffuse recharge to artesian GAB aquifers by as much as 25 to 50%. Modelled decreases in diffuse recharge may have a longer term bearing on the water balance for artesian GAB aquifers in the Cooper GBA region, as they represent a decrease in the predicted volume of aquifer throughflow from recharge zones into the region. Furthermore, (Evans et al., 2018) only considered diffuse recharge using the chloride mass balance method and did not take into account other recharge processes, such as episodic recharge where surface drainage crosscuts the recharge beds.

Aside from recharge, groundwater can move in and out via the following processes: (i) inter-aquifer leakage between aquifers (e.g. from artesian aquifers across a Rolling Downs aquitard into near-surface sub-artesian aquifers (Figure 33); (ii) aquifer throughflow out of the Cooper GBA region (Figure 32); (iii) spring discharge; (iv) bore water extraction; and (v) evapotranspiration. Diffuse discharge from GAB aquifers can occur if groundwater levels are near the surface (generally less than 20 m (Lewis et al., 2018)). Inter-aquifer leakage between GAB aquifers will occur if hydrogeological conditions allow (see hydrogeology technical appendix (Evans et al., 2020)). Where aquifers extend beyond the Cooper GBA region boundary, aquifer throughflow in and out of the region would become a component of water balance. As detailed for Queensland in (Klohn Crippen Berger, 2016a), from 1900 to 2015, bore discharge (particularly free-flowing discharge) has comprised a substantial outflow component of the water balance for artesian GAB aquifers. Water produced as part of petroleum production is another source of artificial discharge. Further detail on near-surface groundwater processes are outlined in Section 3.3.

Spring discharge from artesian GAB aquifers does not occur within the Cooper GBA region (see Section 3.3 and Evans et al. (2020)), with the nearest springs situated some 20 km west of the region in the vicinity of Lake Blanche. However, maintaining aquifer pressures and discharge from the Cadna-owie – Hooray Aquifer is crucial for the ongoing function of GAB springs (Keppel et al., 2016; Keppel et al., 2013). Changes to artesian GAB aquifer water balance could potentially affect springs that lie outside the Cooper GBA region (Keppel et al., 2016). For instance, a decrease in aquifer pressures from artesian to sub-artesian will extinguish flow at a spring.

Regional potentiometric mapping from Ransley et al. (2015b) for the main artesian aquifer present in the region, the Cadna-owie – Hooray Aquifer, is shown in Figure 32. Hydraulic head is greater than 300 m above sea level in the east, decreasing to 50 to 100 m in western parts of Cooper GBA region. Groundwater flow is generally from north-east to south-west across the Cooper GBA region. Several potentiometric sinks occur in SA, which coincide with areas of petroleum production from the Eromanga Basin sequence (e.g. fields around Moomba) and a near-stagnant zone of groundwater flow (groundwater sink) that occurs in the vicinity of the Central Eromanga depocentre, which also coincides with zones of reduced porosity.

Artesian pressures in the Cadna-owie – Hooray Aquifer may induce upward vertical leakage across the Rolling Downs Group aquitard toward the sub-artesian Winton-Mackunda partial aquifer. Conversely, potential for downward leakage may occur where pressures in underlying GAB aquifers are less than those in the Cadna-owie – Hooray Aquifer. This could occur in vicinity of oil and gas fields producing from underlying Eromanga petroleum reservoirs such as the Hutton Sandstone.

In general, groundwater from the artesian GAB aquifers is of better quality than that from the Winton-Mackunda partial aquifer (see hydrogeology technical appendix, Evans et al., 2020) with salinities in the order of 1000 to 4000 mg/L. These groundwaters are typically classed as Na-HCO_3 type water, although some Na-Cl-type waters are also present (Evans et al., 2020).

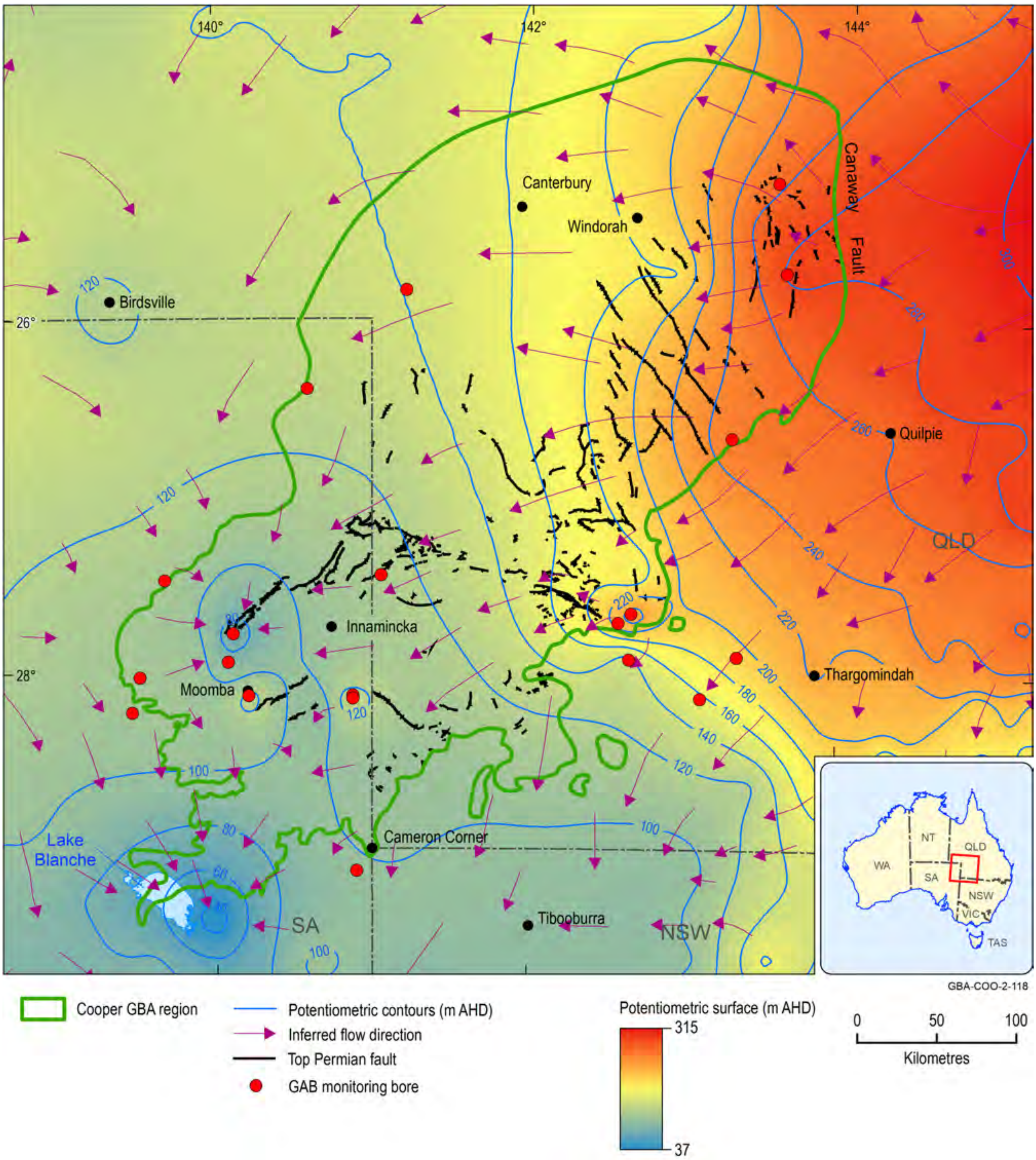

Figure 32 Cadna-owie – Hooray Aquifer: distribution of groundwater bores and potentiometric mapping

GAB = Great Artesian Basin
Source: Ransley et al. (2015b)
Element: GBA-COO-2-118

The Rolling Downs Group aquitard does not outcrop in the Cooper GBA region. Regionally, the thick Rolling Downs Group aquitard overlies the Cadna-owie – Hooray Aquifer and forms a barrier to vertical groundwater migration, largely due to its thickness. However, some areas of the aquitard are known to contain pervasive polygonal fault systems that offer potential conduits for vertical leakage (Ransley et al., 2015b). Potential leakage pathways across this regional aquitard include structural complexities, lithological variations (e.g. sand on sand) and polygonal faulting systems (Figure 33). Polygonal faulting is also evident at surface in the overlying Winton-Mackunda partial aquifer (Ransley et al., 2015b).

Leakage through polygonal faults has been proposed conceptually (Kulikowski et al., 2018); (Ransley et al., 2015b; Ransley et al., 2012a), but no estimates of leakage are available. In a recent regional water balance estimate for the Eromanga Basin, (Klohn Crippen Berger, 2016a) suggested that in Queensland there has been up to a 30% decline in the upward leakage potential across the Rolling Downs Group aquitard since 1900, due to long-term groundwater production from free-flowing artesian bores primarily drilled for pastoral uses. Geological faults are present in the Eromanga Basin in the Cooper GBA region and may influence groundwater pressures and flow directions (Ransley et al., 2015b; Ransley et al., 2012a; Smith et al., 2015). As an example, significant fault offsets are evident at the eastern margin of the Cooper Basin, along the Canaway Fault (Evans et al., 2020). This zone coincides with some striking changes in groundwater flow direction, which suggests that this fault may be influencing groundwater flow and connectivity. Recently, it has been recognised that the Coorikiana Sandstone, a part of the Rolling Downs Group aquitard, may be a contributing source aquifer for some GAB springs located just to the west of Cooper GBA region (see Figure 47, Section 3.3 and Keppel et al. (2016)).

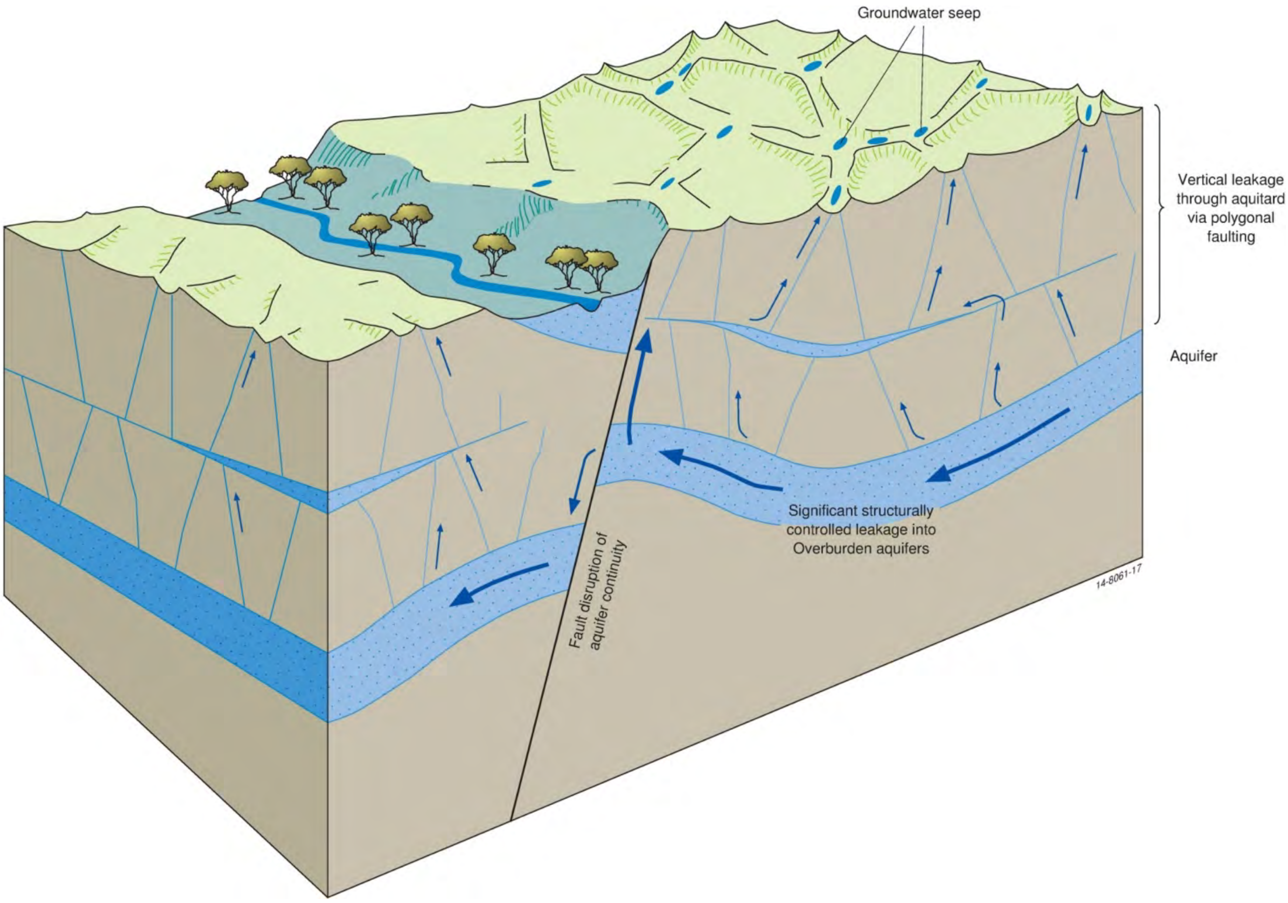

Figure 33 Conceptualisation of potential leakage pathways from Great Artesian Basin aquifers to near-surface aquifers through the Rolling Downs Group aquitard

Arrows represent inferred groundwater flow paths. Bold arrows represent potential higher flow rates in aquifer, whereas smaller arrows represent leakage through the regional aquitard. Polygonal faulting is shown in cross-section as a vertical leakage pathway, as well as on surface as a polygonal shape associated with groundwater seeps.
Source: Ransley et al. (2015b)
Element: GBA-COO-2-182

The Winton-Mackunda partial aquifer forms a significant aquifer system across the Cooper GBA region, with many existing bores (570 of 1566) drawing water from it (Evans et al., 2020). The average depth to groundwater (from 466 samples) is 25 m. Average bore depth is 140 m, with 90% having a depth less than 305 m. While the Winton-Mackunda partial aquifer is not artesian, the shallow depths to groundwater are such that, where a connectivity pathway exists, there is potential for leakage to occur into the overlying Cenozoic aquifers. Salinity varies considerably from 600 to 20,000 mg/L and water types range from Na-Cl to Na-HCO_3 type waters (Evans et al., 2020).

As outlined in Ransley et al. (2015a) and Figure 34, watertable contours for the Winton-Mackunda partial aquifer are strongly influenced by local and regional topography. Regionally inferred groundwater flow is to the south-west toward regional topographic low points such as Lake Blanche in SA. At a more local scale, groundwater mounding is evident (Evans et al., 2020; Ransley et al., 2015b) under elevated topographic areas and in areas where the aquifer outcrops. Here, inferred groundwater flow is from elevated areas to low-lying areas; thus, any flow would tend to be toward major drainage lines such as the Cooper Creek floodplain. Once at the floodplain, it would tend to flow in a south-westerly direction.

Depth to groundwater suggests that water levels in the Winton-Mackunda partial aquifer generally sit about 10 to 20 m below surface in the vicinity of the Cooper Creek floodplain. Whether this exceeds the depth of major waterholes in the floodplain is largely unknown and would require local site-specific data, including waterhole bathymetry and site-specific water level of the regional watertable. If the level of regional watertable is always lower than base of the waterhole then regional groundwater cannot discharge into the waterholes. Short-term variations in surface water and shallow groundwater levels will lead to spatial and temporal variations in gaining and losing conditions. Time-series water level data are not available for these aquifers and waterholes.

Information from monitoring bores, including time-series water levels, aquifer hydraulic properties and water quality information for the Winton-Mackunda partial aquifer, including salinity, hydrochemistry and environmental tracer analyses, is sparse or not available. Furthermore, it is difficult to determine the boundary between the Winton Formation and Lake Eyre Basin sediments from available groundwater bore data due to scant stratigraphic well picks and lithological information. This could be improved if further investigation of existing petroleum well data were undertaken. This may better define the boundary between the two aquifer systems.

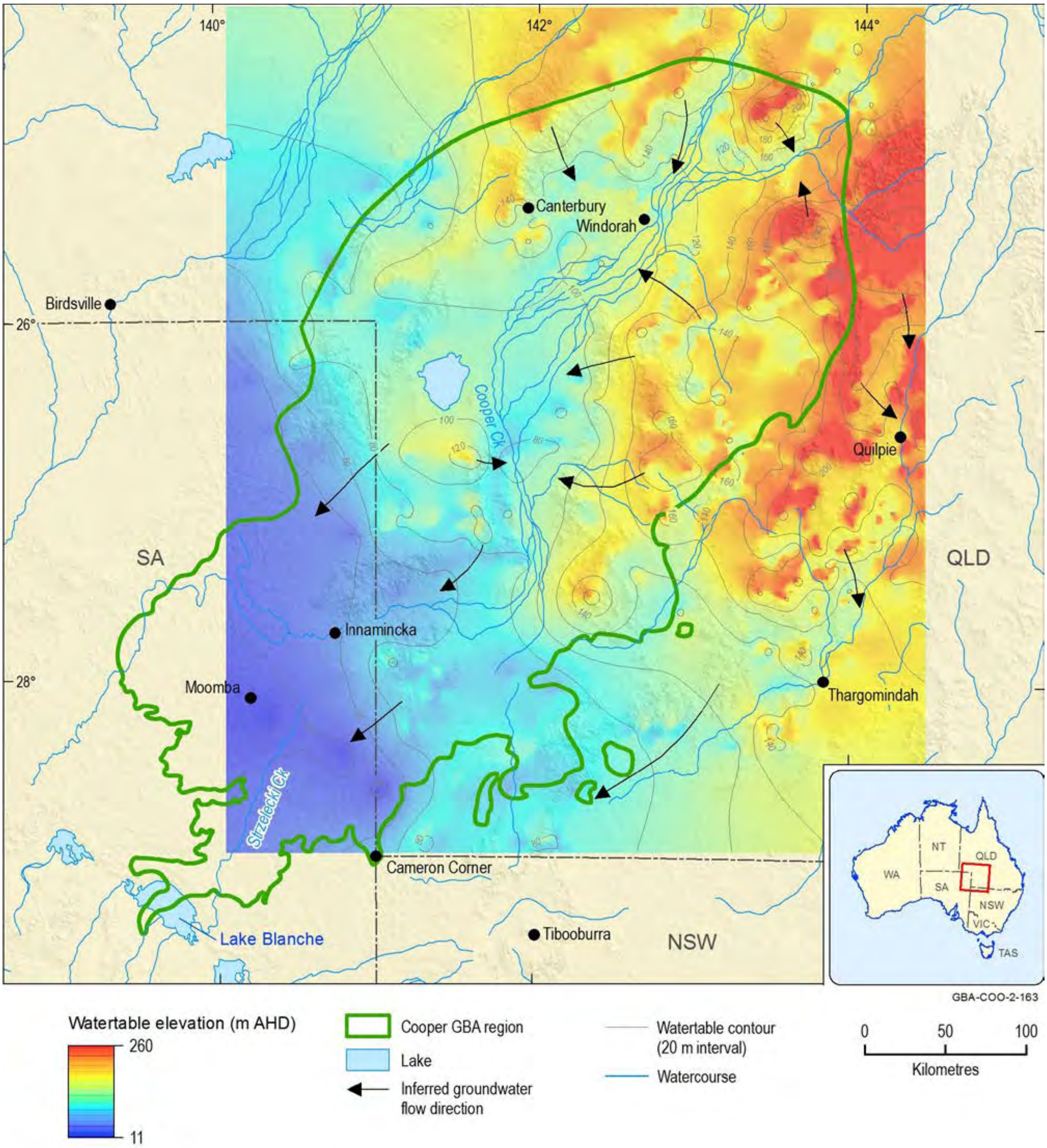

Figure 34 Winton-Mackunda partial aquifer watertable elevation and flow paths

Distribution of Winton outcrop and data points used to calculate watertable are outlined in (Evans et al., 2020).
Source: Geological and Bioregional Assessment Program (2018b)
Element: GBA-COO-2-163

3.1.3 Lake Eyre Basin

Cenozoic sediments belonging to the Lake Eyre Basin cover much of the Eromanga Basin (Figure 20) and can be up to 300 m thick in the Callabonna Sub-basin in SA. In other areas, such as under the Cooper Creek floodplain and Strzelecki Desert plains in Queensland, the thickness of Cenozoic sediments is more poorly known, but in some areas it exceeds 100 m.

The Lake Eyre Basin sedimentary sequence (Figure 21, Table 8) encompasses several locally important aquifer systems, including aquifers in the Namba and Eyre formations in SA and the Glendower Formation in Queensland (Evans et al., 2020). Cenozoic sands are considered good aquifers in SA, but relatively few bores access these aquifers in Queensland (Evans et al., 2020; Klohn Crippen Berger, 2016a). The Eyre Formation is characterised as a variably confined to unconfined aquifer, depending on the nature of overlying material (Radke et al., 2012). Due to its variable lithology, the Namba Formation can act as an aquitard in many places. However, local aquifers exist where fluvial channel sands are present; hence, overall it is classified as a partial aquifer (Keppel et al., 2016; Radke et al., 2012).

Like the Winton-Mackunda partial aquifer, aquifers in the Lake Eyre Basin form an aquifer system across the Cooper GBA region, with many existing bores (779 of 1566) drawing water from it (Evans et al., 2020). Average depth of bores drawing water from the Lake Eyre Basin is 55 m, with 90% of bores being less than 95 m deep. Depth to groundwater for aquifers in the Cenozoic sequence is generally less than 20 m.

Watertable mapping for Cenozoic aquifers suggests that groundwater flow is strongly influenced by local topography (Evans et al., 2020). As was the case for the Winton-Mackunda partial aquifer, overall there is a regional south-westerly flow trend toward regional topographic low points in the landscape such as large salt lakes (e.g. Lake Blanche), particularly south and west of the Innamincka Dome. In general, chemistry of groundwater in Lake Eyre Basin aquifers is similar to that found in the Winton-Mackunda partial aquifer, which suggests some degree of connectivity, but differs from hydrochemistry of deeper artesian GAB aquifers.

Salinity data suggest that there are at least two discrete aquifer systems in the Cenozoic. These are a near-surface system (typically less than 60 to 80 m below the land surface) with highly variable salinity and a deeper system (below about 60 to 80 m) that is of relatively good quality (less than 12,000 mg/L) with more consistent salinity (Evans et al., 2020). While not well defined, the potential distribution of a deeper aquifer may potentially be inferred from the depth of bores tapping aquifers in Lake Eyre Basin sediments (Figure 35). Although most of the deeper bores occur in the Callabonna Sub-basin in SA, some also occur on the Cooper Creek floodplain, which suggests there is potential for a deeper aquifer here as well.

From one study located near the SA border on the Cooper floodplain, Cendón et al. (2010) identified near-surface (within 20 m) relatively fresh groundwater lenses, particularly in the vicinity of large near-permanent waterholes. These freshwater lenses occurred within about 300 m of a channel and result from mixing between fresh surface water and shallow groundwater in the alluvium. Groundwater became gradually more saline away from the waterhole (Cendón et al., 2010). These freshwater lenses were associated with flood-related episodic recharge to shallow groundwater. Further discussion on surface water – groundwater interactions is included in Section 3.3. As outlined in Evans et al. (2020), it is uncertain whether the findings of Cendón et al. (2010) are representative of all waterholes on the Cooper Creek floodplain, or just a subset of them.

Recharge to the uppermost portions of Cenozoic aquifers may occur through episodic flood events or heavy rainfall (Cendón et al., 2010). However, existing studies have only investigated groundwater in the top 20 m of the Cenozoic sequence. It is uncertain whether episodic recharge leaks into older and more deeply buried Cenozoic aquifers (i.e. below 60 to 80 m) in the Cooper Creek floodplain or the Callabonna Sub-basin. The contribution of upward leakage into the Cenozoic aquifers from the Winton-Mackunda partial aquifer is unknown.

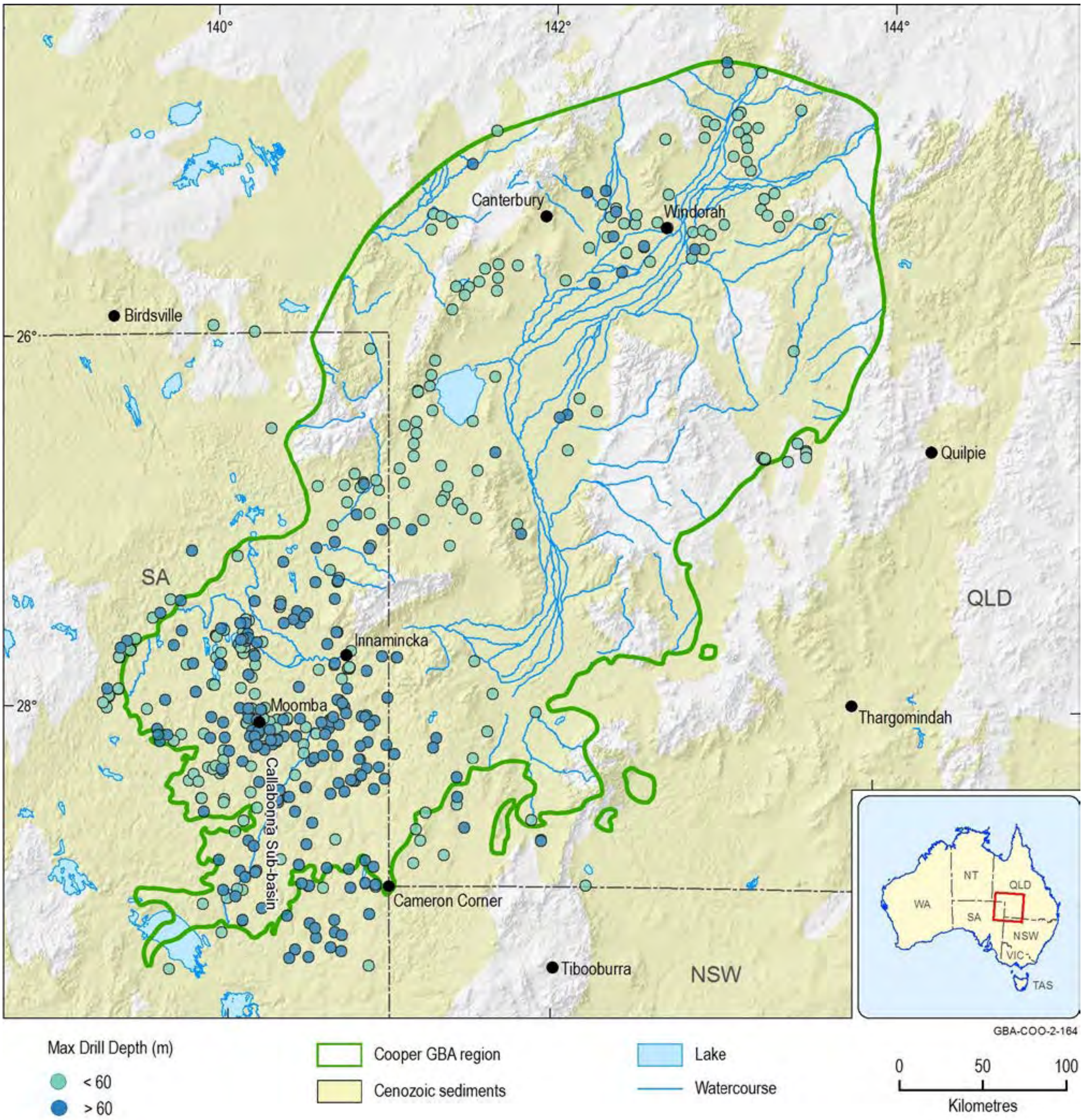

Figure 35 Potential distribution of the 'deeper' aquifer in Lake Eyre Basin using maximum groundwater bore depth as an analogue

Source: Geological and Bioregional Assessment Program (2018g)
Element: GBA-COO-2-164

Discharge from Cenozoic aquifers can take the form of (i) evapotranspiration; (ii) diffuse discharge from shallow groundwater, discharge to salt lakes or other surface water features; (iii) groundwater pumping; (iv) potential for baseflow to large permanent waterholes (if deep enough to intercept the watertable; or (vi) leakage into the underlying Winton-Mackunda partial aquifer. These aspects are discussed further in Section 3.3.

The hydrogeology and hydrostratigraphic framework for the Cenozoic sequence contains substantial knowledge and data gaps ((Evans et al., 2020); Section 7.2)). For example, there is uncertainty about how much recharge, connectivity and leakage there is from shallow near-surface systems and deeper Lake Eyre Basin aquifers. Fresher water at depth in these aquifers could relate to an unknown pathway or could be the result of recharge during wetter climate regimes thousands of years ago (Evans et al., 2020). This may have implications for the management of future groundwater usage and the potential for cumulative impacts.

3.1.4 Potential water sources for drilling and hydraulic fracturing

In Queensland, water licences and water permits in the Great Artesian Basin And Other Regional Aquifers (GABORA) water plan (Department of Natural Resources and Mines (Qld), 2017b) are granted under its 16 groundwater units, including nine groundwater units that intersect the region (Betts Creek Beds, Cadna-owie, Clematis, Hooray, Hutton, Precipice, Rolling Downs, Springbok, Walloon and Winton-Mackunda) (Figure 36). In the 2017 GABORA water plan, the Queensland Government reserved 39,505 ML/year (or 108 ML/day) of unallocated water (10,015 ML for general reserve, 880 ML for Indigenous reserve and 28,610 ML for state reserve) under its 16 groundwater units to meet future demand (Department of Natural Resources and Mines (Qld), 2017b).

Groundwater management areas in the Warrego, Paroo, Bullo and Nebine water plan (Department of Natural Resources and Mines (Qld), 2016b) do not overlie prospective areas and are unlikely to be sources of water for future shale, tight and deep coal gas development (Figure 29), so licensed volumes for these resources are not reported in this section.

In the SA Arid Lands Natural Resource Management (NRM) region, groundwater resources are managed by the water allocation plan for the Far North Prescribed Wells Area (FNPWA) Water Allocation Plan (South Australian Arid Lands Natural Resources Management Board, 2009). Adopted in 2009, the plan is undergoing statutory review prior to the draft plan being presented to the minister for consideration and adoption by July 2019. As part of the FNPWA Water Allocation Plan, it is estimated that a volume of 116,435 ML/year (350 ML/day) is sufficient to meet water demand for various purposes, including stock and domestic, produced water from conventional oil and gas extraction, mining, camp water and industrial uses.

Groundwater accounts information is provided for groundwater source areas that are within or intersect with the Cooper GBA region and draw on bore data from across the region and water-sharing plan (WSP) information, where plans exist.

Currently, under the GABORA water plan, there are 6500 water licences and 21 water permits, with a cumulative water usage of 315,000 ML/year (Department of Natural Resources and Mines (Qld), 2017a). Under the GABORA water plan, water use comprises ‘Petroleum and gas operations’ (64,000 ML/year), ‘Stock and domestic’ (66,000 ML/year; 86% of total number of licences granted), ‘Stock and domestic (losses)’ (94,000 ML/year); and ‘Other uses’ (93,000 ML/year). As of 2016, stock and domestic usage is estimated to be approximately 20% of total Queensland GAB water extractions. Some (<10%) of the water extracted for petroleum and gas operations is recycled or reinjected into a GAB aquifer (Department of Natural Resources and Mines (Qld), 2017a, 2016a).

The FNPWA Water Allocation Plan (South Australian Arid Lands Natural Resources Management Board, 2009) estimates groundwater extraction from GAB aquifers is approximately 12,228 ML/year for stock and domestic use and 1460 ML/year for town water supply. Of the stock and domestic use, approximately 8139 ML/year is sourced from the artesian system and 4124 ML/year is sourced from the non-artesian system.

Total groundwater discharge to natural springs is estimated to be 24,090 ML/year (South Australian Arid Lands Natural Resources Management Board, 2009). This estimate has inherent uncertainty due to difficulties in measuring flows and the small number of spring flow measurements. Petroleum operations have a current allocation of 21,900 ML/year for co-produced water (water that is extracted as a by-product of hydrocarbon extraction processes) and this allocation may vary in the revised FNPWA Water Allocation Plan. Mining operations have a current allocation of 16,279 ML/year.

To estimate the total volume of water that is licensed to be extracted from groundwater within the Cooper GBA region, the water entitlement volumes were summed for every bore in the groundwater database supplied by the Queensland Government (Department of Natural Resources, Mines and Energy (Qld), 2018e) and the South Australian Government (Department for Environment and Water (SA), 2018). A total of 37,081 ML/year of groundwater (12,706 ML/year for Queensland and 24,375 ML/year for SA) is allocated for extraction each year (Table 15). This estimate does not include basic water rights for stock and domestic use (around 13 bores) located in the Queensland part of the region. In this part of the Cooper GBA region, the volume of take is not specified but is generally assumed to be 5 ML/year per bore, or not more than about 65 ML/year for all stock and domestic bores (Santos, 2016). The authorised purpose, number of bores for each licence type and total entitlement annual volumes are shown in Table 15 and total entitlement annual volumes are shown in Figure 37.

Table 15 Summary of licensed water allocations in the Cooper Basin located in Queensland and South Australia

Authorised purpose	Qld Number of bores	Qld Total entitlement volume (ML)	SA Number of bores	SA Total entitlement volume (ML)
Stock and domestic	13	65	17	266
Stock and urban	1	70	na	na
Irrigation	2	161	na	na
Town water supply	1	50	na	na
Co-produced water	Various bores	12,425[a]	Various bores	21,900
Mining	na	na	5	1,430
Camp water	na	na	6	733
Industrial	na	na	2	45

[a] Volume of water extracted as of 31 December 2017 for permit located in the Cooper Basin, 'na' = not applicable
Data: Department of Natural Resources, Mines and Energy (Qld) (2018e); Department for Environment and Water (SA) (2018); Department of Natural Resources, Mines and Energy (Qld) (2018c)

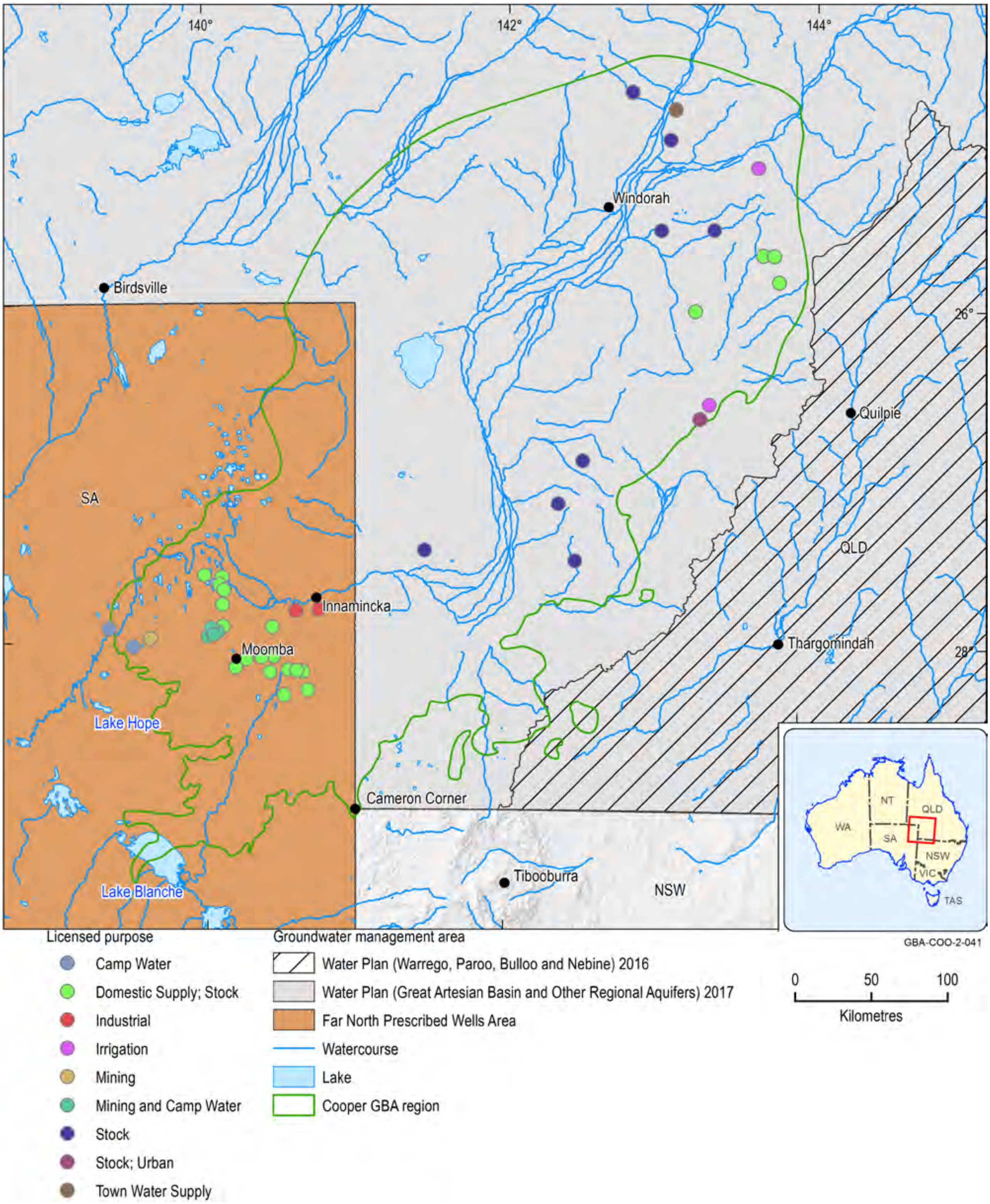

Figure 36 Groundwater management areas and identified purposes of bores in the Cooper Basin

Data: Department of Natural Resources, Mines and Energy (Qld) (2018e); Department for Environment and Water (SA) (2018); Department of Natural Resources, Mines and Energy (Qld) (2018c)
Element: GBA-COO-2-041

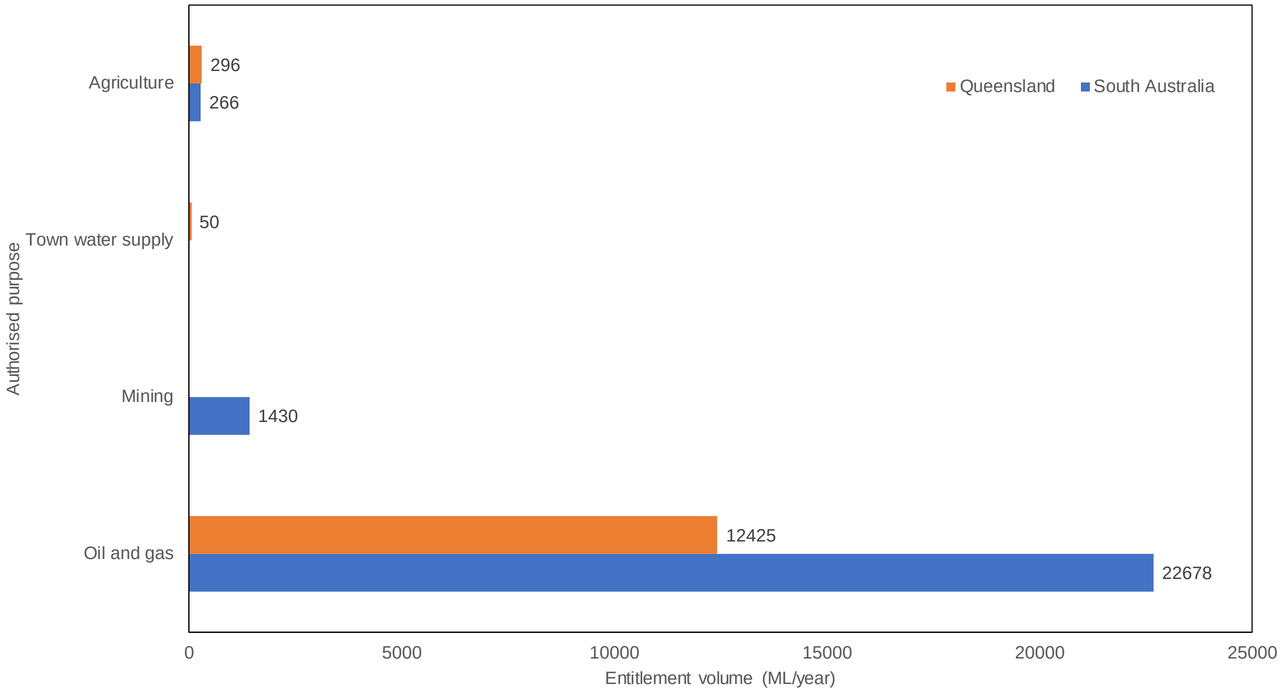

Figure 37 Licensed water allocations in Cooper Basin

Data: (Department of Natural Resources, Mines and Energy (Qld), 2018e)
Agriculture is the sum of 'Stock and domestic' and 'Irrigation'; 'Oil and gas' is the sum of 'Co-produced water', 'Camp water' and 'Industrial volumes' reported in Table 15.
Element: GBA-COO-2-042

Hydraulic fracturing requires approximately 8 to 16 ML for a vertical well and up to 24 ML for a horizontal well (RPS Aquaterra, 2012). In most cases, produced water is used as a water source for hydraulic fracturing and drilling operations. At locations where storage ponds are not available, produced water is usually transported by water trucks or piped depending on the distance from the source (i.e. storage pond) and the infrastructure (i.e. tanks) at the activity areas. In limited cases where produced water is not available and the exploration and appraisal wells are geographically spread – likely to be tens of kilometres apart – water is extracted from shallow water wells drilled within the lease area of each of the exploration wells (Beach Energy, 2016; Santos, 2015; Senex Energy, 2015; Strike Energy, 2014).

Produced water is also used for secondary purposes, including road construction, dust suppression, drilling and well completion activities, enhanced oil recovery through water flooding, and ballast water for oil field tankers. Prior to secondary use, produced water is treated to satisfy the relevant water quality guidelines for the intended use. Some of the disposal methods for treated produced water include infiltration ponds (Senex Energy, 2017) or reinjection into formations with good containment (Beach Energy, 2016; Santos, 2015; Senex Energy, 2015; Strike Energy, 2014). However, reinjection programs are not typically being undertaken (only one in about ten developments use water in this way) in the Cooper GBA region because of the high cost associated with installation and ongoing operation of the infrastructure.

3.2 Surface water conceptualisation

Cooper Creek supports the Ramsar-listed Coongie Lakes and many waterholes and terminal lakes and has one of the most variable flow regimes of all rivers worldwide. When flooded, the floodplain becomes a huge inland 'sea' broken only by a few ridges and stunted trees; it eventually contracts to channels, lagoons and claypans. Runoff is generated in the upper reaches (outside the Cooper GBA region) and flows through the Barcoo and Thomson river systems before becoming Cooper Creek, which flows over large areas (typically 20,000 to 50,000 km^2, depending on the flood conditions) of floodplain below Windorah. High evapotranspiration rates reduce streamflow by about half between the confluence of the Thomson and Barcoo rivers and the Nappa Merrie gauge near the SA border.

Seven large waterholes make up half the estimated volume of waterhole capacity on the Cooper floodplain. Potential water sources for a future shale, tight and deep coal gas industry in the Cooper GBA region are unlikely to include surface water sources.

The Cooper GBA region contains three surface water catchments: the Diamantina River, Cooper Creek and Bulloo River. Cooper Creek has the largest catchment area of 296,000 km^2, with the Diamantina River contributing 157,000 km^2 and the Bulloo River contributing 76,000 km^2. All three rivers follow a similar pattern, with most of the runoff generated in the higher rainfall headwater areas (outside the region) before flowing down into extensive floodplains and ending up in terminal lake systems (McMahon et al., 2008b). The Diamantina and Bulloo rivers only overlie a small portion of the Cooper Basin, covering 11% and 0.4%, respectively. These surface water catchments are not prospective for shale, tight and deep coal gas development (see Figure 29 in Section 3) and so will not be considered further in this section. The focus will be on the Cooper Creek system only.

Headwater streams originate in the Great Dividing Range of Queensland and are drained by the Thomson and Barcoo rivers. Cooper Creek is formed by the confluence of these rivers and is characterised by complex anastomosing channels and numerous wetlands and waterholes.

The Water Observations from Space (WOfS) Water Summary (Figure 38) outlines the occurrence of water in the landscape for a portion of the Cooper Creek floodplain in the vicinity of the Queensland–SA border. It shows that water is confined to certain parts of floodplains (green colours) and that, in particular, more permanent water at the surface over a ~30-year period (1987–2014) tends to be confined to in-channel waterholes. Seven large waterholes, 6 to 25 km long and 7 to 10 m deep on average, are the only major water storages on the Cooper floodplain, making up approximately half the estimated waterhole volume (Lake Eyre Basin Ministerial Forum, 2017).

The permanent waterholes on the floodplain are important ecological refugia that are highly valued by the community (as explained by the user panel). In times of flood, resources are plentiful and the ecological communities 'boom' (Figure 5a in Section 1.1). Minor floods occur most years and will replenish the major waterholes, but the floodplain will dry out and be subject to drought conditions that cause the ecological communities to transition to 'bust' conditions

(Figure 5b in Section 1.1). The minor floods with a recurrence interval of two to five years are important to maintaining the water supply to the permanent waterholes. It is doubtful that these waterholes are maintained by groundwater discharge (see Section 3.1.3) and are possibly a source of water to localised perched aquifers (see Section 3.3).

It is not known whether an increase in surface infrastructure (roads, pipelines, well pads etc.) will have an impact on the flood regime and filling of these ecologically important permanent waterholes.

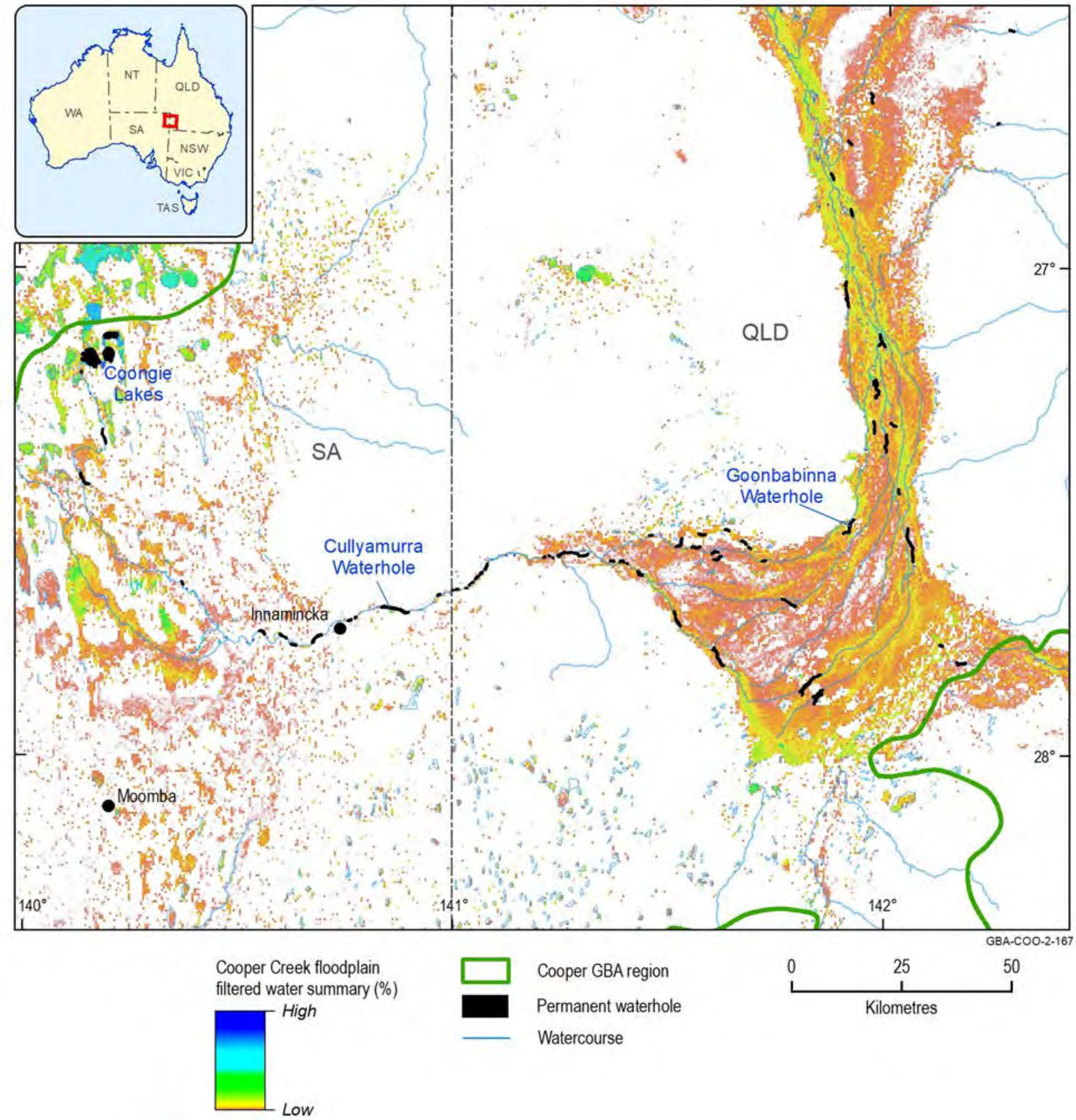

Figure 38 Water Observations from Space (WOfS) for a portion of the Cooper Creek floodplain in the vicinity of the Queensland–SA border

Source: Geoscience Australia (2018c); Queensland Department of Environment and Resource Management (2009)
Element: GBA-COO-2-167

3.2.1 Surface water flows

The area of the Cooper Creek floodplain within the region is approximately 34,000 km^2 (based on the 2010 flood) and the width can exceed 60 km at many locations. In the dry season, the channels are restricted to numerous lagoons and claypans, but during high flows the actual main channel is difficult to define. When a flood occurs, the area becomes a huge inland sea broken only by a few ridges and numerous stunted trees (Knighton and Nanson, 2001). Records of large floods in the area extend back as far as the late 19th century, with the most significant episodes of flooding occurring in 1893, 1906, 1949, 1955, 1963, 1974, 1990, 2000 and 2010, resulting in flow to Lake Eyre (Bureau of Meteorology, 2010).

After crossing the border into SA, Cooper Creek can split its flow three ways during high flows. Firstly, the main branch flows toward the south-west to its final terminus in Lake Eyre. Secondly, the north-west branch flows into Coongie Lakes. Thirdly, Strzelecki Creek flows south into Lake Blanche.

Coongie Lakes is a Ramsar-listed wetland (Figure 39). The Ramsar site includes the Cooper Creek system from the Queensland–SA border downstream to Lake Hope, the north-west branch of Cooper Creek, the northern overflow and their many waterholes and terminal lakes covering an area of over 19,800 km^2 (Butcher and Hale, 2011).

Figure 39 Coongie Lakes, looking south

Credit: Geological and Bioregional Assessment Program, Alex Tomlinson (Department of Energy and the Environment), September 2018
Element: GBA-COO-2-225

Flow in Cooper Creek is not affected by diversion of water for irrigated agriculture or major dams or weirs (McMahon et al., 2008b). This is at least partially due to unsuitable locations for instream storages and the unreliable flows. Runoff is generated in the upper parts of the Cooper Creek–Diamantina–Bulloo river catchment and gradually decreases from the north-east to the south-west (Figure 40). In the lower reaches, mean annual runoff approaches zero.

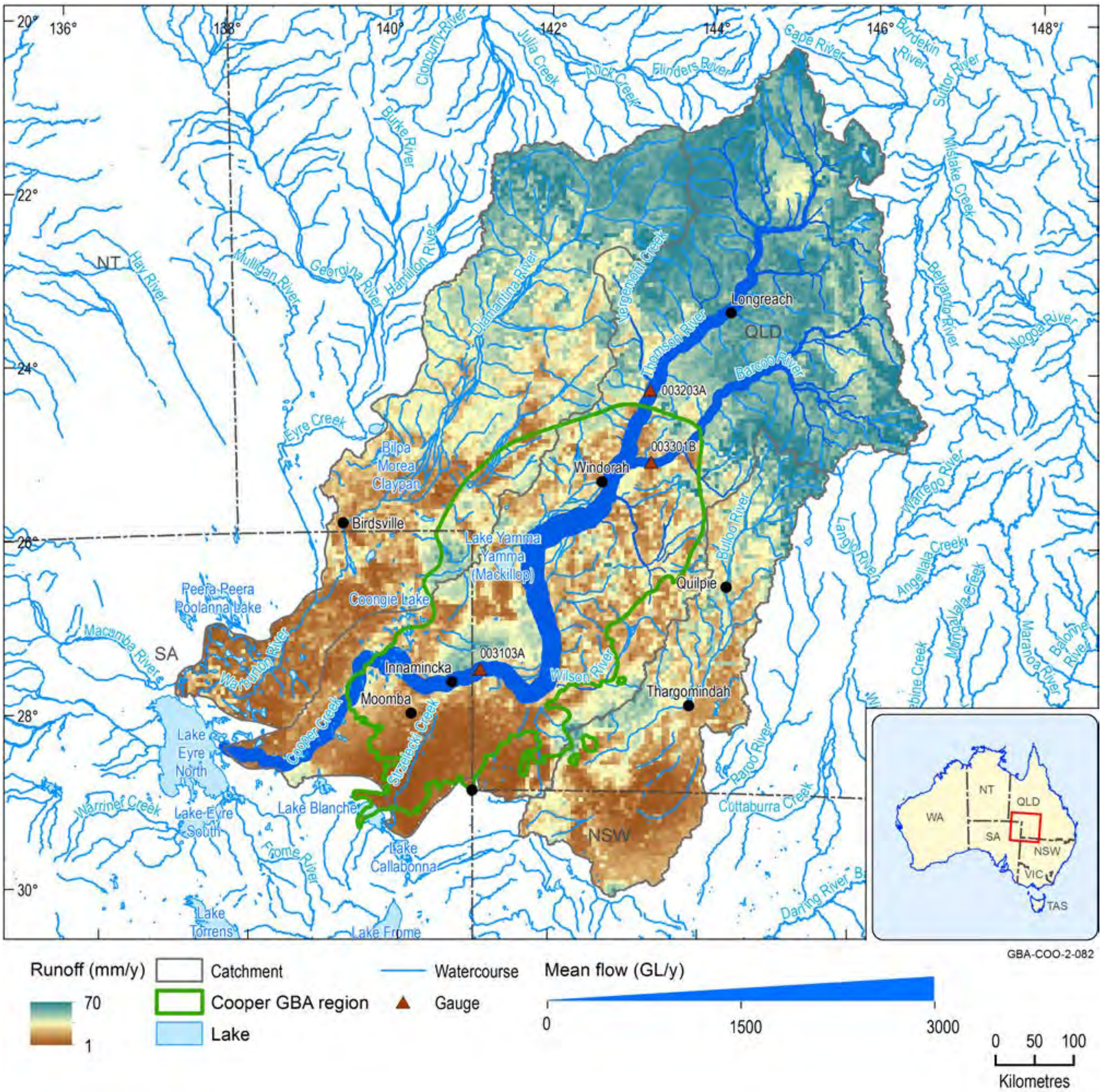

Figure 40 Surface water conceptualisation across the Cooper Creek catchment and Diamantina and Bulloo river catchments

Mean flow estimates (GL/year) are generated from the difference between precipitation and evapotranspiration (P-ET) (Figure 41).
Data: CSIRO (2015, 2014); Queensland Department of Natural Resources Mines and Energy (2018)
Element: GBA-COO-2-082

Cooper Creek has an extensive floodplain containing braided channels that lead to long travel times and large transmission losses (Jarihani et al., 2015). The transmission losses support terrestrial vegetation and pasture used for grazing, as well as filling lakes and recharging shallow groundwater. On average, runoff is generated in the upper reaches of the Barcoo and Thomson rivers, where rainfall is greater than mean annual evaporation (Figure 41). In the middle and lower reaches where there are large areas of floodplains, mean annual evaporation is greater than the mean annual rainfall (Figure 41).

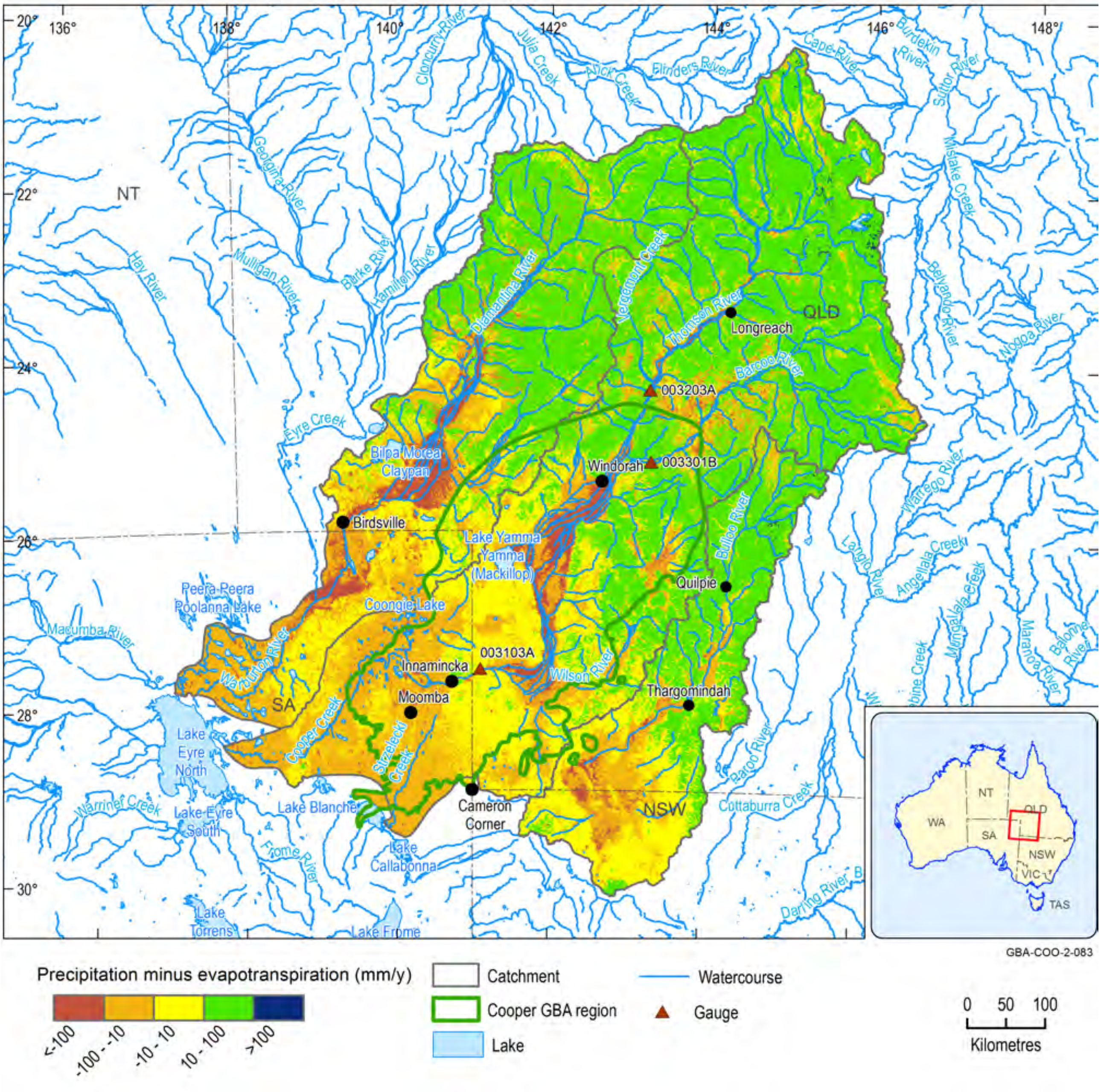

Figure 41 Precipitation minus evapotranspiration (P–ET) for 2001 to 2010 showing areas exporting water (headwaters are mostly green) and areas of lateral inflows (floodplains are mostly red)

Data: CSIRO (2014)
Element: GBA-COO-2-083

Monthly flows (Figure 42a,b&c) at the three gauges in the Cooper Creek catchment are unevenly distributed throughout the year. Maximum flows occur in February for the Thomson River at Stonehenge (gauge 003203A) and Cooper Creek at Nappa Merrie (gauge 003103A) and in January for the Barcoo River at Retreat (gauge 003301B). Minimum flows occur in different months. The driest month is August for the Thomson River at Stonehenge (gauge 003203A). Flow is very low from May to August for the Barcoo River at Retreat (gauge 003301B) and flow is very low from September to December for Cooper Creek at Nappa Merrie (gauge 003103A).

Cooper Creek has one of the most variable flow regimes of all rivers worldwide (Puckridge et al., 1998), with annual flows ranging from less than 1000 GL/year in some years to over

10,000 GL/year in 1974 (Figure 42d,e&f) at the three streamflow gauges in the Cooper Creek catchment. (Note that annual flow data are missing for some years because of missing daily flow data. However, there are no years with zero flow, so all gaps in the figures represent years with missing data (Figure 42). Furthermore, there are no missing data in any of the remaining annual totals.) For the last 40 years, the mean annual flow for the Thomson River at Stonehenge (gauge 003203A) has been about 1863 GL/year and about 1011 GL/year for the Barcoo River at Retreat (gauge 003301B) (Figure 42). Downstream of these two gauges on Cooper Creek at Nappa Merrie (gauge 003103A) the flow is only 1393 GL/year, which is less than half the combined flow of the two major tributaries (Figure 42).

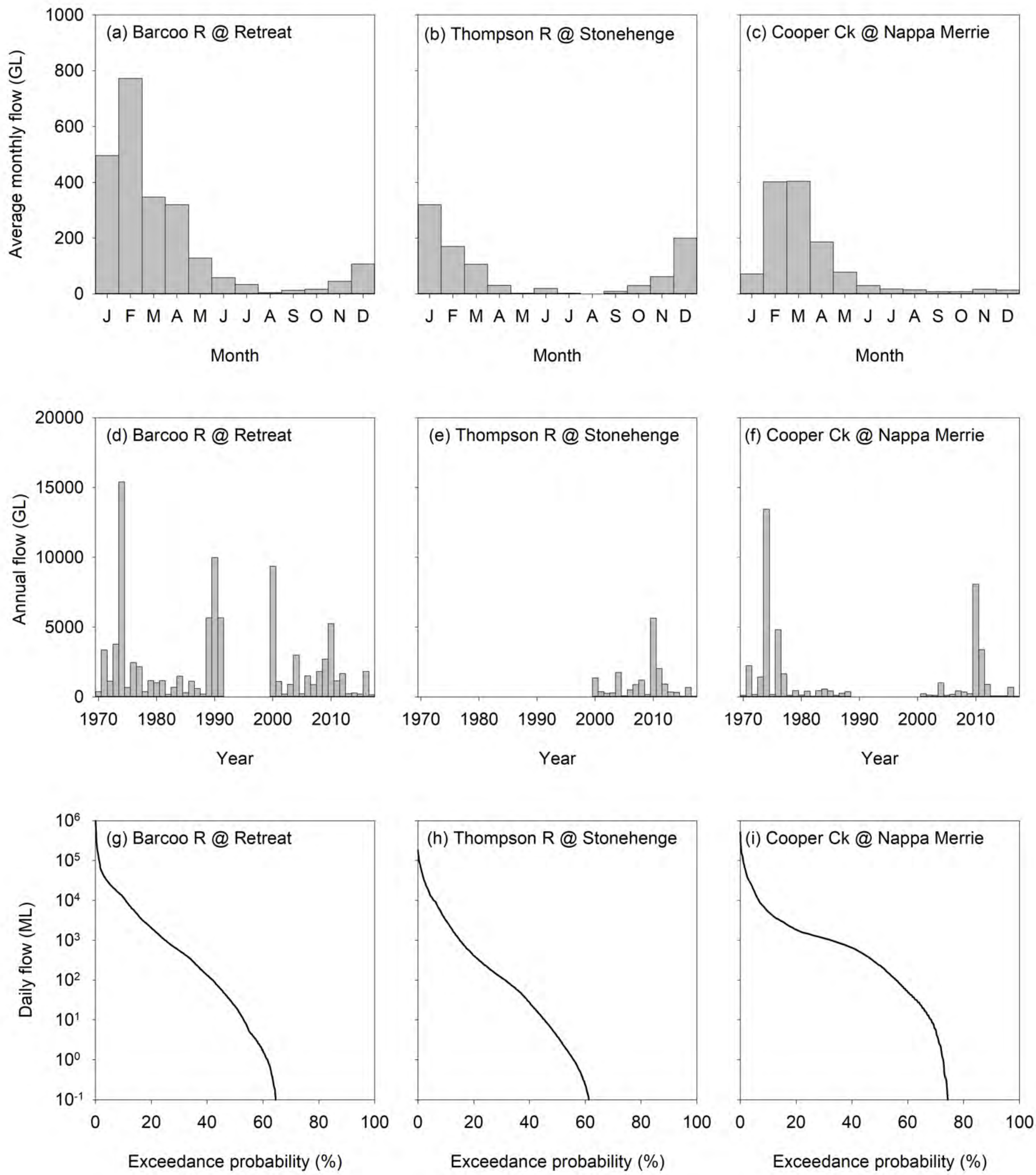

Figure 42 Monthly distribution of streamflow (top three panels), annual variability of streamflow (middle three panels) and flow duration curves (lower three panels) for three gauges located in the Cooper GBA region

Data: Department of Natural Resources, Mines and Energy (Qld) (2018a)
Element: GBA-COO-2-095

Flow in the Cooper Creek catchment is ephemeral, flowing 62% to 75% of the time at the three streamflow gauges (Figure 42g,h&i). The flow duration curves for the three streamflow gauges in the Cooper GBA region show that all three gauges record significant periods of zero flow. The percentage of time that zero flow is experienced ranges from about 25% for Cooper Creek at Nappa Merrie to about 38% for Thomson River at Stonehenge and about 35% for the Barcoo River at Retreat. It is important to note that the flooding flow (i.e. less than 2% of exceedance probability) for Thomson River at Stonehenge is higher than that for Cooper Creek at Nappa Merrie. This indicates that, on average, there are significant flows intercepted by the floodplain region and only part of the flood flows into the lower reaches. The transmission losses in Cooper Creek across the floodplain in Queensland have been reported to exceed 75% (Knighton and Nanson, 1994a). With flow rarely reaching Lake Eyre, the transmission losses in SA are frequently even higher.

