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BIOREGIONAL ASSESSMENTS

CSIRO

Geological and environmental baseline assessment for the Beetaloo GBA region

Geological and Bioregional Assessment: Stage 2

2020

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

The Geological and Bioregional Assessment Program

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

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

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Authorship is listed alphabetically after the basin leader, second author and former basin leader.

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

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Cover photograph

Mataranka Thermal Pools, Beetaloo GBA extended region, October 2018
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Element: GBA-BEE-2-381

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At a glance

The $35.4 million Geological and Bioregional Assessment Program is assessing the potential environmental impacts of shale and tight gas development to inform regulatory frameworks and management approaches. The geological and environmental baseline assessment for the Beetaloo GBA region (Stage 2) evaluates the available data, knowledge and conceptual models that are the building blocks for the impact analysis and considerations for management approaches (Stage 3). The Beetaloo GBA region (Figure 1) is located about 500 km south-east of Darwin between Katherine and Tennant Creek and hosts significant gas reserves.

Geology and gas resources: Areas of higher prospectivity for shale gas, tight gas and shale oil include the Kyalla and Velkerri formations within the Mesoproterozoic Roper Group and the Hayfield mudstone. This is consistent with the location of recent exploration activity.

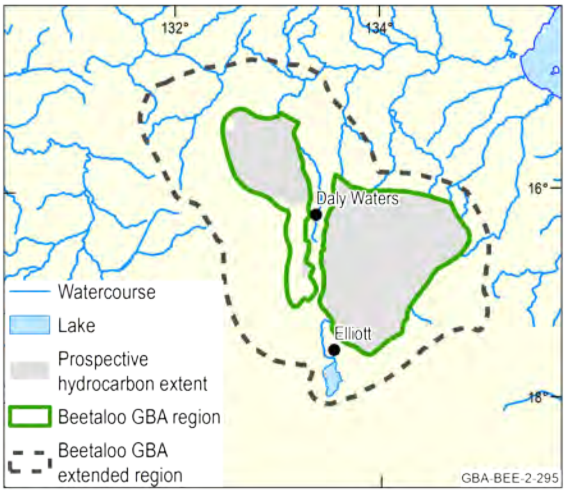

Figure 1 The Beetaloo GBA region and Beetaloo GBA extended region

Element: GBA-BEE-2-295

Groundwater: The Cambrian Limestone Aquifer (CLA) system is an important groundwater resource with water quality suitable for agricultural, domestic and industrial uses. The Mesoproterozoic Roper Group, prospective for oil and gas, is not accessed for groundwater due to its depth for drilling required and poor water quality.

Surface water: Most streams in the region are ephemeral and only flow in response to wet season rains. Baseflow from groundwater supports the Roper River and important wetlands such as Mataranka Thermal Pools and Limmen Bight (Port Roper) Tidal Wetlands System.

Water availability: Under new NT Government policy, surface water is unavailable for use in a future unconventional petroleum industry and groundwater extraction must be licensed. Groundwater and produced water from future unconventional resource extraction are possible water sources that need further investigation.

Potential hydrological connections: The characteristics of the Kyalla and Velkerri formations within the Roper Group are likely to impede connections between the petroleum resource and groundwater. Possible connections between the Hayfield mudstone and overlying groundwater systems will be investigated in Stage 3.

Protected matters: National and NT protected matters were documented and prioritised based on the importance of the Beetaloo GBA extended region to the matter. Stage 3 will assess in greater detail five protected species (four nationally listed, one territory listed), two nationally important wetlands and groundwater-dependent ecosystems.

Regional-scale assessment (priority 2) will focus on landscape classes based on conceptual models of how landscapes function ecologically. The Beetaloo GBA region was categorised into six landscape classes, dominated by the 'loamy and sandy plains' and 'clay plains' landscape classes.

Potential impacts: The impact and risk assessment approach uses hazard identification as a first step, with about 180 individual hazards identified. Using causal pathways – the logical chain of events that links unconventional gas resource development with potential impacts on water and the environment – 13 causal pathways were identified and aggregated into three groups.

In Stage 3 the links between the causal pathways and potential impacts will be investigated. For example, do unconventional petroleum resource development activities change groundwater quality and availability, fragment habitats and/or introduce invasive species? Eleven causal pathways will be assessed for these and other impacts in Stage 3.

The Geological and Bioregional Assessment Program

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

In consultation with state and territory governments and industry, three geological basins were selected based on prioritisation and ranking in Stage 1: Cooper Basin, Isa Superbasin and Beetaloo Sub-basin. In Stage 2, geological, hydrological and ecological data were used to define 'GBA regions': the Cooper GBA region in Queensland, SA and NSW; the Isa GBA region in Queensland; and the Beetaloo GBA region in NT.

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

The GBA Program aims to:

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

The GBA Program commenced in July 2017 and comprises three stages:

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

As part of the 2019 budget, the Australian Government committed an additional $5.022 million to the GBA Program to align the delivery of the assessment of the Beetaloo Sub-basin with the NT Government's Strategic Regional Environmental Baseline Assessment (SREBA). The additional funds will be used to undertake terrestrial and aquatic biodiversity surveys, additional water sampling to improve the understanding of groundwater flow and water quality, baseline seismic monitoring and development of data delivery systems.

