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Impact assessment for the Cooper GBA region

Geological and Bioregional Assessment: Stage 3 synthesis

2021

Cattle along the roadside in the Cooper GBA region © Russell Crosbie, CSIRO

Great Artesian Basin groundwater bore sampling in the Cooper GBA region © Matthias Raiber, CSIRO

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Alvinna waterhole windmill © Russell Crosbie, CSIRO

At a glance

The Geological and Bioregional Assessment (GBA) Program developed a robust methodology using causal networks to assess the regional-scale risks of unconventional gas resource development on water and the environment. The methodology allows consistent analysis of risks at each step in a chain of events – called pathways – from gas resource development activities to protected environmental and water-related values. The methodology can be applied to other regional-scale assessments in the future.

The GBA Program has developed a publicly accessible online tool (the GBA Explorer) which allows anybody to interact with the complex causal network supporting the assessment. The tool lets users focus on the matters of relevance to them and examine the underlying scientific evidence in more detail. The Program worked closely with people living and working in the region. The experience and insights given by the local community and stakeholders directly informed what was investigated in detail by Program scientists and then assessed through the GBA Program.

Key finding: The potential impacts due to future unconventional gas resource development on water and the environment were evaluated along 2,815 pathways.

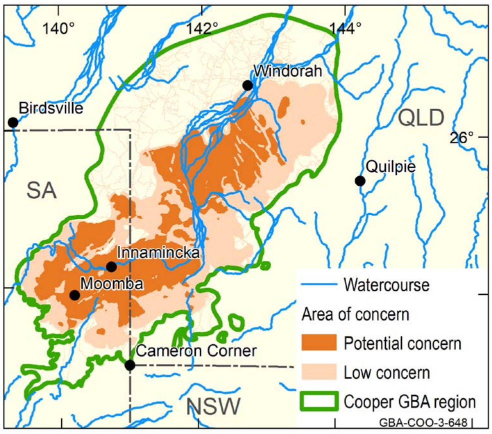
Potential impacts could occur in 27% of the Cooper GBA region, the area of 'potential concern' in Figure 1. These can be mitigated through ongoing compliance with existing regulatory and management controls. Potential impacts in remaining areas are either not possible or change does not exceed a defined threshold.

Assessment: Spanning the borders of southwest Queensland and northeast South Australia, the Cooper GBA region covers an area of approximately 130,000 km^2 (Figure 1).

The maximum development scenario is projected to increase existing disturbance by up to 27 km^2, spread over less than 6% of the Cooper GBA region. This is 3% more than the existing oil and gas industry footprint in the Cooper GBA region.

Of the potential impacts that could occur, most are at the surface and can be mitigated by existing controls.

FIGURE 1 Area of concern in the Cooper GBA region



Source: Geological and Bioregional Assessment Program (2021c). Element: GBA-COO-3-648

Surface water: Development activities could potentially obstruct the flow of water across about 6% of the Cooper Creek floodplain. Ongoing careful design and existing management controls can mitigate these impacts.

Groundwater: Below the surface, natural barriers protect overlying aquifers. Less than 1% of the aquifer extent in the Cooper GBA region could potentially be impacted. Potential impacts in this area can be managed through mitigation and compliance with existing regulatory controls.

Environment: Invasive predators and weeds, and broadscale landscape changes due to fire or intensive grazing have the strongest influence on threatened species and protected areas in the Cooper GBA region.

Protected fauna and flora: Seven protected animals and 5 protected plants were prioritised for assessment based on the importance of the Cooper GBA region to each species.

Explore this assessment

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

This assessment identifies potential impacts on water and the environment. Causal networks were used to determine where potential impacts cannot be ruled out. Governments, industry and the community can then focus on areas that are potentially impacted and apply local-scale modelling when making regulatory, water management and planning decisions. The GBA Program comprises 3 stages:

- **Stage 1 Rapid regional basin prioritisation:** identification of geological basins with the greatest potential to deliver shale and/or tight gas to the East Coast Gas Market within the next 5 to 10 years.
- **Stage 2 Geological and environmental baseline assessments:** compilation and analysis of available data to form a baseline and identify knowledge gaps to guide collection of additional baseline data. This includes integration of data, knowledge and conceptual models that are the building blocks for Stage 3.
- **Stage 3 Impact assessment:** analysis of the potential impacts on water resources and matters of environmental significance to inform and support Australian Government and state management and compliance activities.

Supporting information

User panels: The GBA Program has been informed by user panels that provide a forum for the discussion and inclusion of user needs and concerns. User panels help guide the assessment process, provide a forum to communicate findings and enable the sharing of information for the regions. The user panel in the Cooper GBA region consists of representatives from relevant local governments, natural resource management bodies, Queensland and South Australian governments, Traditional Owner groups, industry and other land user groups. The GBA Program team is grateful for the contributions of the user panel members over the course of this project.

Causal networks: Causal networks are used to assess potential impacts on water and the environment (Peeters et al., 2021b). They are graphical models that describe the cause-and-effect relationships between development activities and endpoints, the values to be protected, for example, the internationally protected Coongie Lakes. Information can be accessed online through GBA Explorer.

GBA Program outputs: This synthesis is supported by the Stage 1 rapid regional prioritisation report, a Stage 2 geological and environmental baseline assessment report, and Stage 2 technical appendices. The *Introduction to causal networks* (Peeters et al., 2021a), the online technical impact assessment summary for the Cooper GBA region and the synthesis of findings from the impact assessment for the Cooper GBA region all use outputs from the interactive causal network, GBA Explorer.

Journal papers: Journal papers and fact sheets that support the method, outputs and investigations for the GBA Program are listed at bioregionalassessments.gov.au/gba. Listings will be updated as journal papers are completed and published.

Datasets: The full suite of information, including instruction on how to access GBA datasets through data.gov.au is provided at bioregionalassessments.gov.au/gba. Underpinning datasets, including geographic data and modelling results, will assist decision makers at all levels to review the work undertaken to date; explore the results using different thresholds; or using their own spatial analysis tools (e.g. ArcGIS, MapInfo or QGIS) to extend or update the assessment as new models and data become available.

The Program's rigorous commitment to data access is consistent with the Australian Government's principles of providing publicly accessible, transparent and responsibly managed public sector information.

User panel for the Cooper GBA region at Jackson Creek © Rod Dann, Department of Agriculture, Water and the Environment

Executive summary

The $35.4 million Geological and Bioregional Assessment (GBA) Program assesses potential environmental impacts of unconventional gas resource development. The geological and environmental knowledge, data and tools produced by the Program is informing decision-making, regulatory frameworks and appropriate management approaches to underpin coordinated management of potential impacts across governments, industry, land users and the community.

About the region

The 130,000 km^2 Cooper GBA region contains diverse habitats that support important environmental, cultural, social and economic values that interact and respond to the episodic, irregular and extreme boom-and-bust periods that are characteristic of the Channel Country in Queensland and South Australia. The braided channels, vast floodplains and terminal lakes of Cooper Creek include internationally and nationally listed wetlands, as well as regionally protected areas. Most of the region is used to graze sheep and cattle on natural pastures. Flooding provides a significant boost to agricultural productivity in the region.

The assessment considers potential impacts on these landscapes, protected areas and threatened species. Results are reported as ‘areas of concern’ – based on evaluation of the likelihood and consequence of potential impacts, and where compliance with existing mitigation strategies is required.

About the assessment

Unconventional gas resources are found in a range of geological settings in the Cooper GBA region and include shale gas, tight gas and deep coal gas. Accessing these resources involves a range of activities including drilling, hydraulic fracturing, construction of roads, well pads, pipelines and processing facilities, extraction of water, and establishment of facilities to manage waste and wastewater. The assessment considered potential impacts from these activities on water and the environment in the Cooper GBA region. It does not replace site specific assessments or consider other unconventional gas resource types, such as coal seam gas. The outcomes of this assessment provide regional knowledge, data and tools for regulators and proponents to use to inform more detailed environmental impact assessment, management and monitoring for potential future developments.

The assessment is based on a maximum development scenario matching current conventional gas production in the Cooper GBA region of 92 petajoules per year over a 50-year period. Under this scenario, a projected 1,180 petroleum wells are estimated to disturb a total of 27 km^2 of the Cooper GBA region. The total development area, including undisturbed areas between well pads, roads and seismic lines, is estimated to be up to 7350 km^2. Under this scenario, development would extract or reuse up to 20 gigalitres of water over 50 years, equivalent to 400 megalitres per year.

The assessment determined with high confidence that all potential impacts on water and the environment in the Cooper GBA region from unconventional gas resource development can be mitigated through compliance with existing regulatory and management controls. Confidence in this assessment will be improved as knowledge about potential ecological impacts increases. Future monitoring objectives can be prioritised using the impact assessment and structure of the causal network to establish baseline conditions, detect changes, trends and impacts, monitor for compliance and address knowledge gaps.

Potential impacts on water

Surface water can be extracted under licence from river channels, the floodplain and permanent waterholes. Further, construction activities for roads and development facilities can obstruct the flow of water across the floodplain. For the first time, a state-of-the-art flood inundation model has been developed for the Cooper Creek floodplain, one of the most complex floodplains in the world. The model can evaluate how future development could impact on flooding to show regulators and proponents how proposed activities could impact on surface water flows on the floodplain.

The assessment determined with high confidence that existing licensed surface water extraction – approximately 2% of annual flows – will not impact flows or alter scouring or flooding in Cooper Creek. Activities that block or obstruct surface water flow are of ‘potential concern’ for about 6% (1,613 km^2) of the Cooper Creek floodplain. Further investigation of changes to agricultural productivity, protected wetlands, as well as protected fauna and flora on the floodplain is warranted. Despite this, there is high confidence that state regulations, as well as industry mitigation strategies, can mitigate potential impacts in sensitive areas including permanent waterholes.

Leaks and spills could release chemicals or compounds used in unconventional gas resource development, or produced as a result of development, into the environment. If a spill occurs near surface waters, chemicals could either directly enter the water, or result in soil contamination that then pollutes water. Contamination of groundwater is of ‘potential concern’ where groundwater is close to the surface (less than 9 m).

Controlled release of wastewater is the intentional and approved release of treated water into the environment, including evaporation from storage ponds, reuse for operations water, dust suppression, irrigation or stock drinking water, and disposal of treated wastewater into existing drainage features in the landscape.

If a spill occurs near surface waters, contaminants could spread rapidly and accumulate in sediments. Surface water contamination is of 'potential concern' in 12% of the Cooper GBA region. Compliance reporting shows existing regulations, approval conditions and industry practices are effective in preventing, or ensuring quick remediation of, spills and leaks.

Controlled release of wastewater to the environment is strongly regulated by both state and Commonwealth governments and is of 'low concern'. Stringent approval conditions, monitoring, treatment and compliance requirements ensure that the treated wastewater is consistent with the sensitivity of the receiving environment.

Groundwater extraction is a likely source of water for unconventional gas operations in the Cooper GBA region. As costs increase with depth, it is assumed groundwater would be sourced from the shallower aquifers in the region, where possible, in preference to deeper confined aquifers. Groundwater extraction must adhere to Queensland and South Australian government regulations and must not affect other water users including groundwater-dependent ecosystems.

Compromised aquitard integrity describes changes in the integrity of low permeability rock layers between gas reservoirs and aquifers. This is important where there is concern for groundwater contamination resulting from unconventional gas resource development activities including hydraulic fracturing. Compromised well integrity refers to breaches of a well system that allow the unintended movement of fluids, including contaminants, outside of the well. Standards require two independent well barriers that form a protective leak-tight seal between the well and surrounding rock.

The assessment determined that potential impacts on groundwater-dependent ecosystems due to groundwater extraction are generally of 'low concern'. Exceptions are ecosystems dependent on the Cenozoic aquifer in the west of the Cooper GBA region and near existing groundwater bores accessing the Cadna-owie – Hooray aquifer, where it is less than 150 m thick, in the south-west of the region. Sourcing groundwater from other aquifers, or reuse of wastewater, could avoid potential impacts on groundwater-dependent ecosystems in these areas.

Hydraulic fracture growth into an aquifer, well or fault has a low likelihood of occurring and natural barriers, such as the Nappamerri aquitard, protect overlying aquifers from contamination. Compromised aquitard integrity is of 'potential concern' in an area of less than 0.01% of the Cadna-owie – Hooray aquifer where the Nappamerri aquitard is less than 155 m thick. Existing controls outlined in environmental management plans mitigate potential impacts on Cadna-owie – Hooray aquifer condition. Aquifer contamination due to compromised well integrity is of 'very low concern' based on findings from domestic and international inquiries.

Potential impacts on the environment

Riparian ecosystems are an important component of the aquatic habitat and include plants and animals that are dependent on the presence of rivers and streams. Riparian communities provide a range of ecosystem services including supply of organic materials to the river system, regulation of the riverine microclimate and provision of habitat for many species. Riparian vegetation in the Cooper GBA region is relatively undisturbed and covers over 5,000 km^2 (about 4%), with around one-third overlying areas prospective for the development of unconventional gas resources.

Wetlands include swamps, marshes, billabongs and lakes, natural or artificial, and permanent or temporary. In the Cooper GBA region, more than 90 types of wetland ecosystems provide habitat for thousands of species. Some wetlands support populations of wetland bird species in excess of 20,000 birds. Wetland vegetation is relatively undisturbed and covers over 12,000 km^2 (about 9%), with almost half overlying areas prospective for unconventional gas resources. Supply of water to wetlands is naturally highly variable and water quality is dependent on local rainfall or connectivity with Cooper Creek. Wetlands and riparian areas have cultural and economic value to local Indigenous peoples.

In the arid environment of the Cooper GBA region, permanent waterholes are important refuges for native plants and animals during dry times and have customary, spiritual and economic values to Traditional Owners. The Cooper GBA region contains over 3,000 waterholes; 48 are permanent and overlie areas prospective for development of unconventional gas resources. Investigations at 17 of these waterholes confirmed that groundwater below waterholes is recharged from surface water.

Protected riparian and wetland ecosystems in the Cooper GBA region include the Ramsar-listed Coongie Lakes, wetlands listed in the *Directory of important wetlands in Australia* and the Channel Country Strategic Environmental Area (SEA) protected under Queensland Government legislation, as well as habitat for the grey grasswren and the Australian painted snipe.

The assessment determined with high confidence that compliance with existing protections, including legislated no-go areas, and industry controls can minimise future impacts on riparian vegetation. Indirect impacts from unconventional gas resource development are more difficult to mitigate and are of 'potential concern' in over 30% of riparian areas. Stressors include accidental release of chemicals and invasive plants and predators.

Potential impacts associated with site disturbance are of 'potential concern' for nearly half of the area of wetland vegetation; and invasive plants and predators are of 'potential concern' for all wetland ecosystems including protected wetlands in the Cooper GBA region. Compliance with existing approval conditions and protocols in regulatory frameworks is needed to ensure potential impacts are effectively mitigated.

Indirect impacts on waterholes along the Cooper Creek could degrade up to 36% of waterhole habitats. Impacts include soil and surface water contamination from spills and leaks, as well as habitat degradation, fragmentation and loss due to invasive herbivores and livestock grazing, invasive plants and altered fire regimes. There is high confidence in avoidance and mitigation strategies prescribed in state-based regulations and relevant environmental management plans.

Floodplains result from complex interactions between flow, sediment regimes and the character of the river valley. Floodplains in the Cooper GBA region are typical of mid or lower river valleys, meaning the energy associated with flows is lower, valleys tend to be wider, and significant amounts of sediment are deposited in large slow-moving floods, leading to very large floodplains, over 60 km wide in places. Over 25,000 km^2 (about 19%) of the Cooper GBA region is floodplain, mostly undisturbed, and close to one-third overlies areas prospective for unconventional gas resources.

The frequency and duration of flooding is important to floodplain environments as it controls vegetation growth and the potential growing period for plants. Floodplain ecosystems are less diverse than riparian, wetland or dryland ecosystems in the region, containing 6 regional ecosystem types in Queensland and 5 in South Australia. Vegetation is characterised by sparse or open shrublands and low woodlands and provides habitat for protected fauna and flora. Floodwaters support terrestrial vegetation, fill lakes and recharge shallow groundwater. The floodplain supports an agricultural grazing industry worth $65 million per year with single large floods increasing the value by up to $150 million.

Disturbance from unconventional gas resource development is of ‘potential concern’ in up to 30% of floodplain areas. Obstruction to overland flow, a potential impact to water (described earlier), is of ‘potential concern’ for up to 6% of floodplain vegetation due to changes to flooding extent. This has potential to impact on agricultural productivity and the condition of protected areas including the Channel Country Strategic Environmental Area and Coongie Lakes.

Dryland ecosystems in the Cooper GBA region are arid and are solely reliant on rainfall to meet their water needs, receiving a very low mean annual rainfall of 217 mm/year and evaporation in excess of 1700 mm/year. They include inland dunefields, undulating country on fine grained sedimentary rocks, tablelands and duricrusts, loamy and sandy plains, and clay plains. Dryland vegetation is relatively undisturbed and covers close to 90,000 km^2 (about 69%), of which approximately 23% overlies areas prospective for unconventional gas resources.

Despite being very arid, the region is diverse with approximately 70 regional ecosystem types in Queensland and 28 in South Australia. Dryland vegetation communities include chenopod shrublands, Mitchell grass tussock grasslands, hummock grass dominated by spinifex and Acacia dominated woodlands and shrublands. They support protected fauna, including the kowari found in the Sturt Stony Desert and yellow-footed rock-wallaby found in the tablelands and duricrusts. The night parrot is thought to use unburnt spinifex for roosting and breeding.

Soil compaction could increase habitat degradation, fragmentation and loss and soil erosion and is of ‘potential concern’ in 20% of the agricultural grazing and 23% of the dryland areas. Mitigation strategies for soil compaction are well understood but knowledge on soil erosion is limited.

Potential impacts on protected fauna and flora

The Cooper GBA region is biodiverse. The boom-and-bust ecology is a driver of regional biodiversity including over 2,000 known species. The region's relatively intact landscape and stable vegetation communities support high biodiversity. The Cooper GBA region provides potential habitat for 68 species protected under state or national legislation. The assessment prioritised 12 species (4 birds, 3 mammals and 5 plants) based on the importance of the Cooper GBA region to each species. Many species are culturally significant, for example, the iconic river red gum stabilises rivers banks, provides habitat for birds and animals and has long provided food, timber and medicines for Indigenous peoples.

Future unconventional gas resource development is estimated to increase the existing conventional oil and gas development footprint in the Cooper GBA region by 27 km^2. This footprint underestimates ecological impact as expansion of linear networks (roads, fences, seismic lines) facilitates the spread of invasive plants and animals. Invasive species may amplify competition and predation, lead to changes in fire regimes, degrade habitat and change ecological communities. Regional diversity is strongly influenced by these broad landscape impacts to sensitive communities and threatened species.

Mitigation and management of invasive species is best achieved via coordinated industry-wide approaches that work with existing land managers and NRM programs including whole of life-cycle planning and risk management. Dedicated invasive species officers, and raising awareness of workers and contractors are key monitoring and mitigation options. There is medium to high confidence that competition and predation can be effectively managed and mitigated using existing controls, although current data and knowledge is limited in the Cooper GBA region.

Unconventional gas resource development could amplify threatening processes that are already impacting biodiversity in the Cooper GBA region. This includes habitat degradation, fragmentation and loss; competition and predation by invasive species; and ecosystem burning, which are of 'potential concern' in 25 to 30% of the Cooper GBA region.

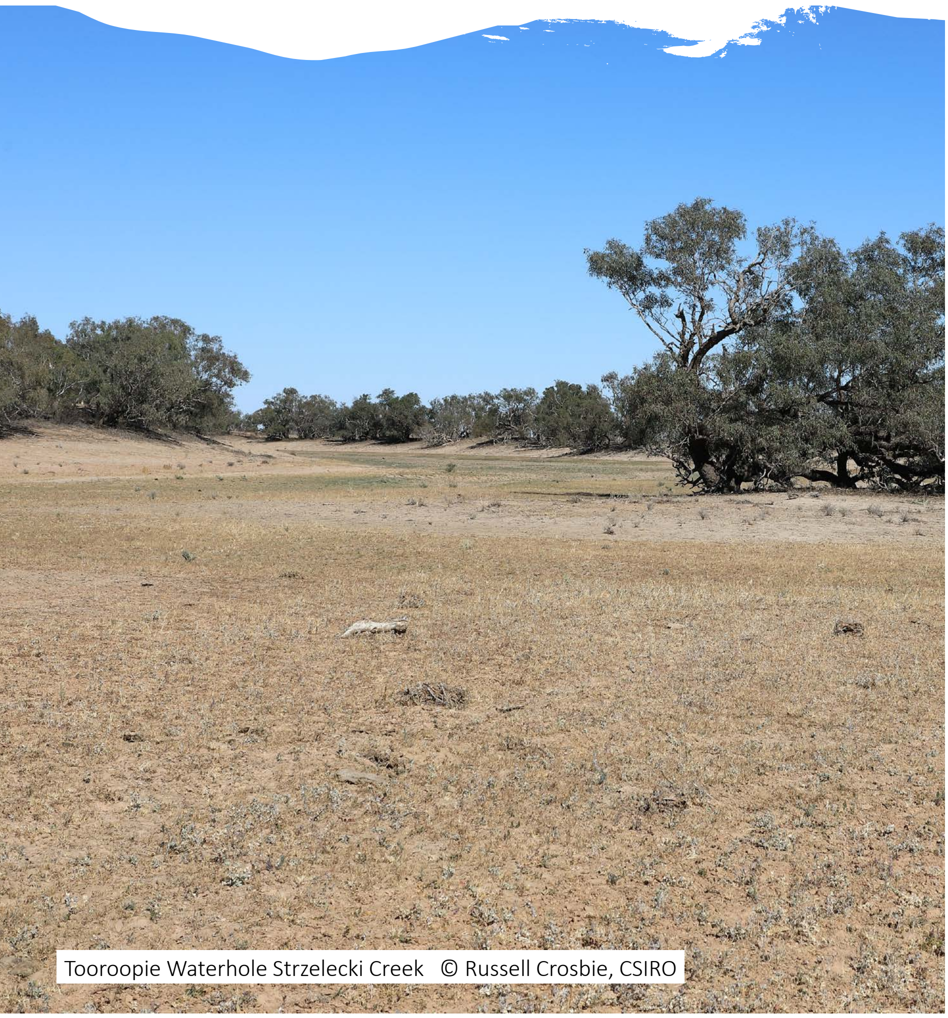
Potential impacts to floodplain inundation and soil or surface water contamination (discussed above) are of 'potential concern' for protected species. Vegetation removal and spread of invasive species can degrade habitat important for protected species. Predation by cats and foxes and competition for resources with feral herbivores are threatening processes for protected fauna species. Changes to fire regimes potentially impact all protected species.

Noise and light pollution can have significant impacts on all animal taxa and are not currently recognised as key threatening processes for protected species. Both impacts are assessed as of 'potential concern' in 25% of the Cooper GBA region. Noise and light pollution may be of particular concern to cryptic or nocturnal species. Potential impacts can be mitigated by minimising the extent and location of new facilities, roads and pipelines and by ensuring rapid and effective remediation of disturbed sites as well as follow up monitoring.

Conclusion

Compliance with approval conditions and protocols in existing state and Commonwealth regulatory frameworks is needed to ensure that potential impacts can be mitigated. Priorities identified by the assessment for future management, mitigation and monitoring at the surface are direct impacts within the development area and indirect impacts that could spread beyond development areas. Current protections and management are focused on direct impacts due to disturbance in the development area.

Indirect impacts can spread beyond development areas into surface waters (accidental release and overland flow obstruction), or change ecological interactions (artificial water sources, invasive plants and invasive predators) and functions (dust generation and operation of industrial machinery). Management of indirect impacts requires regional-scale approaches coordinated across governments, industry, land managers and communities.



Tooroopie Waterhole Strzelecki Creek © Russell Crosbie, CSIRO

Drill rig, Santos development well, Big Lake field
© Russell Crosbie, CSIRO

1 About the assessment

1.1 Purpose

The Cooper GBA region is one of the most prospective sedimentary basins in Australia for development of unconventional gas resources (i.e. gas produced from shales, deep coals or tight sandstones) (Holland et al., 2020). Development of this resource involves a range of activities including drilling, hydraulic fracturing, construction of roads, well pads, pipelines and processing facilities, extraction of water, and establishment of facilities to manage waste and wastewater.

Findings from this assessment provide governments, industry and the broader community with information to support regulatory, water management and planning decisions. These findings support site-specific or project-scale assessments by providing information on where certain matters need more attention. However, the assessment does not replace any state or federal requirements to undertake environmental impact assessments in support of specific development applications or project referrals.

1.2 Scope

A 'GBA region' is defined for each assessment (Figure 2) to constrain the area of investigation (Section 2). The assessment considers activities associated with the exploration, development and production of unconventional gas resources at a regional scale for a 50-year development scenario. The unconventional gas resources that are prospective in the Cooper GBA region include those sourced from shale, tight and deep coal gas reservoirs. These resource types, referred to throughout as 'unconventional gas resources', are described further in the Stage 2 petroleum prospectivity technical appendix (Lech et al., 2020). Coal seam gas was considered as part of the Bioregional Assessment Program (Smith et al., 2016) and is not included in this assessment. This assessment represents a particular point in time as technology, methods and knowledge will change and advance.

Described in this synthesis report are the methods, assessment results, and monitoring strategies in Section 3. The following sections provide more detailed analysis of the assessment and mitigation of potential impacts on surface water and groundwater (Section 4), the environment (Section 5), and protected fauna and flora (Section 6). **Bold text** denotes where causal network node descriptions provide further detail and can be viewed using the interactive causal network in GBA Explorer.

1.3 Context

Context is the key to understanding the impact assessment for the Cooper GBA region. This synthesis report presents key results and findings from the impact assessment. Full context and scientific meaning is available through the interactive causal network in GBA Explorer.

A Glossary of key terms is also provided.

2 About the region

The 130,000 km^2 Cooper GBA region has diverse landscapes and habitats that have environmental, cultural, social and economic benefits. Episodic, irregular and extreme boom-and-bust periods are characteristic of the Channel Country in Queensland and South Australia. The braided channels, vast floodplains and terminal lakes of Cooper Creek include internationally and nationally listed wetlands, as well as regionally protected areas. Unconventional gas resources are found in a range of geological settings in the Cooper GBA region and include shale gas, tight gas and deep coal gas.

2.1 Environmental, cultural, social and economic values

The Cooper GBA region (Figure 2) covers approximately 130,000 km^2 with 95,740 km^2 in Queensland, 34,310 km^2 in South Australia and 8 km^2 in New South Wales. There are few permanent residents; most of the population is part of the large 'fly-in–fly-out' workforce. Major towns include Windorah near the confluence of the Barcoo and Thomson rivers in Queensland, Innamincka to the east of the Ramsar-listed Coongie Lakes wetlands in South Australia, and Moomba, a gas exploration and processing town with no permanent population, to the south of Innamincka in South Australia (Figure 2).

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. 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.

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. Cooper Creek floodplain is more than 60 km wide at its broadest point, stretching east and west of the Innamincka Dome. In this area, Cooper Creek is confined within the rocky and stony walls and steep slopes created by Cooper Creek cutting through the Innamincka Dome (Wakelin-King, 2013).