It is the variability in the flows that drives the ecological boom and bust nature of the catchment. While there is flow at Nappa Merrie every year, the size of the flood determines the hydrological connectivity between the channel flow and the floodplain (Figure 43). A large flood (e.g. 1973, 2010) will ensure that all of the floodplain is inundated, while a small flood (e.g. 2004) will activate most of the distributary channels and fill most of the waterholes.

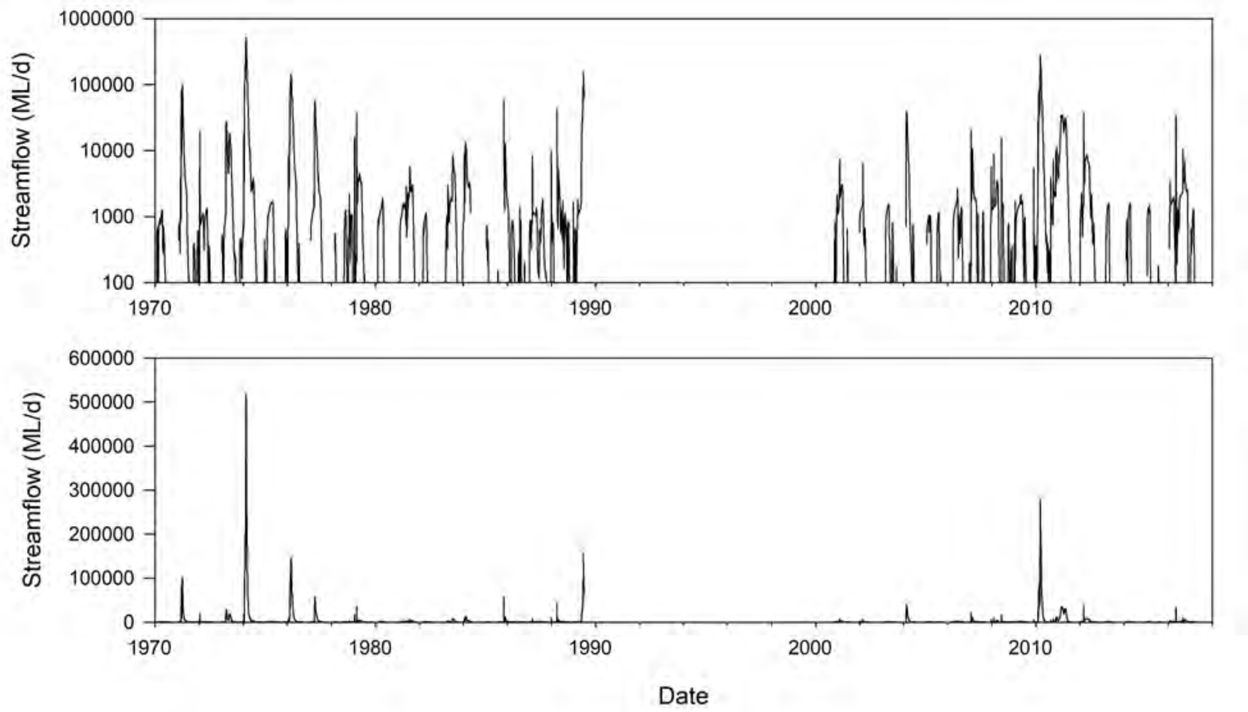

Figure 43 Daily streamflow for Cooper Creek at Nappa Merrie (gauge 003103A) using a log scale (top) and a linear scale (bottom)

Data: Department of Natural Resources, Mines and Energy (Qld) (2018a)
Element: GBA-COO-2-232

3.2.2 Surface water quality

The 2016 State of the Basin Condition Assessment reports:

> No major deterioration of water quality has been observed in the Lake Eyre Basin since the 2008 assessment. Water quality (salinity, turbidity and nutrient levels) at individual waterholes vary greatly through time in response to flow patterns, which are largely natural. There are also significant differences between catchments, notably in salinity and turbidity, due to differences in geology and groundwater systems. Streams of the

> northern and eastern Lake Eyre Basin (the Cooper and Georgina-Diamantina) tend to be mostly fresh, turbid, slightly alkaline and high in nutrients. Waterholes in the lower reaches of these catchments tend to be less turbid and become more saline between flows. Existing national water quality guidelines are unsuitable for evaluating water quality in the Lake Eyre Basin due to the variable river conditions. Levels of nutrients and turbidity are often higher than the guidelines and appear to be naturally higher than in many Australian rivers. New guidelines are currently under development for Australia's temporary waters. *(Lake Eyre Basin Ministerial Forum, 2017).*

Systematic water quality sampling by the Surface Water Ambient Network (SWAN) program has occurred in Queensland since 1960. Median recorded total dissolved solids (TDS) is 90 mg/L for the Barcoo River at Retreat, 91 mg/L for the Thomson River at Stonehenge and 101 mg/L for Cooper Creek at Nappa Merrie (Figure 44a). This is significantly fresher than the regional groundwater (see Section 3.1.3). At all three sites TDS would be considered good quality for drinking water (NHMRC/ARMCANZ, 1996) and suitable for stock watering (ANZG, 2018). There is currently no suitable Environmental Protection Policy (Water) or default ANZECC/ARMCANZ (2018) trigger value specific for the protection of aquatic biota from unsuitable levels of salinity, TDS and nutrients in the Cooper Creek system. In the absence of a comparative benchmark, it is useful to look at changes in these parameters over time (Figure 44a–c). There are no definitive trends of significant increased TDS, total nitrogen and total phosphorus concentrations over time, suggesting that current levels of development have not deteriorated the water quality for aquatic biota. However, it does highlight the importance of developing water quality guideline values tailored to the local environment.

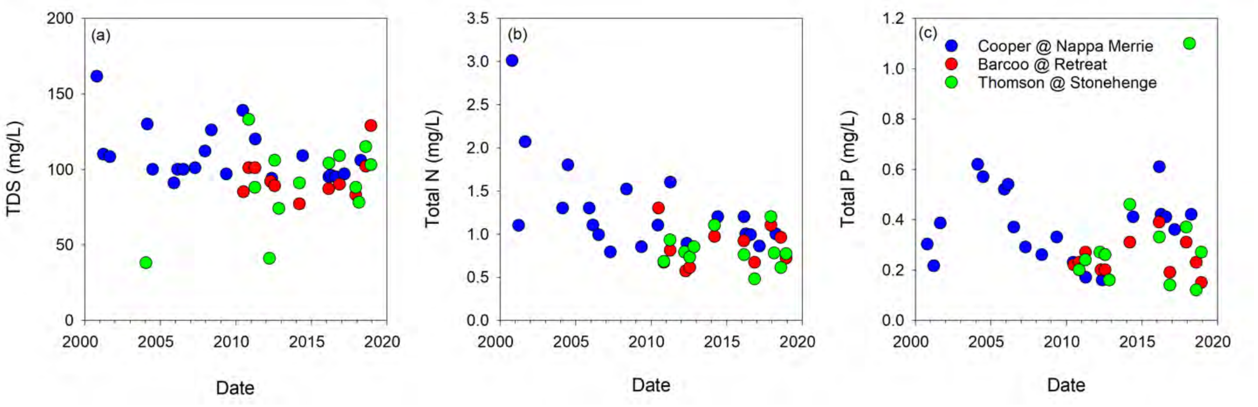

Figure 44 Indicators of water quality for three gauging stations in the Cooper GBA region showing (a) total dissolved solids (TDS); (b) total nitrogen (Total N); and (c) total phosphorous (Total P)

Data: Department of Natural Resources, Mines and Energy (Qld) (2019a)
Element: GBA-COO-2-230

The variations in water quality parameters shown in Figure 44 are from grab samples rather than continuous monitoring during a flood-recession cycle. It would be expected that, where water is stationary in lakes and waterholes during the recession after a flood event, the water quality will change through time due to evapoconcentration. Costelloe et al. (2004) showed that the change in water level in most waterholes in the Lake Eyre Basin was related to evaporation rather than seepage. Evaporation from the waterholes leads to evapoconcentration of salts. This can be seen as an inverse relationship between the water level and salinity, illustrated in Figure 45 for the inlet channel to Coongie Lake.

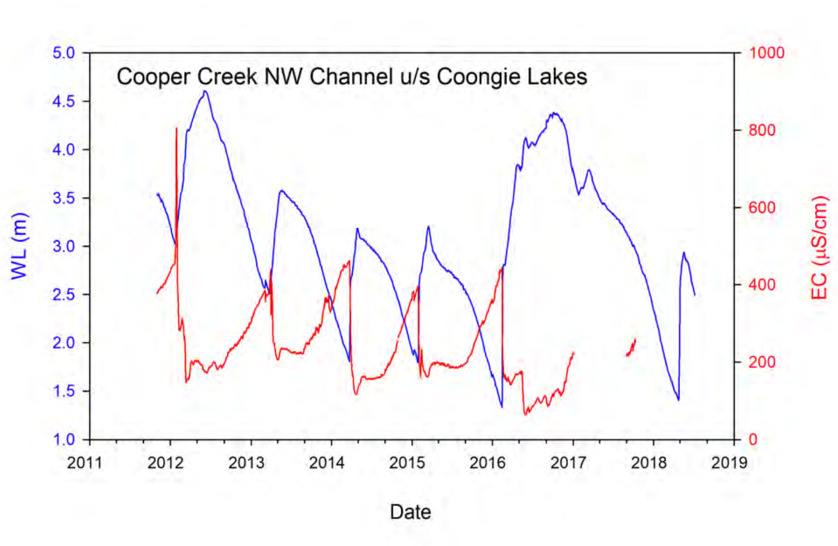

Figure 45 Example of relationship between stage height (WL) and electrical conductivity (EC)

Data: Government of South Australia (2019)

Element: GBA-COO-2-231

3.2.3 Potential water sources for drilling and hydraulic fracturing

In the Cooper GBA region, surface water is managed in Queensland by the Department of Natural Resources, Mines and Energy and the Desert Channels Queensland Incorporated NRM group. In SA, surface water is managed by the Department for Environment and Water and the South Australian Arid Lands Natural Resources Management Board.

In Queensland, relocatable water licences are attached to land, and these water licences are only allowed to be relocated (or permanently traded) or bought with the land. There also non-relocatable water licences, and the only way of accessing water under this type of water licence is to buy the land as well with the water licence attached to the title. As per the *Water Act 2000* (Qld), water allocations are tradeable water rights, are not attached to land and can be bought, leased, bequeathed or seasonally assigned separate from the land. There are no water allocations in the Queensland part of the Cooper GBA region. Water licences (both relocatable and non-relocatable) in the Queensland part of the Cooper GBA region are granted under its six relocatable licence zones (Torrens Towerhill, Alice, Upper Barcoo, Lower Barcoo, Thomson and Cooper) (Figure 46). In the 2011 water plan for Cooper Creek, the Queensland Government reserved 2200 ML of unallocated water (200 ML for general reserve, 200 ML for Indigenous reserve, 1300 ML for strategic/state reserve and 500 ML for the town and community reserve) to meet future demand (Department of Natural Resources and Mines (Qld), 2013).

Water licences (both relocatable and non-relocatable) as part of the Georgina and Diamantina water plan are managed under its five water management areas (Upper Georgina, Lower Georgina, Burke and Hamilton, Upper Diamantina and Lower Diamantina). As part of this water plan, the Queensland Government reserved 13,500 ML of unallocated water (12,000 ML for general purpose and 1500 ML for state significant projects) (Department of Natural Resources, Mines and Water (Qld), 2006).

The Bulloo and Flinders river catchments do not overlie prospective areas and are unlikely to be sources of water for future shale, tight and deep coal gas development (Figure 30), so licensed entitlement volumes for these resources are not reported in this section.

The use of surface water in the SA part of the Cooper GBA region in general is not a licensed activity and is regulated under the South Australia Arid Land Natural Resources Management Business and Operational Plan. Currently, there are no surface water licences and, as the use of surface water is insignificant compared with that of groundwater, for the accounting of water use it is assumed that all water used for stock and domestic purposes is sourced from groundwater (South Australian Arid Lands Natural Resources Management Board, 2009). The use of surface water resourced by the petroleum sector is regulated and managed under the South Australian Department for Energy and Mining Statements of Environmental Objectives (SEO) and or Environmental Impact Report (EIR) process.

Surface water accounts information is provided for three major catchments that overlie the Cooper GBA region: the Diamantina River, Cooper Creek and Bulloo River catchments.

Currently, there are 33 water licences with nominal entitlements amounting to 13,440 ML/year, 22 stock and domestic licences amounting to 260 ML/year and eight town water supply licences amounting to 370 ML/year, as part of the Cooper Creek water plan (Geological and Bioregional Assessment Program, 2018i). Under this plan, there are also 42 flow-dependent licences to impound water through embankment or dams, with a total capacity of 14,170 ML/year. There are three water licences amounting to 6110 ML/year and two licences to divert water as part of the Georgina and Diamantina water plan (Geological and Bioregional Assessment Program, 2018i). Under the Warrego, Paroo, Bulloo and Nebine water plan, for areas in the Cooper GBA region, there are eight water licences with a total entitlement volume of 190 ML/year and 54 licences to interfere by impounding through embankment or dams, with total storage capacity of 3340 ML/year (Geological and Bioregional Assessment Program, 2018i).

Santos, as part of their Cooper Basin Production and Processing operations EIR and SEO process, has approval to periodically extract up to 15 ML/year of water from Cooper Creek in SA to supplement available groundwater supplies and meet project water demands (Santos, 2015). Flow duration curves for Cooper Creek indicate that surface water is unreliable, being available only 70% of the time in the main channel at Nappa Merrie (Figure 42), and there may be no flow for years at a time in some of the minor streams.

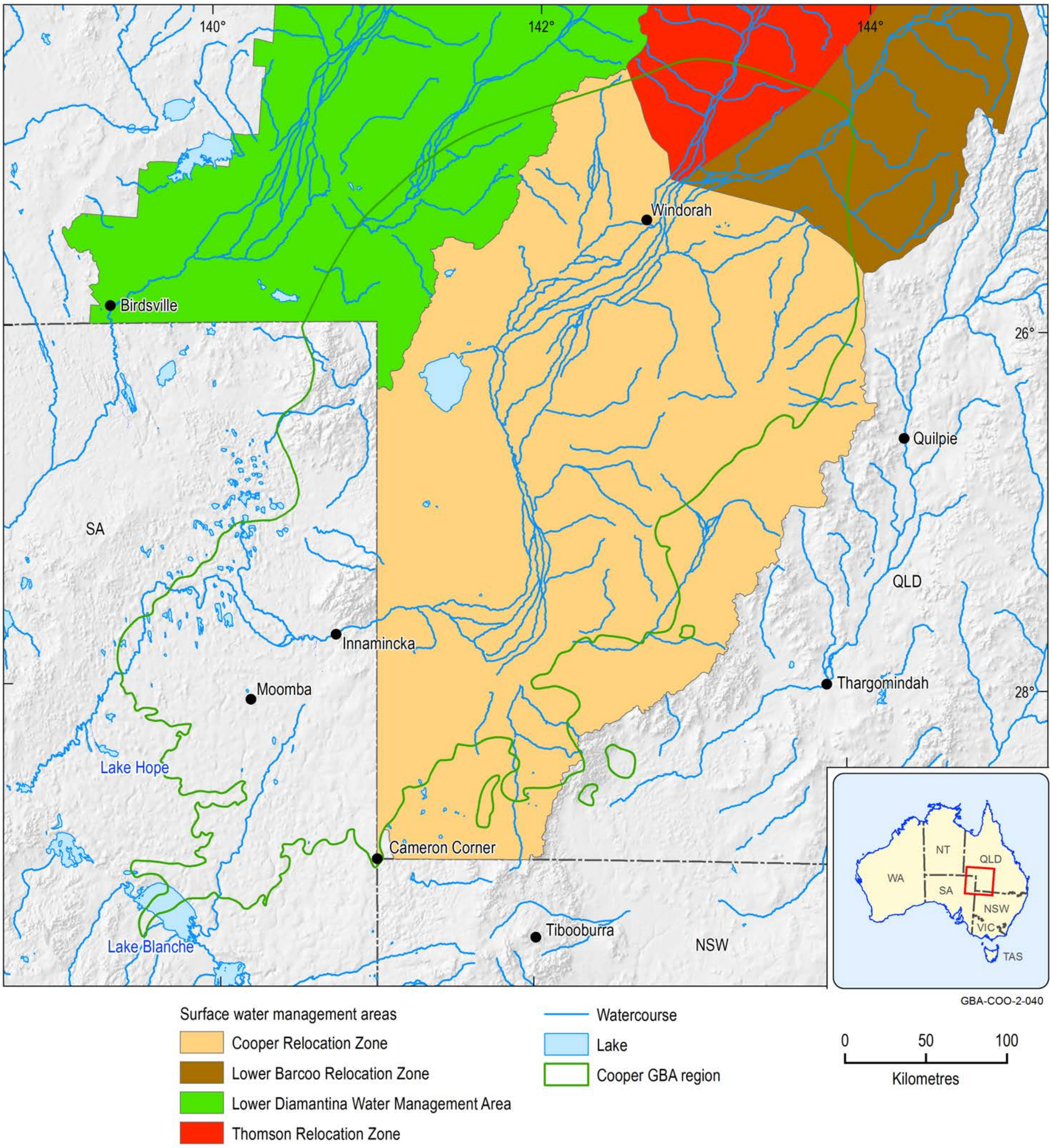

Figure 46 Water management areas and major streams and water bodies in the Cooper GBA region

Data: Department of Natural Resources, Mines and Energy (Qld) (2018d)
Element: GBA-COO-2-040

3.3 Surface water – groundwater conceptualisation

Surface water – groundwater interactions are more likely to occur where water sits in the landscape, which in the Cooper GBA region is primarily the Cooper Creek floodplain. From a small study, the occurrence of freshwater lenses overlying more saline groundwater was noted in the vicinity of some waterholes on the floodplain. This was attributed to recharge during flood events, with water leaking through the base of the waterholes. It is not known, though, whether all waterholes act as points of recharge to shallow aquifers. Also, the degree of separation between waterhole and watertable could change depending on where the waterhole sits in the landscape (e.g. near the margins or in the centre of the flood plain).

Lakes can act as points of recharge or discharge for shallow aquifers. Discharge can occur through evaporation during dry periods, with concentration of salts in the lake floor.

Springs are unlikely to be directly impacted by future developments of shale, tight and deep coal gas plays, as springs in the Cooper GBA region are distant from future development areas. However, cumulative impacts from multiple types of petroleum plays (e.g. conventional oil and gas; coal seam gas (CSG); shale, tight and deep coal gas) to GAB springs near Lake Blanche are difficult to predict at this point in time. This could be considered further once there is a clearer understanding of how resources will be developed in the south-western corner of the Cooper GBA region in the future.

Surface water – groundwater conceptualisations are dependent on understanding the surface water flow regime (Section 3.1.4) as well as shallow groundwater systems (Section 3.1). Duration and extent of ephemeral surface flows, water quality, high evaporation rates, and transmission losses in Cooper Creek catchment (Section 3.1.4), as well as local geomorphology and geology, all contribute to availability of surface water for recharge to shallow groundwaters and riparian ecosystems.

Springs with an artesian GAB aquifer source (Figure 47) do not occur within the Cooper GBA region (Evans et al., 2020). The closest GAB springs are found near the western shore of Lake Blanche in SA (Lake Blanche and Reedy Springs – see Keppel et al. (2016) for details), some 20 km to the west of the Cooper GBA region. These springs are fed through fault conduits. The primary source aquifer for Reedy Springs is considered to be the Cadna-owie – Hooray Aquifer while, for the Lake Blanche springs, the source aquifers are the Coorikianna Sandstone and Cenozoic aquifer (Keppel et al., 2016). Inferred regional groundwater flow in Coorikianna Sandstone, in the vicinity of these springs, is from west to east (so toward the Cooper GBA region). However, groundwater flow directions for the deeper Cadna-owie – Hooray Aquifer in this area are less well constrained, and there is some potential for groundwater flow out of the Cooper GBA region toward the springs in this aquifer.

Development of shale, tight and deep coal gas plays is unlikely to occur in the vicinity of the springs near the south-western margin of the Cooper GBA region (Figure 47). This lessens the potential for direct and indirect impacts to these springs from future gas resource development. However, cumulative impacts from continued development of multiple play types in the Cooper and Eromanga basins, including conventional oil and gas, shale, tight and deep coal gas, and CSG (Smith et al., 2016) may affect these springs in the future.

The source aquifers for springs found around the eastern and north-eastern margin of the Cooper GBA region (Figure 47) are thought to be in the Cenozoic (Silcock et al., 2016). However, limited information is available on these springs and, unlike for the GAB artesian springs found to the west and south of the Cooper GBA region, no detailed assessment using hydrochemical and isotopic fingerprinting has been conducted to determine the source aquifer(s) of these springs.

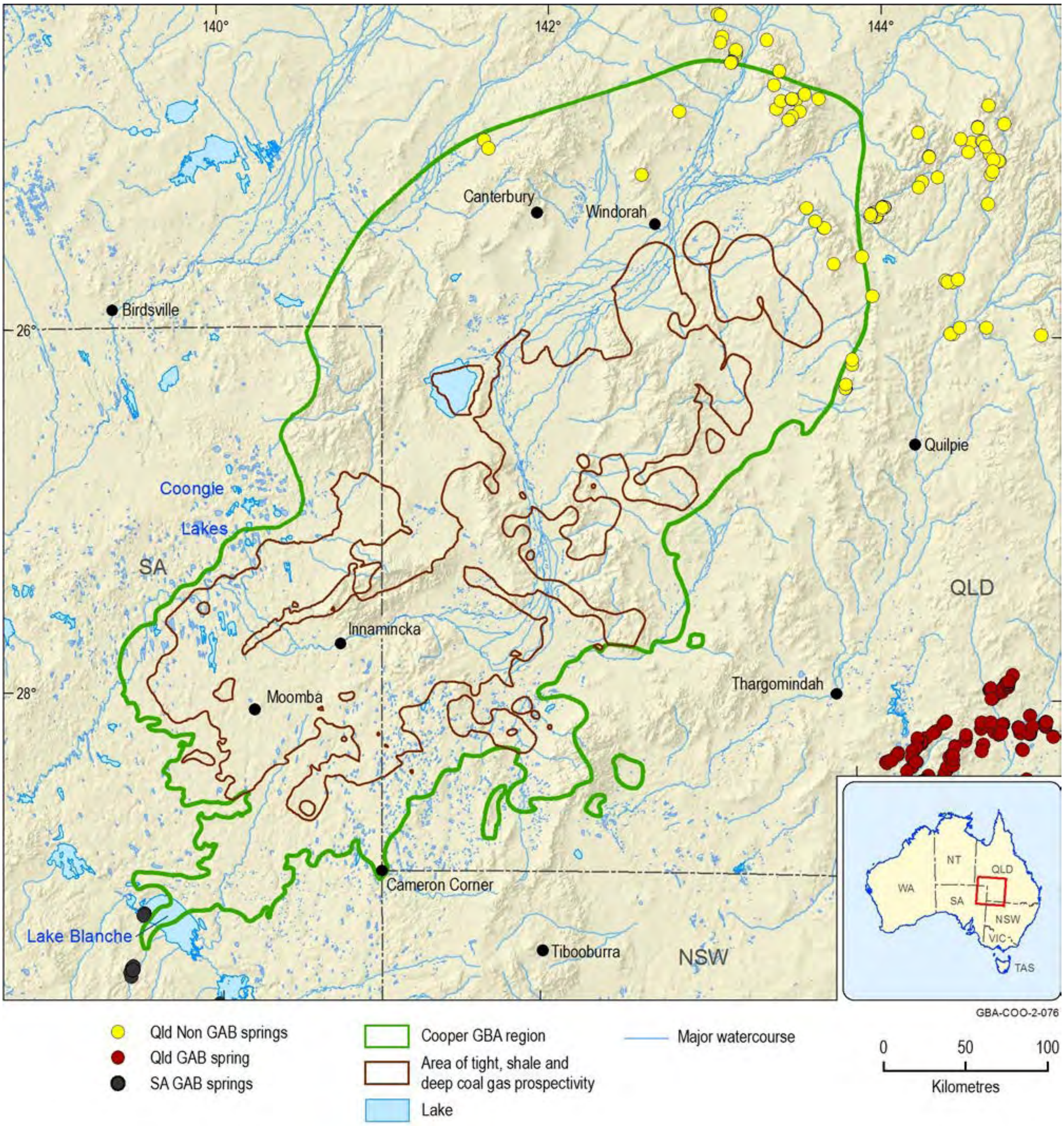

Figure 47 Distribution of springs in and around Cooper GBA region

Source: Government of South Australia - Department of Environment (2012); Government of Queensland - Department of Natural Resources (2018); Geoscience Australia (2019)
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Only two hydrogeological studies have focused on near-surface groundwater (within 20 m) in the Cooper GBA region (e.g. Cendón et al., 2010; Costelloe et al., 2009). These are of direct use for understanding surface water – groundwater interactions. However, these detailed studies are restricted to a small part of the Cooper Creek floodplain and to Coongie Lakes. It is uncertain how representative these studies are for lakes and waterholes throughout the Cooper Creek floodplain system. For instance, there have been no groundwater-related studies undertaken for significant features such as Cullyamurra waterhole. Furthermore, studies on the potential for recharge to deeper Cenozoic aquifers (i.e. aquifers below 20 m deep) have not been undertaken in the Cooper GBA region and are the subject of knowledge gaps outlined in Section 3.1 and Section 3.4.

At the one study site on the Cooper Creek floodplain (Goonbabinna waterhole – see Figure 38 for location), episodic flooding of losing streams was found to recharge the shallow aquifers. This resulted in the development of freshwater lenses surrounding major watercourses, particularly in the vicinity of large near-permanent waterholes (Cendón et al., 2010). Freshwater lenses either lie directly on a more saline regional watertable (Figure 48) or are perched above it. In the Cooper Creek floodplain, clay layers lining the base of waterholes probably limit leakage during periods of no flow. Deep-rooted vegetation could use shallow groundwater as a water source during dry periods (Evans et al., 2020; Cendón et al., 2010).

At Coongie Lakes (Figure 38), it was found that, during dry periods, evaporative groundwater discharge from shallow groundwater can lead to development of salinised soil profiles, particularly under ephemeral lakes (Costelloe et al., 2009). However, during periods of inundation, leakage from lakes may recharge the shallow aquifers and in the process flush some of salts out of the soil profile into the aquifer.

Aside from near-surface processes, such as those mentioned for Coongie Lakes, shallow aquifers around Lake Blanche could potentially receive groundwater via other mechanisms, such as diffuse leakage from underlying aquifer or spring discharge. Additionally, Lake Blanche is situated down a regional hydraulic gradient from the Cooper GBA region and may on a regional scale be a focus for discharge from aquifers in Lake Eyre Basin and Winton-Mackunda partial aquifers (Evans et al., 2020).

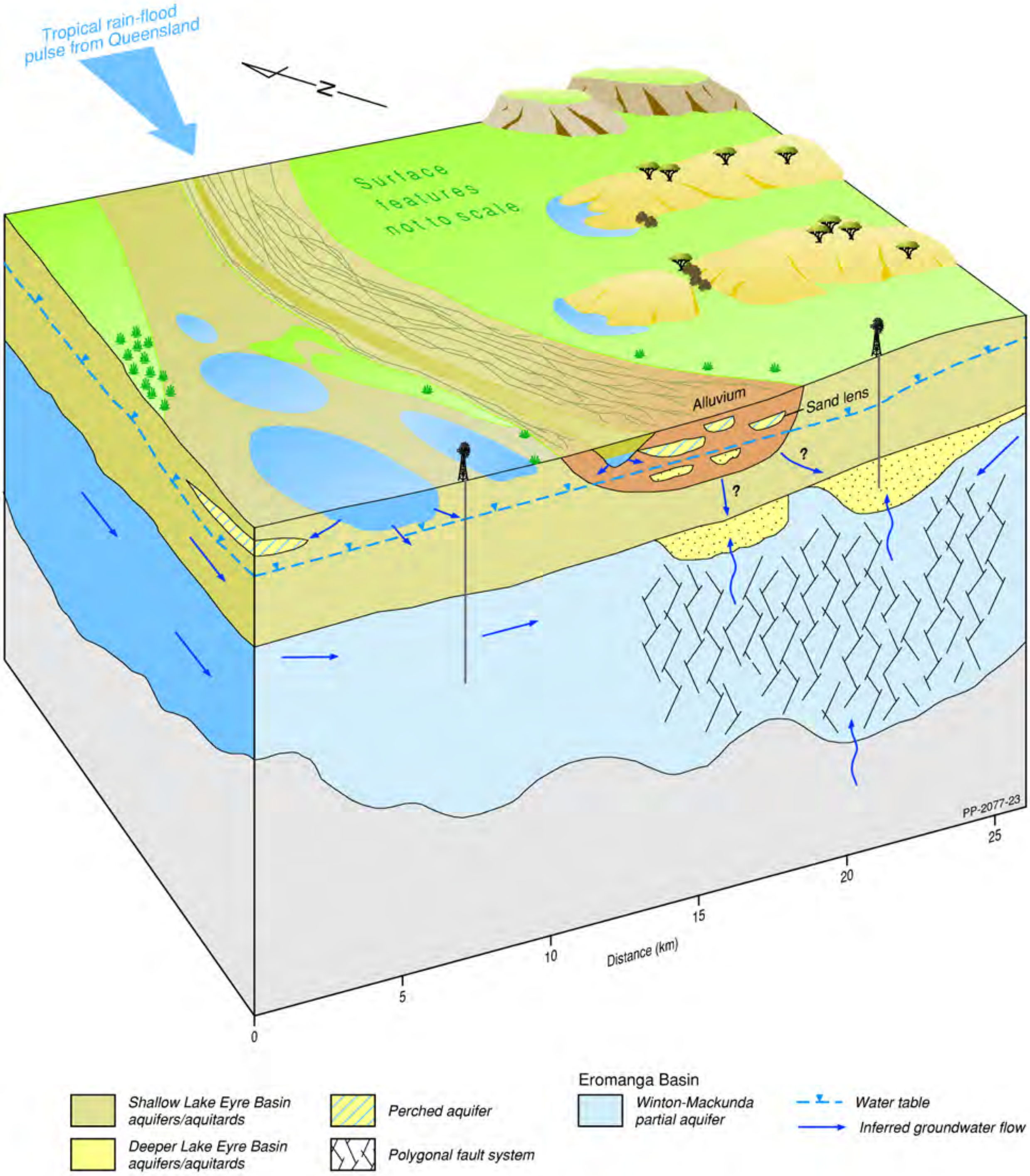

Figure 48 Conceptual model of surface water – groundwater interactions and shallow groundwater for a portion of the Cooper Creek floodplain

Interactions include leakage from rivers and lakes recharging shallow aquifers during flood events; leakage to perched aquifers above the regional watertable; leakage from shallow aquifers to deeper aquifers in the Lake Eyre Basin; regional south-westward directed groundwater flow in Cenozoic and Winton-Mackunda partial aquifers; and upwards leakage via polygonal faulting pathways; and groundwater extraction.

Question marks on the flow directions highlight the uncertainty around how deeper aquifers in Cenozoic are recharged and their degree of connectivity.

Source: Evans et al. (2020)

Element: GBA-COO-2-283

Investigations using spatial and temporal remote sensing data would assist in understanding the distribution of water in the landscape, surface water – groundwater interactions, floodplain and riparian vegetation dynamics, and land use.

3.4 Potential hydrological connections

The nature of the hydrological connection (if any) between deeper groundwaters (Cooper, Eromanga and Lake Eyre basins), shallow aquifers and surface waters is poorly understood. Five potential hydrological connections are postulated for the Cooper GBA region related to migration via dilation faults or through porous aquifers, partial aquifers or aquitards due to contact between formations near the basin margin and steep hydraulic gradients at catchment constrictions. Investigations in Stage 3 will focus on potential hydrological connections relevant to risks from future shale, tight and deep coal gas development.

Hydrochemistry and dissolved gas concentrations provide some evidence of potential connectivity between deep and shallow system components. However, the assessment also highlights that considerable data and knowledge gaps exist and leads to several hypotheses to be tested during Stage 3 or in future studies to better estimate the likelihood of hydrological connections between stressors and assets.

Development of unconventional gas plays in the Gidgealpa Group of the Cooper Basin (including shale, tight and deep coal gas) is a stressor that has the potential to affect migration of groundwater and fluids between deeper formations and assets near the surface (Figure 49). Extraction of water from shallower aquifers (e.g. from Cenozoic aquifers or shallower aquifers of the Eromanga Basin) is another stressor that can have an impact on groundwater and surface water assets. Important assets in the Cooper GBA region include:

- **springs**, represented by two groups located near the north-east and south-west corners of the Cooper GBA region. The springs are located both inside and outside the region (see Section 4.3 and Figure 47)
- **groundwater-dependent ecosystems (GDEs)**, including aquatic and terrestrial ecosystems that depend on groundwater and are described in five major conceptual models: alluvia, catchment constrictions, permeable rocks, sedimentary rocks (GAB) and wind-blown inland sand dunefields (Queensland Government, 2018)
- **streams** and **wetlands**, including Cooper and Strzelecki creeks, Barcoo and Thomson rivers and Blanche (south-west), Coongie (west) and Yamma Yamma lakes (central) (see Sections 3.2, 3.3 and 4.3)
- **waterholes** throughout the Cooper Creek floodplain system, as discussed Section 4.2
- **shallow groundwater bores** used for stock and domestic water supply, as registered in the Queensland and SA groundwater databases (see Section 3.1) and deeper groundwater bores that source water from the Eromanga Basin.

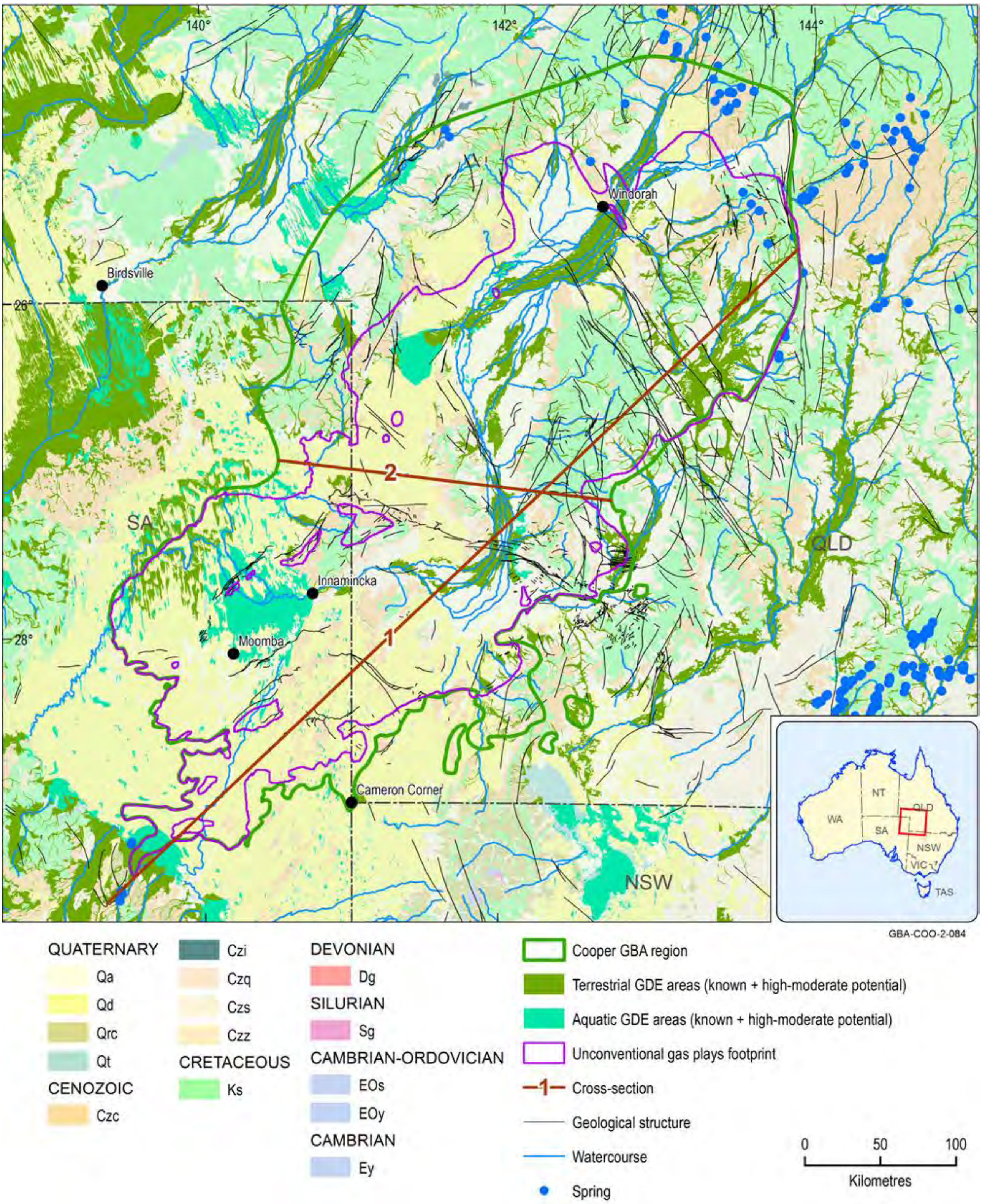

Figure 49 Cooper GBA region – surface geology, structures, footprint of unconventional gas plays, environmental assets (groundwater-dependent ecosystems (GDEs), springs and watercourses) and orientation of cross-sections presented in Figure 50 and Figure 51

Data: Queensland Department of Environment and Science (2018); Geoscience Australia (2018b, 2018a, 2012); Department for Environment and Water (2015); Bureau of Meteorology (2017); Geological and Bioregional Assessment Program (2018c)
Element: GBA-COO-2-084

Five potential hydrological connections between stressors and assets that could plausibly affect migration of groundwater and fluids are described below. In the absence of detailed hydrological studies, the evidence for these potential hydrological connections includes the conceptual understanding of aquifer and aquitard architecture, proximity of assets to faults, vertical continuity of faults, and geological heterogeneities near the basin margins. The five possible hydrological connections are:

1. vertical migration via dilation faults
2. migration through porous aquifers
3. migration through partial aquifers/aquitards
4. migration due to contact between gas plays and overlying aquifers near the basin margin
5. vertical migration at catchment constrictions where steep hydraulic gradients exist between alluvial aquifers and underlying GAB formations.

Multiple datasets are integrated to develop conceptual models that describe the potential for hydrological connections (if any) between deep unconventional gas plays or water source aquifers (Cooper, Eromanga and Lake Eyre basins) and environmental assets (including GDEs) at the surface. Stressors include the development of unconventional shale, tight and deep coal gas plays in the Cooper Basin and extraction from shallower aquifers to support development. The geological framework uses key horizons represented in the three-dimensional geological model prepared by (Geoscience Australia, 2016) and fault structures generated by Geoscience Australia (2013) and Geological and Bioregional Assessment Program (2018a). The conceptual models are based on the interpretation of several two-dimensional cross-sections through the Cooper and Eromanga basins and their immediate vicinity. The conceptual models aim to identify areas where there is a greater likelihood of hydrological connections based on a combination of factors, including:

- the footprint and thickness of the unconventional gas play intervals and their linear distance (predominantly vertical) to GAB aquifers and assets (both near-surface and at-surface)
- upwards formation pore pressure (or hydraulic) gradient potentials between the unconventional plays and the overlying hydrostratigraphic units that are more susceptible to being immediately affected by depressurisation of the gas fields
- a regional stress regime associated with geological structures that is conducive to fault reactivation and enhancement
- spatial distribution of thickness and hydraulic properties of the aquitard/seals positioned between the unconventional plays and the identified assets, including shallow aquifers
- anomalies identified in physical–chemical, hydrochemical and gas measurements from reservoir fluids, aquifers, springs and surface waters
- the spatial location and extent of environmental assets, including GDEs, springs, waterholes, reaches where baseflow to streams and/or waterholes occurs, and shallow groundwater bores used for water supply.

① Vertical migration via faults

Fault zones can result in vertical hydraulic connection between different hydrostratigraphic layers and/or where strata are compartmentalised horizontally. These conditions could potentially connect unconventional gas plays with overlying GAB aquifers (Hutton Sandstone, Adori Sandstone or Cadna-owie – Hooray Aquifer), the Winton-Mackunda partial aquifer, shallower Cenozoic and possibly alluvial aquifers, or surficial assets such as perched watertables, GDEs and springs. Vertical migration via faults is more likely at shallower depths, such as unconventional gas plays targeted by CSG wells. To assess whether hydrological connections exist, a comprehensive and reliable fault zone analysis that involves multiple complementary methods (e.g. geophysics, structural geology, hydrochemistry and environmental tracers) is recommended (Underschultz et al., 2018).

The Cooper and Eromanga basins have been affected by at least six tectonic events between 450 and 23 Ma, highlighting the structural complexity of the region. The likelihood for fault reactivation and fault dilation (or the likelihood of open fractures or faults) following these events has been estimated for a part of the Cooper GBA region in SA, near the Gidgealpa–Merrimelia–Innamincka ridges (see Figure 49) by Kulikowski and Amrouch (2018). They found that the two most recent tectonic events affecting the Cooper–Eromanga – Lake Eyre basins during the Late Cretaceous and Paleogene, despite being of compressional nature, may have resulted in the reactivation of north-east–south-west striking faults and potential dilation of north–south and east–west striking faults, all with dip angles ranging from 50 to 70 degrees. The numerous high angle faults striking the geological units of the Cooper and Eromanga basins coincide with vertical shifts in the lateral distribution of geological units represented by the three-dimensional geological model from Geoscience Australia (2016), as indicated in cross-sections 1 and 2 (Figure 50 and Figure 51). These features are clearly present at the boundaries of the Weena and Nappamerri troughs (cross-section 1, Figure 50), which form a graben (a trough bound on both sides by faults), controlled by the reactivation of basement structures following the six major tectonic events.

The Cooper Basin and overlying parts of the Eromanga Basin are considered a hydrocarbon-producing system (see ‘Shale, tight and deep coal gas’ in Section 2.2; petroleum prospectivity technical appendix (Boreham and Summons, 1999; Radke, 2009; Lech et al., 2020)) with most hydrocarbons in the Eromanga Basin originally migrating from source rocks in the Cooper Basin. Resultant hydrocarbon and fluid migration and accumulation, as well as compaction diagenesis, have, over time, substantially modified the hydrogeological character of the Cooper and Eromanga basin sequences through changes to porosity and permeability, causing aquifer compartmentalisation and resulting in a highly variable potential for connectivity.

In the Eromanga Basin within the extent of the Cooper Basin, methane concentration measurements are available from only ten groundwater bores. These measurements were mostly taken from bores screened in the Winton-Mackunda formations, Hooray Sandstone and Adori Sandstone, with a median bore depth of approximately 1000 m. Although few measurements are publicly available, the available data show presence of considerable methane concentrations, ranging from 150 to 216,500 µg/L (median 32,050 µg/L). The highest measured methane concentration is in a relatively shallow bore (bore depth of 456 m) screened in the Winton-Mackunda formations near the north-eastern margin of the Cooper Basin. The Winton

Formation contains coal (Lewis et al., 2014), and methane can also be produced in-situ within the GAB formations via biogenic reactions. However, the gas concentrations from these bores in relatively shallow aquifers of the Eromanga Basin are unusually high compared with other sedimentary basins in Australia. This suggests that gas and potentially fluid migration pathways may connect the deeper formations with the shallower ones, although it is not known when and through which migration pathways the gas may have leaked. It could be that methane leaked millions of years ago and these high values are localised. Alternatively, there could be other areas where methane concentrations are high. Further baseline data are required to test the extent of methane in shallow aquifers. The degree to which leakage occurs could be investigated through groundwater modelling scenarios and hydrochemistry.

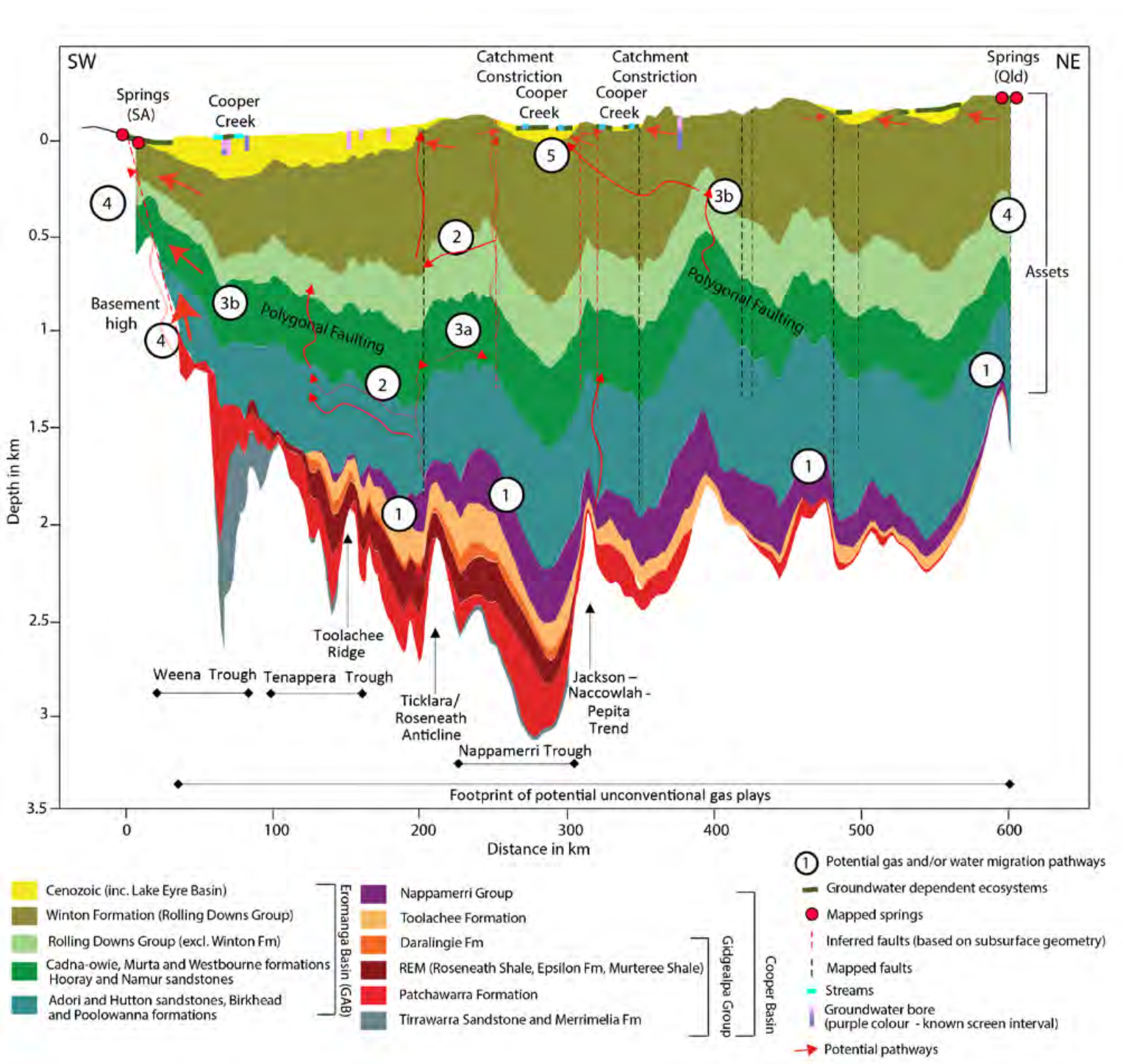

Figure 50 Cross-section 1 with north-east–south-west orientation through Cooper and Eromanga basins, representing north-eastern and south-western basin margins and major geological structures within the Cooper and Eromanga basins and five potential hydrological connections for water or gas migration

The five potential hydrological connections are: 1. vertical migration via dilation faults; 2. migration through porous aquifers; 3. migration through the Rolling Downs Group aquitard via PFS (a – lateral; b – vertical); 4. migration due to contact between gas plays and overlying aquifers near the basin margin; and 5. vertical migration at catchment constrictions where steep hydraulic gradients exist between alluvial aquifers and underlying GAB formations. GAB = Great Artesian Basin.
Data: Geoscience Australia (2008c, 2013, 2018b); Department of Environment and Science (Qld) (2018c); Bureau of Meteorology (2017); Department of Environment, Water and Natural Resources (SA) (2012); three-dimensional geological model from Hall and Palu (2016); Geological and Bioregional Assessment Program (2018c)
Element: GBA-COO-2-097

Regions of higher prospectivity for shale, tight and deep coal gas and much of the deep coal gas areas are in the central parts of Cooper Basin troughs (see Section 2.2). Here, vertical connectivity is likely to be minimised by the Nappamerri Group, which contains a series of discrete intra-formational seals. However, although faults are not represented in the three-dimensional geological model of the Cooper and Eromanga basins, subsurface geometry and mapped faults (e.g. Figure 50) indicate that the Nappamerri Group is likely to be significantly displaced by major faults and may therefore not form a continuous seal in these areas.

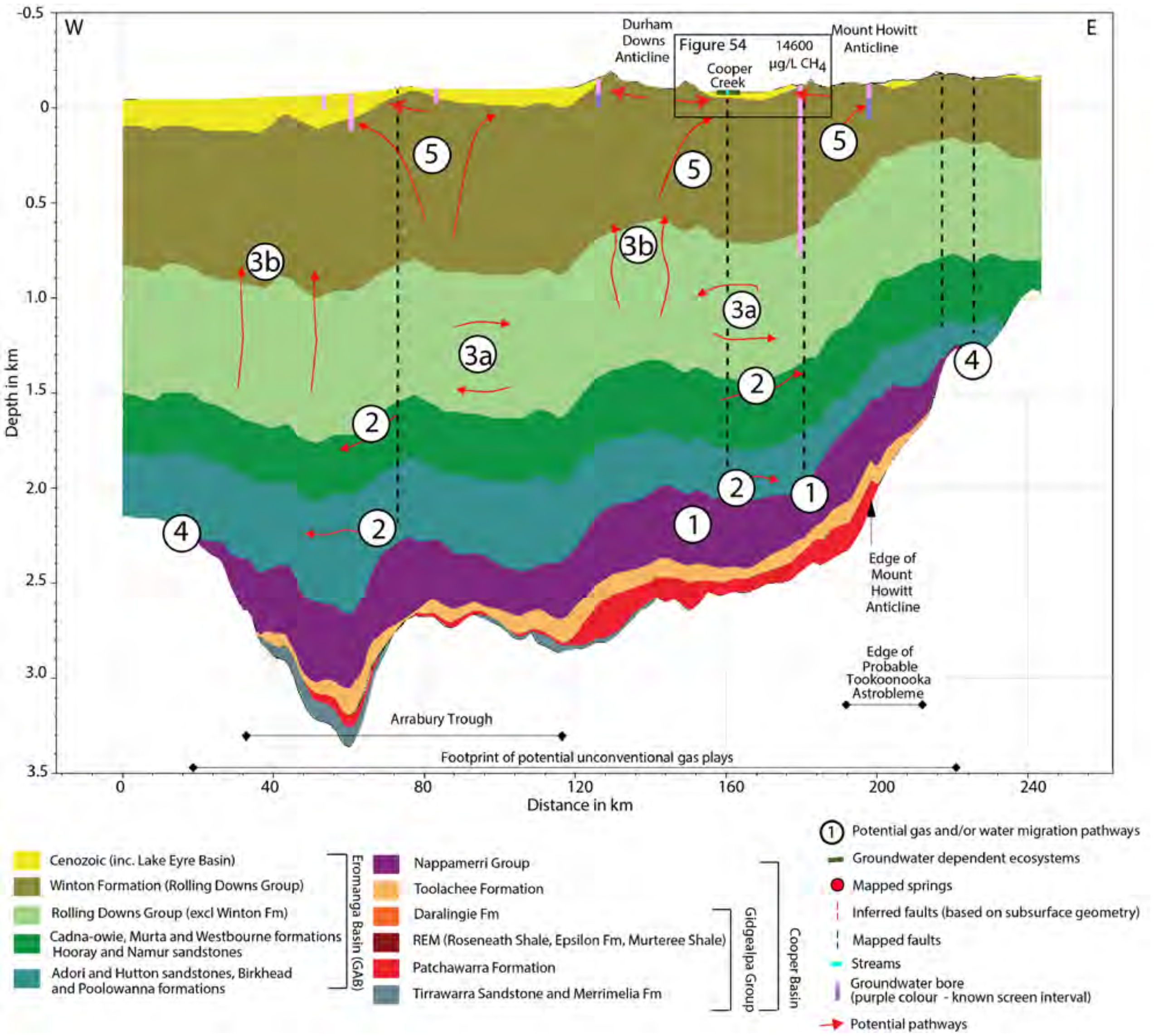

Figure 51 Cross-section 2, with north-west–south-east orientation, representing likely geological structural control of Cooper Creek alluvium, very high concentration of methane in a groundwater bore at the centre of Packsaddle Ridge and five potential hydrological connections for water or gas migration

The five potential hydrological connections are: 1. vertical migration via dilation faults; 2. migration through porous aquifers; 3. migration through the Rolling Downs Group aquitard via PFS (a – lateral; b – vertical); 4. migration due to contact between gas plays and overlying aquifers near the basin margin; and 5. vertical migration at catchment constrictions where steep hydraulic gradients exist between alluvial aquifers and underlying Great Artesian Basin formations. Refer to Figure 54 for detailed view of cross-section.

Data: Geoscience Australia (2008c, 2013, 2018b); Department of Environment and Science (Qld) (2018c); Bureau of Meteorology (2017); Department of Environment, Water and Natural Resources (SA) (2012); three-dimensional geological model from Hall and Palu (2016); Geological and Bioregional Assessment Program (2018c)

Element: GBA-COO-2-098

② Migration through porous aquifers

The hydrochemical assessment of data from 390 groundwater bores and 14 spring samples (Figure 52 and see Evans et al. (2020)) suggests there are six distinct clusters with median electrical conductivity (EC) values ranging between 528 to 16,065 µS/cm; and median bore depths varying from approximately 50 to 1300 m below ground surface, along with distinct ionic ratios, were identified (Figure 52). Hydrochemical records from the Hooray Sandstone (61 samples) were predominantly assigned to clusters 1 and 2. Both of these clusters are characterised by high HCO3/Cl ratios, low Ca and Mg, high Na (Figure 52), relatively high F and low SO4, and are relatively fresh (528 and 2010 µS/cm, respectively). Most samples assigned to clusters 1 and 2 were collected from deep bores (median bore depth of 900 and 1303 m below ground surface, respectively). Only two samples were available from the Hutton Sandstone and the Patchawarra Formation and both were assigned to cluster 1. Most of the Winton-Mackunda formations samples (a total of 169 samples) were assigned to clusters 3, 4 and 6. These clusters differ from clusters 1 and 2 by having shallower median bore depth (maximum of 128 m) and a dominance of Cl over HCO3, higher Ca and Mg, lower F and higher SO4. Similar characteristics can be observed in samples collected from Cenozoic units, which are mostly assigned to clusters 1 to 4. The cluster analysis indicates a relatively clear distinction between hydrochemistry of deep GAB units and the shallower GAB units. However, as deep and shallow bores are, in most instances, not sampled from the same area as multi-level bores, this does not necessarily provide evidence for or against a potential hydrological connection, and more observations are needed. Likewise, hydrochemistry suggests that the Cenozoic aquifers are hydrochemically distinct from the artesian GAB aquifers (e.g. Hooray Sandstone) yet have some similarity with Winton-Mackunda partial aquifer. Hydrochemistry and water level data suggest there is a reasonable degree of connectivity between the Cenozoic aquifers and Winton-Mackunda partial aquifer. There is no hydrochemical data on the deeper Cooper Basin water or the surficial groundwater associated with the permanent waterholes, so no inferences can be made on migration of groundwater from the gas plays to the environmental assets. If such a connection exists, it would be an indirect and low-likelihood connection.

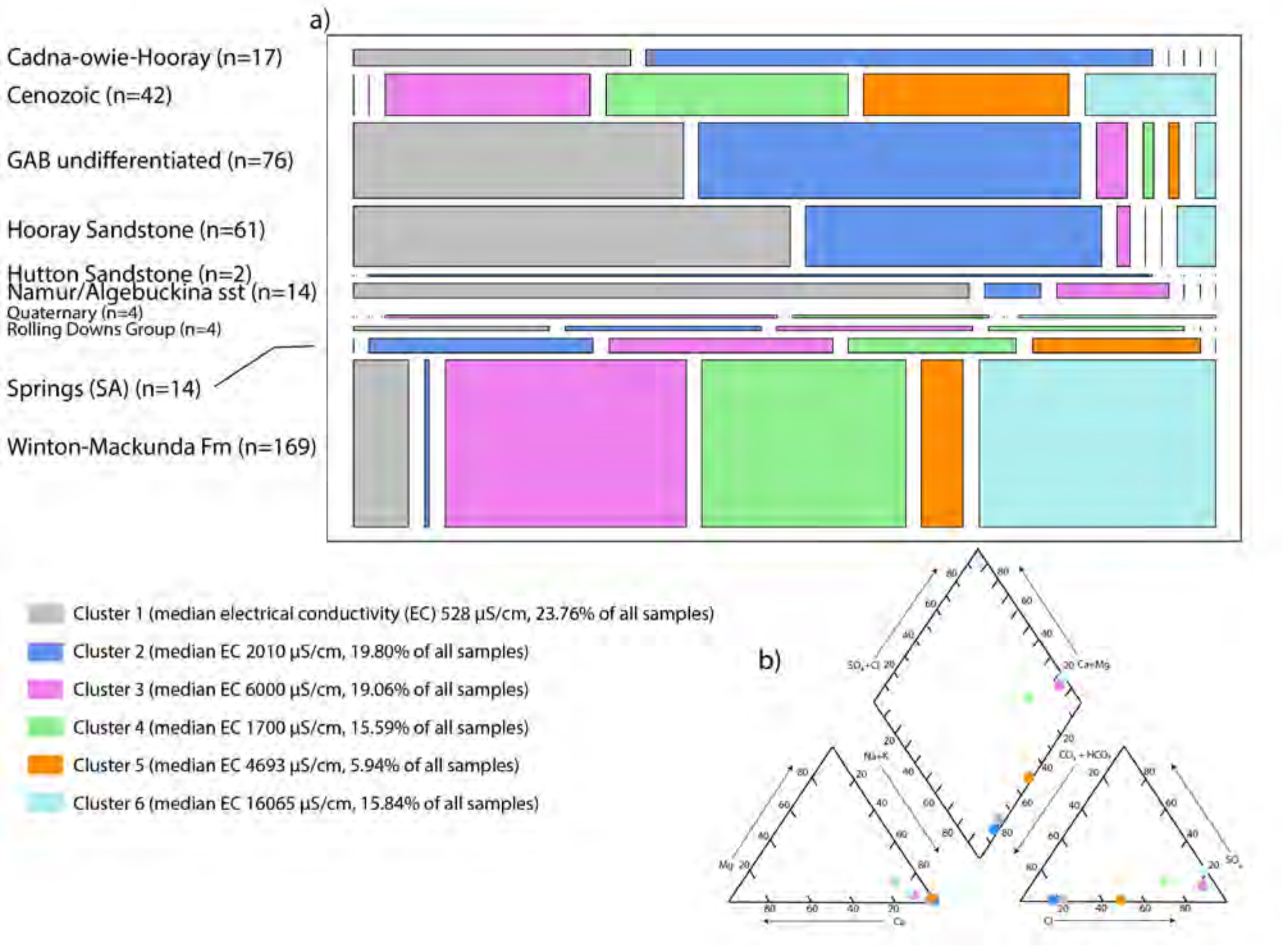

Figure 52 a) Aquifer cluster membership of aquifers b) and Piper plot showing hydrochemical composition of groundwater chemical clusters (based on the median of each cluster) in the Eromanga Basin

(a) The width of the bars represents the relative percentage of groundwater records assigned to each cluster. The numbers in brackets behind the hydrostratigraphic unit correspond to the number of hydrochemical samples for each formation. (b) The Piper plot shows the median concentrations (e.g. Mg + Ca + Na + K) of the different clusters.

EC = electrical conductivity; Fm = formation; GAB = Great Artesian Basin; sst = sandstone

Data: Geological and Bioregional Assessment Program (2019d)

Element: GBA-COO-2-099

③ Migration through partial aquifers/aquitards

Migration through the Rolling Downs Group aquitard via the polygonal fault system could potentially connect GAB aquifers with permeable sections of the Winton-Mackunda partial aquifer. This can induce lateral migration within the Rolling Downs Group (potential hydrological connection 3a) or vertical migration through the Rolling Downs Group aquitard to reach permeable intervals of the Winton-Mackunda partial aquifer (potential hydrological connection 3b) (Table 16). In the Eromanga Basin, the Rolling Downs Group partial aquitard (Evans et al., 2020)) has substantial but variable thickness (Ransley et al., 2015a). Despite its considerable thickness, this entire leaky aquitard sequence may be compromised by pervasive polygonal fault systems that offer potential conduits for vertical leakage. Shallower faulting in the Rolling Downs Group aquitard and Winton-Mackunda partial aquifer does not appear to be coupled with the deeper faults, which is a characteristic of the ubiquitous polygonal fault systems (Nicol et al., 2003; Watterson et al., 2000). The intraformational and pervasive faulting system identified as a polygonal fault system has been described as providing potential pathways for fluid migration in the Rolling Downs Group aquitard by some regional studies conducted in the GAB (Ransley et al., 2015a; Ransley et al., 2015b; Smerdon et al., 2012). Kulikowski et al. (2018) geomechanically modelled the randomly oriented polygonal faults and found that a set of near-vertical dipping north-east or north-west striking faults is likely to be open to fluid flow. Even though the focus of their study was assessing fluid migration, including gases and liquids (both groundwater and hydraulic fracturing fluids), from the lower Cretaceous sediments into shallow Cretaceous sequences, the same pathways could also allow groundwater and gas flow under upward pressure gradient conditions.

The groundwater sample from the Winton-Mackunda partial aquifer, where the highest methane concentration was observed (described in Hydrological connection 1 – Vertical migration via dilation faults) within the study area, is assigned to a cluster of samples with specific hydrochemical properties dominated by hydrochemical records from deep bores (cluster 1), with only 7% of hydrochemistry records within the Winton-Mackunda formations assigned to this group. The combined evidence from methane, hydrochemistry and its location at the edge of the Cooper Basin could also be an indicator for an upward flux from a deeper hydrostratigraphic unit and validates this potential hydrological connection.

The likely uncoupled nature of both deeper faults and polygonal faults may be a possible impediment for direct connectivity pathways to the near-surface unconfined aquifers. This would suggest that it is an indirect and low-likelihood connection from the gas plays to the environmental assets at the surface.

④ Migration due to contact between gas plays and overlying aquifers near the basin margin

A narrow band of Gidgealpa Group rocks is in contact with overlying Eromanga Basin aquifers near the south-western margins of the Cooper Basin (Figure 50 and Figure 53), although this is a long way from the prospective areas for unconventional gas development. Due to their lithological properties, regardless of depth, the Murteree and Roseneath shales (part of the Gidgealpa Group) act as regional aquitards, limiting inter-basinal groundwater flow. Other units, such as the Patchawarra Formation, may contain groundwater and interact to some degree with overlying Eromanga Basin aquifers. Elsewhere, the Cooper Basin subcrop below the Eromanga Basin consists almost entirely of the Nappamerri Group, which is predominantly considered as a leaky aquitard (see hydrogeology technical appendix). Groundwater salinities in the Nappamerri Group have a similar range to that found in overlying artesian GAB aquifers, which suggests there has been some interaction .

While there is some evidence of connectivity at depth between the Eromanga Basin and Gidgealpa Group in the Cooper Basin, the actual areas of connectivity by and large do not coincide with prospective areas for tight, shale and deep coal gas.

Springs in SA have variable groundwater chemistry, with some springs assigned to hydrochemical groups (clusters 3 to 5, Figure 52) that are also linked to shallow GAB aquifers (Winton-Mackunda formations). In addition, groundwater samples from four springs also indicate a hydrochemical signature similar to those samples collected from deeper aquifers (cluster 2), which may indicate some degree of contribution from one or several of these deeper aquifers. As shown by Keppel et al. (2016), these springs have low ^{14}C and low ^{36}Cl values, indicative of very old groundwater, and some of them are located near a fault zone. Together, this could suggest that there is a contribution from deeper aquifers, as proposed by Keppel et al. (2016) and discussed in Section 3.3. Although these springs are likely to have a component of flow from deeper aquifers, they are located some distance away from areas that are prospective for unconventional gas development.