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

About this report

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

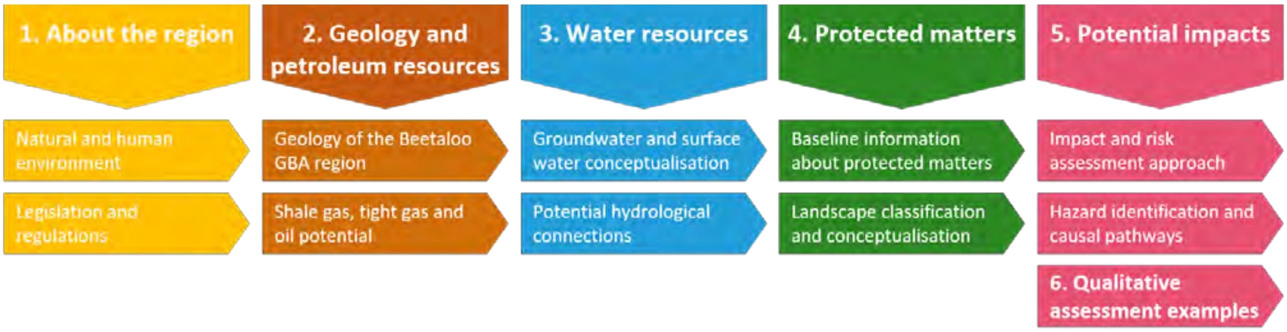

Figure 2 Geological and environmental baseline assessment report structure

Element: GBA-BEE-2-003

1. **'About the region'** briefly introduces the natural and human environments of the Beetaloo GBA region and summarises the legislative and regulatory controls governing water and gas resource development.
2. **'Geology and petroleum resources'** defines the stratigraphic and structural characteristics that may influence shale gas, tight gas and shale oil prospectivity, extraction and potential environmental risks. The spatial extent and relative prospectivity of the resources are assessed.
3. **'Water resources'** describes the current conceptual understanding of surface water and groundwater and water quality, and the surface water – groundwater interactions in the region. This section concludes with an assessment of the availability of water resources for future drilling and hydraulic fracturing for shale gas, tight gas and shale oil development.
4. **'Protected matters'** describes the environmental and cultural knowledge in the region, with an emphasis on Matters of National Environmental Significance and Matters of Territory Environmental Significance. Landscape classification is used to systematically define geographical areas with similar physical and/or biological and hydrological characteristics.
5. **'Potential impacts'** identified by a systematic hazard analysis of the potential hazards associated with all life-cycle stages of shale gas, tight gas and shale oil development, definition of a set of causal pathways, which represent the logical chain of events, either planned or unplanned, that may link shale gas development activities with potential impacts on water and the environment (Figure 58) and then aggregated into three causal pathway groups.
6. **'Qualitative assessments'** presents assessments of three important issues to the community, government and industry: screening of drilling and hydraulic fracturing chemicals, hydraulic fracturing and well integrity.

All maps for the Beetaloo GBA region use the Map Grid of Australia (MGA) projection (zone 53) and the Geocentric Datum of Australia 1994 (GDA94).

User values

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

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

The user panel for the Beetaloo GBA region met in July 2018 and May 2019 and has:

- identified sources of additional data and knowledge from government, industry and communities and reinforced the cultural, hydrological and ecological uniqueness of the region
- highlighted the importance of the findings of this work contributing to the SREBA that will be required by the NT Government prior to any granting of production approvals, particularly in the areas of ecological and hydrological baseline assessments, geological studies and data delivery.

Technical appendices

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

- Orr ML, Bernardel G, Owens R, Hall LS, Skeers N, Reese B and Woods M (2020) Geology of the Beetaloo GBA region.
- Hall LS, Wang L, Bailey AHE, Orr ML, Owens R, Jarrett AJM, Lech ME, Skeers N, Reese B and Woods M (2020) Petroleum prospectivity of the Beetaloo Sub-basin.
- Evans TJ, Radke BM, Martinez J, Buchanan S, Cook SB, Raiber M, Ransley TR, Lai ÉCS, Skeers N, Woods M, Evenden C, Cassel R and Dunn B (2020) Hydrogeology of the Beetaloo GBA region.
- Pavey C, Herr A, MacFarlane CM, Merrin LE and O'Grady AP (2020) Protected matters for the Beetaloo GBA region.
- Kirby JK, Golding L, Williams M, Apte S, Mallants D, King J, Otalega I and Kookana R (2020) Qualitative (screening) environmental risk assessment of drilling and hydraulic fracturing chemicals for the Beetaloo GBA region.
- Kear J and Kasperczyk D (2020) Hydraulic fracturing and well integrity review for the GBA regions.

Executive summary

About the region *see Section 1, page 1*

The Beetaloo GBA region (Figure 1) is located about 500 km south of Darwin and is sparsely populated, with Daly Waters and Elliott the most populated settlements. The Beetaloo GBA region has been defined specifically for GBA purposes as the geological Beetaloo Sub-basin defined by the Northern Territory Geological Survey and covers an area of about 28,000 km^2 in the NT. Additionally, the Beetaloo GBA extended region is also used throughout this report to allow potential environmental and hydrological impacts immediately adjacent to the region boundary to be investigated. To date, there has been limited exploration for petroleum resources in the Beetaloo Sub-basin, with exploration permits currently operated by Origin Energy, Santos and Pangaea Resources.