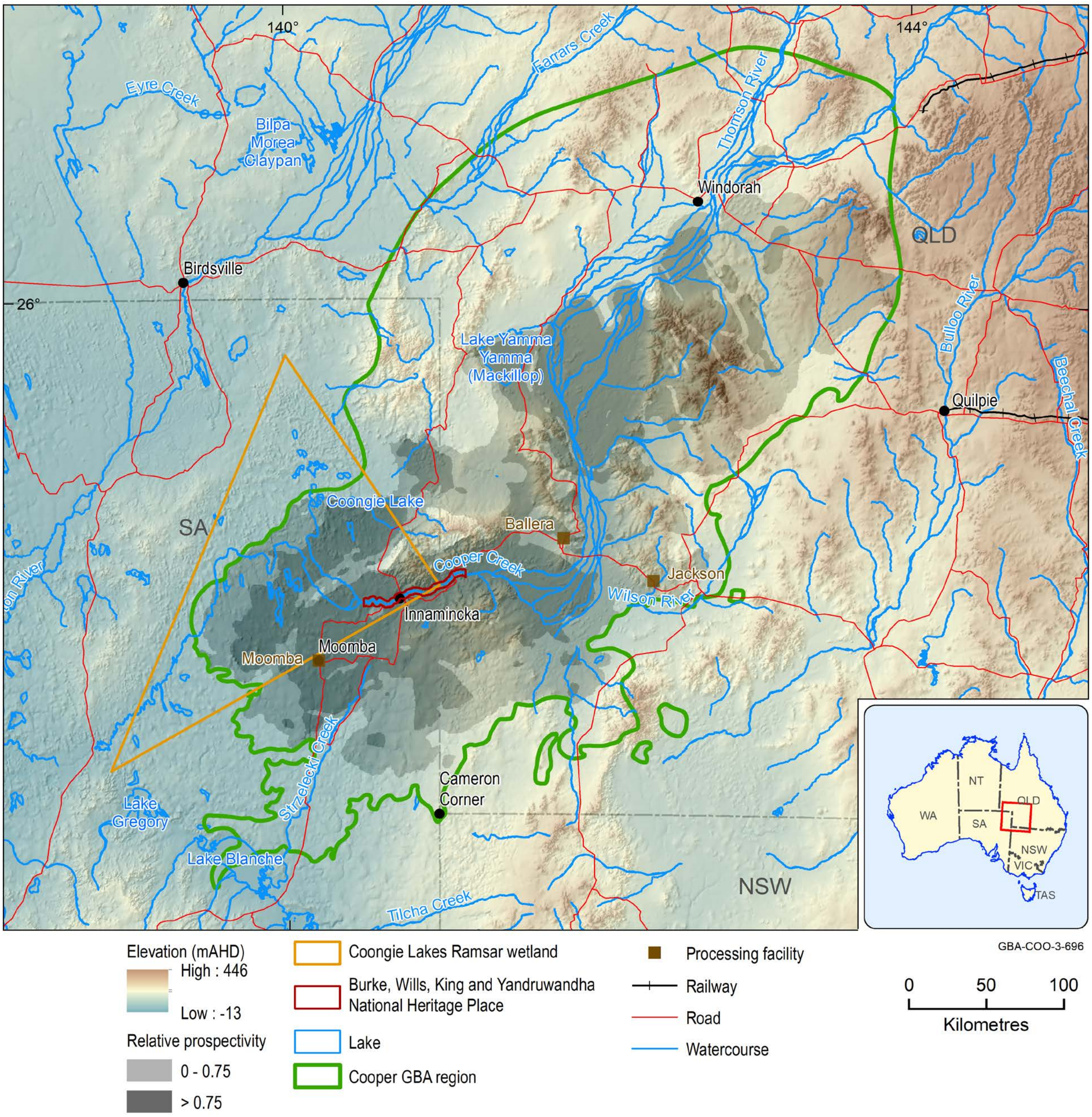
Natural systems in the Cooper GBA region are driven by resource pulses and boom-and-bust ecological dynamics, shaping the high diversity of ecological communities and species (Figure 3). Cooper Creek floodplain is characterised by a hydrologic gradient from the wetter riparian vegetation – including channels, waterholes and fringing vegetation – to the less frequently flooded wetland and floodplain vegetation. The surrounding dryland environment is characterised by gibber plains, low hills, and mesas and high sand dunes with swale wetlands. Icons in Figure 3 represent stressors on the system that may contribute to an impact due to unconventional gas resource development. A stressor is a physical, chemical or biological agent, environmental condition or external stimulus that might contribute to an impact.

Matters of National Environmental Significance (MNES) in the Cooper GBA region include a Ramsar-listed wetland (Coongie Lakes) and the Burke, Wills, King and Yandruwandha National Heritage Place located along the course of Cooper Creek, the one national heritage place listed under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act) (protected matters technical appendix (O'Grady et al., 2020)). There are also 8 nationally important wetlands (Bulloo Lake; Coongie Lakes; Cooper Creek – Wilson River Junction; Cooper Creek Overflow swamps – Nappa Merrie; Cooper Creek Overflow swamps – Windorah; Lake Cuddapan; Lake Yamma Yamma; and the Strzelecki Creek Wetland system) in the Cooper GBA region. In addition, Queensland and South Australia contain areas reserved for the region's iconic landforms and biota, important wetlands and groundwater-dependent ecosystems (Section 4.1.2 in baseline synthesis and gap analysis (Holland et al., 2020)).

The Cooper GBA region provides potential habitat for 68 species protected under state or national legislation – 38 birds, 2 fish, 10 mammals, 15 plants and 3 reptiles (protected matters technical appendix (O'Grady et al., 2020)). There are 26 species (plants, reptiles, birds and mammals) listed under the EPBC Act as threatened (critically endangered, endangered or vulnerable). Matters of State Environmental Significance (MSES) in Queensland include 28 species listed as endangered, near threatened, vulnerable or special least concern. In South Australia, 17 species are listed as endangered or vulnerable. The assessment prioritised 12 species (4 birds, 3 mammals and 5 plants) based on the importance of the Cooper GBA region to each species (protected matters technical appendix (O'Grady et al., 2020)).

More than 60% of the region is covered by Indigenous Land Use Agreements and is within the Eyre region for Indigenous language groups. The Cooper GBA region hosts areas of Indigenous and cultural significance. The Register of the National Estate lists 9 Indigenous sites, 12 heritage sites and 2 recreational areas. Cooper Creek and associated waterholes have a long and enduring cultural significance as part of traditional trade routes.

FIGURE 2 Location, topography and relative prospectivity of unconventional gas resources in the Cooper GBA region

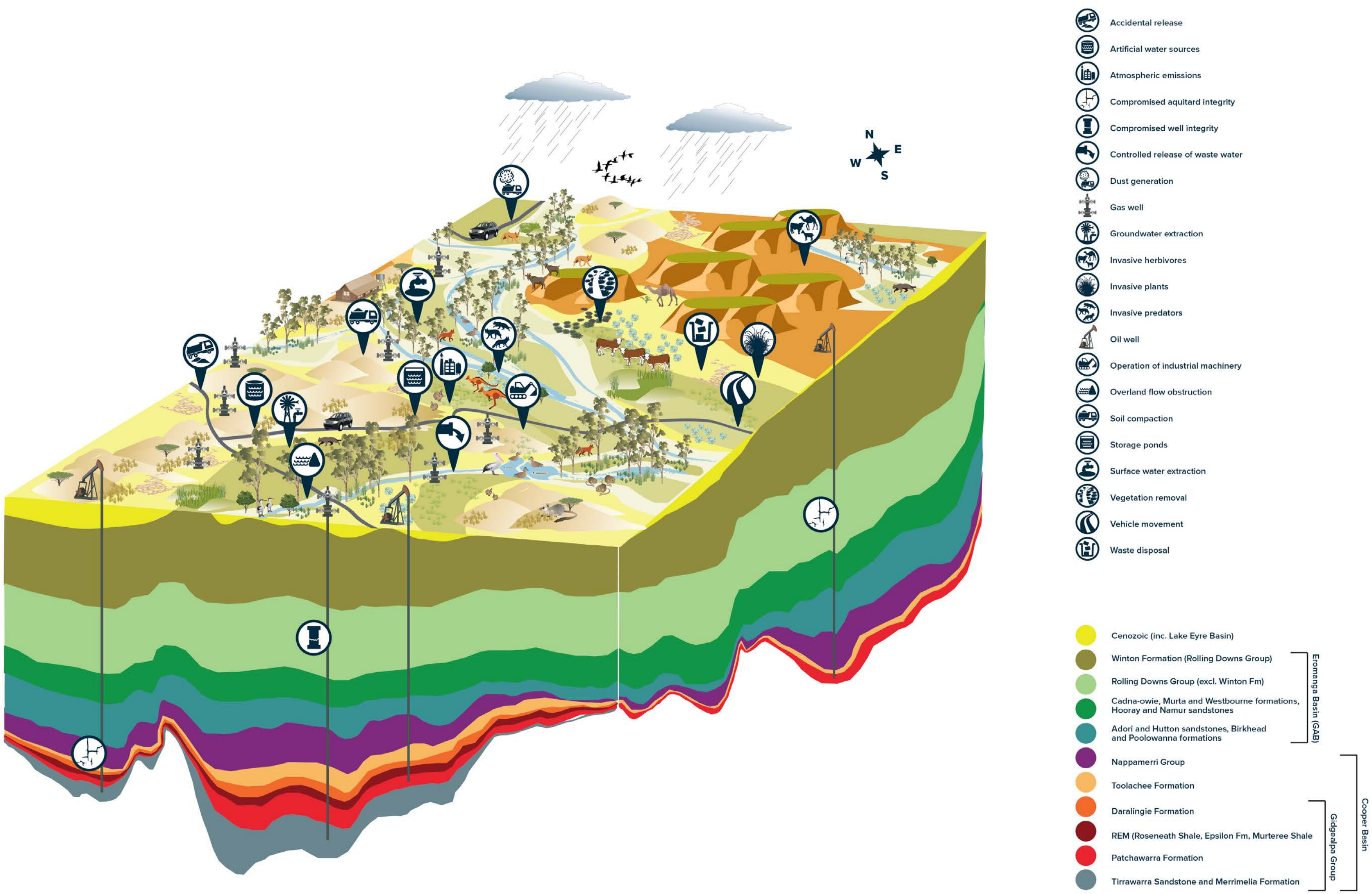


Relative prospectivity is the likelihood of discovering a given resource, such as oil, gas or groundwater, through analysis of geological properties (for example formation depth and extent, rock properties, reservoir characteristics). A relative prospectivity threshold of 0.75 was chosen based on the distribution of values and as it indicates high scores for several input parameters.

Data: Geoscience Australia (2008); Geological and Bioregional Assessment Program (2020a)

Element: GBA-COO-3-696

FIGURE 3 Conceptualisation of stressors associated with unconventional gas resource development in the Cooper GBA region



Fm = Formation. This schematic diagram is not drawn to scale. Icons represent the 19 stressors associated with unconventional gas resource development in the Cooper GBA region. Important landscapes at the surface are the Cooper Creek floodplain, inland dunefields, gibber plains, tablelands and duricrusts. Major geological layers in the Lake Eyre, Eromanga and Cooper basins are represented below the surface.
Element: GBA-COO-3-690

2.2 Gas resources

The Cooper GBA region is defined by the surface projection of the outline of the Cooper Basin geological province. 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 over 50 years. GBA baseline studies identified areas of higher relative prospectivity for unconventional shale, tight and deep coal gas plays that include the Nappamerri, Patchawarra, Windorah, Allunga and Wooloo troughs (Figure 4), which is consistent with the location of recent exploration activity (petroleum prospectivity technical appendix (Lech et al., 2020)).

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 3,000 petroleum wells have been drilled and more than 81,000 line km of two-dimensional seismic data and 10,000 km^2 of three-dimensional seismic data have been acquired (Section 2.2 in baseline synthesis and gap analysis (Holland et al., 2020); petroleum prospectivity technical appendix (Lech et al., 2020)).

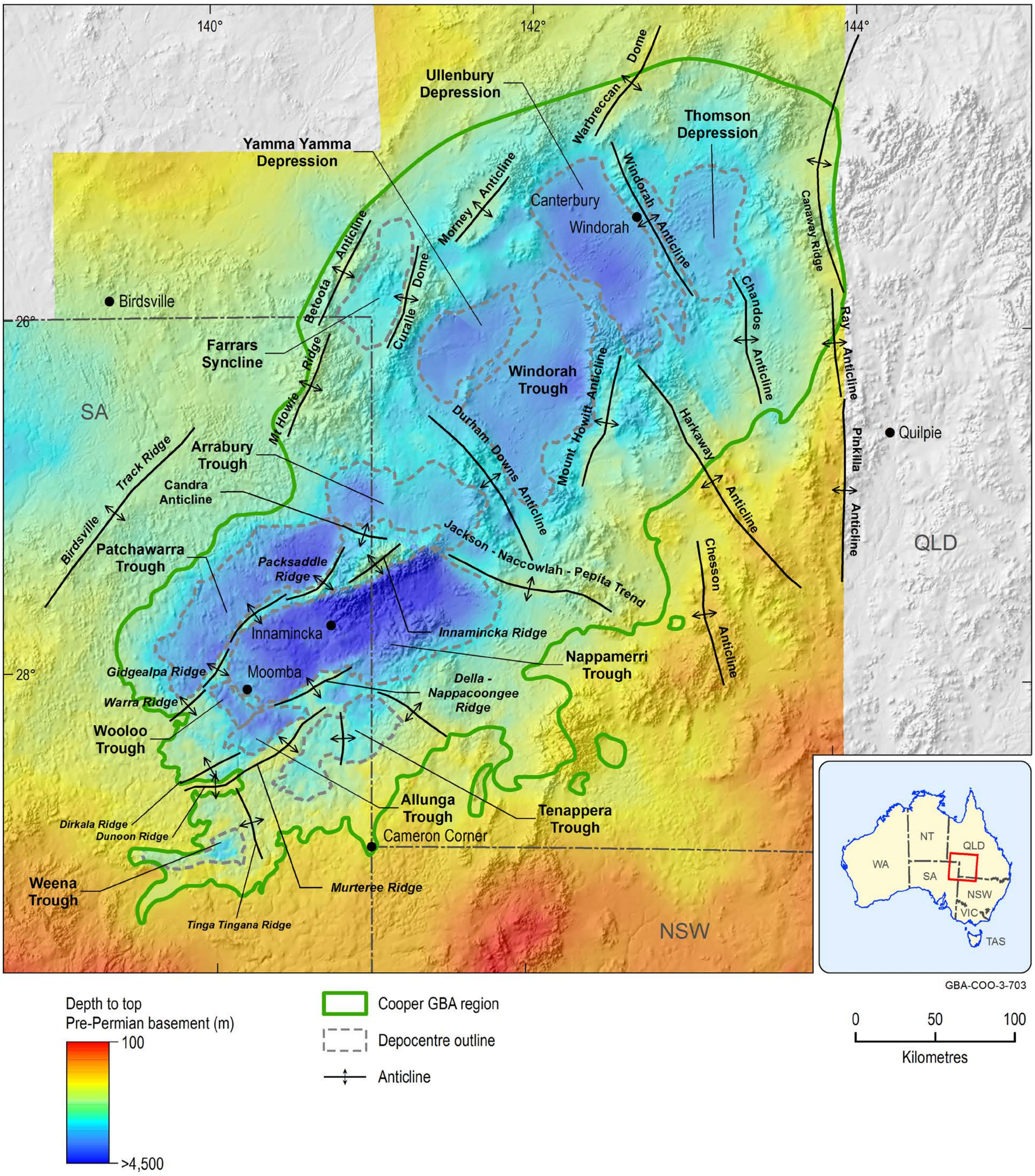
While the development of shale, tight and deep coal gas resources is an emerging industry in Australia, the existing legislation, regulations, approval conditions and industry practices reflect more than 50 years of conventional oil and gas production in the Cooper Basin. The industry is regulated at federal, state and local levels to ensure that industry development is sustainable and responsible and minimises impacts on water resources, biodiversity, social and human capital, and other non-renewable natural resources such as air quality.

2.3 Hydrogeology

There are 3 major geological basins in the Cooper GBA region: the Cooper Basin, the Eromanga Basin and the Cenozoic sediments of Lake Eyre Basin (Figure 3). In the Cooper Basin, the Permian Gidgealpa Group hosts the unconventional gas resources and is overlain by the Nappamerri Group. Due to depth of burial (generally greater than 1,500 m), the Cooper Basin is not directly used as a groundwater source. Between 600 and 2,000 m of sedimentary rock typically separates aquifers, such as those in the Cenozoic and Winton-Mackunda formations or deeper Great Artesian Basin (GAB) aquifers, from shale, tight and deep coal gas plays in the Cooper Basin (Section 3.1 in baseline synthesis and gap analysis (Holland et al., 2020); hydrogeology technical appendix (Evans et al., 2020)).

The Cadna-owie – Hooray aquifer is an artesian aquifer, where the natural water pressure in a bore can rise to the ground surface. It is hosted in the Cadna-owie and Murta formations, and the Hooray, Namur and Algebuckina sandstones, which are part of the Great Artesian Basin (GAB). The Winton-Mackunda aquifer is a sub-artesian aquifer, which covers the entire Cooper GBA region and includes outcrops, as well as confined areas where it is overlain by significant thicknesses of Lake Eyre Basin sediments (Cenozoic aquifer). The Cenozoic aquifer is the uppermost aquifer, which covers parts of the Cooper GBA region where the older Winton Formation sediments do not outcrop. The Cenozoic and unconfined parts of the Winton-Mackunda aquifer support groundwater-dependent ecosystems where the watertable is near the surface in the west of the Cooper GBA region.

FIGURE 4 Cooper Basin structural elements overlain on the top of the pre-Permian basement depth horizon



Cooper GBA region has the same extent as the geological Cooper Basin that is referred to in this figure.
After Hall et al. (2015); Carr et al. (2016). Structural elements after Draper (2002); Gravestock and Jensen-Schmidt (1998); McKellar (2013); and Ransley and Smerdon (2012); see also Owens et al. (2020)

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

Element: GBA-COO-3-703

3 Assessment, mitigation and monitoring

Potential impacts on water and the environment are assessed using a causal network. The assessment uses spatially explicit and systematic evaluations of the likelihood and consequence of potential environmental harm. It also evaluates how compliance with existing regulatory controls and operational practices can minimise and mitigate potential impacts. The causal network also allows local- and regional-scale monitoring objectives to be systematically identified and prioritised. An interactive online tool, GBA Explorer, presents this comprehensive information base.

3.1 Causal networks

Causal networks are graphical models that describe the cause-and-effect relationships between development activities and endpoints – the values to be protected – for example, the internationally protected Coongie Lakes wetland. The causal network illustrates the complex and interconnected nature of the natural environment and unconventional gas resource development activities in the Cooper GBA region. It provides a comprehensive and clearly identified set of inferred direct and indirect pathways where development activities may impact on environmental values. Systematic evaluation of likelihood, consequence and mitigation strategies allows qualitative and quantitative information to be integrated, even when the available knowledge base is limited.

In this impact assessment for the Cooper GBA region, a causal network with detailed node descriptions is central to the environmental impact assessment (Figure 5). The impact assessment method was developed as part of the GBA Program based on existing approaches described in Peeters et al. (2021a). The causal network illustrates the complex and interconnected nature of the natural environment and unconventional gas resource development activities in the region. Evaluations in the causal network assess how undertaking these activities may cause material changes (a change that exceeds defined thresholds) in nodes linking from activities. The evaluations also consider the degree to which existing regulatory controls and industry practices can mitigate potential impacts.

Existing mitigation and management practices associated with development activities are typically represented by links from activities to stressors along a causal pathway. Whereas subsequent links in the causal network represent the effect an activity has on a process once it occurs. Changes to natural processes are often difficult, if not impossible, to mitigate. This is why it is important that mitigation strategies are implemented early in the chain of events from activities to endpoints.

Nodes represent the different components of the system that make up a causal pathway – drivers, activities, stressors, processes and endpoints (Table 1). Links – represented by arrows – show the hypothesised cause-and-effect relationships between nodes. Grids associated with each link enable representation of spatial variability when evaluating each pathway (Peeters et al., 2021a). Constructing the causal network (Figure 6) is an exercise that involves multiple disciplines and wide stakeholder engagement. Hazards and causal pathways identified in the baseline synthesis and gap analysis (Holland et al., 2020) were refined and incorporated into the causal network. A comprehensive process of stakeholder engagement in the hazard analysis and technical reviews aimed to accurately capture unconventional gas operation and regulation while addressing user needs. Extensive independent technical reviews of evaluations and documentation in the causal network was also undertaken.

Endpoints are represented in the causal network as 'assessment endpoints' defined as an explicit expression of the ecological, economic and/or social values to be protected, and as 'measurement endpoints' defined as measurable characteristics or indicators related to the valued characteristic chosen as the assessment endpoint (Suter, 1990; US EPA, 2016) (Section 5.1 in baseline synthesis and gap analysis (Holland et al., 2020)). Endpoints in the causal network for the Cooper GBA region represent aquifers, such as the Cenozoic aquifer; landscapes, such as floodplain vegetation communities; protected areas, such as Coongie Lakes Ramsar wetland; and protected fauna and flora, such as the kowari or braided sea heath listed under state or national legislation (Table 1).

TABLE 1 Node types, examples and number of each node type in the causal network for the Cooper GBA region

Node type	Description	Examples	Number of nodes
Driver	Major external driving forces (human or natural) that have large-scale influences on natural systems	Resource development	1
Activity	A planned event associated with unconventional gas resource development	Civil construction Transport of materials and equipment	8
Stressor	Physical, chemical or biological agent, environmental condition or external stimulus caused by activities	Dust generation Vehicle movement	19
Process	A naturally occurring mechanism that could change a characteristic of an endpoint	Air pollution Habitat degradation, fragmentation and loss	22
Endpoint	A value pertaining to water and the environment that may be impacted by development of unconventional gas resources	Cadna-owie – Hooray aquifer condition Floodplain vegetation extent and condition Coongie Lakes Ramsar wetland condition Persistence of kowari Persistence of braided sea heath	25

Visually, the causal network illustrates the complex and interconnected nature of natural and regulatory environments in the Cooper GBA region. In general, links from activities to stressors can be mitigated by existing regulatory and industry management frameworks, whereas links from processes to endpoints associated with changes to natural processes are often difficult, if not impossible, to mitigate. Links to subsurface processes and endpoints evaluated as not possible or not material represent the natural barriers that protect overlying aquifers from drawdown or contamination due to gas production in deeper gas reservoirs.

The causal network for the Cooper GBA region (Figure 6) consists of 75 nodes, 268 links and 2,815 pathways. Nodes are organised from left to right, starting with the driver node '**resource development**'. Hazards and causal pathways identified in the Stage 2 baseline synthesis and gap analysis (Holland et al., 2020) were refined and incorporated into the causal network.

Links are evaluated according to their likelihood ('possible', 'not possible'), consequence ('material', 'not material') and management ('avoidable', 'unavoidable but can be mitigated', 'unavoidable and cannot be mitigated') (Table 2). Outcomes of the overall assessment categorise potential impacts on endpoints (Table 2).

TABLE 2 Evaluation language used to describe links in the causal network and the corresponding level of concern used to describe the impact pathway through to endpoints

Evaluation			
Not possible	Possible but not material Possible and material but can be avoided	Possible, material and unavoidable but can be mitigated	Possible, material, unavoidable and cannot be mitigated
Level of concern			
Very low concern	Low concern	Potential concern	Potentially high concern
Impacts are not physically possible or are extremely unlikely (having a probability of less than 1 in 1,000)	Impacts can be avoided by current legislation or because the impact does not represent a material change	Impacts can be minimised or mitigated by existing management controls	Impacts cannot be avoided or mitigated at the scale of the GBA region

The causal networks for the GBA Program are presented in the GBA Explorer. This web-based tool allows users to interact with a graphical presentation of the causal networks with immediate access to the node descriptions, link evaluations and overall assessment summary. Users can visualise the whole entire causal network or simplify it by selecting specific pathways. Spatial data are also presented via interactive maps that include the spatial information used to inform the assessment and spatial link evaluations, and to make spatial impact maps depicting pathways for activity to endpoint, stressor to endpoint and process to endpoint.

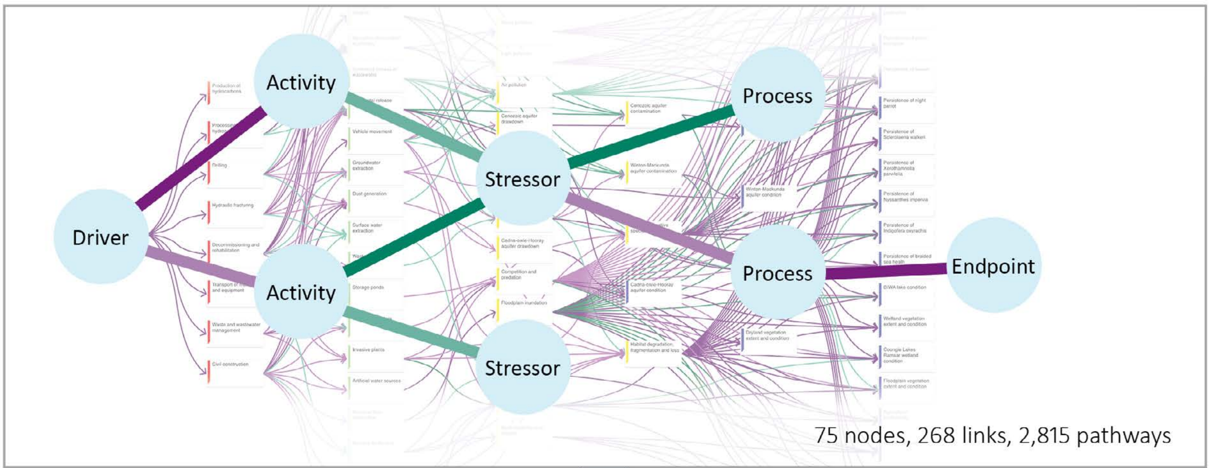
Future studies could extend the causal network to other industries, such as pastoralism or tourism. What is not possible with this method is assessing the cumulative impact of multiple stressors on a baseline. This requires firstly a comprehensive and quantitative baseline assessment, which is not yet available, and secondly future projections of the magnitude and likelihood for all stressors (Peeters et al., 2021b).

FIGURE 5 The impact assessment for the Cooper GBA region explained

CAUSAL NETWORKS

Causal networks assess how unconventional gas resource development activities create stressors that alter natural processes and lead to potential impacts on the values to be protected in the Cooper GBA region.