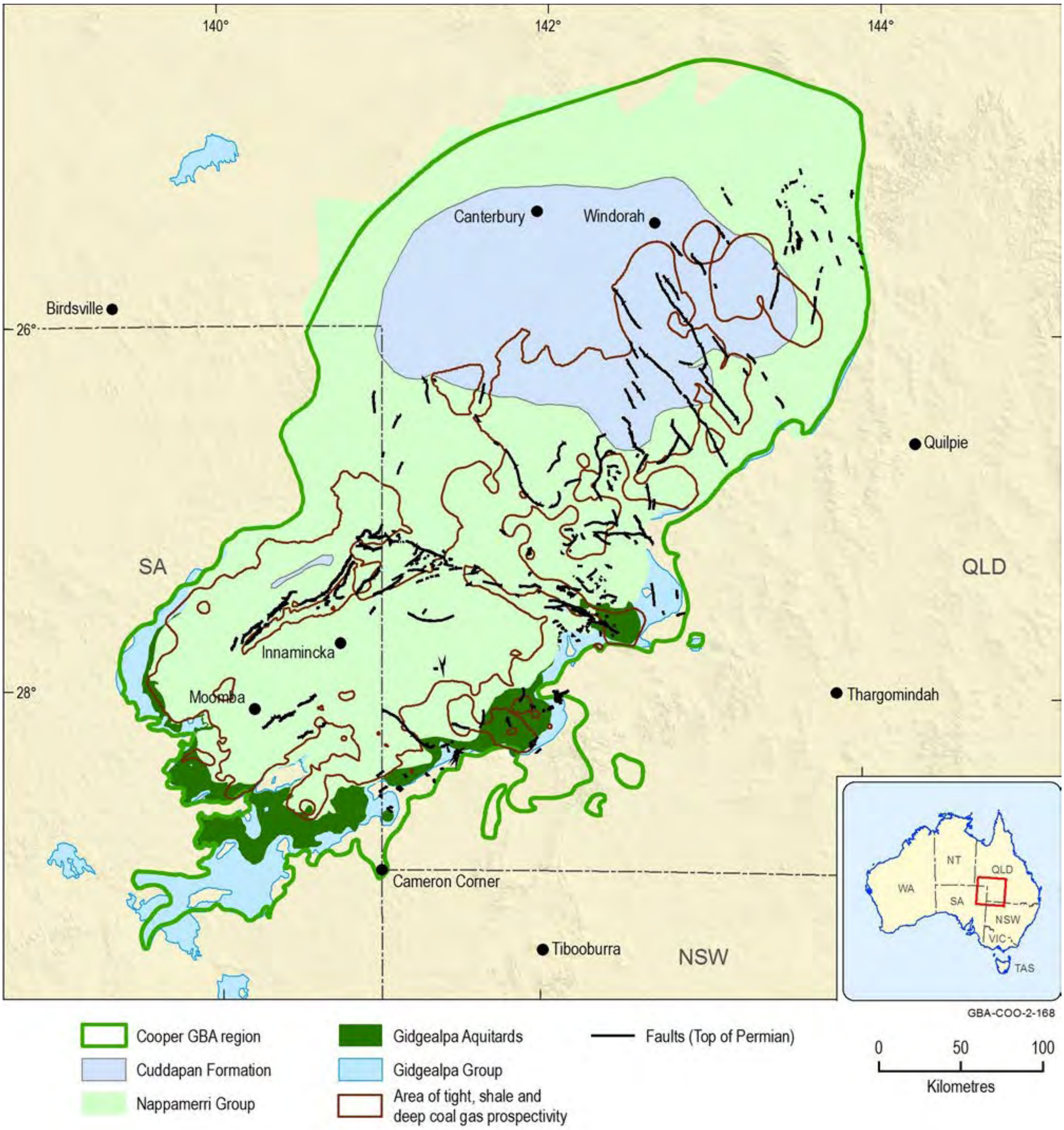

Figure 53 Potential hydrological connectivity due to direct contact between the Cooper and Eromanga basins

The Cuddapan Formation is a partial aquifer between the Eromanga Basin aquifers and the Nappamerri Group leaky aquitard. Roseneath and Murteree shales are regional aquitards in the Gidgealpa Group.
All other units in the Gidgealpa Group subcrop beneath the Eromanga Basin. At shallow levels these units are likely to be water-saturated (unless hydrocarbon accumulations are present). Hence, at these relatively shallow depths (1100-1600 m below surface) and structural setting, much of the Gidgealpa Group subcrop would be classed as partial aquifers as per Smith et al. (2015).
Source: Hall et al. (2015b); Geoscience Australia (2018d, 2019)
Element: GBA-COO-2-168

⑤ Vertical migration at catchment constrictions where steep hydraulic gradients exist between alluvial aquifers and underlying GAB formations

Migration may occur from the Winton-Mackunda partial aquifer and/or Cenozoic aquifers (bedrock) to alluvial aquifers at the edge of the alluvium (near catchment constrictions), where the alluvium pinches out against the hydraulically connected part of the bedrock and where upward pressure gradients are present. The sharp reduction in thickness and width of the alluvial aquifers (and associated GDEs) in the vicinity of the catchment constrictions creates large hydraulic gradients, which means that groundwater levels are more sensitive to hydrological changes than in the wider parts of the alluvial plains. A pressure reduction in the sub-alluvial bedrock due to shallow water extraction for drilling and hydraulic fracturing can result in a rapid response (at timescales of years to decades) of water levels and water quality within shallow aquifers or streams. This could be of concern if areas where shallow aquifers utilised as a groundwater supply are located close to catchment constriction or a waterhole.

Catchment constrictions occur in the mid-catchment of Cooper Creek, such as near the Ticklara - Roseneath Anticline (Figure 50) and Innamincka Dome (Figure 51). These constrictions appear to be structurally controlled, based on the presence of faults (mapped or inferred from subsurface geometry) on both margins of the alluvial aquifers (Figure 54). Catchment constrictions often occur in areas where sub-alluvial bedrock, alluvia and streams are in close proximity (<1 km from each other) as the alluvial systems become considerably thinner and narrower. In the mid-catchment of Cooper Creek, the floodplain narrows significantly from approximately 60 km width upstream to less than 15 km, and aquifer thickness decreases from more than 100 m in the wider alluvial floodplain to 10 to 30 m where it narrows (Figure 54). There is a higher likelihood of connectivity and potential for groundwater and/or gas hydrological connections between sub-alluvial bedrock, alluvia and streams in these areas, as observed in many other catchment constrictions elsewhere (e.g. Condamine River alluvium constriction near Chinchilla in Queensland). As an additional line of evidence on the potential influence of faulting on the architecture and potential connectivity of shallow alluvial systems with sub-alluvial bedrock in this central catchment constriction, the course of Cooper Creek closely coincides with the orientation of a mapped fault over approximately 10 to 15 km (Figure 49). In these catchment constrictions, terrestrial GDEs cover nearly the entire width of the alluvium (Figure 49).

Importantly, Figure 38 highlights that most of the permanent waterholes mapped within the Cooper Creek catchment are located within catchment constrictions and/or close to the edge of the alluvial aquifers, where the alluvium is in close contact with the underlying sub-alluvial bedrock. In contrast, only few of the permanent waterholes are located within the wide alluvial plains where these are over 30 km wide. As shown in Figure 54, in some of these catchment constrictions, reactivated basement faults are likely to have a significant control on the geomorphology and the association of the position of the Cooper River channels in relation to geological contacts. More importantly, the location of the faults here infers the presence of potential hydrological pathways connecting the shallow aquifers (i.e. alluvial aquifer) and the sub-alluvial bedrock units.

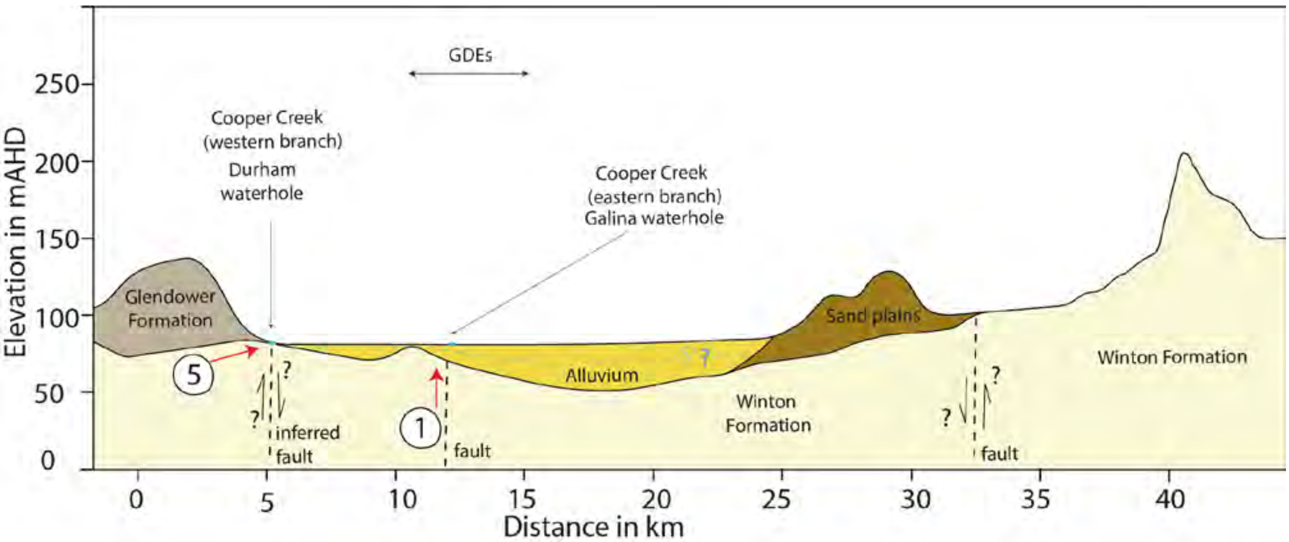

Figure 54 Detailed representation of potential hydrological connection 5 – vertical migration at catchment constrictions in a segment of cross-section 2 (see inset of Figure 51)

Geomorphological and geological frameworks suggest an alternative conceptual representation of surface water – groundwater interactions at waterholes near catchment constrictions. Pathways 1 and 5 are described in Figure 51. The blue dashed line represents inferred watertable.

Data: Geoscience Australia (2008c, 2012, 2018b, 2013)

Element: GBA-COO-2-312

Closer inspection of the shallower aquifer systems (Figure 54) indicates there is more than one possible conceptualisation of the connectivity between waterholes, underlying aquifers and potential sources of water that change with the seasons and cycles of droughts and floods.

Durham Waterhole is on the western branch of Cooper Creek near the geological contact between the Glendower Formation, Winton Formation and the alluvium. While the spatial data is sparse, the regional watertable elevation map for the Winton-Mackunda partial aquifer (Figure 26 of (Evans et al., 2020)) suggests possible interactions with the overlying alluvium. Groundwater flows into the waterhole are predominantly from the alluvium, with additional contributions from the Winton Formation partial aquifer. The western branch of Cooper Creek is incised into the bedrock units (Glendower Formation and Winton Formation), which indicates that the western Cooper Creek channel is potentially controlled by faulting (as inferred in Figure 54).

The Galina Waterhole, on the other hand, associated with eastern branch of Cooper Creek, is located closer to the central parts of a flat but relatively narrow alluvial plain (~20km wide) within a catchment constriction, as previously described. As shown by the inferred shallow watertable, Galina Waterhole may be hydraulically connected to a shallow perched watertable within the alluvium and potentially primarily fed by surface water, similar to the waterholes described by (Cendón et al., 2010) for a site located approximately 50 km south in the Cooper Creek catchment.

An alternative conceptual model could be that groundwater moves vertically via the fault mapped in the Winton Formation underlying the Galina Waterhole (Figure 54). Alternative conceptual models representing waterhole hydraulic gradients based on geomorphology, geology and hydrogeology could identify changing groundwater sources through time. As well, alternative conceptual models can test the effect of groundwater extraction from the shallow alluvial or underlying aquifers (e.g. Winton Formation) in the source aquifer(s) that support the overlying waterholes. Further investigations to test these hypotheses are summarised in Table 16.

Table 16 Summary of potential hydrological connections, potential impacts on water and the environment, evidence base, questions and possible avenues for future investigations in the Cooper GBA region

Potential hydrological connections	Potential impacts on water and the environment	Evidence base	Questions	Possible avenues for future investigations
① Vertical migration via deep-seated dilational faults connecting unconventional gas plays to overlying aquifers	Water bores and springs that access artesian GAB aquifers.	• North–south and east–west striking faults along Gidgealpa–Merrimelia–Innamincka ridges have been modelled to have some dilation tendency (Kulikowski and Amrouch, 2018). • Hydrochemistry and pressure data indicate potential connectivity between Nappamerri Group and the lower GAB aquifer.	• What is the likelihood for vertical fluid or gas migration through deep-seated faults from unconventional gas plays to overlying aquifers and near-surface assets?	**GBA Stage 3** • Use analytical model scenarios to determine time frames and potential for fluid migration and pressure changes through Nappamerri Group and Rolling Downs Group aquitards. **Future** • Collate and assess borehole image logs from oil and gas wells to analyse in-situ stress orientations. • Update the three-dimensional geological model to incorporate faults. • Determine areas where aquifers are displaced against aquitards.
② Lateral migration through porous GAB aquifers and Winton-Mackunda partial aquifer	Water bores tapping the GAB aquifers and Winton-Mackunda partial aquifer.	• Hydrocarbon shows are reported to occur in certain Eromanga Basin units that host GAB aquifers.	• To what extent can water and/or gas migrate laterally through GAB aquifers?	**GBA Stage 3** • Carry out hydrochemical and isotopic fingerprinting of groundwater and dissolved gases at representative bores in different hydrostratigraphic units for inter-aquifer connectivity assessment and surface water – groundwater interaction, including helium, methane and tracers such as $^{87}Sr/^{86}Sr$.
③a) Lateral migration through the Rolling Downs Group aquitard via polygonal fault system (PFS)	Not directly.	• Not available.	• Can this correspond to an actual hydrological connection between deeper and shallower aquifer systems via faults? • How effective is the Rolling Downs aquitard as a barrier to fluid movement?	**Future** • Carry out targeted sampling for environmental tracers in the Rolling Downs Group to better understand lateral connectivity.
③b) Vertical migration through the Rolling Downs Group aquitard via PFS reaching permeable intervals of the Winton-Mackunda partial aquifer	Water bores in the Winton-Mackunda partial aquifer.	• Hydraulic upward flow from underlying GAB aquifer (Smerdon et al., 2012).	• Is there evidence to confirm that fluids or gases migrate vertically and horizontally through the Rolling Downs Group aquitard due to the influence of the polygonal faulting?	**GBA Stage 3** • Use analytical model scenarios to determine time frames and potential for drawdown to migrate through the Rolling Downs Group aquitard to the Winton-Mackunda partial aquifer. • Carry out targeted sampling for environmental tracers in the Winton-Mackunda partial aquifer, Lake Eyre Basin, surface water and/or trees to better understand the hydraulic connections at shallow depths as well as with artesian GAB aquifers, which underlie the Rolling Downs Group aquitard. **Future** • Carry out a sampling campaign to constrain the sources of springs in the Queensland part of the Cooper Basin, in proximity to mapped faults.

Potential hydrological connections	Potential impacts on water and the environment	Evidence base	Questions	Possible avenues for future investigations
④ Migration due to contact between gas plays and overlying aquifers near the basin margin (due to the top of the Nappamerri Group pinching out and/or through inferred fault zones associated with basement highs).	Springs fed by GAB aquifers in the south (Lake Blanche Springs) and GDEs associated with lakes in the south (e.g. Lake Blanche). Impacts from shale, tight and deep coal developments would be quite indirect, as these types of plays occur in the Cooper Basin, and not the Eromanga Basin.	• Hydrological connections inferred from subsurface geometry as shown in cross-sections 1 (Figure 50) and 2 (Figure 51). • Potential contributions from deep GAB aquifers to springs in SA inferred from hydrochemistry data (Figure 52). • Migration due to contact between gas plays and overlying aquifers near the basin margin.	• How can hydrocarbon compounds associated with GAB aquifers be distinguished from hydrocarbons associated with unconventional gas plays if detected in an asset (e.g. springs)? • How can GAB groundwaters that feed spring complexes in the south-west Cooper Basin be differentiated from Patchawarra Formation groundwaters? • Is there any contribution from GAB groundwaters to springs in Queensland?	**GBA Stage 3** • Use analytical model scenarios to determine time frames and potential for fluid migration and pressure changes through Nappamerri Group and Rolling Downs Group aquitards. **Future** • Use oil and gas production well chemistry data to update the multi-variate statistical analysis to identify connections between deep reservoirs and shallower aquifers. • Carry out targeted sampling for environmental tracers at springs to better understand the hydraulic connection and define groundwater flow paths of GAB aquifers in the vicinity of the springs. • Environment tracers, including noble gases such as helium, could detect contributions to springs in Queensland from deeper aquifers. These springs are not a priority, as they are located outside the prospective areas.
⑤ Vertical migration at catchment constrictions where steep hydraulic gradients exist between alluvial aquifers and underlying GAB formations.	Impacts due to extracting water, particularly from Winton-Mackunda partial aquifer and Lake Eyre Basin.	• GAB discharges into Cenozoic along fault-controlled drainage in the north-east Cooper Basin (Kellett et al., 2012).GAB discharges into Cenozoic along fault-controlled drainage in the north-east Cooper Basin (Kellett et al., 2012) • Potential contributions from deep GAB aquifers to springs in SA inferred from hydrochemistry data (Figure 52).	• Is there sufficient evidence to confirm that mapped springs in Queensland are not supplied by GAB aquifers despite their close proximity to faulting zones mapped near the basin margins? • Are the faults mapped in the GAB and underlying hydrostratigraphic units potentially extending to permeable zones near the surface, including the Winton-Mackunda, Cenozoic, alluvial aquifers and streams? • Is it proposed that the mapped GDEs will rely on perched watertables integrating the alluvial aquifer system or are they connected to more regional watertable? • Is there evidence to eliminate a potential hydraulic connectivity between the permeable intervals of the Winton-Mackunda partial aquifer with the overlying alluvial aquifer?	**GBA Stage 3** • Conduct a synoptic surface water chemistry and tracer survey along the permanent waterholes of Cooper Creek during no flow conditions to assess surface water–groundwater interactions. • Carry out targeted sampling for environmental tracers in the Winton-Mackunda partial aquifer, Lake Eyre Basin, surface water and/or trees to better understand the hydraulic connection. **Future** • Carry out shallow geophysical survey (e.g. transient electromagnetics (TEM)) to locate and characterise structural elements in the top 100 m near sensitive environmental assets. • Reassess two- and three-dimensional seismic lines and refine the fault zone architecture, offsets and juxtaposition analysis. • Carry out hydrochemical and isotopic fingerprinting of springs in Queensland. Note that springs in Queensland occur outside the prospective area.

GAB = Great Artesian Basin; GDE = groundwater-dependent ecosystem; PFS = polygonal fault system

3.5 Knowledge gaps

3.5.1 Potential water sources for drilling and hydraulic fracturing

The aquifers in Lake Eyre Basin sequences and the Winton-Mackunda formations are likely to be a major source of water for drilling and hydraulic fracturing. Knowledge gaps affecting management and use of these aquifers include the following:

- Baseline groundwater monitoring bores and time-series water level and salinity data are sparse in the Cenozoic and Winton-Mackunda aquifers. Additional baseline data would improve analysis of conceptualisation and the potential for future impacts.
- Hydraulic properties of the Cenozoic and Winton-Mackunda aquifers are poorly understood.
- The lateral and vertical extent of the 'deep' Cenozoic aquifer (below 60–80 m), which has better quality water than the 'shallow' Cenozoic aquifer, may consist of discrete aquifer units or be part of a more ubiquitous groundwater system.
- Recharge to the deeper Cenozoic aquifer system may represent paleo-recharge or recharge due to episodic flooding. Environmental tracers can distinguish between possible recharge sources and better characterise aquifer processes.

3.5.2 Potential hydrological connections

The nature of the hydrological connection (if any) between the Cooper Basin, Eromanga Basin, Lake Eyre Basin and surface water system is poorly understood. In particular:

- The potential for vertical migration of fluids and gas via deep-seated dilation faults connecting the unconventional gas plays to overlying Eromanga Basin aquifers and associated lateral flow is poorly constrained due to a limited regional knowledge of the fault systems.
- There is insufficient evidence to rule out possible lateral and vertical fluid migration through the Rolling Downs Group partial aquitard from the Eromanga Basin to the Lake Eyre Basin due to polygonal faulting because of insufficient data on pressure, hydrochemistry, isotopes and methane concentrations.
- Very few of the permanent waterholes have been studied for a potential connection to the regional groundwater system. Multiple conceptual models are possible and tracer studies and physical measurements can provide data to improve the conceptualisation.

3.5.3 Surface water system

The permanent waterholes of the Cooper Creek floodplain are the water-related environmental asset that the community values most highly (as explained by the user panel). It is not known what impact surface infrastructure could potentially have on the flooding regime of these waterholes:

- An appropriately high-resolution digital elevation model, coupled with a hydrodynamic flood inundation model, would enable potential impacts from surface infrastructure to be assessed.
- In combination with remotely sensed ecohydrological information, a flood inundation model could also inform an improved understanding of water regime changes over time that support vegetation on the floodplains and along river channels and the spatial distribution of flow velocities that are important for aquatic flora and fauna.

4 Protected matters

The environmental and cultural baseline syntheses identify Matters of National Environmental Significance (MNES) and Matters of State Environmental Significance (MSES) (protected matters), as well as key threatening processes identified under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act) that are relevant to the region. The key ecological and hydrological systems are conceptualised into landscape classes to underpin the assessment of potential hydrological and other environmental impacts due to shale, tight and deep coal gas development in Stage 3.

4.1 *Environmental baseline synthesis*

MNES in the Cooper GBA region include a Ramsar-listed wetland (Coongie Lakes) and 26 taxa (plants, reptiles, birds and mammals) listed as threatened (critically endangered, endangered or vulnerable). The threatened ecological community 'The community of native species dependent on natural discharge of groundwater from the Great Artesian Basin' is located outside of the region but is likely to be hydrologically connected to groundwater in the region. The Lake Eyre Basin Intergovernmental Agreement recognises the Cooper Creek system and its tributaries.

There are eight nationally important wetlands in the Cooper GBA region: (i) Bulloo Lake; (ii) Coongie Lakes; (iii) Cooper Creek – Wilson River Junction; (iv) Cooper Creek Overflow Swamps – Nappa Merrie; (v) Cooper Creek Overflow Swamps – Windorah; (vi) Lake Cuddapan; (vii) Lake Yamma Yamma; and (viii) the Strzelecki Creek Wetland system.

MSES in Queensland include 28 species listed as endangered, near threatened, vulnerable or special least concern. In SA, 17 species are listed as endangered or vulnerable. The region contains areas of significant environmental value, including protected areas, High Ecological Value Aquatic Ecosystems (HEVAE) and regional ecosystems listed as 'of concern' in Queensland. The floodplains of Cooper Creek are recognised as a strategic environmental area in Queensland. The region also contains important wetlands and groundwater-dependent ecosystems that are not recognised as MNES or MSES. These include springs, waterholes and groundwater-dependent wetlands and terrestrial vegetation that may be impacted by shale, tight and deep coal gas resource development.

4.1.1 Matters of National Environmental Significance

MNES are Australia's national environmental assets as defined in the EPBC Act. MNES that occur in the Cooper GBA region that may potentially be impacted due to shale and tight gas developments are identified for further assessment.

The EPBC Act protected matters for the Cooper GBA region in Queensland and SA (using the online search reporting tool: http://www.environment.gov.au/epbc/pmst/index.html) identified one Ramsar-listed wetland, eight nationally important wetlands and 39 species that are known, likely or may occur in the region. This includes 26 taxa (plants, reptiles, birds and mammals) listed as 'threatened' (critically endangered, endangered or vulnerable), one threatened species listed as 'migratory' and 'marine' and one threatened species listed as 'marine'. A further 13 species occur, or potentially occur, in the Cooper GBA region and are listed under the EPBC Act but are not listed as threatened (Table 17). These include ten species listed as both migratory and marine and four species listed as marine. The search also identified a site listed as national heritage.

MNES were identified in an EPBC Act protected matters search for the Cooper GBA region run by the Australian Government Department of the Environment and Energy on the 18 March 2018. Searches were run separately for the Queensland and SA portions of the Cooper GBA region and combined to create a unified list of nationally protected matters. MSES included species listed under state legislation, protected areas and as heritage sites. In addition to these, the MSES assets were regulated vegetation (in Queensland) and groundwater-dependent ecosystems.

4.1.1.1 Wetlands of international significance

The Cooper GBA region contains one wetland of international significance. The Ramsar-listed Coongie Lakes is located in the north-east corner of SA near the township of Innamincka (Figure 55). The site includes the Cooper Creek system from the SA border downstream to Lake Hope, the north-west branch of Cooper Creek, the northern Overflow and their many waterholes and terminal lakes covering an area of almost 19,800 km^2. A detailed description of the ecological character of these sites is presented by Butcher and Hale (2011).

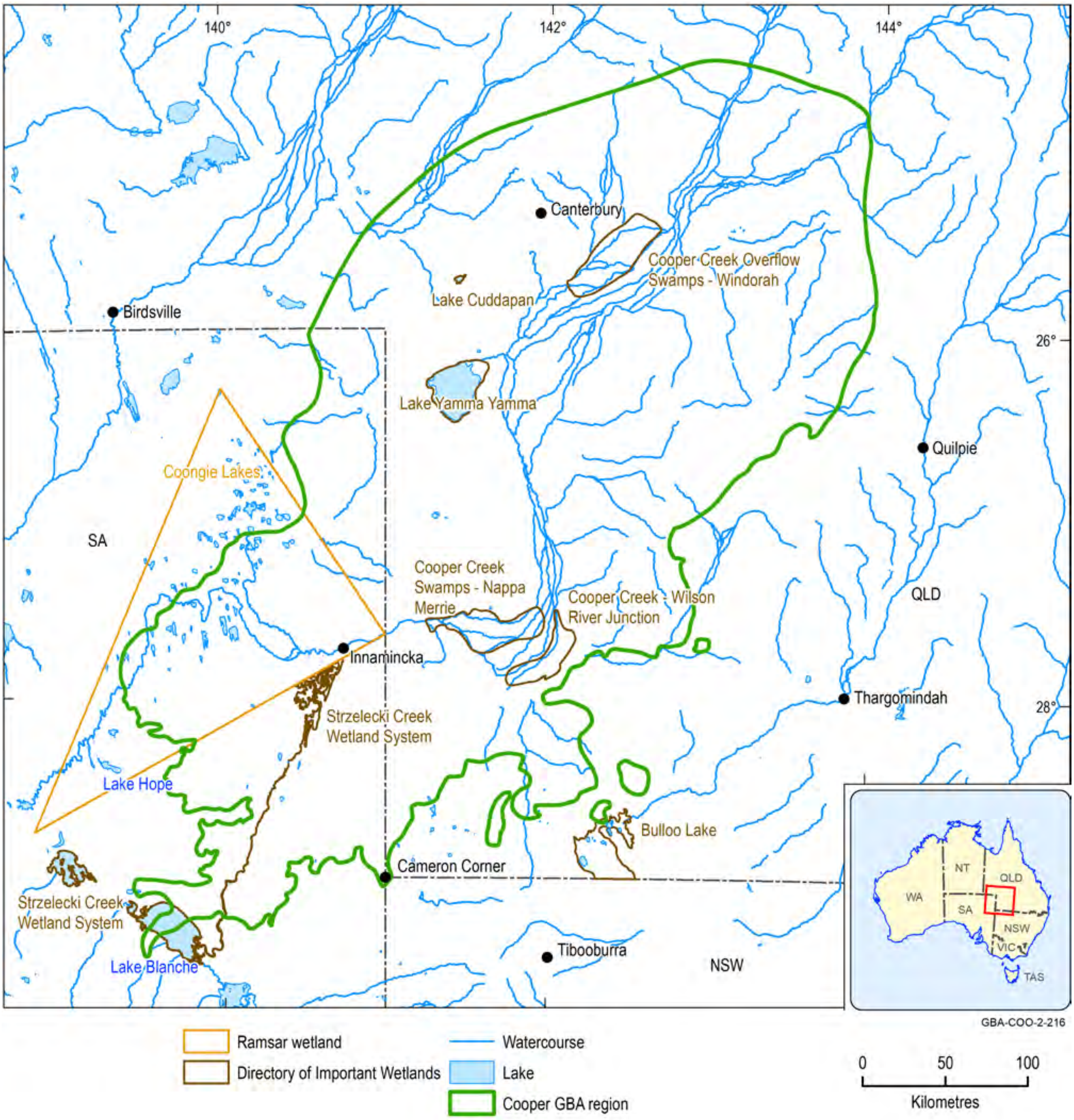

Figure 55 Wetlands of international and national significance in the Cooper GBA region

Dataset: Department of the Environment and Energy (2018b); Department of the Environment and Energy (2010)
Element: GBA-COO-2-216

4.1.1.2 Nationally listed threatened species and communities

In total, 26 taxa are listed as threatened (critically endangered, endangered or vulnerable) and include plants, reptiles, birds and mammals (Table 17). No invertebrates or frogs that are listed as threatened under the EPBC Act occur, or are likely to occur, within the Cooper GBA region. Two subspecies of bar-tailed godwit (*Limosa lapponica*) are listed separately as threatened under the EPBC Act: one is critically endangered (*L. l. menzbieri*); the other is vulnerable (*L. l. baueri*). The bar-tailed godwit is listed as migratory and marine only at the species level.

Each of the 26 threatened taxa is described in the protected matters technical appendix (O'Grady et al., 2020). The appendix provides an overview of the ecology, distribution and status of the taxon, followed by an assessment of its water dependency and a comment on the hazards associated with shale, tight and deep coal gas developments that may impact the conservation status of the taxon.

In addition to these species, 13 species listed as marine and/or migratory were identified in the Cooper GBA region. Each of these species is listed as 'least concern' on the International Union for Conservation of Nature (IUCN) red list of threatened species. These have a large global population and widespread distribution in Australia.

No threatened ecological communities were identified within the Cooper GBA region. Springs belonging to the threatened ecological community 'The community of native species dependent on the natural discharge of groundwater from the Great Artesian Basin' occur at Lake Blanche (Figure 47), outside of the Cooper GBA region, but are likely to be hydrologically connected to groundwater in the region (Sparrow et al., 2015); therefore, they are considered herein.

4.1.1.3 Other matters not protected by the EPBC Act

The Cooper Creek system, including the Thomson and Barcoo rivers and their tributaries, are identified specifically in the Lake Eyre Basin Intergovernmental Agreement. The agreement recognises that future prosperity in the region is contingent on the continued health and functioning of this system, which is internationally recognised as an outstanding example of an unregulated, low-gradient, dryland river system (Kingsford et al., 1999).

The directory of important wetlands lists eight wetlands in the Cooper GBA region: (i) Bulloo Lake; (ii) Coongie Lakes; (iii) Cooper Creek – Wilson River Junction; (iv) Cooper Creek Overflow Swamps – Nappa Merrie; (v) Cooper Creek Overflow Swamps – Windorah; (vi) Lake Cuddapan; (vii) Lake Yamma Yamma; and (viii) Strzelecki Creek Wetland System (Figure 55).

The listed nationally and internationally important wetlands in the region are all hydrologically connected to the Cooper Creek system.

Table 17 Matters of National Environmental Significance that occur, or potentially occur, in the Cooper GBA region

Listing	Category	Status	Number
EPBC listed threatened species	Bird	Critically endangered	3
EPBC listed threatened species	Bird	Endangered	4
EPBC listed marine species	Bird	Marine species	4
EPBC listed migratory species	Bird	Migratory species	10
EPBC listed threatened species	Bird	Vulnerable	3
EPBC listed threatened species	Fish	Vulnerable	2
EPBC listed threatened species	Mammal	Vulnerable	7
EPBC listed threatened species	Plant	Endangered	1
EPBC listed threatened species	Plant	Vulnerable	4
EPBC listed threatened species	Reptile	Vulnerable	2
EPBC listed threatened ecological community	Community	Endangered	1
Ramsar Convention	Wetland	Listed	1
National Heritage	Land	Heritage	1
Other matters not protected by the EPBC Act			
Directory of Important Wetlands of Australia	Wetland	Listed	8
Lake Eyre Basin Intergovernmental Agreement	Wetland	Listed	2
Total			**53**

Data: Asset dataset (Geological and Bioregional Assessment Program, 2019a)

4.1.2 Matters of State Environmental Significance

Queensland MSES focus on threatened species and areas of environmental values (e.g. HEVAEs or regional ecosystems) that are protected under Queensland legislation. The *Nature Conservation Act 1992* (Qld) (which includes the *Nature Conservation (Wildlife) Regulation 2006*) identifies wildlife that is 'extinct in the wild', 'endangered', 'vulnerable', 'near threatened' and 'least concern' and 'special least concern'. In SA, the *National Parks and Wildlife Act 1972* identifies wild threatened species in four Schedules: 'endangered' (Schedule 7), 'vulnerable' (Schedule 8), 'rare' (Schedule 9) and 'unprotected species' (Schedule 10). The latter is not of concern for the GBA Program. MSES are summarised in Table 18.

The component of the Cooper Creek system in Queensland is listed as a strategic environmental area under the *Regional Planning Interests Act 2014* (Qld). Three protected areas occur in the Cooper GBA region: Welford National Park, Innamincka regional reserve and the Strzelecki regional reserve. In addition, 24,806 km^2 of the region is identified as a strategic environmental area under the *Regional Planning Interests Act 2014* (Qld).

Eight of the 81 regional ecosystems classified by Queensland that occur in the region are considered to be 'of concern'. The Cooper GBA region also contains springs and groundwater-dependent ecosystems that are not listed as MSES but may be impacted by shale, tight and deep coal gas resource development.

Table 18 Matters of State Environmental Significance that occur, or potentially occur, in the Cooper GBA region

Listing	Category	Status	Number
Queensland listed threatened species	Birds	Vulnerable	2
	Birds	Endangered	2
	Birds	Special least concern	10
	Mammals	Vulnerable	3
	Mammals	Endangered	3
	Mammals	Special least concern	1
	Plants	Vulnerable	4
	Plants	Near threatened	2
	Reptiles	Vulnerable	1
Queensland protected area	Land	Regulated habitat	6
Queensland regional ecosystem	Vegetation community	Of concern	8
South Australia listed threatened species	Birds	Vulnerable	4
	Birds	Extinct or Endangered	3
	Mammals	Vulnerable	4
	Plants	Vulnerable	4
	Plants	Extinct or Endangered	1
	Reptiles	Vulnerable	1
South Australia groundwater-dependent ecosystem (GDE)	GDE database	na	1
South Australian protected area	Land	Regulated habitat	3
Total			**63**

na = not applicable
Source: Asset dataset (Geological and Bioregional Assessment Program, 2019a)

4.1.3 Threatening processes with potential to impact species

Key threatening processes identified under the EPBC Act that are relevant to the Cooper GBA region include:

- competition and land degradation by rabbits
- competition and land degradation by unmanaged goats
- land clearance
- loss of climatic habitat caused by anthropogenic emissions of greenhouse gases
- novel biota and their impact on biodiversity (e.g. feral horses, donkeys, camels)
- predation by European red foxes
- predation by feral cats

- predation, habitat degradation, competition and disease transmission by feral pigs
- biological effects, including lethal toxic ingestion, caused by cane toads (*Rhinella marina*).

4.2 Cultural baseline synthesis

The Burke, Wills, King and Yandruwandha National Heritage Place, consisting of several sites along Cooper Creek, is listed under the EPBC Act. The sites along the course of Cooper Creek tell the story of the ill-fated Burke and Wills expedition of 1860 to 1861 and the support provided by the Yandruwandha people.

The Australian Heritage Database lists nine Indigenous sites, 12 heritage sites and two recreational areas located in the Cooper GBA region. Cooper Creek and its associated waterholes have a long and enduring cultural significance and are part of traditional trade routes.

No world heritage-listed or Commonwealth heritage-listed places were identified for the Cooper GBA region. The Burke, Wills, King and Yandruwandha National Heritage Place is the only MNES heritage place in the region and includes several sites located along the course of Cooper Creek on either side of the Queensland–SA border (Figure 57). These sites are listed due to their historical significance – they tell the story of the Burke and Wills expedition and the support provided to it by the Yandruwandha people. Provisions were buried at The Dig Tree on Cooper Creek for Burke and Wills returning from an exploration to the Gulf of Carpentaria – the tree was marked to let the returning explorers find the provisions (Saenger, 2012).

The five expedition sites that make up the national heritage-listed place include:

- **The Dig Tree and Fort Wills Site**, which marks the location of the tragedy that characterises much of the expedition. The inscriptions on the coolibah tree are now mostly obscured.
- **Burke's Tree** and **Wills' Site**, which marks where Burke and Wills respectively died.
- **King's Site**, which is marked by a tree trunk that bears the inscription 'King', blazed many years after the expedition as a reminder of the role played by King and the Yandruwandha people.
- **Howitt's Site**, which marks the camp from where Howitt's relief party discovered King.

In addition to the Burke, Wills, King and Yandruwandha National Heritage Place, nine Indigenous sites, 12 heritage sites and two recreational areas listed in the Register of the National Estate were reported in the water-dependent asset register for the bioregional assessment for the Cooper subregion (Sparrow et al., 2015).

The Cooper GBA region has supported Indigenous cultures for millennia, and communities maintain an ongoing connection to the region. Many of the Cooper Creek waterholes and Cooper Creek itself form part of extensive trading routes throughout Lake Eyre Basin. Cullyamurra waterhole (Figure 56) is an important cultural site and the site of grindstone quarries. Innamincka is also an important Indigenous meeting place comprising an intersection of a number of trade routes (Lake Eyre Basin Community Advisory Committee, 2018).

Figure 56 Cullyamurra waterhole, looking north-west

Credit: Geological and Bioregional Assessment Program, Russell Crosbie (CSIRO), September, 2018
Element: GBA-COO-2-224

Cultural assets listed as MNES were identified in an EPBC Act protected matters search for the Cooper GBA region run on 9 July 2018. The search was run separately for the SA and Queensland portions of the region and combined to create a unified list of nationally protected matters for the Cooper GBA region.

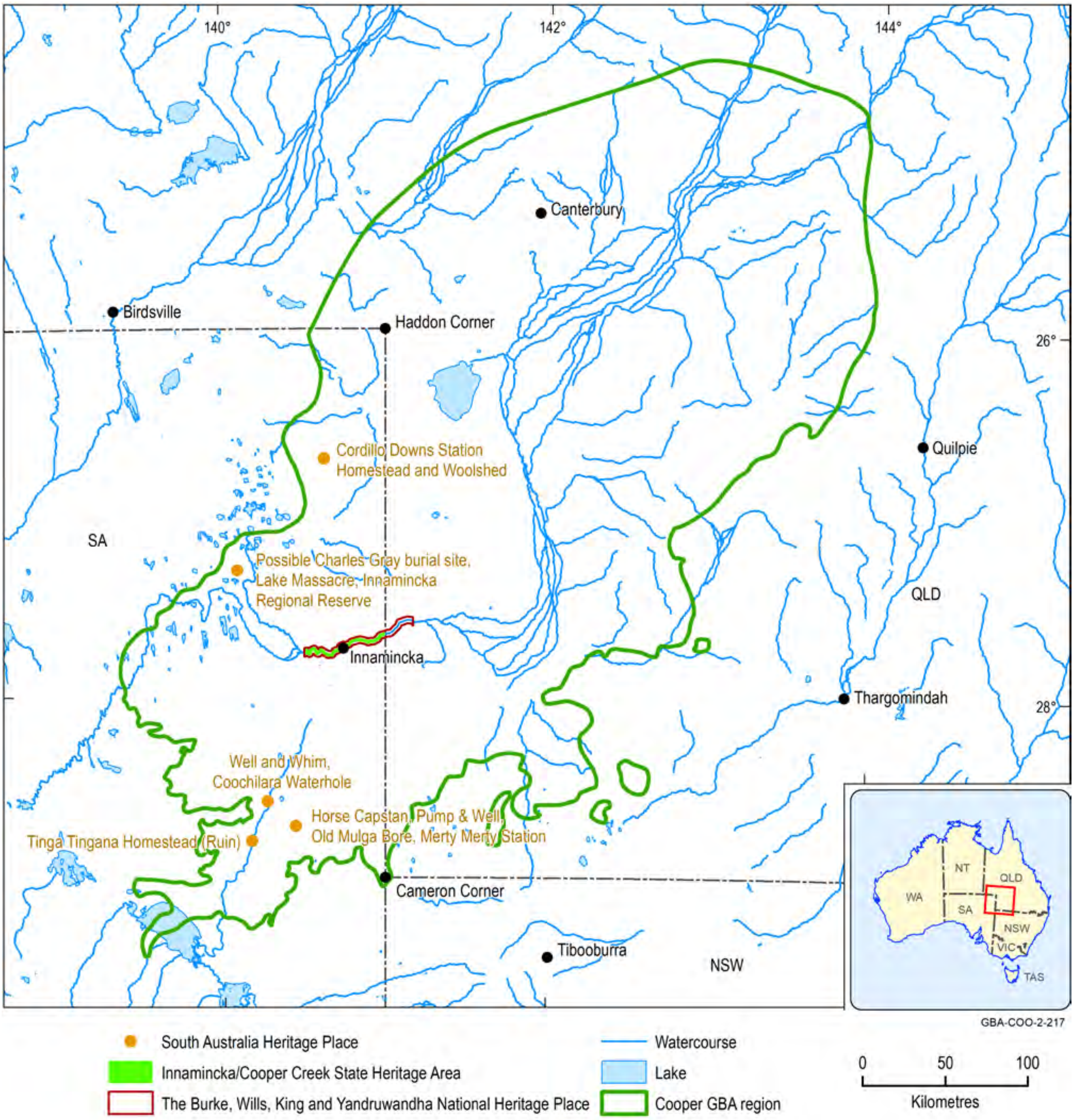

Figure 57 Location of the Burke, Wills, King and Yandruwandha National Heritage Place and other state heritage places along Cooper Creek

Data: Department of the Environment and Energy (2008); Department for Environment and Water (SA) (2019); Department of Planning, Transport and Infrastructure (SA) (2019)
Element: GBA-COO-2-217

4.3 Landscape classification and ecohydrological conceptualisation

Landscape classification categorises the key ecological and hydrological systems in the region. This ecohydrological conceptualisation underpins the assessment of potential hydrological and other environmental impacts due to shale, tight and deep coal gas development at a landscape scale in the Cooper GBA region. Seven landscape classes are identified for the Cooper GBA region. The Cooper GBA region is dominated by floodplain and alluvium, inland dunefields, and undulating country on fine-grained sedimentary rocks. There are smaller areas of loamy and sandy plains, and tablelands and duricrusts, with small areas of clay plains and some springs.

Conceptually, landscape classes can be considered as bundles of ecosystem assets (Bureau of Meteorology, 2013; United Nations et al., 2014) that provide ecosystem services that provide benefit to humanity. Landscape classification aims to:

- reduce ecosystem and landscape complexity to a manageable number of regional-scale landscape classes that are mutually exclusive and comprehensive
- guide the development and review of conceptual models
- define the spatial scope of these conceptual models
- where possible, use existing data sources and existing classifications and/or typologies
- provide a natural aggregation for conceptualising and reporting potential impacts
- be applicable to data-poor regions.

A landscape classification approach was used to systematically categorise geographical areas into landscape classes that are similar in physical and/or biological and hydrological character. The methodology for defining landscape classes is based on the Bioregional Assessment Programme’s submethodology M03 for assigning receptors to water-dependent assets (O'Grady et al., 2016), with modifications that reflect the broader purpose of the GBA Program.

The landscape classification developed for the Cooper GBA region (Geological and Bioregional Assessment Program, 2018d) is a harmonisation of the Queensland Land Zones (Wilson and Taylor, 2012) and South Australian Land Systems (Santos, 1997), reflecting the substantial areas of the Cooper GBA region in both states (Table 19, Figure 58). Both land zones and land systems are categories that describe the major geologies, associated landforms and geomorphic processes that result in marked differences in the function of their respective ecosystems and their associated biodiversity. The landscape classification sought to use existing data sources and to leverage the extensive effort already expended to develop the relevant conceptual models at both landscape scale and wetland scale by the Queensland Government as part of its Wetlands Program (Department of Environment and Science (Qld), 2017).

Detailed land zones within the Cooper GBA region developed by the Queensland Government (Department of Environment and Science (Qld), 2018a) were assigned to corresponding landscape classes (Table 19). Land systems in SA were only coarsely mapped in the 1990s; hence, landscape classes for the Cooper GBA region within SA were refined from land systems based on detailed (1:100 K) surface geology (Department for Energy and Mining (SA), 2018c) and elevation (Geoscience Australia, 2008b) data. Landsat TM images (30 m spatial resolution) were also examined to identify the landform and geomorphological context (Neldner et al., 2017).

Table 19 Landscape classes within the Cooper GBA region, and corresponding Queensland Land Zones and South Australian Land Systems

Landscape class (GBA)	Queensland Land Zones [a]	South Australian Land Systems	Area (km^2)
Floodplain and alluvium	Recent Quaternary alluvial systems	Floodplain	41,244
Inland dunefields	Quaternary inland dunefields	Dunefields	39,752
Undulating country on fine-grained sedimentary rocks	Fine-grained sedimentary rocks	Gibber plain	25,986
Tablelands and duricrusts	Cainozoic duricrusts	Tableland	11,813
Loamy and sandy plains	Tertiary-early Quaternary loamy and sandy plains and plateaus	na	11,189
Clay plains	Tertiary-early Quaternary clay plains	na	21
Springs	na	na	na
Total			**130,005**

na = not applicable

[a] Typology and punctuation are consistent with Queensland Land Zones (Wilson and Taylor, 2012), which refer to Cainozoic and Tertiary-aged sediments.

Dataset: Geological and Bioregional Assessment Program (2018d); Santos (1997); Department of Environment and Science (Qld) (2018a)

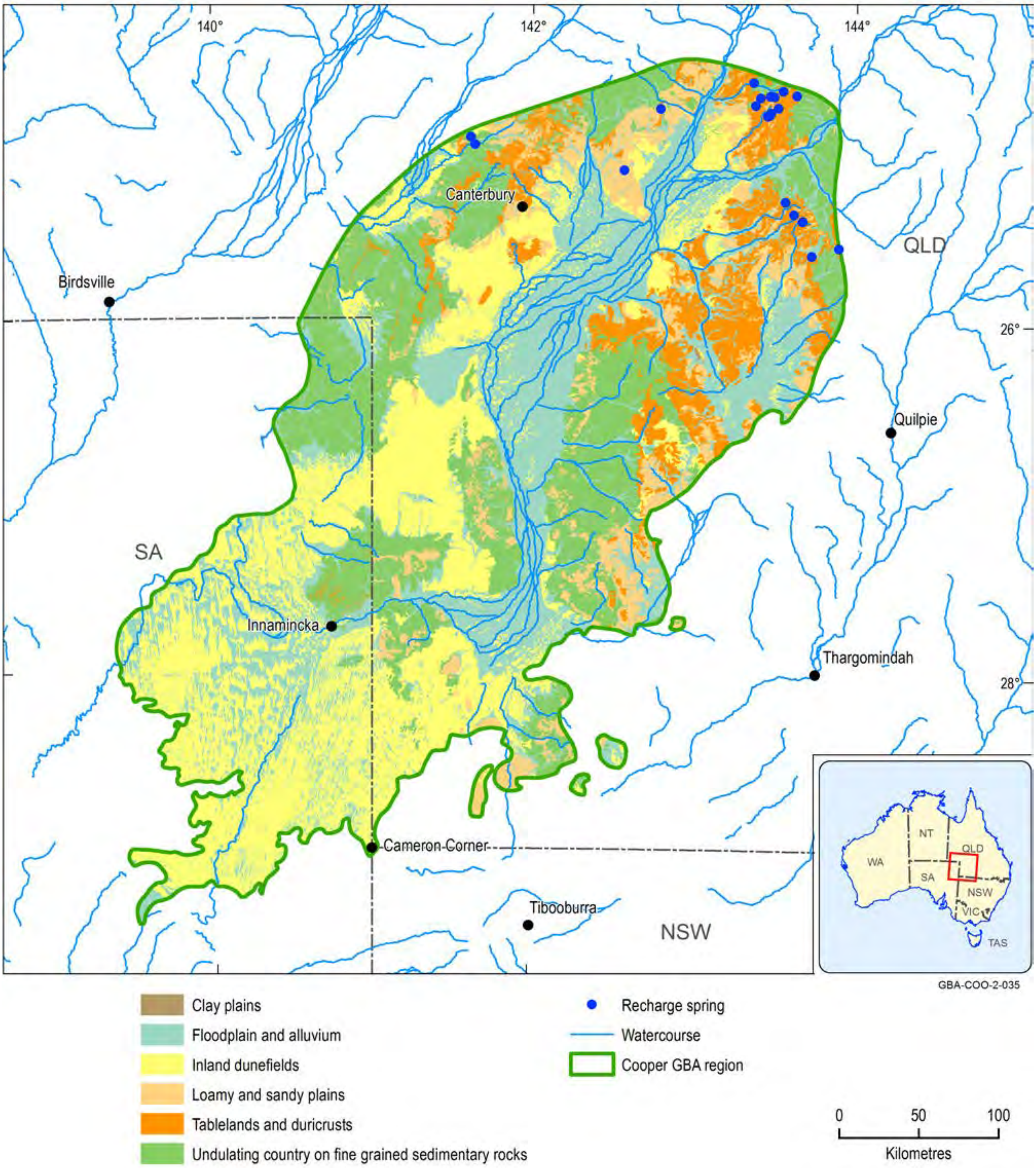

Figure 58 Landscape classes within the Cooper GBA region

Data: Geological and Bioregional Assessment Program (2018d)
Element: GBA-COO-2-035

General descriptions of the landscape classes, along with preliminary ecohydrological conceptual models that describe their structures (e.g. geology, landform, biota) and processes (e.g. hydrology) are in the following section. The preliminary ecohydrological conceptualisation of the Cooper GBA region (see the protected matters technical appendix (O'Grady et al., 2020)) is based on landscape-scale and wetland-scale conceptual models developed by the Queensland Government as part of its Wetlands Program (Department of Environment and Science (Qld), 2017), with the exception of the 'Springs' landscape class, which is based on (Fensham et al., 2016).

4.3.1 Description of landscape classes

4.3.1.1 Floodplain and alluvium

Floodplain and alluvium areas derived from Quaternary alluvial deposits are the most extensive landscape class within the Cooper GBA region, occupying 41,244 km^2 (Table 19). Floodplains are areas of the landscape that occur between a river system and the enclosing valley walls and are exposed to during periods of high discharge (Rogers, 2011). Floodplains are considered to be alluvial plains that experience channelled or overbank streamflow at least once every 50 years (Aquatic Ecosystems Task Group, 2012). The floodplain of Cooper Creek exceeds 60 km at its widest point and is very broad on the Cooper Plain from Windorah to its entrance into the east of the Innamincka Dome. This complex anastomosing or braided system of channels is known as 'Channel Country' (Figure 59).

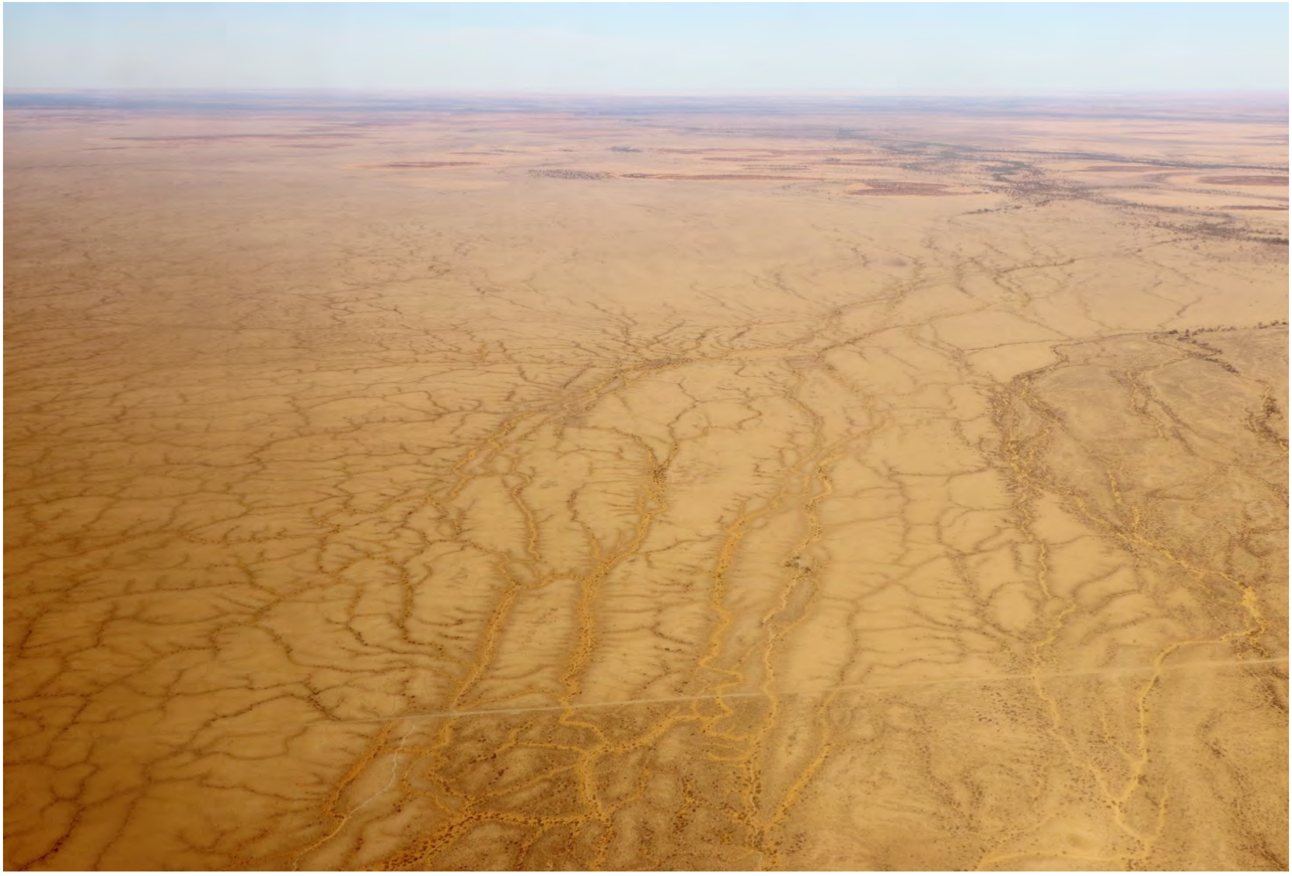

Figure 59 'Channel Country'

Credit: Geological and Bioregional Assessment Program, Russell Crosbie (CSIRO), September, 2018
Element: GBA-COO-2-223

While much of the floodplain supports terrestrial vegetation that is not groundwater-dependent and relies on localised rainfall, there are also extensive areas of palustrine and lacustrine wetlands on floodplains in south-west Queensland and west of Innamincka in SA, including salt lakes, which are terminal lakes or pans that result from excess evaporation and the concentration of soluble salts that form a surface crust (Santos, 2015). Palustrine wetlands are primarily vegetated non-channel environments of less than 8 hectares and include billabongs, swamps, bogs, springs, soaks and so on that have more than 30% emergent vegetation. Lacustrine wetlands are large, open, water-dominated systems (e.g. lakes) (Department of Environment and Science (Qld), 2017). Smaller pans may be interconnected and coalesce during floods. Water levels of the lakes fluctuate with episodic flooding of the river systems, but the lakes are predominantly dry. The lakes are typically fringed by chenopod shrubland but may also be bare. Lake Blanche and Lake Gregory to the south of the Cooper GBA region make up most of this landscape class, although smaller salt lakes are scattered throughout the region in SA. Lunette sand dunes may be found along parts of their eastern shores.

Within the Cooper Basin, the alluvium can be broadly divided into four sections from north-east to south-west: (i) the lower Thomson River from Stonehenge to the confluence of the Thomson and Barcoo rivers; (ii) the Cooper Plain from the Thomson/Barcoo confluence to Nappa Merrie; (iii) Cooper Creek within the Innamincka Valley from Nappa Merrie to Innamincka; and (iv) the Cooper Fan from Innamincka to Lake Blanche and Lake Gregory. These sections are briefly described below.

Lower Thomson River

The physical characteristics of the valleys of the lower Thomson River differ from those of the Cooper Plain (described below). The alluvial valley of the lower Thomson River is relatively narrow (3–10 km) and, although less well studied than Cooper Creek, has been described by Wakelin-King. The valley contains floodplain bars, floodways, channels and waterholes that are strongly confined by steeply sloping hills of erosion-resistant rock of the Eromanga Lowlands physiographic unit, which are capped with gibber and silcrete. Swamps are absent from the lower Thomson River. The anastomosing network of floodways contains one to several main channels and numerous minor channels. Waterholes are channel segments located along primary flow paths that are notably wider and deeper than the primary channels. Channel width is generally less than 30 m, but waterholes may be up to 75 m wide and several kilometres long. Waterhole depth varies, but waterholes that act as key refugia in the system are typically deeper than 4 m.

Cooper Plain

Similar to the lower Thomson River, most of the Cooper Plain is flanked by gibber and silcrete mantled hillslopes, and it has a small gradient (0.015% – 0.019%). However, along the Cooper Plain the river valley is very wide (8–60 km). In addition to floodplain bars, floodways, channels and waterholes, the Cooper Plain also contains numerous swamps (Figure 60). The dominant channel network is an anabranching system of one to four primary channels, together with secondary and minor channels (Knighton and Nanson, 1994b). In general, the channels are narrow and deep, with moderate to steeply dipping banks that lack levees. Waterholes can be wider and longer than in the lower Thomson River, in the order of 70 to 150 m wide and 1 to 17 km long. Average maximum depth for major waterholes ranges from 2.9 m at North Chookoo to 6.3 m at Tabbareah (Knighton and Nanson, 2000). After the channels and floodplains have dried out, the waterholes provide a long-term reservoir of water; hence, they are both ecologically and culturally important

(Silcock, 2009). They tend to have steep banks of cohesive muddy sediments and are crowned by tree-covered levees (Knighton and Nanson, 1994b, 2000).

Riparian vegetation, particularly trees and lignum (*Duma florulenta*), play an important role in maintaining waterhole depth, trapping bank top sediments and also reducing stream power and flow velocity (Knighton and Nanson, 2000; Wakelin-King, 2010 (unpublished), 2015). Lignum is not present on all channel/waterhole banks, but where it is present clumps of lignum extend from the bank lip down to a level below that of the bank trees.

Away from the main channels, along the floodplain of the Cooper Plain, the great width of the alluvium allows for the development of swampy areas, where there is a dense and complex network of distributary or reticulate channels. These occur in locations where inundation frequency is sufficient to develop prominent microtopography from repeated wetting and drying of cracking clay soils or gilgai heave, but where flow energy is not sufficient to move soil particles. Linear depressions in the gilgai microtopography locally concentrate flow, creating and maintaining the reticulate channels (Fagan and Nanson, 2004). The reticulate channels can occur on higher as well as lower floodplain surfaces. Swamps typically have dense vegetation dominated by lignum.

Where inundating flows have sufficiently high energy to erode and redistribute floodplain sediment, gilgai microtopography is suppressed (Fagan and Nanson, 2004) and a braided floodplain results. This consists of alternating floodplain bars (elongated landforms of slightly higher elevation) and floodways (wide shallow swales). The elevation difference between swales and floodplain bars is generally less than 1 m (Wakelin-King, 2015). Floodplain vegetation is an important roughness element that promotes sediment deposition and maintains valley-floor integrity (e.g. Bull, 1997). Dryland river trees (e.g. black box, coolibah, red gum, *Acacia*) have different requirements for period of inundation, groundwater salinity and/or duration of waterlogging. Within the swales, perennial floodplain vegetation that traps sediment includes waterlogging-resistant species such as blue bush, rats-tail couch, sedges and lignum. The floodplain bars are very sparsely vegetated, low-relief surfaces. Unchannelled floodplain surfaces are always at higher elevations, and flood records demonstrate that these surfaces are rarely inundated. As a result, both braided channels and gilgai are absent from these surfaces (Fagan and Nanson, 2004).

Figure 60 Cooper Plain, just south of Windorah

Credit: Geological and Bioregional Assessment Program, Russell Crosbie (CSIRO), March, 2018
Element: GBA-COO-2-222

Innamincka Valley

Between Nappa Merrie and Innamincka, the Cooper Creek valley is confined within the rocky and stony walls and steep slopes created by Cooper Creek cutting through the Innamincka Dome (Wakelin-King, 2013).

The higher stream power in this narrow valley carved deeper (in excess of 25 m maximum depth at Cullyamurra) and longer waterholes than in other parts of Cooper Creek, and the width of the valley is very irregular. There are two very narrow reaches (minimum width 150 m) with almost no floodplain at the Cullyamurra Choke and near the Nappa Merrie waterhole. In other parts, the modern channels are set within a wide (up to 10 km) floodplain comprising paleochannels and modern floodplain. High elevation terraces and bars may flood in extreme events. The waterholes generally have very steep banks with a levee and densely vegetated riparian zones.

Cooper Creek Fan

West of the Innamincka Dome is the Cooper Creek Fan, which rises 40 to 245 m above the Strzelecki Plain (Wakelin-King, 2013). This alluvial fan has its apex located where Cooper Creek exits the Innamincka Valley and Strzelecki Creek begins. The fan forms a complex distributary network of flow paths, lakes and wetland systems as it passes through the Strzelecki Desert on its way to Lake Eyre North (Costelloe, 2013). The overall gradient is very low. The topography of the Cooper Creek Fan is dominated by orange–brown compound sand dunes; broad, apparently featureless flat areas of greyish dusty muds; and lakes and swamps. The Cooper Creek Fan is divided into an inner and an outer fan.

The inner fan is a sinuous, large single-thread channel from the apex to the fork of the main and north-west branches of Cooper Creek (Wakelin-King, 2013). Secondary channels forming anabranches are active in high flows. Channels along the inner fan are generally deep waterholes separated by shallow reaches. Waterholes are relatively deep, have steep sides and are lined with various eucalypt trees. Cease-to-flow depths of waterholes range from less than 1 m up to 7 m (Costelloe, 2013). The more gently sloping shallow reaches are vegetated with dense lignum and young riparian trees on their banks with larger trees in the channels. Shallow reaches tend to dry out between floods. Distributary channels are created within the inner fan by floodwaters and carry water and sediments out to flats, depending on their length.

The outer fan consists of anabranching, anastomosing and reticulate channels along the main and north-west branches of Cooper Creek, with swamps and lakes on the flats (Wakelin-King, 2013). Waterholes are less well developed than in other parts of Cooper Creek but occur along the main branch in high-energy locations. In exceptional circumstances, flows from Strzelecki Creek can reach Lake Blanche and Lake Gregory; however, these terminal lakes are generally dry.

Floodplain and alluvium within the lower Thomson River, Cooper Plain and Innamincka Valley are represented by the 'alluvia – mid catchment' conceptual model (Queensland Government, 2017a; protected matters technical appendix (O'Grady et al., 2020)) owing to the substantial development of alluvium and low gradient (0.017%).

The section of the landscape class on the Cooper Creek Fan is represented by the 'alluvia – lower catchment' conceptual model (Queensland Government, 2017a; protected matters technical appendix (O'Grady et al., 2020)). Other relevant conceptual models include the 'riparian woodland groundwater-dependent ecosystems' and 'evaporative influence groundwater-dependent ecosystems' from Miles and Costelloe (2015), although these represent components of the broader landscape-class model rather than a landscape class themselves.

4.3.1.2 Inland dunefields

The inland dunefields landscape class occupies 39,752 km^2 of the Cooper GBA region (Table 19). The Strzelecki Plain (the central and western portions of the Strzelecki Desert (Figure 4)) in SA is a topographic low, south and west of the Cooper Creek Fan, within which sand dunes have accumulated among river and lake deposits. Dunefields are also prevalent west of Cooper Creek, north of Lake Yamma Yamma in Queensland and north of the Innamincka Dome. Dunefields are scattered in other parts of the region. The Cooper GBA region dunefields are characterised by parallel dunes of red, yellow or white aeolian sands (Rudosols) of the Simpson Sand (Drexel and Preiss, 1995), dominated by single-crested linear sand ridges (Figure 61). Dunes are separated by flat interdune corridors (swales), which usually consist of claypans (Santos, 1997; Twidale and Wopfner, 1990). Dunes range in height from 5 to 35 m and trend approximately north-east (Twidale and Wopfner, 1990). Sand cover rarely exceeds 30 m and a stony base may be exposed in interdune areas. In those parts of the region where salt lakes and distributary channels occur in interdune corridors, the soils between dunes are dominantly grey and brown clays. Elsewhere, the common interdune soils are solonised brown soils (carbonate rich), calcareous red earths and earthy sands (Wright et al., 1990).

The dunefields are extremely arid and generally lack any permanent surface water. In some areas, good quality groundwater can be found at shallow depths in dunefield areas adjacent to major watercourses (e.g. Strzelecki and Cooper creeks). This water is non-artesian and contained within unconfined aquifers that are recharged primarily from surface streamflow.

Vegetation types differ between the upper slopes and crests of dunes and interdune areas. Dune crests are often sparsely vegetated (depending on seasonal conditions) with sandhill canegrass (*Zygochloa paradoxa*) and ephemeral herbs and shrubs (Santos, 1997). Dune flanks are characterised by marpoo (*Acacia ligulata*), whitewood (*Atalaya hemiglauca*) and grevilleas and hakeas; lobed spinifex grassland is also common on dune flanks in the Strzelecki Desert (Santos, 2015). Vegetation in interdunal areas depends largely on dune spacing. Narrowly spaced areas contain similar vegetation to dune flanks. Widely spaced dune areas, where gibber or floodplain soils are exposed, may contain low shrubland of saltbush or bluebush . In general, interdune vegetation may consist of hummock grassland, chenopod shrubland, open shrubland or low open woodland.

This landscape class is represented by the 'wind-blown inland sand dunefields' conceptual model (Queensland Government, 2017b; protected matters technical appendix (O'Grady et al., 2020)).