The Beetaloo GBA region is located entirely in the tropics of the NT between Katherine and Tennant Creek (Figure 4), with tropical elements in the north and semi-arid elements in the south. The area overlies the extensive Cambrian Limestone Aquifer (CLA) – the principal water resource in the Beetaloo GBA region (Section 3.1). Most of the Beetaloo GBA region is deeply weathered, consisting of gently undulating plains at elevations of 180 to 260 m above sea level. Surface drainage in most of the Beetaloo GBA region is weakly developed. The region is characterised by soils of low agricultural potential, which support natural pastures used primarily for beef cattle production (Section 1.2).

With its tropical climate the Beetaloo GBA region has distinct wet seasons (November to March) and dry seasons (April to October), hot summers and warm winters. The inter-annual variability of rainfall (variation of rainfall from one year to the next) is high (Figure 6). A hotter and somewhat wetter climate is forecast by global climate models (Section 1.3).

Fewer than 500 people live in the Beetaloo GBA region, with around 1400 in the Beetaloo GBA extended region, over 700 of whom are Aboriginal and/or Torres Strait Islander people. More than 90% of the land area is perpetual pastoral leasehold (Figure 10). Native title has been determined to exist for the majority of these leases, and the remainder are under application. The Wubalawun, Mangarrayi and Murranji Aboriginal Land Trusts are all partially within the Beetaloo GBA region and the Alawa, Gurungu, Marlinja, Dillinya, Karlantijpa and Mambaliya Rrumburriya Wuyaliya Aboriginal Land Trusts are within, partially within or immediately adjacent to the Beetaloo GBA extended region.

The emerging shale gas, tight gas and shale oil industry is regulated at federal, state and local levels to ensure that industry development is sustainable and responsible and minimises impacts on environmental and social values. Commonwealth, intergovernmental and NT regulations relevant to the development of shale gas, tight gas and shale oil resources are summarised (Section 1.5). The development and regulation of a petroleum industry targeting onshore unconventional resources is a contentious matter in the NT and a moratorium on hydraulic fracturing was announced in 2016. There have been two inquiries into hydraulic fracturing activities in the petroleum industry in the NT over the last five years: the Hawke inquiry (Hawke, 2014) and the Pepper inquiry (Pepper et al., 2018). These inquiries have found that if the recommendations, including significant changes to the regulatory framework, are implemented then risks will be reduced to an acceptable level. The changes to regulation of petroleum activities in the NT require implementation of all recommendations prior to exploration recommencing or production commencing. The NT Government has since lifted the moratorium on hydraulic fracturing (Section 1.5.2.1).

Geology and gas resources *see Section 2, page 27*

The Beetaloo Sub-basin is a structural component of the greater McArthur Basin in the NT (Figure 12) and contains a succession of Mesoproterozoic Roper Group sediments more than 5000 m thick that were deposited over 1000 million years ago. The Beetaloo Sub-basin represents a broad depression bounded by several prominent structural highs, and it is divided into eastern and western elements by the Daly Waters High (Figure 13). Overlying sedimentary basins include the Georgina, Wiso and Daly basins and the Mesozoic Carpentaria Basin (Figure 16).

The Beetaloo Sub-basin is prospective for unconventional hydrocarbons and is estimated to contain significant technically recoverable unconventional petroleum resources. Plays most likely to be developed in a five- to ten-year time frame include shale plays in the Kyalla Formation and the Amungee Member of the Velkerri Formation, along with a tight sandstone play in the Hayfield sandstone member of the Hayfield mudstone. Production testing at the Amungee NW-1H exploration well in October 2016, which was reported by Origin Energy in 2017, showed that 6.6 Tcf of contingent gas resource may be present within the organic-rich shales of the Velkerri Formation (Section 2.2).

Characterisation of the hydrocarbons present within the plays in the Beetaloo GBA region was undertaken to support further work on understanding likely development scenarios in Stage 3 (Figure 22). Results show that the Amungee Member of the Velkerri Formation is potentially prospective for either liquids-rich or dry gas over most of the Beetaloo Sub-basin extent. The Kyalla Formation liquids-rich gas play and the Hayfield sandstone member liquids-rich gas/oil play are likely to be restricted to the central part of the eastern sub-basin. The mapped depth and extent of these plays inform where the plays are most likely to be present within the Beetaloo GBA region and inform the likely development scenarios (Figure 25, Figure 26, Figure 28). Liquids-rich gas resources are currently more favourable to develop from an economic perspective. These results in turn inform the assessment of potential impacts on associated assets at the surface and overlying surface water – groundwater systems. If and how an unconventional play is developed will be dependent on its economic viability, along with other cultural and environmental considerations.