Graphical representations and analytical tools of complex systems



Based on a regional resource development scenario

Development time

50 years

Number of wells

4

8

Slow = 63 wells

Fast = 1180 wells

Number of well pads

Slow = 52 well pads

Fast = 295 well pads

Energy produced

Slow = 23 PJ/year

Fast = 92 PJ/year

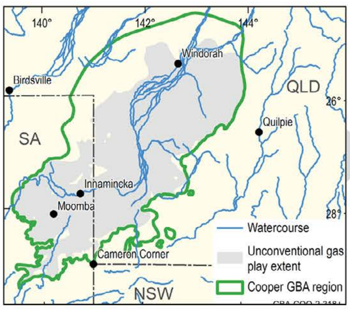
Well numbers: up to 1,180 wells over 50 years with 4 to 8 wells per well lease

Well pads: up to 12 km² or 0.009% of the Cooper GBA region

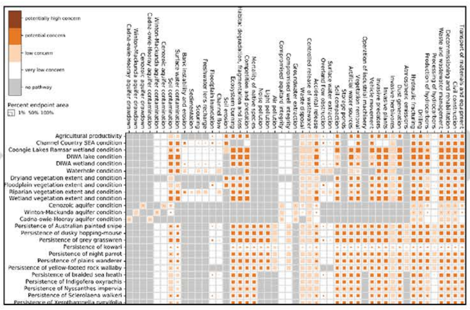
Access roads: up to 15 km² or 0.01% of the Cooper GBA region

Three-dimensional seismic area: up to 885 km² or 0.6% of the Cooper GBA region

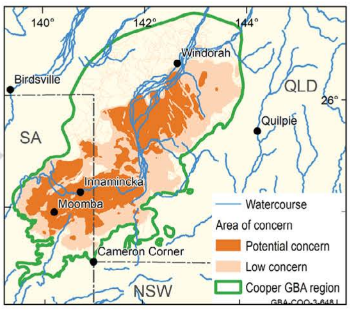
Outputs from the Cooper GBA causal network



01 Areas within the 130,000 km² of the Cooper GBA region where more detailed local-scale assessments are required



02 Activities, stressors and processes of concern



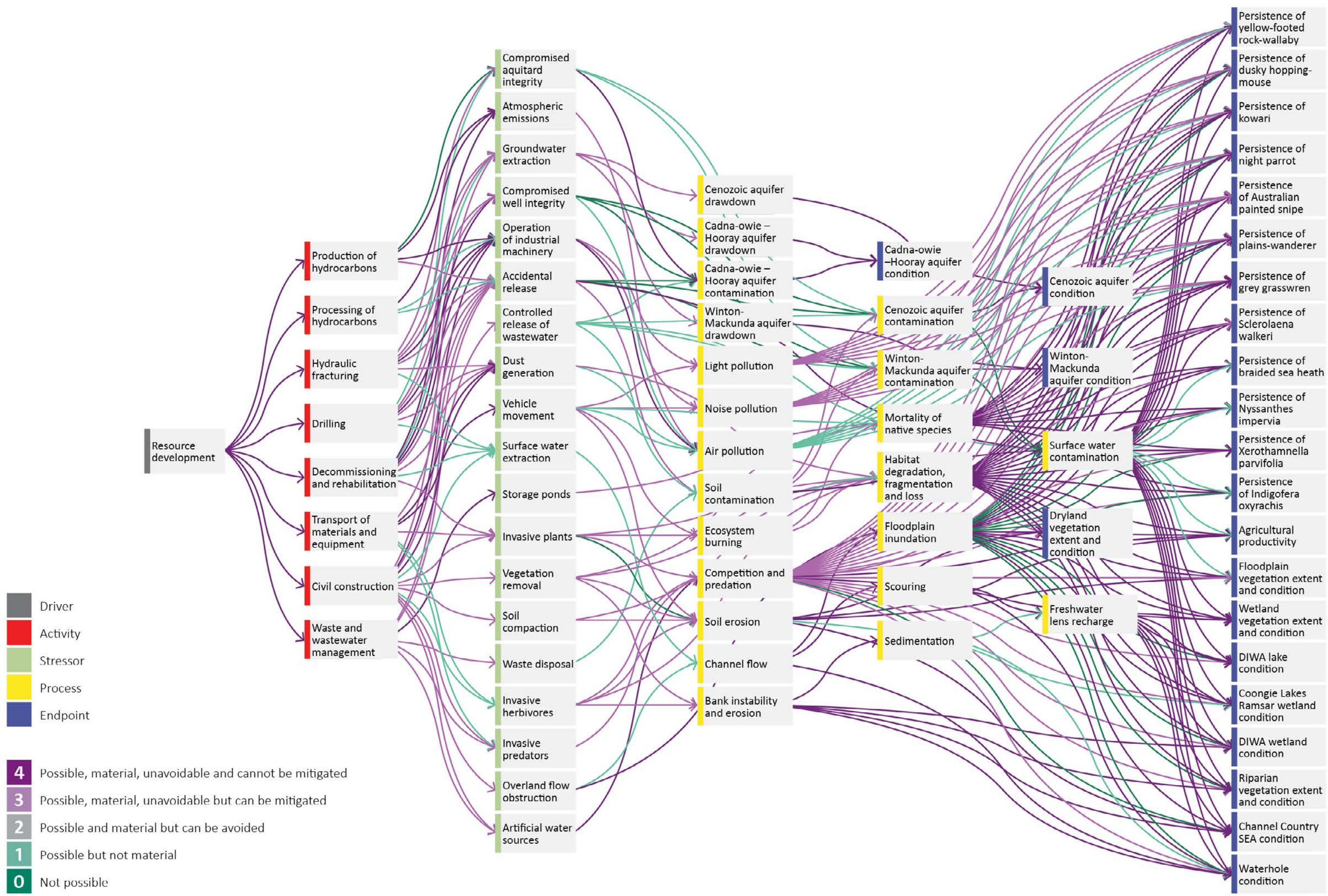
03 Potential impacts on 7 protected fauna, 5 protected flora, 3 aquifers, and protected waterholes, wetlands and other areas

Images in this figure are representative only because many are too detailed for interpretation. They are available from the causal network for the Cooper GBA region in GBA Explorer.

Data: Geological and Bioregional Assessment Program (2021c)

Element: GBA-COO-3-639

FIGURE 6 Causal network for the Cooper GBA region with links colour coded according to their evaluation of likelihood, consequence and mitigation (Table 2)



Interact with the GBA Explorer.
Data: Geological and Bioregional Assessment Program (2021c)
Element: GBA-COO-3-640

3.2 Confidence in the assessment

There is high confidence that potential impacts due to unconventional gas resource development can be mitigated for all pathways of 'potential concern'. However, the knowledge base is generally limited for the threshold of material change and for some cause-and-effect relationships. Confidence in the assessment will be improved as knowledge of these relationships and thresholds is established.

In the causal network, each link evaluation is based on the best available data and knowledge. However, in some cases the knowledge base may be limited for: (i) the cause-and-effect relationship, (ii) the threshold of material change, or (iii) the mitigation strategies and whether they are available and effective. For example, there is considerable uncertainty associated with the impacts of noise and light pollution on fauna species.

Each link evaluation is assigned a confidence score of 'low', 'medium' or 'high' (Table 3). Where the knowledge base is limited, it is reflected in the causal network as uncertainty. Where there is insufficient knowledge to support a robust threshold of material change, links are generally evaluated as material by applying the precautionary principle. This approach enables uncertainty to be addressed and potential impacts, though not well-defined or understood, to be considered in decision making.

TABLE 3 Confidence assessment of links in the causal network

Are we confident that the link is possible? [a]	Are we confident that the link is or is not material? [b]	Are we confident the link can or cannot be mitigated? [c]	Confidence
Yes	Yes / Not applicable	Yes / Not applicable	High
Yes	Yes	No	Medium
Yes	No	Yes	Medium
No	Yes	Yes	Medium
Yes	No	No / Not applicable	Low
No	Yes	No / Not applicable	Low
No	No	Yes	Low
No	No / Not applicable	No / Not applicable	Low

[a] based on publication(s) with local system relevance or self-evident
[b] based on publication(s) with local system relevance
[c] based on publication(s) with local system relevance or publicly documented in approval conditions or proponent protocols

Confidence statements for each link (Table 3) are combined into overall confidence statements for pathways (Table 4). Confidence in the cause-and-effect relationship is mixed but is generally low for the thresholds of material change, reflecting that the knowledge base on hydrological and ecological functioning at a local scale is emerging. However, there is high confidence that regulation and management procedures can mitigate potential impacts (Table 4).

TABLE 4 Number of causal pathways with high or low confidence in cause-and-effect relationship, threshold of material change and mitigation strategies

Level of concern	Cause-and-effect relationship (number of causal pathways)		Threshold of material change (number of causal pathways)		Mitigation strategy (number of causal pathways)	
Level of confidence	Low	High	Low	High	Low	High
Very low concern	186	1,066	1,222	30	0	852
Low concern	109	602	688	23	0	711
Potential concern	176	676	830	22	0	1,252
Potentially high concern	0	0	0	0	0	0
Total	471	2,344	2,740	75	0	2,815

Data: Geological and Bioregional Assessment Program (2021c)

3.3 Assumptions

Any assessment of the impact of future development requires assumptions to be made. For unconventional gas resource development these include overarching assumptions about the scale of development, technologies used, existing regulatory requirements and baseline knowledge of the resource, ecological and water systems. It is also assumed that the causal network correctly represents these characteristics for the assessment. Detailed assumptions about individual aspects of an assessment, such as characteristics of an activity or parameters for a particular process are documented in the relevant node descriptions in GBA Explorer.

The impact assessment is designed to be structured, robust and transparent. The evaluation of potential effects requires assumptions to be made by the assessment team. These assumptions are documented in GBA Explorer and justified based on literature, GBA investigations and expert consultation. Major assumptions for the assessment for the Cooper GBA region are:

- Unconventional gas resource development occurs within the clearly defined Cooper GBA region and adheres to existing regulations and practices, which are enforced by the relevant regulator.
- The assessment is based on current and immediately foreseeable technologies. However, unconventional gas resource development technologies and practices are continuously evolving and so new technologies may result in different changes to the environment.
- Development activities associated with the 5 life-cycle stages of unconventional gas resource development are correctly represented in the causal network (Holland et al., 2020): (i) exploration, (ii) appraisal, (iii) development, (iv) production and (v) rehabilitation.

- The resource development scenario is based on areas that are relatively more prospective for gas and estimates of the likely magnitude of future development based on the amount and rate at which gas could be produced in the future. However, it does not include commercial considerations, such as supply and demand factors and proximity to infrastructure, which are important drivers of any future development scenario. More detailed assumptions for the resource development scenario that form the foundation of the assessment are described in Section 3.4.
- The causal network adequately represents the activities and stressors associated with unconventional gas resource development, their interactions with complex ecological and hydrological systems and their endpoints at a regional scale.
- Other drivers (climate change, other industries) are not assessed. There is an implicit assumption that those drivers are not changing processes and predicted responses to such a degree that impacts on endpoints would be materially altered.
- Links between nodes within the causal network have been correctly evaluated, including if they are possible, if they constitute a material change and if they can be mitigated. It is also assumed that confidence in those evaluations is correctly described.
- Where evidence to support the evaluations is not available, the precautionary principle is applied, and a higher level of concern is selected.
- Where an action may have both adverse and beneficial impacts, only adverse impacts are assessed.
- All risks to water and the environment from unconventional gas resource development are identified and risks are not accounted for more than once.
- The mitigation strategies identified are appropriate and effective.
- The confidence statements adequately reflect the uncertainty in the evaluation of links in the causal network.

3.4 Resource development scenario

Two resource development scenarios were used for this impact assessment; a fast development scenario that matches the current conventional gas production in the Cooper GBA region (92 petajoules per year) and a slow development scenario, which is one-quarter of the fast development scenario (23 petajoules per year) over a 50-year time period. A total of 27 km^2 is estimated to be disturbed when drilling the 1,180 petroleum wells needed for the fast development scenario. The total area encompassed by well pads and access roads, including undisturbed areas between well pads, roads and seismic lines, is between 586 and 7,350 km^2. This is less than 6% of the Cooper GBA region. The fast development scenario would require the extraction or reuse of up to 19,680 megalitres of water over a 50-year development period, equivalent to approximately 400 megalitres per year for 50 years.

Unconventional gas resources are found in a range of geological settings in the Cooper GBA region and include 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 (refer to Section 2.2 in baseline synthesis and gap analysis (Holland et al., 2020)).

The resource development scenario differs from a specific project-based environmental impact assessment where the location, scale and nature of planned activities are well delineated. For this assessment where the exact nature of the development is unknown, a resource development scenario is used to describe the characteristics of activities for the impact assessment. Two development scenarios are considered:

- a fast development scenario based on unconventional gas production matching the current Cooper GBA region conventional gas production, which is approximately 92 petajoules per year
- a slow development scenario, which is one-quarter of the fast development scenario (23 petajoules per year).

As there is no way of knowing exactly what future development may look like, the resource development scenario is based on the relative prospectivity of unconventional gas plays in the Cooper GBA region (refer to Stage 2 petroleum prospectivity technical appendix (Lech et al., 2020)), as well as potential restrictions prescribed in regulatory frameworks. Gas production increases in the first 5 to 10 years to meet the desired energy production rate. Relative prospectivity determines the likelihood of discovering a given resource (for example, oil, gas, groundwater) through analysis of geological properties (for example, formation depth and extent, rock properties, reservoir characteristics). A relative prospectivity threshold of 0.75 was chosen based on the distribution of values and as it indicates high scores for several input parameters (Figure 2).

It is assumed that a well pad is up to 4 ha (Senex Energy, 2016; Santos, 2015) and typically requires 5 km of access road with a width of 10 m. Prior to drilling, 3 km^2 of additional 3-dimensional seismic surveys is needed (Holland et al., 2020). Seismic lines are assumed to be between 4 and 5 m wide (Doudy and Cockshell, 2016). All seismic lines, well pads and access roads are progressively rehabilitated to meet regulatory requirements (Holland et al., 2020).

A resource development footprint of 8.85 to 26.55 km^2 includes the following disturbed areas:

- well pad area of 5.9 km^2 to 11.8 km^2; 4 to 8 wells per well pad, 63 to 1,180 wells drilled on 52 to 295 well pads (Pan et al., 2021)
- roads of 2.95 km^2 to 14.75 km^2; 5 km of access road with a width of 10 m per well pad
- 3-dimensional seismic surveys of 442 km^2 to 885 km^2; additional 3 km^2 seismic surveys per well pad.

The spatial extent for the entire unconventional gas resource development scenario, which is a combination of development area — for example, roads, well pads and seismic lines — as well as the areas between well pads and seismic lines, is estimated to be between 586 and 7,350 km^2 (or 0.5 to 5.6% of the Cooper GBA region) of which the estimated disturbed area is less than 27 km^2. This estimate assumes that the development of unconventional gas resources in the Cooper GBA region would require drilling of a maximum of 1,180 wells with 4 to 8 wells per well pad over a 50-year development period (Figure 5). The well pad area extends to the limit of disturbance where a well is to be drilled and where drill rigs, pumps, engines, generators, mixers and similar equipment, fuel, pipes, and chemicals are located.

By way of comparison, the existing physical footprint of the oil and gas industry is relatively small (878 km^2), covering approximately 0.7% of the Cooper GBA region. This excludes disturbances associated with seismic exploration activities (831 km^2, approximately 0.6%), which typically persist for 7 to 8 years, and 10 to 20 years in gibber plain land systems (Doudy and Cockshell, 2016). The disturbance footprint is estimated to increase by 27 km^2 (or 3%) under the maximum development scenario (Figure 5).

Based on this resource development scenario, a total volume of 9,210 to 19,680 megalitres of water is required over a 50-year time period (Pan et al., 2021), equivalent to less than 400 megalitres per year in the entire Cooper GBA region. Likely water sources are groundwater (from aquifers in and above the Great Artesian Basin) and co-produced water extracted during conventional oil and gas development (Section 3.1.4 in baseline synthesis and gap analysis (Holland et al., 2020)). Water supply for unconventional gas resource development activities is governed by a water allocation plan and regulatory conditions overseen by the Queensland and South Australia governments. Surface water is not considered a reliable water source for unconventional gas resource development.

3.5 Assessment results

The assessment is built on a large body of evidence and a significant level of detail is provided in the interactive causal network. **Bold hyperlinked text** in the following sections denotes where causal network node descriptions are available. This brief synthesis cannot capture the full weight of evidence behind the assessment and interested readers are encouraged to interact with the causal network.

All potential impacts due to unconventional gas resource development identified by the assessment can be mitigated through ongoing compliance with existing regulatory and management controls.

The impact assessment for the Cooper GBA region determined: (i) areas of concern (i.e. how much of an endpoint area is of a particular level of concern), (ii) activities, stressors and processes of concern, and (iii) potential impacts on protected fauna, protected flora, aquifers, waterholes, wetlands and other areas.

The causal network for the Cooper GBA region consists of 1 driver node, 8 activity nodes, 19 stressor nodes, 22 process nodes and 25 endpoints (Table 1). Potential impacts due to stressors associated with unconventional gas resource development on water, the environment and selected protected matters are conceptualised in Figure 3. The percentage of the area in an endpoint that is of 'potential concern' is used to indicate the level of concern for each endpoint (Figure 7). However, this does not distinguish between components of an endpoint that may be more or less important. For example, loss of critical food sources or breeding habitat could cause catastrophic loss of an individual endpoint. Endpoint area is the 'potential' distribution of protected fauna and flora, or where aquifers, waterholes, wetlands and other areas represented by the endpoint are mapped.

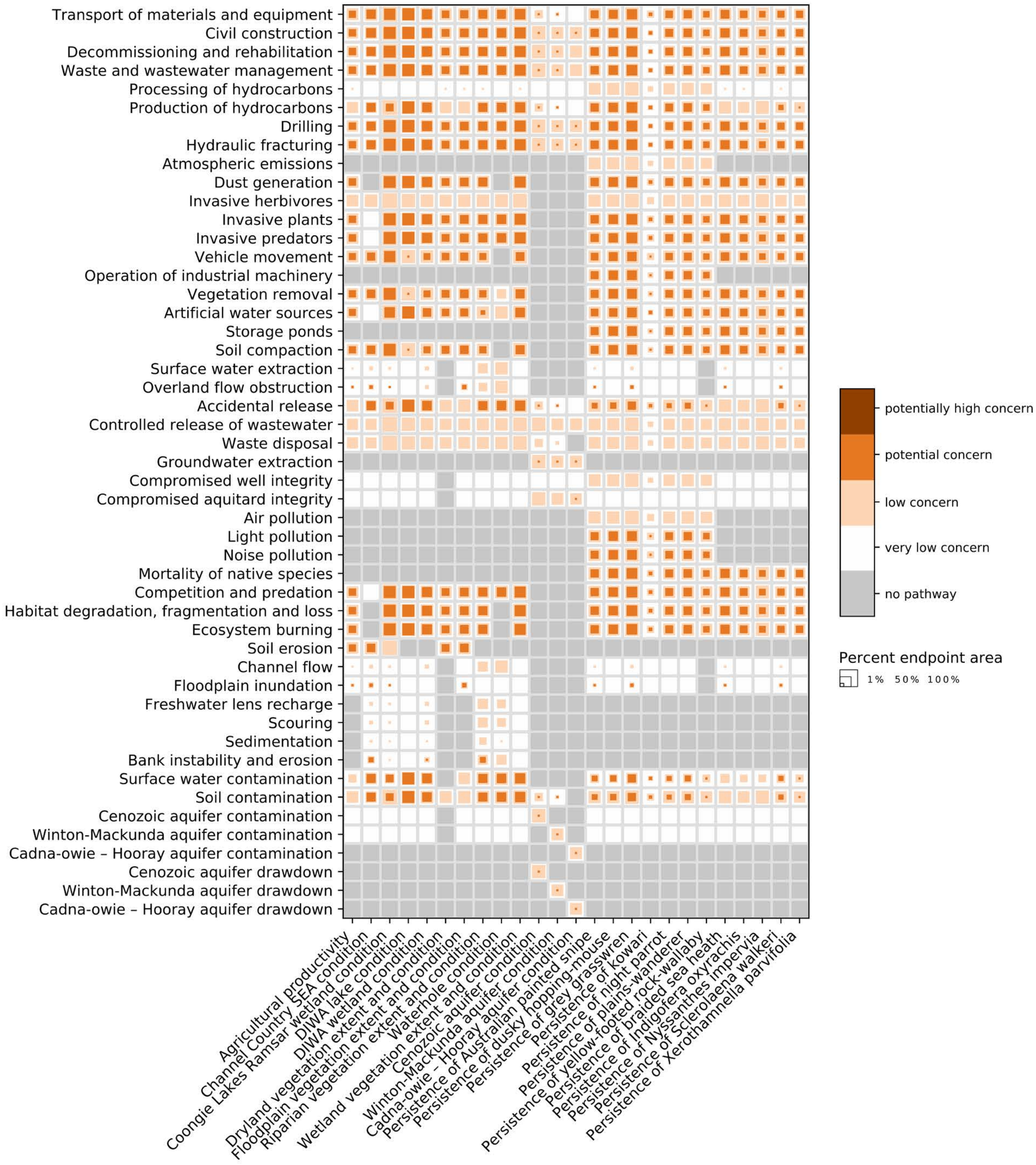
There are 13 environment-related endpoints that were selected to represent important environmental values in the Cooper GBA region. This includes 4 mutually exclusive endpoints that represent the extent and condition of dryland, floodplain, riparian and wetland vegetation in the Cooper GBA region. Another 9 environment-related endpoints represent agricultural grazing, aquifers, nationally and internationally listed wetlands, regionally protected areas and permanent waterholes. In addition, the 12 species prioritised for further assessment are represented by 7 protected fauna and 5 protected flora endpoints.

There are no pathways of 'potentially high concern' identified in the impact assessment for the Cooper GBA region. All potential impacts identified by the assessment can be mitigated through ongoing compliance with existing regulatory and management controls. Potential impacts on water, the environment, protected fauna and protected flora that are of 'potential concern' include 869 pathways associated with 7 of the 8 development activities, 13 of the 19 stressors, 16 of the 22 processes and 23 of the 25 endpoints (Figure 7). Remaining pathways are of 'low concern' or 'very low concern' (Table 2) in the Cooper GBA region.

Pathways of 'potential concern' are identified in 27% of the Cooper GBA region (Table 5). In Figure 8, coloured areas show areas where one or more endpoints are of 'potential concern'. These areas can be prioritised for future assessment, mitigation and management actions. Remaining areas in the Cooper GBA region (no colour) are of 'low concern' (33%) or 'very low concern' (40%). In these areas, relative prospectivity is generally lower, meaning that unconventional gas resource development activities are unlikely to occur, or pathways from development activities to endpoints are evaluated as not possible, not material or can be avoided.

The following sections discuss potential impacts on water (Section 4) and the environment (Section 5) in more detail. Section 6 discusses potential impacts on protected fauna and flora.

FIGURE 7 Cross-tabulation of the level of concern for activities, stressors, processes and endpoints



Each square in the figure represents the highest level of concern for the endpoint from all the pathways that pass through each activity, stressor or process node (Peeters et al., 2021a).

Data: Geological and Bioregional Assessment Program (2021c)

Element: GBA-COO-3-687

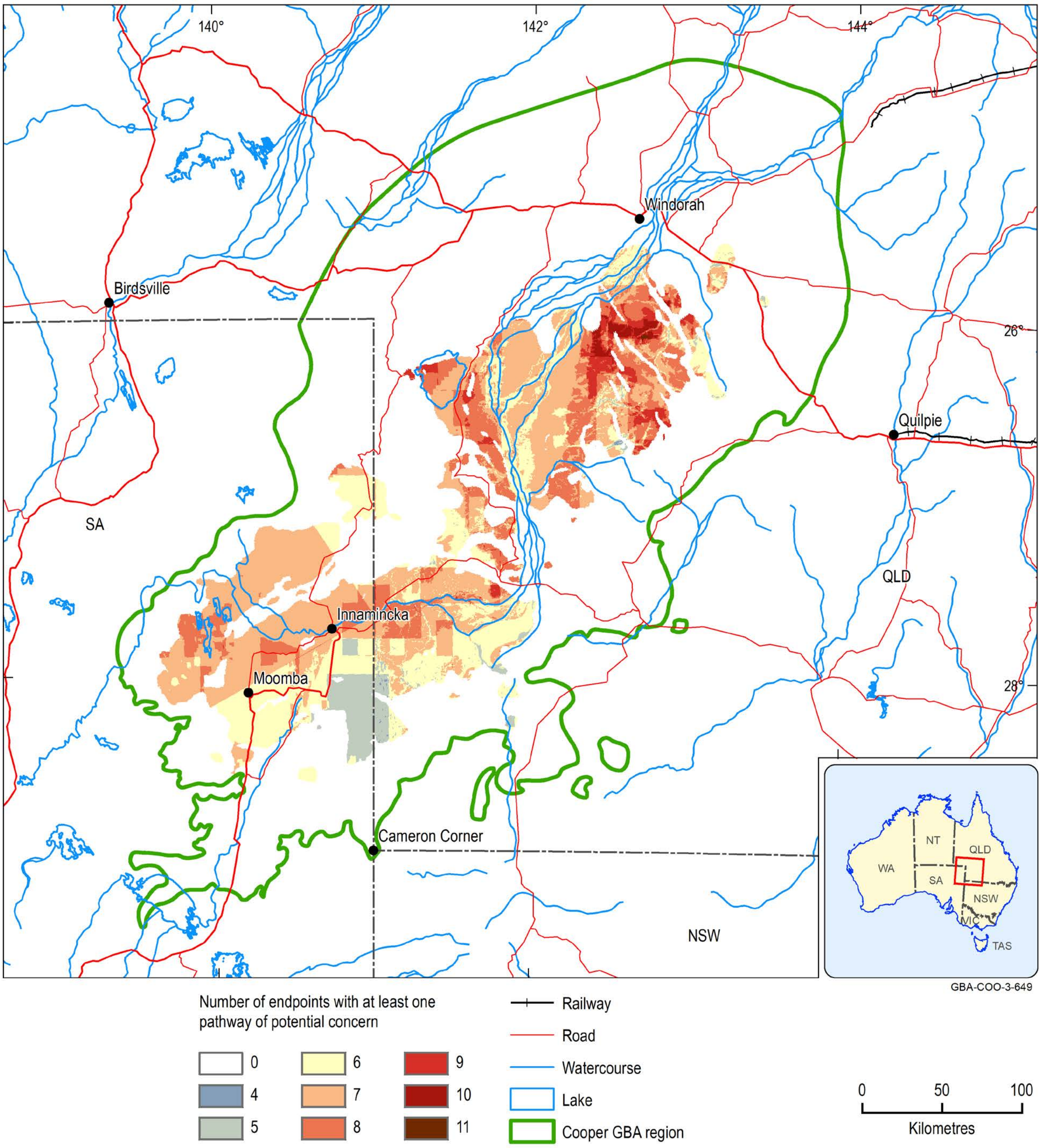
TABLE 5 Percentage of endpoint area (%) by level of concern and total endpoint area (km²)

Endpoint	Very low concern	Low concern	Potential concern	Potentially high concern	Endpoint area	Cooper GBA region
	%	%	%	%	km²	%
Agricultural productivity	45	34	21	0	100,771	76.6
Channel Country SEA condition	35	27	37	0	27,834	21.2
Coongie Lakes Ramsar wetland condition	9	33	57	0	12,392	9.4
DIWA lake condition	27	14	59	0	1,135	0.9
DIWA wetland condition	35	24	41	0	3,566	2.7
Dryland vegetation extent and condition	43	34	23	0	88,538	67.3
Floodplain vegetation extent and condition	37	33	29	0	25,283	19.2
Riparian vegetation extent and condition	37	31	33	0	5,626	4.3
Waterhole condition	32	33	36	0	569	0.4
Wetland vegetation extent and condition	21	30	49	0	12,143	9.2
Cenozoic aquifer condition	25	74	<0.9	0	52,531	39.9
Winton-Mackunda aquifer condition	43	57	<0.4	0	131,589	100.0
Cadna-owie – Hooray aquifer condition	43	57	<0.1	0	129,866	98.7
Persistence of dusky hopping-mouse	38	27	35	0	37,180	28.3
Persistence of grey grasswren	23	32	45	0	35,972	27.3
Persistence of kowari	81	15	4	0	9,223	7.0
Persistence of night parrot	43	33	24	0	98,845	75.1
Persistence of plains-wanderer	37	34	29	0	115,311	87.6
Persistence of yellow-footed rock-wallaby	47	37	16	0	18,936	14.4
Persistence of braided sea heath	36	31	33	0	99,448	75.6
Persistence of *Indigofera oxyrachis*	45	32	23	0	24,886	18.9
Persistence of *Nyssanthes impervia*	29	54	17	0	7,923	6.0
Persistence of *Sclerolaena walkeri*	48	33	19	0	80,928	61.5
Persistence of *Xerothamnella parvifolia*	50	29	21	0	1,542	1.2
Total in Cooper GBA region[a]	**40**	**33**	**27**	**0**	**131,589**	**100**

[a] Total in Cooper GBA region is the percentage of the endpoint area for each level of concern. It is not the sum total of the percentage of the endpoint area for all endpoints but is the maximum level of concern in each grid cell.