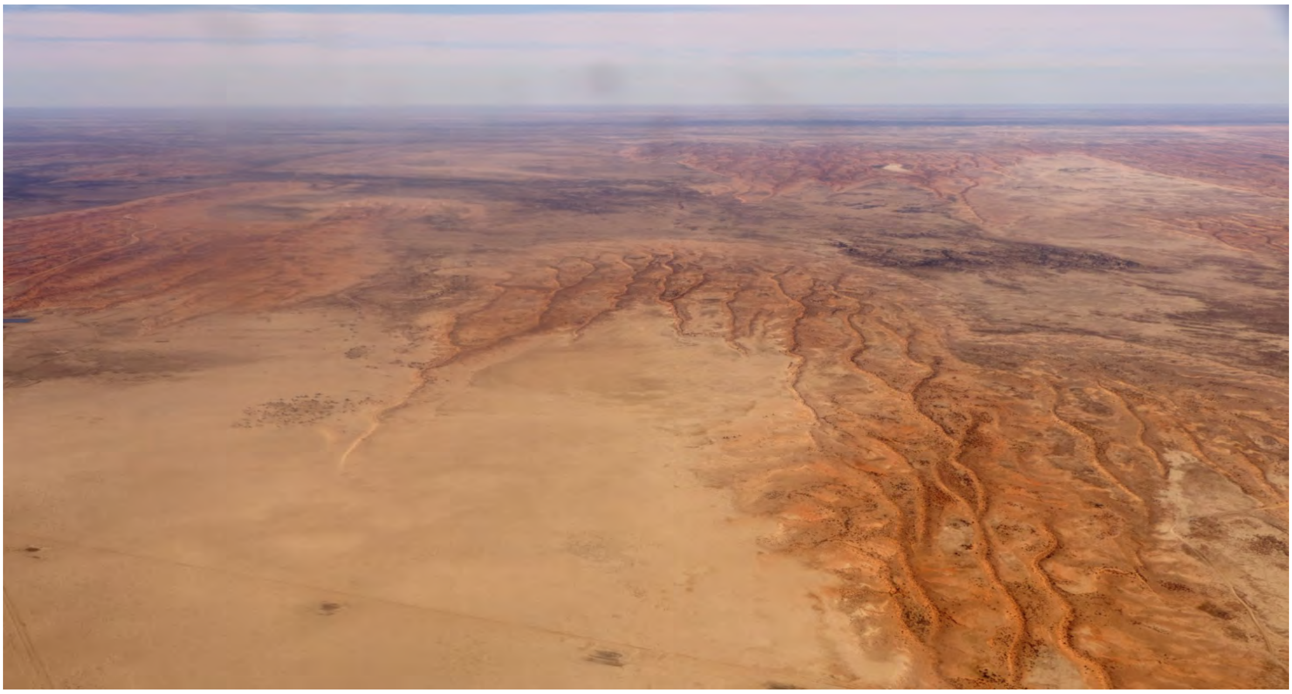

Figure 61 Examples of dunefields in the Cooper GBA region

Credit: Geological and Bioregional Assessment Program, Russell Crosbie (CSIRO), September, 2018
Element: GBA-COO-2-221

4.3.1.3 Clay plains

Only a small area (21 km^2) of the Cooper GBA region, north-west of Kyabra in Queensland in the east of the region, is classified as 'clay plain'. Clay plains include paleo-clay unconsolidated sediments originating from 'old' alluvial processes and aeolian clays forming predominantly level to gently undulating plains, but they also include lesser rises and low hills, particularly in arid areas. These paleo-clay deposits are now elevated and usually isolated from the alluvial valleys and floodplains (Wilson and Taylor, 2012). As a result, this is now an erosional landscape with poorly defined drainage. These clay soils have been extensively cleared for introduced pastures and cropping in higher rainfall areas due to their relatively high soil water availability and high fertility. Soils are dominated by Vertosols with gilgai microrelief. Larger gilgai may provide ephemeral wetland habitat as a result of ponding of rainfall.

Vegetation associated with these soils usually has restricted rooting depth due to the adverse effects of high sodium levels. They are typically gently undulating plains, with clay soils and texture-contrast soils derived from fine-grained sediments deposited in Paleogene to early Pleistocene lakes, basins and alluvial plains, and from aeolian clays (parna). These support brigalow (*Acacia harpophylla*), gidgee (*A. cambagei*, *A. georginae*), belah (*Casuarina cristata*), blackwood (*A. argyrodendron*), and some box (*Eucalyptus populnea*, *E. brownii*, *E. moluccana*) communities, grasslands (*Astrebla pectinata*, various bluegrasses) herblands and semi-evergreen vine thicket in more favourable areas.

This landscape class is represented by the ‘high-level alluvia’ conceptual model (Queensland Government, 2017a; protected matters technical appendix (O’Grady et al., 2020)).

4.3.1.4 Loamy and sandy plains

Loamy and sandy plains occupy 11,189 km^2 of the Cooper GBA region (Table 19). Patches of loamy and sandy plains have been mapped in the Cooper GBA region in Queensland, typically on sloping terrain between uplands and alluvium. The most extensive area of loamy and sandy plains is in the north of the region, north-west of Windorah and Jundah. There is no corresponding land system in SA and it is possible that limited areas classified as ‘tableland and duricrust’ in SA may contain loamy and sandy plains. However, it is likely that this landscape class is very uncommon in the Cooper GBA region in SA owing to the great amount of recent alluvial deposition and its generally low elevation compared with the Cooper GBA region in Queensland. Geological mapping does not reliably show unconsolidated surface layers.

Loamy and sandy plains may be formed by redeposition of colluvium or be formed in situ from ‘old’ alluvial processes (Wilson and Taylor, 2012). They may also result from prolonged, intense, deep weathering of parent rock material high in iron and/or aluminium oxides and kaolin clays. Landforms are flat to gently undulating plains, plateaus and dissected tablelands. A variety of vegetation communities exist within this landscape class, depending on local climate and soil factors. In semi-arid areas, vegetation generally consists of mulga, other *Acacia* species and poplar box; however, in the arid landscapes within the Cooper Basin, *Acacia* species are most common.

This landscape class is represented by the ‘sandy plains’ conceptual model (Queensland Government, 2015; protected matters technical appendix (O’Grady et al., 2020)).

4.3.1.5 Undulating country on fine-grained sedimentary rocks

Fine-grained sedimentary rocks, covering 25,986 km^2 of the region (Table 19), include siltstones, mudstones and shales that readily weather to form landforms dominated by gently undulating plains and rises with clayey soils or soils with clay subsoils. Coarse-grained sedimentary rocks are included in the fine-grained sedimentary rock group if these rocks also weather to clayey soils. For example, the labile sandstones of the Winton Formation form gently undulating plains with cracking clay soils. Soils are predominantly Vertosols, Sodosols and Chromosols, although Dermosols and Kurosols are also present.

In places where soil fertility is moderate to high, the undulating plains and rises have been developed or cleared for pasture. The Mitchell grass downs and herbfields of western Queensland have been used traditionally for grazing of sheep and cattle. The vegetation includes a diverse range of eucalypt open forest and woodland, *Acacia* woodlands (gidgee, brigalow), grasslands and herbfields, and some vine forest in more favourable sites.

Within the Channel Country Interim Biogeographic Regionalisation for Australia (IBRA) region, gibber plains are likely to be present. These are extremely flat to undulating plains that were formed during the breakdown and gradual recession of former tablelands (Santos, 2015). Soils typically consist of red and brown clays that are mantled by stone or recent deposits of silcrete pebbles, referred to as ‘gibbers’. Where gibbers form a stable pavement, they protect the underlying soil from erosion. Similarly, for clay plains, permanent surface water sources are generally lacking, but temporary pools of water often form after rain in low depressions or gilgai. Minor drainage channels occur throughout lowland plain areas.

There is a range of vegetation throughout gibber country (Santos, 2015). On the southern and south-western margins, relatively dense, low open shrubland of bladder saltbush, low bluebush and cotton bush are common. Further north, much of the area is naturally bare, but Mitchell grass tussock grasslands become more frequent. In other areas, the main cover may be short-lived copperburrs and ephemeral grasses. There is still further variation caused by hills and drop-offs where small trees or tall shrubs, particularly emu bush, may form a tall open shrubland.

This landscape class is represented by the ‘exclusion zones’ conceptual model (Queensland Government, 2017c; protected matters technical appendix (O’Grady et al., 2020)).

4.3.1.6 Tablelands and duricrusts

Tableland and duricrust areas are also known as dissected residuals, breakaways or ironstone jump-ups. They occupy 11,813 km^2 of the Cooper GBA region (Table 19). They are characterised by a silcrete or ferricrete surface that has been eroded to form low but steep escarpments, mesas and buttes (Santos, 2015) with colluvial slopes (talus) containing shallow soils (<0.5 m) over deeply weathered rock (Wilson and Taylor, 2012). Soils are either absent (exposed rock) or dominated by shallow (<0.5 m) Rudosols and Tenosols, with Kandosols on plateau and tableland margins. They may have gibber-covered foot slopes. Permanent surface water is scarce in elevated areas of tablelands (Santos, 2015).

In SA, this landscape class corresponds to the following surface geologies: Mount Howie Sandstone, unnamed undifferentiated Paleogene silcrete and unnamed regionally older silcrete; approximately late Eocene to mid Miocene.

Vegetation is extremely variable depending on climate conditions, depth of soil and position in the landscape (Wilson and Taylor, 2012). The absence of vegetation on the bare rock and scarp areas is typical. In western areas, lancewood (*Acacia shirleyi*), bendee (*A. catenulata*) and spinifex (*Triodia* spp.) are dominant communities on the edges of the exposed duricrusts. Mulga

(*A. aneura*) and bastard mulga (*A. clivicola*) are dominant on shallow soils on the level to gently undulating flat tops. Lower slopes range from *Acacia* shrublands, including gidgee (*A. cambagei*) to various eucalypt communities, including *Eucalyptus normantonensis* and mountain yapunyah (*E. thozetiana*).

This landscape class is represented by the 'exclusion zones' conceptual model (Queensland Government, 2017c; protected matters technical appendix (O'Grady et al., 2020)).

4.3.1.7 Springs

Recharge springs, also known as 'outcrop' springs, emanate from fractures in sandstone aquifers in clusters throughout semi-arid Queensland (Fensham et al., 2016). The springs occur primarily in the north of the Cooper GBA region, with scattered springs also in the west of the region (Figure 47). They often occur at the base of cliffs or escarpments, where they are fed by watertables from higher terrain under gravitational pressure. Water drains out of the rocks or through the intersection of the ground surface with a saturated aquifer rather than welling upwards under artesian pressure. After a succession of wet summers, water can seep out from recharge springs for some months but then, unlike discharge springs, they may be dry for years. Some recharge springs feed quite large waterholes and streams, while others form small shallow pools or soaks. Water is generally slightly acidic and has low conductivity, reflecting its relatively short residence time.

Recharge springs also tend to have more variable flows and are less unusual as a habitat type compared with GAB discharge springs (Fensham et al., 2011). Although their overall diversity is greater than rockholes, no endemic species have been recorded at any non-GAB springs in the Cooper Basin. This type of spring is represented by the 'recharge springs' conceptual model (protected matters technical appendix (O'Grady et al., 2020)), where the aquifer is confined by impermeable sandstone above and Cretaceous sediments of the Winton Formation below (Fensham et al., 2016). The aquifer is fed by local rainfall through fissures in the impermeable sandstone.

4.4 Protected matters prioritisation

In order to focus the assessment in Stage 3, protected matters were prioritised based on how important the Cooper GBA region is to each matter. Detailed assessments will focus on 12 protected species and 18 protected areas that are known or expected to occur in the region (priority 1). High-level assessments will focus on 20 protected areas identified in the Cooper GBA region (priority 2). Further assessment is not warranted for 58 protected species and 73 protected areas in the Cooper GBA region (priority 3) based on the listed conservation status or expected occurrence in the region.

The prioritisation identified 12 protected species and 18 protected areas to be assessed in greater detail in Stage 3 (priority 1). This includes ten threatened species, one threatened ecological community, one internationally listed Ramsar wetland and one national heritage site listed under the EPBC Act. A further eight nationally important wetlands, two threatened species (MSES) and seven protected areas listed under Queensland legislation are also prioritised for detailed assessment in Stage 3. Two assets that form part of the Lake Eyre Basin Intergovernmental Agreement were also identified (Table 20).

The ten threatened species listed under the EPBC Act are:

- Critically endangered: *Pedionomus torquatus* (plains-wanderer)
- Endangered: *Frankenia plicata* (braided sea heath), *Amytornis barbatus barbatus* (grey grasswren (bulloo)), *Pezoporus occidentalis* (night parrot), *Rostratula australis* (Australian painted snipe)
- Vulnerable: *Sclerolaena walker*, *Xerothamnella parvifolia*, *Dasyuroides byrnei* (kowari), *Notomys fuscus* (dusky hopping-mouse) and *Petrogale xanthopus celeris* (yellow-footed rock-wallaby (central-western Queensland)).

The two threatened plant species listed as vulnerable under Queensland state legislation are *Indigofera oxyrachis* and *Nyssanthes impervia*. Two species are listed under EPBC, Queensland and SA legislation: *Dasyuroides byrnei* (kowari) and *Notomys fuscus* (dusky hopping-mouse). The yellow-footed rock-wallaby (central-western Queensland) (*Petrogale xanthopus celeris*) is listed under EPBC and Queensland legislation. Two species are listed under EPBC and SA legislation: *Pezoporus occidentalis* (night parrot) and *Rostratula australis* (Australian painted snipe).

Springs belonging to the threatened ecological community 'The community of native species dependent on the natural discharge of groundwater from the Great Artesian Basin threatened ecological community' (Figure 47) are likely to be hydrologically connected to groundwater in the region and are also considered a priority protected matter, as is the Coongie Lakes Ramsar site. Stage 3 will also assess the Burke, Wills, King and Yandruwandha National Heritage Place, consisting of several sites along Cooper Creek listed under the EPBC Act, and two Queensland protected areas – 'Channel country strategic environmental area' and 'High ecological significance wetlands' – are hydrologically connected to the Cooper Creek and floodplain system in detail.

Landscape classes will be used to assess 26 protected areas, including regional ecosystems and other protected areas at a regional scale.

Table 20 Prioritisation of protected matters that occur, or potentially occur, in the Cooper GBA region

Priority 1 – Importance of the region to the matter warrants a detailed level of assessment. Priority 2 – Importance of the region to the matter warrants a high-level assessment. Priority 3 – Importance of the region to the matter does not warrant further assessment. See the description of prioritisation criteria below.

Listing	Category	Priority 1	Priority 2	Priority 3
Protected species	Bird	4	0	35
	Mammal	3	0	7
	Plant	5	0	10
	Fish	0	0	2
	Reptile	0	0	4
Protected areas	Threated ecological communities	1	0	0
	Regional ecosystems	0	8	73
	Wetland (national)[a]	8	0	0
	Wetland (international)	1	0	0
	Other protected areas	9	1	0
	Heritage sites	0	11	0
Total		**30**	**20**	**131**

[a] Coongie Lakes is listed twice: as a Ramsar-listed wetland (international) and as a DIWA wetland (national).
Source: Asset dataset (Geological and Bioregional Assessment Program, 2019a)

Prioritisation criteria

The spatial extent of each protected matter – for example, wetlands of national significance, known records (e.g. Atlas of Living Australia, WildNet) and predicted species distributions (Species Profile and Threats Database) – was used to assess endemism and the importance of the region to the survival of the species. Important populations are defined in the significant impact guidelines for vulnerable species (Department of the Environment and Energy 2013) and for migratory shorebirds (Department of the Environment and Energy, 2017a).

Priority 1 – Importance of the region to the matter warrants a detailed level of assessment

- Species is listed as endangered or critically endangered and is known or expected to occur in the region
- Important populations of migratory or vulnerable species that are known or expected to occur in the region
- Expert opinion suggests the threatened species is likely to occur in the region
- Any threatened ecological community or endangered regional ecosystem (RE)
- All listed wetlands in or downstream of the region – Ramsar-listed wetlands, nationally important wetlands, high ecological significance wetlands and high ecological value waters (wetland and watercourse)

- Any strategic environmental areas in or downstream of the region

Priority 2 – Importance of the region to the matter warrants a high-level assessment

- Species is listed as vulnerable and may or is known to occur in the region, or species is listed as endangered or critically endangered and may occur in the region
- Species is listed as migratory and may or is known to occur in the region but not as a proportion of an important population
- Region is an ‘of concern’ RE
- The region contains any heritage listed feature/item

Priority 3 – Importance of the region to the matter does not warrant further assessment

- Species is listed as conservation dependent, of concern or near threatened
- Species is listed as vulnerable, migratory, endangered or critically endangered and is not expected to occur in the region
- Region is a ‘no concern’ at present RE

4.5 Knowledge gaps

Key knowledge gaps identified for the assessment of potential impacts to protected matters in the Cooper GBA region include detailed knowledge of ecology, distribution and threats to individual threatened species, as well as accurate mapping of species habitat. Further work is required to develop conceptual models that explicitly link risks due to shale, tight and deep coal gas development with individual threatened species, other important ecological assets and other extant threatening processes. These models also need to address how these interactions vary through time, within and between landscape classes and how they are mediated by hydrological connections between these landscape classes.

A lack of accurate records of the spatial distribution of individual species, particularly for threatened and migratory species, are an important knowledge gap for the Cooper GBA region. Currently, a number of these species are identified as ‘likely to occur’ or ‘may occur’ rather than ‘known to occur’ within the Cooper GBA region. Further work is also required to explicitly identify habitat requirements within and across landscape class boundaries. Further research is needed to better understand whether an individual species is present or whether suitable habitat exists in the Cooper GBA region, as well as the groundwater and surface water requirements for these assets (species and or habitat).

The nature of interactions between existing threatening processes – for example, listed threatening processes and additional stressors associated with shale, tight and deep coal gas development – have rarely been studied in Australia or in arid environments globally. These are likely to vary both spatially and temporally or may act in additive, multiplicative and nonlinear ways, further complicating the interpretation of the cumulative impacts associated with resource development.

Threatening processes have not been identified for species that are only listed under state legislation (Queensland or SA) – that is, they are not listed nationally. This knowledge is critical for assessing cumulative impacts of existing threatening processes and future development of shale, tight and deep coal gas resources.

The landscape classification is limited by the quality of available datasets, including surface geology, elevation, vegetation and landform mapping; and extent and quality of ground observations. In particular, the distribution of clay plains is not clearly indicated in geological mapping. Reference to additional land resource data – in particular, geomorphology, together with interpretation of satellite imagery, aerial photographs and soil information – are necessary to identify clay plains. Similarly, determining the extent and nature of unconsolidated deposits can be problematic and can only be accurately determined with the aid of soil cores.

Conceptual models associated with landscape classes are generic in nature and do not adequately reflect the boom and bust nature of the system or the impacts of the sequencing of events (e.g. flood clusters), and these are important drivers of ecological processes in the region.

5 Potential impacts due to shale, tight and deep coal gas development

Potential impacts to water and the environment due to shale, tight and deep coal gas development are systematically identified to determine which causal pathways should be considered further in Stage 3 and which, given the evidence base presented in this report and the technical appendices, may be ruled out or considered a minimal risk. Risks are evaluated using causal pathways – the logical chain of events that links unconventional gas resource development with potential impacts on water and the environment. In this report, analysis of the three causal pathway groups – (i) 'landscape management'; (ii) 'subsurface flow paths'; and (iii) 'water and infrastructure management' – is used to integrate understanding of risks to water and the environment from the development of shale, tight and deep coal gas resources in the Cooper GBA region.

5.1 Impact and risk assessment approach

The risk assessment approach follows the principles for ecological risk assessment, with a view to meeting regulatory processes for the Cooper GBA region. Stage 2 establishes the context for the impact and risk assessment, including identifying hazards that are aggregated into a smaller set of causal pathways. Much of the impact and risk assessment will occur in Stage 3, when the causal pathways and endpoints identified in Stage 2 – the key building blocks for the impact and risk assessment – are finalised.

The assessment takes the form of a risk assessment and follows the principles for ecological risk assessment outlined by the US EPA (1998) and Hayes (2004) with a view to meeting regulatory processes for the Cooper GBA region. At the highest level it seeks to evaluate the likelihood and consequence of adverse environmental impacts as a result of the development of unconventional hydrocarbon resources.

While there are many different formulations, all risk assessments go through phases related to:

- *Identification and formulation* – this stage determines the scope, boundaries and objectives; collates and summarises the existing information and understanding; and identifies and prioritises hazards – an event, or chain of events, that might result in an effect – and potential causal pathways.
- *Analysis and evaluation* – this stage determines the basis for assessing risks; assesses the likelihood and consequence of adverse impacts; and identifies or considers risk factors that influence either the consequence or likelihood of impact, including mitigation or management options for reducing specific risks.
- *Characterisation* – this stage appraises and interprets risks in relation to the values that the assessment is trying to protect, summarises and documents the evidence base and identifies knowledge gaps and uncertainties that need to be considered further.

- *Monitoring and validation* – this stage describes the process for monitoring outcomes and validating (or invalidating) the assessed risks.

Components of the risk assessment occur in Stage 2 and Stage 3, as summarised in Figure 62.

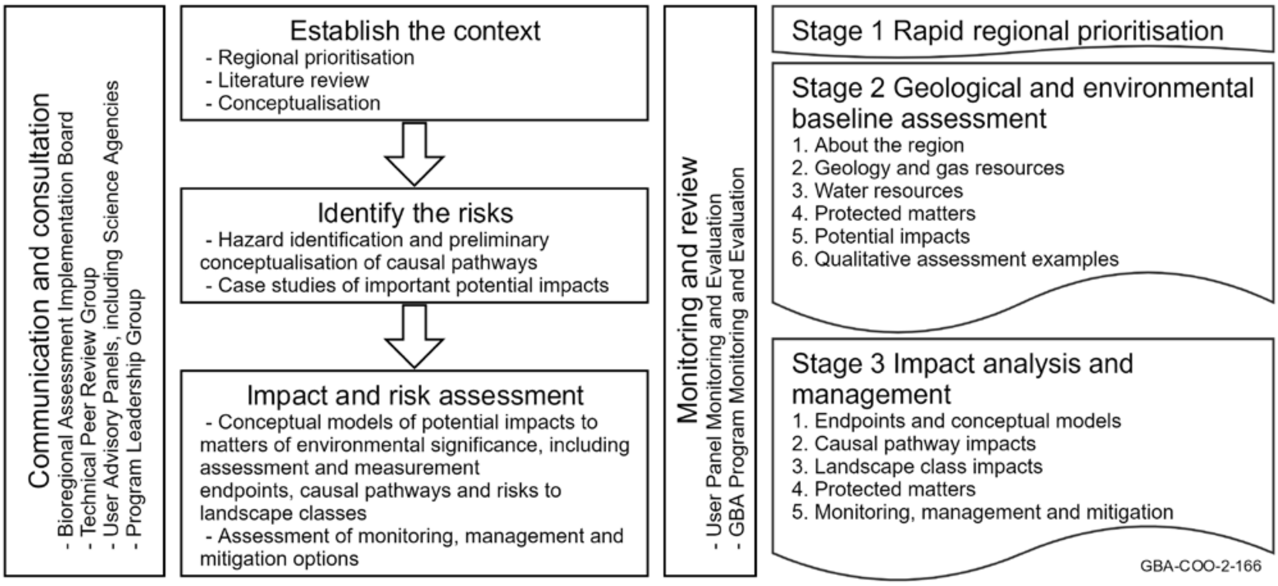

Figure 62 Impact and risk assessment approach and staged reporting structure for the Geological and Bioregional Assessment Program

Element: GBA-COO-2-166

Section 5.2 describes a systematic hazard analysis that (i) identifies potential changes that may stem from the development of unconventional hydrocarbon resources; (ii) aggregates individual hazards to a smaller set of causal pathways; and (iii) uses hazard scores to prioritise the causal pathways to be considered further in Stage 3. It also presents preliminary conceptual models for each causal pathway from hazards to potential impacts on landscape classes and values assessed as endpoints. *Endpoints* include *assessment endpoints* – an explicit expression of the ecological, economic and/or social values to be protected; and *measurement endpoints* – measurable characteristics or indicators related to the assessment endpoint. *Potential impacts* include changes to endpoints caused by *potential effects*, which are specific types of impacts or changes to water or the environment.

The hazard identification and preliminary conceptualisation are complemented by a qualitative assessment of three risks associated with drilling and hydraulic fracturing activities (see Section 6). The evaluation of these risks in Stage 2 was prompted by their importance to government, the community and industry. The three risks are (i) drilling and hydraulic fracturing chemicals; and two causal pathways: (ii) 'hydraulic fracturing' and (iii) 'compromised well integrity'.

Much of the impact and risk assessment will occur in Stage 3. The causal pathways and endpoints – the key building blocks for the impact and risk assessment – are identified in Stage 2 and will be finalised in Stage 3. Figure 63 emphasises the central role of the causal pathways in the assessment, connecting hazards arising from unconventional gas resource development activities, as well as existing activities (see Section 4.1.3), to potential impacts on the values to be protected represented in the assessment by endpoints. The assessment of potential impacts on ecological, economic and/or social values represented by endpoints will account for conceptual differences between landscape classes.

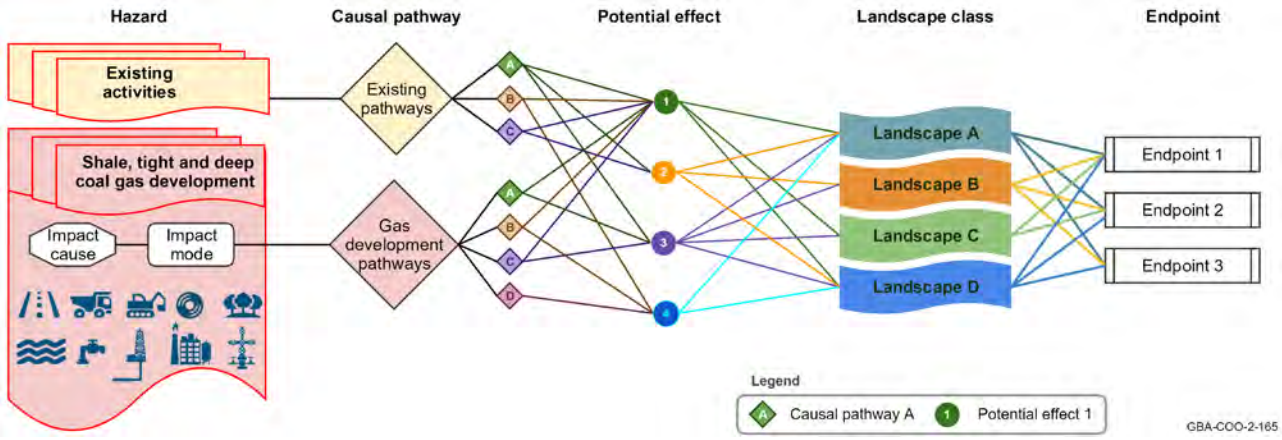

Figure 63 Overview of GBA impact and risk assessment approach, connecting hazards and potential effects from existing and future development through causal pathways to landscape classes and values assessed as endpoints

'Hazard' = an event, or chain of events, that might result in an effect; 'impact cause' = an activity (or aspect of an activity) that initiates a hazardous chain of events; 'impact mode' = the manner in which a hazardous chain of events (initiated by an impact cause) could result in an effect (change in the quality or quantity of surface water or groundwater); 'causal pathway' = the logical chain of events, either planned or unplanned, that link unconventional gas resource development and potential impacts on water and the environment; 'potential effect' = specific types of impacts or changes to water or the environment, such as changes to the quantity and/or quality of surface water or groundwater or to the availability of suitable habitat; 'landscape class' = a collection of ecosystems with characteristics that are expected to respond similarly to changes in groundwater and/or surface water due to unconventional gas resource development; 'endpoint' = includes 'assessment endpoints' – an explicit expression of the ecological, economic and / or social values to be protected; and 'measurement endpoints' – measurable characteristics or indicators related to the assessment endpoint. Conceptual links are shown by coloured lines.
Element: GBA-COO-2-165

5.1.1 Defining endpoints

Two types of endpoints are described by Suter (1990) and the US EPA (2016b). 'Assessment endpoints' are defined as an explicit expression of the ecological, economic and/or social values to be protected, while 'measurement endpoints' are measurable characteristics or indicators related to the valued characteristic chosen as the assessment endpoint. For example, where an assessment endpoint to avoid might be risks to the condition of the natural environment due to a decline in water quality, the associated measurement endpoints could be drawn from the Australian and New Zealand Environment and Conservation Council (ANZECC) water quality guidelines (ANZG, 2018) or established toxic concentrations of specific chemicals for individual species. Where the assessment endpoint to avoid might be the long-term decrease in the size of a population of an endemic native species, the measurement endpoint could be measures of population abundance or occurrence of that species from targeted ecological surveys.

The ecological assessment endpoints used for the GBA Program follow the approach of Beckett (2019) and are adapted from the criteria used in the significant impact guidelines developed by the Department of the Environment and Energy (Commonwealth of Australia, 2013) to determine whether an action may cause harm to one or more Matter of National Environmental Significance (MNES) under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act). There are several categories for threatened species and ecological communities within the MNES, and assessment endpoints are considered for threatened species (which cover critically endangered, endangered species and vulnerable species), migratory species, ecological communities and wetland ecosystems (wetlands of international importance). The *Significant impact guidelines 1.3: coal seam gas and large coal mining developments – impacts on water resources* (Commonwealth of Australia, 2013) provides further details on the protection of water resources from coal seam gas (CSG) and large coal mining. This includes changes to hydrological characteristics and water quality, which are relevant to the GBA Program.

MNES also include world heritage-listed properties and national heritage places, which contain places or groups of places with outstanding heritage value to Australia. They can be natural, Indigenous or historic, or a combination of these. An important component of these is cultural heritage values. Some MNES defined in the EPBC Act are assessed as not relevant to the GBA Program. They include Commonwealth marine areas, the Great Barrier Reef Marine Park and nuclear actions.

The GBA Program will consider additional endpoints, such as those related to agriculture and water resources, in order to assess cumulative impacts on water and the environment due to the development of shale, tight and deep coal gas resources. Potential socio-economic impacts, such as to tourism or urban environments, are beyond the scope of the Program.

Table 21 presents examples of assessment endpoints for different categories of MNES, water resources and agriculture. The approach taken here is consistent with Beckett (2019) and reduces the criteria used in the significant impact guidelines (Commonwealth of Australia, 2013) for each category of threatened species into a single set of assessment endpoints. It then applies these endpoints to all sets of native species regardless of their listed status. These examples are intended to provide context for the direction of the impact and risk assessment in Stage 3.

Table 21 Examples of assessment endpoints

Ecological endpoints are derived from the significant impact guidelines (Commonwealth of Australia, 2013) and representation by Beckett (2019). The full suite of assessment and measurement endpoints will be finalised in Stage 3.

Category	Assessment endpoint examples
Endemic native species	• area of occupancy of the endemic native species • spatial coherence of the population of an endemic native species • extent of harmful invasive species in the habitat of endemic native species
Migratory species	• integrity of an area of important habitat for a migratory species • life cycle (breeding, feeding, migration or resting behaviour) of the population of a migratory species
Ecological communities	• species composition of an ecological community, including functionally important species • extent of harmful invasive species in the ecological community
Wetland ecosystems	• wetland area • hydrological regime of the wetland • habitat or life cycle of native species, including invertebrate fauna and fish species
Water resources	• water availability for human consumptive or other uses, including environmental and public benefit outcomes • hydrological or hydrogeological connections of a water resource (e.g. inter-aquifer connectivity) • suitability of water quality for consumptive or other uses
Cultural heritage	• use as a cultural or ceremonial site • preservation of cultural values for a community or group • preservation of cultural artefacts, archaeological deposits, Indigenous built structures or ceremonial objects
Agriculture	• safety of livestock from exposure to toxins or harmful substances • suitability of terrestrial environment for farming and agriculture

Measurement endpoints will be identified as specific indicators of potential changes for all assessment endpoints in Stage 3. They will draw on existing literature or expert opinion and be complemented by jurisdictional input. For instance, from Butcher and Hale (2011) the ecological character of the Coongie Lakes Ramsar-listed wetlands may be assessed through measurement endpoints such as the frequency of decadal inflows, vegetation leaf area index, the abundance of waterbirds during inundation events, and the number of fish species recorded during target fish surveys. More generally, the choice of measurement endpoints may include metrics such as the extent of habitat for an ecological community, frequency of inundation events, age structure of a population, measures of breeding success or the ANZECC/ARMCANZ water quality guideline values for key water quality parameters or contaminants. The choice of measurement endpoints will be guided by Suter (1990), US EPA (2016b) and Hayes (2004).

The potential for ‘significant impacts’ for each measurement endpoint (Table 21) will be described using thresholds to more precisely describe the aspects of tolerance, resilience and persistence of the asset to be protected, how cumulative impacts interact and the spatial and temporal scales of the response. For instance, Butcher and Hale (2011) use limits of acceptance change for Coongie Lakes to specify thresholds for indicators beyond which there may be material change to aspects of the ecological character.

Potential impacts on the suite of assessment endpoints arising from each causal pathway (described in Section 5.3) will be assessed for the range of development profiles to be developed in Stage 3. Development profiles represent the range of spatial and temporal infrastructure needed for gas resource development – that is, number of wells, pipelines, access roads, etc. The assessment will identify the likely mitigation and management measures, assess the likelihood and consequence of potential impacts for each pathway, identify risk factors that amplify or diminish potential impacts, describe confidence in existing knowledge and identify knowledge gaps.

Landscape class case studies will be used in Stage 3 to assess the relevance and importance of different causal pathways for different ecosystems identified in Section 4.3. Control and stressor conceptual models – see, for example, Gross (2003) – for each landscape class will be used to consider causal pathways from unconventional gas resource development that may interact with causal pathways from existing activities and are relevant to that landscape class.

Protected matters (e.g. threatened species, threatened ecological communities, Ramsar-listed wetlands, etc.) will be investigated through individual asset-level assessments that consider the potential exposure of that asset to causal pathways and the impacts to the asset that may arise from that exposure.

Mitigation and management options that could be considered in an abatement plan for individual assets and that are relevant for specific causal pathways will be identified. Monitoring recommendations, including design principles, possible indicators and relative monitoring emphases, that could validate (or invalidate) the risk predictions and underpin a baseline will be provided in Stage 3.

5.2 Hazard identification

Hazards were systematically identified by considering all the possible ways an activity in the life cycle of shale, tight and deep coal gas development (Figure 64) may have an impact on ecological, economic and/or social values. The range of severity and likelihood scores for each hazard was agreed by experts from government and industry and members of the assessment team at five workshops for the Cooper GBA region between May and August 2018. Stage 3 of the GBA Program will assess the likelihood and the consequences of the identified risks (risk analysis and risk evaluation phases).

Causal pathways were prioritised using the highest hazard score (severity + likelihood), which means that future analysis in Stage 3 can focus on higher priority risks. Seven causal pathways were prioritised for a detailed level of assessment in Stage 3 (priority 1). Remaining causal pathways were prioritised for assessment (priority 2). Important potential impacts to be assessed in Stage 3 are changes to groundwater quality; surface water flows; cultural heritage damage or loss; habitat fragmentation and loss; introduction of invasive species; and contamination of soil, groundwater and or surface water. Most of the priority hazards are in the landscape management (43 out of 94) and water and infrastructure management (41 of 90) causal pathway groups, with fewer (nine out of 22) in the subsurface flow paths causal pathway group.

This section examines hazards from shale, tight and deep coal gas activities in the Cooper GBA region. This assessment is based on a high-level description of these activities and is not based on a particular development scenario or specific set of activities. While care has been used in the identification of these hazards, by necessity they are general in nature.

Hazard identification is a key component of the *Identification and formulation* step of the GBA impact and risk assessment approach outlined in Section 5.1. As part of this step, the hazards are prioritised based on a high-level assessment of their likelihood and consequence based on expert opinion. Stage 2 has not quantified the probability of any single hazard occurring or its impacts on endpoints. Stage 3 will do a more detailed assessment, including the role of industry standards and environmental and operational regulations in mitigating these hazards.

5.2.1 Impact mode and effects analysis

Hazards associated with shale, tight and deep coal gas development were identified using the structured Impact Mode and Effects Analysis (IMEA) framework developed for the Bioregional Assessment Program (Ford et al., 2016). IMEA is based on a well-established engineering method for identifying hazards in complex systems with multiple components called 'Failure Modes and Effects Analysis' (FMEA). It is widely used by industries that operate complex plants, such as the petrochemical industry and the automotive industry, and has also been applied to mining operations in relation to mine equipment safety (Dhillon, 2009; Daling and Geffen, 1983) and the construction and operation of a tailings dam (Correia dos Santos et al., 2012).

IMEA is a 'bottom-up' hazard analysis tool. It begins with a thorough description of the overall system and its subsystems, individual components and activities. It then identifies all the possible ways in which each activity can have an impact (the 'impact modes') and assesses the severity of the impact on the ecological, economic and/or social values (the 'endpoints'). It considers the 'impact modes', which are the manner in which a hazardous chain of events (initiated by an 'impact cause') could result in a '*potential* effect' (Figure 63). An 'impact cause' is an activity (or aspect of an activity) that initiates a hazardous chain of events. 'Potential effects' are specific types of impacts or changes to water or the environment, such as changes to the quantity and/or quality of surface water or groundwater, or to the availability of suitable habitat. Multiple impact modes and potential effects may be associated with each activity. The range of severity and likelihood of the potential effect is scored on an interval (minimum to maximum) for each hazard. Current controls that are in place are identified and considered in the scoring, and they are thus part of the hazard prioritisation. These controls, and additional mitigation or management options that may reduce the severity and/or likelihood of potential impact, will be considered in detail in the analysis of causal pathways in Stage 3. The IMEA used in the GBA Program differs from the IMEA used in the Bioregional Assessment Program (Ford et al., 2016) in that it does not score the detectability of the impact. Detectability can be useful for weighting more highly those hazards that are harder to detect. In this context these are often subsurface hazards which may take years to present. This was assessed as more important for bioregional assessments given the subsurface causal pathways are typically nearer to assets at the surface for CSG and coal mining compared with deeper shale, tight and deep coal gas resources.

Impact cause describes *why* and impact modes describe *how* potential effects may be initiated by an activity. For example, an impact mode during drilling and well construction is 'intersection of permeable geological layer causing loss of drilling fluid into permeable geological layer'. The impact cause is due to 'human error or accident', where the combination of the high permeability in the non-target formation and low viscosity of the drilling fluid leads to 'changed groundwater quality' (potential effect) that is not adequately controlled. Current regulatory and operational controls are the management of well integrity, including the management of drilling fluid properties and industry standards for design and installation of well casing.

5.2.2 Typical shale, tight and deep coal gas development activities

Activities that typically occur during shale, tight and deep coal gas development have been grouped into ten major activities (Figure 64) that span five life-cycle stages (Figure 65). The ten major activities are:

1. Civil construction
2. Water extraction
3. Water and supply transport
4. Fluid mixing and pressurisation
5. Drilling and hydraulic fracturing
6. Production and processing
7. Wastewater storage and reuse
8. Wastewater transport
9. Wastewater treatment and disposal
10. Decommissioning and rehabilitation.

The five life-cycle stages of unconventional gas resource development are (i) exploration; (ii) appraisal; (iii) development; (iv) production; and (v) rehabilitation. Activities may be specific to a particular life-cycle stage (e.g. well workover during production) or may occur in several different life-cycle stages (e.g. drilling occurs during exploration, appraisal, development and production life cycles but is expected to peak during the development stage, when the greatest number of wells are drilled).

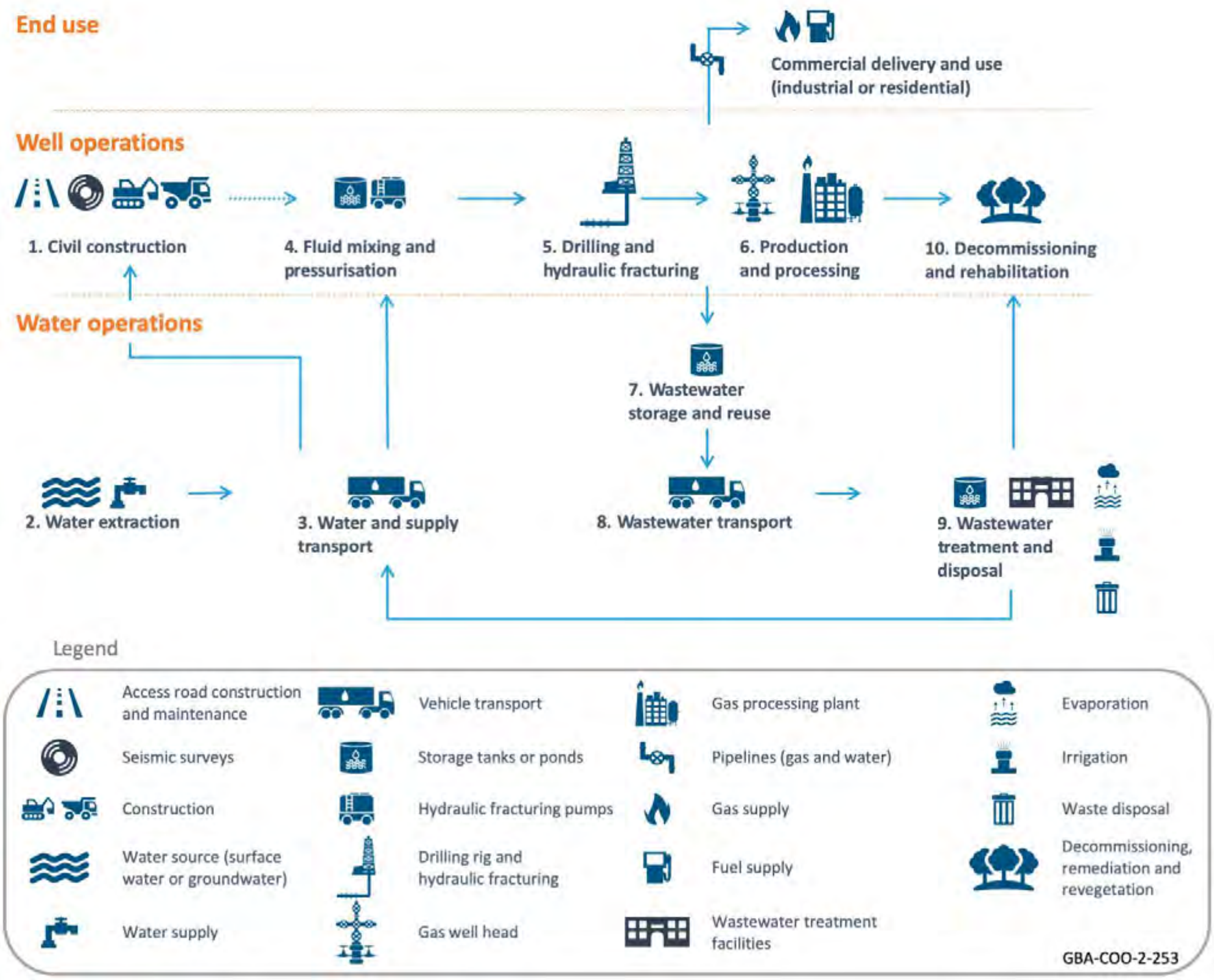

Figure 64 Ten major activities involved in typical shale, tight and deep coal gas resource development

Source: Adapted from Litovitz et al. (2013)
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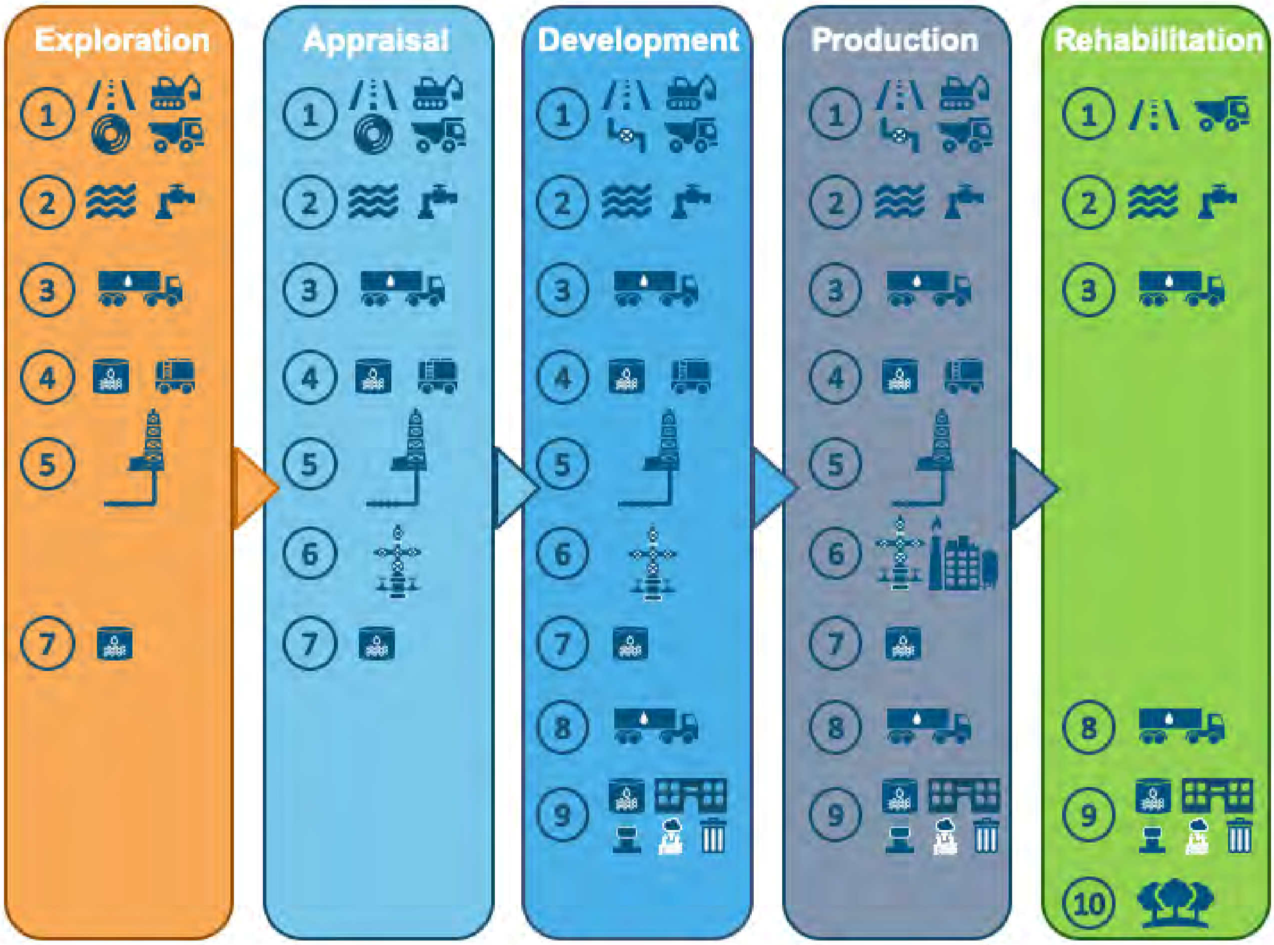

Figure 65 Life-cycle stages and major activities for unconventional gas resource development in the Cooper GBA region

Symbols for each of the ten major activities (1. Civil construction; 2. Water extraction; 3. Water and supply transport; 4. Fluid mixing and pressurisation; 5. Drilling and hydraulic fracturing; 6. Production and processing; 7. Wastewater storage and reuse; 8. Wastewater transport; 9. Wastewater treatment and disposal; and 10. Decommissioning and rehabilitation) are defined in Figure 64.
Element: GBA-COO-2-151

1. Civil construction

Vegetation clearing and preliminary earthworks are usually early steps in shale, tight and deep coal gas operations and include construction of supporting infrastructure such as access roads, fire breaks, seismic lines, pipelines (gas and water), power lines, storage dams, processing plant and equipment, surface infrastructure and well pads. Civil construction increases in intensity during the development stage and is likely to take at least several years, with construction of individual well pads taking approximately six months.

Construction materials, such as gravel and soil, are excavated from borrow pits. The location and dimensions of borrow pits vary depending on the land systems and soil types, as well as the quality and quantity of material available (Santos, 2015). Soils are stockpiled for later use in rehabilitation activities around the site to aid in the return of vegetation and the creation of fauna habitat. The IMEA process assumes that relevant environmental, heritage, land tenure and legal commitments are managed prior to and during any vegetation clearing.

Contamination of soils, surface water and/or groundwater bodies may arise from disposal and storage of site materials, reuse of extracted water onsite and due to failure of surface infrastructure when leading-practice management protocols are ineffective. Construction activities may also damage cultural heritage, increase soil erosion and reduce soil productivity when management protocols are not used effectively. Changed air quality, bank instability and erosion near watercourses, habitat fragmentation and loss, increased mortality of native species and contamination of soils, surface water and/or groundwater during construction and clearing activities may threaten natural habitat and species distribution. Access roads and vegetation clearance may transport seeds and pest species that increase the threat of competition and predation by invasive species on native species.

2. Water extraction

Water is extracted for site operations, which includes access road construction, drilling and hydraulic fracturing, sand quarry development, rehabilitation and well workover, intervention and hydraulic fracturing. Water is needed to develop shale, tight and deep coal gas resources during drilling and hydraulic fracturing. Greater volumes of water are required for hydraulic fracturing than for drilling (10s of ML versus 1s of ML; Huddlestone-Holmes et al. (2018) and Section 5.3). The hazard identification workshops used a conservative assumption of approximately 15 to 20 ML/well are needed for drilling and hydraulic fracturing during the exploration, appraisal and development stages. Water use will be highest in the development stage, when drilling intensity is highest relative to the exploration and appraisal stages. During the production stage, approximately 10 ML/well will be required for well workovers, intervention and refracturing to extend gas production. Huddlestone-Holmes et al. (2018) note that low-salinity water is preferred because high-salinity water may damage equipment and target formations.

Surface water in the Cooper GBA region is unregulated and unreliable (see Section 3.1.4), which means that water for drilling and hydraulic fracturing is more likely to either be extracted from groundwater bores or sourced from produced water from conventional oil and gas production that is treated and reused. Water extraction for site operations can affect groundwater levels or pressures and/or groundwater quality in source aquifers. The sourcing of water from surface water bodies, while less likely in the Cooper GBA region, has the potential to affect flows and water quality and/or cause bank instability and erosion in watercourses.

3. Water and supply transport

Water, sand and chemicals used in drilling fluids and hydraulic fracturing are typically transported by truck to well pads. Transport of water and supplies may be more intensive during peak periods of construction (and associated drilling and hydraulic fracturing) and minimal at other times. Hydraulic fracturing equipment and construction materials are also transported, particularly during the development stage. Drilling and hydraulic fracturing equipment to access shale, tight and deep coal gas resources is likely to be larger than for CSG due to the greater depth of the target formations. Development of shale gas resources is estimated to need approximately 3000 heavy truck movements per well pad over two years to develop each horizontal well (Pepper et al., 2018; Clancy et al., 2018).

Vehicle transport can directly impact native species through habitat fragmentation and loss due to dust and emissions, including noise and light pollution; increased road mortality; and transport of invasive seeds and pests that increase the threat of competition and predation by invasive species on native species. Spills or leaks of water, chemicals and sand during transport and water spray for dust suppression may lead to soil, surface water and/or groundwater contamination.

4. Fluid mixing and pressurisation

Water and chemicals for use in drilling fluids and hydraulic fracturing are typically stored in bunded areas at the well pad before being mixed and ready for use. Hydraulic fracturing fluid comprises water, sand and other chemical additives. Risks from the likely chemical constituents of hydraulic fracturing fluids are assessed qualitatively in Section 6.1. Fluids are mixed and stored in tanks and/or ponds prior to injection by hydraulic fracture pumps. Use of drilling and hydraulic fracturing fluids is greatest during the development stage, when most of the wells are drilled and hydraulic fracturing performed. Smaller volumes are needed during exploration and appraisal and during production for workover of wells or refracturing, as fewer wells are drilled and fractured at this time.

Dust and emissions from operation of machinery may affect natural habitat and species distribution through habitat fragmentation and loss, including changes to air quality and noise and light pollution. Accidental spillage during disposal and storage, or failure of well integrity or surface infrastructure, may lead to soil, groundwater and/or surface water contamination, or changes to groundwater composition.

5. Drilling and hydraulic fracturing

Shale, tight and deep coal gas resources in the Cooper Basin are typically greater than 2000 m deep (Section 2). To maximise gas production, multiple wells (four to eight wells) with horizontal (lateral) extensions of 500 to 3000 m into the target formation will typically be drilled from each 2 to 4 ha well pad (Huddlestone-Holmes et al., 2018). The hazard identification workshops assumed that between 1000 and 1500 wells to extract available shale, tight and deep coal gas resources will be drilled over the next 50 years in the Cooper Basin. Given the greater focus on horizontal drilling, well pads are likely to be 3.5 to 4 km apart (well pad density less than 0.125 well pads/km^2) (EHS Support, 2018), which is less than for CSG fields (typically 1.1 well pads/km^2).

Hydraulic fracturing will be needed to stimulate gas flow from the target formation. In the exploration and appraisal life cycles, drilling and hydraulic fracturing are focused on assessing the potential of the shale, tight or deep coal gas resources. Well appraisal involves drill stem tests, diagnostic fracture injection tests and reservoir testing. Horizontal or lateral extensions are less likely during these life-cycle stages. During the production stage, new wells are sequentially drilled and hydraulically fractured to maintain gas production and maximise use of drilling and hydraulic fracturing equipment. Existing wells may also be worked over to improve productivity by cleaning out the well and refracturing the target formation.

Risks associated with hydraulic fracturing (see Section 6.1.4) and compromised well integrity (see Section 6.2.2) are reviewed in more detail in two of the qualitative assessment examples in response to strong community concern. Dust and emissions from operation of machinery may affect natural habitat and species distribution through habitat fragmentation and loss, including changes to air quality or noise and light pollution. Disposal and storage of site materials may contaminate soil, surface water and/or groundwater through accidental spillage or leaks and leaching from drill cuttings. Unplanned intersection or hydraulic fracture growth into faults, non-target geological layers or offset abandoned wells during drilling and hydraulic fracturing may change subsurface physical flow paths. Loss of well control and failure of well integrity (gas and fluids) may lead to soil, surface water and/or groundwater contamination and changes to air quality, groundwater composition and pressures. Changes to groundwater pressures could potentially lead to fault reactivation and induced seismicity.

6. Production and processing

Following drilling and hydraulic fracturing of a well, gas will flow from the target formation. Gas produced from individual wells is transported by pipeline to a small number of centralised gas processing facilities. Gas is separated from formation water and hydrocarbons before being dehydrated, then compressed and transported by pipeline to the broader gas distribution network and market. Processing and compression of gas includes production and transport of fluids, flaring or venting of gas, and power supply to the processing facility and ultimately for commercial delivery and use by industrial and residential customers.

Gas production is intensive during the production stage and tails off at an individual well as it ages. A typical shale, tight or deep coal gas well in the Cooper GBA region may be expected to produce gas for 15 to 20 years. Wells will typically be sequentially added during the production stage to maintain production rates. Gas produced from the small number of wells drilled during the exploration and appraisal stages is often 'flared off' during well testing. Gas is also vented and flared from gas processing facilities and during pipeline commissioning and maintenance.

Processing and compression of gas, including flaring or venting of gas, can affect air quality or light and noise levels, which may alter natural habitat and species distributions. Failure of surface infrastructure may affect air quality through leaks from equipment or pipelines. Natural hazards, such as bushfires or floods, may increase soil erosion if control measures are inadequate during this stage of development. Unconventional gas extraction may alter groundwater quality and pressures, which can lead to subsidence of land surface, fault reactivation and induced seismicity.

7. Wastewater storage and reuse

Drilling and hydraulic fracturing fluid returned to the surface is typically referred to as 'flowback water'. Flowback water contains water and chemical additives used for hydraulic fracturing as well as water from the target formation (e.g. it is often more saline and may contain heavy metals). The volume of flowback water is highly variable but is likely to be approximately 25% to 75% of the fluid volume injected (Cook et al., 2013b). The hazard identification workshops assumed that the total volume injected during each hydraulic fracturing stage is up to 1 ML, approximately 0.3 ML/stage enters the target formation and 40% to 60% is recovered as flowback water. The volume of water produced from shale, tight and deep coal gas wells is considerably less than for CSG wells (approximately 10 ML/year) (Office of Groundwater Impact Assessment, 2016; Huddlestone-Holmes et al., 2018).

Flowback and wastewater are stored at the well pad prior to treatment and disposal or reuse. Storage is typically in ponds or tanks, with the greatest volumes stored during the development stage, when most of the wells are drilled and fractured. Water and fluid storage are more limited during other stages, when fewer wells are drilled and fractured. The workover of existing wells during the production stage to improve productivity generates more wastewater, although typically at a reduced rate compared with the initial drilling and hydraulic fracturing.

Storage of water in dams may unintentionally affect water availability and water quality of habitat for waterbirds and other native species. Additional water points may also favour invasive species in a water-limited environment. Soil, surface water and/or groundwater contamination may arise from leaks, spills or overflows due to integrity failure or uncontrolled releases during floods.

8. Wastewater transport

Wastewater from drilling and hydraulic fracturing at individual well pads needs to be transported from the well pad to an offsite water processing facility for treatment. Transport will typically be by truck and will be the most intensive during drilling and hydraulic fracturing in the construction phase. It is more limited during other life-cycle stages but increases with the number of wells.

Vehicle transport can have direct impacts on native species through habitat fragmentation and loss due to dust and emissions, including noise and light pollution; increased road mortality; or transport of invasive seeds and pests that affect natural and agricultural landscapes. Failure of surface infrastructure may lead to soil, surface water and/or groundwater contamination due to leaks during transport or pipeline failure.

9. Wastewater treatment and disposal

Disposal of treated wastewater from drilling and hydraulic fracturing operations is carefully managed and governed by state regulations. Disposal options include discharge to surface waters under suitable hydrological conditions, reinjection into groundwaters in ways that do not affect the beneficial uses of that groundwater, and evaporation from storage ponds.

The disposal of treated water peaks during drilling and hydraulic fracturing in the development stage given the large increase in the number of wells coming into operation at that time. It occurs during other life-cycle stages (e.g. during production as new wells are introduced to maintain production) but is substantially less during the exploration and appraisal stages.

Fluid disposal into surface waters, aquifers or evaporation ponds may increase mortality of water-dependent native species. Discharging water into surface waters may lead to bank instability and erosion; contamination of soil, surface water and/or groundwater; and changes to surface water flows and quality. Reinjecting water into aquifers may change groundwater quality and levels or pressures. Changes to groundwater pressures could lead to fault reactivation and induced seismicity.

10. Decommissioning and rehabilitation

Rehabilitation primarily occurs after production operations cease and includes the decommissioning of surface infrastructure (e.g. water treatment plants, pipes, gas processing plant, compression stations, water/fluid storage facilities, offices and workshops), decommissioning wells by plugging with concrete prior to abandonment, and the remediation of land impacted by revegetation and landscaping as part of gas production and exploration. Some of the decommissioned infrastructure and materials will be transported offsite by trucks for disposal and reuse. In some cases, rehabilitation may occur sequentially, particularly with revegetation and landscaping during production to minimise visual impact.

Site decommissioning and rehabilitation activities may temporarily increase soil erosion, reduce soil productivity, transport invasive seeds and pests, and change surface water flows. Contamination of soil, surface water and/or groundwater may arise from incorrect disposal and storage of site materials, failure of surface infrastructure, reuse of treated water and incorrectly plugged and abandoned wells. Incorrectly plugged and abandoned wells may also lead to changed groundwater quality due to fluid or gas migration along the casing.

5.2.3 Hazard workshops and consultation

Participants at five hazard identification workshops systematically ranked over 200 hazards associated with future shale, tight and deep coal gas development in the Cooper Basin. The hazard identification dataset describes the activity, current control, impact cause, impact mode, major activity, peak life-cycle stage and potential effect, as well as the upper and lower estimates for severity, likelihood and hazard score, for each individual hazard (Geological and Bioregional Assessment Program, 2019c).

The workshops commenced with an internal workshop comprising staff from CSIRO, Geoscience Australia and the Department of the Environment and Energy. Workshop participants systematically considered individual activities associated with each life-cycle stage and all plausible pathways to impact and the associated effects. Four follow-up IMEA workshops occurred that involved representatives from the SA and Queensland governments and industry (Santos and Beach Energy). In addition, there was a broader program workshop in Brisbane (21–22 August 2018) that had strong representation from government and industry. Preliminary findings were also discussed at the user panel meeting in Thargomindah on 19 September 2018. The workshops focused on confirming the priority hazards and identifying if any low-priority hazards needed to be elevated, by examining subsets of the activities and impact modes. Representatives providing the scores in these workshops were blind to the scores from preceding workshops, although hazards considered a priority in any of the preceding workshops were identified in the final workshop.

The workshops considered the range of likely future shale, tight and deep coal gas development profiles – a critical assumption underpinning the hazard identification and analysis. This includes an indication of the likely number of wells, well pads and roads and whether pipelines are buried. IMEA assumes that relevant control measures, such as standard Australian gas industry operating procedures and regulatory requirements, are met. However, at this preliminary stage it is not possible to provide a thorough assessment of the effectiveness of these controls in mitigating identified hazards. A closer examination will be conducted as part of the detailed assessment in Stage 3 that will be guided by development profiles. Key assumptions made during the workshops are summarised in Table 22.

Table 22 Assumptions for hazard identification workshops

Category	Assumptions
Access roads	Approximately 5 km/well pad is required. It is assumed access roads increase from minor tracks covering 20% of the total road network in the exploration stage to unsealed roads covering 40% of the total road network in the appraisal stage and 100% of the total road network in the development production stages. Access roads are rehabilitated following decommissioning and rehabilitation of well pads.
Borrow pits	Pits are 2–3 m deep in clay-rich areas, with the floodplain and alluvium landscape class being most affected. Gibber plain (undulating country) environments are most prone to gully erosion.
Development profile	Between 1000 and 1500 wells to be drilled over a 50-year development time frame. It is assumed that 2% of wells are drilled in the exploration stage, 10% by the end of the appraisal stage and 100% by the end of the development stage. Horizontal or deviated wells reduce the development footprint by drilling multiple wells from a single pad, typically 6–8 wells per pad. Well pads will be 3.5–4 km apart, each well pad accessing an area of 8–12 km^2.
Dust suppression	Remote location and sparse population reduce the need for dust suppression. Water is sourced from Lake Eyre Basin or Great Artesian Basin aquifers, or untreated water. This is not strongly regulated.
Hydraulic fracturing	Total volume injected per stage is up to 1 ML, approximately 0.3 ML/well enters target formation and 40%–60% is recovered as flowback. Likelihood of intersecting offset wells is low in Queensland due to sparse existing well network.
Pipelines (gas and water)	Pipeline network is similar to road network but buried, so minimal dust suppression is required. Open trenches could trap native fauna.
Seismic surveys	Approximately 3 km^2/well of new three-dimensional seismic lines.
Storage dams	Located at least 200 m from mapped watercourses. Severity and likelihood of dam failure represents loss from single dam with total storage volume of 10–20 ML.
Water requirements	Approximately 15–20 ML/well is required for drilling and hydraulic fracturing during the exploration, appraisal and development stages; and 10 ML/well to refracture wells during the production stage. Water is sourced from Lake Eyre Basin or Great Artesian Basin aquifers.

Workshop participants agreed to a range of scores associated with each hazard, which allows the experts to express their uncertainty in the severity and likelihood of potential impacts. Potential hazards were then prioritised using the highest score for each interval, which meant that low-priority hazards can be 'ruled out'.

The severity of potential effects ranges from 'no impact' (severity score = 3) through to 'catastrophic impact' (severity score = 9), where there is an order of magnitude or a tenfold change in the degree of impact, its spatial extent and reversibility (Table 23). For example, the severity of potential effects is considered 'minor' (severity score = 6) if the effects are moderate, contained within the petroleum lease and reversible in five to ten years. The severity score considers potential impacts from each hazard for ecological, sociocultural and economic values.

The likelihood of potential environmental impacts ranges from 'extremely rare' or one event in 1000 years (likelihood score = –3) through to 'every day' or 365 events in one year (likelihood score = 2.5) (Table 23). A one-unit increase (or decrease) in the likelihood score indicates a tenfold increase (or decrease) in the probability of occurrence.

Table 23 Categories, descriptions and scores for severity of environmental impact and likelihood of recurrence

Category	Description	Score
Severity	**Indicative environmental impact**	
None	No impact	3
Tiny	Minimal impact on ecosystem; contained within petroleum lease; reversible in 1 year	4
Minimal	Moderate impact on ecosystem; contained within petroleum lease; reversible in 1 to 5 years	5
Minor	Moderate impact on ecosystem; contained within petroleum lease; reversible in 5 to 10 years	6
Moderate	Significant impact on ecosystem; impact across petroleum lease; reversible in ~10 years	7
Major	Significant harm or irreversible impact (for example to World Heritage Area); widespread, catchment-scale; long-term impacts, >10 years	8
Catastrophic	Incidents due to unforeseen circumstances causing significant harm or irreversible impact (for example, to World Heritage Area); widespread; long-term	9
Likelihood	**Indicative recurrence**	
Extremely rare	One event in 1000 years	−3.0
Very rare	One event in 333 years	−2.5
Rare	One event in 100 years	−2.0
Very unlikely	One event in 33 years	−1.5
Unlikely	One event in 10 years	−1.0
Possible	One event in 3 years	−0.5
Likely	One event in 1 year	0
Almost certain	Three events in 1 year	0.5
Most certain	Ten events in 1 year	1.0
Frequently	33 events in 1 year	1.5
Very frequently	100 events in 1 year	2.0
Every day	365 events in 1 year	2.5

Source: Geological and Bioregional Assessment Program (2019c)

5.2.4 Causal pathway prioritisation

Hazards that have similar potential impacts are grouped together in causal pathways. Causal pathways describe the logical chain of events – either planned or unplanned – that link unconventional gas resource development and potential impacts on water and the environment. Causal pathways often overlap or link. For example, the extraction of unconventional gas resources needs a water source for drilling and hydraulic fracturing, and flowback water needs to be managed or disposed of at the surface.

Hazards are ranked from 1 to 206 by the upper hazard score, which ranges from a maximum of 7.5 to a minimum of 1.0. Lower hazard scores range from a maximum of 4.0 to a minimum of 0.5. Ranked upper hazard scores (Figure 66) decrease rapidly for high scores (17 hazards between 7.5

and 5.5), moderately for medium-high scores (76 hazards between 5.0 and 4.0) and minimally for lower ranked scores (113 hazards between 3.5 and 1.0).

The top 8% of hazard scores (17 hazards) are prioritised for a detailed level of assessment in Stage 3 (priority 1) (Table 24). Severity of potential impact estimates range from 'minimal' (moderate impact on ecosystem; contained within petroleum lease; reversible in one to five years) to 'major' (significant harm or irreversible impact (for example, to World Heritage Area); widespread, catchment-scale; long-term impacts, >10 years). Likelihood estimates range from 'very unlikely' (one event in 33 years) to 'almost certain' (three events in one year). Seven causal pathways are included in the priority 1 hazards:

- altering cultural heritage
- altering natural habitat and species distributions
- altering surface water hydrology
- compromised well integrity
- disposal and storage of site materials
- failure of surface infrastructure (ponds, tanks, pipelines, etc.)
- introduction of invasive species.