Water resources *see Section 3, page 65*

The hydrogeology of the Beetaloo GBA region is conceptualised as three individual groundwater subsystems: (i) Neoproterozoic rocks and overlying Cambrian Antrim Plateau Volcanics – water quality unknown for Neoproterozoic rocks, generally good for Antrim Plateau Volcanics; (ii) the CLA system – water quality good (Figure 39); and (iii) Cretaceous Carpentaria Basin and Cenozoic sediments – where saturated water quality can be moderately saline. Those components are underlain by the sedimentary rocks of the Roper Group, hosting the key unconventional hydrocarbon resources, which, for the most part, is an aquitard. The most significant and documented of these subsystems is the CLA due to its importance as a water source for the pastoral industry and community as well as for the presence of karst systems that may cause local groundwater flow paths to substantially deviate from the regional flow (Section 3.1). For potential hydrological connections between the prospective petroleum resource and groundwater, consideration is given to three connectivity issues associated with (i) gas and petroleum production from prospective Roper Group formations, whereby impacts could propagate to overlying groundwater systems; extracting groundwater from units above the Roper Group to use in petroleum resource development, where impacts may spread to existing groundwater users and the environment through shallow groundwater systems; and (iii) shallow aquifers (e.g. karst features in the CLA) enabling migration of contamination due to infiltration of surface spills from petroleum development or production (Section 3.4). Local investigations relevant to risks from future shale gas, tight gas and shale oil development will be undertaken in Stage 3 to obtain a better understanding of potential connections (Section 3.6.1).

Surface water systems of the Beetaloo GBA region consist of five surface water catchments: the Roper River, Daly River, Limmen Bight River, the Wiso region and the Barkly region (Figure 40). The Roper (44%) and Wiso (47%) cover the majority of the region. There are no permanent streams within the Beetaloo GBA region; however, the groundwater discharge from the Beetaloo GBA region supports the perennial flows in the Roper River downstream of the region through discharge at Mataranka Thermal Pools and baseflow to streams in Elsey National Park. In the Beetaloo GBA extended region lie wetlands listed in *A directory of important wetlands in Australia* (DIWA): Mataranka Thermal Pools, Limmen Bight (Port Roper) Tidal Wetlands System in the Roper Basin, and Lake Woods in the Wiso region. Water quality is considered fair to good quality for drinking water (Figure 42) for gauged sites shown in Figure 40.

Investigations of hydrological connection between deeper groundwaters and surface waters reveal that across much of the Beetaloo GBA region the regional watertable lies below the ground surface (generally greater than 20 m), which precludes significant interactions between surface water features, vegetation and the regional watertable. Connectivity between the surface water and groundwaters is likely to be limited to localised shallow perched aquifer systems, rather than more regional watertables, such as those found in the CLA. Large lakes south of the region (e.g. Lake Woods), when inundated, appear to act as sources of localised recharge to the underlying watertable.

Groundwater-dependent ecosystems (GDEs) have been noted in the Beetaloo GBA region (Figure 44), some of these have potential to interact with shallow groundwater found in perched aquifers. Springs have not been identified in the Beetaloo GBA region. However, numerous springs occur to the north of the Beetaloo GBA region, where significant groundwater discharge occurs from CLA aquifers to rivers and wetlands, such as Mataranka Thermal Pools and Roper River, approximately 50 km north (Section 3.3). Hydrochemistry and dissolved gas concentrations from the CLA provide some evidence of existing hydrological connectivity between deep and shallow system components. However, the assessment also highlights that considerable data and knowledge gaps exist (Section 3.6), including for springs associated with aquifers of Proterozoic age.

Potential water sources for a future unconventional petroleum industry in the Beetaloo GBA region do not include surface water, as the NT Government has prohibited its extraction for this use (Section 3.5.1). Unallocated water reserves and other strategies in existing groundwater allocation plans do not currently consider the potential quantity of water that may be taken by the petroleum industry. The potential implications for water plans and other water users will be investigated as part of Stage 3 (Section 3.5.2). Produced water from future unconventional resource extraction is a potential water source for drilling and hydraulic fracturing operations that may be used by resource companies in the Beetaloo GBA region (Section 3.5.2). Aside from groundwater in the CLA, other sources are being considered, including the potential to use groundwater from deeper aquifers such as the Bukalara and Jamison sandstones.

Protected matters *see Section 4, page 119*

Matters of National Environmental Significance (MNES) potentially in the Beetaloo GBA region include 14 threatened species, 13 migratory species and 1 species that is both threatened and migratory. Other protected matters include 21 listed marine species. Within the Beetaloo GBA extended region there is one threatened ecological community, 15 threatened species, 15 migratory species and two species that are both threatened and migratory. Other protected matters in the Beetaloo GBA extended region comprise 23 listed marine species and five areas of Commonwealth lands.

Among Matters of Territory Environmental Significance, one territory reserve – Bullwaddy Conservation Reserve – occurs entirely within the Beetaloo GBA region. A further four reserves are outside the Beetaloo GBA region but are contained by 100% of their area within the Beetaloo GBA extended region. Also included among Matters of Territory Environmental Significance are two nationally important wetlands: Mataranka Thermal Pools and Lake Woods. These occur in the Beetaloo GBA extended region. Four species that are classified as threatened under the NT's *Territory Parks and Wildlife Conservation Act* but not under the Commonwealth's *Environmental Protection and Biodiversity Conservation Act 1999* (EPBC Act) have been recorded in the Beetaloo GBA region since 1990 and are considered likely to still occur there.

Among GDEs, springs do not occur within the Beetaloo GBA region but are present within the Beetaloo GBA extended region to the north-north-east and east as discharge complexes from the major northward flowing groundwater systems of the CLA. The springs at Mataranka Thermal Pools sustain dry-season flows in the Roper River system and support terrestrial and wetland GDEs. Connectivity between surface water and groundwater is limited within the Beetaloo GBA region because of the depth to groundwater (typically >40 m). Terrestrial GDEs are mostly limited to shallow perched aquifer systems that are fed by groundwater.