Data: Geological and Bioregional Assessment Program (2021c)

FIGURE 8 Number of endpoints with pathways of 'potential concern' in each grid cell of the Cooper GBA region



Data: Geological and Bioregional Assessment Program (2021c)
Element: GBA-COO-3-649

3.6 Monitoring

The causal network identifies activities, stressors and processes from unconventional gas resource development that may lead to changes in endpoints related to water and the environment. Monitoring is critical for evaluating changes in a system associated with specific known impacts (Gitzen et al., 2012). The causal network identifies particular points along a causal pathway where monitoring would be most useful.

The impact assessment results and structure of the causal network are used to prioritise 4 broad monitoring objectives: (i) estimating baseline and trend; (ii) comparing areas of potential impact with areas where no changes occur (control sites); (iii) monitoring compliance with, and effectiveness of, mitigation strategies; and (iv) monitoring to validate and refine the causal network.

Specific monitoring objectives define the attributes to be measured, the spatial domain, timeframe of monitoring, and detection of the magnitude of change. Selection of attributes for each of the monitoring objectives is based on 'measurement endpoints' and 'environmental condition indicators' associated with the causal network. A measurement endpoint is a measurable attribute of the 'assessment endpoint' associated with a link from a process to an endpoint. An example is the 'number of mature Australian painted snipe individuals', which is a measurement endpoint for the **persistence of Australian painted snipe** endpoint. A measurement endpoint links from a process in the causal network, such as mortality of native species, to an endpoint. Environmental condition indicators are attributes of stressors or processes that are relevant to, but not directly related or linked to an endpoint. An example is the 'area burned by bushfire', which is an attribute of the **ecosystem burning** process node. **Ecosystem burning** links to **habitat degradation, fragmentation and loss**, which then links to the **persistence of Australian painted snipe** endpoint. Environmental condition indicators are often measured at a regional scale and relate to many endpoints.

Baseline and trend monitoring can establish the initial extent and condition of endpoints and can also detect trends or changes in the future. Natural capital accounting provides a framework to capture spatial and temporal changes to water and the environment.

Baseline data establishes the condition of endpoints related to water and the environment prior to unconventional gas resource development. Regional-scale data were compiled in the baseline synthesis and gap analysis for the Cooper GBA region (Holland et al., 2020). Natural capital accounting was used to compile a set of ecosystem extent and condition accounts for the Cooper GBA region (Box 1, Geological and Bioregional Assessment Program (2021m)). Proposals for future unconventional gas resource development require additional monitoring to provide local-scale baseline data on measurement endpoints and environmental condition indicators, which can include the extent and condition of the endpoint.

Measurement endpoints for:

- protected fauna and flora relate to the abundance of the species and are based on the criteria for listing outlined in the EPBC Act. Environmental condition indicators include habitat extent, surface water quality and streamflow.
- aquifers relate to groundwater chemistry and aquifer levels or pressures. Environmental condition indicators include soil chemistry to detect soil contamination that could contaminate unconfined aquifers.
- vegetation communities relate to vegetation extent or condition. Environmental condition indicators include floodplain inundation extent and duration, streamflow, surface water quality, soil chemistry, area of bare ground and area affected by bushfire.
- protected areas relate to attributes listed in the relevant legislation and management plans (Channel Country SEA, DIWA lakes and wetlands) or those for which thresholds of material change are available (Coongie Lakes Ramsar wetland condition). Environmental condition indicators can be measured with remote sensing tools.

Box 1 Ecosystem extent and condition accounts

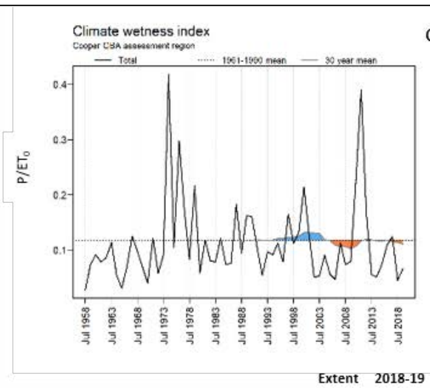
Natural capital accounting seeks to capture changes to water and the environment (i.e. stocks and flows of natural resources and ecosystem services). This requires conceptualisation and measurements of the natural environment over space and time. Processes causing change and the resulting change to the environment can be measured with tools such as remote sensing, aerial mapping and weather stations. A CSIRO-developed, custom-designed spatial information system – *SynthEEA (Synthesis for Environmental-Economic Accounting)* – streamlines natural capital accounting by providing standardised, reproducible, auditable and efficient methods for processing unique datasets. *SynthEEA* interacts with a spatial database to manage the accounting process from input of data through to generating charts and tables.

Ecosystem extent and condition accounts compiled for the Cooper GBA region include data recorded between 1957 and June 2019 (Geological and Bioregional Assessment Program, 2021m). The data are available from data.gov.au. Baseline accounts include indirect measures of productivity (relative climate wetness; Figure 9), stressors (disturbance and fire regime) and composition (vegetation condition; Figure 16) and biodiversity persistence; Box 10). Figure 9 shows that on average, while changes at a regional scale appear to be minor, there are important spatial and inter-annual variations that are important drivers of ecosystem condition. Baseline estimates of disturbance due to existing oil and gas industry activity (seismic surveys and other development), as well as other industries, such as agriculture and tourism, are summarised for the 4 key vegetation communities in the Cooper GBA region in Section 5. Time-series estimates of disturbance due to seismic surveys is consistent with historical observations of vegetation recovery for different landscape classes (Doudy and Cockshell, 2016).

Box 1 Ecosystem extent and condition accounts *continued*

FIGURE 9 Relative climate wetness index showing a) temporal changes for annual and 30-year means from 1958 to 2019 relative to the 1961 to 1990 reference period for the entire region; b) annual extent and condition account in 2018 to 2019 for ecosystem types; and c) spatial changes for 1990 to 2019 relative to the 1961 to 1990 reference period

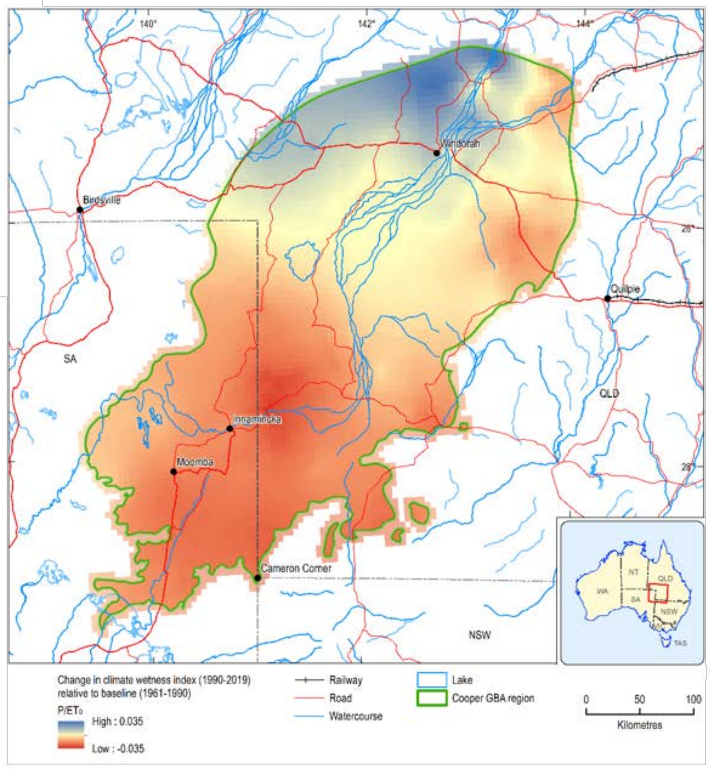
a)



b)

Ecosystem type	Extent km²	2018-19 P/ET0
BVG 16	2,231	0.07
BVG 19	141	0.17
BVG 23	16,271	0.09
BVG 24	19,872	0.06
BVG 25	8	0.07
BVG 26	6,980	0.10
BVG 27	1,217	0.17
BVG 30	19,417	0.06
BVG 31	25,106	0.07
BVG 33	17,960	0.05
BVG 34	5,470	0.03
Bare, very sparse or non-remnant	724	0.15
Lacustrine wetland	1,491	0.05
Palustrine wetland	5,809	0.06
Riverine wetland	572	0.09
Unclassified wetland	6,780	0.04
Water	1	0.09
Not classified	10	0.04
GBA region	**130,060**	**0.07**

c)



GBA-COO-3-689

BVG = basic vegetation group; P/ET0 = ratio of annual precipitation (P) to annual reference evapotranspiration (ET0)
Data: Geological and Bioregional Assessment Program 2021m
Element: GBA-COO-3-689

Control and impact monitoring is needed to detect the true impact of resource development. Ideally, control and impact sites are almost identical in nature and differ only with respect to the level of concern assessed for multiple stressors.

When assessing the potential effect of environmental impacts, it is often necessary to measure one or more indicators about the environmental condition at the potentially impacted site and compare the measurements against those collected at control sites (absence of impact or disturbance). In the absence of specific development proposals, it is not possible to provide local advice on which areas would be suitable for impact monitoring and which would be suitable as control sites. At a regional scale, locations where no or few processes lead to pathways of 'potential concern' are prime locations to establish regional control sites. Locations potentially affected by multiple processes of 'potential concern' (Figure 10) are preferred locations to establish regional impact sites. The final location of control and impact sites for any local monitoring design will depend on the location and footprint of existing and proposed resource developments. For example:

- **Control sites** are where no pathways of 'potential concern' are identified by the assessment. This includes large areas overlying relatively low prospectivity areas, such as areas outside of the Cooper Creek floodplain and on the floodplain downstream of Windorah in Queensland (Figure 10).
- **Impact sites** are where multiple pathways of 'potential concern' are identified. An example is a 'hotspot' on the Cooper Creek floodplain south of Windorah in Queensland, where up to 12 processes are of 'potential concern'. There are also smaller hotspots in the west of the Cooper GBA region, where the mapped watertable is shallow and in South Australia where surface water is mapped (Figure 10).

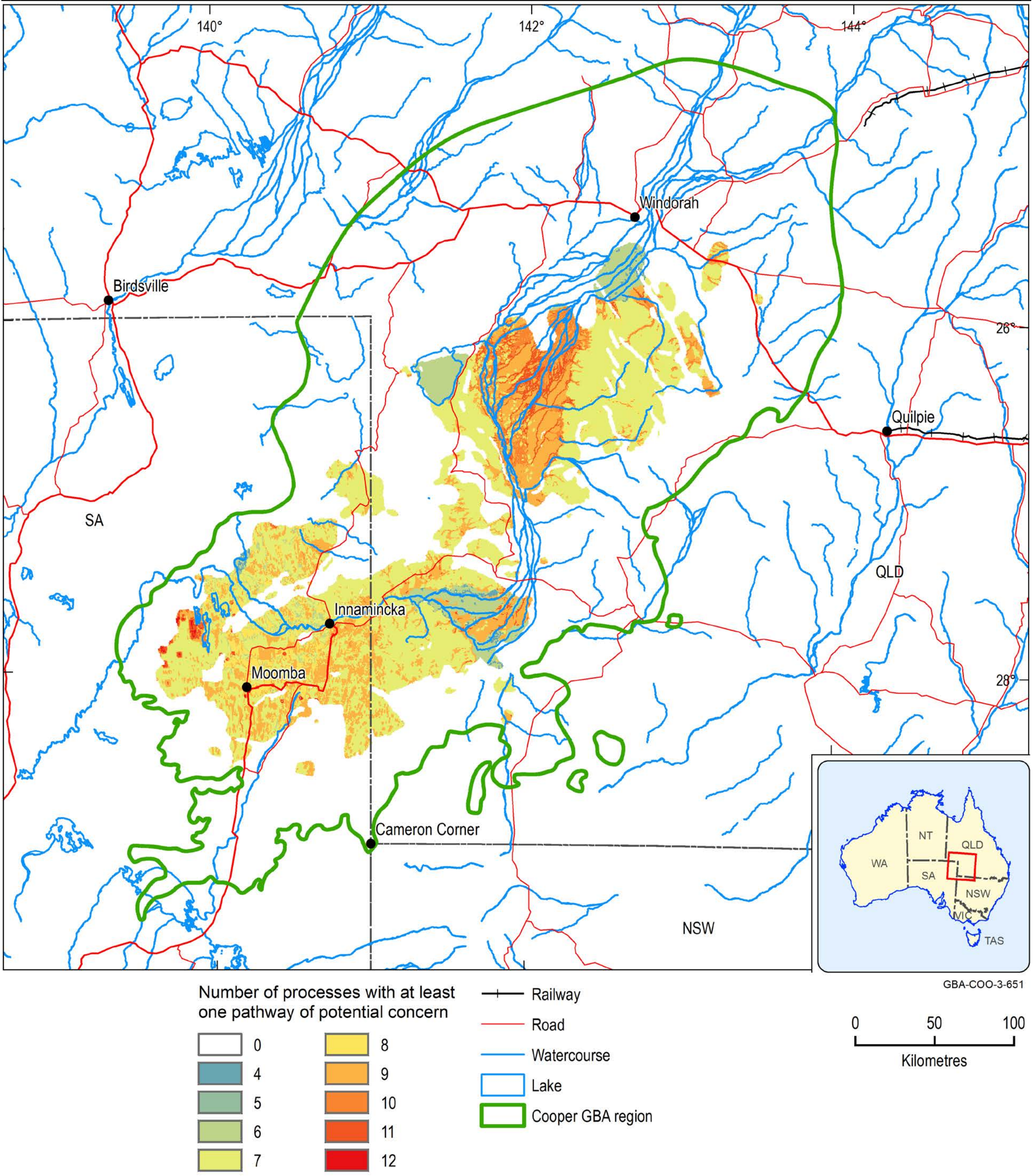
Monitoring for compliance evaluates operator adherence to legal requirements. **Monitoring effectiveness of mitigation strategies** checks if mitigation strategies required under regulations are meeting their objectives.

Regulation at both state and Australian Government levels monitors compliance with legal requirements. For example, the *Code of Practice for the construction and abandonment of petroleum wells and associated bores in Queensland* (Department of Natural Resources, Mines and Energy (Qld), 2018) requires reporting on requirements for the construction and maintenance of wells, the *Petroleum and Geothermal Energy Act 2000 (SA)* produces an annual compliance report of the regulatory performance of the petroleum and geothermal industries, and the *Industrial Chemicals (Notification and Assessment) Act 1989* notifies and assesses the use of industrial chemicals.

Monitoring for effectiveness of mitigation strategies can focus on pathways of 'potential concern'. Mitigation strategies are based on existing gas industry controls and regulatory approval conditions, effective planning and design, and adherence to best practice international standards and procedures. Site management protocols aim to avoid or mitigate potential impacts on natural habitat and species distributions. However, wherever resource development occurs – particularly in the vicinity of protected species – monitoring of compliance with, and effectiveness of, mitigation strategies associated with activities and stressors is needed. Here, rather than focusing on extrapolating inference to the broader region, the intention is to closely monitor targeted sites at a local level where an impact or change is most likely to occur.

Compliance monitoring is related to mitigation strategies associated with links between activities and stressor, while the environmental condition indicators are associated with links from stressors to processes and are good candidates for monitoring the effectiveness of mitigation strategies associated with a stressor.

FIGURE 10 Number of processes with pathways of 'potential concern' in each grid cell of the Cooper GBA region



Data: Geological and Bioregional Assessment Program (2021c)
Element: GBA-COO-3-651

Monitoring to validate and refine the causal network can increase confidence in cause-and-effect relationships and material change thresholds. However, monitoring to evaluate causation requires careful design.

Monitoring of environmental condition indicators related to links between stressors and processes along pathways of concern in the causal network can improve understanding and confidence of the assessment and individual links. Future monitoring could reduce uncertainty in critical links along pathways by increasing confidence in the cause-and-effect relationship or providing more information on material thresholds. Monitoring designs to evaluate causation are challenging. Even when data from monitoring reveals strong associations, correlations do not always indicate causation, unless the monitoring program has been designed to allow this to be estimated. Hayes et al. (2019) provide guidance on monitoring designs to establish causation.

FIND MORE INFORMATION

The causal network for the Cooper GBA region has been delivered as an interactive online tool, GBA Explorer. This allows users to explore the full detail of the causal network.

- Impact assessment methodology (Peeters et al., 2021b)
- Impact assessment summary for the Cooper GBA region
- Introduction to causal networks (Peeters et al., 2021a)
- Causal network dataset (Geological and Bioregional Assessment Program, 2021c)

Fact sheets are available on the Geological and Bioregional Assessment website.

- *Fact sheet 22:* Seismic surveys (Geological and Bioregional Assessment Program, 2021o)
- *Fact sheet 26:* Using natural capital accounting to track changes to ecosystem extent and condition (Geological and Bioregional Assessment Program, 2021p)
- *Fact sheet 28:* Development scenarios for unconventional gas resource development (Geological and Bioregional Assessment Program, 2021q)

4 Potential impacts on water

The causal network is used to identify potential impacts on surface waters, groundwaters and subsurface flow paths in the Cooper GBA region. The assessment results can be used to identify existing avoidance and mitigation strategies and to prioritise where local-scale assessment is needed. Pathways of 'potential concern' identified by the assessment include contamination or obstruction of surface waters, and contamination or drawdown of aquifers. The assessment is supported by findings from the Program's LiDAR data collection (Box 2) and hydrological modelling investigations (Box 3, Box 4, Box 5).

4.1 Surface water

Activities that block or obstruct small flood runners are of 'potential concern' in about 6% (1,613 km^2) of the Cooper Creek floodplain, excluding the riparian and wetland areas. Ongoing site-based assessment and investigation of changes to agricultural productivity, protected wetlands, and protected fauna and flora on the floodplain is warranted to protect these sensitive ecosystems. Water-affecting activities are regulated under state legislation to mitigate potential impacts on sensitive areas.

Changes in runoff and annual flows are often difficult to detect given the large variability in runoff response and inaccuracy of stream gauge data, especially for low flows (Tomkins, 2014; Zhang et al., 2018). Overland flow obstruction decreases the extent and duration of floodplain inundation (Figure 59, Butcher and Hale, 2011). Tall embankments and soil removal to form the embankments, which are no longer standard practice, have altered inundation patterns at Embarka Swamp (Reid, 1988). Embarka Swamp is located on the Main Branch of Cooper Creek in the Coongie Lakes Ramsar wetland site. These and other impacts can be avoided by careful design to minimise flow obstructions and impoundments (refer to the **civil construction node** description). Estimates of water impounded under a maximum likely future resource development scenario are unlikely to be greater than a conservative estimate of the minimum detectable change in annual flows at a stream gauge (refer to the **overland flow obstruction** node description).

Activities that impact on water are regulated to limit the extent of an affected watercourse or volume of water that is impounded (Department of Environment and Science (Qld), 2016; South Australian Arid Lands Natural Resources Management Board, 2017a). Proponents have strategies to avoid or mitigate overland flow obstruction during civil construction (for example, Santos (2015); Senex Energy (2016); Beach Energy (2019)). There is high confidence that state and regional regulations, as well as industry mitigation strategies, can mitigate potential impacts in sensitive areas.

Flooding can be catastrophic for agricultural production in terms of loss of stock, fodder, topsoil and crops, as well as damage to surface infrastructure. However, flooding is also essential for riparian and wetland ecosystems, with flood pulses replenishing instream waterholes, and connecting wetlands with main river channels. Detailed flood modelling enables careful design of roads and other infrastructure on the floodplain to minimise flow obstructions, impoundments and damage to infrastructure. The user panel for the Cooper GBA region identified a need for detailed flood modelling to better understand how resource development could impact the floodplain and landscape of the Cooper GBA region (Box 2).

Box 2 Collecting data to build a hydrodynamic flood inundation model of Cooper Creek floodplain

The Cooper Creek floodplain spans across Queensland and South Australia, is large (about 32,000 km^2) and floods frequently. It has extremely complex terrain, very low gradients and sparse observed data. It is among one of the most complex floodplains in the world and is by far the most complex floodplain in Australia. Until now, detailed floodplain inundation modelling has never been attempted in the region due to the size and complexity of the Cooper Creek floodplain.

In 2019, the Program conducted light detection and ranging (LiDAR) aerial surveys covering an area of 31,780 km^2 across the Cooper Creek floodplain, and the Thompson and Barcoo river systems. The digital elevation model developed from the LiDAR dataset has been used to build a hydrodynamic flood inundation model to better understand how and where to manage potential impacts on the floodplains of the Cooper GBA region.

The LiDAR data are available for download in 1 km^2 tiles through the national Elevation Information System (ELVIS) data portal or from data.gov.au. The digital elevation model can be used by regulators, proponents and the public to inform decisions and improve future management and protection of Cooper Creek floodplain.

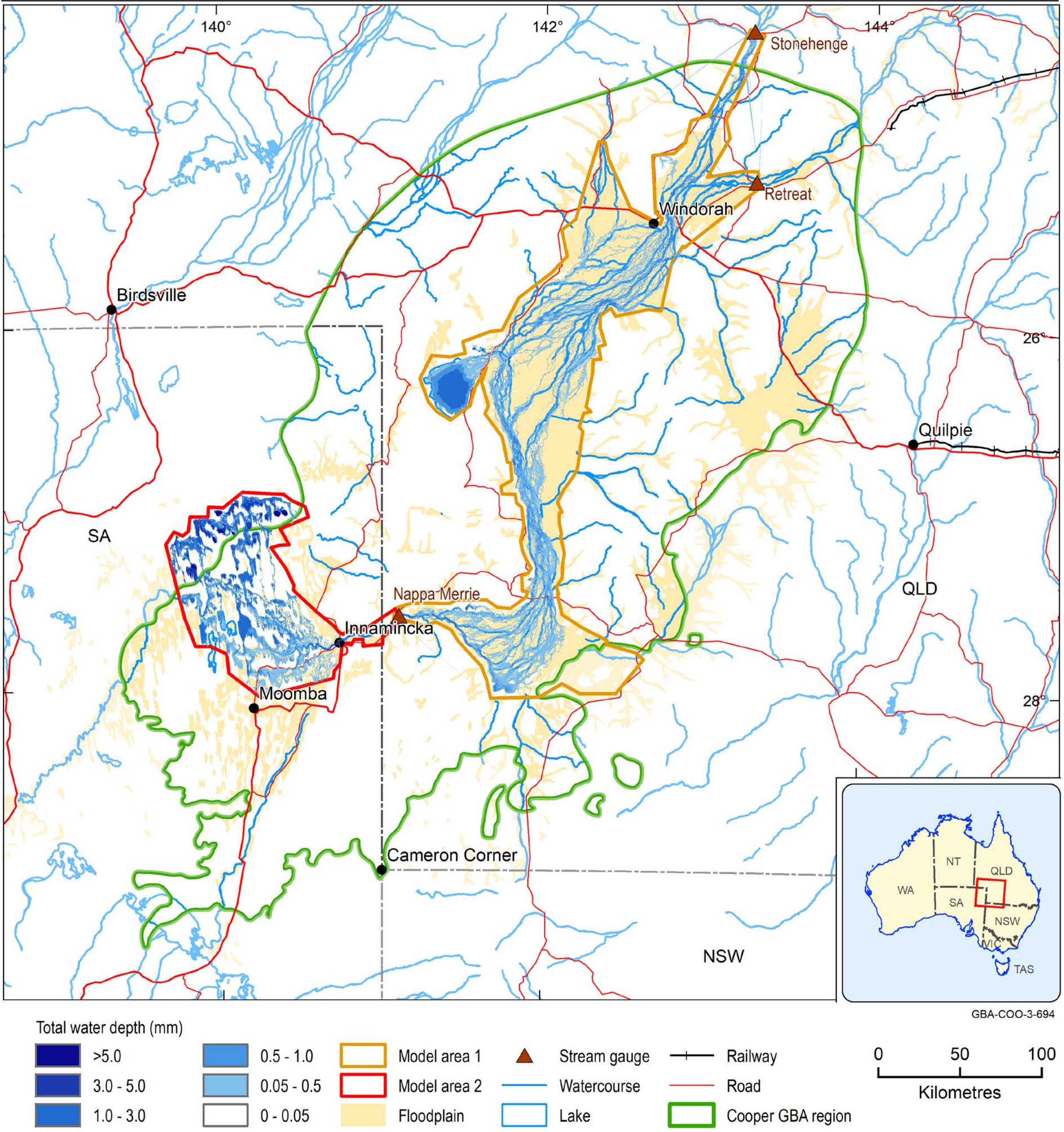
The calibrated hydrodynamic flood inundation models developed for the Cooper GBA region can evaluate how flood characteristics may change under future development and climate change scenarios in the complex Cooper Creek floodplain (Box 3). The size and complexity of Cooper Creek floodplain meant the flood model was divided into the Queensland (23,000 km^2 with 7,420,953 mesh elements) and South Australia (9,000 km^2 with 4,754,440 mesh elements) models.

Box 3 State-of-the-art 2D hydrodynamic flood inundation models

For the first time, a state-of-the-art 2D hydrodynamic flood inundation model (MIKE21FM) has been developed for all 32,000 km^2 of the Cooper Creek floodplain. The flood inundation model was calibrated using stream gauge and satellite monitoring data for historical floods. There is good agreement between the calibrated model and Landsat and MODIS satellite data for historical floods in an area characterised by extremely complex terrain, very low gradients and sparse water level observations. Figure 11 shows the modelled extent of 1-in-10-year floods for the Queensland and South Australia flood models. Different dates are shown for each model as the spatial extent of data meant that satellite data to calibrate the model was not available for both areas at the same time.

Box 3 State-of-the-art 2D hydrodynamic flood inundation models *continued*

FIGURE 11 Modelled extent of a 1-in-10-year flood showing modelled flood depth on 31/01/2004 for the Queensland flood model (model area 1) and on 03/04/2010 for the South Australian flood model (model area 2)



The Queensland flood model extends from the Stonehenge and Retreat stream gauges in Queensland to the Nappa Merrie stream gauge in South Australia. The South Australian flood model extends downstream from the Nappa Merrie stream gauge into Coongie Lakes wetland area.

Data: Geological and Bioregional Assessment Program (2021e)

Element: GBA-COO-3-694

Any **accidental release** of contaminants into surface waters could spread rapidly and accumulate in sediments and so is of 'potential concern' in 12% of the Cooper GBA region. Compliance reporting in Queensland and South Australia demonstrates that existing state-based regulations, approval conditions and industry practices designed to avoid spills and leaks, and in the event of a spill to ensure remediation occurs quickly, are effective.

Chemicals or compounds used or produced in unconventional gas resource development can be unintentionally released to the environment beyond any engineered bunding or control, including spills and leaks of liquid or solid contaminants. Surface water contamination leading to pollution due to accidental release, or from accidental release via soil contamination, occurs when the concentration of a biological, chemical or physical property is sufficient to cause an adverse effect (refer to the **soil contamination** and **surface water contamination** node descriptions).

Potential impacts due to accidental release are primarily managed through existing avoidance and mitigation strategies prescribed in state-based regulations (Government of South Australia, 2015; Department of Environment and Science (Qld), 2016) (refer to the **accidental release** node description). The assessment assumes that if an accidental spill occurs there are limited options to avoid or remediate surface water contamination due to more rapid spreading of chemicals through surface water and partitioning to and accumulation in sediments (National Research Council, 2000; Eggleton and Thomas, 2004; Jaffé, 1991). This highlights the importance of compliance with existing state-based regulations and approval conditions to avoid spills and leaks. Confidence in existing avoidance and mitigation strategies is high. However, there is insufficient species-specific information to establish robust thresholds to evaluate material thresholds for the toxicity of potential pollutants for protected fauna.