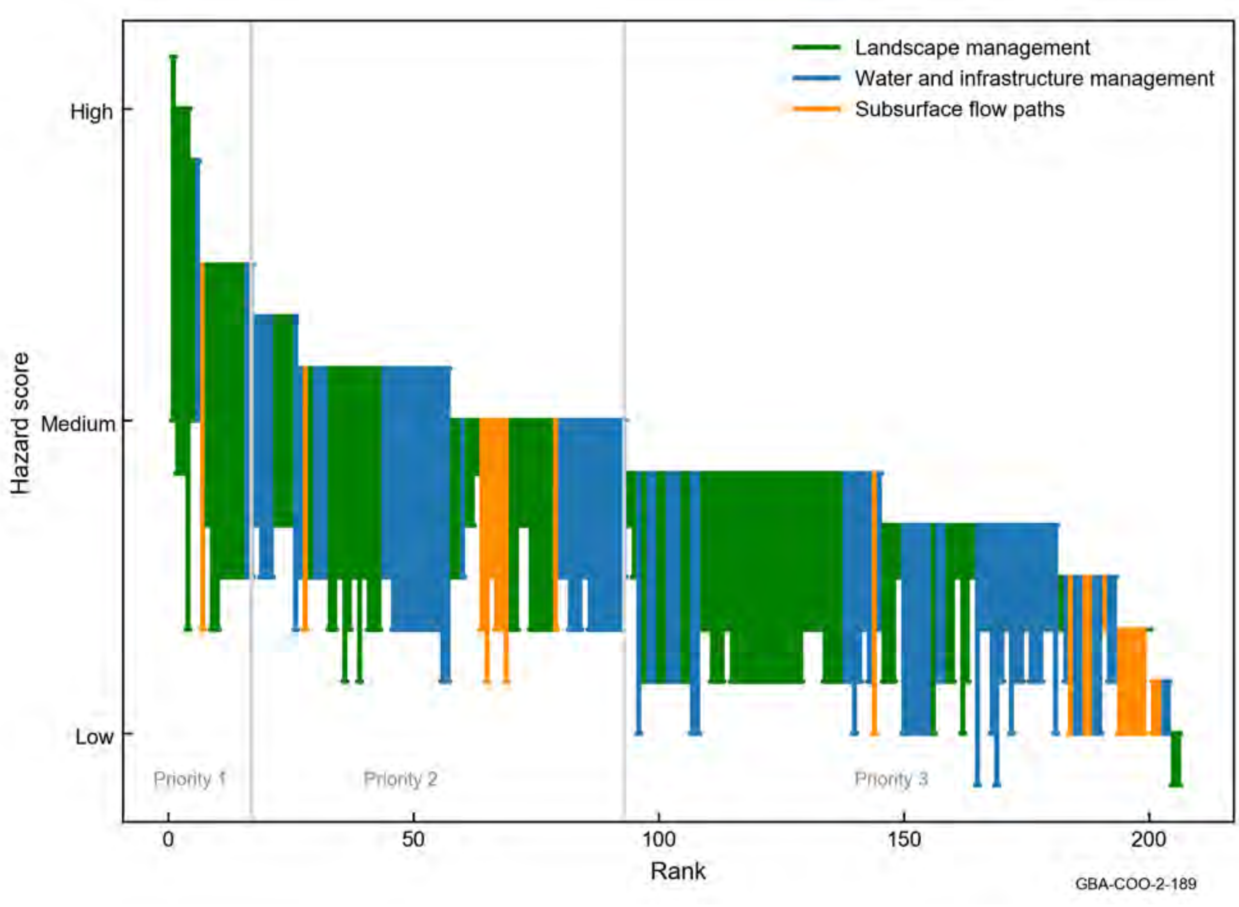

Figure 66 Upper and lower hazard scores ranked by upper hazard score for the Cooper GBA region

Hazard score = severity + likelihood scores
Source: Geological and Bioregional Assessment Program (2019c)
Element: GBA-COO-2-189

The next 37% of ranked hazard scores (76 hazards) were also prioritised for assessment in Stage 3 (priority 2) (Table 24). Severity of potential impact estimates range from 'none' to 'minor' (moderate impact on ecosystem; contained within petroleum lease; reversible in five to ten years). Likelihood estimates range from 'rare' (one event in 100 years) to 'most certain' (ten events in one year). The seven remaining causal pathways prioritised for assessment in Stage 3 (priority 2) are:

- altering natural and agricultural productivity
- discharging into surface waters
- gas extraction altering groundwaters
- hydraulic fracturing
- processing and using extracted water
- reinjecting water into aquifer
- sourcing water for site operations.

The severity and likelihood of the remaining 113 hazards does not warrant further assessment (priority 3) (Table 24). Severity of potential impact estimates for these hazards range from 'none' to 'minimal' (moderate impact on ecosystem; contained within petroleum lease; reversible in one to five years) and likelihood estimates range from 'very rare' (one event in 333 years) to 'almost certain' (three events in one year).

Table 24 Prioritisation of causal pathways for the Cooper GBA region

Causal pathway	Priority 1	Priority 2	Priority 3
'Landscape management' causal pathway group	**13**	**30**	**51**
Altering cultural heritage	2	3	2
Altering natural and agricultural productivity	0	4	16
Altering natural habitat and species distributions	4	17	22
Altering surface hydrology	3	5	4
Introduction of invasive species	4	1	7
'Subsurface flow paths' causal pathway group	**1**	**8**	**13**
Compromised well integrity	1	5	5
Gas extraction altering groundwaters	0	1	2
Hydraulic fracturing	0	2	6
'Water and infrastructure management' causal pathway group	**3**	**38**	**49**
Discharging into surface waters	0	8	2
Disposal and storage of site materials	1	7	11
Failure of surface infrastructure (ponds, tanks, pipelines, etc.)	2	13	15
Processing and using extracted water	0	7	1
Reinjecting water into aquifer	0	1	9
Sourcing water for site operations	0	2	11
Total	**17**	**76**	**113**

Source: Geological and Bioregional Assessment Program (2019c)

Six potential effects are prioritised for a detailed level of assessment in Stage 3 (priority 1) (Table 25):

- changed groundwater quality
- changed surface water flows
- cultural heritage damage or loss
- habitat fragmentation and loss
- increased competition and predation
- soil, groundwater and / or surface water contamination.

Seven additional potential effects are prioritised for assessment in Stage 3 (priority 2) (Table 25):

- bank instability and erosion
- changed air quality
- changed groundwater levels or pressures
- changed surface water quality
- increased mortality of native species
- increased soil erosion
- reduced soil productivity.

Fault reactivation and induced seismicity are not considered priorities and do not warrant further assessment in Stage 3 (priority 3) (Table 25).

Table 25 Prioritisation of potential effects for the Cooper GBA region

Potential effect	Priority 1	Priority 2	Priority 3
Bank instability and erosion	0	3	1
Changed air quality	0	3	11
Changed groundwater levels or pressures	0	3	12
Changed groundwater quality	1	6	8
Changed surface water flows	3	6	9
Changed surface water quality	0	3	1
Cultural heritage damage or loss	2	3	2
Fault reactivation and induced seismicity	0	0	4
Habitat fragmentation and loss	4	8	8
Increased competition and predation	4	1	7
Increased mortality of native species	0	5	5
Increased soil erosion	0	3	7
Reduced soil productivity	0	1	9
Soil, groundwater and/or surface water contamination	3	31	29
Total	**17**	**76**	**113**

Source: Geological and Bioregional Assessment Program (2019c)

Priority 1. Severity and likelihood of hazards warrants a detailed level of assessment

Rapid decrease in ranked upper hazard scores (Figure 66). The top 8% of hazard scores are prioritised for a detailed level of assessment in Stage 3. This includes 17 hazards with upper hazard scores between 7.5 and 5.5.

Priority 2. Severity and likelihood of hazards warrants assessment

Moderate decrease in ranked upper hazard scores. The next 37% of hazard scores (76 hazards) are prioritised for assessment in Stage 3. This includes 40 hazards with upper hazard scores between 5.0 and 4.0.

Priority 3. Severity and likelihood of hazards does not warrant further assessment

Minimal decrease in ranked scores (113 hazards between 3.5 and 1.0).

5.3 Causal pathways

Priority hazards in the 'landscape management' causal pathway group occur when best-practice design and management protocols, techniques and practices are not effective or properly implemented. Potential effects include changed surface water flows; cultural heritage damage or loss; habitat fragmentation or loss; introduction of invasive species leading to increased competition and predation and change in habitat structure; increased mortality of native species; increased soil erosion; and contamination of soil, groundwater and/or surface water.

In the 'subsurface flow paths' causal pathway group, priority hazards include water-related impacts that may occur at various depths below the surface (e.g. changes to groundwater quality or groundwater pressures within an aquifer). The likelihood of these hazards occurring is reduced by existing gas industry controls and regulatory approval conditions, including good geological knowledge, effective planning and design, monitoring, and adherence to best-practice international standards and procedures.

Priority hazards in the 'water and infrastructure management' causal pathway group occur when management protocols, techniques and practices are not effective or as a consequence of natural hazards. Potential effects include contamination of soil, groundwater and/or surface water and changes to surface waters or groundwaters – principally changes to levels, pressures or flows and water quality.

Three groups of causal pathways were identified for the Cooper GBA region: (i) 'landscape management'; (ii) 'subsurface flow paths'; and (iii) 'water and infrastructure management', as shown in Figure 67 and described in Table 26.

Section 5.3.1 describes the preliminary conceptualisation of the five causal pathways in the 'landscape management' causal pathway group in greater detail, which reflects the greater number of hazards identified as priority 1 (13 hazards) or as priority 2 (30 hazards) in this group

(Table 24). The preliminary conceptualisation for the six causal pathways in the ‘water and infrastructure management’ causal pathway group is described in less detail (Section 5.3.2), which reflects the smaller number of hazards identified as priority 1 (three hazards) or as priority 2 (38 hazards) in this group (Table 24). Section 5.3.3 provides a brief overview of the preliminary conceptualisation for the three causal pathways in the ‘subsurface flow paths’ causal pathway group, which reflects the small number of hazards identified as priority 1 (one hazard) or as priority 2 (eight hazards) in this group (Table 24).

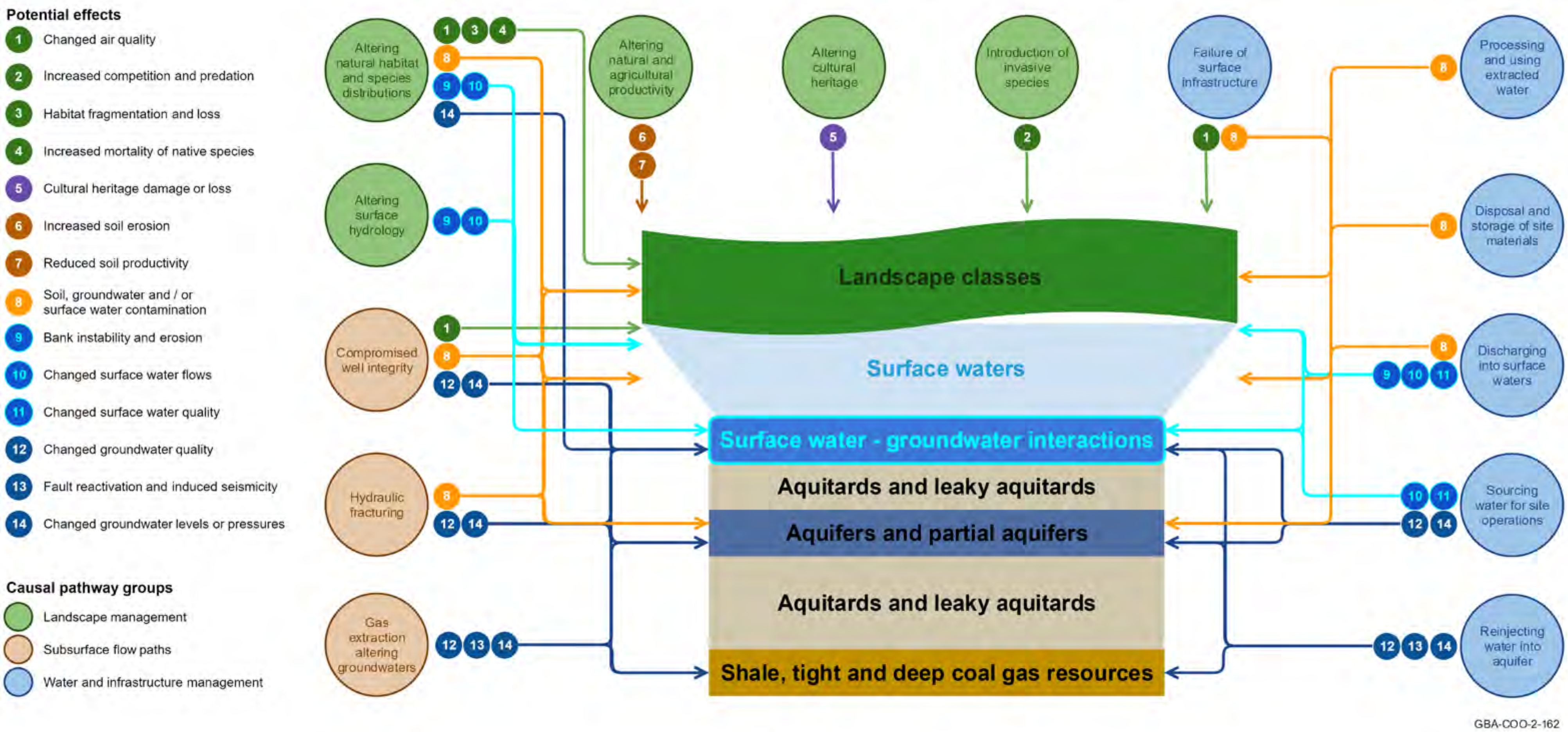

Figure 67 Causal pathways, causal pathway groups and potential effects identified for the Cooper GBA region

Arrows show how the causal pathways interact with key components: aquifers and partial aquifers; aquitards and leaky aquitards; landscape classes; shale, tight and deep coal gas resources; surface water – groundwater interactions; and surface waters. This figure has been optimised for printing on A3 paper (297 mm x 420 mm).

Typology and punctuation are consistent with the hazard identification dataset (Geological and Bioregional Assessment Program, 2019c).

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Table 26 Description of potential effects arising from hazards grouped by causal pathway and causal pathway group

Causal pathway group	Causal pathway	Potential effects
Landscape management (94 hazards)	Altering cultural heritage (7 hazards)	Construction of access roads and surface infrastructure may diminish cultural values through alteration, damage, disturbance, diminution, removal or restriction of use of cultural artefacts, ceremonial objects, rock art and cultural values. Cultural heritage clearances, training and site-based protocols manage potential impacts to cultural heritage.
	Altering natural and agricultural productivity (20 hazards)	Construction and rehabilitation of access roads, seismic surveys, surface infrastructure and well pads can cause increased soil erosion, reduced soil productivity and changed vegetation composition. Site management protocols aim to avoid sensitive areas (such as slopes, sensitive vegetation and fragile landscapes), minimise extent and timing of vegetation disturbance and earthworks and use progressive clearing and reinstatement practices to restore natural topsoil, contours and seedstock during rehabilitation.
	Altering natural habitat and species distributions (43 hazards)	Changed air quality, groundwater levels or pressures, surface water flows, soil erosion, habitat fragmentation and loss, increased mortality of native species and exposure to soil, groundwater and/or surface water contamination can affect natural habitat and species distributions. Habitat fragmentation and loss can arise through direct impacts, such as alteration of natural fire regime, excavation and site vegetation removal; and by indirect impacts, such as light and noise impacts on fauna. Mortality of native species can arise by entrapment; increased road mortality; and changes to vegetation, groundwaters and surface water bodies. Natural habitat and species distributions can also be affected by the 'introduction of invasive species' causal pathway. Site management protocols aim to avoid, minimise or mitigate potential impacts on natural habitat and species distributions.
	Altering surface hydrology (12 hazards)	Civil construction, rehabilitation and surface water extraction can alter the topography of the landscape, as well as the distribution of vegetation, which can change surface water flows and potentially cause bank instability and erosion. Surface water extraction can alter the magnitude, timing and duration of surface water flows. Water-sharing plans regulate access and provide an upper limit for surface water use. Subsurface fluid production and groundwater extraction can cause subsidence of land surface, creating artificial topographic lows where surface water may pool, altering surface water flows.
	Introduction of invasive species (12 hazards)	Construction of access roads and surface infrastructure can increase competition and predation on native species by invasive species. Invasive plants may displace or reduce cover of native vegetation, reducing available habitat and food sources (e.g. seeds) for native species such as some threatened birds. Dispersal associated with vehicle transport, landscape modification and ecosystem disturbance are managed by site-based conditions and rules. Other dispersal mechanisms associated with agricultural activities, stock movements and natural methods (via wind, water and dispersal activities by fauna) are managed by Commonwealth, state and local government regulations.

Causal pathway group	Causal pathway	Potential effects
Subsurface flow paths (22 hazards)	Compromised well integrity (11 hazards)	Failure of well barriers may create a direct fluid pathway between the target formation and overlying aquifers or the surface; or between non-target formations. Well barriers may be compromised by exposure to high fluid pressure, mechanical stresses, poor well construction, degradation of the cement or steel casing or thermal cycling. Changes to air quality, groundwater composition, levels or pressures, and soil, groundwater and/or surface water contamination may arise from compromised well integrity. After well decommissioning, abandoned wells may act as preferential pathways for fluid movement between geological layers. Well barriers ensure that control of the well is maintained during all life-cycle phases.
	Gas extraction altering groundwaters (3 hazards)	Subsurface fluid production and migration may change groundwater composition, levels or pressures and may cause fault reactivation and induced seismicity due to pressure changes in the target formation. Unlike conventional oil and gas production, the shale, tight and deep coal formations in the Cooper Basin are unlikely to yield large volumes of produced water. Target formations in the Cooper Basin are 'gas-charged', as the high pressure of the gas has expelled much of the groundwater. In addition, water-sharing plans regulate access and provide an upper limit for water use.
	Hydraulic fracturing (8 hazards)	Hydraulic fracturing increases the productivity of petroleum wells by propagating hydraulic fractures that increase the effective permeability of the reservoir. Potential impacts that may arise following hydraulic fracturing include changed groundwater levels or pressures and groundwater composition, as well as fault reactivation and induced seismicity due to pressure changes. Potential impacts may arise from unplanned fracture growth into non-target geological layers, faults or wells that have higher permeability than the natural geological layers. Potential impacts are managed to a suitably low level by state government regulatory controls, sufficient understanding of the baseline geological and environmental systems, and acceptable industry practices.
Water and infrastructure management (90 hazards)	Discharging into surface waters (10 hazards)	Storage of flowback and produced water in ponds before discharge to surface waters may change water quality and flows and lead to bank instability, erosion and contamination of soil, groundwater and/or surface waters. Discharge of water into surface water system is a regulated activity governed by specific conditions and rules. The Queensland wastewater management hierarchy means that, after treatment, beneficial reuse of wastewater is preferred, then discharge to a watercourse or evaporation if other options are not possible. Discharge of treated water into surface waters can be used to water stock, irrigate crops or manage surface water flows. However, discharge to a watercourse can interfere with aquatic ecosystems by altering natural flow regimes (e.g. change ephemeral streams into perennial streams) or changing nutrient dynamics.

Causal pathway group	Causal pathway	Potential effects
	Disposal and storage of site materials (19 hazards)	Soil, groundwater and/or surface water contamination may arise from disposal and storage of materials during construction, drilling and hydraulic fracturing, decommissioning, rehabilitation, vehicle transport, waste disposal and wastewater treatment. Potential spills from storage areas are contained by bunding and hardstand within designated facilities. Typical waste streams include cement; contaminated soils; drill cuttings; drilling and hydraulic fracturing chemicals; fluids; fertilisers and herbicides used for rehabilitation; sand; and evaporated waste from water treatment facilities, including biosolids, brines and sludge. Disposal and storage of site materials is a regulated activity governed by specific conditions and rules, particularly for waste that is stored onsite or taken offsite for disposal in an approved facility.
	Failure of surface infrastructure (ponds, tanks, pipelines, etc.) (30 hazards)	Leaks, spills or overflow from surface infrastructure during construction, drilling and hydraulic fracturing, natural hazards such as floods or bushfires, water management and rehabilitation can affect air quality and lead to soil, groundwater and/or surface water contamination. Ponds, tanks and pipelines are designed and managed to maintain integrity and operability. Management protocols include leak detection, corrosion mitigation, overpressure protection and fencing to exclude native fauna and livestock. Leaks, spills and overflow from surface infrastructure are regulated activities governed by specific conditions and rules, but (less commonly) they may be unregulated – for example, due to extreme flood inundation, natural hazards or failure of storage dams.
	Processing and using extracted water (8 hazards)	Reuse of extracted water can lead to soil, groundwater and/or surface water contamination. Beneficial or productive reuse of water is a regulated activity that aims to protect the environment and maximise the productive use of water. Reused water must meet relevant water quality guidelines for the end use and receiving environment. Potential beneficial reuse options include aquaculture, construction, dust suppression, industrial and manufacturing operations, landscaping and revegetation, and stock and domestic water supplies.
	Reinjecting water into aquifer (10 hazards)	Reinjection of water into aquifer or deep reservoirs can be used to dispose of treated wastewater (along with beneficial reuse, discharge to surface water and evaporation). Reinjection may change groundwater composition, groundwater levels or pressures and can potentially reactivate faults, leading to induced seismicity. Reinjection to dispose of treated water is unlikely in arid environments, as treated wastewater has other beneficial uses. Reinjected water is treated to remove solids and then biocide dosing and other chemical treatments ensure the water is of similar quality to that of the target formation to minimise the potential for degradation of reservoir conditions.
	Sourcing water for site operations (13 hazards)	Water is extracted from surface water and groundwaters for onsite operations. This may change groundwater composition, groundwater levels or pressures, surface water flows and surface water quality. Existing water-sharing plans regulate access and provide an upper limit on water use. Make-good provisions apply for interference with existing users and the environment.

Number of hazards in each causal pathway or causal pathway group is indicated in the brackets.
Source: Geological and Bioregional Assessment Program (2019c)

5.3.1 Landscape management causal pathways

Five causal pathways are in the 'landscape management' causal pathway group:

- altering cultural heritage (seven hazards)
- altering natural and agricultural productivity (20 hazards)
- altering natural habitat and species distributions (43 hazards)
- altering surface hydrology (12 hazards)
- introduction of invasive species (12 hazards).

The individual hazards and potential effects associated with these causal pathways in the Cooper GBA region are illustrated conceptually in Figure 68. Each causal pathway includes a range of different impact modes and potential effects identified through the IMEA process, most of which are focused on impacts at the land surface, such as habitat fragmentation and loss, increased competition and predation from invasive species, changed surface water flows and increased mortality of native species.

Priority hazards are identified in all five causal pathways:

- altering cultural heritage (five out of seven hazards)
- altering natural and agricultural productivity (four of 20 hazards)
- altering natural habitat and species distributions (21 out of 43 hazards)
- altering surface hydrology (eight out of 12 hazards)
- introduction of invasive species (five out of 12 hazards).

Potential effects associated with priority hazards in the 'landscape management' causal pathway group are:

- habitat fragmentation and loss (12 out of 20 hazards)
- changed surface water flows (six out of ten hazards)
- cultural heritage damage or loss (five out of seven hazards)
- increased mortality of native species (five out of ten hazards)
- increased competition and predation (five out of 12 hazards)
- increased soil erosion (three out of ten hazards)
- changed air quality (three out of nine hazards)
- bank instability and erosion (two out of three hazards)
- soil, groundwater and/or surface water contamination (one out of two hazards)
- reduced soil productivity (one out of ten hazards).

These hazards arise when current leading-practice design, construction and management protocols, techniques and practices are not effective or properly implemented. Potential effects that are not associated with priority hazards in the 'landscape management' causal pathway group are changed groundwater levels or pressures (one hazard).

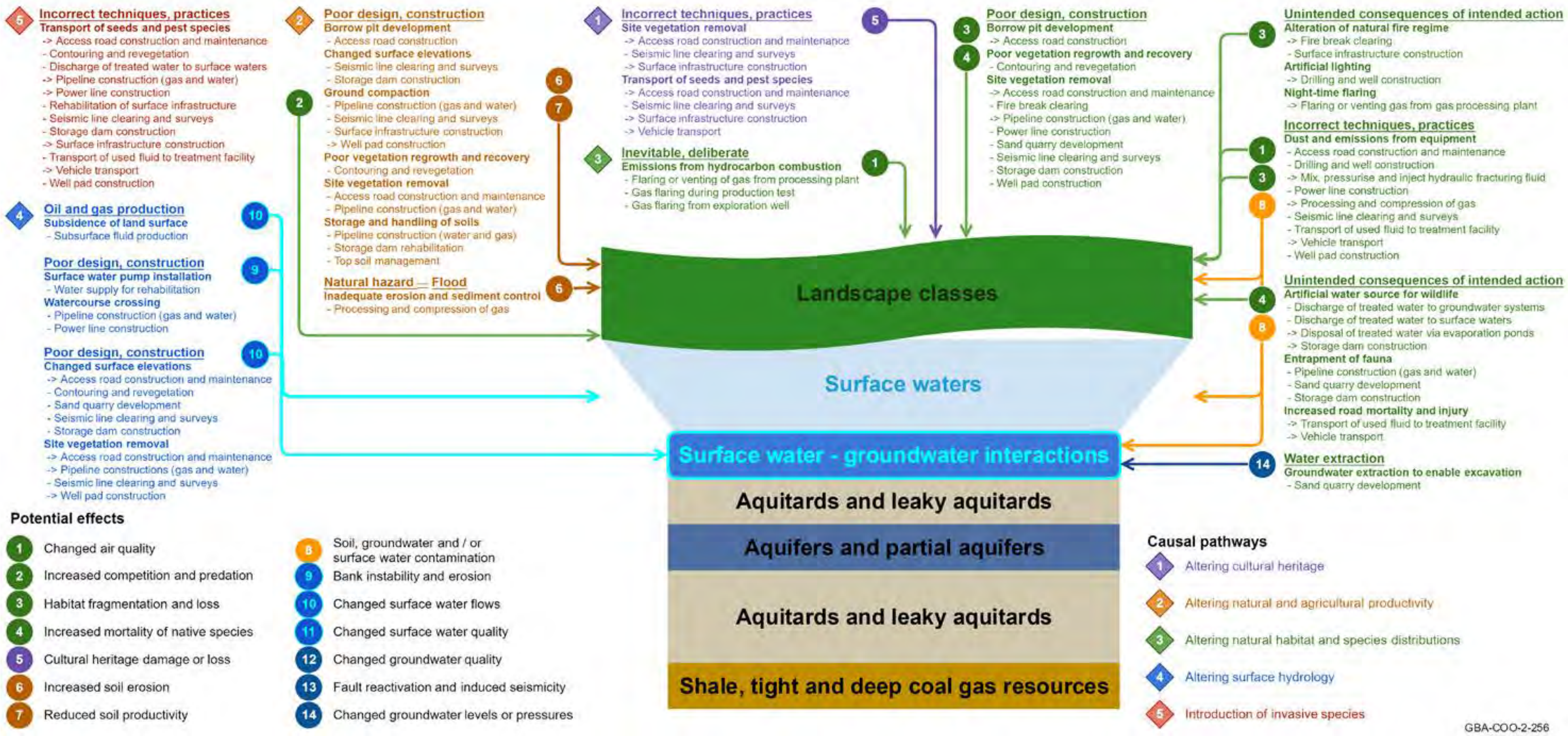

Figure 68 Hazards (impact causes, impact modes and activities) and associated effects in the 'landscape management' causal pathway group identified for shale, tight and deep coal gas development in the Cooper GBA region

Impact causes are underlined, impact modes are bold, activities are bullet points (low-priority hazards = '-' and priority hazards = '->'). An individual activity may lead to more than one hazard if multiple potential effects are associated with an activity. Arrows show how the individual hazards interact with key components: aquifers and partial aquifers; aquitards and leaky aquitards; landscape classes; shale, tight and deep coal gas resources; surface water – groundwater interactions; and surface waters. Causal pathways are identified by number and text colour. This figure has been optimised for printing on A3 paper (297 mm x 420 mm).

Typology and punctuation are consistent with the hazard identification dataset (Geological and Bioregional Assessment Program, 2019c).

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Altering cultural heritage

Cultural heritage sites can be physically, socially and spiritually linked to ecologically significant areas and archaeological or historic sites across the region (Figure 57). Risks to cultural heritage in the Cooper GBA region are related to site vegetation removal (three hazards) and transport of seeds and pest species (four hazards), which may alter values associated with water resources, vegetation and wildlife that have strong connections with cultural traditions (Constable et al., 2015). Traditional Owners value their country and have good knowledge of ecosystem function and the physicochemical and biological processes that drive an ecosystem and sustain life (Trivedi et al., 2018), particularly the links between water, vegetation and wildlife in arid landscapes. Damage or loss of cultural heritage values may permanently diminish cultural values for a community or group. Waterholes, lakes and rivers have spiritual values, with many sites attached to creation stories. Traditional Owners are concerned about damage to sacred sites that may restrict or inhibit use as a cultural or ceremonial site. This includes waterholes associated with customary rituals, such as women's business and historic burial sites (Constable et al., 2015).

The Cooper GBA region also contains historic heritage sites (see Section 4.2) associated with the early explorers, Burke and Wills. Impacts from gas development operations on surface water flow and water quality and siltation could potentially affect tree survival. Increased visitation to the sites may also increase vehicle traffic, which may lead to erosion and damage to the site.

Risks to cultural heritage values in the region include potential changes to water resources, including bank erosion from release of treated water; or shrinkage of spring-fed waterholes from water extraction (surface water and groundwater). Construction activities and changes to water regimes may also facilitate the introduction and establishment of invasive species that can diminish cultural heritage values.

Vegetation removal for the development of roads and surface infrastructure could potentially remove food and medicinal plants and may also affect cultural values associated with natural habitat and species distributions. Site vegetation removal that causes minor to moderate damage or loss to cultural heritage (reversible in ten years or less) is a priority hazard in the Cooper GBA region. Changes to cultural heritage can affect food supply and cultural connectedness of Traditional Owners. Introduction of invasive weeds and pests could also change vegetation composition, potentially affecting cultural values (Figure 69). Incorrect techniques or practices used during development may remove, damage or substantially disturb cultural artefacts, archaeological deposits, Indigenous built structures or ceremonial objects. This includes resource areas, paintings, engravings, scar trees, quarries, shell middens, dwellings, burial sites, landscape features, artefact scatters, stone arrangements, hearth ovens, pathways and important story places (Constable et al., 2015).

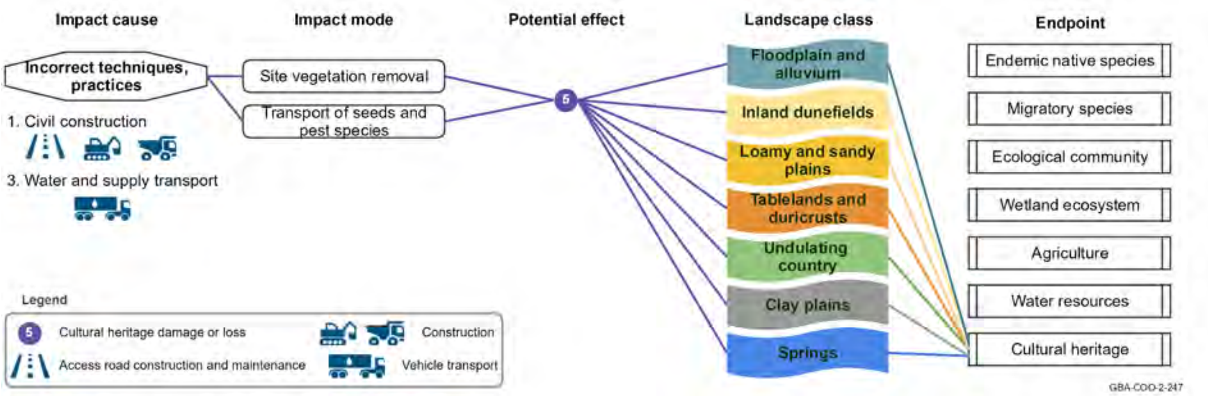

Figure 69 Preliminary conceptualisation of hazards associated with future shale, tight and deep coal gas development in the Cooper GBA region for the 'altering cultural heritage' causal pathway

Numbered items refer to the ten major activities described in Figure 64 e.g. '1. Civil construction'
Data: Geological and Bioregional Assessment Program (2019c)
Element: GBA-COO-2-247

Cultural heritage consultation and clearances, along with training and education to promote awareness of cultural heritage values and to improve recognition of culturally sensitive areas, are part of existing site-based management protocols.

Altering natural and agricultural productivity

Risks to natural and agricultural productivity in the Cooper GBA region include increased soil erosion (ten hazards) and reduced soil productivity (ten hazards). Increased soil erosion is caused by disturbance to the soil structure by natural or mechanical means, which causes removal of rocks and soil particles and changes in landform. Poor design and construction of access roads, borrow pits, pipelines (gas and water), seismic surveys, surface infrastructure and well pads can alter drainage pathways, increase soil erosion and reduce soil productivity. Increased soil erosion due to ground compaction during well pad construction is a priority 2 hazard. It is possible (one event in three years) that the severity will be minimal – a moderate impact on ecosystems that is reversible in one to five years.

Changes to surface elevations, site vegetation removal, poor topsoil management and ground compaction from earthmoving equipment can reduce soil productivity in nutrient-poor environments, and this may reduce regrowth and recovery during the re-establishment of native flora as part of site rehabilitation. Changes to surface water flows, spring and waterhole depth and extent, and water quality from unconventional gas resource development operations can also affect natural and agricultural productivity through change in soil moisture (too much or too little) and loss of waterhole connectivity. Removal of nutrients from soil erosion and facilitation or introduction of invasive species can also affect the productivity of natural ecosystems. Changes to soil structure can also alter agricultural productivity.

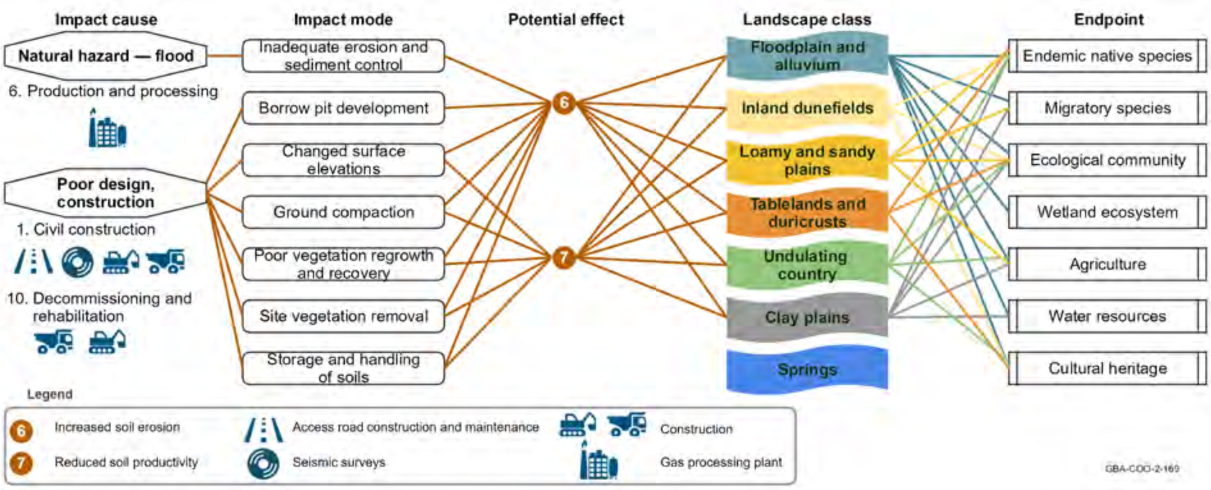

Figure 70 Preliminary conceptualisation of hazards associated with shale, tight and deep coal gas development in the Cooper GBA region in the 'altering natural and agricultural productivity' causal pathway

Numbered items refer to the ten major activities described in Figure 64 e.g. '1. Civil construction'.
Data: Geological and Bioregional Assessment Program (2019c)
Element: GBA-COO-2-169

Site management protocols aim to mitigate risks by minimising construction footprints and avoiding fragile areas, including slopes, water bodies and sensitive vegetation communities. Earthworks are planned to minimise vegetation disturbance, as well as protect and restore the natural topsoil layer by using contouring during rehabilitation.

Altering natural habitat and species distributions

Natural habitat and species distribution may be affected in a number of ways, including habitat fragmentation and loss (20 hazards), increased mortality of native species (ten hazards), changed air quality (nine hazards), contamination of soil, groundwater and/or surface water (two hazards), changed groundwater levels or pressures (one hazard) and changed surface water flows (one hazard) (Figure 71). In particular, land clearance is a key threatening process identified under the EPBC Act. Vegetation removal can potentially affect both terrestrial and aquatic environments, as well as removing ground cover that is important natural habitat.

Suitable habitat for threatened species – for example, the critically endangered plains-wanderer *Pedionomus torquatus* – can also be reduced following disturbance when invasive species out-compete native vegetation, creating monocultures (see the 'introduction of invasive species' causal pathway, Figure 74). Introduced plant species, such as invasive grasses, can also increase the severity and likelihood fire, which can be detrimental to fire-sensitive plant communities and less mobile native wildlife.

Artificial watering points can also alter natural habitat and species distributions by allowing some native species populations to increase or by allowing introduced species to establish within the area, thereby creating an imbalance within the ecosystem – for example, an increased number of predators in a region – and potentially impacting on threatened species. Populations of introduced species – for example, feral pigs and unmanaged goats – can lead to increased erosion that can also result in change in habitat structure.

Changing surface water flows can alter flooding regimes, which can impact on species distributions and natural habitat when surface flow is reduced, or increased, in areas in which native species are not adapted to the changed flow regime. This is can lead to increased mortality or reduced productivity of the water-sensitive species.

Dust and emissions from equipment occur throughout development, but effects on natural habitat and species distributions are greatest when incorrect techniques or practices are used when mixing drilling and hydraulic fracturing fluids, during processing and production of gas and from vehicle transport. Compounds and particulate matter emitted during operation of wells can lead to air pollution, including nitrogen oxides, sulphur dioxide, carbon monoxide and volatile organic compounds (Huddlestone-Holmes et al., 2018). Noise and light pollution can also affect habitat quality and species distribution. Terrestrial mammals, birds and reptiles are at risk due to collisions with increased vehicle traffic during development. Entrapment of native fauna in quarries, dams and trenches – that is, pitfall traps – can also increase mortality of native species.

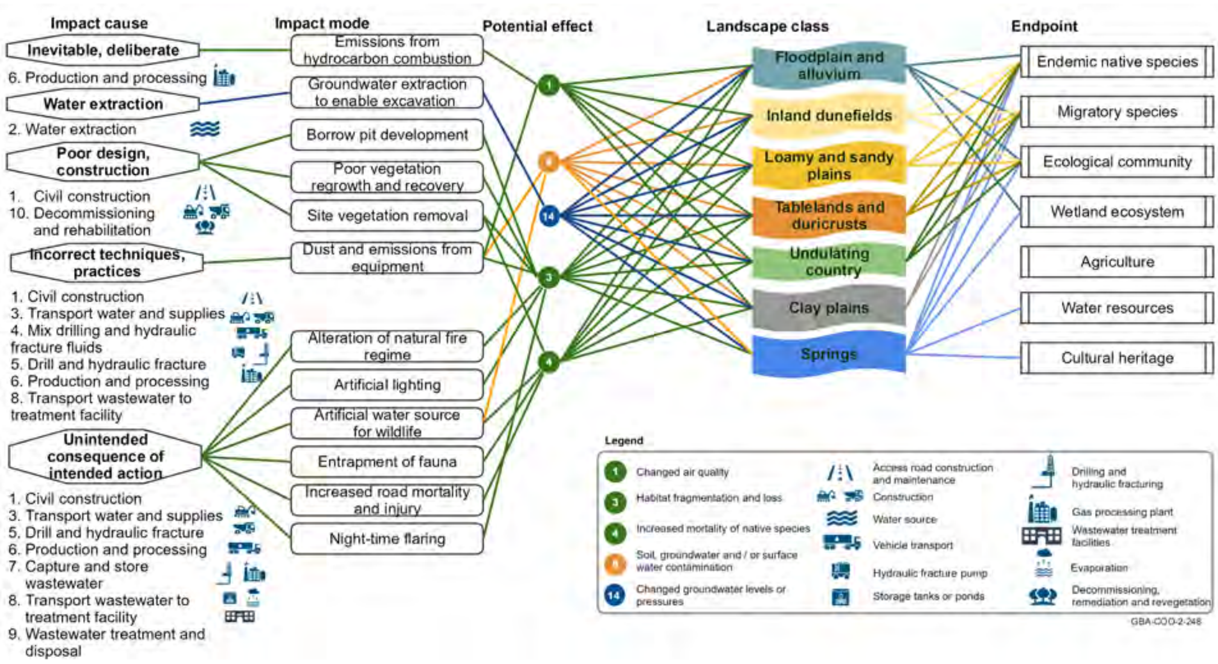

Figure 71 Preliminary conceptualisation of hazards associated with shale, tight and deep coal gas development in the Cooper GBA region in the 'altering natural habitat and species distribution' causal pathway

Numbered items refer to the ten major activities described in Figure 64 e.g. '1. Civil construction'.
Data: Geological and Bioregional Assessment Program (2019c)
Element: GBA-COO-2-248

Other priority hazards that may cause habitat fragmentation and loss include unintended consequences of intended actions, such as alteration of natural fire regime during construction of fire breaks; artificial lighting during drilling and well construction; artificial water sources for wildlife, such as evaporation ponds; increased road mortality and injury from vehicle transport; and night-time flaring from gas processing plants. Poor design or construction of access roads and pipelines for borrow pits and site vegetation removal are priority hazards that may have a moderate impact on ecosystems that is reversible in less than ten years.

Construction and maintenance of roads, pipelines and seismic survey lines can lead to habitat fragmentation and loss through removal of vegetation. In excess of 81,000 km of two-dimensional seismic surveys and over 10,000 km^2 of three-dimensional seismic surveys have been conducted in the Cooper GBA region (see Figure 24 in Section 2.2). Historically, methods used to clear vegetation for seismic surveys permanently fragmented the landscape – for example, a two-dimensional seismic survey at Tirrawarra floodplain in 1982, which remains evident in aerial photographs taken in 2006 and 2016 (Figure 72). New acquisition methods used for recent seismic surveys result in more rapid vegetation recovery – for example, a three-dimensional seismic survey at Baryulah floodplain in 2004 (shown in 2006 in Figure 72) is no longer evident in 2018. Recent analysis of seismic surveys in the Cooper GBA region found that vegetation takes seven to eight years to recover in dune and floodplain land systems, and up to ten to 20 years in gibber plain land systems (Doudy and Cockshell, 2016).

Site management protocols aim to avoid, minimise or mitigate potential impacts on natural habitat and species distributions. Mitigation measures include reducing the development footprint and ensuring earthworks are conducted with minimal damage and rehabilitated as soon as possible. Training is provided for fauna identification and habitat restoration to ensure fauna entrapment does not occur, including leaving measures for fauna to escape during construction or assisting with relocation of trapped fauna. Site-based protocols to mitigate impacts of dust and emissions, including noise and light, involve monitoring of air quality and ensuring that noise and light emissions are minimised in space and time.

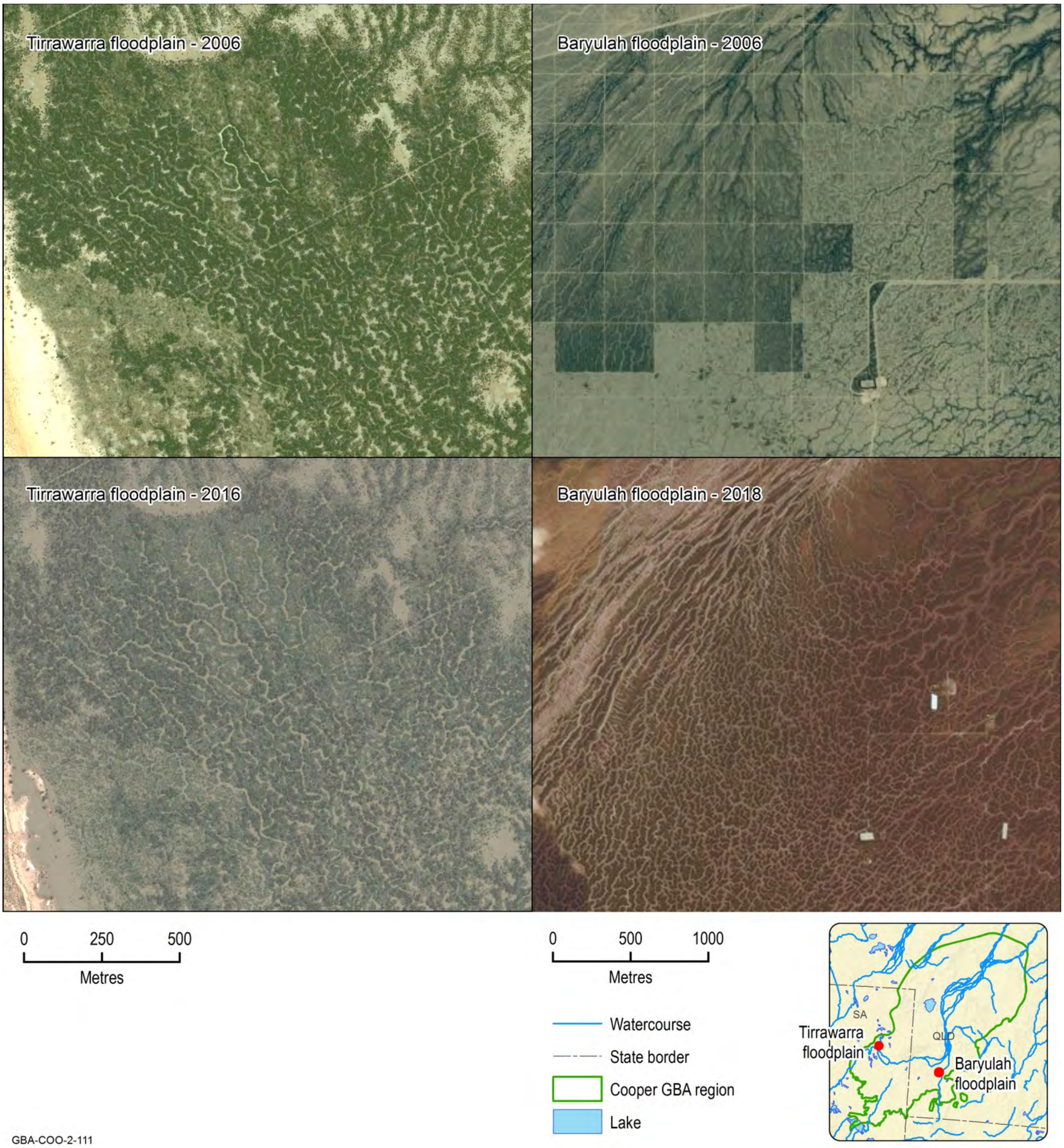

Figure 72 Comparison of seismic lines observed on the Cooper Creek floodplain at Tirrawarra (two-dimensional seismic survey conducted in 1982) and Baryulah (three-dimensional seismic survey conducted in 2004) in aerial photography from 2006, 2016 and 2018

Source: The 2006 and 2016 images are from Google Earth Pro 7.3 (2019) Map data: © 2019 DigitalGlobe © 2019 CNES Distribution Airbus DS (image acquisition: 2006; 2016). The 2018 image is from Bing Maps Aerial © 2019 Microsoft Corporation Map data: © 2019 DigitalGlobe ©CNES (2019) Distribution Airbus DS (image acquisition: 2018)
Element: GBA-COO-2-111

Altering surface hydrology

Surface water hydrology may be affected by bank instability and erosion (three hazards), as well as changed surface water flows (nine hazards) (Figure 73). This is most likely to occur in channels and on floodplains but can also occur anywhere in the landscape where surface water flows occur. Activities related to reducing surface water availability due to extraction of water for hydraulic fracturing and disposal of treated flowback water are described in the 'water and infrastructure management' causal pathway group (see Section 5.3.3). Four of the 12 activities that can alter surface hydrology are identified as priority 1 or 2 hazards, including construction of access roads and well pads that could affect the magnitude, duration, timing and frequency of surface water flows.

To assess potential impacts to surface hydrology from future shale, tight and deep coal gas development, a two-dimensional hydrodynamic flow model will be developed in Stage 3 from a high-resolution LiDAR aerial survey of the Cooper Creek floodplain. The flood inundation model will allow the potential impacts and risks to protected matters due to changes in surface water flows to be assessed for a range of future development scenarios.

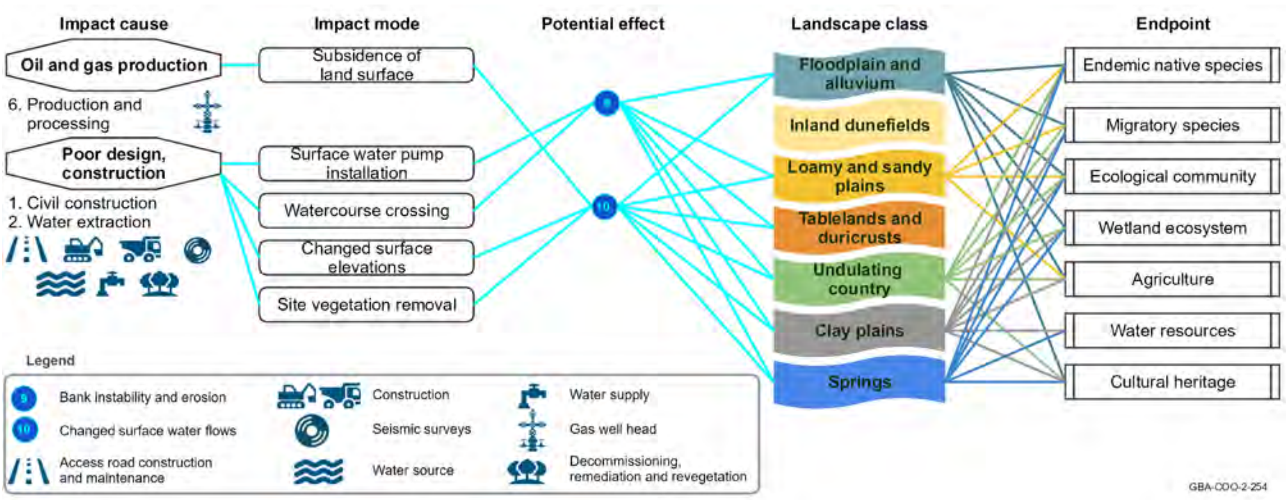

Figure 73 Preliminary conceptualisation of hazards associated with future shale, tight and deep coal gas development in the Cooper GBA region in the 'altering surface hydrology' causal pathway

Numbered items refer to the ten major activities described in Figure 64 e.g. '1. Civil construction'.
Data: Geological and Bioregional Assessment Program (2019c)
Element: GBA-COO-2-254

Surface disturbance occurs during all stages of development and can potentially increase sediment load in surface waters. Siltation of streams and waterholes, as well as a decline in surface water quality associated with changed water regimes, can negatively impact aquatic flora and fauna by decreasing fitness and survival of aquatic plants, invertebrates and fish.

Santos use management protocols to minimise the impact of road construction on surface waters, including ensuring that roads and access tracks are constructed in accordance with applicable Australian standards and state legislation. Erosion control measures are installed where required and 'where relevant, a detailed hydrological assessment is undertaken for these structures to ensure that there are no significant impacts on surface water flows or aquatic fauna' (Santos, 2015).

Introduction of invasive species

Invasive species can be introduced through incorrect techniques or practices throughout development (12 hazards) (Figure 74). Transport of seeds and pest species during construction of access roads, pipelines, powerlines and surface infrastructure, as well as transport of water and supplies, may have a moderate to major impact on ecosystems. Four of the 12 hazards in the 'introduction of invasive species' causal pathway are identified as priority 1 hazards, including construction and maintenance of access roads, pipelines (gas and water), power lines and other surface infrastructure. Introduction of invasive species via vehicle transport is a priority 2 hazard.

Once weeds and pests become established, eradication becomes very difficult. Disturbance of ground cover provides opportunities for weeds to establish. Weeds are typically fast growing and reach reproductive capability before native species, therefore out-competing native species in disturbed soils. Pest plant seeds can be introduced by vehicles and machinery during construction and maintenance activities. Soil disturbance and vegetation removal increase the risk of establishment of introduced plants.

Pest species can also become established when areas are disturbed. Predators, such as wild dogs and foxes, will use access roads, increasing predation rates on native species in these areas. However, this effect is less prevalent in rangeland environments, where predator movement is less impeded, than in forested environments. Predators also congregate where food resources are more plentiful. Newsome et al. (2013) observed larger group size and smaller home ranges of dingoes in arid areas near supplementary food resources from mine camps than for dingoes where no supplementary food resources occurred. If the supplementary food resource stops, such as when mining activity in the area ends, these larger packs could turn to more natural food sources, affecting local wildlife populations.

Invasive species can also alter habitat structure and food sources that may be crucial for threatened species, such as the invasive buffel grass (*Cenchrus ciliaris*), which can out-compete native grasses, forming a dense spreading tussock that limits habitat for invertebrates and some native birds, as well as limiting native seed sources for granivorous birds. Invasive plants can also change the fire regime for an area, increasing risk of fire that may be detrimental to any fire-sensitive native plants (Friedel et al., 2006).

Pest species can also take advantage of artificial water points, such as water tanks and leaking pipes, as well as storage dams, and this can allow pests to become established. Artificial water points can attract introduced species, such as feral goats (*Capra hircus)* and cane toads (*Rhinella marina*), that can be detrimental to local wildlife (Letnic et al., 2014). Uncontrolled outflow of groundwaters from artesian bores can increase the potential for populations of gambusia to invade spring habitats and threaten their endemic fish species (Lake Eyre Basin Ministerial Forum, 2017).

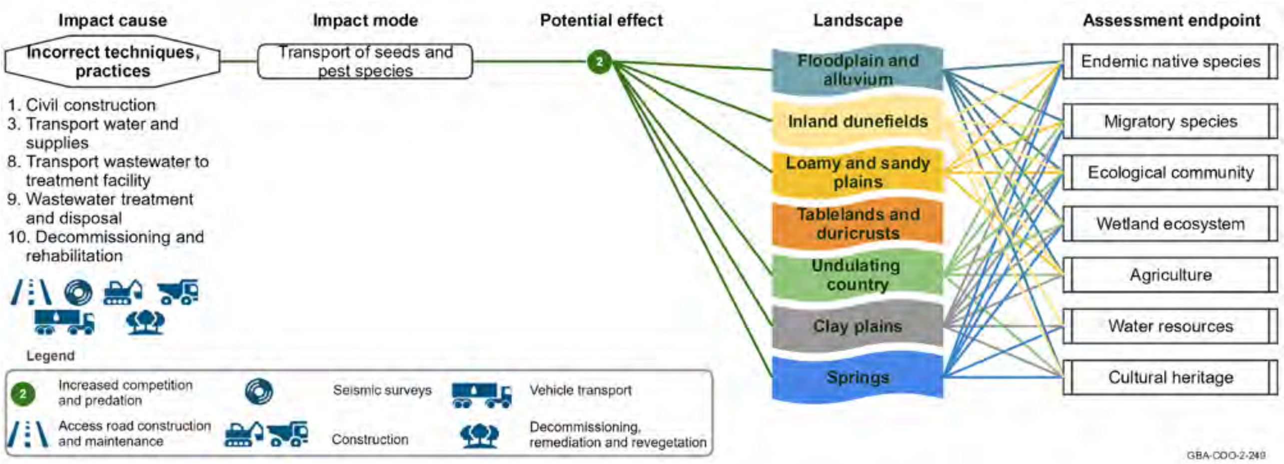

Figure 74 Preliminary conceptualisation of hazards associated with future shale, tight and deep coal gas development in the Cooper GBA region in the 'introduction of invasive species' causal pathway

Numbered items refer to the ten major activities described in Figure 64 e.g. '1. Civil construction'.
Data: Geological and Bioregional Assessment Program (2019c)
Element: GBA-COO-2-249

Site-based protocols include vehicle and machinery cleaning, when arriving and leaving sites, to remove all seeds or plant material – particularly washdown of drill rigs for interstate movement. Most introduced plants in the Cooper GBA region are naturalised or widespread species of limited concern. Of particular concern are invasive species, such as buffel grass (*Cenchrus ciliaris*) and Noogoora burr (*Xanthium strumarium*), Mexican poppy (*Argemone ochroleuca* ssp. *ochroleuca*) and couch grass (*Cynodon dactylon*) (Santos, 2015). Management protocols target the detection and assessment of the spread of pest plants and animals.

5.3.2 Subsurface flow paths causal pathways

Three causal pathways are in the 'subsurface flow paths' causal pathway group:

- compromised well integrity (11 hazards)
- hydraulic fracturing (eight hazards)
- gas extraction altering groundwaters (three hazards).

'Subsurface flow paths' causal pathways are focused on water-related impacts that may occur at various depths below the surface, such as changes to groundwater quality or groundwater pressures in an aquifer (Figure 75).

Priority hazards are identified in all three causal pathways:

- compromised well integrity (six out of 11 hazards)
- hydraulic fracturing (two out of eight hazards)
- gas extraction altering groundwaters (one out of three hazards).

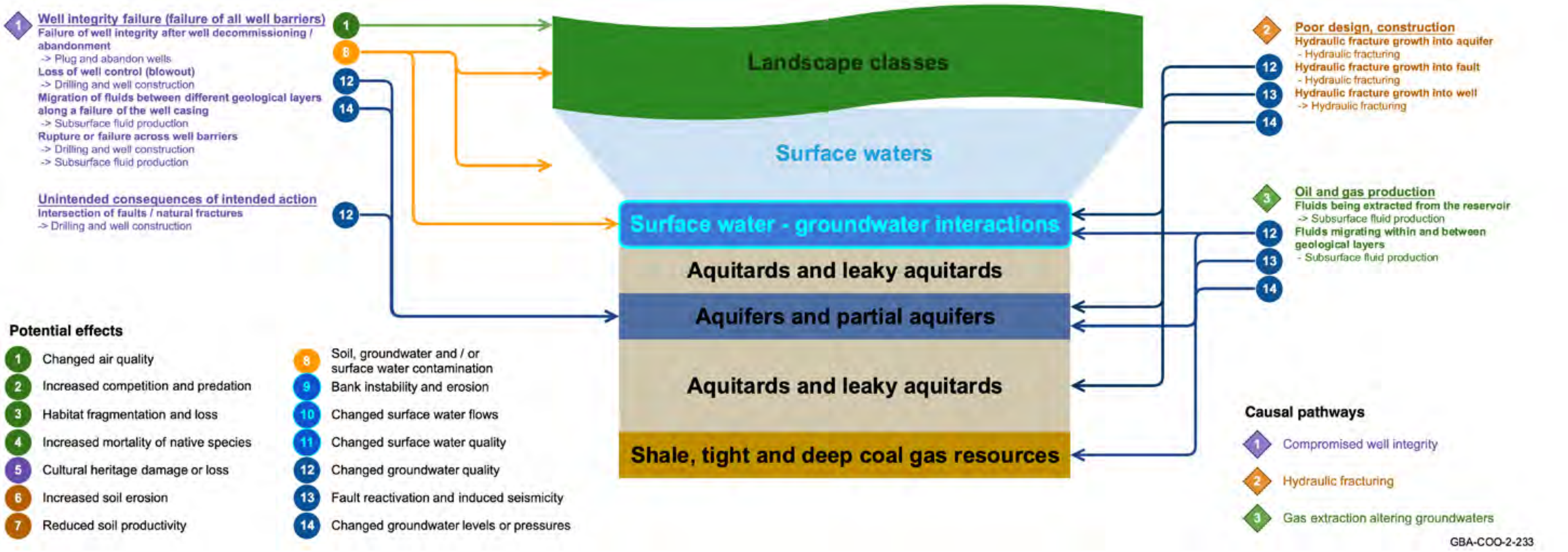

Figure 75 Hazards (impact causes, impact modes and activities) and associated effects in the 'subsurface flow paths' causal pathway group identified for shale, tight and deep coal gas development in the Cooper GBA region

Impact causes are underlined, impact modes are bold, activities are bullet points (low-priority hazards = '-' and priority hazards = '->'). An individual activity may lead to more than one hazard if multiple potential effects are associated with an activity. Arrows show how the individual hazards interact with key components: aquifers and partial aquifers; aquitards and leaky aquitards; landscape classes; shale, tight and deep coal gas resources; surface water – groundwater interactions; and surface waters. Causal pathways are identified by number and text colour. This figure has been optimised for printing on A3 paper (297 mm x 420 mm).
Typology and punctuation are consistent with the hazard identification dataset (Geological and Bioregional Assessment Program, 2019c).
Element: GBA-COO-2-233

Compromised well integrity

The effective maintenance of well integrity throughout all life-cycle stages of a petroleum well is critical for its safe operation and to ensure the protection of water resources and the environment. This includes wells drilled to explore for, appraise or produce hydrocarbons from the types of unconventional gas reservoirs in the Cooper Basin that are the focus of the GBA Program (shale, tight and deep coal gas plays). If the integrity of a well is compromised at any stage in its life cycle (including for decommissioned wells), it may create an unintended pathway for fluids to flow either out of or into the well, or between different geological formations (potentially including aquifers), or even to the surface. For these reasons, well integrity is of paramount importance to the oil and gas industry, service companies and regulatory organisations and is also commonly recognised as a key concern of local communities in areas of unconventional gas development. Several international standards exist for managing well integrity, and current industry operations pay close attention to managing the acknowledged risks associated with drilling, installation and operation of gas wells.

Potential impacts from compromised well integrity can occur at various stages in the life cycle of a well, including during construction, while the well is in operation (i.e. producing gas) or after the well has been decommissioned (e.g. plugged and abandoned) at the end of its operational lifespan. Huddlestone-Holmes et al. (2018) summarised the four main well barrier failure mechanisms as:

- failure during drilling
- failure due to casing and cementing issues (during construction or operation)
- failure due to impact of hydraulic fracturing operations
- failure of decommissioned wells (plugged and abandoned wells after gas production has ceased).

Hazards associated with compromised well integrity are most likely to have a localised impact on groundwater systems, with the potential to affect groundwater quality (five hazards) and groundwater levels or pressures (one hazard). However, if well integrity failure results in uncontrolled release of gas and/or fluids to the surface, there is also potential for changes to air quality (e.g. escape of methane to the atmosphere – three hazards), as well as contamination of soils, surface waters or shallow groundwaters (two hazards). In situations where gas and fluids are released at surface due to compromised well integrity, the most severe impacts are likely to be localised to the landscape class where the well is located, although other landscape classes may be affected to a lesser degree – for example, due to airborne dispersal of methane (Figure 76).

The highest priority hazards in the compromised well integrity pathway relate to potential impacts on groundwater quality (three priority hazards). The uncontrolled migration of fluids between different geological layers due to well casing failure is the highest priority hazard in this causal pathway group. This hazard is of particular concern in situations where fluids migrate into an aquifer that is used as a water source to support ecological, economic or cultural values – for example, where changes to groundwater quality affect the source aquifer for an important spring ecosystem; or where groundwater quality changes affect an aquifer being used as a pastoral water supply. Consequently, the most likely landscape classes to be affected by well integrity failure are the 'springs' and 'floodplain and alluvium' classes.

Failure of integrity after decommissioning of a well is a priority 2 hazard for the Cooper GBA region. It can affect groundwater quality, potentially leading to similar effects on aquifers as noted above. It is possible (one event in three years) that the severity will be minimal – a moderate impact on ecosystems that is reversible in one to five years.

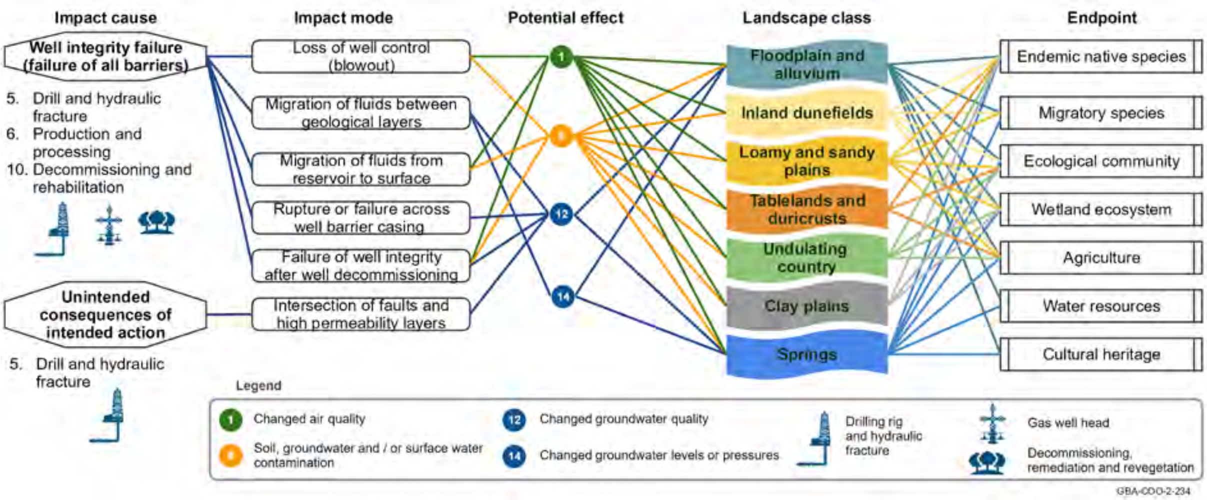

Figure 76 Preliminary conceptualisation of hazards associated with shale, tight and deep coal gas development in the Cooper GBA region in the 'compromised well integrity' causal pathway

Numbered items refer to the ten major activities described in Figure 64 e.g. '1. Civil construction'.
Data: Geological and Bioregional Assessment Program (2019c)
Element: GBA-COO-2-234

Prior to the drilling and operation of a shale, tight or deep coal gas well, considerable planning is required to ensure that the well can be installed and operated safely and efficiently. For example, it is critical to understand key geological parameters of the gas reservoir and the surrounding rock formations so that the well is designed to withstand the local geological conditions. Good knowledge of local geology that guides the installation of an appropriately designed well is essential in ensuring that well integrity is maintained throughout all life-cycle stages. Well barriers and operational practices are designed to prevent the uncontrolled release of fluids – between the well and geological formations, between geological formations or to the surface. Well barriers are the main features of the well that ensure its integrity. They include well barrier elements such as drilling muds, steel drill casing, high-quality cement, well heads and blowout preventers. There are also various operational, administrative and regulatory aspects to successfully maintaining well integrity (Huddlestone-Holmes et al., 2018).