Key threatening processes operating in the Beetaloo GBA region include competition and land degradation by rabbits and unmanaged goats; predation by European red foxes and feral cats; predation, habitat degradation, competition and disease transmission by feral pigs; novel biota and their impact on biodiversity (e.g. feral horses, donkeys and camels); and biological effects, including lethal toxic ingestion, caused by cane toads.

No socio-economic or cultural assets were identified from searches of the EPBC Act on protected matters.

The assessment of potential hydrological and environmental impacts due to shale gas, tight gas and shale oil development in Stage 3 is underpinned by landscape classifications. The key ecological and hydrological features are categorised into six landscape classes (Table 15, Figure 52). Up to 70% of the Beetaloo GBA region is covered by the 'loamy and sandy plains' landscape class (Section 4.3).

In order to focus the assessment in Stage 3, protected matters were prioritised based on how important the Beetaloo GBA extended region is to each matter (Section 4.4). Detailed assessments will focus on five protected species (four nationally listed, one territory listed), two nationally important wetlands, and GDEs (priority 1).

Potential impacts due to shale gas, tight gas and shale oil development

see Section 5, page 143

The risk assessment approach follows the principles for ecological risk assessment outlined by the United States Environmental Protection Agency (1998) and Hayes (2004) to meet regulatory requirements for the Beetaloo GBA region (Figure 54). Identifying causal pathways in Stage 2 is a key component of the identification and formulation step of the GBA impact and risk assessment approach outlined in Section 5.1. Prioritised causal pathways will be the focus of the impact and risk assessment, which will be conducted in Stage 3.

Individual hazards were systematically identified and scored by considering all the possible ways an activity in the life cycle (Section 5.2.2, Figure 55) of shale gas, tight gas and shale oil development may cause impact (Section 5.2). Hazards that have similar potential impacts are grouped together in causal pathways. Causal pathways describe the logical chain of events – either planned or unplanned – that link unconventional gas resource development and potential impacts on water and the environment. There are 13 causal pathways that are aggregated into three groups (Section 5.3). Causal pathways play a central role in the assessment (Figure 58), connecting hazards arising from existing activities (Section 1.4) and potential unconventional gas resource development activities (Section 5.2) with the values to be protected (Sections 4.1 and 4.2) for each landscape class (Section 4.3). Causal pathways were prioritised for two levels of assessment in Stage 3: priority 1, where severity and likelihood warrant a detailed level of assessment; and priority 2, where severity and likelihood warrant assessment. The impact and risk assessment in Stage 3 will assess cumulative impacts and how the hazards in each causal pathway might impact on a suite of endpoints, such as endemic native species, migratory species, ecological communities, wetland ecosystems, water resources, cultural heritage and agriculture (Section 5.3).

Qualitative assessment examples *see Section 6, page 195*

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

The Tier 1 qualitative screening assessed 116 chemicals used between 2011 and 2016 for drilling and hydraulic fracturing at shale, tight and deep coal gas operations in the three GBA regions (chemicals used in shale oil developments were not assessed) (Section 6.1). About one-third (42 chemicals) were of 'low concern' and pose minimal risk to aquatic ecosystems. A further 33 chemicals were of 'potentially high concern' and 41 were of 'potential concern'. The identified chemicals of potential concern and potentially high concern would require further site-specific quantitative chemical assessments to be performed to determine risks from specific gas developments to aquatic ecosystems.

Natural rock formations contain elements and compounds (geogenic chemicals) that could be mobilised into flowback and produced waters during hydraulic fracturing. Laboratory-based leachate and extraction tests were undertaken to provide an upper-bound estimate of geogenic chemical mobilisation from target formations in the Beetaloo GBA region; and are intended to guide future field-based monitoring, management and treatment options (Section 6.1). Leachate tests on powdered rock samples identified several elements that could be substantially mobilised into solutions by hydraulic fracturing fluids: aluminium, cadmium, cesium, cobalt, iron, lanthanum, manganese, neodymium, nickel, lead, silver, yttrium and zinc. Priority organic chemicals such as phenol, polycyclic aromatic hydrocarbon (PAHs) and total recoverable hydrocarbons (TRHs) were detected in extracts of powdered rock samples. Targeted analysis of PAHs represented a small fraction of the total organic geogenic compounds present in the sample extracts. Hence, the majority of organic compounds in sample extracts (as TRHs) were unidentified and their risk (individual and mixtures) to aquatic environments is unknown.

Companies undertake an environmental risk assessment (ERA) process of gas operations (in consultation with government agencies) that identifies potential hazards (e.g. chemical transport and storage, hydraulic fracturing fluid injection, flowback and produced water storage), determines the likelihood and consequence of a risk occurring, identifies and evaluates control and mitigation measures (e.g. what controls are in place or need to be in place to address the identified risk and how effective these controls are), and develops a monitoring program to ensure controls and management strategies are adequate/effective and for compliance. Despite undertaking these detailed ERAs, there is still public concern surrounding the potential environmental impacts of hydraulic fracturing – particularly the threats posed by the mixture of industrial chemicals used and geogenic chemicals that could be mobilised and their impacts on water quality. The Stage 3 chemical assessment project will undertake water quality monitoring of future shale gas operations in the Beetaloo GBA region. The project will provide open and transparent reporting of water quality monitoring data before, during and after hydraulic fracturing to improve community and government understanding of the ERA process (for chemical assessments), controls and monitoring of chemicals; and inform wastewater management and treatment options.