Controlled release of wastewater to the environment is of 'low concern' as it is strongly regulated by both the Australian Government and state governments. Stringent approval conditions, monitoring, treatment and compliance requirements ensure that the treated wastewater is consistent with the sensitivity of the receiving environment.

Controlled release of wastewater is the intentional and approved release of treated water into the environment, including evaporation from storage ponds, reuse for operations water, dust suppression, irrigation or stock drinking water, and disposal of treated wastewater into existing drainage features in the landscape or by reinjection into deep underground formations such as depleted oil and gas reservoirs or deep unused aquifers (Holland et al., 2020).

Quality of treated wastewater released to surface waters is closely monitored and strongly regulated by both the Australian Government and state governments (Commonwealth of Australia, 2014). While there is very little baseline water quality information available for the Lake Eyre Basin, the water quality requirements stipulated in approval conditions are informed by the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* (ANZG, 2018) and are designed to prevent adverse effects of contamination of soils, surface waters, aquifers and riparian or floodplain environments. There is high confidence in the cause-and-effect relationships and existing mitigation strategies, and low confidence in the material change thresholds for protected fauna, flora, wetlands and areas.

Water-affecting activities are regulated under state legislation to mitigate potential impacts on sensitive areas. There is high confidence that licensed **surface water extraction** – currently approximately 2% of annual flows – is of 'low concern' as it will not materially alter channel flows, scouring or flooding in Cooper Creek.

Surface water can be extracted from water flowing in channels and the water stored in waterholes. **Surface water extraction** could reduce channel flows downstream of the extraction point. A licence is required in both Queensland and South Australia (refer to the **civil construction, drilling** and **hydraulic fracturing** node descriptions) under the relevant water sharing plans.

Total licensed surface water extraction for all water users is approximately 30 gigalitres per year, or about 2% of annual surface water flows in Cooper Creek at Nappa Merrie (gauge 003103A) (Santos, 2017; Geological and Bioregional Assessment Program, 2018a). Total estimated water volumes (surface water, groundwater and reuse of co-produced water) needed over 50 years for the maximum resource development scenario is approximately 400 megalitres per year. This contrasts with extraction of 40,000 megalitres per year from Cooper Creek as part of unsuccessful irrigation proposals in the 1990s and 2000s (for example, Walker et al. (1997); Carini et al. (2006); Sheldon et al. (2010)) (refer to the **channel flow** node description).

There is high confidence that surface water extraction for future development will not materially alter channel flows, scouring or flooding in Cooper Creek. This is supported by state and regional water allocation regulations, total extraction volumes and mean annual flows in Cooper Creek. However, less is known about how material changes to floodplain inundation and scouring will affect environmental values.

4.2 Groundwater

Groundwater drawdown due to **groundwater extraction** is estimated using conservative numerical modelling. Potential impacts are of 'low concern' except where groundwater-dependent ecosystems that may access the Cenozoic aquifer are mapped in the west of the Cooper GBA region, or near existing bores where the saturated thickness of the Cadna-owie – Hooray aquifer is less than 150 m in the south-west of the Cooper GBA region. Alternative water sources, such as groundwater from other aquifers, or reuse of co-produced water, could avoid potential impacts on groundwater-dependent ecosystems or water bores in these areas.

Groundwater extraction causes a decrease in pressure and groundwater levels in the pumped aquifer in the vicinity of production bores that may propagate to over- or under-lying aquifers. To protect sensitive ecosystems, such as groundwater-dependent ecosystems (GDEs), prevention or mitigation options are required where predicted drawdown is greater than 0.2 m under established legal frameworks (NSW DPI, 2012; Queensland Government, 2000; South Australian Arid Lands Natural Resources Management Board, 2009). A 2-m aquifer drawdown threshold is used to assess interference with existing water users.

Any new groundwater extraction to support unconventional gas operations in the Cooper GBA region (refer to the **civil construction**, **drilling**, **hydraulic fracturing**, **decommissioning and rehabilitation** node descriptions) must adhere to relevant Queensland and South Australia regulations and water-sharing objectives without affecting other water users (including groundwater-dependent ecosystems). As the cost of drilling bores is proportional to the depth, the Cenozoic and Winton-Mackunda aquifers are the primary targets for groundwater because they are relatively shallow and salinity is not a major constraint (Holland et al., 2020). Water from Cadna-owie – Hooray system system bores is not preferred due to drilling depths greater than 1,000 m; however, petroleum exploration bores that intersect sections of the Cadna-owie – Hooray system may be repurposed into groundwater bores for production.

Conservative numerical modelling estimates of groundwater drawdown (Box 4) in excess of 0.2 m are only of 'potential concern' across 0.9% of the Cenozoic aquifer's distribution, where GDEs are mapped in the west of the Cooper GBA region. In these areas, potential impacts can be mitigated by extracting groundwater from deeper aquifers (such as Winton-Mackunda or Cadna-owie – Hooray). Groundwater drawdown is of 'low concern' in the Cenozoic and Winton-Mackunda aquifers where the saturated aquifer thickness is greater than 20 m, except within 1 km of existing bores where drawdown more than 2 m cannot be ruled out.

Groundwater drawdown in excess of 2 m cannot be ruled out within 1 km of existing bores that access the Cadna-owie – Hooray aquifer and where the saturated aquifer thickness is less than 150 m in the south-west of the Cooper GBA region (Geological and Bioregional Assessment Program, 2020b; Geological and Bioregional Assessment Program, 2021v). This occurs in less than 0.1% of the aquifer. There is high confidence in existing mitigation strategies, materiality thresholds and cause-and-effect relationships associated with drawdown due to groundwater extraction.

Box 4 Groundwater modelling without a development footprint

As detailed scenarios of groundwater extraction locations and volumes are not available, numerical models simulate groundwater extraction everywhere in the Cooper GBA region (refer to the **groundwater extraction** and the **Cenozoic aquifer drawdown**, **Cadna-owie – Hooray aquifer drawdown** and **Winton-Mackunda aquifer drawdown** node descriptions). Conservatively, it is assumed that 200 megalitres is extracted in one year for a single groundwater extraction bore in each grid cell. This is half of the average annual volume of water needed for the maximum resource development scenario (400 megalitres per year over 50 years).

Groundwater drawdown is estimated by considering three mechanisms: (i) drawdown from groundwater extraction in the same aquifer, (ii) drawdown from groundwater extraction in an over- or under-lying aquifer, and (iii) drawdown from depressurisation of an underlying gas reservoir. The model uses local information on layer thicknesses and the presence of faults, and conservative estimates of hydraulic properties based on regional measurements because local information is not available at the scale required (Geological and Bioregional Assessment Program, 2020b; Geological and Bioregional Assessment Program, 2021v).

Spills and leaks of liquid or solid contaminants can be unintentionally released to the environment beyond any engineered bunding or control, leading to aquifer contamination. **Accidental release** is of 'potential concern' when the concentration of a biological, chemical or physical property is sufficient to cause an adverse effect (refer to the **soil contamination** and **surface water contamination** node descriptions).

Conservative chemical transport modelling shows that contamination in the Cenozoic and Winton-Mackunda aquifers due to spills and leaks is of 'potential concern' where depth to groundwater is less than 9 m, and of low concern when groundwater is less than 14 m from the surface (Geological and Bioregional Assessment Program, 2021l, 2021t) (Box 5). The chemical transport modelling also estimated dilution rates when contaminants travel through the aquifer. However, due to modelling constraints, aquifer contamination cannot be ruled out within 500 m of an existing water bore or GDE.

Potentially affected areas are predominantly along waterways in the central and western parts of the region and are of 'potential concern' in 0.2% of the Cenozoic aquifer, and in less than 0.01% of the Winton-Mackunda and Cadna-owie – Hooray aquifers. There is high confidence in existing mitigation strategies, materiality thresholds and cause-and-effect relationships associated with groundwater contamination due to accidental release.

Box 5 Natural attenuation and environmental fate of hydraulic fracturing chemicals

The quantitative assessment accounts for key landscape parameters that determine natural attenuation, such as soil type, depth to groundwater and groundwater velocity. Migration of chemicals through deep unsaturated zones is calculated with the HYDRUS-1D simulator, taking account of best-available hydraulic properties from a digital soil database. A 3-dimensional analytical solution of the advection–dispersion equation provides estimates of groundwater dilution. The modelling estimates when concentrations of chemicals in hydraulic fracturing fluids or flowback water accidentally released into the environment decrease to levels that are no longer considered harmful to the environment.

Waste disposal is of 'low concern' as it is unlikely to materially increase soil or aquifer contamination outside of licensed waste disposal sites. Stringent approval and management requirements ensure that contamination is effectively managed and/or mitigated.

Waste disposal is the handling, storage, transport and disposal of waste materials, excluding wastewater (refer to the **controlled release of wastewater** node description) and gases (refer to the **atmospheric emissions** node description), resulting from the construction, operation and decommissioning phases of production and processing activities needed for unconventional gas resource development. This includes disposal of brines and synthetic pond liners as regulated waste at a licensed waste facility (Department of Environment and Science (Qld), 2016). **Waste disposal** is unlikely to materially increase soil or aquifer contamination.

Reinjection of wastewater is managed by regulations and site-specific investigations to determine a suitable water quality similar to the receiving groundwater. Treatment of water to be reinjected is not required where investigations determine the water quality is suitable for the receiving environment (Santos, 2017; Commonwealth of Australia, 2014) (refer to the **controlled release of wastewater** node description).

Stringent approval and management requirements (refer to the **controlled release of wastewater** and **waste disposal** node descriptions) ensure that contamination is effectively managed and/or mitigated on site or at a licensed waste facility. Loss of containment during waste processing and disposal is described in the **accidental release** node description.

4.3 Subsurface flow paths

Hydraulic fracture growth into an aquifer, well or fault has a low likelihood but warranted further investigation to address community concerns. Hydraulic fracture modelling shows that natural barriers, such as the Nappamerri aquitard, protect overlying aquifers from contamination caused by hydraulic fracturing and gas production in the Cooper Basin. **Compromised aquitard integrity** is of 'potential concern' in less than 0.01% of the Cadna-owie – Hooray aquifer. This is where the Nappamerri aquitard is less than 155 m thick, the estimated distance a contaminant can travel along an open fracture in 250 years.

Compromised aquitard integrity describes changes in the integrity of low permeability rock layers (called strata) between gas reservoirs and aquifers. Low permeability rock layers have very slow groundwater flows. There are 2 main regional aquitards in the Cooper GBA region: the Nappamerri Group, which separates the Gidgealpa Group (the host for tight, shale and deep coal gas plays) from confined aquifers in the Eromanga Basin, and the Rolling Downs Group aquitard, which separates the Cadna-owie – Hooray aquifer from aquifers at the surface in the Winton-Mackunda and Cenozoic sediments (Evans et al., 2020).

Compromised aquitard integrity is of 'potential concern' in less than 0.01% of the Cadna-owie – Hooray aquifer. This is where the Nappamerri aquitard is less than 155 m thick, the estimated distance a contaminant can travel along an open fracture in 250 years. Aquifer contamination leading to pollution cannot be ruled out within 500 m of existing water bores due to modelling constraints, as dilution of contaminants may be insufficient over this distance (refer to the **Cenozoic aquifer drawdown**, **Cadna-owie – Hooray aquifer drawdown** and **Winton-Mackunda aquifer drawdown** node descriptions). The overlying Winton-Mackunda and Cenozoic aquifers are protected by the more than 550 m thick Rolling Downs Group and Nappamerri Group aquitards that form natural barriers.

Conservative modelling of vertical hydraulic fracture growth (Geological and Bioregional Assessment Program (2021i)) supports a high level of confidence in the cause-and-effect relationship and materiality threshold for any new fluid pathway created through the Nappamerri or Rolling Downs Group aquitards due to hydraulic fracturing activities (Box 6). Furthermore, there is high confidence that existing controls outlined in environmental management plans (Santos, 2015; Beach Energy, 2019) can mitigate potential impacts on Cadna-owie – Hooray aquifer condition. This is based on the review of the findings of domestic and international inquiries (Pepper et al., 2018), Cooper GBA region monitoring data and petroleum industry compliance reports (refer to Section 2 of Stage 2 hydraulic fracturing technical appendix; (Kear and Kasperczyk, 2020)).

Box 6 Visualising and assessing risks to aquifers from hydraulic fracturing

To assess and visualise the potential for hydraulic fractures to propagate vertically through an aquitard and thus create a new fluid pathway to an aquifer, the output of a probability bounds analysis of potential hydraulic fracture growth (Pandurangan et al., 2018) was combined with spatial geological data for the Cooper GBA region (Owens et al., 2020).

The probability bounds analysis predicted vertical hydraulic fracture extents of 56 to 389 m, with a mean vertical hydraulic fracture extent of 151 m (Geological and Bioregional Assessment Program (2021i)). In areas where the predicted vertical fracture height exceeds the thickness of the Nappamerri Group aquitard, there is a slightly higher potential likelihood of a hydraulic fracture extending through an aquitard into an aquifer and greater care needs to be taken in the design, injection and monitoring of hydraulic fracturing treatments. The risk of hydraulic fractures intersecting an aquifer is able to be adequately mitigated by controls in existing regulation, sufficient understanding of the baseline geological and environmental systems, and accepted industry practices (Kear and Kasperczyk, 2020).

Aquifer contamination due to **compromised well integrity** is of 'very low concern' in the Cooper GBA region based on findings from domestic and international inquiries, as well as historical compliance reports for Cooper Basin petroleum wells.

Compromised well integrity refers to breaches of a well system that allow the unintended movement of fluids (gas, hydrocarbons and water) into, out of or along the outside of the well. A minimum of 2 independent well barrier elements are required to form a leak-tight seal between the well and the rock (International Organization for Standardization, 2017; Department of Natural Resources, Mines and Energy (Qld), 2019; Northern Territory Government, 2019). This provides redundancy such that a failure in one well barrier does not lead to unintended fluid infiltration into geological layers or to the surface.

There is high confidence in the effectiveness of mitigation strategies, materiality thresholds and cause-and-effect relationships associated with aquifer contamination due to compromised well integrity. This is based on a review of the 2,288 petroleum wells drilled in the Cooper GBA region (noting there were 3,000 bores drilled but only 2,288 were reviewed), which identified 2 reported instances of fluid flow between formations or to the surface that were subsequently detected and remediated (Kear and Kasperczyk, 2020). Findings from domestic and international inquiries (Pepper et al., 2018) (refer to Section 2 of Stage 2 hydraulic fracturing technical appendix; (Kear and Kasperczyk, 2020)) also support this analysis.

Aquifer reinjection of wastewater is subject to detailed technical assessment, which includes modelling and requires regulatory approval prior to commencement (Santos, 2015). This includes comprehensive evaluation against a range of criteria, including understanding of 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). For this reason, fault reactivation and induced seismicity were not prioritised for further assessment in Stage 3 (Section 5.2 in baseline synthesis and gap analysis (Holland et al., 2020)).

FIND MORE INFORMATION

Impact assessment summary for the Cooper GBA region
Causal network dataset (Geological and Bioregional Assessment Program, 2021c)

Fact sheets are available on the Geological and Bioregional Assessment website.

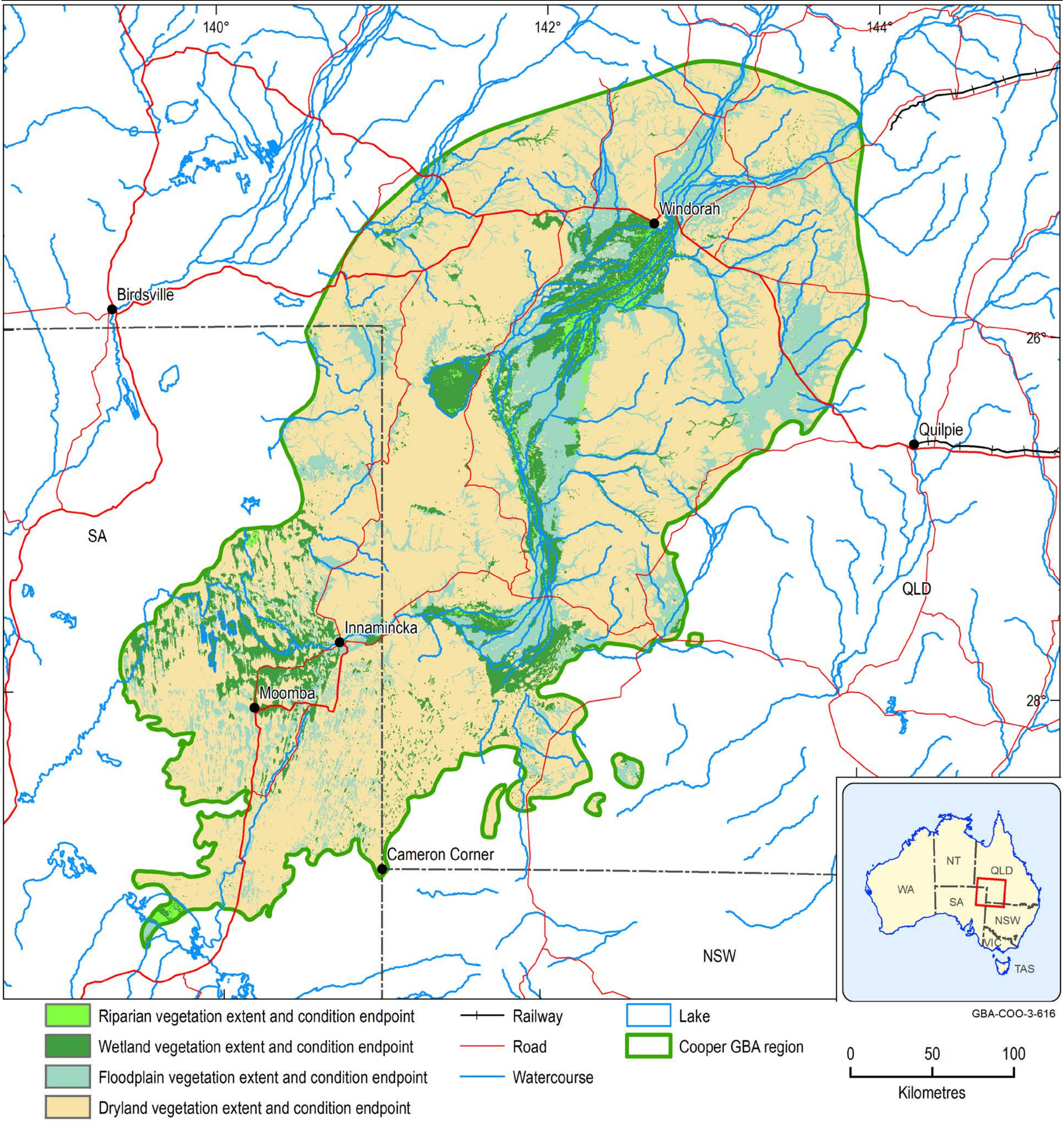
- *Fact sheet 2:* Assessing hydraulic fracture risks to groundwater (Geological and Bioregional Assessment Program, 2021i)
- *Fact sheet 8:* Characterising the connectivity between the Cooper Basin, Great Artesian Basin and shallow aquifers (Geological and Bioregional Assessment Program, 2021j)
- *Fact sheet 9:* Application of the chemical screening framework (Geological and Bioregional Assessment Program, 2021l)
- *Fact sheet 10:* Groundwater sampling in the Cooper, Eromanga and Lake Eyre basins (Geological and Bioregional Assessment Program, 2021s)
- *Fact sheet 11:* Environmental fate of hydraulic fracturing chemicals (Geological and Bioregional Assessment Program, 2021t)
- *Fact sheet 13:* Flood inundation modelling for Cooper Creek floodplain (Geological and Bioregional Assessment Program, 2021a)
- *Fact sheet 16:* Has development impacted flood characteristics? (Geological and Bioregional Assessment Program, 2021f)
- *Fact sheet 21:* Revising the geology of aquifers in the Cenozoic Lake Eyre Basin in the Cooper GBA region (Geological and Bioregional Assessment Program, 2021u)

5 Potential impacts on the environment

The causal network is used to identify potential impacts on protected environmental assets and values – represented by 13 environment-related endpoints in the causal network. Assessment results can be used to identify existing avoidance and mitigation strategies and to prioritise local-scale assessment, mitigation and monitoring. Environment-related endpoints include agricultural productivity, 4 key vegetation communities (dryland, floodplain, riparian and wetland; Figure 12), and 9 protected areas. Pathways of 'potential concern' between unconventional gas resource development activities and environment-related endpoints are primarily related to activities that create a disturbance at the surface (transport of materials and equipment, civil construction, decommissioning and rehabilitation, and seismic acquisition). Potential impacts at the surface include contamination; reduced flooding; habitat degradation, fragmentation and loss; increased competition and predation; and mortality of native species. The assessment is supported by findings from field data collection and analysis of remote sensing data (Box 7, Box 8, Box 9).

Riparian vegetation in the Cooper GBA region © Russell Crosbie, CSIRO

FIGURE 12 Key vegetation communities in the Cooper GBA region



Data: Geological and Bioregional Assessment Program (2021c)
Element: GBA-COO-3-616

5.1 Riparian ecosystems

Riparian ecosystems provide important connections between terrestrial and aquatic habitats and include parts of key ecological assets such as the Ramsar-listed Coongie Lakes, wetlands listed in the *Directory of important wetlands in Australia* (DIWA) and the Channel Country Strategic Environmental Area, as well as plants and animals of cultural significance for Indigenous peoples. Riparian vegetation is relatively undisturbed by existing development.

Riparian ecosystems include plants and animals whose composition can be directly or indirectly attributed to the presence of rivers and streams (Kauffman and Krueger, 1984). They are important connections between terrestrial and aquatic habitats and are an important component and driver of aquatic ecosystems, controlling and regulating a range of biological and physical processes within the riparian environment (Capon et al., 2016). Riparian communities provide a range of ecosystem services including the inputs of organic materials into the riparian system, regulation of the riverine microclimate and provision of habitat to a range of species (Sheldon et al., 2010).

The spatial extent of the **riparian vegetation extent and condition** endpoint in the Cooper GBA region is 5,626 km^2 (about 4%), of which about one-third overlies areas that are prospective for the development of unconventional gas resources (Figure 12). Riparian vegetation in the Cooper GBA region is relatively undisturbed (1.3%) , with seismic surveys (24 km^2) accounting for 32% of total disturbance (75 km^2) (Geological and Bioregional Assessment Program, 2021m).

The capacity to provide a range of cultural (Constable et al., 2015) and economic services (Hawden et al., 2006) is tightly coupled to the extent and condition of the riparian vegetation along Cooper Creek. For Indigenous peoples, riparian ecosystems are culturally significant, containing a range of spiritual, economic and ecological values (Constable et al., 2015). Important ecological assets include DIWA-listed wetlands (for example, Cooper Creek – Wilson River junction) and the Ramsar-listed Coongie Lakes, which is also protected under the EPBC Act. There are also significant cultural assets associated with this endpoint, including the Burke, Wills, King and Yandruwandha National Heritage Place and a range of Indigenous values that include important species (for example, Eucalyptus coolabah) and places (for example, Strzelecki Creek) (refer to the **DIWA wetland condition** and **riparian vegetation extent and condition** endpoints).

In Queensland, the Channel Country Strategic Environmental Area (SEA) protects floodplains, wetlands and riparian areas. Designation as a strategic environmental area under the *Regional Planning Interest Act 2014* seeks to protect environmental attributes important for the maintenance of ecological function. In the Channel Country SEA these are:

- natural hydrological processes of the area (unrestricted flows in and along stream channels, overflow from stream channels, natural flow paths across floodplains and groundwater sources important for maintaining the persistence of waterholes and ecosystems in the area)
- natural water quality
- beneficial flooding that supports floodplain grazing and ecological processes in the area.

Riparian vegetation in the Cooper GBA region is relatively undisturbed. There is high confidence that compliance with existing protections, including legislated, 'no-go', areas, and industry controls can minimise future direct impacts on riparian vegetation. However, indirect impacts from unconventional gas resource development are of 'potential concern' in over 30% of riparian areas. Stressors such as accidental release of chemicals, invasive plants and predators could spread beyond directly affected areas and exacerbate existing environmental drivers, such as invasive herbivores and altered fire regimes.

Pathways of 'potential concern' at the surface for riparian vegetation includes stressors associated with site disturbance, which is of 'potential concern' in 20% of riparian areas (refer to the **soil compaction**, **vegetation removal** and **vehicle movement** node descriptions).

Development of linear infrastructure, such as roads and pipelines, has direct impacts on habitat, but can also facilitate the spread of invasive species that, once established, are difficult to control. Riparian vegetation is also sensitive to fire (Queensland Herbarium, 2018b), and requires long periods without burning to provide the necessary structural complexity (for example, hollow formation). Potential impacts that could spread outside of the development area include increased competition and predation, altered fire regimes, or habitat degradation, fragmentation and loss. These impacts are of 'potential concern' in 33% of riparian areas (refer to the **dust generation**, **invasive plants** and **invasive predators** node descriptions).

Bank instability and erosion can impact on water quality, as well as channel form and geometry, which influence flow and sediment transport dynamics (Castro-Bolinaga and Fox, 2018). Bank instability and erosion is mainly associated with vegetation removal for civil construction activities and is of 'potential concern' in up to 13% of the riparian vegetation extent and condition, Channel Country SEA condition and DIWA wetland condition endpoint areas. Potential impacts could be exacerbated by invasive herbivores such as goats, rabbits, horses and pigs, which also contribute to bank instability via removal of vegetation and digging or pulverising soils (Marshall et al., 2013; Desert Channels Queensland, 2013; Schmarr et al., 2013; Department of Environment and Science (Qld), 2013). Impacts are likely to be concentrated around permanent water sources, including river channels and waterholes (McBurnie et al., 2015; Box et al., 2016; Box et al., 2019).

There is high confidence in available mitigation strategies as infrastructure development is not permitted under state regulations and legislation in many sensitive riparian areas in Queensland (Department of Environment and Science (Qld), 2016; Department of Environment, Water and Natural Resources (SA), 2014) and South Australia (South Australian Government Gazette, 2003; South Australian Arid Lands Natural Resources Management Board, 2017b). Integration and coordination of industry management plans and mitigation strategies with regional planning is critical for effective management of indirect impacts on riparian areas associated with invasive plants, predators and fire.

Key threats to waterholes along Cooper Creek are related to indirect impacts, such as soil and surface water contamination, habitat degradation, fragmentation and loss by invasive herbivores and livestock grazing, invasive plants and altered fire regimes. These indirect impacts could degrade up to 36% of waterhole habitats. Confidence in existing avoidance and mitigation strategies prescribed in state-based regulations, and relevant environmental management plans is high.

Waterholes are defined as enlarged segments of the river channel that hold water after flow has ceased. They typically form in channels where flow is concentrated and constricted and are maintained by river flows that scour the riverbed of sediments (Silcock, 2009). Waterholes include permanent and semi-permanent waterholes (those that contain water more than 70% of the time) (Butcher and Hale, 2011; Silcock, 2009) identified using Water Observations from Space (WOfS) images over a 20-year time-series (Geoscience Australia, 2018) at the resolution of the 500 m grid. This includes 334 waterholes that are inundated more than 70% of the time in the Cooper GBA region.