In addition to the IMEA hazard identification, a more detailed qualitative analysis of well integrity and hydraulic fracturing was undertaken in Stage 2 of the GBA Program for the Cooper GBA region, leading to a supporting technical appendix (see Kear and Kasperczyk (2020), with a summary provided in Section 6.2). The specific focus on these aspects of unconventional gas resource development was considered appropriate given the high level of community concern raised about these issues at the first user panel meeting for the Cooper GBA region. This review focused in detail on summarising the findings from nine domestic and international inquiries, as well as analysing Cooper Basin data relating to historical well integrity failures.

Hydraulic fracturing

Hydraulic fracturing is a subsurface engineering technique routinely applied following drilling of a production well to increase the production rate of unconventional gas resources, such as those from shale, tight and deep coal gas reservoirs within the Cooper Basin. Hydraulic fracture fluid, consisting of water, proppant (such as sand) and various chemical additives, is injected into the target reservoir via the well at high pressures to fracture (stimulate) these otherwise low-permeability rocks. Hydraulic fracturing creates a network of fractures within the unconventional gas target reservoir (e.g. shale, tight or deep coal formation), directly connecting fractures to the well. The created fractures are held open by the proppant once the hydraulic fracture fluid pressure is released, and the propped fractures serve to increase the permeability of the reservoir. The newly enhanced permeability allows for gas to flow from the reservoir to surface via the well.

Hydraulic fracturing of an unconventional gas well is usually undertaken in multiple stages, typically along sections of a horizontally drilled well (or near-horizontal well). Aspects of the hydraulic fracturing process, such as volume and rate of the injected hydraulic fracturing fluid and the pressure applied, depend greatly on the local geological conditions, such as rock strength and in-situ stresses of the target reservoir. Hydraulic fracturing stages are designed to restrict the fracture network to the target reservoir, thereby minimising the growth of fractures into surrounding (non-target) geological layers and/or structures. This helps to maximise gas production rates and reduces the potential for unintentional flow of gas or fluids away from the reservoir.

Potential effects that may arise during hydraulic fracturing (Figure 77) of shale, tight and deep coal gas wells include changes to the groundwater quality of an aquifer (three hazards) and changes to groundwater pressures in confined aquifers (three hazards). These effects arise due to the unplanned release of hydraulic fracturing fluids into subsurface formations beyond the extent of the target gas reservoir. There is also potential for hydraulic fracturing to intersect other petroleum or water supply wells that could contaminate soil, groundwater or surface waters (one hazard). Growth of a fracture into a fault that could lead to fault reactivation and induced seismicity was also considered (one hazard). Elevated cyclical pressures applied to wells during hydraulic fracturing could also affect the integrity of the well (Huddlestone-Holmes et al., 2018), which is addressed by the ‘compromised well integrity’ causal pathway (Figure 76).

The main impact modes associated with hydraulic fracturing relate to the unplanned or unexpected growth of a fracture beyond the extent of the unconventional gas target reservoir. This could result in part of a hydraulic fracture network intersecting a non-target geological layer (such as an aquifer), a permeable fault zone, or even another existing water bore or petroleum well (including abandoned wells). In these cases, the hydraulic fracture network grows larger than intended, potentially leading to the unintentional migration of hydraulic fracturing fluids into subsurface formations other than the gas reservoir, potentially affecting the quality of deep groundwaters. Potential impacts at the surface are very unlikely due to the typical depths at which hydraulic fracturing of unconventional gas reservoirs occur in the Cooper Basin (e.g. commonly greater than 3 km below surface).

Section 6 summarises the more detailed qualitative evaluation of drilling and hydraulic fracturing chemicals (see Section 6.1) and hydraulic fracturing (see Section 6.2). Hydraulic fracturing fluids contain a diverse range of chemical additives, meaning that there are risks (and significant community concerns) associated with the unintended release of such fluids into other geological units. However, domestic and international inquiries (US EPA, 2016a; Hawke, 2014; Cook et al., 2013b; The Royal Society and The Royal Academy of Engineering, 2012; Wright, 2014; Council of Canadian Academies, 2014; Atherton et al., 2014; Pepper et al., 2018; Hatton et al., 2018) all find that likelihoods of these impact modes range between ‘unlikely’ and ‘rare’, and that risks associated with hydraulic fracturing are manageable to suitably low levels. Recent research from (Shanafield et al., 2018) fits vertical hydraulic fracture growth data from Davies et al. (2012) to a log normal distribution to estimate the likelihood of hydraulic fractures intersecting an overlying aquifer as 1 in 1,000,000 or less for a vertical separation of 2000 m. Knowledge gaps related to the likelihood of hydraulic fracture intersection of an overlying aquifer and separation distance between unconventional gas reservoirs and aquifers in the Cooper GBA region are discussed in Section 6.2 (and the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020)).

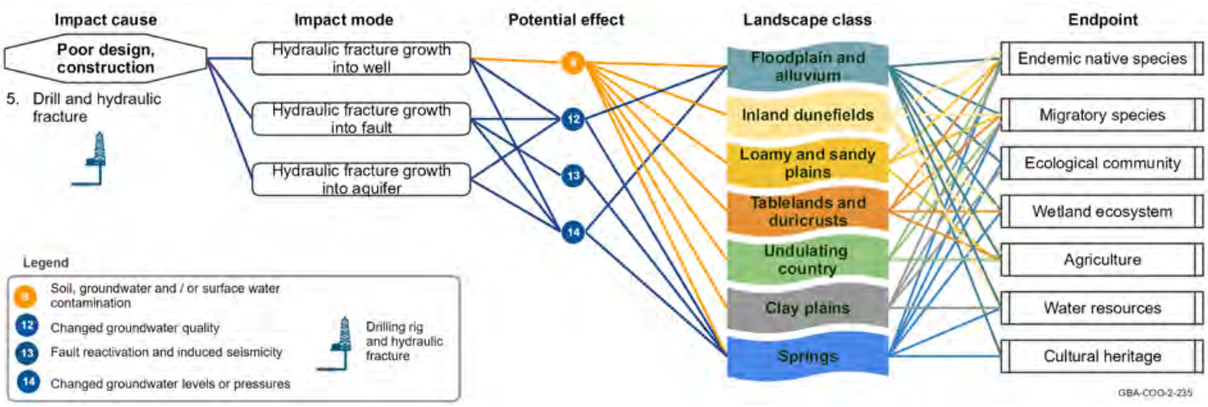

Figure 77 Preliminary conceptualisation of hazards associated with shale, tight and deep coal gas development in the Cooper GBA region in the ‘hydraulic fracturing’ causal pathway

Numbered items refer to the ten major activities described in Figure 64 e.g. ‘1. Civil construction’.
Data: Geological and Bioregional Assessment Program (2019c)
Element: GBA-COO-2-235

Effective planning, design and implementation of each hydraulic fracturing stage are critical to ensuring that the risks to groundwater associated with hydraulic fracturing are adequately managed. Given adherence to existing controls and guidelines designed to safeguard the process, the risks posed by hydraulic fracturing are generally regarded as acceptable to both the gas industry and government regulators. Indeed, the IMEA for the Cooper GBA region ranked all hazards associated with the 'hydraulic fracturing' causal pathway as priority 3 hazards – the lowest tier of hazards classified in this assessment. However, due to heightened community concern related to hydraulic fracturing impact modes, the qualitative assessment outlined in Section 6.2 recommends undertaking analysis in Stage 3 of the Cooper GBA to further evaluate the potential for hydraulic fracture growth into overlying aquifers specific to the unconventional gas target reservoirs in the Cooper GBA region.

Gas extraction altering groundwaters

Production of gas from unconventional reservoirs may cause changes in reservoir pressures as gas is extracted during the life of the well (typically ten to 20 years), with potential effects on the quality and/or pressure of groundwaters (two hazards) (Figure 78). Another potential effect relates to changes in reservoir pressures, which may lead to fault reactivation and potentially induced seismic activity (one hazard).

The extraction of gas from within the reservoir via a well will gradually reduce subsurface fluid pressures. These pressure changes are greatest within the gas reservoir itself, although potentially they can be transmitted to adjacent geological layers over time. However, at the typical depths of shale, tight and deep coal gas reservoirs, there are relatively low volumes of groundwater naturally contained within these low-permeability rocks (i.e. they tend to be gas-charged systems – see Section 3.1.1). This differs from CSG reservoirs, where extensive aquifer depressurisation (by active pumping of the coal seam) is required to dewater coal seams and cause gas to desorb from the coal matrix. Once the shale, tight or deep coal gas reservoir is sufficiently fractured, gas enters the production well and eventually flows to surface under its own inherent buoyancy. Consequently, pressure changes are typically much smaller and more localised in shale, tight and deep coal gas reservoirs than in CSG reservoirs.

The potential for pressure changes during production from a gas reservoir to affect existing faults and generate seismic activity is poorly documented. The density and magnitude of existing faults that intersect or occur close to the unconventional reservoir, as well as their structural character and nature of fault infill material and other characteristics, are all likely to be important in determining if gas production can affect existing faults or generate new seismic events. However, even in cases where faults are relatively extensive and conditions are conducive to fault reactivation, gas production from deep unconventional reservoirs is unlikely to result in pressure changes of sufficient magnitude to generate noticeable seismicity (seismicity that can be detected at the surface by a person).

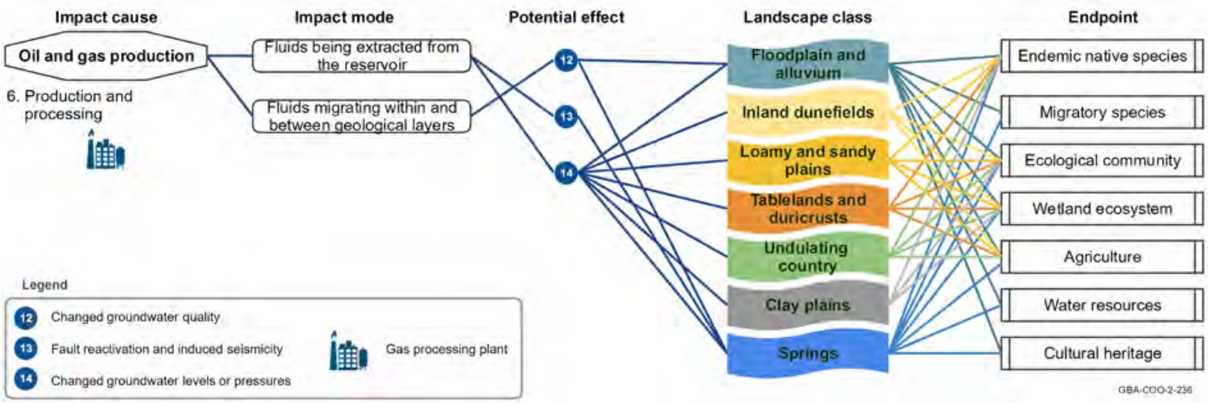

Figure 78 Preliminary conceptualisation of hazards associated with shale, tight and deep coal gas development in the Cooper GBA region in the 'gas extraction altering groundwaters' causal pathway

Numbered items refer to the ten major activities described in Figure 64 e.g. '1. Civil construction'.
Data: Geological and Bioregional Assessment Program (2019c)
Element: GBA-COO-2-236

Although the reduction in reservoir pressures due to gas production will invariably occur to some degree in shale, tight and deep coal gas systems, the typical depth of gas production and lack of active dewatering mean that such pressure reductions are unlikely to propagate far beyond the boundaries of the target reservoir. Additionally, the low permeability of these reservoir rocks (and potentially other fine-grained geological layers above and below the reservoir) is likely to further impede the propagation of subsurface pressure changes from the reservoir. Only one of the three gas extraction hazards are considered to be a priority, which reflects the much greater depths below surface at which shale, tight and deep coal gas reservoirs occur and the significant vertical separation that exists between these reservoirs and most groundwaters, especially the shallower (<300 m deep) groundwaters that are most commonly used in the Cooper GBA region. There may be minor potential for connection with groundwater-dependent ecosystems, such as springs and riparian vegetation in the floodplain and alluvium landscape classes.

5.3.3 Water and infrastructure management causal pathways

Six causal pathways are in the 'water and infrastructure management' causal pathway group:

- discharging water into surface waters (ten hazards)
- disposal and storage of site materials (19 hazards)
- failure of surface infrastructure (ponds, tanks, pipelines, etc.) (30 hazards)
- processing and using extracted water (eight hazards)
- reinjecting water into aquifer (ten hazards)
- sourcing water for site operations (13 hazards).

The individual hazards and potential effects associated with these causal pathways in the Cooper GBA region are illustrated conceptually in Figure 79. The impact modes and potential effects are mostly focused on impacts to surface waters or groundwaters, including changes to levels, pressures or flows and water quality.

Priority hazards were identified for all six causal pathways:

- failure of surface infrastructure (ponds, tanks, pipelines, etc.) (13 out of 30 hazards)
- discharging water into surface waters (seven out of ten hazards)
- sourcing water for site operations (two out of 13 hazards)
- disposal and storage of site materials (two out of 19 hazards)
- processing and using extracted water (one out of eight hazards)
- reinjecting water into aquifer (one out of ten hazards).

Potential effects associated with priority hazards are:

- soil, groundwater and/or surface water contamination (32 out of 58 hazards)
- changed surface water quality (three out of four hazards)
- changed surface water flows (three out of eight hazards)
- bank instability and erosion (one out of one hazard)
- changed groundwater quality (one out of six hazards)
- changed groundwater levels or pressures (one out of nine hazards).

These hazards arise when current leading-practice design, construction and management protocols, techniques and practices are not effective, which can be exacerbated by natural hazards such as floods. Potential effects that are not associated with priority hazards in the 'water and infrastructure management' causal pathway group are changed air quality (two hazards) and fault reactivation and induced seismicity (two hazards).

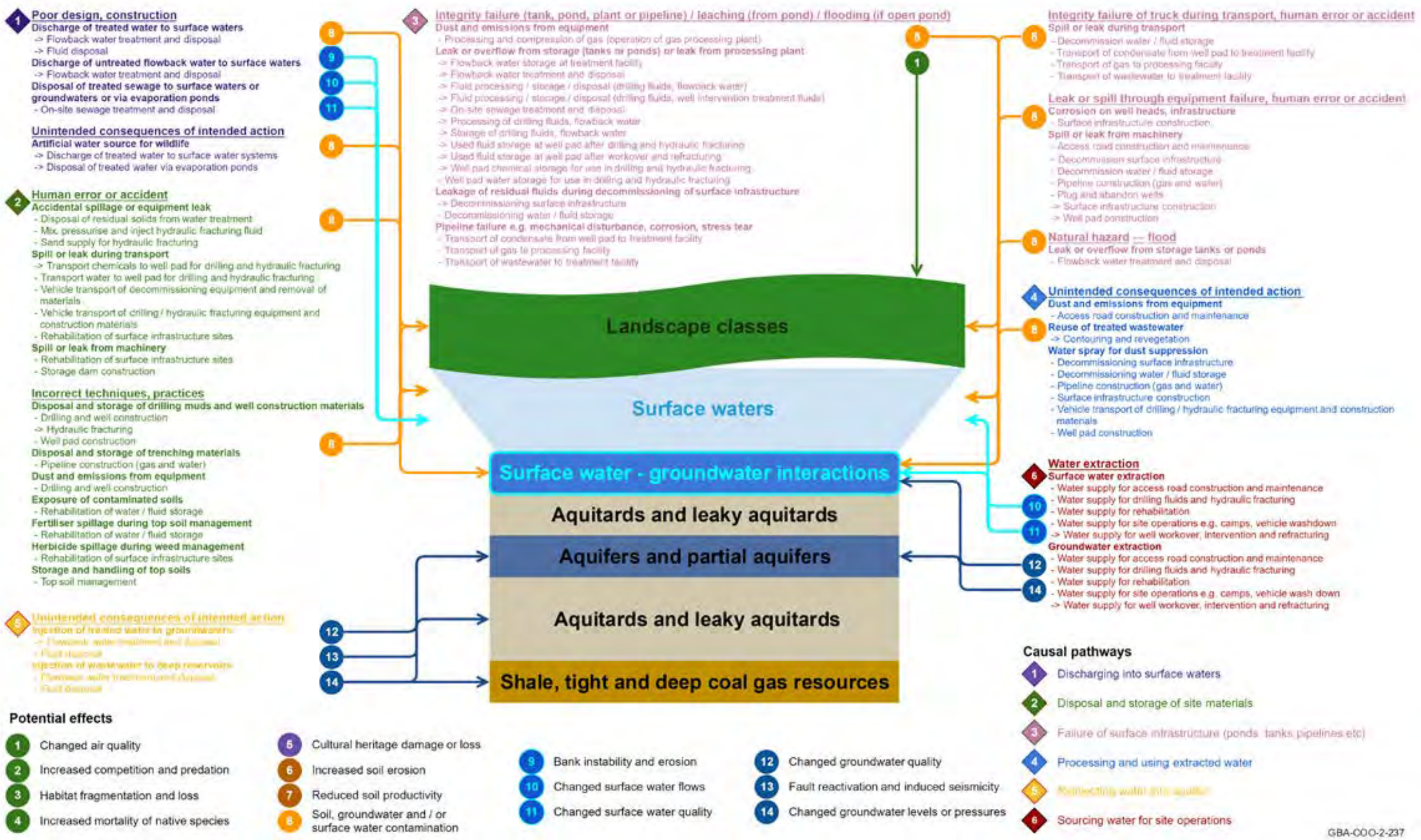

Figure 79 Hazards (impact causes, impact modes and activities) and associated effects in the 'water and infrastructure management' causal pathway group identified for shale, tight and deep coal gas development in the Cooper GBA region

Impact causes are underlined, impact modes are bold, activities are bullet points (low-priority hazards = '-' and priority hazards = '->'). An individual activity may lead to more than one hazard if multiple potential effects are associated with the activity. Arrows show how the individual hazards interact with key components: aquifers and partial aquifers; aquitards and leaky aquitards; landscape classes; shale, tight and deep coal gas resources; surface water – groundwater interactions; and surface waters. Causal pathways are identified by number and text colour. This figure has been optimised for printing on A3 paper (297 mm x 420 mm).

Typology and punctuation are consistent with the hazard identification dataset (Geological and Bioregional Assessment Program, 2019c).

Element: GBA-COO-2-237

Discharging into surface waters

Surface waters can be impacted by discharge of treated or untreated flowback water into streams and rivers, as well as disposal of treated water into streams and rivers or via evaporation ponds (Figure 80). Potential effects are changed surface water flows (three hazards) or quality (three hazards), contamination of soil, groundwater and/or surface waters (three hazards) and bank instability and erosion (one hazard). Potential impacts from discharge and storage of water are typically limited to changes in the floodplain and alluvium landscape class. Surface water discharge or ponds may also affect other landscape classes, such as inland dunefields or springs.

An unintended consequence of discharging treated water into streams or for storage in evaporation ponds is the creation of artificial water sources for wildlife. While this may be positive for some species, it may have negative consequences for native species if the additional water favours introduced species.

In addition to providing a greater volume of water, discharge of treated and untreated water may change the quality of receiving waters, which may affect aquatic ecosystems, depending on their water quality requirements.

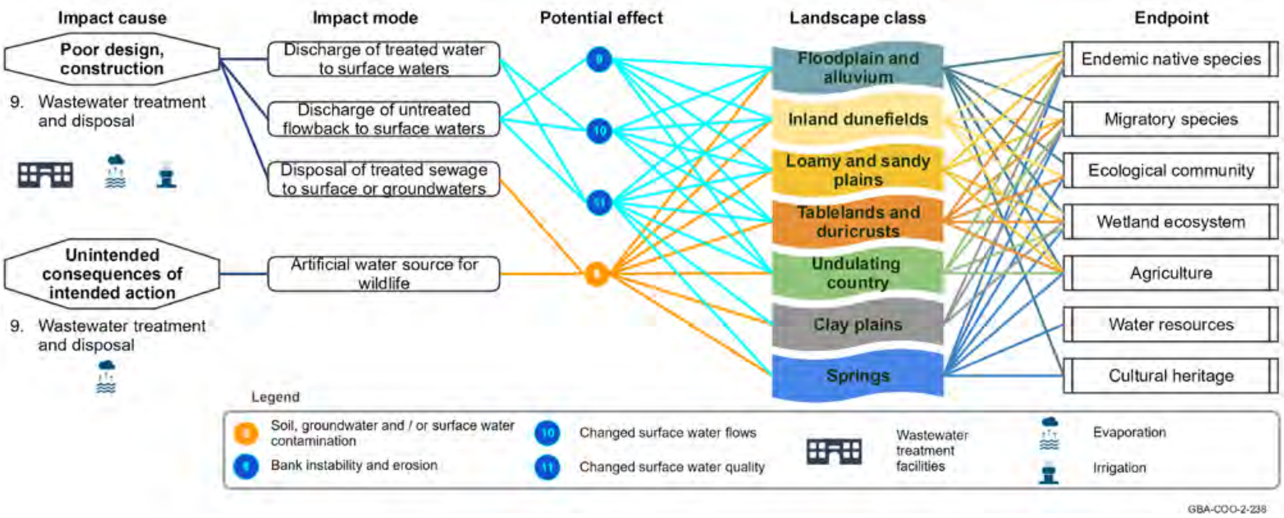

Figure 80 Preliminary conceptualisation of hazards associated with shale, tight and deep coal gas development in the Cooper GBA region in the 'discharging into surface waters' causal pathway

Numbered items refer to the ten major activities described in Figure 64 e.g. '1. Civil construction'.
Data: Geological and Bioregional Assessment Program (2019c)
Element: GBA-COO-2-238

Several management protocols are in place to reduce the impact of discharge into waterways and via evaporation ponds. These include the requirement to treat water to an acceptable level before discharge; only discharging during high flow events, when the relative impact of additional water of a lower (or higher) quality will be diminished; water quality testing; and fencing to minimise the potential for access by native fauna and livestock. Whether evaporation ponds are fenced depends upon water quality considerations and consultation with landholders (Santos, 2015).

Disposal and storage of site materials

Soil, groundwater and/or surface water contamination may arise due to human error or accident (ten hazards) or when incorrect techniques and practices (nine hazards) are used for the disposal and storage of site materials (Figure 81). Spills in chemical storage areas are contained by bunding and hardstand within designated facilities. Typical waste streams include cement; contaminated soils; drill cuttings; drilling and hydraulic fracturing chemicals; fluids; fertilisers and herbicides used for rehabilitation; sand; and evaporated waste from water treatment facilities, including biosolids, brines and sludge. Disposal and storage of site materials is a regulated activity governed by specific conditions and rules, particularly for waste that is stored onsite or taken offsite for disposal in an approved facility. Spills and accidents involving chemicals could occur during all phases of operation (e.g. well blowouts, well casing failures, spills during fluid transport) and could potentially lead to contamination of soils, surface water and/or shallow groundwater. Changes to water quality may increase stress and/or mortality of aquatic species. Potential impacts are typically restricted to the floodplain and alluvium landscape class but may also affect other landscape classes, such as inland dunefields or springs.

Accidental spills or leaks during transport of drilling and hydraulic fracturing equipment that contaminate soil, groundwater and/or surface waters due to human error or accident is considered a priority hazard. While it is unlikely to occur (one in ten years), it may have a moderate impact on ecosystems that is reversible in five to ten years. Similarly, it is possible that incorrect techniques and practices used in the disposal and storage of drilling muds and well construction materials during drilling and hydraulic fracturing, and exposure of contaminated soils, fertiliser or herbicide spillage during decommissioning and rehabilitation, may lead to similar impacts and so is also considered a priority hazard.

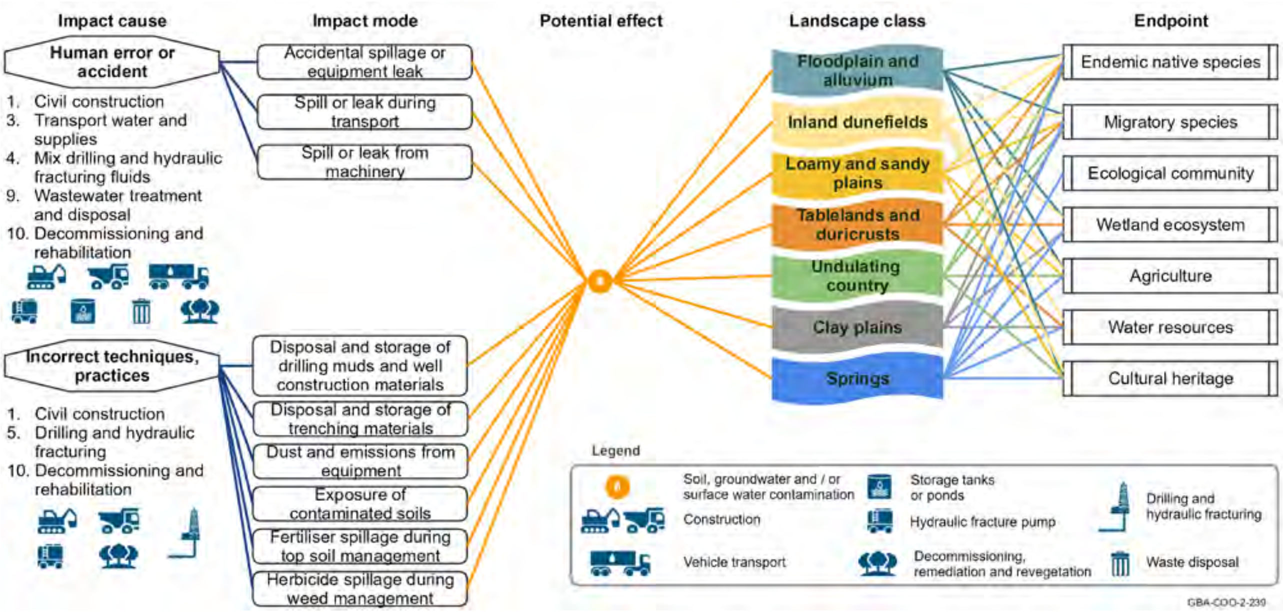

Figure 81 Preliminary conceptualisation of hazards associated with shale, tight and deep coal gas development in the Cooper GBA region in the 'disposal and storage of site materials' causal pathway

Numbered items refer to the ten major activities described in Figure 64 e.g. '1. Civil construction'.
Data: Geological and Bioregional Assessment Program (2019c)
Element: GBA-COO-2-239

Risks associated with transportation, storage and handling of chemicals, fuels and oils are managed in accordance with relevant standards and guidelines. This is supplemented by regular education, review and monitoring, as well as implementation of corrective actions based on incident investigation (Santos, 2015).

Failure of surface infrastructure (ponds, tanks, pipelines, etc.)

Failure of surface infrastructure may result in changes to air quality (two hazards) or contamination of soil, groundwater and/or surface water (28 hazards) (Figure 82). Surface infrastructure includes pipelines, storage tanks, transport vehicles, machinery (civil construction equipment, drilling and hydraulic fracturing equipment) and operating plant. Fluids that may be released from infrastructure include produced hydrocarbon gas and liquids, produced water, flowback water, hydraulic fracturing fluids, fuels and lubricants in machinery and plant, and process chemicals that are used in some infrastructure.

Release of fluids may result from a failure in the integrity of the fluid storage/delivery system (storage vessels and tanks, tankers and pipelines) or operating equipment (pumps and other plant); human error or accidents during transport or operation of equipment; and overflow of open storage tanks or ponds due to heavy rainfall and/or flooding associated with cyclonic weather systems. Any of the seven landscape classes may be impacted by contamination or possibly changes to air quality in the event of failure of surface infrastructure.

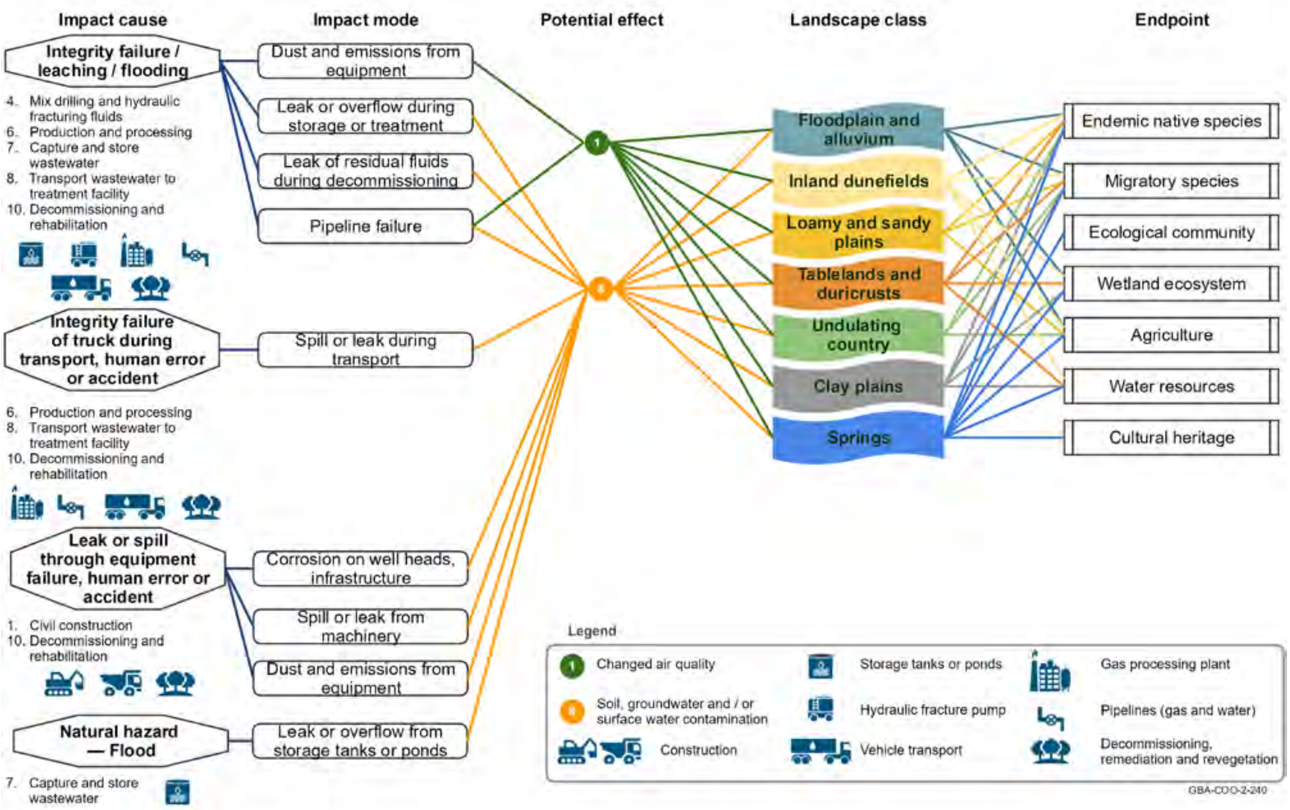

Figure 82 Preliminary conceptualisation of hazards associated with shale, tight and deep coal gas development in the Cooper GBA region in the 'failure of surface infrastructure' causal pathway

Numbered items refer to the ten major activities described in Figure 64 e.g. '1. Civil construction'.
Data: Geological and Bioregional Assessment Program (2019c)
Element: GBA-COO-2-240

Ponds, tanks and pipelines are designed and managed to maintain integrity and operability. Management protocols include leak detection, maintenance, corrosion mitigation, overpressure protection, and fencing to exclude native fauna and livestock. Leaks, spills and overflow from surface infrastructure are regulated activities governed by specific conditions and rules, but (less commonly) they may be unregulated – for example, due to floods or failure of unregulated storage dams.

Processing and using extracted water

Reuse of extracted water – that is, produced or flowback water – reduces the volume of water extracted and the volume of wastewater to be disposed of and managed during gas resource development. Extracted water may be reused for activities including drilling and well completions, hydraulic fracturing, earthworks, dust suppression on well pads and access tracks, and rehabilitation and revegetation. Beneficial reuse of extracted water outside of petroleum activities is also possible – for example, for agricultural uses such as irrigation or stock watering or as process water for other industries. The water may undergo varying levels of treatment depending on its quality and the end use.

Potential effects of processing and use of extracted water (Figure 83) relate primarily to the use of water for dust suppression during civil construction, transport of water and supplies, and remediation and revegetation activities (eight hazards). Reuse of extracted water can lead to soil, groundwater and/or surface water contamination, which is not limited to particular landscape classes (Figure 83). An unintended consequence of reuse of treated wastewater for contouring and revegetation during rehabilitation that may possibly (one in three years) cause soil, groundwater and/or surface water contamination of minimal severity that is reversible in one to five years is a priority hazard. Contamination from dust suppression is considered to be of minimal severity and so is not considered to be a priority hazard. No other priority hazards were identified in the processing and using extracted water causal pathway.

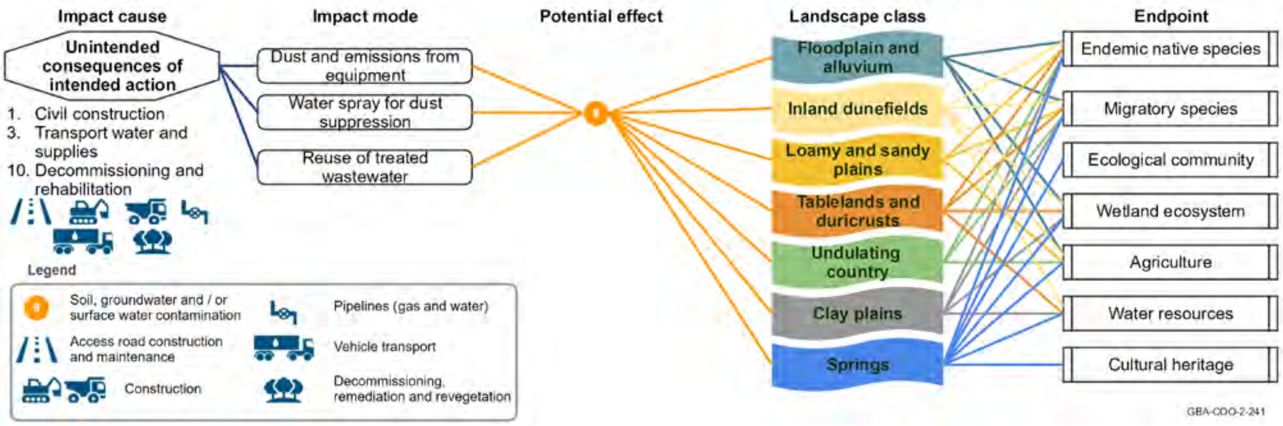

Figure 83 Preliminary conceptualisation of hazards associated with shale, tight and deep coal gas development in the Cooper GBA region in the 'processing and using extracted water' causal pathway

Numbered items refer to the ten major activities described in Figure 64 e.g. '1. Civil construction'.
Data: Geological and Bioregional Assessment Program (2019c)
Element: GBA-COO-2-241

Beneficial or productive reuse of water is a regulated activity that aims to protect the environment and maximise the productive use of water. Reused water is treated to meet relevant water quality guidelines for the intended end use and receiving environment (e.g. ANZECC/ARMCANZ (2000)).

Reinjecting water into aquifer

Effective management of wastewaters produced during shale, tight and deep coal gas production is critically important, especially as these types of fluids are potentially harmful to the environment if inappropriately managed. Wastewaters produced from unconventional gas developments in the Cooper GBA region are primarily flowback waters that return to the surface following the injection of hydraulic fracturing fluids (which are used to fracture the gas reservoir and enhance permeability, thereby allowing gas to be extracted). The proportion of hydraulic fracturing fluid that returns to the surface can vary from well to well and field to field (due to factors such as the physical properties of the reservoir and the type of fluids used in the fracturing process) but is typically 25% to 75% of the total injected volume (The Royal Society and The Royal Academy of Engineering, 2012). The hazard identification workshops assumed that the total volume injected is approximately 1 ML/stage and that 40% to 60% is recovered as flowback water. Consequently, in areas with many production wells, significant volumes of flowback water are likely to exist and thus require appropriate management over the life of the gas field.

Produced water is typically a minor component of overall wastewater recovered from shale, tight and deep coal reservoirs (particularly in comparison to volumes of co-produced water from CSG wells). This is due to the greater depths, lower reservoir permeability and lack of water saturation in available pore space within these types of unconventional gas reservoirs. Flowback waters may potentially also contain other constituents that are initially absent from the hydraulic fracturing fluid. These components may form due to mobilisation of geogenic chemicals within the reservoirs or due to chemical reactions between the injected fluid mixture and the in-situ mineral and/or organic components of the reservoir. A preliminary assessment of geogenic chemicals that may be mobilised in flowback waters from the Cooper Basin is provided in the chemical screening technical appendix (Kirby et al., 2020) and is summarised in Section 6.1.

Disposal of wastewater fluids (both treated and untreated) from unconventional gas wells by reinjection into deep underground formations (such as depleted oil/gas reservoirs or deep unutilised aquifers) is common practice in many parts of the US (US EPA, 2016a). In the Cooper GBA region, improved/enhanced oil recovery or water flooding is used for conventional oil and gas production. Injection of treated water to groundwater systems and injection of wastewater to deep reservoirs can potentially change groundwater levels or pressures (four hazards) or groundwater quality (four hazards) or lead to reactivation of existing geological faults, which may cause subsequent seismic events (known as ‘induced seismicity’) (two hazards) (Figure 84). Changes to groundwater quality or pressures caused by wastewater reinjection are likely to largely be restricted to subsurface formations, due to their hydrological isolation and significant depths. There may be a low probability of groundwater changes affecting isolated areas of floodplains and alluvium or possibly some springs, although most landscape classes in the Cooper GBA region (and their associated values) are unlikely to be directly affected by reinjection.

An unintended consequence of the injection of treated flowback water to groundwater systems that has a minimal impact on groundwater quality in the receiving aquifer and is reversible in one to five years is considered to be a priority hazard. No other priority hazards were identified in the ‘reinjecting water into aquifer’ causal pathway.

Injecting substantial volumes of wastewater into deep aquifers will invariably alter the pre-injection groundwater pressures and quality of the target aquifer to some extent. Consequently, it is necessary to develop a comprehensive understanding of the local geology and groundwater systems in the area prior to reinjection, so that the likely changes can be evaluated and/or modelled.

Probably the highest profile hazard associated with reinjection of wastewaters (with several notable examples from the US – e.g. Magnani et al. (2017)) is the potential for fault reactivation and associated induced seismic events to occur. This hazard can arise when increased aquifer pressures (that result from the large volumes of fluid pumped underground) cause pre-existing faults to be reactivated and for some degree of fault plane movement to occur. Indeed, the magnitude of seismic events caused by wastewater disposal injection is typically much greater than events caused by hydraulic fracturing (Zoback, 2012). The probability of seismic events occurring will depend on local geological conditions, such as the number and nature of faults that intersect the reinjection target and the nature of the subsurface stress field, as well as on the volume and rate of reinjected fluid. The most likely landscape class to be affected by fault reactivation is ‘springs’, particularly those springs that rely on groundwater flow along geological structures. In such cases, it may be possible for fault movement caused by wastewater reinjection to impede existing flow to springs, thereby disrupting their ecological functioning or affecting their cultural or economic values. There may also be minor potential for connection with groundwater-dependent ecosystems in the floodplain and alluvium landscape classes.

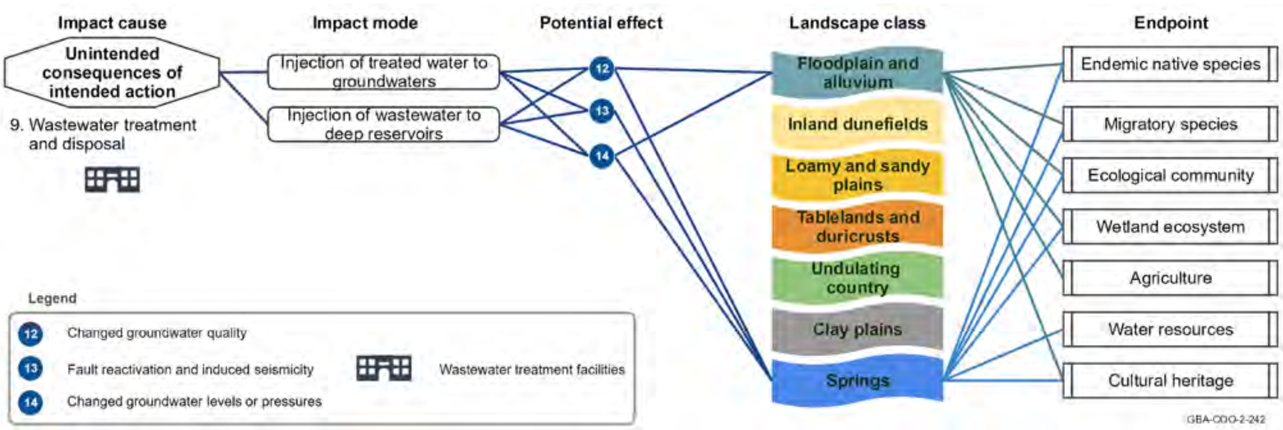

Figure 84 Preliminary conceptualisation of hazards associated with shale, tight and deep coal gas development in the Cooper GBA region in the ‘reinjecting water into aquifer’ causal pathway

Numbered items refer to the ten major activities described in Figure 64 e.g. ‘1. Civil construction’.
Data: Geological and Bioregional Assessment Program (2019c)
Element: GBA-COO-2-242

Protocols exist in some countries (such as the US) for mitigating seismicity associated with wastewater disposal via aquifer reinjection. These protocols require comprehensive evaluation of reinjection plans against a range of criteria, including understanding historical seismic events, local geology, regional stress fields and the nature of the proposed reinjection process (The Royal Society and The Royal Academy of Engineering, 2012). Reinjection programs are subject to detailed technical assessment which includes modelling and require regulatory approval prior to commencement (Santos, 2015). Seismic monitoring may be needed to manage long-term risks associated with wastewater reinjection.

Effective planning is also needed to ensure that the deep aquifer targeted for reinjection contains non-potable groundwater that is effectively isolated from other (i.e. shallower) aquifers that may be used for water supply purposes, such as for human or environmental use. An adequate monitoring network can detect early changes in groundwater pressure and quality and thereby avoid future risks to productive aquifers.

Sourcing water for site operations

The development and operation of shale, tight or deep coal gas wells requires significant volumes of water throughout all major life-cycle stages, especially during the production phase, when the greatest number of wells are drilled. Water is also required for other site operations, such as the construction and maintenance of access roads, pipelines and gas production facilities, as well as site decommissioning and rehabilitation activities. Although the actual volume of water needed for drilling and hydraulic fracturing of a well depends on a variety of factors (such as local geological conditions, vertical drilling depths and horizontal well lengths, and the number of hydraulic fracturing stages per well), typical estimates are around 1 to 2 ML per well needed for drilling operations, and anywhere from 10 to 25 ML (or more) per well may be needed for fracturing operations. For example, Origin Energy indicated in their submission to the NT fracking inquiry that around 50 to 60 ML of water may be needed to drill and hydraulically fracture each production well in the Beetaloo Sub-basin (Pepper et al., 2018). The hazard identification workshops assumed that approximately 15 to 20 ML/well is needed during the exploration, appraisal and development stages and approximately 10 ML/well during the production stage.

Potential effects from water extraction for site operations are changes to groundwater levels or pressures (five hazards), groundwater quality (two hazards), surface water flows (five hazards) and surface water quality (one hazard) (Figure 85). Groundwater extraction from aquifers that changes groundwater levels or pressures is typically localised near production borefields and will begin to recover to pre-development levels once pumping ceases. Extraction of groundwater from one aquifer may induce inter-aquifer flow, thereby affecting water quality in the source aquifer. The preliminary conceptualisation for the ‘sourcing water for site operations’ causal pathway also considers indirect effects to groundwater and surface water levels, pressures or flows and quality (Figure 85). Water supply for well workover, intervention and refracturing during the production life-cycle stage that changes groundwater levels or pressures (groundwater extraction) is almost certain to have a ‘tiny’ impact that is reversible in one year and is considered to be a priority hazard.

Due to the arid nature of the Cooper GBA region, surface water resources are generally an unreliable source of water for drilling and hydraulic fracturing (see Section 3.2 for details). Surface water extraction can reduce surface water flow volumes and may also have minor effects on surface water quality. Surface water extraction for well workover, intervention and refracturing that changes surface water flows and is almost certain to have a ‘tiny’ impact that is reversible in one year is considered to be a priority hazard. No other priority hazards were identified in the ‘sourcing water for site operations’ causal pathway.

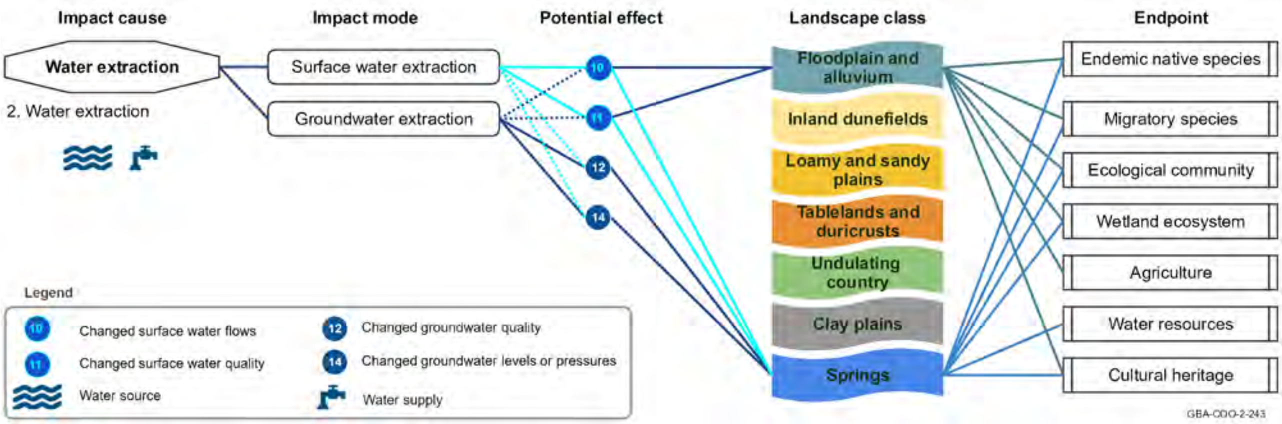

Figure 85 Preliminary conceptualisation of hazards associated with shale, tight and deep coal gas development in the Cooper GBA region in the ‘sourcing water for site operations’ causal pathway

Numbered items refer to the ten major activities described in Figure 64 e.g. ‘1. Civil construction’.
Dotted line indicates indirect potential effects to groundwater and surface water levels, pressures or flows and quality.
Source: Geological and Bioregional Assessment Program (2019c)
Element: GBA-COO-2-243

Water supply for gas resource development is governed by existing water management plans and regulatory conditions overseen by state or territory governments. Any new water withdrawals to support unconventional gas operations in the Cooper GBA region must adhere to relevant Queensland and SA regulations and water-sharing objectives without inadvertently affecting other water users (including groundwater-dependent ecosystems). In the Cooper GBA region, groundwater allocations for 'Petroleum and gas operations' under the Great Artesian Basin And Other Regional Aquifers (GABORA) water plan is 64,000 ML/year and 21,900 ML/year in the SA Arid Lands Natural Resource Management (NRM) region. Relevant water-sharing plans and water accounts for the Cooper GBA region are summarised in Section 3.1.4 (groundwater) and Section 3.2.3 (surface water).

5.4 Knowledge gaps

The assumptions about the nature of the possible future development profile for the Cooper GBA region is a knowledge gap that affects estimates of severity and likelihood of potential impacts made at the hazard workshops. Stage 3 will develop detailed spatial and temporal representations of the range of possible future development profiles to reduce the uncertainty of the nature and severity of risks expressed by experts at the hazard workshops – particularly how impacts are affected by the pulsed nature of flows and water inputs at and near the surface in a boom–bust ecosystem. Stage 3 will build on the causal pathways and endpoints identified in Stage 2 to assess risks from unconventional gas resource development activities, as well as existing activities such as climate change, grazing and land clearing.

Conceptualisation of the regional geology and hydrogeology, as well as the potential hydrological connections from stressors to assets, includes a number of uncertainties and alternative conceptual models. These uncertainties will be captured, represented and tested in Stage 3 using simple, screening numerical models. Uncertainty will be propagated through models used for the assessment in Stage 3 by basing predictions upon plausible distributions of model parameters rather than fixed values. The preliminary conceptualisations presented here for each causal pathway will be updated in Stage 3 using a range of approaches, including expert elicitation.

6 Qualitative assessment examples

Potential impacts from (i) chemicals used for drilling and hydraulic fracturing; and (ii) two causal pathways – 'hydraulic fracturing' and 'compromised well integrity' – are assessed in greater detail because of their importance to government, the community and industry.

6.1 *Screening of drilling and hydraulic fracturing chemicals*

A total of 116 chemicals have been identified as being associated with drilling and hydraulic fracturing at shale, tight and deep coal gas operations in the GBA regions between 2011 and 2016. Of the 116 chemicals, nine were drilling chemicals, 99 were hydraulic fracturing chemicals and eight were chemicals used for both drilling and hydraulic fracturing. Fifty-eight per cent of the chemicals identified in the current study were not assessed in the national assessment of chemicals associated with coal seam gas (CSG) extraction in Australia (NICNAS, 2017). A Tier 1 qualitative (screening) environmental risk assessment (ERA) of the chemicals found that 42 chemicals were of 'low concern' and were considered to pose minimal risk to aquatic ecosystems. A further 33 chemicals were of 'potentially high concern' and 41 were of 'potential concern'. Further site-specific, quantitative chemical assessments could be used to assess risks from specific gas developments to aquatic ecosystems from the identified chemicals of potential concern and potentially high concern.

Natural rock formations contain elements and compounds (geogenic chemicals) that could be mobilised into flowback and produced waters during hydraulic fracturing. Laboratory-based leachate tests were designed to provide an upper-bound estimate of geogenic chemical mobilisation from target formations in the Cooper GBA region and are intended to guide future field-based monitoring, management and treatment options. Laboratory-based leachate tests on powdered rock samples identified several elements that could be substantially mobilised into solutions by hydraulic fracturing fluid including aluminium, arsenic, barium, cadmium, cobalt, chromium, copper, iron, lead, lithium, nickel and zinc. Priority organic chemicals such as phenols, polycyclic aromatic hydrocarbons (PAHs) and total recoverable hydrocarbons (TRHs) were also detected in extracts of powdered rock samples. Independent collection, as well as open and transparent reporting of water quality data at future gas operations before, during and after hydraulic fracturing would improve knowledge of the process and outputs, and inform wastewater management and treatment options.

6.1.1 Identification of chemicals associated with shale, tight and deep gas operations

Industrial chemicals are required in shale, tight and deep coal gas operations for activities such as drilling, cementing, well construction and completion, well cleanup, hydraulic fracturing, and waste treatment. The composition and concentration of chemicals will depend on site-specific conditions such as geology and mineralogy of formations, environmental conditions such as temperature and pressure, and requirements to maintain well integrity and production. The managed use or accidental release of chemicals (industrial and geogenic) may have negative impacts on local and regional water quality (surface water and groundwater) and water-dependent ecosystems if not adequately controlled or managed.

Companies undertake an ERA of gas operations that includes the identification of potential hazards (e.g. chemical transport and storage, hydraulic fracturing fluid injection, flowback and produced water storage), determines the likelihood and consequence of a risk occurring, identifies and evaluates control and mitigation measures (e.g. what controls are in place or need to be in place to address the identified risk and how effective are these controls), and develops a monitoring program to ensure controls and management strategies are adequate/effective and for compliance.

Drilling chemicals

Shale, tight, and deep coal gas operations will require the construction of a well to access formations at depths to liberate the gas reserves. The wells are constructed to provide the necessary integrity and isolation (e.g. from groundwater) during the operational phase and post-decommissioning. As the well is being drilled, a series of metal casings are installed and cemented to provide the well stability, integrity, and isolation from aquifers and formations. The target formation(s) for gas production are accessed at specific well depths by perforating (creating small holes in) the well casing and cement using small explosive charges or guns. Well pressure is tested at different stages during drilling and completion prior to hydraulic fracturing to monitor and confirm the well integrity. Industrial chemicals are used to support the effectiveness and efficiency of drilling and maintenance of well integrity. The chemical additives are used for roles such as: (i) mobilise and remove cuttings; (ii) lubricate and support the drill bit and assembly; (iii) reduce friction; (iv) facilitate cementing; (v) minimise damage to formations; (vi) seal permeable formations; and (vii) prevent corrosion and bacterial growth.

Hydraulic fracture fluid chemicals

Hydraulic fracturing involves the injection of fluids with chemical additives under high pressure into target formations to fracture the rock to create high conductivity gas flow paths to the well. Common chemical additives in hydraulic fracturing fluids for shale, tight and deep coal gas operations are listed in Table 27.

Table 27 Common hydraulic fracturing fluid chemical additives used in shale, tight, and deep coal gas operations

Chemical additive	Purpose
Acid/solvent	Removes mineral scales and deposits and cleans the wellbore prior to hydraulic fracturing; dissolves minerals and initiates fractures in formations.
Buffer/acid	Adjusts pH to maintain the effectiveness of fluid components and iron control.
Biocide	Prevents or limits bacterial growth that can result in clogging, unwanted gas production, and corrosion.
Clay stabiliser	Prevents swelling or shifting in formations.
Crosslinking agent	Used to link polymers or gelling agent to improve cohesion, adhesion and thermal stability, and maintain fluid viscosity.
Inhibitor mineral scales and deposits	Prevents build-up of material on sides of well casing and surface equipment; iron-control agent prevents precipitation of metal oxides, such as iron oxides and hydroxides.
Friction reducer	Minimises friction of the hydraulic fracturing fluid.
Corrosion inhibitor	Prevents damage to the wellbore and corrosion of pipes.
Surfactant	Allows for increased matrix penetration and aids in recovery of water/fluid.
Proppant	Holds open fractures to allow gas flow.
Gelling agent/viscosifier	Alters fluid viscosity and thickens fluid in order to suspend the proppant.
Breaker/deviscosifier	Degrades or breaks down the gelling agent/viscosifier.

In general, the majority of the hydraulic fracturing fluid consists of water (>97%), with smaller proportions of proppant (sand) and chemical additives (Figure 86).

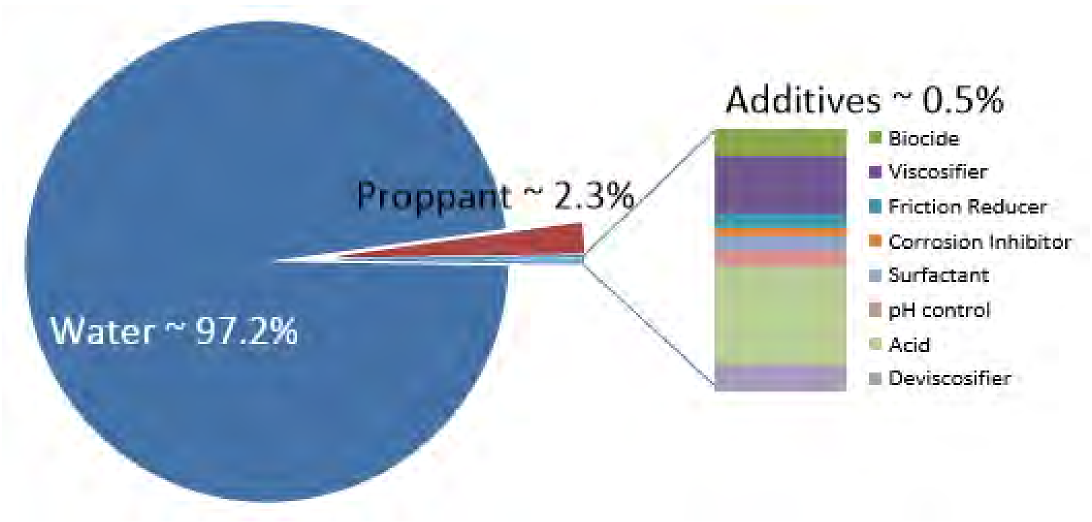

Figure 86 An example of overall percentages of water, proppant and chemical additives in hydraulic fracturing fluid in a deep shale gas well fracturing operation in the Cooper Basin

Source: figure reproduced from Beach Energy and RPS (2012)
Element: GBA-COO-2-115

The well pressure and volumes of hydraulic fracturing fluids added and recovered are routinely monitored in wells during stimulation to assess well integrity and optimise gas production. Typically, flowback and produced water, and liquid from the gas separator, are directed to storage locations/ponds/tanks (above or below ground), which have specifications dependent on the environmental conditions and requirements at the specific well site. Depending on the water quality, environmental conditions and treatment/management costs, the stored wastewater can be (i) treated onsite (e.g. reverse osmosis); (ii) reused, or recycled onsite (e.g. dust suppression); (iii) used for beneficial purposes by the company or a third party (pending the necessary approvals and it being fit for purpose); (iv) evaporated onsite in ponds to a solid waste or brine for storage in a controlled manner; (v) reinjected to deep aquifers (pending the necessary approvals); or (vi) transported and disposed of offsite at an approved treatment/disposal facility.

Geogenic (natural) chemicals

Natural rock formations contain geogenic chemicals (compounds and elements) that could be mobilised into flowback and produced waters during hydraulic fracturing. These geogenic chemicals include nutrients, organics (e.g. PAHs and phenols), metals (e.g. arsenic, manganese, barium, boron and zinc) and naturally occurring radioactive materials (NORMs) (e.g. isotopes of radium, thorium and uranium). The composition and concentration of geogenic chemicals in flowback waters will depend on many factors, including (i) geology and mineralogy of formations; (ii) surface area of the fracture network exposed to hydraulic fracturing fluids; (iii) composition and concentration of chemicals used in hydraulic fracturing; (iv) residence time of hydraulic fracturing fluids in formations; (v) operational and environmental conditions (e.g. volumes added and recovered, temperature, pressure); and (vi) chemical and physical reactions (e.g. adsorption, complexation, precipitation, aggregation, degradation and transformations).

Aim, objectives and methods

The aim of the chemical screening study was to gain a better understanding of risks of chemicals to surface water and groundwater quality and aquatic ecosystems from shale, tight, and deep coal gas operations in Australia. The objectives were:

1. to conduct a Tier 1 qualitative ERA for chemicals identified associated with shale, tight and deep coal operations from GBA regions in Australia
2. to identify geogenic chemicals (compounds and elements) that could be mobilised into flowback and produced waters due to hydraulic fracturing – using powdered rock samples sourced from formations in the Cooper GBA region.

The Australian Government Department of the Environment and Energy has outlined a framework for performing an ERA of chemicals associated with CSG extraction in Australia (Department of the Environment and Energy, 2017b) (chemical screening technical appendix (Kirby et al., 2020)). The framework provides a sound basis for undertaking an ERA of chemicals associated with shale, tight and deep coal gas operations in Australia. A tiered approach to ERA is often used to provide a systematic way of evaluating risk that is proportional to resources, complexity and cost (Department of the Environment and Energy, 2017b; US EPA, 2004).

A Tier 1 qualitative ERA was undertaken on drilling and hydraulic fracturing fluid chemicals used in shale, tight and deep coal gas activities in GBA regions during 2011 to 2016 (chemical screening technical appendix (Kirby et al., 2020)). The main exposure pathway for chemicals if released during shale, tight and deep coal gas operations will be likely to occur through water (surface water and groundwater); hence, this assessment focused on the potential effects to aquatic organisms. The Tier 1 assessment used a decision tree framework that evaluates sourced data for chemicals in relation to their persistence, bioaccumulation and toxicity to aquatic organisms (Figure 87). A precautionary approach was applied to the evaluation of data and Tier 1 qualitative ERA.

Laboratory-based leachate tests on powdered rock samples from formations in the Cooper GBA region were undertaken to examine potential mobilisation of geogenic chemicals (compounds and elements) into solution from exposure to a hydraulic fracturing fluid (chemical screening technical appendix (Kirby et al., 2020)). The powdered rock samples (<70 µm) were sourced from formations based on their potential as targets for shale, tight and deep coal gas developments in the Cooper GBA region: Roseneath, Epsilon, Murteree and Patchawarra. For inorganic elements, the leachate test solutions comprised a synthetic groundwater, a dilute hydrochloric acid and an in-house hydraulic fracturing fluid at 80 °C. Leachate tests were also conducted at an elevated pressure (18,400 KPa) in order to ascertain if pressure had an effect on geogenic chemical (element) mobilisation. A wide range of inorganic elements (> 60) were quantified in leachates using inductively coupled plasma-atomic emission spectrometry (ICP-AES) and inductively coupled plasma-mass spectrometry (ICP-MS). For organic compounds, powdered rock samples were leached using an accelerated solvent extraction (ASE) system and a combination of hydrophilic and hydrophobic solvents. The solvent extracts were analysed for a range of targeted priority organics compounds: 14 substituted phenols, 15 PAHs, and TRH fractions (C10-C40).

Additional information on the experimental design, methodology, findings, and conclusions can be found in the chemical screening technical appendix (Kirby et al., 2020).

6.1.2 Chemical screening assessment

Chemicals associated with shale, tight and deep coal gas operations in the GBA regions of Australia

A total of 116 chemicals were identified for use in drilling and hydraulic fracturing at shale, tight and deep coal gas operations between 2011 and 2016 (chemical screening technical appendix (Kirby et al., 2020)). Of the 116 chemicals identified, nine were drilling chemicals, 99 were hydraulic fracturing chemicals and eight were chemicals used for both activities. An additional 32 proprietary chemicals (in products) were identified used for drilling and hydraulic fracturing but are not assessed further due to limitations in public disclosure of information.

A similar number of chemicals (n=113) were identified associated with CSG extraction in Australia (NICNAS, 2017). Fifty-eight per cent of the chemicals (n=67) identified in the current study were not assessed in the national assessment of chemicals associated with CSG extraction (NICNAS, 2017). Of the 67 chemicals not previously assessed, a Tier 1 qualitative ERA found 16 chemicals were of ‘low concern’, 28 chemicals were of ‘potential concern’ and 23 chemicals were of ‘potentially high concern’. The additional chemicals identified in this study for shale, tight and deep coal gas operations may be due to site-specific requirements needed for higher temperatures and pressure, geology and minerology of the formations, scale and biofilm build-up, fluid stability and viscosity, proppant transport, improved gas extraction and efficiency, and a move by industry toward 'greener, safer' options.

The Tier 1 screening of 116 chemicals identified 42 of 'low concern' (Screen 1 (13) and Screen 4 (29)), 33 of 'potentially high concern' (Screen 2), and 41 of 'potential concern' (Screen 3 (18) and Screen 4 (23)) (Figure 88). Data on persistence, bioaccumulation and ecotoxicity for individual chemicals and screening categories are reported in the chemical properties and ecotoxicity database (Geological and Bioregional Assessment Program, 2018h) and chemical screening technical appendix (Kirby et al., 2020).

Of the 33 chemicals identified as being of 'potentially high concern', five chemicals (one biocide and four defoaming agents) are not likely to be easily degraded (persistent), are bioaccumulative (potentially can accumulate in aquatic organisms) and exhibit very high acute toxicity to aquatic organisms (normally persistent, bioaccumulative and toxic chemicals) (Table 28, Figure 88) (chemical screening technical appendix (Kirby et al., 2020)). Such chemicals are considered a high concern/risk to the environment, as they can pose serious harm to aquatic ecosystems if released and require specific controls to prevent their release into the environment.

Table 28 Chemicals of 'potentially high concern' that are persistent (P) and bioaccumulative (B), and exhibit very high acute toxicity (T)

Chemical	CAS RN	Use	P[1]	B[2]	T[3]
Dicoco dimethyl ammonium chloride	61789-77-3	Biocide/surfactant	##	‡‡	***
Decamethylcyclopentasiloxane (D5)	541-02-6	Defoaming agent/surfactant	##	‡‡	***
Silicone oil (poly(dimethyl siloxane)	63148-62-9	Defoaming agent/surfactant	##	‡‡	***
Dodecamethylcyclohexasiloxane (D6)	540-97-6	Defoaming agent/surfactant	##	‡‡	***
Octamethylcyclotetrasiloxane (D4)	556-67-2	Defoaming agent/surfactant	##	‡‡	***

[1] Persistence = half-life >60 days (##); [2] Bioconcentration factor = BCF >2000 or octanol/water partition coefficient = Log Kow ≥4.2 (‡‡); [3]Toxicity = ≤1 mg/L (***); CAS RN = Chemical Abstracts Services Registry Number
Source: Geological and Bioregional Assessment Program (2018h)

The remaining 28 chemicals identified as being of 'potentially high concern' are persistent or bioaccumulative and are harmful to very toxic chemicals (n=18) (Table 29, Figure 88), or not persistent or bioaccumulative (or no data available) and very toxic (n=10) chemicals (Table 30, Figure 88) to aquatic organisms. These chemicals can pose serious harm to aquatic ecosystems if released and require specific controls to prevent their release into the environment. Persistent and bioaccumulative chemicals are generally considered of high concern in the environment due to the potential for organisms to be exposed for longer time periods (chronic effects). There were limited aquatic chronic toxicity data available (using standard tests) for most of the 116 chemicals associated with shale, tight and deep coal gas operations in Australia.