Risks from hydraulic fracturing have been the focus of many studies for industry, government and academia, including the NT 2018 Pepper inquiry and the 2014 Hawke inquiry, for more than a decade. The potential environmental risks of hydraulic fracturing were qualitatively reviewed from nine domestic and eight international inquiries into onshore gas industry operations. This information was supplemented by a review of Beetaloo GBA region operations to date and hazard scoring. Potential impacts were grouped into 'impact modes' – the manner in which a hazardous chain of events (initiated by an 'impact cause') could result in an effect. From these qualitative reviews an impact mode – of low likelihood but high importance to the government, the community and industry – that cannot be ruled out for further investigation of potential impact assessment endpoints in the Beetaloo GBA region is 'F1 – Hydraulic fracture growth into aquifer'.

Regulated construction of wells for shale gas, tight gas and shale oil development activities requires all aquifers in the area to be isolated from each other, the surface and any hydrocarbon-bearing zones by appropriate well barriers. In this qualitative review, Beetaloo GBA region data were compared with findings from international and domestic inquiries and specifically the findings from the 2018 Pepper inquiry to present an initial evaluation of five conceptual impact modes (Table 27). These were compared with the prioritisations from Beetaloo GBA region hazard identification (Section 5.2) and are broadly consistent. Two impact modes have been prioritised for inclusion in Stage 3 analysis: 'W3 – Migration of fluids along casing between geological layers' and 'W4 – Migration of fluids along decommissioned or abandoned wells' (Section 6.2.2).

Conclusion *see Section 7, page 197*

The baseline data, knowledge and conceptual models presented (Section 7) are the building blocks for the Beetaloo GBA region impact analysis and management (Stage 3). Plausible development scenarios, to test the range of potential impacts, will be developed in consultation with industry, the NT Government and Australian Government agencies. Field work and modelling will be undertaken (where required) to address stakeholder questions and priority knowledge gaps (Section 7.2). Monitoring and management options will be considered as part of the impact analysis. User panel input will help target the analysis to key issues for regulation and management.

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

Contents

Figures

Tables

Contributors to the Program

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

Role or team	Contributor(s)
Program Director	Department of the Environment and Energy: Anthony Swirepik
Program Implementation Board	Department of the Environment and Energy: Beth Brunoro, Nicholas Post Bureau of Meteorology: Kirsten Garwood, Kate Vinot CSIRO: Jane Coram, Warwick MacDonald Geoscience Australia: Stuart Minchin, Richard Blewett
Basin Leader	CSIRO: Kate Holland, Cameron Huddlestone-Holmes, Paul Wilkes Geoscience Australia: Steven Lewis
Program management	CSIRO: Karen Barry, Emanuelle Frery, Linda Merrin, Ruth Palmer Department of the Environment and Energy: Mitchell Bouma, Rod Dann, Andrew Stacey, David Thomas, Alex Tomlinson
Product integration and stakeholder engagement	CSIRO: Clare Brandon, Justine Lacey, Michelle Rodriquez, Sally Tetreault-Campbell
Analysis and visualisation	CSIRO: Dennis Gonzalez, Steve Marvanek Geoscience Australia: Adrian Dehelean, Chris Evenden, Chris Lawson, Bianca Reese, Nigel Skeers, Murray Woods
Basin geology and prospectivity	Geoscience Australia: Lisa Hall (Discipline Leader), Adam Bailey, George Bernardel, Barry Bradshaw, Donna Cathro, Merrie-Ellen Gunning, Amber Jarrett, Megan Lech, Meredith Orr, Ryan Owens, Tehani Palu, Martin Smith, Liuqu Wang
Chemical assessment	CSIRO: Jason Kirby (Discipline Leader), Simon Apte, Lisa Golding, Rai Kookana, Dirk Mallants, Michael Williams
Data management and transparency	Bureau of Meteorology: Andre Zerger (Discipline Leader), Derek Chen, Trevor Christie-Taylor, Donna Phillips CSIRO: Nicholas Car, Philip Davies, Stacey Northover, Matt Stenson Geoscience Australia: Matti Peljo
Hydrogeology	Geoscience Australia: Tim Ransley (Discipline Leader), Sam Buchanan, Scott Cook, Prachi Dixon-Jain, Bex Dunn, Tim Evans, Éamon Lai, Bruce Radke, Baskaran Sundaram
Impact analysis	CSIRO: David Post (Discipline Leader), Brent Henderson, Dane Kasperczyk, James Kear, Regina Sander
Impacts on protected matters	CSIRO: Anthony O'Grady (Discipline Leader), Alexander Herr, Craig MacFarlane, Justine Murray, Chris Pavey, Stephen Stewart
Spatial analysis	CSIRO: Dennis Gonzalez, Steve Marvanek Geoscience Australia: Adrian Dehelean, Murray Woods, Nigel Skeers
Water quantity	CSIRO: Russell Crosbie (Discipline Leader), Jorge Martinez Praveen Kumar Rachakonda, Matthias Raiber, Yongqiang Zhang, Hongxing Zheng

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This technical product was reviewed by several groups:

Internal Peer Review Group:

- CSIRO – Natasha Herron
- Geoscience Australia – Jade Anderson and Merrie-Ellen Gunning
- Basin Leaders – Kate Holland (Cooper Basin), Steven Lewis (Isa Superbasin).