In the arid environment of the Cooper GBA region, permanent waterholes are important habitats and form refuge for fauna and flora during dry times (Hamilton et al., 2005; Carini et al., 2006; Silcock, 2009). Many waterholes have customary, spiritual and economic values to Traditional Owners and have been part of traditional trade routes for tens of thousands of years (Constable et al., 2015). The importance of permanent waterholes means that understanding the source of the water that sustains them is central to understanding any potential impacts from changes due to unconventional gas resource development (Box 7).

Box 7 Are permanent waterholes along Cooper Creek connected with regional aquifers?

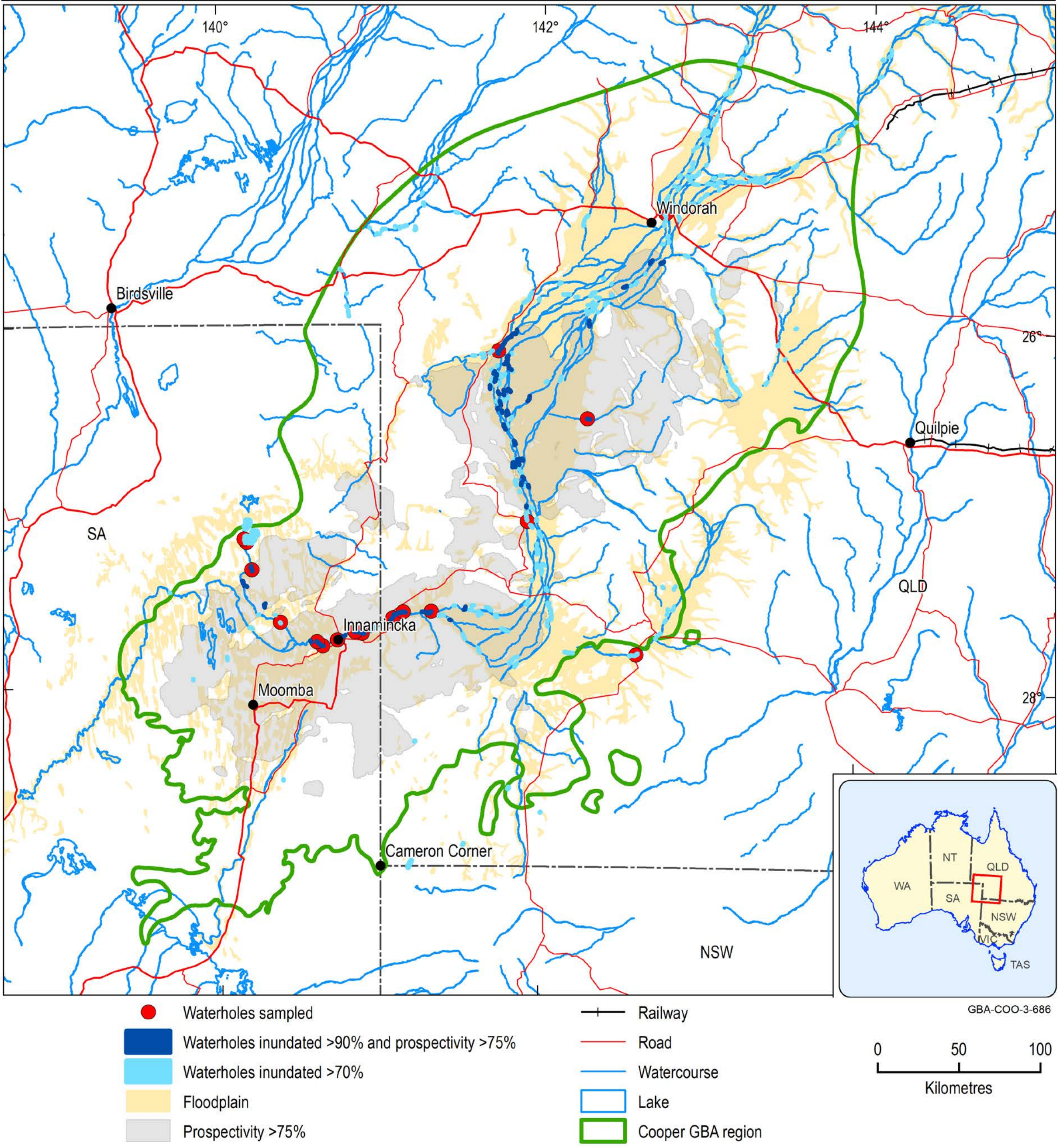
The Cooper GBA region contains over 3,000 waterholes. Water level observations and satellite image analysis identified 48 waterholes that are inundated 90% of the time and overlie areas that are prospective for the development of unconventional gas resources (Figure 13). Of these 48 wetlands, 17 were sampled for depth to groundwater, water chemistry and environmental tracers. Water level data indicate the 17 waterholes are perched above the regional watertable. The chemistry and tracer data show they are surface water fed and provide conduits for ephemeral groundwater recharge. Similarly, water balance estimates at Cullyamurra and Nappa Merrie waterholes, showed no detectable groundwater inputs.

The investigations found that surface water is a source of periodic freshwater recharge that sustains fringing riparian vegetation. In other words, groundwater drawdown in the regional unconfined aquifers hosted by Cenozoic and Winton-Mackunda sediments will not impact on groundwater-dependent vegetation growing on the floodplains of Cooper Creek.

Box 7 Are permanent waterholes along Cooper Creek connected with regional aquifers?

continued

FIGURE 13 Location of permanent and sampled waterholes that overlie areas prospective for unconventional gas resources



Relative prospectivity is the likelihood of discovering a given resource (e.g. oil, gas, groundwater) through analysis of geological properties (e.g. formation depth and extent, rock properties, reservoir characteristics).

Data: Geoscience Australia (2018); Department of Environment and Resource Management (Qld) (2009); Geological and Bioregional Assessment Program (2020c)

Element: GBA-COO-3-686

Key threats to waterholes along Cooper Creek identified by previous studies (Kingsford et al., 1998) include habitat degradation, fragmentation and loss due to invasive herbivores and livestock grazing (for example, increasing waterhole turbidity, Davis et al. (2002)); invasive plants (for example, Noogoora burr and Mexican poppy, Capon et al. (2016)); and altered fire regimes (for example, climate change, Capon et al. (2016)). Environmental drivers of fish losses in isolated waterholes in the Cooper Creek system include wetted perimeter and depth, habitat structure and waterhole quality (for example, eroded banks, gross primary production; Arthington et al. (2010); Schmarr et al. (2013)).

These key threats are represented in the causal network by over 100 pathways from development activities to the waterhole condition endpoint (refer to the **bank instability and erosion**, **channel flow**, **competition and predation**, **freshwater lens recharge**, **scouring**, **sedimentation**, **soil contamination** and **surface water contamination** node descriptions). Indirect impacts are of 'potential concern' in 36% of waterhole habitats (refer to the **accidental release**, **invasive plants** and **invasive predators** node descriptions). Confidence in existing avoidance and mitigation strategies prescribed in state-based regulations (Government of South Australia, 2015; Department of Environment and Science (Qld), 2016) and under Queensland's *Biosecurity Act 2014* and the *Landscape South Australia Act 2019*, and relevant environmental management plans (Santos, 2015) is high.

5.2 Wetland ecosystems

Wetland ecosystems are extensive in the Cooper GBA region and include key ecological assets such as the Ramsar-listed Coongie Lakes, DIWA-listed lakes and wetlands, as well as habitat for the grey grasswren (*Amytornis barbatus barbatus)* and the Australian painted snipe *(Rostratula australis)*, and plants and animals with significant cultural and economic values for Indigenous peoples.

Wetlands are defined as swamps, marshes, billabongs, lakes, salt marshes, mudflats, mangroves, coral reefs, fens, peat bogs or bodies of water, natural or artificial, permanent or temporary. Water in wetlands can be static, flowing, fresh brackish or saline and include inland rivers and coastal or marine water to a depth of 6 m at low tide (Department of Agriculture, Water and the Environment, 2016). The spatial extent of the wetland vegetation extent and condition endpoint in the Cooper GBA region is 12,143 km^2 (about 9%, Figure 12), of which almost half overlies areas that are prospective for unconventional gas resources (Figure 2). Existing disturbance affects about 2% of wetland areas in the Cooper GBA region, including existing infrastructure (167 km^2) and seismic surveys (91 km^2) (Geological and Bioregional Assessment Program, 2021m).

Wetlands in the Cooper GBA region have highly variable water regimes and water quality dominated by connectivity with Cooper Creek, as well as local rainfall (Box 8). Two wetland types are predominant in the Cooper GBA region: palustrine – vegetated wetlands associated with floodplain environments that include billabongs, swamps, bogs, springs and soaks – and the larger lacustrine wetlands dominated by open-water. Wetlands also occur in other landscapes, such as dune fields of the Strzelecki Desert, where water regimes are dominated by localised rainfall.

The highly variable nature of the water regimes in the region gives rise to high diversity of ecosystems (refer to the **wetland vegetation extent and condition** endpoint). This includes more than 90 regional ecosystems that provide habitat for thousands of species (Hobbs et al., 2017; Queensland Herbarium, 2018a). Some wetlands support significant congregations of wetland bird species with populations in excess of 20,000 birds (Jaensch, 2009; Butcher and Hale, 2011). Key ecological assets include lakes and wetlands listed in the *Directory of important wetlands in Australia*, and the Coongie Lakes Ramsar wetland site. Wetlands also provide habitat for the endangered grey grasswren (*Amytornis bartbatus barbatus*) and the Australian painted snipe (*Rostratula australis*). Like riparian areas, wetland values are culturally important for Indigenous peoples in the region, with plants and animals being significant from cultural and economic perspectives (Constable et al., 2015).

Box 8 Detecting changes to historical flooding associated with gas resource development

Paired-floods analysis (such as comparing flood characteristics of similar sized floods before and after development) suggests historic infrastructure development, including oil and gas fields, has had negligible impacts on flood characteristics. Co-analysis of streamflow data and two satellite remote sensing open water datasets from 2000 to 2020 provides estimates of the baseline frequency and extent of floodplain inundation in the Cooper GBA region (Geological and Bioregional Assessment Program, 2021k).

These baselines distinguish between inundation from floods (such as lateral inflow into the floodplain from the upper parts of the Cooper Creek catchment) and inundation caused by rainfall received on the floodplain. Future development on the floodplain, including gas extraction and associated activities, may impact flood inundation but will not impact rainfall received on the floodplain. Analysis of the 2 satellite datasets reduces uncertainty associated with spatial resolution and frequency of cloud-free observations to better understand the value of these datasets for long-term environmental monitoring.

Direct impacts from development activities are of ‘potential concern’ in up to 33% of wetland areas. Indirect impacts, such as competition and predation, ecosystem burning, and habitat degradation, fragmentation and loss, that could spread beyond development areas are of ‘potential concern’ in almost half of all mapped wetland areas. There is high confidence that direct impacts can be effectively managed on site, primarily by avoiding development in or near wetlands. However, coordinated regional responses and management plans are needed to manage indirect impacts.

Direct disturbance is of 'potential concern' in up to 33% of wetland areas (refer to the **soil compaction**, **vegetation removal** and **vehicle movement** node descriptions). Indirect impacts that could spread beyond the development area, disrupting natural processes, are of 'potential concern' in up to 49% of wetland areas (refer to the **competition and predation**, **ecosystem burning**, and **habitat degradation**, **fragmentation and loss** node descriptions). Important wetland areas are represented in the causal network by the **Coongie Lake Ramsar wetland condition**, **DIWA lake condition** and **DIWA wetland condition** endpoints.

There is high confidence that development activities can be effectively managed to prevent degradation on site, primarily by avoiding development in or near wetlands. The extent of the potential development area means that direct impacts on important ecological or cultural values can be avoided through considered planning. However, to manage indirect stressors, such as introduced plants, predators and herbivores, coordinated regional responses and management plans are needed.

5.3 Floodplain ecosystems

Floodplains are extensive in the Cooper GBA region and provide habitat for many species, including threatened plant species such as braided sea heath*, Schleroleana walkeri and Xerothamnella impervia.* Water regimes – particularly the frequency, extent and duration of flooding – control the structure and dynamics of floodplain ecosystems. Flooding provides a significant boost to productivity in the region – in particular, the pastoral industry, which grazes natural pastures on floodplains.

Floodplains are the outcome of a complex set of interactions between flow, sediment regimes and the character of the valley trough (Thoms and Parsons, 2016). Floodplain environments in the Cooper GBA region are conceptualised as mid and lower catchment floodplains. In these environments, energy associated with flows is lower, valleys tend to be wider, and there are high rates of sediment deposition associated with large slow-moving floods that have contributed to the development of very large, wide (greater than 60 km) floodplains. The spatial extent of the **floodplain vegetation extent and condition** endpoint in the Cooper GBA region is 25,283 km^2 (about 19%), of which almost 30% overlies areas that are prospective for the development of unconventional gas resources (Figure 12). Existing disturbance, including existing infrastructure for agriculture, tourism and oil and gas development (393 km^2) and seismic surveys (145 km^2), affects about 2% of floodplain areas in the Cooper GBA region (Geological and Bioregional Assessment Program, 2021m).

The frequency and duration of flooding is an important characteristic of floodplain environments as it controls vegetation growth and the potential growing period including flowering and seed set. Floodplain ecosystems are less diverse than riparian, wetland or dryland ecosystems, containing just 6 regional ecosystems in Queensland (Queensland Herbarium, 2018a) and 5 mapped ecotypes in South Australia (Hobbs et al., 2017). Vegetation in these ecosystems is characterised by low, often sparse or open, chenopod and other shrublands, and low woodlands. Floodplain vegetation provides habitat for protected fauna and flora prioritised for the assessment, such as the grey grasswren, and plants such as braided sea heath, *Scleroleana walkeri* and *Xerothamnella parvifolia*.

Cooper Creek has an extensive floodplain containing braided channels that lead to long travel times and large transmission losses, with over 75% of the water flowing into the system from the Barcoo and Thompson rivers lost by the time it reaches the Queensland – South Australian border (Jarihani et al., 2015). Transmission losses support terrestrial vegetation and pasture used for grazing, as well as filling lakes and recharging shallow groundwater. Cooper Creek floodplain supports an agricultural grazing industry worth $65 million per year with single large floods increasing the value up to $150 million (Phelps et al., 2007). Satellite monitoring of water use was used to determine to where Cooper Creek floodwaters go (Box 9).

Box 9 When Cooper Creek floods, where does all the water go?

To trace where over 75% of Cooper Creek floodwaters go before they reach the Queensland – South Australian border, remotely sensed measurements of actual evapotranspiration were separated into open water, riparian, floodplain and rain-fed areas (Figure 14). Water use by open-water areas represent direct evaporation losses from river channels and permanent waterholes. Riparian vegetation uses a combination of water sources derived from rainfall and infiltration from bank recharge from river channels and permanent waterholes, as well as overbank flooding. Floodplain vegetation relies on soil moisture from rainfall and overbank flooding. Outside of the floodplain, dryland vegetation relies solely on rainfall.

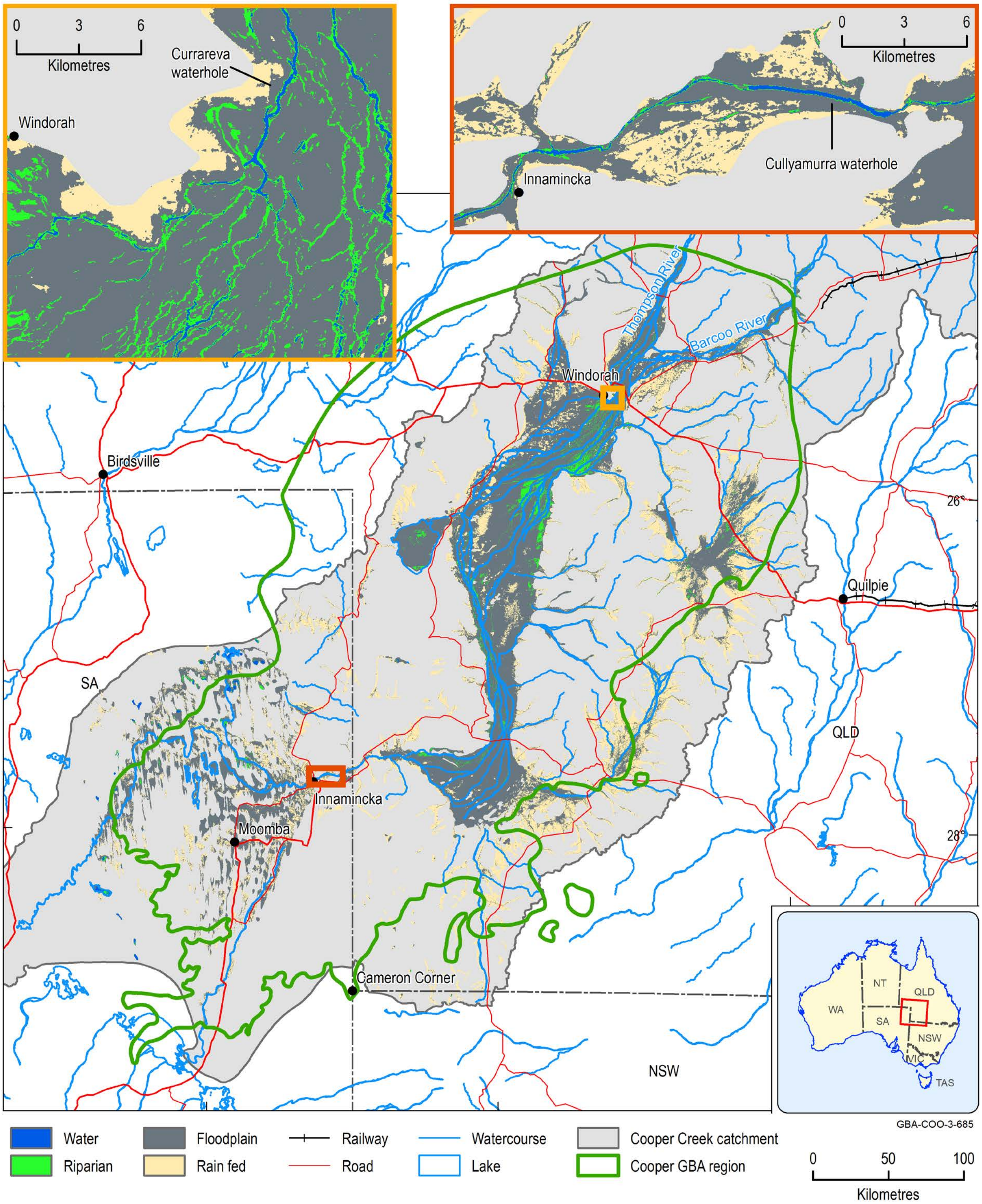
For the period 2000 to 2018, 77% of actual evapotranspiration losses were from floodplain areas, associated with overbank flooding, where it supports pasture growth. The remaining 23% of actual evapotranspiration losses were from fringing riparian vegetation or as evaporation from open water in waterholes. In other words, high ecological value wetlands, waterholes and fringing riparian vegetation account for less than a quarter (23%) of total water use on Cooper Creek floodplain.

Coongie Lakes © Russell Crosbie, CSIRO

Cenozoic observation bore © Russell Crosbie, CSIRO

Box 9 When Cooper Creek floods, where does all the water go? *continued*

FIGURE 14 Classification of open water, riparian, floodplain and rain-fed areas based on water use



Data: Geological and Bioregional Assessment Program (2020d)
Element: GBA-COO-3-685

Overland flow obstruction can change flow paths on the floodplain and in small flood runners. This can cause reduced flooding, which is of 'potential concern' in up to 6% of the floodplain vegetation areas. Reduced flooding in these areas could also affect less than 4% of the **agricultural productivity**, **Channel Country SEA condition** and **Coongie Lakes Ramsar wetland** endpoint areas, as well as habitat for the grey grasswren and the Australian painted snipe, and areas where braided sea heath and *Sclerolaena walker* are mapped.

Direct disturbance at the surface is of 'potential concern' in up to 29% of floodplain areas (refer to the **soil compaction**, **vegetation removal** and **vehicle movement** node descriptions). Indirect impacts that could spread beyond the resource development area, disrupting natural processes, are of 'potential concern' in up to 30% of floodplain areas (refer to the **competition and predation**, **ecosystem burning**, and **habitat degradation**, **fragmentation and loss** node descriptions).

Localised stressors, such as **dust generation**, **soil compaction**, overland flow obstruction and **vegetation removal**, are managed by site-based protocols and controls. Regional-scale stressors include those that may lead to increased ecosystem burning, such as vehicle movements that can promote the spread of fire in the landscape, or competition and predation, such as the proliferation of the artificial water sources that support and can facilitate the spread of invasive herbivores and predators; in the region.

5.4 Dryland ecosystems

Dryland ecosystems are extensive in the Cooper GBA region and despite the aridity, the diversity of dryland landscapes and landforms supports a high diversity of ecosystems and grazing on natural pastures. These areas provide habitat for many species, including the kowari, yellow-footed rock-wallaby, and possibly the night parrot. Development activities are likely to amplify existing threatening processes such as habitat degradation, fragmentation and loss; competition and predation; ecosystem burning and soil erosion.

A diversity of dryland ecosystems is represented in the **dryland vegetation extent and condition** endpoint. These ecosystems are solely reliant on rainfall to meet their water requirements. The 5 landscape classes outside of the floodplain and alluvium landscape class (Section 4.3 in baseline synthesis and gap analysis (Holland et al., 2020); protected matters technical appendix (O'Grady et al., 2020)) are also represented: inland dunefields; undulating country on fine grained sedimentary rocks; tablelands and duricrusts; loamy and sandy plains; and clay plains.

The spatial extent of the dryland vegetation extent and condition endpoint in the Cooper GBA region is 88,538 km^2, of which approximately 23% overlies areas that are prospective for the development of unconventional gas resources (Figure 12). Dryland vegetation in the Cooper GBA region is relatively undisturbed (less than 1.7% of dryland areas are disturbed), with seismic surveys (571 km^2) accounting for 40% of total disturbance (1,442 km^2) (Geological and Bioregional Assessment Program, 2021m).

The key distinguishing feature of dryland landscapes is the high dependency on localised rainfall. Dryland ecosystems or 'rangelands' are defined as areas that are hyper-arid, arid, semi-arid or dry sub-humid systems. Most of the Cooper GBA region is arid, with a mean annual rainfall of 217 mm/year and evaporation in excess of 1,700 mm/year. As a result, water availability is a major driver of the productivity of these ecosystems.

Despite the aridity, the diversity of landscapes and landforms in the Cooper GBA region supports a high diversity of ecosystems. In Queensland, there are approximately 70 regional ecosystems mapped (Queensland Herbarium, 2018a), and in South Australia, there are 28 ecotypes mapped (Hobbs et al., 2017) within the dryland vegetation extent and condition endpoint. Dominant vegetation communities include the chenopod shrublands, Mitchell grass tussock grasslands, spinifex-dominated hummock grass and Acacia-dominated woodlands and shrublands.

Dryland areas support protected fauna, including the kowari (*Dasyuroides byrnei*) found in the gibber pavements of the Sturt Stony Desert and yellow-footed rock-wallaby (*Petrogale xanthopus celeris*) found in the tablelands and duricrusts landscape class. Although unconfirmed, the night parrot (*Pezoporus occidentalis*) may use long unburnt spinifex for roosting and breeding in dryland areas.

The main land use is grazing on natural pastures represented by the agricultural productivity endpoint. Agricultural productivity is measured as the ratio of outputs produced to inputs used in agricultural production and is defined as land classified as grazing of native vegetation in the catchment scale land use map of Australia (Australian Bureau of Agricultural and Resource Economics and Sciences, 2016).

Soil compaction could increase habitat degradation, fragmentation and loss and soil erosion, which is of 'potential concern' in 20% of the agricultural productivity and 23% of the dryland areas. Soil compaction leading to loss of habitat is well studied and the effectiveness of relevant regulations and mitigation strategies is well documented. Knowledge and data available to evaluate materiality thresholds for soil erosion is limited.

Soil compaction in dryland, floodplain and agricultural landscapes can increase soil erosion, depending on the soil properties, ground slope, vegetation, and a combination of the frequency, intensity and duration of wind, rainfall and human activities (Morgan, 2009; Montgomery, 2007). Soil compaction leading to loss of habitat is well studied and documented (Håkansson and Reeder, 1994; Pringle et al., 2019), with mitigation strategies identified by operators (Santos, 2015). Pringle et al. (2019) and Wakelin-King (2013) provide an overview of methods to avoid erosion, including not grading a road down below the ground surface, not leaving road-edge windrows, and properly directed spoon drains. Confidence in pathways related to soil erosion is low as knowledge of materiality thresholds is limited.

FIND MORE INFORMATION

Impact assessment summary for the Cooper GBA region
Causal network dataset (Geological and Bioregional Assessment Program, 2021c)

Fact sheets are available on the Geological and Bioregional Assessment website.

- *Fact sheet 1:* Actual evapotranspiration in the Cooper Creek floodplain: transmission losses and groundwater recharge (Geological and Bioregional Assessment Program, 2021r)
- *Fact sheet 7:* Characterising the connectivity between permanent waterholes and groundwater (Geological and Bioregional Assessment Program, 2021g)

6 Potential impacts on protected fauna and flora

The causal network is used to identify potential impacts on protected fauna and flora in the Cooper GBA region. Assessment results can be used to identify existing avoidance and mitigation strategies and to prioritise local-scale assessment, mitigation and monitoring. Existing key threatening processes could be amplified by pathways of 'potential concern' identified by the assessment. Potential impacts at the surface include contamination, competition and predation, ecosystem burning, habitat degradation, fragmentation and loss, and reduced flooding. The assessment is supported by analysis of remote sensing data and tools for natural capital accounts (Box 10, Box 11).

The biodiversity-rich Cooper GBA region provides potential habitat for 68 species protected under state or national legislation. The assessment prioritised **12 protected species** (4 birds, 3 mammals and 5 plants) based on the importance of the Cooper GBA region to each species in order to better understand potential impacts of unconventional gas resource development on protected fauna and flora.

The Cooper GBA region is very biodiverse. Its boom-and-bust ecology is a key driver of the region's biodiversity that, to date, includes over 2,000 species (Atlas of Living Australia, 2019). Modelling of biodiversity persistence in the region (Box 10) indicates that the relatively intact landscape can support relatively high biodiversity (greater than 0.9; Figure 15) and that trends in vegetation condition are relatively stable (Geological and Bioregional Assessment Program, 2021n). The Cooper GBA region provides potential habitat for 68 species protected under state or national legislation – 38 birds, 2 fish, 10 mammals, 15 plants and 3 reptiles. Many of the region's species are also culturally significant. For example, the iconic river red gum (*Eucalyptus camaldulensis)* not only provides a range of ecosystem services such as bank stabilisation and habitat, but also provides food, timber for tools and utensils, and medicines for Indigenous peoples.

To assess potential impacts on biodiversity due to unconventional gas resource development, the assessment prioritised fauna and flora endpoints based on the importance of the Cooper GBA region to the continued persistence of each species ((Holland et al., 2020); protected matters technical appendix (O'Grady et al., 2020)). Fauna endpoints include 2 of the 20 bird species identified for priority conservation – the night parrot and the plains-wanderer – identified in Australia's Threatened Species Strategy (Australian Government, 2015). Protected fauna and flora included in the assessment are:

- 4 bird species (plains-wanderer, Australian painted snipe, night parrot and the grey grasswren)
- 3 mammals (kowari, dusky hopping-mouse, yellow-footed rock-wallaby)
- 5 plants (braided sea heath, *Scleroleana walkeri*, *Indgofera oxyrachis*, *Nyssanthes impervia* and *Xerothamnella parvifolia*).