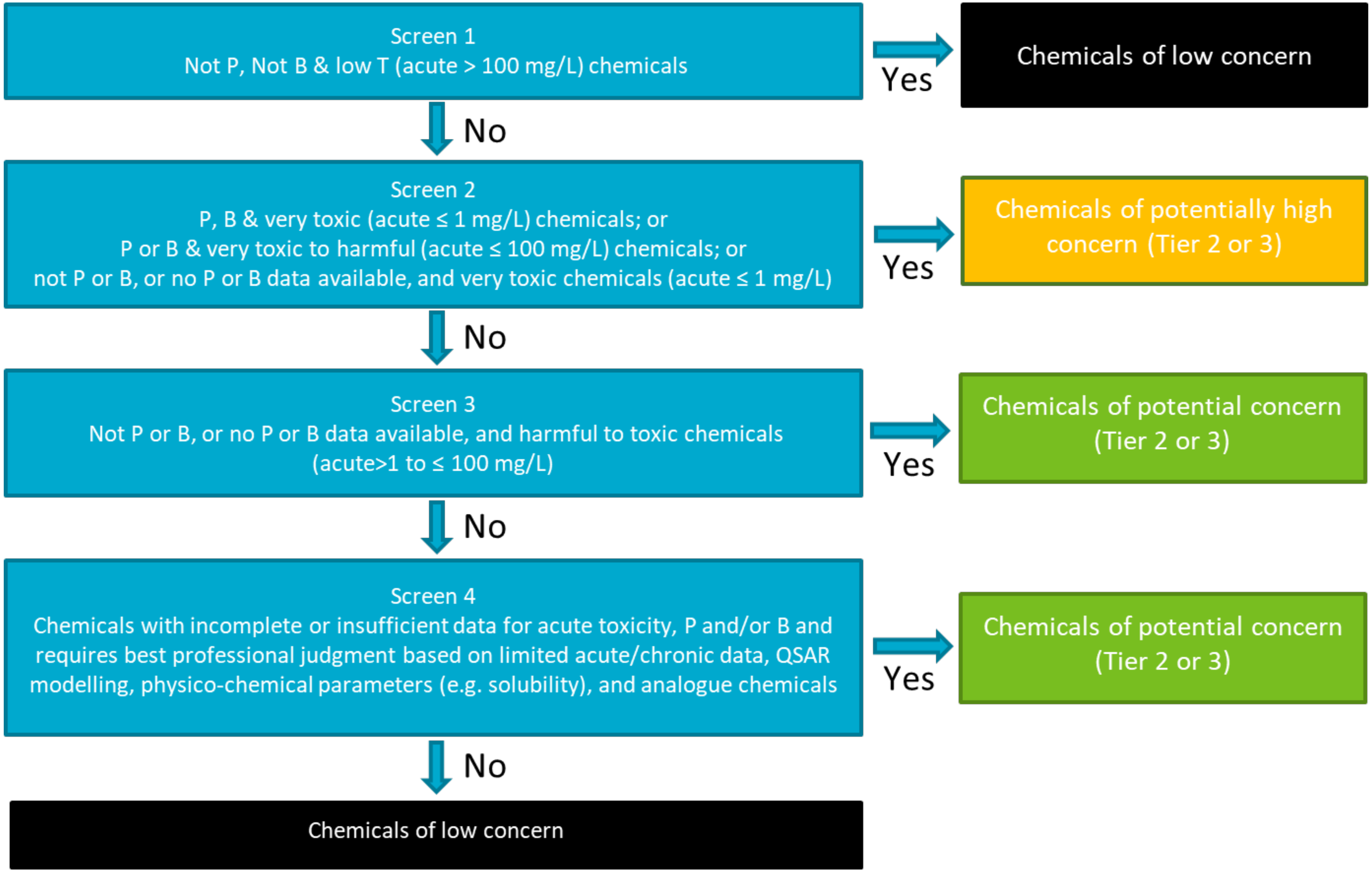

Figure 87 Decision tree framework for Tier 1 qualitative (screening) ERA of chemicals associated with shale, tight and deep coal gas operations in Australia

P = persistent, B = bioaccumulative, T = toxic; QSAR = quantitative structure–activity relationship

Element: GBA-COO-2-116

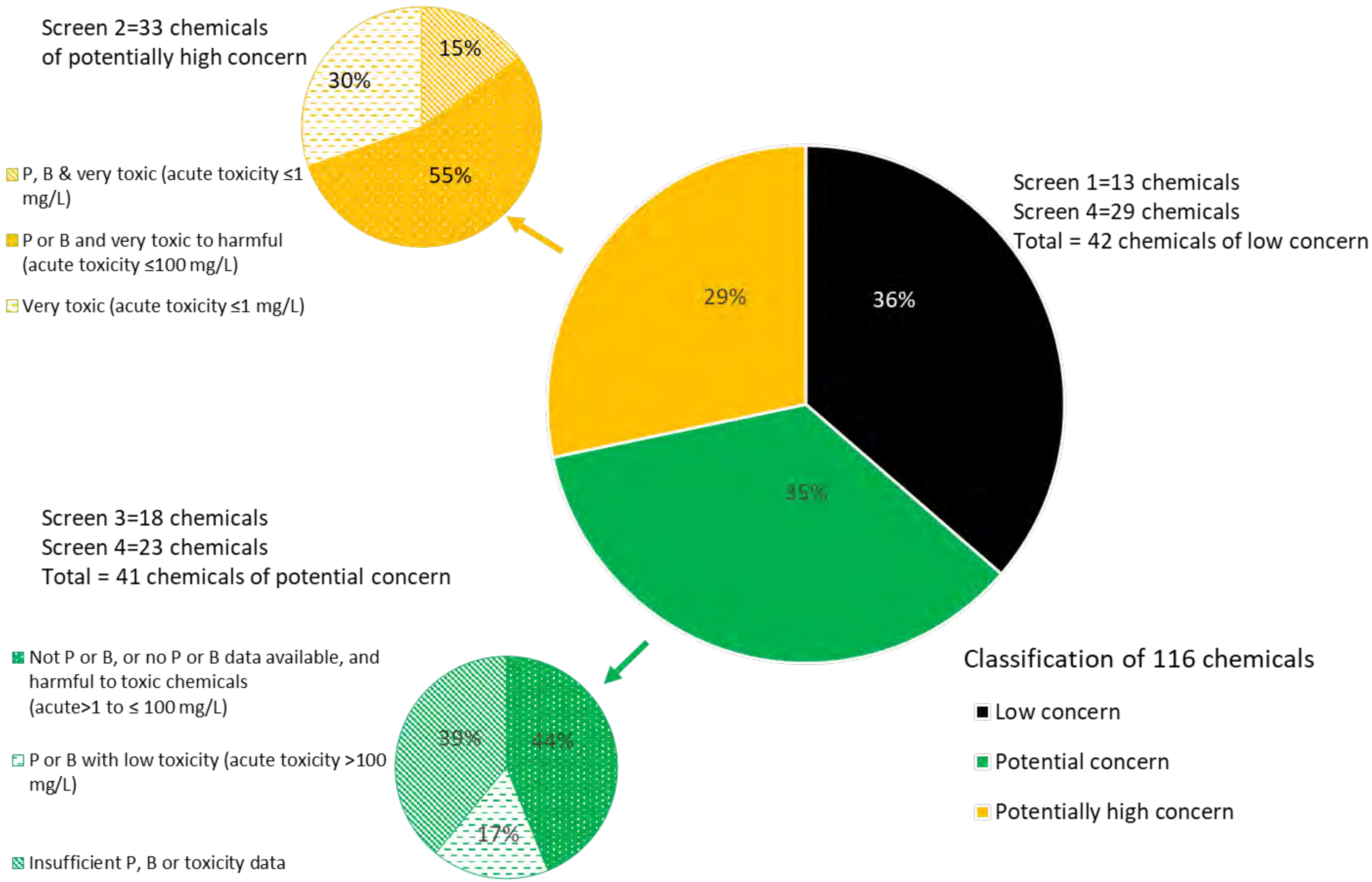

Figure 88 Tier 1 qualitative ERA of chemicals associated with shale, tight and deep coal gas operations in Australia

Refer to Figure 87 for Screen 1 to 4 details; percentage of chemicals in each category are shown in each segment; further breakdown of chemicals of 'potential concern' and 'potentially high concern' are shown in the smaller coloured circles; P = persistent; B = bioaccumulative; T = toxic
Source: Geological and Bioregional Assessment Program (2018h)
Element: GBA-COO-2-117

The 41 chemicals identified as being of 'potential concern' are not persistent and not bioaccumulative (or no persistence and bioaccumulation data could be sourced) but are toxic or harmful chemicals (n=18) (Screen 3) and are chemicals with incomplete data that require professional judgment (n=23) (Screen 4) (Figure 88). These chemicals have the potential to harm aquatic ecosystems if released and may require specific control and management measures to prevent their release into the environment.

For Screen 4 (Figure 88), seven of the 52 chemicals identified were found to be persistent or bioaccumulative and have low toxicity. These seven chemicals are (i) 1-benzyl quinolinium chloride; (ii) sodium acryloyldimethytaurate; (iii) amaranth (acid red 27); (iv) alcohols, C6-12 ethoxylated propoxylated; (v) ethylene glycol butyl ether; (vi) poly(ethylene glycol); and (vii) tall oil (fatty acids). Since the Tier 1 ERA used mainly acute toxicity data, these chemicals are considered to be of 'potential concern' due to their unknown effects on organisms that may occur due to long-term exposure (chronic toxicity).

Table 29 Chemicals of 'potentially high concern' that are persistent (P) or bioaccumulative (B), and very toxic (T)

Chemical	CAS RN	Use	P[1]	B[2]	T[3]
1,2,4-Trimethylbenzene	95-63-6	Solvent	##	‡	**
1-Benzyl methyl pyridinium chloride	68909-18-2	Corrosion inhibitor	##	‡	***
5-Chloro-2-methyl-4-isothiazolol-3-one	26172-55-4	Biocide	##	‡	***
2-Mercaptoethyl alcohol	60-24-2	Surfactant	##	‡	***
2-Methyl-4-isothiazol-3-one	2682-20-4	Biocide	##	‡	***
Acrylamide	79-06-1	Friction reducer / gelling agent	##	‡	*
Alcohols, C10-16, ethoxylated propoxylated	69227-22-1	Surfactant	##	‡	***
Alcohols, C12-C16, ethoxylated	68551-12-2	Surfactant	##	‡	***
Amines, tallow alkyl, ethoxylated	61791-26-2	Surfactant	##	‡	***
C12-18-alkyldimethylbenzyl ammonium chlorides	68391-01-5	Biocide	##	‡	***
Coco alkyldimethyl oxide	61788-90-7	Surfactant	#	‡‡	***
Dipentene terpene hydrocarbon by-products	68956-56-9	Friction reducer / gelling agent	#	‡‡	**
Naphthalene	91-20-3	Friction reducer / gelling agent	##	‡	***
Naphthenic acids, ethoxylated	68410-62-8	Friction reducer / gelling agent	##	‡	*
Polyethylene glycol monohexyl ether	31726-34-8	Non-emulsifier	##	‡	*
Pontacyl carmine 2B (acid violet 12)	6625-46-3	Tracking dye	##	‡	*
Heavy aromatic solvent naphtha (petroleum)	64742-94-5	Friction reducer / gelling agent	##	‡	**
Hydrotreated light distillate (C13-C14 isoparaffin)	64742-47-8	Friction reducer / gelling agent	##	‡	***

[1] Persistence = half-life >60 days (##), half-life ≤60 days (#); [2] Bioconcentration factor = BCF >2000 or octanol/water partition coefficient = Log Kow ≥4.2 (‡‡); BCF ≤2000 or octanol/water partitioning coefficient = Log Kow <4.2 (‡)
[3] Toxicity = ≤1 mg/L (***), >1 to ≤10 mg/L (**), >10 to ≤100 mg/L (*); CAS RN = Chemical Abstracts Services Registry Number
Data: Geological and Bioregional Assessment Program (2018h)

Table 30 Chemicals of 'potentially high concern' that are not persistent (P) or bioaccumulative (B), and very toxic (T)

Chemical	CAS RN	Use	P[1]	B[2]	T[3]
2-Bromo-2-nitro-1,3-propanediol	52-51-7	Biocide	#	‡	***
Chromium (VI) (soluble hexavalent chromium compounds)	18540-29-9	Breaker	na	na	***
Copper (II) sulfate	7758-98-7	Biocide/breaker	na	na	***
Glutaraldehyde	111-30-8	Biocide	#	‡	***
Hydrochloric acid	7647-01-0	Scale remover	na	na	***
Sodium chlorite ($NaClO_2$)	7758-19-2	Biocide/breaker	na	na	***
Sodium hypochlorite	7681-52-9	Biocide/breaker	na	na	***
Sodium iodide	7681-82-5	Breaker/breaker	na	na	***
Tetrakis(hydroxymethyl) phosphonium sulfate	55566-30-8	Biocide	#	‡	***
Tributyl-tetradecylphosphonium chloride	81741-28-8	Biocide	na	na	***

[1] Persistence = half-life ≤60 days (#), not applicable (na); [2] Bioconcentration factor = BCF ≤2000 or octanol/water partition coefficient = Log Kow <4.2 (‡), not applicable or no data (na); [3] Toxicity = ≤1 mg/L (***)
Data: Geological and Bioregional Assessment Program (2018h)

Biocides are used in drilling and hydraulic fracturing to prevent excess biofilm production in wells and formations, which may lead to clogging, unwanted gas production (e.g. hydrogen sulfide gas) and corrosion of underground casing/tubing and equipment (Kahrilas et al., 2016; Kahrilas et al., 2015). Biocide selection will depend on factors, including (i) the minerology and biogeochemistry of the formation; (ii) compatibility with environmental conditions (e.g. temperature, pressure, salinity, and organic matter contents); (iii) abiotic transformations; (iv) sorption reactions; (v) performance against specific microbial species (mode of action); and (vi) cost.

Biocides are inherently toxic and are, therefore, of 'potentially high concern' if released into the environment. Four biocides identified are water-soluble, persistent and highly toxic to aquatic organisms (chemical screening technical appendix (Kirby et al., 2020)): (i) dicoco dimethyl ammonium chloride (CAS RN 61789-77-3); (ii) 2-methyl-4-isothiazol-3-one (CAS RN 2682-20-4); (iii) 5-chloro-2-methyl-4-isothiazolol-3-one (CAS RN 26172-55-4); and (iv) C12-18-alkyldimethylbenzyl ammonium chlorides (CAS RN 68391-01-5). The effect on biota in a receiving aquatic environment is likely to be dependent on the release scenario (e.g. surface spills, pond overflow to soil and surface water or well leakage to groundwater), exposure concentrations, fate and behaviour in environments (e.g. rate of degradation and transformation, partitioning and complexation), bioavailability and sensitivity of aquatic organisms.

Biocides such as glutaraldehyde (CAS RN 111-30-8) and tetrakis (hydroxymethyl) phosphonium sulfate (CAS RN 55566-30-8), which are very toxic to aquatic organisms, may pose a lower risk to aquatic organisms due to their expected rapid (≤60 days) degradation in aquatic environments (chemical screening technical appendix (Kirby et al., 2020)). However, degradation products of some biocides have been reported to be more toxic and/or persistent than their parent compounds (Kahrilas et al., 2016; Kahrilas et al., 2015). This highlights the need for the development of sensitive and selective analytical methods to detect parent and transformation products in wastewaters and receiving waters to assess potential impacts on aquatic ecosystems.

Siloxanes are added to hydraulic fracturing fluids as defoaming agents and surfactants. These chemicals have low water solubility (soluble/miscible in solvents), are hydrophobic and, in the case of cyclic siloxanes, are volatile. The siloxanes are of ‘potentially high concern’ to aquatic organisms due to their persistence and bioaccumulative and highly toxic nature (Geological and Bioregional Assessment Program, 2018h). The three cyclic siloxanes – octamethylcyclotetrasiloxane (CAS RN 556-67-2), decamethylcyclopentasiloxane (CAS RN 541-02-6) and dodecamethylcyclohexasiloxane (CAS RN 540-97-6) – are likely to volatilise or degrade in water (via hydrolysis) but, due to their hydrophobic nature, are also likely to strongly associate with sediments/suspended solids where they can persist.

Furthermore, there are currently conflicting ERAs on the cyclic siloxanes due to difficulties in conducting aquatic toxicity tests because of their volatility, making the toxicity assessments highly uncertain (ECHA, 2018; Environment Canada Health Canada, 2008; Fairbrother et al., 2015; Fairbrother and Woodburn, 2016; Government of Canada, 2012b, 2012a). The National Industrial Chemicals Notification and Assessment Scheme (NICNAS, 2017) conducted a Tier 2 ERA on these chemicals and found all three to be persistent, two (octamethylcyclotetrasiloxane and decamethylcyclopentasiloxane) to be bioaccumulative and one (octamethylcyclotetrasiloxane) to have ‘uncertain toxicity’. These chemicals, therefore, if used at operations, will require a more detailed quantitative ERAs to be undertaken with realistic exposure scenarios that assess and model the likelihood and consequence of a risk event occurring, identify and evaluate control and mitigation measures (e.g. what controls are in place to address the identified risk and how effective are these controls), and monitor to ensure controls and management strategies are adequate to prevent impacts on environments.

Laboratory-based leachate tests on powdered rock samples (geogenic chemicals)

Leachate tests conducted with dilute hydrochloric acid and synthetic hydraulic fracturing fluid generated the highest inorganic element concentrations in solutions compared to synthetic groundwater (chemical screening technical appendix (Kirby et al., 2020)). This demonstrates the role of acidity and chemical constituents of hydraulic fracturing fluid (e.g. chelating agents, surfactants, solvents) can play in mobilising elements from powdered rocks in formations. The inorganic elements showing substantially increased mobilisation into hydraulic fracturing fluid included aluminium, arsenic, barium, cadmium, cobalt, chromium, copper, iron, lithium, nickel, lead and zinc. It was noted that there was variability between rock types in formations in terms of both the total content of elements and the concentrations of elements mobilised into solution. Further studies are required to determine underlying relationships between element concentrations and physico-chemical properties of the rock formations and the fate of chemicals in the hydraulic fracturing fluid.

Higher pressure led to increased mobilisation into solutions of elements such as aluminium, arsenic, lithium, phosphorus, and sulfur; and decreased mobilisation for elements such as barium, calcium and magnesium (chemical screening technical appendix (Kirby et al., 2020)). The findings highlight the important role pressure can play in the mobilisation of geogenic chemicals from powdered rocks in formations during hydraulic fracturing.

Targeted priority organic chemicals such as phenols, PAHs and TRHs were detected in extracts of powdered rock samples (chemical screening technical appendix (Kirby et al., 2020)). Phenols and PAHs were detected in six of nine sample extracts. The deep coal sample from Holdfast-1 Epsilon contained the largest number of targeted PAHs and highest concentration in sample extracts (e.g. benzo(ghi)perylene (318 mg/kg), indeno-(1,2,3-cd)-pyrene (101 mg/kg), and benzo(ghi)perylene (66 mg/kg)). The highest concentration of TRHs was found to be associated with the TRH C15-C28 (75 to 245 mg/kg; 32 to 53% TRHs) and >C16-C34 NEPM TRH (52 to 129 mg/kg; 24 to 44% TRHs) fractions for all powdered rock sample extracts. Targeted analysis of phenols and PAHs represented a small fraction of the total organic geogenic compounds (based on TRHs) present in the sample extracts (i.e. ~ 0.17% for deep coal sample from Holdfast-1; <0.04% for the other eight sample extracts analysed). Hence, most of the geogenic organic compounds in sample extracts (as TRHs) were unidentified and their risk (individual and mixtures) to aquatic environments is unknown.

Further work is required to determine the relationship between pressure (and temperature) on the hydraulic fracturing fluid and mobilisation of geogenic chemicals from powdered rocks in shale, tight and deep coal formations in the Cooper GBA region.

Fate and behaviour of chemicals in the environment

The ecotoxicity of chemicals released during shale, tight and deep coal gas operations will probably be affected by reactions and processes in environments that can modify their fate and bioavailability (e.g. exposure concentrations) (Adriano, 2001; ANZECC/ARMCANZ, 2000; Neilson, 1994). Organic chemicals can be volatilised, photodegrade, undergo abiotic and biotic degradation and transformations, and complex/adsorb to a range of solid phases (e.g. organic matter). Inorganic chemicals can undergo neutralisation, displacement, ionisation, redox and precipitation reactions; biotransform (e.g. arsenic methylation); and complex/partition to a range of solid phases (e.g. clays, oxides/hydroxides and organic matter). These reactions and processes will be influenced by the physical and chemical properties of the receiving environment, such as pH, salinity, redox conditions, microbial populations and organic matter content.

Chemical additives used in hydraulic fracturing fluids may also be lost in wells and formations to solid surfaces and/or degrade or be transformed to a smaller percentage of what was initially added. For example, polymers can degrade/decompose, biocides can degrade and complex/adsorb onto solid surfaces, and surfactants can be adsorbed onto solid surfaces in formations. In addition, chemical concentrations from source zones can be attenuated in surface water and groundwater through dilution and volatilisation processes.

The Tier 1 qualitative ERA occurred using mainly aquatic acute ecotoxicity data representing three trophic levels – freshwater alga, water flea and fish species – using standard testing protocols (Geological and Bioregional Assessment Program, 2018h, 2018j). Acute toxicity data may not be sufficient in assessing the environmental risk of persistent and bioaccumulative chemicals that could induce effects on biota due to long-term exposure (chronic effects) in the environment. Chronic toxicity data on aquatic organisms from a range of trophic levels (and sensitive species) are needed to accurately assess effects due to long-term exposure of these chemicals to aquatic organisms. In addition, the approach of single-chemical acute toxicity test data provides a highly uncertain assessment when there is limited detailed knowledge on the interactions that modify toxicity and on the modes of toxicity of the chemicals to aquatic biota. A direct toxicity approach where aquatic biota are exposed to dilutions of a complex chemical mixture (e.g. a hydraulic fracturing fluid, flowback and produced water) would provide a more relevant environmental exposure assessment that incorporates chemical interactions/mixtures. Further, the assessment did not consider pulse discharges and dispersion of chemicals (individual and mixtures) into aquatic ecosystems.

6.1.3 Conclusion

A total of 116 chemicals were identified for use in drilling and hydraulic fracturing at shale, tight and deep coal gas operations between 2011 and 2016 (chemical screening technical appendix (Kirby et al., 2020)). Of the 116 chemicals identified, nine were drilling chemicals, 99 were hydraulic fracturing chemicals and eight were chemicals used for both activities. Fifty-eight per cent of the chemicals identified in the current study were not assessed in the national assessment of chemicals associated with CSG extraction in Australia (NICNAS, 2017).

A Tier 1 qualitative (screening) ERA of the identified chemicals found:

- 42 chemicals were of ‘low concern’ and considered to pose minimal risk to surface water and groundwater aquatic ecosystems
- 33 chemicals were of ‘potentially high concern’
- 41 were of ‘potential concern’.

The chemicals of potential concern and potentially high concern would require site-specific quantitative chemical assessment to be undertaken to determine risks from specific operations to aquatic ecosystems.

Laboratory-based leachate tests on powdered rock samples collected from formations in the Cooper GBA region identified several elements that could be substantially mobilised into solutions by hydraulic fracturing fluid including aluminium, arsenic, barium, cadmium, cobalt, chromium, copper, iron, lead, lithium, nickel and zinc. Priority organic chemicals such as phenols, PAHs and TRHs were detected in extracts of powdered rock samples. Targeted analysis of phenols and PAHs represented a small fraction of the total organic geogenic compounds (based on TRH) present in the sample extracts. The majority of organic compounds in sample extracts (as TRHs) were unidentified and their risk (individual and mixtures) to aquatic environments is unknown.

The composition and concentration of geogenic chemicals in flowback and produced waters will depend on many factors including: (i) geology and mineralogy of formations; (ii) surface area of the fracture network exposed to hydraulic fracturing fluids; (iii) composition and concentration of chemicals used in hydraulic fracturing; (iv) residence time of hydraulic fracturing fluids in formations; (v) operational and environmental conditions (e.g. volumes added and recovered, temperature, pressure); and (vi) chemical and physical reactions (e.g. adsorption, complexation, precipitation, aggregation, degradation and transformations).

Companies undertake an ERA process (in consultation with government agencies) of gas operations that includes the identification of potential hazards (e.g. chemical transport and storage, hydraulic fracturing fluid injection, flowback and produced water storage), determines the likelihood and consequence of a risk occurring, identifies and evaluates control and mitigation measures (e.g. what controls are in place or need to be in place to address the identified risk and how effective are these controls), and develops a monitoring program to ensure controls and management strategies are adequate/effective and for compliance. Despite undertaking these detailed ERAs, there is still public concern surrounding the potential environmental impacts of hydraulic fracturing – in particular, the threats posed by the mixture of industrial chemicals used and geogenic chemicals that could be mobilised and their impacts on water quality.

6.1.4 Knowledge gaps

The assessment of chemicals associated with shale, tight and deep coal operations in GBA regions identified knowledge gaps including the following:

- Chemicals used in drilling and hydraulic fracturing are expected to change with time as the industry adapts to site-specific conditions, improves gas extraction efficiency and uses 'greener, safer' options. A Tier 1 qualitative (screening) ERA for all new chemicals (or chemical not previously assessed) used in shale, tight and deep coal operations in Australia could determine whether these new chemicals represent an environmental risk ('Yes/No'). For identified chemicals of environmental risk, Tier 2 and 3 quantitative ERAs can assess 'what', 'where' and 'how great' is the risk.
- Tier 1 qualitative ERA relies mainly on aquatic acute ecotoxicity data representing three trophic levels – freshwater alga, water flea and fish species. Acute toxicity data may not be sufficient for assessing the environmental risks of persistent and bioaccumulative chemicals that could have effects on aquatic organisms due to long-term exposure. Chronic toxicity data using a range of aquatic organisms and trophic levels are needed to accurately assess the effects of long-term exposure of chemicals to aquatic organisms. In addition, ecotoxicity data on drilling and hydraulic fracturing chemicals for Australian species and ecotoxicity endpoints are currently not available for groundwater organisms (e.g. stygofauna).
- Publicly available data on the composition and concentration of chemicals in hydraulic fracturing fluids, flowback and produced water, and wastes (e.g. muds, brines) from shale, tight and deep coal operations in Australia are limited. The fate and transformations of chemicals present in hydraulic fracturing fluids and flowback and produced water (individual chemicals and mixtures) in the environment are also unknown. In addition, most organic compounds present in sample extracts (as TRHs) from powdered rock samples were unidentified and their risk to aquatic environments is unknown.
- Despite the very low likelihood of a well integrity failure (see Section 6.2.2) or failure of surface infrastructure (ponds, tanks, pipelines etc.) (see Section 5.3.3) associated with shale, tight and deep coal gas operations in Australia (i.e. constructed to highest industry standards and a high level of government regulation and compliance), there is still public concern about the consequences to water quality (drinking, livestock, aquatic ecosystems and cultural) if fluids are released. Surface water and groundwater monitoring and modelling using site-specific conditions and exposure scenarios would improve public understanding of potential impacts to water quality (i.e. localised event) and the adequacy of control and management plans to prevent environmental impacts.

6.2 Hydraulic fracturing and compromised well integrity

Hydraulic fracture stimulation is used to create hydraulic fractures in the target petroleum reservoir to maximise the flow of gas to the well. Hydraulic fracturing has been used to stimulate conventional oil and gas and unconventional gas reservoirs in the Cooper Basin over the past 50 years (Figure 89). Potential environmental risks of hydraulic fracturing have been the focus of active discussion across industry, government and academic agencies for the past decade and have led to several significant domestic and international inquiries into onshore gas industry operations. A review of the findings of these inquiries, along with a review of historical Cooper Basin data and Cooper GBA region hazard identification and scoring (see Section 5.2.3) provide an initial assessment of the relative likelihood of occurrence of three impact modes in the Cooper GBA region (Table 31). While this initial assessment did not highlight any of the three hydraulic fracturing impact modes as a priority, one impact mode – 'Hydraulic fracture growth into aquifer' – will be included in the Stage 3 analysis to address heightened community concern about hydraulic fracturing in the context of the Cooper GBA regional geology.

Compromised well integrity is a concern for government and the community. Regulated construction of wells aims to ensure that fluid and gas are prevented from flowing unintentionally from the reservoir into another geological layer or to the surface. In this qualitative review, Cooper GBA region historical data is compared with findings from international and domestic inquiries to present an initial evaluation of five conceptual impact modes (Table 32). These were compared to the prioritisations from Cooper GBA region hazard identification (Section 5) and are broadly consistent. Two impact modes have been prioritised for inclusion in the Stage 3 analysis: W3 – Migration of fluids along casing between geological layers; and W4 – Migration of fluids along decommissioned or abandoned wells (Section 6.2.2).

6.2.1 Hydraulic fracturing

Hydraulic fracture stimulation is used to increase the productivity of petroleum wells and is critical to the performance of wells in low-permeability 'unconventional' formations. Fluid is injected at sufficient pressure and flow rate to propagate hydraulic fractures into the target formation. After the fluid pressure is released, proppant (sand or artificial ceramics) remains in the created fracture to increase the effective permeability in the target formation and ultimately increase the flow of gas to the well. Wells are usually fractured in stages, where isolated sections are fractured individually. The number of hydraulic fracturing stages depends on the length of the well and can range from one to 50 stages per well.

Hydraulic fracturing has been used to stimulate conventional oil and gas and unconventional gas reservoirs in the Cooper Basin over the past 50 years (Figure 89). Modern hydraulic fracturing techniques have advanced over recent years, and stimulation designs for shale, tight and deep coal gas target formations build upon technologies and processes invented for exploiting conventional oil and gas resources (Golden and Wiseman, 2015; Hatton et al., 2018). In both conventional and unconventional applications of hydraulic fracture stimulation, the design objective is to create hydraulic fractures in the target petroleum reservoir to maximise the flow of gas to the well (Hatton et al., 2018).

Between 1969 and 2017, over 900 wells were stimulated with hydraulic fracturing in the Cooper and Eromanga basins. The number of hydraulic fracturing stages has been increasing since 2000 (Figure 89), primarily in the Nappamerri and Patchawarra troughs (Figure 14).

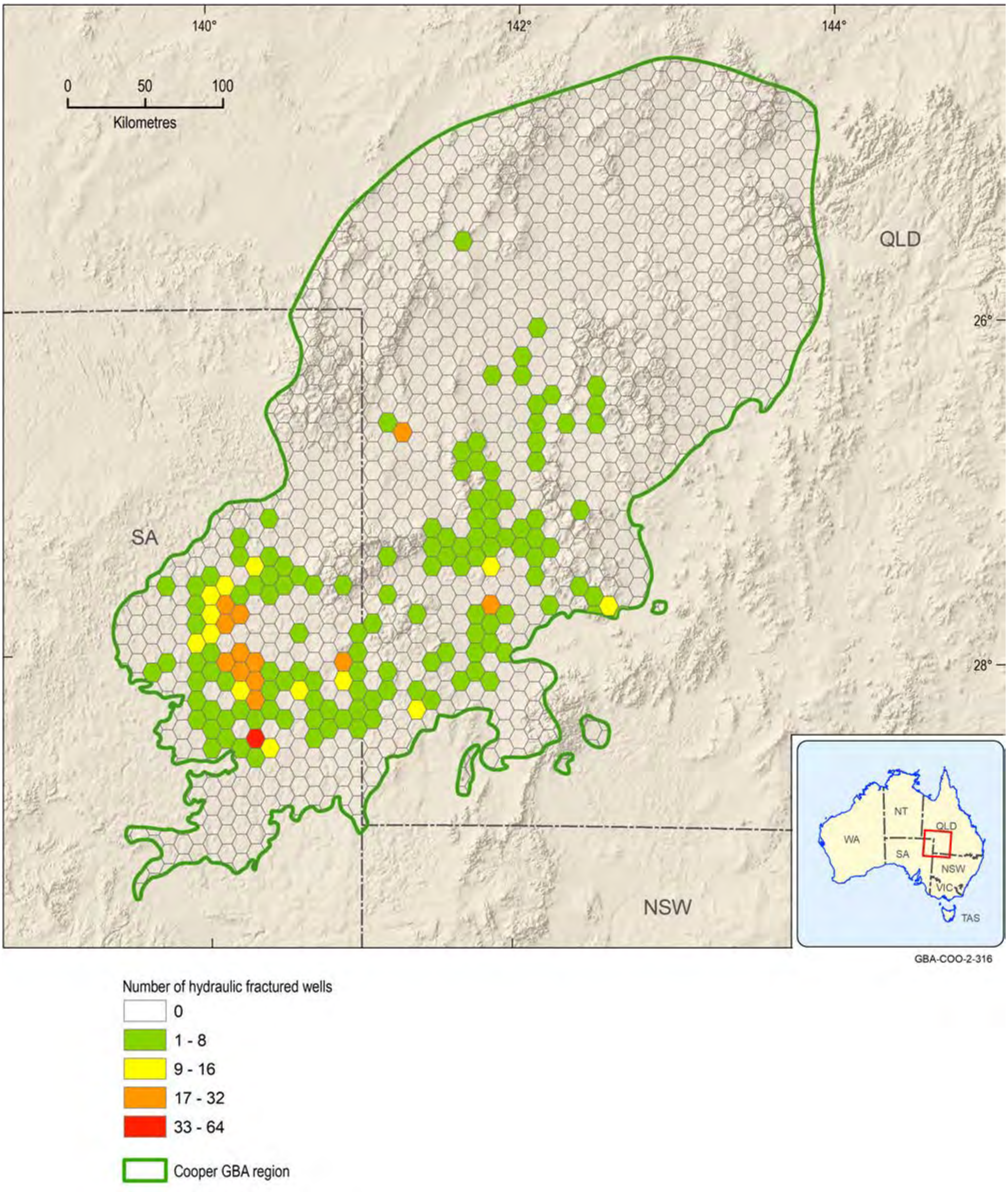

Figure 89 Map of 817 hydraulically fractured petroleum wells in the Cooper GBA region

Data: Department for Energy and Mining (SA) (2018d) and State of Queensland (2018)
Element: GBA-COO-2-316

Over the last decade, the potential environmental risks of hydraulic fracturing have been the focus of active discussion and investigation across industry, government and academic agencies (e.g. US EPA (2016a); Atherton et al. (2014); Vengosh et al. (2014); Wright (2014); Dusseault and Jackson (2014); Hawke (2014); Pepper et al. (2018); Hatton et al. (2018)).

In response to this heightened public interest in the risks associated with hydraulic fracturing, international and domestic inquiries have been conducted to assess hydraulic fracturing activities, including considering the potential likelihoods of many of the impact modes in their local contexts. Although local geological properties, in-situ stresses and applied hydraulic fracture techniques will impact local risk profiles, the qualitative findings of these domestic and international reviews provide an important line of evidence in assessing the relative likelihood of each impact mode in the Cooper GBA region. The findings from nine of these international and domestic inquiries have been interpreted to distil, where possible, a relative likelihood of occurrence for each impact mode. The findings from each of the nine reviewed inquiries are summarised in Table 31, with further details available in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020).

While there are several impact modes by which hydraulic fracturing operations could potentially dilate or create a pathway for fluid migration between subsurface geological layers or to the surface, the likelihood of those impacts occurring is generally considered manageable to a suitably low level given: appropriate regulatory controls, sufficient understanding of the baseline geological and environmental systems, and acceptable industry practices (US EPA, 2016a; Hawke, 2014; Cook et al., 2013b; The Royal Society and The Royal Academy of Engineering, 2012; Wright, 2014; Council of Canadian Academies, 2014; Atherton et al., 2014; Pepper et al., 2018; Hatton et al., 2018). However, a number of sources (US EPA, 2016a; Council of Canadian Academies, 2014; Vidic et al., 2013; Jackson et al., 2013) note that, due to the difficulty in observing potential impacts, especially to groundwater resources, it is difficult to validate many of the estimates of rates of these occurrences. The uncertainty caused by the lack of validation data cannot be fully overcome within the scope of the GBA Program.

The qualitative review in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020) compares Cooper GBA region historical data with findings from international and domestic hydraulic fracturing inquiries to present an initial evaluation of the likelihood of three impact modes by which hydraulic fracturing could conceivably cause contaminants to impact environmental systems in the Cooper GBA region.

The three impact modes relating to hydraulic fracture stimulation which were considered in the hazard analysis and qualitative review (Kear and Kasperczyk, 2020) are:

- F1 – Hydraulic fracture growth into aquifer
- F2 – Hydraulic fracture growth into well
- F3 – Hydraulic fracture growth into fault.

Each of the above impact modes was evaluated against the findings of significant domestic and international inquiries, historical data from the Cooper GBA region and the results from the GBA hazard screening workshop. The evaluation results are shown in Table 31, with details of the review presented in the accompanying technical appendix (Kear and Kasperczyk, 2020).

The scoring from the Cooper GBA region hazard identification workshops (see Section 5.2.3) did not highlight any of the three hydraulic fracturing impact modes as a priority based on estimated severity and likelihood of the potential impacts. This finding is broadly consistent with the findings of the qualitative review of the domestic and international inquiries.

The analysis of the Cooper GBA region historical and geological data showed that the Cooper GBA region exhibited a slightly higher potential likelihood (Unlikely vs Rare) of a hydraulic fracture extending into an overlying aquifer unit (Hawke, 2014). This is due to the relative proximity of the deeper GAB aquifers and the shale, tight and deep coal gas plays (a cross-section of the Cooper GBA region is shown in Figure 15). The vertical separation between the deeper GAB aquifers and the upper potential target formations is typically between 600 and 2000 m across the Cooper GBA region (Evans et al., 2020; Owens et al., 2020). However, in some parts of the Cooper GBA region, this vertical separation can be smaller, such as the 300 – 800 m reported by Hawke (2014) based on an interpretation of the geology reported by Cook et al. (2013). Although the likelihood of this occurrence is considered low and the hazard score is not sufficient to warrant prioritisation, impact mode ‘Hydraulic fracture growth into aquifer’ will be included in the Stage 3 analysis on the basis of the heightened community concern around hydraulic fracturing and the local Cooper GBA regional geology.

Table 31 Summary of likelihoods for hydraulic fracturing impact modes

Likelihood terminology definitions and further details of the reviews are available in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020).

Likelihood estimates	F1 – Hydraulic fracture growth into aquifer	F2 – Hydraulic fracture growth into well	F3 – Hydraulic fracture growth into fault
Cooper GBA region hazard identification (Geological and Bioregional Assessment Program, 2019c)	Rare – Very unlikely	Very unlikely– Unlikely	Rare – Very unlikely
Likelihood estimated from historical Cooper Basin data (Kear and Kasperczyk, 2020)	Unlikely	Unlikely	Rare
Overall qualitative likelihood from the nine inquiries	Rare	Unlikely	Rare
Range of inquiry qualitative likelihood ratings	Rare – Unlikely	Rare – Unlikely	Rare – Unlikely
Hydraulic fracturing for oil and gas: Impacts from the hydraulic fracturing water cycle on drinking water resources in the United States (US EPA, 2016a)	Unlikely	Unlikely	Rare
Report of the independent inquiry into hydraulic fracturing in the Northern Territory (Hawke, 2014)	Rare	Not assessed	Unlikely
Engineering energy: Unconventional gas production. report for the Australian council of learned academics (Cook et al., 2013b)	Unlikely	Not assessed	Unlikely
Shale gas extraction in the UK: A review of hydraulic fracturing (The Royal Society and The Royal Academy of Engineering, 2012)	Rare	Not assessed	Unlikely
Drilling for oil and gas in New Zealand: Environmental oversight and regulation (Wright, 2014)	Not assessed	Not assessed	Not assessed
Environmental impacts of shale gas extraction in Canada (Council of Canadian Academies, 2014)	Rare	Unlikely	Rare
Nova Scotia independent panel on hydraulic fracturing (Atherton et al., 2014)	Rare	Unlikely	Not assessed
Scientific inquiry into hydraulic fracturing in the Northern Territory (Pepper et al., 2018)	Rare	Not assessed	Rare
Independent scientific panel inquiry into hydraulic fracture stimulation in Western Australia (Hatton et al., 2018)	Rare	Rare	Unlikely

6.2.2 Compromised well integrity

Petroleum wells are constructed to have integrity such that fluid and gas are prevented from flowing unintentionally from the reservoir into another stratigraphic layer or to the surface. The components which prevent this fluid movement are known as ‘well barrier elements’ and form ‘well barriers’. The well barriers are pressure containment envelopes. A minimum of two independent well barriers is often required under international standards for industry practice and regulations (e.g. ISO 16530 (International Organization for Standardization, 2013), NORSOK Standard D-010 (Norwegian Petroleum Industry, 2004) and ANSI/API RP 100-1 and 100-2 (2015a, 2015b). By having multiple well barriers, a failure within one well barrier element does not result in the loss of integrity of a well (US EPA, 2016a).

If the integrity of a well were to be compromised, there could be a potential pathway for fluids to flow vertically between geological layers and to the surface. While there are several impact modes by which loss of well integrity could potentially cause the well to act as a conduit for fluid migration, the likelihood of those impact modes occurring is generally considered manageable to a suitably low level given appropriate regulatory controls, sufficient understanding of the baseline geological and environmental systems, and acceptable industry practices (US EPA, 2016a; Hawke, 2014; Cook et al., 2013b; The Royal Society and The Royal Academy of Engineering, 2012; Wright, 2014; Council of Canadian Academies, 2014; Atherton et al., 2014; Pepper et al., 2018; Hatton et al., 2018). However, data limitations make it difficult to assess the rates at which well integrity failures have impacted groundwater resources (Council of Canadian Academies, 2014; Jackson et al., 2013; Vidic et al., 2013; US EPA, 2016a). The uncertainty caused by the lack of validation data cannot be fully overcome within the scope of the GBA Program.

The qualitative review in Kear and Kasperczyk (2020) compares Cooper GBA region historical data with findings from international and domestic inquiries to present an initial evaluation of the likelihood of five impact modes by which well integrity failures could conceivably cause contaminants to impact assessment endpoints in the Cooper GBA region.

Three of the reviewed well integrity failure impact modes relate to the production phase of a well:

- W1 – Rupture or failure across well barriers that allows fluids to move between the inside and the outside of the well
- W2 – Migration of fluids from the reservoir to the surface along a failure of the well casing
- W3 – Migration of fluids between different geological layers along a failure of the well casing.

Two of the reviewed impact modes relate to well integrity failure during construction, workover and decommissioning operations:

- W4 – Failure of well integrity after well decommissioning / abandonment
- W5 – Loss of well control (blowout).

Each of the five reviewed well integrity failure impact modes has been evaluated against the findings of significant domestic and international inquiries, historical data from the Cooper GBA region and the results from the GBA hazard screening workshop. The evaluation results are shown in Table 32, with detail available in Kear and Kasperczyk (2020).

Table 32 Summary of likelihoods for compromised well integrity impact modes

Likelihood terminology definitions and further details of the reviews are available in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020).

Likelihood estimates	W1 – Well rupture or failure across barriers	W2 – Migration of fluids to the surface along a failure of the well	W3 – Migration along casing between geological layers	W4 – Migration along decommissioned /abandoned wells	W5 – Loss of well control
Cooper GBA region hazard identification (Geological and Bioregional Assessment Program, 2019c)	Rare – Unlikely	Rare – Unlikely	Rare – Possible	Unlikely – Possible	Rare – Unlikely
Likelihood estimated from historical Cooper Basin data (Kear and Kasperczyk, 2020)	Rare	Very unlikely	Unlikely	Not assessed	Very unlikely
Overall qualitative likelihood from the nine inquiries	Rare	Rare	Unlikely	Unlikely	Not assessed
Range of inquiry qualitative likelihood ratings	Vary rare – Rare	Rare – Unlikely	Very rare – Unlikely	Unlikely – Likely	Not assessed
Hydraulic fracturing for oil and gas: Impacts from the hydraulic fracturing water cycle on drinking water resources in the United States (US EPA, 2016a)	Rare	Unlikely	Unlikely	Unlikely	Not assessed
Report of the independent inquiry into hydraulic fracturing in the Northern Territory (Hawke, 2014)	Rare	Rare	Vary rare	Unlikely	Not assessed
Engineering energy: Unconventional gas production. Report for the Australian council of learned academics (Cook et al., 2013b)	Rare	Not assessed	Unlikely	Unlikely	Not assessed
Shale gas extraction in the UK: A review of hydraulic fracturing (The Royal Society and The Royal Academy of Engineering, 2012)	Not Assessed	Rare	Not assessed	Unlikely	Not assessed
Drilling for oil and gas in New Zealand: Environmental oversight and regulation (Wright, 2014)	Rare	Rare	Not assessed	Unlikely	Not assessed
Environmental impacts of shale gas extraction in Canada (Council of Canadian Academies, 2014)	Rare	Unlikely	Unlikely	Unlikely	Not assessed
Nova Scotia independent panel on hydraulic fracturing (Atherton et al., 2014)	Vary rare	Rare	Rare	Likely	Rare
Scientific inquiry into hydraulic fracturing in the Northern Territory (Pepper et al., 2018)	Rare	Rare	Unlikely	Unlikely	Not assessed

Likelihood estimates	W1 – Well rupture or failure across barriers	W2 – Migration of fluids to the surface along a failure of the well	W3 – Migration along casing between geological layers	W4 – Migration along decommissioned /abandoned wells	W5 – Loss of well control
Independent scientific panel inquiry into hydraulic fracture stimulation in Western Australia (Hatton et al., 2018)	Vary rare	Not assessed	Rare	Unlikely	Not assessed

The scoring from the Cooper GBA region hazard screening workshops (see Section 5) identified two of the five compromised well integrity impact modes as priorities for assessment in Stage 3 on the basis of the assessed severity and likelihood of the potential impacts. The two priority compromised well integrity impact modes are:

- W3 – Migration of fluids along casing between geological layers.
- W4 – Migration of fluids along decommissioned or abandoned wells.

These prioritisations are broadly consistent with the findings of the qualitative review of the domestic and international inquiries as summarised in Table 32, with detail presented in the accompanying technical appendix (Kear and Kasperczyk, 2020). Therefore, the two above prioritised impact modes are recommended for inclusion in the Cooper GBA Stage 3 analysis.

6.2.3 Knowledge gaps

Qualitative assessments of hydraulic fracturing and compromised well integrity for the Cooper GBA region identified knowledge gaps that include the following:

- Potential environmental risks from hydraulic fracture stimulation are generally considered manageable to a suitably low level, but there is heightened community concern about hydraulic fracturing. Inclusion of a spatial analysis in Stage 3 could serve to address the identified knowledge gap between engineering risk assessments and community concerns of the risks in the Cooper GBA region. Therefore, one impact mode, ‘Hydraulic fracture growth into aquifer’, is recommended for inclusion in Stage 3 analysis based on the heightened community concern around hydraulic fracturing and the Cooper GBA regional geology. Spatial analysis of vertical hydraulic fracture height growth in the Cooper GBA region will improve understanding of the likelihood of hydraulic fractures intersecting the Hutton Sandstone aquifer in the overlying Eromanga Basin (Figure 15).
- Quantification of the likelihood and potential rate of subsurface flow of fluids along compromised wells in the Cooper GBA region was identified as a priority impact mode and knowledge gap. Stage 3 investigation of two impact modes – ‘Migration of fluids along casing between geological layers’ and ‘Migration of fluids along decommissioned or abandoned wells’ – is designed to address this knowledge gap. Spatial analysis of potential flow along compromised wells will improve understanding of the likelihood of environmental impacts of well integrity failure in the Cooper GBA region.
- The challenges of observing and validating potential impacts from hydraulic fracture stimulation and compromised well integrity remain a source of uncertainty for future

assessments. Numerical modelling of hydraulic fracturing and groundwater flow will provide quantitative estimates of fracture heights and fluid flow between aquifer units in the Cooper GBA region in Stage 3 to improve confidence in the assessment of risks.

7 Conclusion

The geological and environmental baseline assessment for the Cooper GBA region provides a synthesis of the geology and prospectivity of future shale, tight and deep coal gas resources, water resources and protected matters (environmental and cultural). Risks to water (quantity and quality) and the environment are identified and prioritised for further investigation and assessment in Stage 3. The insights and needs emanating from informal discussions with governments, industry, landowners and the community at GBA workshops and user panel meetings are incorporated in this report.

7.1 Key findings

About the region

The Cooper GBA region is generally flat, with the braided channels of Cooper Creek flowing from the north-east to the south-west toward Lake Eyre. The climate is hot and dry, with summer-dominated (December to February) rainfall and high inter-annual variability. Global climate models predict a hotter and drier climate in the region, with the mean number of hot days projected to increase (currently 84 to 114 days per year) by between 30 and 90 days per year. Most of the region is used to graze sheep and cattle on native vegetation. Smaller areas are used for nature conservation and oil and gas treatment, storage and distribution at Ballera, Jackson and Moomba. There are few permanent residents – more people are employed in the region than live there due to the large 'fly-in–fly-out' workforce. The Cooper and Eromanga geological basins have produced 6.54 Tcf of gas since 1969. They contain 256 gas fields and 166 oil fields currently in production that deliver significant volumes of gas to the East Coast Gas Market.

The development of shale, tight and deep coal gas resources is an emerging industry in Australia that is regulated at federal, state and local levels to ensure that development is sustainable and responsible and minimises impacts on environmental and social values. At a national level, the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act) provides the legal framework to protect and manage nationally and internationally important flora, fauna, ecological communities and heritage places — referred to as Matters of National Environmental Significance (MNES). This is the overarching legislation for strategic assessments, which enable the consideration of cumulative impacts on MNES and opportunities for conservation and planning outcomes at a broad scale that could not be addressed via a project-by-project approvals process. In addition, state (Queensland and SA) legislation focuses on governing petroleum resources and protecting threatened species and areas of environmental value – referred to as Matters of State Environmental Significance (MSES).

Geology and unconventional gas resources

The Cooper Basin is a Late Carboniferous to Late Triassic sedimentary basin, located in south-west Queensland and north-east SA. It is overlain by the Early Jurassic to Late Cretaceous Eromanga and Cenozoic Lake Eyre basins, which host major aquifer systems.

Although the Cooper Basin is a mature basin in terms of conventional hydrocarbon production, it remains highly prospective for both conventional and unconventional oil and gas resources. Queensland and SA petroleum title holders have or are pursuing a range of unconventional gas plays hosted within the Permian succession. These plays include shale gas associated with the Patchawarra Formation and the Roseneath and Murteree shales, deep coal gas accumulations within the Toolachee, Epsilon and Patchawarra formations, and tight gas within the Gidgealpa Group.

To underpin further work on understanding likely development scenarios and recovery factors, the key physical formation properties required for the shale, tight and deep coal gas plays in the Cooper Basin to be successful were characterised. The physical properties evaluated, which vary by play type, include formation depths and extents, source rock properties (net thickness, total organic carbon (TOC), quality and maturity), reservoir characteristics (porosity, permeability, gas saturation and brittleness), regional stress regime and pressure gradient.

Areas with the highest potential for shale, tight and deep coal gas development were assessed by mapping the relative prospectivity of each play across the basin. Regions of higher prospectivity were identified within most depocentres, including the Nappamerri, Patchawarra, Windorah, Allunga and Wooloo troughs, which is consistent with recent exploration activity.

Water resources

Groundwater occurs in three major hydrostratigraphic sequences in the Cooper GBA region. The deepest is the Cooper Basin, which is not directly used as a groundwater source due to the depth of burial (generally greater than 1500 m) and presence of extensive petroleum accumulations. The Nappamerri Group forms a regional seal to petroleum systems between the Cooper and Eromanga basins. The Eromanga Basin overlies all of the Cooper Basin and contains a sequence of aquifers and aquitards that are part of the Great Artesian Basin. The overlying Lake Eyre Basin includes several locally important aquifer systems.

Groundwater in the aquifers of the Eromanga and Lake Eyre basins in the Cooper GBA region are generally suitable for stock and domestic use. Most (90%) of the 2137 groundwater bores registered in the Cooper GBA region are less than 300 m deep and access water from the Winton-Mackunda partial aquifer and aquifers in the Cenozoic Lake Eyre Basin.

The main potential for connectivity between the Eromanga and Cooper basins is where the Gidgealpa Group subcrops beneath the Eromanga Basin, particularly where sandier units in the Nappamerri Group are in direct contact with the Eromanga Basin or where major faults significantly offset aquifer sequences. Between 600 and 2000 m of sedimentary rock typically separate aquifers, such as those in the Cenozoic and Winton-Mackunda formations or deeper GAB aquifers, from shale, tight and deep coal gas plays in the Cooper Basin. However, in some parts of the Cooper GBA region, this vertical separation can be smaller, such as the 300 – 800 m reported by Hawke (2014) based on an interpretation of the geology reported by Cook et al. (2013b). This sedimentary rock impedes potential hydrological connectivity between the gas plays and groundwaters.

Surface water is an unregulated and unreliable water source for future unconventional gas development. Potential water sources for a future shale, tight and deep coal gas industry in the Cooper GBA region are treated, produced water from conventional oil and gas activities within approximately 20 km of drilling operations and existing groundwater bores on exploration leases.

Cooper Creek, which supports the Ramsar-listed Coongie Lakes and many waterholes and terminal lakes, has one of the most variable flow regimes of all rivers worldwide. When flooded, the floodplain becomes a huge inland sea broken only by a few ridges and stunted trees. It contracts in the dry season to channels, lagoons and claypans. High evapotranspiration rates reduce streamflow in Cooper Creek by about half between the confluence of the Thomson and Barcoo rivers and the Nappa Merrie gauge near the SA border. Surface water quality is variable in space and over time, with floodwaters in the upper reaches having low salinity and the terminal lakes tending to be saline. Median salinity recorded at three stream gauges on the Cooper, Barcoo and Thomson rivers is approximately 100 mg/L total dissolved solids (TDS), which is suitable for drinking water and for stock watering.

Connectivity between the surface water and groundwater in the Cooper GBA region is limited to recharge of small freshwater lenses near waterholes during floods. Groundwater levels in shallow aquifers are consistently below stream bed levels, indicating that streams in the region are losing disconnected systems that are not fed by groundwater discharge or spring flow. Hydrochemistry and dissolved gas concentrations provide some evidence of the nature of the hydrological connection (if any) between deeper groundwaters (Cooper, Eromanga and Lake Eyre basins) and surface waters.

Protected matters

The baseline environmental assessment identified 53 MNES and 63 MSES in the Cooper GBA region. This includes 12 threatened species (ten MNES and two MSES), one threatened ecological community, one internationally listed Ramsar wetland, eight nationally important wetlands (includes Coongie Lakes), two wetlands listed as part of the Lake Eyre Basin Intergovernmental Agreement and nine protected areas listed as MSES. Key threatening processes identified under the EPBC Act include competition and land degradation by rabbits and unmanaged goats; land clearance; loss of climatic habitat caused by anthropogenic emissions of greenhouse gases; introduced species; predation by European red foxes and feral cats; habitat degradation, competition and disease transmission by feral pigs; and biological effects, including lethal toxic ingestion, caused by cane toads (*Rhinella marina*).

A national heritage place, consisting of several sites along Cooper Creek, is listed under the EPBC Act due to the historical significance of the ill-fated Burke and Wills expedition in 1860 to 1861 and the support provided to it by the Yandruwandha people. Many of the Cooper Creek waterholes and Cooper Creek itself form part of extensive Indigenous trading routes throughout Lake Eyre Basin. Indigenous language groups include the Birria, Wangkumara, Yandruwandha, Yawarrawarrka and Karuwali tribal or language groups. Most of the region (71%), including all of the region in SA and 60% in Queensland, is covered by Indigenous Land Use Agreements (ILUAs). Of the 43 ILUAs registered in the Cooper GBA region in October 2018, six are related to the petroleum industry.

Landscape classification and associated conceptual models are used to characterise the key ecological and hydrological systems in the region. The ecohydrological conceptualisation for each landscape class will underpin the assessment of potential hydrological and other environmental impacts due to shale, tight and deep coal gas development in Stage 3. Seven landscape classes are identified for the Cooper GBA region. The largest areas include floodplain and alluvium, inland dunefields, and undulating country on fine-grained sedimentary rocks. The region includes smaller areas of loamy and sandy plains, tablelands and duricrusts, and clay plains and springs.

In order to focus the assessment in Stage 3, protected matters were prioritised based on how important the Cooper GBA region is to each matter. Detailed assessments will focus on 12 protected species and 18 protected areas that are known or expected to occur in the region (priority 1). High-level assessments will focus on 20 protected areas, including regional ecosystems and heritage sites identified in the Cooper GBA region (priority 2). Further assessment is not warranted for 58 protected species and 73 protected areas in the Cooper GBA region (priority 3) based on the listed conservation status or expected occurrence in the region.

Potential impacts

Stage 2 establishes the context for the impact and risk assessment, including identifying hazards to determine which causal pathways should be considered further in Stage 3 and which, given the evidence base, may be ruled out or considered a minimal risk. Hazards were systematically identified by considering all the possible ways an activity in the life cycle of shale, tight and deep coal gas development may have an impact on ecological, economic and social values. The range of severity and likelihood scores for each hazard was agreed by experts from government, industry and members of the assessment team at five workshops for the Cooper GBA region between May and August 2018. Stage 3 of the GBA Program will assess the likelihood and consequences of the identified risks (risk analysis and risk evaluation phases).

Causal pathways were prioritised using the highest hazard score (severity + likelihood) to enable future analysis in Stage 3 to focus on higher priority risks. Seven causal pathways were prioritised for a detailed level of assessment in Stage 3 (priority 1). Another five causal pathways were prioritised for assessment (priority 2). Important potential impacts to be assessed in Stage 3 are changes to groundwater quality; surface water flows; cultural heritage damage or loss; habitat fragmentation and loss; introduction of invasive species; and contamination of soil, groundwater and or surface water.

Most of the priority hazards are in the landscape management (43 out of 94) and water and infrastructure management (41 of 90) causal pathway groups, with fewer (nine out of 22) in the subsurface flow paths causal pathway group:

- Priority hazards in the 'landscape management' causal pathway group occur when best-practice design and management protocols, techniques and practices are not effective or properly implemented – that is the likelihood of these hazards occurring is generally low. Potential effects include changed surface water flows, cultural heritage damage or loss, habitat fragmentation or loss, increased competition and predation, increased mortality of native species, increased soil erosion and contamination of soil, groundwater and/or surface water.

- In the 'subsurface flow paths' causal pathway group, priority hazards include water-related impacts that may occur at various depths below the surface (e.g. changes to groundwater quality or groundwater pressures within an aquifer). The likelihood of these hazards occurring is reduced by existing gas industry controls, including good geological knowledge, effective planning and design, monitoring and adherence to best-practice international standards and procedures.
- Priority hazards in the 'water and infrastructure management' causal pathway group occur when management protocols, techniques and practices are not effective or as a consequence of natural hazards – that is the likelihood of these hazards occurring is generally low. Potential effects include contamination of soil, groundwater and/or surface water and changes to surface waters or groundwaters, principally changes to levels, pressures or flows and water quality.

The impact and risk assessment in Stage 3 will assess how each causal pathway might impact on the suite of endpoints – endemic native species, migratory species, ecological communities, wetland ecosystems, water resources, cultural heritage and agriculture – for the range of development profiles to be developed in Stage 3. Development profiles represent the range of spatial and temporal infrastructure needed for gas resource development. The assessment will identify the likely mitigation and management measures, assess the likelihood and consequence of potential impacts for each pathway, identify risk factors that amplify or diminish potential impacts, describe confidence in existing knowledge and identify knowledge gaps.

Control and stressor conceptual models for each landscape class will be used to consider causal pathways in relation to key system processes and other threatening processes relevant to each landscape class. Protected matters (e.g. threatened species, threatened ecological communities, Ramsar-listed wetlands) will be investigated through individual asset-level assessments that consider the potential exposure of that asset to causal pathways for each landscape class (and how this may vary between landscape classes) and the impacts to the asset that may stem from that exposure. As an example, Figure 90 is a preliminary conceptualisation of potential linkages between existing drivers, threatening processes and causal pathways leading to potential impacts from future shale and tight gas development on the Bulloo grey grass wren (*Amytornis barbartus barbartus*) – a species listed as endangered under the EPBC Act. Mitigation and management options that could be considered in an abatement plan for individual assets and that are relevant for specific causal pathways will also be identified. Monitoring recommendations, including design principles, possible measurement endpoints and relative monitoring emphases, that could validate (or invalidate) the risk predictions and underpin a baseline will be provided.

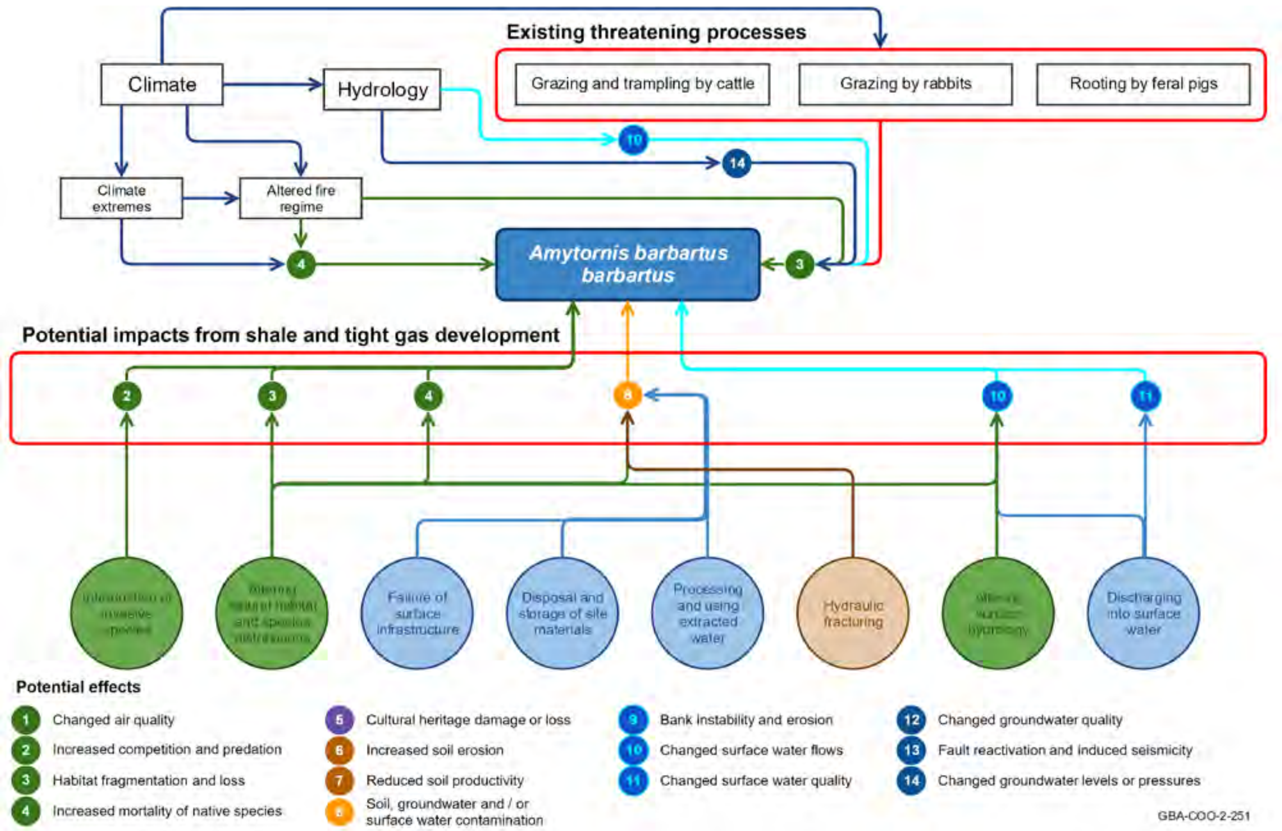

Figure 90 Preliminary conceptualisation of linkages between existing drivers, threatening processes and causal pathways leading to potential impacts from future shale and tight gas development on the Bulloo grey grass wren (*Amytornis barbartus barbartus*)

The upper part of the conceptual model represents the 'control model' and represents system drivers and existing threatening processes currently impacting on the Bulloo grey grass wren. The full model, which includes the casual pathways associated with shale, tight gas and deep coal development, represents the stressor model.
Element: GBA-COO-2-251

Screening of drilling and hydraulic fracturing chemicals

The Tier 1 qualitative screening assessed 116 chemicals used between 2011 and 2016 for drilling and hydraulic fracturing at shale, tight and deep coal gas operations. Of the 116 chemicals identified, most (58%) were not assessed in the national assessment of chemicals associated with CSG extraction in Australia (NICNAS, 2017). About one-third (42 chemicals) were of 'low concern' and pose minimal risk to aquatic ecosystems. A further 33 chemicals were of 'potentially high concern' and 41 were of 'potential concern'. These chemicals would require site-specific assessments to be undertaken to determine risks from specific operations to aquatic ecosystems.

The chemicals used in drilling and hydraulic fracturing are expected to change with time as industry adapts to site-specific conditions, improves gas extraction efficiency and endeavours to use 'greener, safer' options. A Tier 1 qualitative (screening) environmental risk assessment (ERA) for all new chemicals (or chemicals not previously assessed) used in shale, tight and deep coal operations in Australia could be used to determine if a potential environmental risk exists ('Yes/No'). If a potential environmental risk from chemicals exists, the questions will change to 'what', 'where' and 'how great' is the risk (i.e. Tier 2 and 3 quantitative ERAs).

Laboratory-based leachate tests on powdered rock samples from formations in the Cooper GBA region detected several elements and priority organic chemicals that could be mobilised by hydraulic fracturing fluid. These include aluminium, arsenic, barium, cadmium, cobalt, chromium, copper, iron, lead, lithium, nickel and zinc, as well as priority organic chemicals such as phenols, polycyclic aromatic hydrocarbons (PAHs) and total recoverable hydrocarbons (TRHs). The majority of organic compounds in sample extracts (as TRHs) were unidentified and their risk (individual and mixtures) to aquatic environments is unknown.

The composition and concentration of geogenic chemicals in flowback and produced waters will depend on many factors including: (i) geology and mineralogy of formations; (ii) surface area of the fracture network exposed to hydraulic fracturing fluids; (iii) composition and concentration of chemicals used in hydraulic fracturing; (iv) residence time of hydraulic fracturing fluids in formations; (v) operational and environmental conditions (e.g. volumes added and recovered, temperature, pressure); and (vi) chemical and physical reactions (e.g. adsorption, complexation, precipitation, aggregation, degradation and transformations).