Technical Peer Review Group:

- Andrew Boulton, Peter McCabe, Catherine Moore, Jenny Stauber.

State Government Science Technical Review:

- Northern Territory – Department of Environment and Natural Resources, Department of Primary Industry and Resources, Northern Territory Geological Survey, Department of the Chief Minister.

Abbreviations and acronyms

Abbreviation/acronym	Definition
AAPA	Aboriginal Areas Protection Authority
API	American Petroleum Institute
CLA	Cambrian Limestone Aquifer
CSG	Coal seam gas
DIWA	*A directory of important wetlands in Australia*
EIA	US Energy Information Administration
EPBC Act	*Environment Protection and Biodiversity Conservation Act 1999*
GBA	Geological and Bioregional Assessment
GCM	Global climate model
GDE	Groundwater-dependent ecosystem
IBRA	Interim Biogeographic Regionalisation of Australia
IMEA	Impact Modes and Effects Analysis
ISO	International Organization for Standardization
MNES	Matters of National Environmental Significance
NORM	Naturally occurring radioactive material
NSW	New South Wales
NT	Northern Territory
PAH	Polycyclic aromatic hydrocarbon
PET	Annual potential evapotranspiration
SA	South Australia
SREBA	Strategic Regional Environmental Baseline Assessment
TOC	Total organic carbon
TRH	Total recoverable hydrocarbon
WAP	Water allocation plan
WCD	Water control district
WOMP	Well Operations Management Plan

Units

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

1 About the region

1.1 Beetaloo GBA region

The Beetaloo GBA region has been defined specifically for GBA purposes as the geological Beetaloo Sub-basin and covers an area of about 28,000 km^2 in the NT (Figure 3). For the purposes of this assessment, the Beetaloo GBA region has been defined based on the maximum extent of the geological Beetaloo Sub-basin (see Section 2.1), as defined by the Northern Territory Geological Survey (Department of Primary Industry and Resources (NT), 2017). This definition is based on the extent of key formations within the sub-basin. Outside this boundary, the sub-basin's sedimentary fill shallows towards the surface, and in many areas it becomes extensively faulted and deformed. There is also limited availability of sub-surface (well and seismic) data required for the petroleum prospectivity assessment outside of this region.

The Beetaloo Sub-basin is part of the greater McArthur Basin, which is located in the North Australian Craton that covers much of north-western Queensland, the NT and northern WA. Areas of the geological sequence of the Beetaloo Sub-basin are exposed in rocky outcrops in the Urapunga and the Batten fault zones to the north and east respectively.

A broader region, referred to as the 'Beetaloo GBA extended region', has also been defined (Figure 3). This larger region is used to constrain additional data discovery and to allow impacts immediately adjacent to the Beetaloo GBA region to be considered. It has been developed in consultation with the NT Government and defines the area for a Strategic Environmental Baseline Assessment (SREBA) (see Section 1.5.2.10) for the Beetaloo Sub-basin. It follows the principles in the SREBA guidelines (in draft form at time of writing). The Beetaloo GBA extended region captures appropriate catchment or subcatchment boundaries, biogeographical boundaries and wetlands listed in *A directory of important wetlands in Australia* (DIWA) such as Mataranka Thermal Pools in the north and Lake Woods in the south.

To date, there has been limited exploration for petroleum resources in the Beetaloo Sub-basin, with exploration permits currently operated by Origin Energy, Santos and Pangaea Resources. Recently, Origin Energy and Santos have recommenced exploration activities in the sub-basin.