Box 10 Modelling persistence of biodiversity at a regional scale

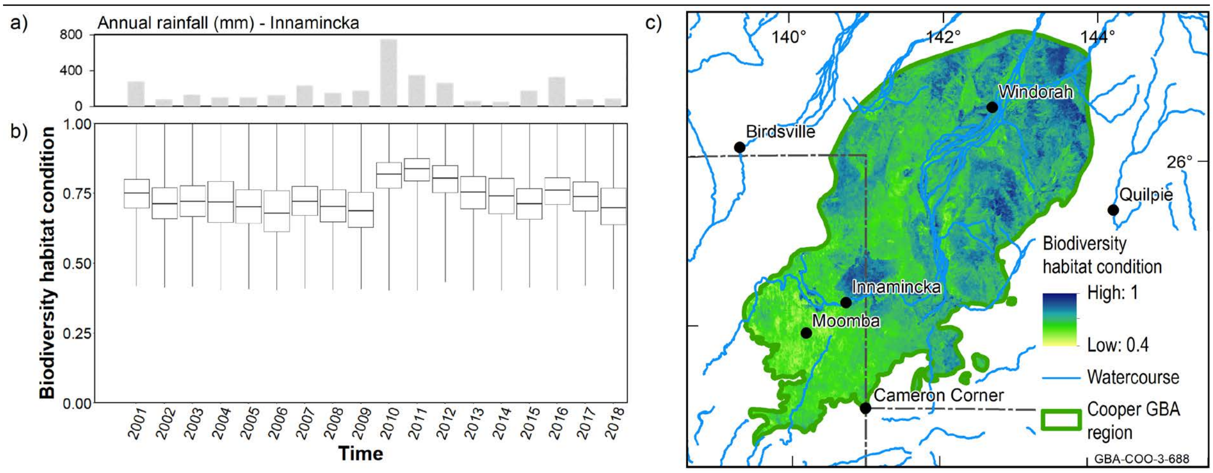
Broadscale landscape management (grazing, fire) strongly influences biodiversity persistence at a regional scale. While intense localised impacts on habitat (for example, roads, fence lines, seismic lines and well pads) are important for large regions, these are dwarfed by land management across vast areas (Eldridge et al., 2016). While wetter years offer potential for recovery, ongoing land use impacts in dryer years may amplify habitat degradation, which may be relevant when considering a potentially warmer and drier future.

Habitat condition changes with annual precipitation and declines spatially along the rainfall gradient from the north-east of the region to the south-west (Figure 15). During low rainfall periods (for example, 2001 to 2009, 2012 to 2015) habitat condition declines, and then increases after high rainfall (for example, 2010, 2011, 2016).

Opportunities to offset potential impacts of localised development activities exist, whereby loss and degradation of habitat could be offset by changes in broadscale land management practices in larger areas. Considering broader biodiversity persistence at the regional scale could enable disturbance for economic development to be balanced with conservation of important biodiversity values. This analysis can inform regional prioritisation of sites for rehabilitation and management.

An existing continental model of plant community biodiversity persistence (Mokany et al., 2018) was compared with vegetation cover condition (Donohue et al., 2021) to assess changes in habitat condition on plant biodiversity in the Cooper GBA region. Biodiversity persistence is the proportion of the original plant diversity retained in each 250 m grid cell at annual intervals from 2001 to 2018 reported on a scale from 0 to 1. Estimates of habitat condition combine historical changes in disturbance (Box 1) with changes to vegetation condition (Figure 15). The biodiversity analyses used CSIRO's bilbi61 package in Python (Ware, 2020).

FIGURE 15 Modelled biodiversity persistence in the Cooper GBA region showing a) annual rainfall at Innamincka; b) temporal variation in annual biodiversity habitat condition from 2001 to 2018; and c) spatial variation in 2018



Data: Geological and Bioregional Assessment Program 2021m); Department of Environment and Science (Qld) (2018)
Element: GBA-COO-3-688

Unconventional gas resource development could amplify existing threatening processes that are impacting on biodiversity in the Cooper GBA region. This includes **habitat degradation**, **fragmentation and loss**, **competition and predation** by invasive species and **ecosystem burning**, which are of 'potential concern' in 25 to 30% of the Cooper GBA region. Unconventional gas resource development may also introduce threatening processes that are not currently recognised and for which there is less knowledge, such as noise and light pollution, soil compaction, and contamination of soil and water.

Habitat degradation, fragmentation and loss is a reduction in the quality, extent or connectivity of habitat, leading to increasingly isolated and smaller patches of habitat in poorer condition (Soille and Vogt, 2009; IPBES, 2019). While widely accepted as a key threatening process the capacity to develop species-specific models of vulnerability to habitat degradation, fragmentation and loss remains limited. Habitat degradation, fragmentation and loss is an inevitable consequence of expansion of the gas industry in the region, even though the physical footprint is likely to be relatively small and can be mitigated in sensitive areas.

Increased habitat degradation, fragmentation and loss, and competition and predation associated with introduced plants and predators are important drivers of the global decline in biodiversity (Woolley et al., 2019). Unconventional gas resource development activities could amplify these processes without appropriate mitigation and management. Construction of surface infrastructure to support the industry, such as roads, pipelines, well pads and camps requires removal of vegetation and the associated loss, fragmentation and degradation of habitat. Under the maximum resource development scenario, direct disturbance could increase by 27 km^2, spread over up to 7,350 km^2 (or 0.5 to 5.6% of the Cooper GBA region), including roads, well pads and seismic lines, as well as the areas between the disturbed areas.

The physical disturbance footprint potentially underestimates the ecological footprint of the industry in the region. The expansion of linear networks can facilitate the spread of invasive predators (for example, cats and foxes), invasive plants (for example, buffel grass) and invasive herbivores (for example, feral goats, rabbits) or other ecosystem disturbers such as pigs. The spread of invasive species may amplify competition and predation, lead to changes in fire regimes, or could degrade habitat via compositional changes in communities or soil compaction and degradation that impact on the persistence of threatened species in the region.

Furthermore, activities associated with the industry could introduce threatening processes that are not currently recognised, such as noise, light and dust pollution, as well as soil and water contamination. While there is an emerging understanding of the impacts of these threats on biodiversity (Longcore and Rich, 2004; Sordello et al., 2020), the species-specific information needed to assess these potential impacts for individual species in the Cooper GBA region is not currently available, but could be the focus of future investigations.

Habitat degradation, **fragmentation and loss** is recognised, based on existing EPBC Act conservation advice and recovery plans, as a key threatening process for the Australian painted snipe, the grey grasswren, plains-wanderer, kowari, dusky hopping-mouse, yellow-footed rock-wallaby and the endangered plant braided sea heath, and is a suspected threat for the remaining species in the region. Key stressors associated with habitat degradation fragmentation and loss include vegetation removal for infrastructure and the spread of invasive species, particularly those likely to lead to habitat degradation such as introduced herbivores or pigs.

Potential impacts can be mitigated by minimising the extent and location of new infrastructure, particularly roads or pipelines and by ensuring rapid and effective remediation of disturbed sites. However, there is limited knowledge to assess the efficacy of mitigation strategies for individual species, or the precise location, scale and nature of future development activities. Thus, monitoring of habitat degradation, fragmentation and loss requires continued assessment of specific developments and its intersection with important habitats and ecosystems to tailor future mitigation strategies and enable the gas industry to avoid degradation of potential habitat for protected species.

Disturbance footprints associated with the existing oil and gas industry compiled for the assessment provide a regional baseline for future comparison (Geological and Bioregional Assessment Program, 2021m). There is medium to high confidence that pathways associated with habitat degradation, fragmentation and loss could be effectively managed and mitigated by existing controls. Important knowledge gaps include a lack of species-specific information on habitat extent and condition, as well as vulnerability to degradation, fragmentation and loss and associated materiality thresholds. Remote sensing technologies provide a pathway to better support and coordinate regional-scale monitoring to improve the effectiveness and efficiency of mitigation and management by the gas industry, pastoralists and other community groups (Box 11).

Box 11 Detecting changes to vegetation condition associated with gas resource development

Vegetation condition, defined as the capacity of landscapes to produce and maintain vegetation cover from available water, is estimated using satellite imagery from 2001 to 2018. Satellite-derived measures of the fraction of ground covered by live vegetation and litter provide an excellent proxy for the health of agricultural landscapes, such as the Cooper GBA region.

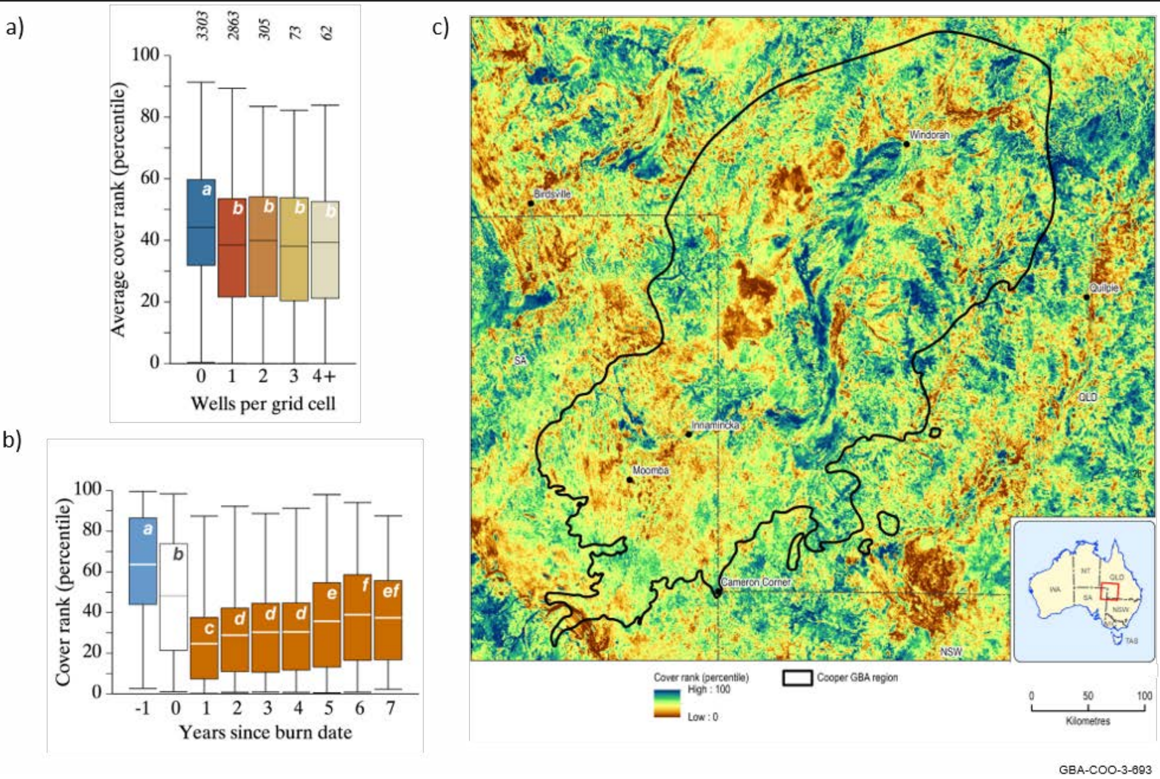
Vegetation condition is assessed using *Compere*, a relative benchmarking framework that separates management-driven impacts on ecosystem resources from the natural dynamics in those resources (Donohue et al., 2021). It works by identifying locations in a region that share similar biophysical properties to a target location and comparing it with all biophysically equivalent locations, with any differences being attributed to the effect of management activities.

Analysis of satellite monitoring vegetation cover data detected a 12 to 41% decrease in vegetation cover near gas extraction wells. Vegetation cover condition decreased within a year of establishment, started to recover after about 4 years, and had recovered to pre-development condition after 5 to 7 years.

Similarly, analysis of satellite-derived fire occurrence data (Figure 16), detected rapid decreases in vegetation cover of up to 60% due to fire, with much longer recovery periods in excess of a decade. This suggests that the largest direct impact that the gas resource development is likely to have on vegetation cover condition is through changes to fire regimes.

Box 11 Detecting changes to vegetation condition associated with gas resource development *continued*

FIGURE 16 Vegetation cover condition showing a) effect of gas well density; b) effect of fire through time; and c) spatial patterns in 2018



Vegetation cover condition is reported as 'cover rank (percentile)'. Boxes show the mean (white bar) and middle 50% of values. Tails show the 1st and 99th percentiles. Letters denote significantly different means (P = 0.05) using Student's t-test.

Source: Donohue et al. (2021)

Data: (Geological and Bioregional Assessment Program, 2021d)

Element: GBA-COO-3-693

Predation by cats and foxes is recognised as a key threatening process for 4 of the 7 protected fauna species: plains-wanderer, kowari, dusky hopping-mouse and yellow-footed rock-wallaby. While there is less evidence in the scientific literature, predation is also likely to affect the other 3 fauna species in the region: the Australian painted snipe, grey grasswren and night parrot. In addition, **competition** with feral herbivores for resources, such as food and shelter, is a key threatening process identified for the night parrot, dusky hopping-mouse and yellow-footed rock-wallaby.

Competition and predation are two distinct ecological processes that describe interactions between organisms. Competition occurs when resource availability is limited to such an extent that there are insufficient resources available to meet the needs of all organisms. Interspecific competition refers to competition between species and is often heightened by invasive species (Mangla et al., 2011). Predation is the process where one individual seeks to capture and consume another. Predation also includes the concept of 'landscape of fear' where the presence of predators increases stress in the prey leading to avoidance or physiological stress (Fardell et al., 2020). The **competition and predation** node description describes interactions between native and introduced species.

Competition and predation is of 'potential concern' for all 12 protected species. Predation by invasive predators, such as cats and foxes, is recognised as a significant contributor to biodiversity decline in Australia. Artificial watering points can create an imbalance in an ecosystem – for example increasing native species populations, attracting predators or by providing additional resources to enable introduced herbivores to establish in an area (Letnic et al., 2014) (refer to the **artificial water sources** node description). Increased grazing pressure associated with introduced herbivores can heighten competition for food, seed and shelter that may impact on many species in the Cooper GBA region (for example, night parrot, yellow-footed rock-wallaby). Similarly, invasive plants may colonise degraded sites and quickly displace native flora.

Unconventional gas resource development activities can contribute to the spread of invasive plants and animals when infrastructure such as roads and pipelines acts as corridors of dispersal for invasive predators and plants (Dawson et al., 2018). This allows invasive plants and animals to access areas that may have been otherwise relatively natural. Industry controls focus on the movement of plant and equipment for infrastructure development, which can hasten the movement and dispersal of important weed and pest species if not correctly carried out or without appropriate controls to prevent the spread. Once established, invasive species are difficult and costly to control and manage.

Mitigation and management of invasive species is best achieved via co-ordinated industry-wide approaches that work with existing land managers and natural resource management programs including whole-of-life-cycle planning and risk management. Dedicated invasive species officers and raising awareness of workers and contractors are key monitoring and mitigation options. There is medium to high confidence that pathways associated with competition and predation can be effectively managed and mitigated using existing controls, although understanding of the baselines and trends of the distribution and abundance of invasive species in the region is an important knowledge gap.

Changes to **ecosystem burning** regimes are of 'potential concern' in 30% of the Cooper GBA region and for all protected species in the assessment. Increased average temperatures, number of hot days (more than 35°C) and shifting rainfall patterns combine to increase risks to biodiversity associated with fire. Changes in fire regimes are identified as important threatening processes for the grey grasswren, night parrot, plains-wanderer and yellow-footed rock-wallaby. It is suspected that altered burning regimes are likely to have direct (such as mortality) and indirect (such as habitat modification) impacts on all species in the Cooper GBA region.

Fire regimes can have a major influence on the health and composition of habitat and its associated species (Catterall et al., 2007; Jansen et al., 2007). Many of the ecosystems in the Cooper GBA region are sensitive to fire. Recommended fire management for many ecosystems in the region, particularly those associated with wetland and riparian areas are to avoid or exclude fire altogether (Queensland Herbarium, 2018b). Current fire regimes are a complex interplay between vegetation structure and fuel loads, topography, traditional and contemporary fire management practices. Risks associated with extensive wildfires are generally heightened after several years of above average rainfall, largely due to the accumulation of fuels (Marsden-Smedley et al., 2012; Nano et al., 2012).

Historically, fire regimes have been influenced by lightening-induced fires, traditional and European management of landscapes (Marsden-Smedley et al., 2012). Traditional aboriginal burning practices have been displaced by fire suppression and protection of grazing pastures. However, fire is also used to encourage annual pasture monocultures, to the detriment of perennial species. Altered fire regime may be accelerated or exacerbated by the invasion of exotic pasture grasses, such as buffel grass and climate change (Marsden-Smedley et al., 2012; Silcock et al., 2013; Agnew et al., 2014). The construction of access roads and linear infrastructure within previously contiguous landscapes could increase the number and timing of deliberate or accidental sources of ignition as a result of increased human access and increase the risk of fire due to flaring during gas production (Edwards et al., 2008). However, roads can also act as fire breaks and provide access to control fires. Thus, understanding of the complex interactions between vegetation, land use, climate and fire remains poor and the ecology of fire in central Australia remains a critical knowledge gap.

Mean maximum air temperatures in the Cooper GBA region for the period 1976 to 2005 ranged from 35 to 40 °C and mean minimum temperatures varied from 20 to 24 °C (Geological and Bioregional Assessment Program, 2018c). The number of hot days (maximum air temperature greater than 35 °C) is projected to increase from between 84 and 114 days per year for the period 1976 to 2005 by up to 80 to 90 days in the north-east of the Cooper GBA region under the 90th percentile estimate for the period 2046 to 2075 (Geological and Bioregional Assessment Program, 2018b).

Changes to ecosystem burning regimes are of ‘potential concern’ for all the protected species in the assessment. This threat is recognised in the conservation advice for some species. For other species, impacts on species persistence are likely to be driven by changes to ecosystem condition. Two pathways for changes to ecosystem burning regimes associated with unconventional gas resource development are identified. Firstly, invasive species can increase intensity and frequency of fires. For example, buffel grass is known to increase risks associated with fire as it is a highly flammable fuel that can carry high-intensity fires (Marshall et al., 2012). Secondly, increased access throughout the region and associated traffic can increase the risk of accidental or deliberate ignition (Edwards et al., 2008).

Mitigation and management of ecosystem burning regimes is best achieved via a coordinated regional-scale approach. Localised management options include development of fire management plans that include restricting access to industry roads and tracks by non-industry personnel or during periods of high fire danger and effective control of the invasive weeds.

Key knowledge gaps identified in the assessment relate to a lack of understanding of responses to fire by individual species. Some species such as the grey grasswren or the night parrot require habitats that are relatively free of fire for long periods. However, relationships between species persistence and fire for many species are unclear. There is medium to high confidence that pathways associated with ecosystem burning could be effectively managed and mitigated using existing controls.

Reduced **floodplain inundation** is of 'potential concern' for 2 endangered bird species: the Australian painted snipe and the grey grasswren. It is not identified as a direct threat in existing EPBC Act conservation advice and recovery plans or as a key threatening process for other protected fauna and flora endpoints. Unconventional gas resource development activities could reduce floodplain inundation, which is of 'potential concern' in 1,613 km^2, or 6.4% of floodplain habitat that support these species. Where knowledge of plant biology and water requirements is limited, the precautionary principle is applied, and changes to floodplain inundation are assessed as of 'potential concern' for braided sea heath, *Indigofera oxyrachis* and *Xerothamnella parvifolia*.

Floodplain inundation occurs when very heavy local rainfall exceeds the infiltration capacity of the floodplain, or under high flow conditions when water spills from the river (overbank flows) and spreads over the floodplain, or a combination of the two (refer to the **floodplain inundation** node description). The variability, timing and extent of floods play a major role in sustaining the biodiversity of floodplain environments (Leigh et al., 2010). Vegetation spatial patterns reflect the soil and flood characteristics experienced in an area. Alternating dry and wet phases are especially important for nutrient cycling and system productivity (Jaensch, 2009).

The persistence of the Australian painted snipe and the persistence of the grey grasswren are tied to water regimes required to sustain their habitat. This is true for all floodplain-dependent biota. The Australian painted snipe requires shallow permanent or ephemeral wetlands; changes to water regimes of these habitats is identified as the most critical threat to this species (Commonwealth of Australia, 2019). Similarly, the grey grasswren depends on dense lignum swamps, which form their primary habitat. Thus, changes to floodplain inundation are closely linked with habitat, degradation, fragmentation and loss for these species.

Given the low relief of the Cooper Creek floodplain, any changes to overland flows associated with civil construction could impact on sensitive areas (Wakelin-King, 2013). Legislation prohibits unconventional gas resource development activities, including linear infrastructure, in sensitive areas. Mitigation strategies to avoid or minimise overland flow obstructions are documented in relevant environmental impact plans (Santos, 2015; Senex Energy, 2016; Beach Energy, 2019) (refer to the **civil construction** and **overland flow obstruction** node descriptions).

Key knowledge gaps relate to understanding of the distribution and abundance of the Australian painted snipe and the grey grasswren in the Cooper GBA region and the water regimes required to support critical habitat for the individual species. There is medium to high confidence that impacts associated with changes to floodplain inundation can be managed or mitigated. Baseline data collected by the GBA Program to address knowledge gaps and improve future management of the Cooper Creek floodplain include aerial LiDAR surveys, 2D flood inundation model, and satellite monitoring of floodplain vegetation water use, historical flooding, biodiversity persistence and vegetation condition (refer to Box 7, Box 8, Box 10, Box 11).

Soil and **surface water contamination** are conservatively assessed as of 'potential concern' for all fauna-related endpoints. The assessment of potential impacts on native fauna due to soil and surface water contamination considers population size, habitat extent, proximity to water, water requirements and species mobility. The precautionary principle is applied as there is insufficient species-specific information to establish robust materiality thresholds for the toxicity of potential pollutants on the 7 protected fauna species.

Soil and surface water contamination leading to pollution occurs when the concentration of a biological, chemical or physical property is sufficient to cause an adverse effect (refer to the **soil contamination** and **surface water contamination** node descriptions). What constitutes acceptable change depends on the ecosystem services the soil or surface water provides and may be informed by regulatory requirements, guidelines and approvals.

The current data and knowledge base are insufficient to establish robust materiality thresholds for a decrease in persistence of native fauna due to an increase in surface water contamination (refer to the **surface water contamination** node description). In the absence of a robust materiality threshold, the link is evaluated as of 'potential concern' in line with the precautionary principle.

Surface water and soil contamination are associated with spills and leaks to the environment that could impact on the fitness of species exposed to the contaminants (refer to the **accidental release** node description). Soil contamination is not recognised as a direct threat for any of the species in the assessment, and its impact through habitat degradation, fragmentation and loss is not material. In the case of spills and leaks, exposure to surface water contamination through physical exposure, direct consumption, or consumption of plants, insects, and sediment-dwelling or aquatic worms, crustaceans and invertebrates, could impact on populations of the Australian painted snipe, grey grasswren, night parrot and yellow-footed rock-wallaby (refer to the **surface water contamination** node description). The potential for chemicals to partition and accumulate in sediments indicates that sediment feeders have a higher potential concern. Although there is no direct evidence that the kowari or the dusky hopping-mouse are dependent on surface water to meet their water requirements, their greater population density in areas close to water sources (possibly associated with food sources) means that potential impact cannot be discounted.

Compliance reporting shows existing regulations, approval conditions and industry practices are effective in preventing, or ensuring quick remediation of, spills and leaks. There is high confidence that impacts associated with surface water and soil contamination can be mitigated through existing controls and regulations, despite knowledge gaps associated with species specific thresholds of exposure and toxicity.

Noise and **light pollution** can have significant impacts on all animal taxa. Due to considerable uncertainty and use of the precautionary principle, noise and light pollution is assessed as of 'potential concern' in 25% of the Cooper GBA region. Noise and light pollution may be of particular concern to cryptic (for example, the Australian painted snipe) or nocturnal species (for example, the night parrot, kowari, dusky hopping-mouse). Noise pollution and light pollution are not currently recognised as key threatening processes under the Australian Government and state legislation.

Ecological light pollution is any artificial light that alters the natural patterns of light and dark in ecosystems that can affect the physiology, behaviour and reproduction of a range of animal taxa through changes in vision, foraging and reproductive behaviours, as well as reduced reproductive success (Newport et al., 2014; Longcore and Rich, 2004). Night-time light pollution from gas fields includes light emitted from gas flares, vehicle headlights and lighting required to operate safely during drilling and hydraulic fracturing operations (Jones et al., 2015) (refer to the **light pollution** node description). The draft national light pollution guidelines recommend further assessment if a light source is within 20 km of important habitat for a listed species (Commonwealth of Australia, 2020).

Noise pollution is any human-made sound that alters the behaviour of animals or interferes with their functioning (Newport et al., 2014; Barber et al., 2010) (refer to the **noise pollution** node description). Noise pollution is also known as 'masking' and includes any anthropogenic noise that alters reproduction, communication between individuals (courtship, begging, distress and alarm calls), survivorship, reproduction, habitat use, distribution, abundance or genetic composition (Newport et al., 2014; Barber et al., 2010; Sordello et al., 2020). Similarly, noise pollution can impact on the capacity of nocturnal species to forage, interfere with circadian rhythms, or change patterns of habitat use and occupancy for a range of species (Gaston et al., 2012).

Noise and light pollution can have a significant impact on all animal taxa (Kunc and Schmidt, 2019) and is of 'potential concern' in 25% of the Cooper GBA region. While there is considerable uncertainty associated with the impacts of noise and light pollution on fauna species (Newport et al., 2014), a number of species are nocturnal (for example, kowari, night parrot) or cryptic (for example, Australian painted snipe, grey grasswren, night parrot) and may be susceptible to increased noise and light pollution. Where knowledge of animal physiology and behaviour is limited, the precautionary principle is applied, and changes to noise and light pollution are assessed as of 'potential concern' for all fauna species. Confidence in existing controls is low to medium, as noise and light management plans in the Cooper GBA region primarily address worker health and safety and do not necessarily address potential impacts on wildlife (refer to the **operation of industrial machinery** and **vehicle movement** node descriptions).

FIND MORE INFORMATION

Impact assessment summary for the Cooper GBA region
Causal network dataset (Geological and Bioregional Assessment Program, 2021c)

Fact sheets are available on the Geological and Bioregional Assessment website.

- *Fact sheet 14:* Gas extraction and vegetation condition (Geological and Bioregional Assessment Program, 2021b)
- *Fact sheet 27:* Modelling persistence of biodiversity at a regional scale (Geological and Bioregional Assessment Program, 2021h)

7 Conclusion

The analysis of potential impacts of unconventional gas resource development activities on water resources and matters of environmental significance identified by the assessment will inform and support the Australian Government and state management and compliance activities. Potential impacts identified by the causal network for the Cooper GBA region and key findings from targeted investigations can be used to prioritise future avoidance and mitigation strategies. The insights and needs that have come from discussions with government, industry, land users and the community at GBA workshops and user panel meetings have guided the investigations, development of the assessment method and design of the interactive web-based tool.

7.1 Key findings

The 130,000 km^2 Cooper GBA region contains diverse habitats that support important environmental, cultural, social and economic values that interact and respond to the episodic, irregular and extreme boom-and-bust periods that are characteristic of the Channel Country in Queensland and South Australia (Figure 17). The braided channels, vast floodplains and terminal lakes of Cooper Creek include internationally and nationally listed wetlands, as well as regionally protected areas. The assessment considers potential impacts due to unconventional gas resource development activities on these landscapes, aquifers, protected areas and 12 threatened species (7 fauna and 5 flora). These endpoints were prioritised based on the importance of the Cooper GBA region to each protected matter.