Hydraulic fracturing and compromised well integrity

Review of (i) domestic and international inquiries into onshore gas industry operations; (ii) historical Cooper Basin data; and (iii) hazard identification scores provide initial estimates of the relative likelihood of occurrence of impact modes associated with hydraulic fracturing and compromised well integrity in the Cooper GBA region. None of the three hydraulic fracturing impact modes were considered a priority in the initial assessment. However, further assessment of the 'Hydraulic fracture growth into aquifer' impact mode will be conducted in Stage 3 to address heightened community concern about hydraulic fracturing. Two of the five impact modes associated with compromised well integrity – 'Migration of fluids along casing between geological layers' and 'Migration of fluids along decommissioned or abandoned wells' – have been prioritised for further analysis in Stage 3.

7.2 Gaps, limitations and opportunities

Knowledge gaps identified in Stage 2 were prioritised to address sources of uncertainty in the conceptualisation and analysis of potential impacts from shale, tight and deep coal gas resource development in Stage 3. Field and modelling investigations in Stage 3 will also test current understanding of approaches to the management, mitigation and monitoring of potential impacts.

Geology and unconventional gas resources

The regional-scale prospectivity analysis identifies areas where more detailed work can be undertaken, but this scale of analysis is not suitable for individual play or prospect-scale evaluations. Due to local geological variations not captured by the regional input datasets, not all areas identified as having a high relative prospectivity confidence will result in gas discoveries. In addition to cultural and environmental considerations, the large capital expenditure required to extract unconventional resources (i.e. if and how a shale, tight or deep coal play is developed) is dependent on its economic viability. The development profiles that will underpin the impact and risk assessment in Stage 3 will consider likely economic outcomes from the development of each gas play at a high level.

Additional work, that is beyond the scope of Stage 3, to place the prospectivity analysis in an economic context could include:

- resource assessments to estimate total volume of gas-in-place for priority play types, based on the geological understanding of the plays outlined in this report
- estimation of the proportion of gas-in-place that is technically recoverable
- economic analysis to understand what would be economic to produce, based on market conditions.

Water resources

Stage 3 will refine the geological architecture of the Cenozoic and Winton-Mackunda partial aquifers using existing petroleum well data to improve understanding of aquifer extent and connectivity. This will be complemented by baseline groundwater level and hydrochemistry sampling (including environmental tracers) to improve understanding of important processes such as recharge, aquifer compartmentalisation and connectivity of near-surface aquifers in the Cenozoic and Winton-Mackunda formations. In addition, analysis of produced waters from the Cooper and Eromanga basins will improve understanding of deep groundwater processes to inform future management and reuse options.

Stage 3 will test hypotheses related to the nature of the hydrological connection (if any) between deeper groundwaters (Cooper, Eromanga and Lake Eyre basins) and surface waters. This includes hydrological connectivity between (i) unconventional gas plays and overlying Eromanga Basin aquifers; (ii) Eromanga and Lake Eyre basins via polygonal faults in the Rolling Downs Group partial aquitard; and (iii) permanent waterholes and regional groundwaters.

Cooper Creek floodplain, its permanent waterholes and groundwaters are highly valued by the community. Stage 3 will use the digital elevation model, coupled with the hydrodynamic flood inundation model, to assess potential impacts from surface infrastructure on the flood regime of the Cooper Creek floodplain. Remotely sensed ecohydrological information analysed in Stage 3 and the flood inundation model will improve understanding of water regimes that support flora and fauna along Cooper Creek. Field studies using environmental tracers and other physical measurements in Stage 3 will improve the conceptualisation of hydrological connections between permanent waterholes and the regional groundwater system.

Protected matters

Detailed knowledge of ecosystem function, distribution and threats to individual threatened species and accurate mapping of species habitat are key knowledge gaps. These knowledge gaps will constrain what can be achieved as part of Stage 3. Stage 3 will develop conceptual models that explicitly link risks from existing and future activities (shale, tight and deep coal gas development) for individual threatened species and other important ecological assets (integrating current and future drivers and stressors). In doing so it will compile the best available ecological knowledge to conceptualise potential impacts on protected matters. It will also define important assessment and measurement endpoints to guide future monitoring of potential impacts.

The landscape classification plays an important role in the assessment. Its primary purpose is to develop ecohydrological conceptualisations of the landscape and the connectively of landscape classes to regional-scale processes. They also form natural reporting units for the aggregation of potential impacts. The landscape classification is limited by the quality of available datasets, including surface geology, elevation, vegetation and landform mapping, and extent and quality of ground observations. In particular, the distribution of clay plains is not clearly indicated in geological maps but could be improved using geomorphology mapping, interpretation of satellite imagery, aerial photography and soil cores. However, in the Cooper GBA region this landscape class is only a minor component of the region. A decision to invest further in addressing these knowledge gaps will rely heavily on the scale of potential impacts in this landscape class and associated protected matters.

Remotely sensed data (blended Landsat/MODIS estimates of actual evapotranspiration and vegetation fractional cover) will be used to investigate critical ecological and hydrological characteristics of landscape classes in areas that are prospective for unconventional gas resources. In Stage 3, this will inform (i) water balance estimates; (ii) identification and characterisation of groundwater-dependent ecosystem water regimes; and (iii) habitat fragmentation (changes to vegetation cover and actual evapotranspiration) from selected development activities (e.g. roads, pipelines, seismic lines, well pads, groundwater or surface water extraction).

Potential impacts

Assumptions made at the hazard identification workshops affect estimates of severity and likelihood of potential impacts. Explicit representation of the range of possible future development profiles is needed in Stage 3 to reduce uncertainty in the nature and severity of potential impacts. In particular, the scale of potential impacts for each causal pathway, including changes over time (if relevant) and how they may be affected by the pulsed nature of flows and water inputs at or near the surface in a boom–bust ecosystem, is critical.

Conceptualisation of the regional geology and hydrogeology, as well as the potential hydrological connections from stressors to assets, includes a number of uncertainties and alternative formulations (multiple conceptual models). These uncertainties will be captured, represented and tested using simple screening numerical models. Uncertainty will be propagated through models used for the assessment in Stage 3 by basing predictions upon plausible distributions of model parameters rather than fixed values. The preliminary conceptualisations presented here for each causal pathway will be updated in Stage 3 using a range of approaches, including review of existing conceptual models and expert elicitation.

Screening of drilling and hydraulic fracturing chemicals

Public concern about potential environmental impacts on water quality from hydraulic fracturing remains heightened. In particular, the community is concerned about potential impacts on water quality from the mixture of industrial chemicals used and geogenic chemicals that could be mobilised during shale, tight and deep coal gas resource development. While it is beyond the scope of Stage 3 for the Cooper GBA region, the independent collection and open and transparent reporting of water quality data before, during and after hydraulic fracturing would improve community and government understanding in the ERA process, controls and monitoring, and inform wastewater management and treatment options.

Hydraulic fracturing and compromised well integrity

To address the gap between engineering-based risk assessments and heightened community concerns about hydraulic fracturing and compromised well integrity, Stage 3 will use numerical modelling of hydraulic fracturing and groundwater flow. Analysis of vertical hydraulic fracture height growth will assess the likelihood of hydraulic fractures in Cooper Basin shale, tight and deep coal gas plays intersecting with the Hutton Sandstone aquifer in the overlying Eromanga Basin. Groundwater flow modelling will improve understanding of the likelihood of environmental impacts from well integrity failure in the Cooper GBA region.

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Glossary

The register of terms and definitions used in the Geological and Bioregional Assessment Program is available online at https://w3id.org/gba/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. Many of the definitions for these terms have been sourced from external glossaries – several from international sources; spelling variations have been preserved to maintain authenticity of the source.

abandonment: a process which involves shutting down the well and rehabilitating the site. It includes decommissioning the well.

accumulation: in petroleum geosciences, an 'accumulation' is referred to as an individual body of moveable petroleum

activity: for the purposes of Impact Modes and Effects Analysis (IMEA), a planned event associated with unconventional gas resource development. For example, activities during the exploration life-cycle stage include drilling and coring, ground-based geophysics and surface core testing. Activities are grouped into ten major activities, which can occur at different life-cycle stages.

adsorption: the capability of all solid substances to attract to their surfaces molecules of gases or solutions with which they are in contact

aeolian: relating to or arising from the action of wind

annual flow: the volume of water that discharges past a specific point in a stream in a year, commonly measured in GL/year

anticline: an arch-shaped fold in rock in which rock layers are upwardly convex. The oldest rock layers form the core of the fold and, outward from the core, progressively younger rocks occur.

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 commonly 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

asset: an entity that has value to the community and, for the purposes of geological and bioregional assessments, is associated with a GBA region. An asset is a store of value and may be managed and/or used to maintain and/or produce further value. An asset may have many values associated with it that can be measured from a range of perspectives; for example, the values of a wetland can be measured from ecological, sociocultural and economic perspectives.

barrel: a standard unit of measurement for all production and sales of oil. It has a volume of 42 US gallons [0.16 m^3].

baseflow: the portion of streamflow that comes from shallow and deep subsurface flow, and is an important part of the groundwater system

basement: the oldest rocks in an area; commonly igneous or metamorphic rocks of Precambrian or Paleozoic age that underlie other sedimentary formations. Basement generally does not contain significant oil or gas, unless it is fractured and in a position to receive these materials from sedimentary strata.

basin-centred gas: a type of tight gas that occurs in distributed basin-centred gas accumulations, where gas is hosted in low permeability reservoirs which are commonly abnormally overpressured, lack a down dip water contact and are continuously saturated with gas. This is also sometimes referred to as 'continuous' and 'pervasive' gas.

bed: in geosciences, the term 'bed' refers to a layer of sediment or sedimentary rock, or stratum. A bed is the smallest stratigraphic unit, generally a centimetre or more in thickness. To be labeled a bed, the stratum must be distinguishable from adjacent beds.

bioaccumulation: a process by which chemicals are taken up by a plant or animal either directly through exposure to a contaminated medium (soil, sediment, water) or by consuming food or water containing the chemical

biogenic gas: hydrocarbon gases (which are overwhelmingly (greater than or equal to 99%) methane) produced as a direct consequence of bacterial activity

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.

brittleness: a material is brittle if, when subjected to stress, it breaks without significant plastic deformation

casing: a pipe placed in a well to prevent the wall of the hole from caving in and to prevent movement of fluids from one formation to another

causal pathway: for the purposes of geological and bioregional assessments, the logical chain of events – either planned or unplanned – that link unconventional gas development and potential impacts on water and the environment

causal pathway group: causal pathways with similar attributes (e.g. landscape management) that are grouped for further analysis

cementing: the application of a liquid slurry of cement and water to various points inside and outside the casing

charge: in petroleum geoscience, a 'charge' refers to the volume of expelled petroleum available for entrapment cleat: the vertical cleavage of coal seams. The main set of joints along which coal breaks when mined.

coal: a rock containing greater than 50 wt.% organic matter

coal seam gas: coal seam gas (CSG) is a form of natural gas (generally 95% to 97% pure methane, CH_4) extracted from coal seams, typically at depths of 300 to 1000 m. Also called coal seam methane (CSM) or coalbed methane (CBM).

compression: lateral force or stress (e.g. tectonic) that tends to decrease the volume of, or shorten, a substance

conceptual model: an abstraction or simplification of reality that describes the most important components and processes of natural and/or anthropogenic systems, and their response to interactions with extrinsic activities or stressors. They provide a transparent and general representation of how complex systems work, and identify gaps or differences in understanding. They are often used as the basis for further modelling, form an important backdrop for assessment and evaluation, and typically have a key role in communication. Conceptual models may take many forms, including descriptive, influence diagrams and pictorial representations.

condensate: condensates are a portion of natural gas of such composition that are in the gaseous phase at temperature and pressure of the reservoirs, but that, when produced, are in the liquid phase at surface pressure and temperature

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.

conglomerate: a sedimentary rock dominated by rounded pebbles, cobbles, or boulders

consequence: synonym of impact

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

conventional gas: conventional gas is obtained from reservoirs that largely consist of porous sandstone formations capped by impermeable rock, with the gas trapped by buoyancy. The gas can often move to the surface through the gas wells without the need to pump.

Cooper Basin: the Cooper Basin geological province is an Upper Carboniferous – Middle Triassic geological sedimentary basin that is up to 2500 m thick and occurs at depths between 1000 and 4400 m. It is overlain completely by the Eromanga and Lake Eyre basins. Most of the Cooper Basin is in south-west Queensland and north-east SA, and includes a small area of NSW at Cameron Corner. It occupies a total area of approximately 130,000 km^2, including 95,740 km^2 in Queensland, 34,310 km^2 in SA and 8 km^2 in NSW.

crust: the outer part of the Earth, from the surface to the Mohorovicic discontinuity (Moho)

cumulative impact: for the purposes of geological and bioregional assessments, the total environmental change resulting from the development of selected unconventional hydrocarbon resources when all past, present and reasonably foreseeable actions 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).

deep coal gas: gas in coal beds at depths usually below 2000 m are often described as 'deep coal gas'. Due to the loss of cleat connectivity and fracture permeability with depth, hydraulic fracturing is used to release the free gas held within the organic porosity and fracture system of the coal seam. As dewatering is not needed, this makes deep coal gas exploration and development similar to shale gas reservoirs.

deformation: folding, faulting, shearing, compression or extension of rocks due to the Earth's forces

delta: a low, nearly flat area near the mouth of a river, commonly forming a fan-shaped plain that can extend beyond the coast into deep water. Deltas form in lakes and oceans when sediment supplied by a stream or river overwhelms that removed by tides, waves, and currents

depocentre: an area or site of maximum deposition; the thickest part of any specified stratigraphic unit in a depositional basin

deposition: sedimentation of any material, as in the mechanical settling of sediment from suspension in water, precipitation of mineral matter by evaporation from solution, and accumulation of organic material

depositional environment: the area in which, and physical conditions under which, sediments are deposited. This includes sediment source; depositional processes such as deposition by wind, water or ice; and location and climate, such as desert, swamp or river.

development: a phase in which newly discovered oil or gas fields are put into production by drilling and completing production wells

discovered: the term applied to a petroleum accumulation/reservoir whose existence has been determined by its actual penetration by a well, which has also clearly demonstrated the existence of moveable petroleum by flow to the surface or at least some recovery of a sample of petroleum. Log and/or core data may suffice for proof of existence of moveable petroleum if an analogous reservoir is available for comparison.

diversion: see extraction

dome: a type of anticline where rocks are folded into the shaped of an inverted bowl. Strata in a dome dip outward and downward in all directions from a central area.

drill stem test: an operation on a well designed to demonstrate the existence of moveable petroleum in a reservoir by establishing flow to the surface and/or to provide an indication of the potential productivity of that reservoir. Drill stem tests (DSTs) are performed in the open hole to obtain reservoir fluid samples, static bottomhole pressure measurements, indications of productivity and short-term flow and pressure buildup tests to estimate permeability and damage extent.

drilling fluid: circulating fluid that lifts rock cuttings from the wellbore to the surface during the drilling operation. Also functions to cool down the drill bit, and is a component of well control.

dry gas: natural gas that is dominated by methane (greater than 95% by volume) with little or no condensate or liquid hydrocarbons

economic values: values associated with agriculture, aquaculture, drinking water supply, industry or intensive development and tourism activities

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), a change to water or the environment, such as changes to the quantity and/or quality of surface water or groundwater, or to the availability of suitable habitat. An effect is a specific type of an impact (any change resulting from prior events).

endpoint: for the purposes of geological and bioregional assessments, an endpoint is a value pertaining to water and the environment that may be impacted by development of unconventional gas resources. Endpoints include assessment endpoints – explicit expressions of the ecological, economic and/or social values to be protected; and measurement endpoints – measurable characteristics or indicators that may be extrapolated to an assessment endpoint as part of the impact and risk assessment.

Eromanga Basin: an extensive geologic sedimentary basin formed from the Early Jurassic to the Late Cretaceous that can be over 2500 m thick. It overlies several older geological provinces including the Cooper Basin, and is in part overlain by the younger Cenozoic province, the Lake Eyre Basin. The Eromanga Basin is found across much of Queensland, northern SA, southern NT, as well as north-western NSW. The Eromanga Basin encompasses a significant portion of the Great Artesian Basin.

erosion: the wearing away of soil and rock by weathering, mass wasting, and the action of streams, glaciers, waves, wind, and underground water exploration: the search for new hydrocarbon resources by improving geological and prospectivity understanding of an area and/or play through data acquisition, data analysis and interpretation. Exploration may include desktop studies, field mapping, seismic or other geophysical surveys, and drilling.

extraction: the removal of water for use from waterways or aquifers (including storages) by pumping or gravity channels. In the oil and gas industry, extraction refers to the removal of oil and gas from its reservoir rock.

facies: the characteristics of a rock unit that reflect the conditions of its depositional environment

fairway: a term used in geology to describe a regional trend along which a particular geological feature is likely to occur, such as a hydrocarbon fairway. Understanding and predicting fairways can help geologists explore for various types of resources, such as minerals, oil and gas.

fault: a fracture or zone of fractures in the Earth's crust along which rocks on one side were displaced relative to those on the other side

field: in petroleum geoscience, a 'field' refers to an accumulation, pool, or group of pools of hydrocarbons or other mineral resources in the subsurface. A hydrocarbon field consists of a reservoir with trapped hydrocarbons covered by an impermeable sealing rock, or trapped by hydrostatic pressure.

floodplain: a flat area of unconsolidated sediment near a stream channel that is submerged during or after high flows

flowback: the process of allowing fluids and entrained solids to flow from a well following a treatment, either in preparation for a subsequent phase of treatment or in preparation for cleanup and returning the well to production. The flowback period begins when material introduced into the well during the treatment returns to the surface following hydraulic fracturing or refracturing. The flowback period ends when either the well is shut in and permanently disconnected from the flowback equipment or at the startup of production.

flowback water: the fluids and entrained solids that emerge from a well during flowback

fluvial: sediments or other geologic features formed by streams

fold: a curve or bend of a formerly planar structure, such as rock strata or bedding planes, that generally results from deformation

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

formation water: water that occurs naturally in sedimentary rocks

fracking: see hydraulic fracturing

fracture: a crack or surface of breakage within rock not related to foliation or cleavage in metamorphic rock along which there has been no movement. A fracture along which there has been displacement is a fault. When walls of a fracture have moved only normal to each other, the fracture is called a joint. Fractures can enhance permeability of rocks greatly by connecting pores together, and for that reason, fractures are induced mechanically in some reservoirs in order to boost hydrocarbon flow. Fractures may also be referred to as natural fractures to distinguish them from fractures induced as part of a reservoir stimulation or drilling operation. In some shale reservoirs, natural fractures improve production by enhancing effective permeability. In other cases, natural fractures can complicate reservoir stimulation.

free gas: the gaseous phase present in a reservoir or other contained area. Gas may be found either dissolved in reservoir fluids or as free gas that tends to form a gas cap beneath the top seal on the reservoir trap. Both free gas and dissolved gas play important roles in the reservoir-drive mechanism.

gas-in-place: the total quantity of gas that is estimated to exist originally in naturally occurring reservoirs

gas saturation: the relative amount of gas in the pores of a rock, usually as a percentage of volume

geogenic chemical: a naturally occurring chemical originating from the earth – for example, from geological formations

geological architecture: the structural style and features of a geological province, like a sedimentary basin

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

gilgai: a small ephemeral lake formed from a depression in the soil surface in expanding clay soils

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 require access to groundwater on a permanent or intermittent basis to meet all or some of their water requirements

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

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

horizontal drilling: drilling of a well in a horizontal or near-horizontal plane, usually within the target hydrocarbon-bearing formation. Requires the use of directional drilling techniques that allow the deviation of the well on to a desired trajectory.

hydraulic fracturing: also known as 'fracking', 'fraccing' or 'fracture simulation'. This is a process by which geological formations bearing hydrocarbons (oil and gas) are 'stimulated' to increase the flow of hydrocarbons and other fluids towards the well. In most cases, hydraulic fracturing is undertaken where the permeability of the formation is initially insufficient to support sustained flow of gas. The process involves the injection of fluids, proppant and additives under high pressure into a geological formation to create a conductive fracture. The fracture extends from the well into the production interval, creating a pathway through which oil or gas is transported to the well.

hydraulic fracturing fluid : the fluid injected into a well for hydraulic fracturing. Consists of a primary carrier fluid (usually water or a gel), a proppant such as sand and chemicals to modify the fluid properties.

hydraulic fracturing stage: hydraulic fracture stimulation conducted at a defined interval along a well. Hydraulic fracture stimulation of horizontal wells will often involve multiple hydraulic fracture stages so as to create hydraulic fractures at multiple locations along the length of the well.

hydrocarbons: various organic compounds composed of hydrogen and carbon atoms that can exist as solids, liquids or gases. Sometimes this term is used loosely to refer to petroleum.

hydrogen index: the amount of hydrogen relative to the amount of organic carbon present in kerogen (organic matter). Gross trends of hydrogen indices (HIs) can be used as an indication of maturity.

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

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

hydrostatic pressure: equal pressure in all direction, equivalent to the pressure which is exerted on a portion of a column of water as a result of the weight of the fluid above it

impact: the difference between what could happen as a result of activities and processes associated with extractive industries, such as shale, tight and deep coal gas development, and what would happen without them. Impacts may be changes that occur to the natural environment, community or economy. Impacts can be a direct or indirect result of activities, or a cumulative result of multiple activities or processes.

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.

injection: the forcing or pumping of substances into a porous and permeable subsurface rock formation. Examples of injected substances can include either gases or liquids.

kerogen: insoluble (in organic solvents) particulate organic matter preserved in sedimentary rocks that consists of various macerals originating from components of plants, animals, and bacteria. Kerogen can be isolated from ground rock by extracting bitumen with solvents and removing most of the rock matrix with hydrochloric and hydrofluoric acids.

kerogen type: kerogens are classified into five types: I, II, IIS, III, and IV

Lake Eyre Basin: a geologic province containing Cenozoic terrestrial sedimentary rocks within the Lake Eyre surface water catchment. It covers parts of northern and eastern SA, south-eastern NT, western Queensland and north-western NSW. In the Cooper GBA region, the basin sedimentary package is less than 300 m thick.

landscape class: for the purposes of geological and bioregional assessments (GBA), a collection of ecosystems with characteristics that are expected to respond similarly to changes in groundwater and/or surface water due to unconventional gas 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 GBA region and their spatial coverage is exhaustive and non-overlapping. Conceptually, landscape classes can be considered as types of ecosystem assets.

leaky aquitard: a semi-permeable geological material that can transmit groundwater. Although regionally non-productive, it may be classed as a very low yielding aquitard that is sometimes used to produce groundwater where no other source is available.

life-cycle stage: one of five stages of operations in unconventional gas resource development considered as part of the Impact Modes and Effects Analysis (IMEA). These are exploration, appraisal, development, production, and rehabilitation. Each life-cycle stage is further divided into major activities, 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

lithology: the description of rocks, especially in hand specimen and in outcrop, on the basis of characteristics such as colour, mineralogic composition and grain size major activity: for the purposes of Impact Modes and Effects Analysis (IMEA), a group of activities associated with a common part of the shale, tight or deep coal gas resource development process. There are ten major activities used in geological and bioregional assessments ranging from 'construction' through to 'well abandonment and rehabilitation'. Major activities may occur across different life cycles, though often with differing levels of intensity; for example, drilling may occur in the exploration, appraisal, development and production life cycles but is at its peak during development.

mantle: the region of the Earth composed mainly of solid silicate rock that extends from the base of the crust (Moho) to the core–mantle boundary at a depth of approximately 2900 km

material: pertinent or relevant

mature: a hydrocarbon source rock that has started generating hydrocarbons

methane: a colourless, odourless gas, the simplest paraffin hydrocarbon, formula CH_4. It is the principal constituent of natural gas and is also found associated with crude oil. Methane is a greenhouse gas in the atmosphere because it absorbs long-wavelength radiation from the Earth's surface.

migration: the process whereby fluids and gases move through rocks. In petroleum geoscience, 'migration' refers to when petroleum moves from source rocks toward reservoirs or seep sites. Primary migration consists of movement of petroleum to exit the source rock. Secondary migration occurs when oil and gas move along a carrier bed from the source to the reservoir or seep. Tertiary migration is where oil and gas move from one trap to another or to a seep.

mudstone: a general term for sedimentary rock made up of clay-sized particles, typically massive and not fissile

natural gas : the portion of petroleum that exists either in the gaseous phase or is in solution in crude oil in natural underground reservoirs, and which is gaseous at atmospheric conditions of pressure and temperature. Natural gas may include amounts of non-hydrocarbons.

naturally occurring radioactive materials: radioactive elements and their decay products found in the environment that have been generated from natural processes

net thickness: the accumulated thickness of a certain rock type of a specified quality which is found within a specific interval of formation

oil: a mixture of liquid hydrocarbons and other compounds of different molecular weights. Gas is often found in association with oil. Also see petroleum.

oil field: an area with an underlying oil reservoir. Typically, industry professionals use the term with an implied assumption of economic size

operator: the company or individual responsible for managing an exploration, development or production operation organic matter: biogenic, carbonaceous materials. Organic matter preserved in rocks includes kerogen, bitumen, oil and gas. Different types of organic matter can have different oil-generative potential.

orogeny: the process of mountain building; the process whereby structures within fold-belt mountainous areas formed

outcrop: a body of rock exposed at the surface of the Earth

overpressure: occurs when the pore pressure is higher than the hydrostatic pressure, caused by an increase in the amount of fluid or gas in the rock, or changes to the rock that reduce the amount of pore space. If the fluid cannot escape, the result is an increase in pore pressure. Overpressure can only occur where there are impermeable layers preventing the vertical flow of water, otherwise the water would flow upwards to equalise back to hydrostatic pressure.

partial aquifer: a permeable geological material with variable groundwater yields that are lower than in an aquifer and range from fair to very low yielding locally

pay: a reservoir or portion of a reservoir that contains economically producible hydrocarbons. The term derives from the fact that it is capable of 'paying' an income. Pay is also called pay sand or pay zone. The overall interval in which pay sections occur is the gross pay; the smaller portions of the gross pay that meet local criteria for pay (such as minimum porosity, permeability and hydrocarbon saturation) are net pay.

peak life-cycle stage: the life-cycle stage when impacts from unconventional gas resource development are expected to be greatest. The five life-cycle stages are: (i) exploration, (ii) appraisal, (iii) development, (iv) production and (v) rehabilitation.

percentile: a specific type of quantile where the range of a distribution or set of runs is divided into 100 contiguous intervals, each with probability 0.01. An individual percentile may be used to indicate the value below which a given percentage or proportion of observations in a group of observations fall. For example, the 95th percentile is the value below which 95% of the observations may be found.

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.

petroleum: a naturally occurring mixture consisting predominantly of hydrocarbons in the gaseous, liquid or solid phase

petroleum system: the genetic relationship between a pod of source rock that is actively producing hydrocarbon, and the resulting oil and gas accumulations. It includes all the essential elements and processes needed for oil and gas accumulations to exist. These include the source, reservoir, seal, and overburden rocks, the trap formation, and the hydrocarbon generation, migration and accumulation processes. All essential elements and processes must occur in the appropriate time and space in order for petroleum to accumulate.

play: a conceptual model for a style of hydrocarbon accumulation used during exploration to develop prospects in a basin, region or trend and used by development personnel to continue exploiting a given trend. A play (or group of interrelated plays) generally occurs in a single petroleum system.

play fairway analysis: sometimes referred to as play fairway mapping, play fairway analysis is used to identify areas where a specific play is likely to be successful, and where additional work on a finer scale is warranted in order to further develop an understanding of a prospect. The phrasing 'fairway' is used as prospective areas on the map are often visually similar to fairways on a golf course. Play fairway maps are created at a regional scale, often tens to hundreds of kilometres in scale, from multiple input sources that vary based on what information is available and relevant based on the requirements of the creator.

plug: a mechanical device or material (such as cement) placed within a well to prevent vertical movement of fluids

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

potential effect: specific types of impacts or changes to water or the environment, such as changes to the quantity and/or quality of surface water or groundwater, or to the availability of suitable habitat

produced water: a term used in the oil industry to describe water that is produced as a by-product along with the oil and gas. Oil and gas reservoirs often have water as well as hydrocarbons, sometimes in a zone that lies under the hydrocarbons, and sometimes in the same zone with the oil and gas. The terms 'co-produced water' and 'produced water' are sometimes used interchangeably by government and industry. However, in the geological and bioregional assessments, 'produced water' is used to describe water produced as a by-product of shale and tight gas resource development, whereas 'co-produced water' refers to the large amounts of water produced as a by-product of coal seam gas development.

producing: a well or rock formation from which oil, gas or water is produced

production: in petroleum resource assessments, 'production' refers to the cumulative quantity of oil and natural gas that has been recovered already (by a specified date). This is primarily output from operations that has already been produced.

production well: a well used to remove oil or gas from a reservoir

proppant: a component of the hydraulic fracturing fluid system comprising sand, ceramics or other granular material that 'prop' open fractures to prevent them from closing when the injection is stopped

prospectivity assessment: the assessment of an area to determine the likelihood of discovering a given resource (e.g. oil, gas, groundwater) by analysing the spatial patterns of foundation datasets. The key objective is to identify areas of increased likelihood of discovering previously unrecognised potential. Sometimes referred to as ‘chance of success’ or ‘common risk segment’ analysis.

prospectivity confidence: the relative certainty of hydrocarbons being found (on a scale of zero to one) based on prospectivity mapping

recharge: see groundwater recharge

reserves: quantities of petroleum anticipated to be commercially recoverable in known accumulations from a given date forward under defined conditions. Reserves must further satisfy four criteria: they must be discovered, recoverable, commercial and remaining (as of the evaluation date) based on the development project(s) applied.

reservoir: a subsurface body of rock having sufficient porosity and permeability to store and transmit fluids and gases. Sedimentary rocks are the most common reservoir rocks because they have more porosity than most igneous and metamorphic rocks and form under temperature conditions at which hydrocarbons can be preserved. A reservoir is a critical component of a complete petroleum system.

reservoir rock: any porous and permeable rock that contains liquids or gases (e.g. petroleum, water, CO_2), such as porous sandstone, vuggy carbonate and fractured shale

ridge: a narrow, linear geological feature that forms a continuous elevated crest for some distance (e.g. a chain of hills or mountains or a watershed)

riparian: 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 (ASNZ ISO 3100). This involves assessing the potential consequences and likelihood of impacts to environmental and human values that may stem from an action, under the uncertainty caused by variability and incomplete knowledge of the system of interest.

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

sandstone: a sedimentary rock composed of sand-sized particles (measuring 0.05–2.0 mm in diameter), typically quartz

seal: a relatively impermeable rock, commonly shale, anhydrite or salt, that forms a barrier or cap above and around reservoir rock such that fluids cannot migrate beyond the reservoir. A seal is a critical component of a complete petroleum system.

sediment: various materials deposited by water, wind or glacial ice, or by precipitation from water by chemical or biological action (e.g. clay, sand, carbonate)

sedimentary rock: a rock formed by lithification of sediment transported or precipitated at the Earth's surface and accumulated in layers. These rocks can contain fragments of older rock transported and deposited by water, air or ice, chemical rocks formed by precipitation from solution, and remains of plants and animals.

sedimentation: the process of deposition and accumulation of sediment (unconsolidated materials) in layers seismic survey: a method for imaging the subsurface using controlled seismic energy sources and receivers at the surface. Measures the reflection and refraction of seismic energy as it travels through rock.

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

severity: magnitude of an impact

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

shale: a fine-grained sedimentary rock formed by lithification of mud that is fissile or fractures easily along bedding planes and is dominated by clay-sized particles

shale gas: generally extracted from a clay-rich sedimentary rock, which has naturally low permeability. The gas it contains is either adsorbed or in a free state in the pores of the rock.

siltstone: a sedimentary rock composed of silt-sized particles (0.004 to 0.063 mm in diameter)

source rock: a rock rich in organic matter which, if heated sufficiently, will generate oil or gas. Typical source rocks, usually shales or limestones, contain about 1% organic matter and at least 0.5% total organic carbon (TOC), although a rich source rock might have as much as 10% organic matter. Rocks of marine origin tend to be oil-prone, whereas terrestrial source rocks (such as coal) tend to be gas-prone. Preservation of organic matter without degradation is critical to creating a good source rock, and necessary for a complete petroleum system. Under the right conditions, source rocks may also be reservoir rocks, as in the case of shale gas reservoirs.

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: the study of the history, composition, relative ages and distribution of stratified rock strata, and its interpretation to reveal Earth's history. However, it has gained broader usage to refer to the sequential order and description of rocks in a region.

stress: the force applied to a body that can result in deformation, or strain, usually described in terms of magnitude per unit of area, or intensity

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

structure: a geological feature produced by deformation of the Earth's crust, such as a fold or a fault; a feature within a rock, such as a fracture or bedding surface; or, more generally, the spatial arrangement of rocks

subcrop: 1 - A subsurface outcrop, e.g. where a formation intersects a subsurface plane such as an unconformity. 2 - In mining, any near-surface development of a rock or orebody, usually beneath superficial material.

subsidence: the sudden sinking or gradual downward settling of the Earth's surface with little or no horizontal motion. The movement is not restricted in rate, magnitude, or area involved.

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

thermal maturity: the degree of heating of a source rock in the process of transforming kerogen (derived from organic matter) into hydrocarbon. Thermal maturity is commonly evaluated by measuring vitrinite reflectance or by pyrolysis.

thermogenic gas: hydrocarbon gases generated by the thermal breakdown of organic matter. These usually occur at depths exceeding 1000 m below the land surface or seabed

tight gas: tight gas is trapped in reservoirs characterised by very low porosity and permeability. The rock pores that contain the gas are minuscule, and the interconnections between them are so limited that the gas can only migrate through it with great difficulty.

total organic carbon: the quantity of organic matter (kerogen and bitumen) is expressed in terms of the total organic carbon (TOC) content in mass per cent. The TOC value is the most basic measurement for determining the ability of sedimentary rocks to generate and expel hydrocarbons.

toxicity: inherent property of an agent to cause an adverse biological effect

trap: a geologic feature that permits an accumulation of liquid or gas (e.g. natural gas, water, oil, injected CO_2) and prevents its escape. Traps may be structural (e.g. domes, anticlines), stratigraphic (pinchouts, permeability changes) or combinations of both.

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

unconformity: a surface of erosion between rock bodies that represents a significant hiatus or gap in the stratigraphic succession. Some kinds of unconformities are (a) angular unconformity – an unconformity in which the bedding planes above and below the unconformity are at an angle to each other; and (b) disconformity – an unconformity in which the bedding planes above and below the stratigraphic break are essentially parallel.

unconventional gas: unconventional gas is generally produced from complex geological systems that prevent or significantly limit the migration of gas and require innovative technological solutions for extraction. There are numerous types of unconventional gas such as coal seam gas, deep coal gas, shale gas and tight gas.

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

water-dependent asset: an asset potentially impacted, either positively or negatively, by changes in the groundwater and/or surface water regime due to unconventional gas resource development water saturation: the fraction of water in a given pore space. It is expressed in volume/volume, percent or saturation units. Unless otherwise stated, water saturation is the fraction of formation water in the undisturbed zone. The saturation is known as the total water saturation if the pore space is the total porosity, but is known as effective water saturation if the pore space is the effective porosity. If used without qualification, the term usually refers to the effective water saturation.

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.

weathering: the breakdown of rocks and other materials at the Earth’s surface caused by mechanical action and reactions with air, water and organisms. Weathering of seep oils or improperly sealed oil samples by exposure to air results in evaporative loss of light hydrocarbons.

well: typically a narrow diameter hole drilled into the earth for the purposes of exploring, evaluating, injecting or recovering various natural resources, such as hydrocarbons (oil and gas), water or carbon dioxide. Wells are sometimes known as a ‘wellbore’.

well barrier: envelope of one or several dependent barrier elements (including casing, cement, and any other downhole or surface sealing components) that prevent fluids from flowing unintentionally between a bore or a well and geological formations, between geological formations or to the surface.

well barrier failure: when a single, specific barrier fails to contain fluids (remaining barriers maintaining containment)

well integrity: maintaining full control of fluids (or gases) within a well at all times by employing and maintaining one or more well barriers to prevent unintended fluid (gas or liquid) movement between formations with different pressure regimes, or loss of containment to the environment

well integrity failure: when all well barriers have failed and there is a pathway for fluid to flow in or out of the well

well pad: the area of land on which the surface infrastructure for drilling and hydraulic fracturing operations are placed. The size of a well pad depends on the type of operation (for example, well pads are larger during the initial drilling and hydraulic fracturing than at production).

workover: well procedure to perform one or more remedial or maintenance operations on a producing well to maintain or attempt production increase. Examples of workover operations are downhole pump repairs, well deepening, plugging back, pulling and resetting liners, squeeze cementing and re-perforating.

Glossary

The register of terms and definitions used in the Geological and Bioregional Assessment Program is available online at https://w3id.org/gba/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. Many of the definitions for these terms have been sourced from external glossaries – several from international sources; spelling variations have been preserved to maintain authenticity of the source.

abandonment: a process which involves shutting down the well and rehabilitating the site. It includes decommissioning the well.

accumulation: in petroleum geosciences, an 'accumulation' is referred to as an individual body of moveable petroleum

activity: for the purposes of Impact Modes and Effects Analysis (IMEA), a planned event associated with unconventional gas resource development. For example, activities during the exploration life-cycle stage include drilling and coring, ground-based geophysics and surface core testing. Activities are grouped into ten major activities, which can occur at different life-cycle stages.

adsorption: the capability of all solid substances to attract to their surfaces molecules of gases or solutions with which they are in contact

aeolian: relating to or arising from the action of wind

annual flow: the volume of water that discharges past a specific point in a stream in a year, commonly measured in GL/year

anticline: an arch-shaped fold in rock in which rock layers are upwardly convex. The oldest rock layers form the core of the fold and, outward from the core, progressively younger rocks occur.

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 commonly 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

asset: an entity that has value to the community and, for the purposes of geological and bioregional assessments, is associated with a GBA region. An asset is a store of value and may be managed and/or used to maintain and/or produce further value. An asset may have many values associated with it that can be measured from a range of perspectives; for example, the values of a wetland can be measured from ecological, sociocultural and economic perspectives.

barrel: a standard unit of measurement for all production and sales of oil. It has a volume of 42 US gallons [0.16 m^3].

baseflow: the portion of streamflow that comes from shallow and deep subsurface flow, and is an important part of the groundwater system

basement: the oldest rocks in an area; commonly igneous or metamorphic rocks of Precambrian or Paleozoic age that underlie other sedimentary formations. Basement generally does not contain significant oil or gas, unless it is fractured and in a position to receive these materials from sedimentary strata.

basin-centred gas: a type of tight gas that occurs in distributed basin-centred gas accumulations, where gas is hosted in low permeability reservoirs which are commonly abnormally overpressured, lack a down dip water contact and are continuously saturated with gas. This is also sometimes referred to as 'continuous' and 'pervasive' gas.

bed: in geosciences, the term 'bed' refers to a layer of sediment or sedimentary rock, or stratum. A bed is the smallest stratigraphic unit, generally a centimetre or more in thickness. To be labeled a bed, the stratum must be distinguishable from adjacent beds.

bioaccumulation: a process by which chemicals are taken up by a plant or animal either directly through exposure to a contaminated medium (soil, sediment, water) or by consuming food or water containing the chemical

biogenic gas: hydrocarbon gases (which are overwhelmingly (greater than or equal to 99%) methane) produced as a direct consequence of bacterial activity

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.

brittleness: a material is brittle if, when subjected to stress, it breaks without significant plastic deformation

casing: a pipe placed in a well to prevent the wall of the hole from caving in and to prevent movement of fluids from one formation to another

causal pathway: for the purposes of geological and bioregional assessments, the logical chain of events – either planned or unplanned – that link unconventional gas development and potential impacts on water and the environment

causal pathway group: causal pathways with similar attributes (e.g. landscape management) that are grouped for further analysis

cementing: the application of a liquid slurry of cement and water to various points inside and outside the casing

charge: in petroleum geoscience, a 'charge' refers to the volume of expelled petroleum available for entrapment cleat: the vertical cleavage of coal seams. The main set of joints along which coal breaks when mined.

coal: a rock containing greater than 50 wt.% organic matter

coal seam gas: coal seam gas (CSG) is a form of natural gas (generally 95% to 97% pure methane, CH_4) extracted from coal seams, typically at depths of 300 to 1000 m. Also called coal seam methane (CSM) or coalbed methane (CBM).

compression: lateral force or stress (e.g. tectonic) that tends to decrease the volume of, or shorten, a substance

conceptual model: an abstraction or simplification of reality that describes the most important components and processes of natural and/or anthropogenic systems, and their response to interactions with extrinsic activities or stressors. They provide a transparent and general representation of how complex systems work, and identify gaps or differences in understanding. They are often used as the basis for further modelling, form an important backdrop for assessment and evaluation, and typically have a key role in communication. Conceptual models may take many forms, including descriptive, influence diagrams and pictorial representations.

condensate: condensates are a portion of natural gas of such composition that are in the gaseous phase at temperature and pressure of the reservoirs, but that, when produced, are in the liquid phase at surface pressure and temperature

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.

conglomerate: a sedimentary rock dominated by rounded pebbles, cobbles, or boulders

consequence: synonym of impact

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

conventional gas: conventional gas is obtained from reservoirs that largely consist of porous sandstone formations capped by impermeable rock, with the gas trapped by buoyancy. The gas can often move to the surface through the gas wells without the need to pump.

Cooper Basin: the Cooper Basin geological province is an Upper Carboniferous – Middle Triassic geological sedimentary basin that is up to 2500 m thick and occurs at depths between 1000 and 4400 m. It is overlain completely by the Eromanga and Lake Eyre basins. Most of the Cooper Basin is in south-west Queensland and north-east SA, and includes a small area of NSW at Cameron Corner. It occupies a total area of approximately 130,000 km^2, including 95,740 km^2 in Queensland, 34,310 km^2 in SA and 8 km^2 in NSW.

crust: the outer part of the Earth, from the surface to the Mohorovicic discontinuity (Moho)

cumulative impact: for the purposes of geological and bioregional assessments, the total environmental change resulting from the development of selected unconventional hydrocarbon resources when all past, present and reasonably foreseeable actions 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).

deep coal gas: gas in coal beds at depths usually below 2000 m are often described as 'deep coal gas'. Due to the loss of cleat connectivity and fracture permeability with depth, hydraulic fracturing is used to release the free gas held within the organic porosity and fracture system of the coal seam. As dewatering is not needed, this makes deep coal gas exploration and development similar to shale gas reservoirs.

deformation: folding, faulting, shearing, compression or extension of rocks due to the Earth's forces

delta: a low, nearly flat area near the mouth of a river, commonly forming a fan-shaped plain that can extend beyond the coast into deep water. Deltas form in lakes and oceans when sediment supplied by a stream or river overwhelms that removed by tides, waves, and currents

depocentre: an area or site of maximum deposition; the thickest part of any specified stratigraphic unit in a depositional basin

deposition: sedimentation of any material, as in the mechanical settling of sediment from suspension in water, precipitation of mineral matter by evaporation from solution, and accumulation of organic material

depositional environment: the area in which, and physical conditions under which, sediments are deposited. This includes sediment source; depositional processes such as deposition by wind, water or ice; and location and climate, such as desert, swamp or river.

development: a phase in which newly discovered oil or gas fields are put into production by drilling and completing production wells

discovered: the term applied to a petroleum accumulation/reservoir whose existence has been determined by its actual penetration by a well, which has also clearly demonstrated the existence of moveable petroleum by flow to the surface or at least some recovery of a sample of petroleum. Log and/or core data may suffice for proof of existence of moveable petroleum if an analogous reservoir is available for comparison.

diversion: see extraction

dome: a type of anticline where rocks are folded into the shaped of an inverted bowl. Strata in a dome dip outward and downward in all directions from a central area.

drill stem test: an operation on a well designed to demonstrate the existence of moveable petroleum in a reservoir by establishing flow to the surface and/or to provide an indication of the potential productivity of that reservoir. Drill stem tests (DSTs) are performed in the open hole to obtain reservoir fluid samples, static bottomhole pressure measurements, indications of productivity and short-term flow and pressure buildup tests to estimate permeability and damage extent.

drilling fluid: circulating fluid that lifts rock cuttings from the wellbore to the surface during the drilling operation. Also functions to cool down the drill bit, and is a component of well control.

dry gas: natural gas that is dominated by methane (greater than 95% by volume) with little or no condensate or liquid hydrocarbons

economic values: values associated with agriculture, aquaculture, drinking water supply, industry or intensive development and tourism activities

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), a change to water or the environment, such as changes to the quantity and/or quality of surface water or groundwater, or to the availability of suitable habitat. An effect is a specific type of an impact (any change resulting from prior events).

endpoint: for the purposes of geological and bioregional assessments, an endpoint is a value pertaining to water and the environment that may be impacted by development of unconventional gas resources. Endpoints include assessment endpoints – explicit expressions of the ecological, economic and/or social values to be protected; and measurement endpoints – measurable characteristics or indicators that may be extrapolated to an assessment endpoint as part of the impact and risk assessment.

Eromanga Basin: an extensive geologic sedimentary basin formed from the Early Jurassic to the Late Cretaceous that can be over 2500 m thick. It overlies several older geological provinces including the Cooper Basin, and is in part overlain by the younger Cenozoic province, the Lake Eyre Basin. The Eromanga Basin is found across much of Queensland, northern SA, southern NT, as well as north-western NSW. The Eromanga Basin encompasses a significant portion of the Great Artesian Basin.

erosion: the wearing away of soil and rock by weathering, mass wasting, and the action of streams, glaciers, waves, wind, and underground water exploration: the search for new hydrocarbon resources by improving geological and prospectivity understanding of an area and/or play through data acquisition, data analysis and interpretation. Exploration may include desktop studies, field mapping, seismic or other geophysical surveys, and drilling.

extraction: the removal of water for use from waterways or aquifers (including storages) by pumping or gravity channels. In the oil and gas industry, extraction refers to the removal of oil and gas from its reservoir rock.

facies: the characteristics of a rock unit that reflect the conditions of its depositional environment

fairway: a term used in geology to describe a regional trend along which a particular geological feature is likely to occur, such as a hydrocarbon fairway. Understanding and predicting fairways can help geologists explore for various types of resources, such as minerals, oil and gas.

fault: a fracture or zone of fractures in the Earth’s crust along which rocks on one side were displaced relative to those on the other side

field: in petroleum geoscience, a 'field' refers to an accumulation, pool, or group of pools of hydrocarbons or other mineral resources in the subsurface. A hydrocarbon field consists of a reservoir with trapped hydrocarbons covered by an impermeable sealing rock, or trapped by hydrostatic pressure.

floodplain: a flat area of unconsolidated sediment near a stream channel that is submerged during or after high flows

flowback: the process of allowing fluids and entrained solids to flow from a well following a treatment, either in preparation for a subsequent phase of treatment or in preparation for cleanup and returning the well to production. The flowback period begins when material introduced into the well during the treatment returns to the surface following hydraulic fracturing or refracturing. The flowback period ends when either the well is shut in and permanently disconnected from the flowback equipment or at the startup of production.

flowback water: the fluids and entrained solids that emerge from a well during flowback

fluvial: sediments or other geologic features formed by streams

fold: a curve or bend of a formerly planar structure, such as rock strata or bedding planes, that generally results from deformation

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

formation water: water that occurs naturally in sedimentary rocks

fracking: see hydraulic fracturing

fracture: a crack or surface of breakage within rock not related to foliation or cleavage in metamorphic rock along which there has been no movement. A fracture along which there has been displacement is a fault. When walls of a fracture have moved only normal to each other, the fracture is called a joint. Fractures can enhance permeability of rocks greatly by connecting pores together, and for that reason, fractures are induced mechanically in some reservoirs in order to boost hydrocarbon flow. Fractures may also be referred to as natural fractures to distinguish them from fractures induced as part of a reservoir stimulation or drilling operation. In some shale reservoirs, natural fractures improve production by enhancing effective permeability. In other cases, natural fractures can complicate reservoir stimulation.

free gas: the gaseous phase present in a reservoir or other contained area. Gas may be found either dissolved in reservoir fluids or as free gas that tends to form a gas cap beneath the top seal on the reservoir trap. Both free gas and dissolved gas play important roles in the reservoir-drive mechanism.

gas-in-place: the total quantity of gas that is estimated to exist originally in naturally occurring reservoirs

gas saturation: the relative amount of gas in the pores of a rock, usually as a percentage of volume

geogenic chemical: a naturally occurring chemical originating from the earth – for example, from geological formations

geological architecture: the structural style and features of a geological province, like a sedimentary basin

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

gilgai: a small ephemeral lake formed from a depression in the soil surface in expanding clay soils

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 require access to groundwater on a permanent or intermittent basis to meet all or some of their water requirements

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

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

horizontal drilling: drilling of a well in a horizontal or near-horizontal plane, usually within the target hydrocarbon-bearing formation. Requires the use of directional drilling techniques that allow the deviation of the well on to a desired trajectory.

hydraulic fracturing: also known as 'fracking', 'fraccing' or 'fracture simulation'. This is a process by which geological formations bearing hydrocarbons (oil and gas) are 'stimulated' to increase the flow of hydrocarbons and other fluids towards the well. In most cases, hydraulic fracturing is undertaken where the permeability of the formation is initially insufficient to support sustained flow of gas. The process involves the injection of fluids, proppant and additives under high pressure into a geological formation to create a conductive fracture. The fracture extends from the well into the production interval, creating a pathway through which oil or gas is transported to the well.

hydraulic fracturing fluid : the fluid injected into a well for hydraulic fracturing. Consists of a primary carrier fluid (usually water or a gel), a proppant such as sand and chemicals to modify the fluid properties.

hydraulic fracturing stage: hydraulic fracture stimulation conducted at a defined interval along a well. Hydraulic fracture stimulation of horizontal wells will often involve multiple hydraulic fracture stages so as to create hydraulic fractures at multiple locations along the length of the well.

hydrocarbons: various organic compounds composed of hydrogen and carbon atoms that can exist as solids, liquids or gases. Sometimes this term is used loosely to refer to petroleum.

hydrogen index: the amount of hydrogen relative to the amount of organic carbon present in kerogen (organic matter). Gross trends of hydrogen indices (HIs) can be used as an indication of maturity.

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

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

hydrostatic pressure: equal pressure in all direction, equivalent to the pressure which is exerted on a portion of a column of water as a result of the weight of the fluid above it

impact: the difference between what could happen as a result of activities and processes associated with extractive industries, such as shale, tight and deep coal gas development, and what would happen without them. Impacts may be changes that occur to the natural environment, community or economy. Impacts can be a direct or indirect result of activities, or a cumulative result of multiple activities or processes.

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.

injection: the forcing or pumping of substances into a porous and permeable subsurface rock formation. Examples of injected substances can include either gases or liquids.

kerogen: insoluble (in organic solvents) particulate organic matter preserved in sedimentary rocks that consists of various macerals originating from components of plants, animals, and bacteria. Kerogen can be isolated from ground rock by extracting bitumen with solvents and removing most of the rock matrix with hydrochloric and hydrofluoric acids.

kerogen type: kerogens are classified into five types: I, II, IIS, III, and IV

Lake Eyre Basin: a geologic province containing Cenozoic terrestrial sedimentary rocks within the Lake Eyre surface water catchment. It covers parts of northern and eastern SA, south-eastern NT, western Queensland and north-western NSW. In the Cooper GBA region, the basin sedimentary package is less than 300 m thick.

landscape class: for the purposes of geological and bioregional assessments (GBA), a collection of ecosystems with characteristics that are expected to respond similarly to changes in groundwater and/or surface water due to unconventional gas 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 GBA region and their spatial coverage is exhaustive and non-overlapping. Conceptually, landscape classes can be considered as types of ecosystem assets.

leaky aquitard: a semi-permeable geological material that can transmit groundwater. Although regionally non-productive, it may be classed as a very low yielding aquitard that is sometimes used to produce groundwater where no other source is available.

life-cycle stage: one of five stages of operations in unconventional gas resource development considered as part of the Impact Modes and Effects Analysis (IMEA). These are exploration, appraisal, development, production, and rehabilitation. Each life-cycle stage is further divided into major activities, 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

lithology: the description of rocks, especially in hand specimen and in outcrop, on the basis of characteristics such as colour, mineralogic composition and grain size major activity: for the purposes of Impact Modes and Effects Analysis (IMEA), a group of activities associated with a common part of the shale, tight or deep coal gas resource development process. There are ten major activities used in geological and bioregional assessments ranging from 'construction' through to 'well abandonment and rehabilitation'. Major activities may occur across different life cycles, though often with differing levels of intensity; for example, drilling may occur in the exploration, appraisal, development and production life cycles but is at its peak during development.

mantle: the region of the Earth composed mainly of solid silicate rock that extends from the base of the crust (Moho) to the core–mantle boundary at a depth of approximately 2900 km

material: pertinent or relevant

mature: a hydrocarbon source rock that has started generating hydrocarbons

methane: a colourless, odourless gas, the simplest paraffin hydrocarbon, formula CH_4. It is the principal constituent of natural gas and is also found associated with crude oil. Methane is a greenhouse gas in the atmosphere because it absorbs long-wavelength radiation from the Earth's surface.

migration: the process whereby fluids and gases move through rocks. In petroleum geoscience, 'migration' refers to when petroleum moves from source rocks toward reservoirs or seep sites. Primary migration consists of movement of petroleum to exit the source rock. Secondary migration occurs when oil and gas move along a carrier bed from the source to the reservoir or seep. Tertiary migration is where oil and gas move from one trap to another or to a seep.

mudstone: a general term for sedimentary rock made up of clay-sized particles, typically massive and not fissile

natural gas : the portion of petroleum that exists either in the gaseous phase or is in solution in crude oil in natural underground reservoirs, and which is gaseous at atmospheric conditions of pressure and temperature. Natural gas may include amounts of non-hydrocarbons.

naturally occurring radioactive materials: radioactive elements and their decay products found in the environment that have been generated from natural processes

net thickness: the accumulated thickness of a certain rock type of a specified quality which is found within a specific interval of formation

oil: a mixture of liquid hydrocarbons and other compounds of different molecular weights. Gas is often found in association with oil. Also see petroleum.

oil field: an area with an underlying oil reservoir. Typically, industry professionals use the term with an implied assumption of economic size

operator: the company or individual responsible for managing an exploration, development or production operation organic matter: biogenic, carbonaceous materials. Organic matter preserved in rocks includes kerogen, bitumen, oil and gas. Different types of organic matter can have different oil-generative potential.

orogeny: the process of mountain building; the process whereby structures within fold-belt mountainous areas formed

outcrop: a body of rock exposed at the surface of the Earth

overpressure: occurs when the pore pressure is higher than the hydrostatic pressure, caused by an increase in the amount of fluid or gas in the rock, or changes to the rock that reduce the amount of pore space. If the fluid cannot escape, the result is an increase in pore pressure. Overpressure can only occur where there are impermeable layers preventing the vertical flow of water, otherwise the water would flow upwards to equalise back to hydrostatic pressure.

partial aquifer: a permeable geological material with variable groundwater yields that are lower than in an aquifer and range from fair to very low yielding locally

pay: a reservoir or portion of a reservoir that contains economically producible hydrocarbons. The term derives from the fact that it is capable of 'paying' an income. Pay is also called pay sand or pay zone. The overall interval in which pay sections occur is the gross pay; the smaller portions of the gross pay that meet local criteria for pay (such as minimum porosity, permeability and hydrocarbon saturation) are net pay.

peak life-cycle stage: the life-cycle stage when impacts from unconventional gas resource development are expected to be greatest. The five life-cycle stages are: (i) exploration, (ii) appraisal, (iii) development, (iv) production and (v) rehabilitation.

percentile: a specific type of quantile where the range of a distribution or set of runs is divided into 100 contiguous intervals, each with probability 0.01. An individual percentile may be used to indicate the value below which a given percentage or proportion of observations in a group of observations fall. For example, the 95th percentile is the value below which 95% of the observations may be found.

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.

petroleum: a naturally occurring mixture consisting predominantly of hydrocarbons in the gaseous, liquid or solid phase

petroleum system: the genetic relationship between a pod of source rock that is actively producing hydrocarbon, and the resulting oil and gas accumulations. It includes all the essential elements and processes needed for oil and gas accumulations to exist. These include the source, reservoir, seal, and overburden rocks, the trap formation, and the hydrocarbon generation, migration and accumulation processes. All essential elements and processes must occur in the appropriate time and space in order for petroleum to accumulate.

play: a conceptual model for a style of hydrocarbon accumulation used during exploration to develop prospects in a basin, region or trend and used by development personnel to continue exploiting a given trend. A play (or group of interrelated plays) generally occurs in a single petroleum system.

play fairway analysis: sometimes referred to as play fairway mapping, play fairway analysis is used to identify areas where a specific play is likely to be successful, and where additional work on a finer scale is warranted in order to further develop an understanding of a prospect. The phrasing 'fairway' is used as prospective areas on the map are often visually similar to fairways on a golf course. Play fairway maps are created at a regional scale, often tens to hundreds of kilometres in scale, from multiple input sources that vary based on what information is available and relevant based on the requirements of the creator.

plug: a mechanical device or material (such as cement) placed within a well to prevent vertical movement of fluids

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

potential effect: specific types of impacts or changes to water or the environment, such as changes to the quantity and/or quality of surface water or groundwater, or to the availability of suitable habitat

produced water: a term used in the oil industry to describe water that is produced as a by-product along with the oil and gas. Oil and gas reservoirs often have water as well as hydrocarbons, sometimes in a zone that lies under the hydrocarbons, and sometimes in the same zone with the oil and gas. The terms 'co-produced water' and 'produced water' are sometimes used interchangeably by government and industry. However, in the geological and bioregional assessments, 'produced water' is used to describe water produced as a by-product of shale and tight gas resource development, whereas 'co-produced water' refers to the large amounts of water produced as a by-product of coal seam gas development.

producing: a well or rock formation from which oil, gas or water is produced

production: in petroleum resource assessments, 'production' refers to the cumulative quantity of oil and natural gas that has been recovered already (by a specified date). This is primarily output from operations that has already been produced.

production well: a well used to remove oil or gas from a reservoir

proppant: a component of the hydraulic fracturing fluid system comprising sand, ceramics or other granular material that 'prop' open fractures to prevent them from closing when the injection is stopped

prospectivity assessment: the assessment of an area to determine the likelihood of discovering a given resource (e.g. oil, gas, groundwater) by analysing the spatial patterns of foundation datasets. The key objective is to identify areas of increased likelihood of discovering previously unrecognised potential. Sometimes referred to as ‘chance of success’ or ‘common risk segment’ analysis.

prospectivity confidence: the relative certainty of hydrocarbons being found (on a scale of zero to one) based on prospectivity mapping

recharge: see groundwater recharge

reserves: quantities of petroleum anticipated to be commercially recoverable in known accumulations from a given date forward under defined conditions. Reserves must further satisfy four criteria: they must be discovered, recoverable, commercial and remaining (as of the evaluation date) based on the development project(s) applied.

reservoir: a subsurface body of rock having sufficient porosity and permeability to store and transmit fluids and gases. Sedimentary rocks are the most common reservoir rocks because they have more porosity than most igneous and metamorphic rocks and form under temperature conditions at which hydrocarbons can be preserved. A reservoir is a critical component of a complete petroleum system.

reservoir rock: any porous and permeable rock that contains liquids or gases (e.g. petroleum, water, CO_2), such as porous sandstone, vuggy carbonate and fractured shale

ridge: a narrow, linear geological feature that forms a continuous elevated crest for some distance (e.g. a chain of hills or mountains or a watershed)

riparian: 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 (ASNZ ISO 3100). This involves assessing the potential consequences and likelihood of impacts to environmental and human values that may stem from an action, under the uncertainty caused by variability and incomplete knowledge of the system of interest.

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

sandstone: a sedimentary rock composed of sand-sized particles (measuring 0.05–2.0 mm in diameter), typically quartz

seal: a relatively impermeable rock, commonly shale, anhydrite or salt, that forms a barrier or cap above and around reservoir rock such that fluids cannot migrate beyond the reservoir. A seal is a critical component of a complete petroleum system.

sediment: various materials deposited by water, wind or glacial ice, or by precipitation from water by chemical or biological action (e.g. clay, sand, carbonate)

sedimentary rock: a rock formed by lithification of sediment transported or precipitated at the Earth's surface and accumulated in layers. These rocks can contain fragments of older rock transported and deposited by water, air or ice, chemical rocks formed by precipitation from solution, and remains of plants and animals.

sedimentation: the process of deposition and accumulation of sediment (unconsolidated materials) in layers seismic survey: a method for imaging the subsurface using controlled seismic energy sources and receivers at the surface. Measures the reflection and refraction of seismic energy as it travels through rock.

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

severity: magnitude of an impact

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

shale: a fine-grained sedimentary rock formed by lithification of mud that is fissile or fractures easily along bedding planes and is dominated by clay-sized particles

shale gas: generally extracted from a clay-rich sedimentary rock, which has naturally low permeability. The gas it contains is either adsorbed or in a free state in the pores of the rock.

siltstone: a sedimentary rock composed of silt-sized particles (0.004 to 0.063 mm in diameter)

source rock: a rock rich in organic matter which, if heated sufficiently, will generate oil or gas. Typical source rocks, usually shales or limestones, contain about 1% organic matter and at least 0.5% total organic carbon (TOC), although a rich source rock might have as much as 10% organic matter. Rocks of marine origin tend to be oil-prone, whereas terrestrial source rocks (such as coal) tend to be gas-prone. Preservation of organic matter without degradation is critical to creating a good source rock, and necessary for a complete petroleum system. Under the right conditions, source rocks may also be reservoir rocks, as in the case of shale gas reservoirs.

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: the study of the history, composition, relative ages and distribution of stratified rock strata, and its interpretation to reveal Earth’s history. However, it has gained broader usage to refer to the sequential order and description of rocks in a region.

stress: the force applied to a body that can result in deformation, or strain, usually described in terms of magnitude per unit of area, or intensity

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

structure: a geological feature produced by deformation of the Earth’s crust, such as a fold or a fault; a feature within a rock, such as a fracture or bedding surface; or, more generally, the spatial arrangement of rocks

subcrop: 1 - A subsurface outcrop, e.g. where a formation intersects a subsurface plane such as an unconformity. 2 - In mining, any near-surface development of a rock or orebody, usually beneath superficial material.

subsidence: the sudden sinking or gradual downward settling of the Earth's surface with little or no horizontal motion. The movement is not restricted in rate, magnitude, or area involved.

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

thermal maturity: the degree of heating of a source rock in the process of transforming kerogen (derived from organic matter) into hydrocarbon. Thermal maturity is commonly evaluated by measuring vitrinite reflectance or by pyrolysis.

thermogenic gas: hydrocarbon gases generated by the thermal breakdown of organic matter. These usually occur at depths exceeding 1000 m below the land surface or seabed

tight gas: tight gas is trapped in reservoirs characterised by very low porosity and permeability. The rock pores that contain the gas are minuscule, and the interconnections between them are so limited that the gas can only migrate through it with great difficulty.

total organic carbon: the quantity of organic matter (kerogen and bitumen) is expressed in terms of the total organic carbon (TOC) content in mass per cent. The TOC value is the most basic measurement for determining the ability of sedimentary rocks to generate and expel hydrocarbons.

toxicity: inherent property of an agent to cause an adverse biological effect

trap: a geologic feature that permits an accumulation of liquid or gas (e.g. natural gas, water, oil, injected CO_2) and prevents its escape. Traps may be structural (e.g. domes, anticlines), stratigraphic (pinchouts, permeability changes) or combinations of both.

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

unconformity: a surface of erosion between rock bodies that represents a significant hiatus or gap in the stratigraphic succession. Some kinds of unconformities are (a) angular unconformity – an unconformity in which the bedding planes above and below the unconformity are at an angle to each other; and (b) disconformity – an unconformity in which the bedding planes above and below the stratigraphic break are essentially parallel.

unconventional gas: unconventional gas is generally produced from complex geological systems that prevent or significantly limit the migration of gas and require innovative technological solutions for extraction. There are numerous types of unconventional gas such as coal seam gas, deep coal gas, shale gas and tight gas.

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

water-dependent asset: an asset potentially impacted, either positively or negatively, by changes in the groundwater and/or surface water regime due to unconventional gas resource development water saturation: the fraction of water in a given pore space. It is expressed in volume/volume, percent or saturation units. Unless otherwise stated, water saturation is the fraction of formation water in the undisturbed zone. The saturation is known as the total water saturation if the pore space is the total porosity, but is known as effective water saturation if the pore space is the effective porosity. If used without qualification, the term usually refers to the effective water saturation.

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.

weathering: the breakdown of rocks and other materials at the Earth's surface caused by mechanical action and reactions with air, water and organisms. Weathering of seep oils or improperly sealed oil samples by exposure to air results in evaporative loss of light hydrocarbons.

well: typically a narrow diameter hole drilled into the earth for the purposes of exploring, evaluating, injecting or recovering various natural resources, such as hydrocarbons (oil and gas), water or carbon dioxide. Wells are sometimes known as a 'wellbore'.

well barrier: envelope of one or several dependent barrier elements (including casing, cement, and any other downhole or surface sealing components) that prevent fluids from flowing unintentionally between a bore or a well and geological formations, between geological formations or to the surface.

well barrier failure: when a single, specific barrier fails to contain fluids (remaining barriers maintaining containment)

well integrity: maintaining full control of fluids (or gases) within a well at all times by employing and maintaining one or more well barriers to prevent unintended fluid (gas or liquid) movement between formations with different pressure regimes, or loss of containment to the environment

well integrity failure: when all well barriers have failed and there is a pathway for fluid to flow in or out of the well

well pad: the area of land on which the surface infrastructure for drilling and hydraulic fracturing operations are placed. The size of a well pad depends on the type of operation (for example, well pads are larger during the initial drilling and hydraulic fracturing than at production).

workover: well procedure to perform one or more remedial or maintenance operations on a producing well to maintain or attempt production increase. Examples of workover operations are downhole pump repairs, well deepening, plugging back, pulling and resetting liners, squeeze cementing and re-perforating.

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