FIGURE 17 Scrubby Camp Waterhole on Cooper Creek, west of Innamincka in South Australia

Credit: Geological and Bioregional Assessment Program, Russell Crosbie (CSIRO), November 2019
Element: GBA-COO-3-660

The assessment found that compliance with existing regulatory and management controls can mitigate all potential impacts due to unconventional gas resource development identified in the Cooper GBA region. This includes national and state legislation, regulatory guidelines and approval conditions, industry best practice and management plans. The regional-scale assessment provides independent science to underpin coordinated management of potential impacts across governments, industry, land users and the community. The geological and environmental knowledge, data and tools will enable regulators and proponents to focus local-scale assessment, management and monitoring.

Impact assessment

The complex and interconnected nature of the natural environment and unconventional gas resource development activities were assessed at a regional scale using causal networks. Causal networks are graphical models that describe the cause-and-effect relationships between development activities and the values to be protected (referred to as endpoints); for example, the internationally protected Coongie Lakes wetland. The assessment uses spatially explicit and systematic evaluations of the likelihood and consequence of environmental harm, and availability of control and mitigation strategies. An online tool presents the comprehensive information base underpinning the assessment.

Confidence in the impact assessment is generally high where there is evidence to support the evaluations. Where there is insufficient knowledge to support robust and meaningful evaluations, the precautionary principle is applied so that uncertainty about potentially serious hazards does not lead to underestimation of impacts.

No pathways of 'potentially high concern' are identified in the causal network. This means that all potential impacts identified by the assessment can be mitigated through compliance with existing regulatory and management controls.

The assessment is based on a maximum development scenario matching current conventional gas production in the Cooper GBA region of 92 petajoules per year over a 50-year period. Under this scenario, a projected 1,180 petroleum wells are estimated to disturb a total area of 27 km^2 spread over up to 7,350 km^2 including undisturbed areas between well pads, roads and seismic line, or less than 6% of the total area. This maximum development scenario would require the extraction or reuse of up to 20 gigalitres of water over a 50-year development period, equivalent to approximately 400 megalitres per year for 50 years.

Potential impacts at the surface

Pathways between unconventional gas resource development activities and endpoints of 'potential concern' are primarily related to activities that create a disturbance at the surface (transport of materials and equipment, civil construction, decommissioning and rehabilitation, and seismic acquisition). The pathways of 'potential concern' connect these activities with the endpoints – all vegetation communities (dryland, floodplain, riparian and wetland), protected areas, protected flora and habitat of protected fauna – reflecting how surface disturbance has the potential to impact on these endpoints. These pathways of 'potential concern' warrant local-scale studies to inform decision-making and enable coordinated management of potential impacts. They include the following:

- Surface water contamination in 12% of the Cooper GBA region, as spills and leaks could spread rapidly and accumulate in sediments. Contamination of shallow groundwater is of 'potential concern' in less than 1% of the Cooper GBA region where groundwater is close to the surface (less than 9 m deep). Existing regulations, approval conditions and industry practices are effective in preventing, or ensuring quick remediation of, spills and leaks. There is insufficient species-specific information to establish robust thresholds of material change for the toxicity of potential pollutants for protected fauna. Therefore, soil and surface water contamination are conservatively assessed as of 'potential concern' for all fauna-related endpoints.
- Obstruction of surface water flows in 6% of the Cooper Creek floodplain, or 1.2% of the total area. Licensed surface water extraction – approximately 2% of annual flows – will not impact on flows in the river or scouring or flooding in Cooper Creek. Changes to flood extent could affect agricultural productivity and the condition of protected areas including the Channel Country SEA and Coongie Lakes, as well as habitat for the grey grasswren and Australian painted snipe, braided sea heath and *Sclerolaena walkeri.* Confidence in existing avoidance and mitigation strategies prescribed in state regulations and industry management plans is high.
- Direct impacts of surface disturbance could occur in 25% of the Cooper GBA region due to soil compaction, storage ponds, vegetation removal and vehicle movement. Habitat degradation is of 'potential concern' in 28% of floodplain, wetland and riparian areas and could impact on agricultural productivity and the condition of protected areas including the Channel Country SEA and Coongie Lakes. There is high confidence in existing protections, including legislated, 'no-go', areas, and industry controls can minimise future impacts on riparian vegetation. Mitigation strategies to manage site disturbance are well established. However, knowledge to determine robust and meaningful material change thresholds for processes affecting habitat is limited.
- Indirect impacts of surface disturbance could occur in 27% of the Cooper GBA region due to artificial water sources, introduced plants, predators and herbivores. Competition, predation, and habitat degradation, fragmentation and loss are of 'potential concern' in 23% of dryland areas, which could affect the kowari, yellow-footed rock-wallaby, and possibly the night parrot. Effective mitigation strategies for indirect impacts require coordinated regional responses and management plans.

Potential impacts below the surface

Pathways associated with development activities (drilling, hydraulic fracturing, well decommissioning and rehabilitation, production of hydrocarbons, and waste and wastewater management) could cause aquifer contamination or drawdown. Potential impacts of 'potential concern' below the surface that can be mitigated include the following:

- Aquifer contamination in less than 1% of the Cooper GBA region. Due to modelling constraints, aquifer contamination cannot be ruled out within 500 m of an existing water bore or groundwater-dependent ecosystem. There is high confidence that aquifer contamination can be mitigated through ongoing compliance with existing regulations and approval conditions developed over more than 50 years of conventional oil and gas production in the Cooper Basin. Hydraulic fracture modelling shows that natural barriers, such as the Nappamerri aquitard, protect overlying aquifers from contamination due to compromised aquitard integrity in the Cooper Basin. The risk of hydraulic fractures intersecting an aquifer can be mitigated by controls in existing regulations, sufficient understanding of the baseline geological and environmental systems, and industry practices. Aquifer contamination due to compromised well integrity is of 'very low concern' in the Cooper GBA region based on findings from domestic and international inquiries, as well as historical compliance reports for Cooper Basin petroleum wells. Stringent approval and management requirements, including national guidelines, state regulations and industry waste management plans, give confidence that waste disposal is of 'low concern' in the Cooper GBA region.
- Groundwater drawdown in less than 1% of the Cooper GBA region. Due to modelling constraints, drawdown in the Cadna-owie – Hooray aquifer in excess of 2 m cannot be ruled out within 1 km of existing bores and where the saturated aquifer thickness is less than 150 m in the south-west of the Cooper GBA region. For groundwater-dependent ecosystems that access the shallow unconfined aquifers in the west of the Cooper GBA region, drawdown in excess of 0.2 m in the Cenozoic and Winton-Mackunda aquifers cannot be ruled out where the saturated aquifer thickness is greater than 20 m. Alternative water sources, such as groundwater from other aquifers, or reuse of co-produced water, could avoid potential impacts in these areas.

Potential impacts on the environment

Environmental values in the Cooper GBA region are represented by agricultural productivity, 4 key vegetation communities (dryland, floodplain, riparian and wetland; Figure 12) and 9 protected areas. This includes nationally and internationally listed wetlands, regionally protected areas and permanent waterholes.

Riparian ecosystems provide important connections between terrestrial and aquatic habitats and include parts of key ecological assets such as the Ramsar-listed Coongie Lakes, DIWA-listed wetlands and Channel Country SEA, as well as plants and animals of cultural significance for Indigenous peoples. Riparian areas are relatively undisturbed, which reflects the greater degree of protection for riparian areas than for wetland or floodplain areas. Potential impacts for riparian ecosystems could occur through direct impacts, such as soil compaction, vegetation removal and vehicle movement. However, existing measures to protect riparian areas are not focused on preventing indirect impacts that occur beyond riparian areas, such as invasive plants and predators or accidental release of chemicals into surface waters.

In the arid environment of the Cooper GBA region, permanent waterholes are important habitats and refuges for flora and fauna during dry times. Many waterholes have customary, spiritual and economic values to Traditional Owners and have been part of traditional trade routes for tens of thousands of years. Measurements of water levels, water balance, chemistry and environmental tracer samples from 17 waterholes and 29 groundwater bores confirmed previous studies showing that surface water periodically recharges freshwater lenses that sustain fringing riparian vegetation along permanent waterholes. This means that drawdown in the regional aquifers will not impact on groundwater-dependent vegetation growing on the floodplains of Cooper Creek.

Riparian and wetland ecosystems are closely linked to Indigenous peoples in the region, with plants and animals being significant from cultural and economic perspectives. For example, the iconic river red gum (*E. camaldulensis*) not only provides a range of ecosystem services such as bank stabilisation and the provision of habitat, but also provides food, timber for tools and utensils, and medicines for Indigenous peoples. Satellite monitoring of water use on the floodplains and wetlands, and by fringing riparian vegetation along Cooper Creek showed that floodplain soils and vegetation use more water (77%) than the high ecological value wetlands, waterholes and fringing riparian vegetation, which account for less than a quarter (23%) of total water use.

Wetland ecosystems are extensive in the Cooper GBA region and include key ecological assets such as the Ramsar-listed Coongie Lakes, DIWA-listed lakes and wetlands, as well as habitat for the grey grasswren (*Amytornis barbatus barbatus*) and the Australian painted snipe (*Rostratula australis*), and plants and animals with significant cultural and economic values for Indigenous peoples. Floodplains are extensive in the Cooper GBA region and provide habitat for a range of species including plants such as braided sea heath, *Scleroleana walkeri* and *Xerothamnella parvifolia*. Water regimes – particularly the frequency, extent and duration of flooding – control the structure and dynamics of floodplain ecosystems. Flooding provides a significant boost to the productivity of the region, particularly the pastoral industry which relies on grazing on natural pastures.

Field and modelling studies to address knowledge gaps identified in Stage 2 (Section 7.1 in Stage 2 baseline synthesis and gap analysis (Holland et al., 2020)) include the following:

- Light detection and ranging (LiDAR) aerial surveys and 2D hydrodynamic flood inundation model. Cooper Creek floodplain spans across Queensland and South Australia, is large (about 32,000 km^2) and floods frequently. It has extremely complex terrain, very low gradients and little observed data. Aerial surveys were flown across the Cooper Creek floodplain and the Thompson and Barcoo river systems to capture digital elevation data. There is good agreement between the calibrated 2D hydrodynamic flood inundation model (MIKE21FM) and satellite data for historical floods. The model can evaluate how flood characteristics may change under future development and climate change scenarios in one of the most complex floodplains in the world.
- Regional-scale biodiversity persistence modelling. While intense localised impacts on habitat (for example, roads, fence lines, seismic lines and well pads) are important in large regions, these are dwarfed by land management across vast areas. The intact landscape of the Cooper GBA region supports relatively high biodiversity (greater than 0.9) values. Trends vary between years with rainfall but are generally stable. These data can help establish baseline environmental conditions, detect change and monitor impacts within a natural capital accounting framework.

- Vegetation condition, estimated using satellite imagery from 2001 to 2018, provides estimates of extent and condition of vegetation communities for natural capital accounting. A 12 to 41% decrease in vegetation cover was detected near existing gas extraction wells a year after well establishment, which started to recover after about 4 years, and had recovered to pre-development condition after 5 to 7 years. Rapid decreases in vegetation cover of up to 60% after fire were observed, with recovery periods in excess of a decade.

Potential impacts on protected fauna and flora

Key threatening processes for the 12 protected flora and fauna species could be amplified by future unconventional gas resource development without implementation of appropriate mitigation, management and monitoring measures. These processes are of 'potential concern' in approximately 30% of the Cooper GBA region and include habitat degradation, fragmentation and loss; competition and predation by invasive species; and changed fire regimes. Unconventional gas resource development may also introduce threatening processes that are not currently recognised and for which there is less knowledge, such as noise and light pollution, soil compaction, and contamination that could cause the pollution of soil and water.

Habitat degradation, fragmentation and loss is recognised, based on existing conservation advice and recovery plans, as a threatening process for the Australian painted snipe, grey grasswren, plains-wanderer, kowari, dusky hopping-mouse, yellow-footed rock-wallaby and braided sea heath, and is a suspected threat for remaining species in the region. Key stressors include vegetation removal for infrastructure and the spread of invasive species, particularly those likely to lead to habitat degradation such as introduced herbivores or pigs.

Predation by cats and foxes is recognised as a key threatening process for 4 of the 7 protected fauna species: the plains-wanderer, kowari, dusky hopping-mouse and the yellow-footed rock-wallaby. While there is less supporting evidence, it is likely that predation is important for the other 3 fauna species in the region: the Australian painted snipe, grey grasswren and night parrot. In addition, competition with feral herbivores for resources, such as food and shelter, is a key threatening process identified for the night parrot, dusky hopping-mouse and yellow-footed rock-wallaby.

Altered fire regimes are assessed as of 'potential concern' in 30% of the Cooper GBA region and for all protected species in the assessment. Increased average temperatures, increased number of hot days (more than 35 °C) and shifting rainfall regimes combine to increase risks to biodiversity associated with fire. Changes in fire regimes are identified as important threatening processes for the grey grasswren, night parrot, plains-wanderer and yellow-footed rock-wallaby. Some species such as the grey grasswren or the night parrot require habitats that are relatively free of fire for long periods. However, relationships between species persistence and fire for many species are unclear. It is suspected that altered burning regimes are likely to have direct (such as mortality) and indirect (such as habitat modification) impacts on all species in the Cooper GBA region.

Reduced flood duration and extent is assessed as of 'potential concern' for 2 endangered bird species – the Australian painted snipe and the grey grasswren – but is not identified as a direct threat in existing conservation advice and recovery plans. Where knowledge of plant biology and water requirements is limited, the precautionary principle is applied, and changes to floodplain inundation are assessed as of 'potential concern' for braided sea heath, *Indigofera oxyrachis* and *Xerothamnella parvifolia.*

Soil and surface water contamination are conservatively assessed as of 'potential concern' for all fauna-related endpoints as there is insufficient species-specific information to establish robust materiality thresholds for the toxicity of potential pollutants on the 7 protected fauna species. Assessment of potential impacts on native fauna due to soil and surface water contamination considers population size, habitat extent, proximity to water, water requirements and species mobility.

Noise and light pollution can have significant impacts on all animal taxa. Due to considerable uncertainty, noise and light pollution is assessed as of 'potential concern' in 25% of the Cooper GBA region. Noise and light pollution may impact on cryptic (for example, the Australian painted snipe) or nocturnal species (for example, the night parrot, kowari and dusky hopping-mouse). Noise and light pollution are not currently recognised as key threatening processes for these species.

7.2 Knowledge gaps, limitations and opportunities

The assessment method addresses uncertainties related to the precise location, scale and nature of future development activities to allow government and the community to better understand potential impacts on water and the environment at a regional scale. Systematic evaluation of confidence for each link in the causal network identifies knowledge gaps related to the cause-and-effect relationships, materiality thresholds and mitigation strategies in the assessment. A detailed description of knowledge gaps related to causal pathways from unconventional gas resource development to individual endpoints is detailed for each endpoint (**see causal network**) and reported in the **assessment summary** for the Cooper GBA region.

Knowledge gaps

The details about the nature and characteristics of a future unconventional gas resource development scenario are uncertain, particularly at a local scale. This affects many aspects of the assessment, including:

- The scale, location and timing of future development. There needs to be an economically viable level of infrastructure investment to connect the resource to market (such as production of hundreds of terajoules per day from hundreds of wells over the development lifetime). Development location influences the interactions with environmental, economic, cultural and social values. Location and timing of development affects rate-dependent potential impacts, such as water extraction and vegetation removal.
- The technologies used for future development. The amount and quality of water required for drilling and hydraulic fracturing, the chemicals used for those activities, and the exact nature of the surface footprint (such as number of wells per well pad and the spacing of well pads) will change as new technologies develop. Practices ensuring well integrity and management of drilling and hydraulic fracturing fluids, and the chemicals used in them, are likely to maintain or improve upon current standards.

- The volume and treatment of flowback water. The amount and quality of flowback water from hydraulic fracturing operations and the technologies available for its treatment, ultimately influence how much flowback water can be reused, recycled for subsequent hydraulic fracturing operations, or whether final disposal is required.
- Future interactions with other industries. High-resolution quantitative information on both the state of the environment and the processes acting on the landscape is needed to assess interactions with other drivers of system change (for example, agriculture, tourism, infrastructure development, climate change), which are not in the scope for the GBA.
- How thresholds of material change will be altered due to climate change.
- Ecological processes. Better understanding of the occurrence, distribution and sensitivity to development for each endpoint in the Cooper GBA region is needed, including detailed assessment of habitat requirements of species, estimates of the population size, reliance on surface water, optimum fire management regimes, and impacts of increased competition and predation by invasive species.

Knowledge gaps are prioritised where there is low confidence in cause-and-effect relationships, materiality thresholds and/or mitigation strategies. Specific knowledge gaps identified in the assessment include:

- How habitat is used by protected fauna varies in space and time. Materiality thresholds for links related to key ecological processes such as competition and predation, ecosystem burning, habitat degradation, fragmentation and loss or mortality of native species for individual species are poorly understood.
- Toxicity of chemicals used for future development, and relative toxicity of daughter compounds from chemical reactions and degradation. Limited data are available on the chronic toxicity of these chemicals, which is either largely unknown or extrapolated from acute toxicity studies. Other knowledge gaps that highlight the need for local-scale assessment include the behaviour of contaminants in wetlands and waterbodies, including attenuation of contaminants, changing concentrations with pulsed releases in boom-and-bust ephemeral systems, and partitioning and accumulation in sediments. Better understanding of the materiality thresholds for species or functional groups of species, based on how a single spill at a local scale impacts a protected matter at a large scale, in terms of species population persistence and fitness or wetland health would improve the assessment.
- Management and disposal of brines from treated flowback water at regulated waste disposal facilities. It is not known whether or how this will change in the future, and what additional avoidance and management techniques are needed to reduce the likelihood of impacts if local disposal were to be an option.
- Changes to habitat and water requirements of individual species with climate shifts, particularly increased night-time temperatures. Effect of noise and light pollution for cryptic or nocturnal species is also largely unknown.

Limitations

While the assessment is designed to be structured, robust and transparent, there are limitations for both the method and assumptions made by the assessment team, including representation of the following:

- Non-linear effects or time-varying cause-and-effect relationships that capture the boom-and-bust dynamics of a region. It is not a trivial exercise to represent the complex reality of ecological and hydrological systems in a directional acyclic graph (the graphical causal network). One of the most challenging aspects is that feedback loops cannot be represented. Feedback loops are an essential feature of complex natural systems. When represented in a graph, however, it is no longer possible to unequivocally establish causal pathways between starting and ending nodes.
- Adverse impacts and benefits. In line with guidelines under the EPBC Act (Commonwealth of Australia, 2013), where an action may have both adverse and beneficial impacts, only adverse impacts are assessed. However, positive effects are also evident. For example, while new roads in a landscape may increase bushfires due to an increased likelihood of accidental ignition, roads can also act as firebreaks, limiting the spread of bushfires. To determine net benefits of an action, a more quantitative estimate of the likelihood and magnitude of positive and negative effects is needed.
- Ecological, economic and/or social values to be protected. Environmental values are represented in the assessment by key ecological and hydrological systems in the Cooper GBA region. The 12 protected fauna and flora listed under state or national legislation were prioritised for assessment based on the importance of the Cooper GBA region to the continued persistence of each species. Significant cultural assets, including the Burke, Wills, King and Yandruwandha National Heritage Place and a range of Indigenous peoples, values are considered in the assessment of landscapes and protected areas. However, while the assessment takes a values-based perspective, more detailed assessment of potential impacts on cultural heritage values are beyond the scope of the GBA Program and are not directly represented in the causal network.
- Cumulative impacts of multiple stressors from multiple industries. Future studies could extend the causal network to other industries, such as pastoralism or tourism, to assess the impacts of multiple activities and stressors on processes and endpoints. A quantitative assessment of the magnitude and likelihood of cumulative impacts is not possible without detailed baseline and future development scenarios.
- Ecological processes and interactions. Links between activities, stressors, processes and endpoints are unable to capture all of the nuance of more detailed ecological conceptual models, which may cause unintended assessment outcomes. For example, the stressors **storage ponds**, **vegetation removal** and **vehicle movement** link to the **mortality of native species** process node, which links to all of the fauna and flora endpoint nodes. As such, increased drowning of native species in storage ponds decreases persistence of protected fauna and flora. In future, mortality of mobile and sedentary species could be assessed separately. Increased herbivory associated with the stressors **artificial water sources** and **invasive herbivores** is represented by the process **competition and predation**.

Opportunities

The regional-scale assessment allows regulators and proponents to better focus and coordinate future assessment, management and monitoring. For example, the spread of invasive species may amplify key threatening processes that impact on the persistence of threatened species in the region. Mitigation and management of invasive species is best achieved via coordinated industry-wide approaches that work with existing land managers and natural resource management programs, including whole-of-life-cycle planning and risk management.

The causal network allows systematic examination of potential impacts on water and the environment associated with unconventional gas development activities. At a practical level, this may be useful in the formulation of terms of reference for environmental impact assessments of individual projects, ensuring that the identified pathways of concern are addressed. Importantly, due to its whole-of-region approach, the causal network for the Cooper GBA region is not a substitute for careful assessment of individual unconventional gas development projects in the Cooper GBA region under Australian or state environmental law. Such assessments may use finer scale groundwater and surface water models, consider impacts on matters other than water and the environment, and include interactions with neighbouring developments in greater detail.

Ecosystem extent and condition accounts capture the spatial and temporal trends in the natural resources and services to improve quantification and conceptualisation of the biophysical environment at a regional scale. Baseline accounts compiled for this assessment can be updated to track trends in extent and condition at a regional scale. Improved remote sensing technologies using relative benchmarking approaches (Hobbs et al., 2017; Donohue et al., 2021), when combined with site-scale monitoring data, can clarify trends in ecosystem extent and condition.

At a local scale, the calibrated hydrodynamic flood inundation model can evaluate how flood characteristics may change under future development and climate change scenarios. Design of civil works – such as a watercourse crossing, road, dam or a diversion – that could change flow paths on the floodplain and in small flood runners can be avoided through compliance with state and regional regulations at the design stage.

The assessment method is designed to be updated. New nodes, links and endpoints can be added to the causal network when new data and knowledge become available or the focus of the assessment changes. Link evaluations (and their spatial grids) can be updated to reflect improved knowledge, reduced uncertainty, new mitigation strategies or to better represent local-scale datasets, such as modelled groundwater drawdown. As individual gas resource development projects are assessed, the causal network can be updated to allow proponents and regulators to continue to prioritise future assessment, mitigation and monitoring activities.

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Glossary

Terms and definitions used in the Geological and Bioregional Assessment Program are available online.

accumulation: in petroleum geosciences, an 'accumulation' is referred to as an individual body of moveable petroleum.

activity: for the purposes of geological and bioregional assessments, an activity is 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.

annual flow: the volume of water that discharges past a specific point in a stream in a year, commonly measured in GL/year.

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

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.

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.

avoidance: averting the risk by deciding not to start or continue with the activity that gives rise to the risk. For the purpose of geological and bioregional assessments, the decision not to start an activity is mandated by the locally relevant legislation.

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 labelled a bed, the stratum must be distinguishable from adjacent beds.

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

causal network: graphical models that describe the inferred cause-and-effect relationships linking development activities with ecological, economic and/or social values – referred to as endpoints – that are to be protected.

causal pathway: for the purposes of geological and bioregional assessments, the logical chain of events – either planned or unplanned – that link unconventional gas resource development and potential impacts on water and the environment.

charge: in petroleum geoscience, a 'charge' refers to the volume of expelled petroleum available for entrapment.

coal: a rock containing greater than 50 wt.% organic matter.

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.

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.

consequence: the outcome of an event and has an effect on objectives.

contaminant: a biological or chemical substance or entities that are not normally present in a system or any unusual concentration (high or low) of a naturally occurring substance that has the potential to produce an adverse effect in a biological system.

contamination: an increase in the concentration of a biological, chemical or physical property that has the potential to produce an adverse effect in a biological system.

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 2,500 m thick and occurs at depths between 1,000 and 4,400 m. It occupies a total area of approximately 130,000 km^2 and is overlain completely by the Eromanga and Lake Eyre basins. Most of the Cooper Basin is in south-western Queensland (95,740 km^2) and north-eastern South Australia (34,310 km^2). It includes a small area of New South Wales at Cameron Corner (8 km^2).

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, total impact on endpoints from multiple stressors, and their interactions, due to multiple developments in multiple industries.

dataset: a collection of data in files and/or databases or delivered by services that comprise a related set of information. Datasets may be spatial (for example, a shape file or geodatabase or a Web Feature Service) or aspatial (for example, 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.

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.

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 shape of an inverted bowl. Strata in a dome dip outward and downward in all directions from a central area.

drawdown: a lowering of the groundwater level caused, for example, by pumping.

driver: the major external driving forces that have large-scale influences on natural systems. Drivers can be natural or anthropogenic forces.

ecological values: values associated with estuarine, freshwater and marine aquatic ecosystems, groundwater-dependent and terrestrial ecosystems.

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.

effect: a specific type of an impact (any change resulting from prior events). For the purposes of the impact analysis for the geological and bioregional assessments, an effect is the change in node B due to a change in node A; for example, a change in vegetation removal due to a change in civil construction.

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 their reservoir rock.

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.

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

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.

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

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

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.

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.

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

impact: the difference between what could happen due to changes associated with development of extractive industries, such as shale gas development, and what would happen without development. For the purposes of the geological and bioregional assessments, impacts are adverse changes to endpoints that represent the ecological, economic and/or social values to be protected. Impacts can be a direct or indirect consequence of single or multiple developments. For example, an impact of unconventional gas resource development could be a decrease in the persistence of the grey grasswren.

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.

invasive: for the purposes of the geological and bioregional assessments, refers to a species that (i) has successfully established outside its natural range as a result of human actions, deliberate or inadvertent, that have enabled it to overcome biogeographical barriers; (ii) gone on to has spread rapidly over substantial distances from sites of introduction; and (iii) has the potential to have harmful effects on components of the natural environment.

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.

level of concern: rating that describes assessment of potential impacts on an endpoint in the causal network. This rating is based on evaluation of likelihood and consequence and takes into account compliance with existing regulatory controls and operational practice.

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: the chance that something might happen.

management: for the purposes of geological and bioregional assessments, a coordinated set of activities and methods used to minimise and control risks.

material change: for the purposes of the geological and bioregional assessments, an expression of the severity or consequence of a change. A change that exceeds defined thresholds in terms of magnitude, extent, duration, timing or frequency that is likely to require local-scale assessment, mitigation and monitoring.

mature: a hydrocarbon source rock that has started generating hydrocarbons.

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.

mitigation: minimising the risk by removing the risk source, or changing the likelihood or consequences of the activity that gives rise to the risk.

oil: a mixture of liquid hydrocarbons and other compounds of different molecular weights. Gas is often found in association with oil. Also see petroleum.

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.

petroleum: a naturally occurring mixture consisting predominantly of hydrocarbons in the gaseous, liquid or solid phase.

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.

precautionary principle: a mandate to address uncertainty and to ensure that potential impacts, though not well-defined or understood, are considered in decision making.

process: for the purposes of geological and bioregional assessments, a naturally occurring mechanism (for example, groundwater drawdown) that could change a characteristic of an endpoint.

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.

recharge: see groundwater recharge.

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.

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 (AS/NZS ISO 31000:2009). 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 (for example, clay, sand and 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.

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.

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.

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.

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: for the purposes of geological and bioregional assessments, a stressor is a physical, chemical or biological agent, environmental condition or external stimulus that might contribute to an impact.

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.

surface water: surface-expressed waters that are either permanent or ephemeral.

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.

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 CO2) 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.

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.

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

well: typically a narrow diameter hole drilled into the earth for the purposes of exploring, evaluating, injecting or recovering various natural resources, such as hydrocarbons (oil and gas), water or carbon dioxide. A well is 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 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 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).

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

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