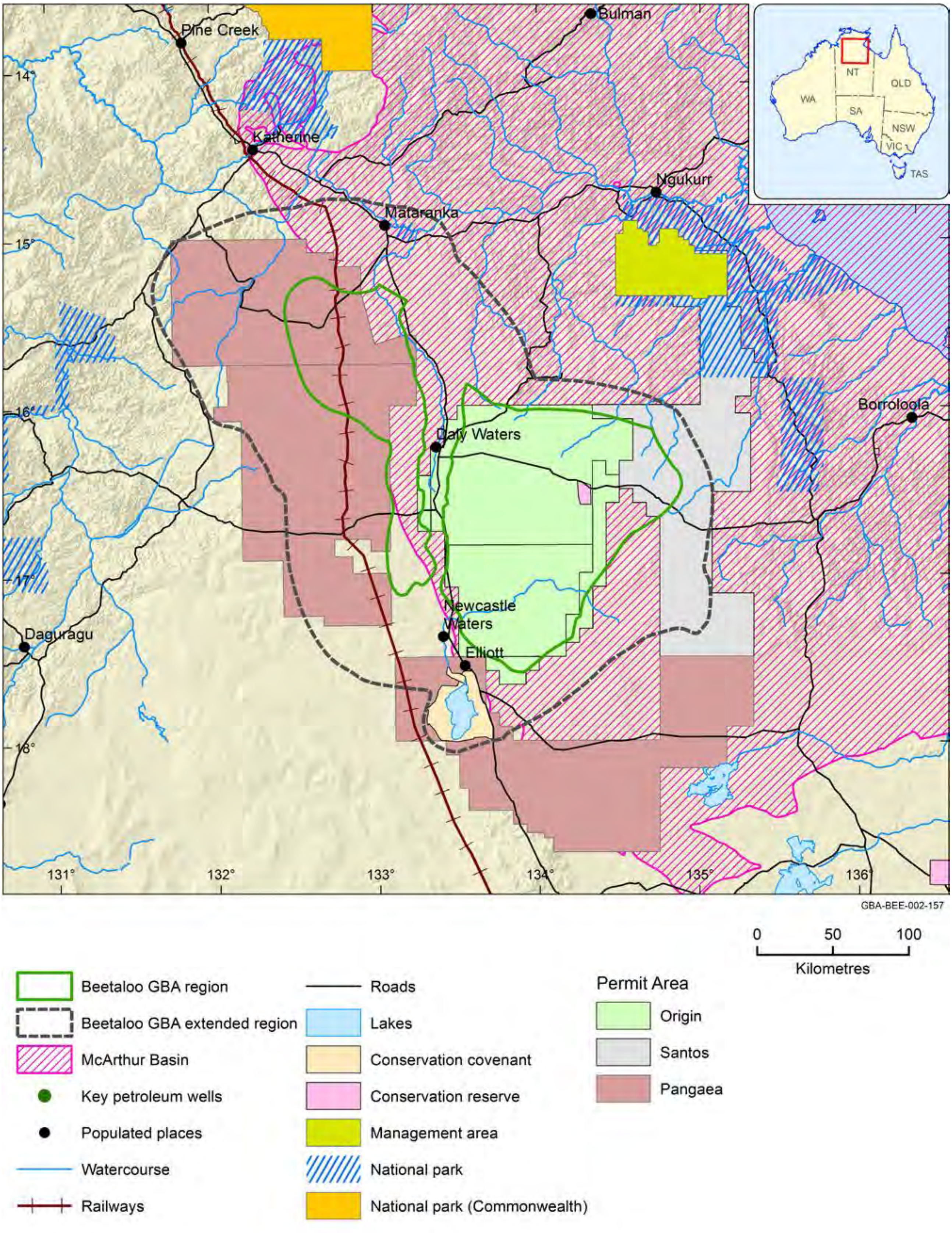

Figure 3 The Beetaloo GBA region, which corresponds to the geological limits of the Beetaloo Sub-basin, and Beetaloo GBA extended region defined for the geological and bioregional assessment of the Beetaloo GBA region

Data: Geological and Bioregional Assessment Program (2018f)
Element: GBA-BEE-2-157

1.2 Landscapes

The Beetaloo GBA region is located entirely in the tropics of the NT, south of the town of Katherine (Figure 4). The area overlies an extensive Cambrian aquifer – the Cambrian Limestone Aquifer (CLA). A distinctive feature of this aquifer is the presence of karst systems which are expressed at the surface in the form of sinkholes. The CLA is composed of two northerly flowing major groundwater flow systems that discharge at springs north of the Beetaloo GBA region. Dry-season flows in the Roper River system are sustained by groundwater discharge from these springs, thus rendering this system as perennial.

The regional groundwater in the Beetaloo GBA region is generally at depths greater than 40 m. Connectivity between surface water and groundwater systems is limited to shallow perched aquifer systems that are fed by groundwater. These systems support groundwater-dependent ecosystems.

Surface drainage in most of the Beetaloo GBA region is weakly developed. Watercourses are typically short and ephemeral. These watercourses only flow in response to wet-season rains. The Beetaloo GBA region intersects with parts of five river basins: the Roper River catchment, Daly River catchment, Limmen Bight River catchment and the catchments of the Wiso region and Barkly region. The Roper and Limmen Bight rivers flow to the Gulf of Carpentaria, the Daly River flows to the Timor Sea and the Wiso and Barkly regions are internally draining. Lake Woods is the most prominent receiving body from the Beetaloo GBA region. It is a temporary freshwater wetland that typically occupies an area of 350 km^2 but has expanded up to 850 km^2 during major floods (1993, 2001).

Most of the Beetaloo GBA region is deeply weathered, consisting of gently undulating plains at elevations of 180 to 260 m above sea level. The landscapes of the Beetaloo GBA region mostly support eucalypt woodlands over a grassy understorey. These woodlands are dominated by species of *Eucalyptus* and *Corymbia*. Among other tree species, Cooktown ironwood (*Erythrophleum chlorostachys*) is most prominent. In the central section of the region large areas of acacia-dominated open forest and woodland dominated by lancewood (*Acacia shirleyi*) occur. These are often interspersed with vegetation where the endemic Northern Territory tree (known as bullwaddy (*Macropteranthes kekwickii*)) is co-dominant or dominant. Lancewood and bullwaddy vegetation differ from eucalypt woodlands in having a dense shady shrub layer with little grass cover, thus providing regional-scale diversity for biota.

The main land use in the Beetaloo GBA region is grazing of beef cattle (there are no sheep) on natural pastures (grazing native vegetation). Pasture modification does not occur in the region. Soils in the region have low agricultural potential. Lateritic soils dominate; however, there are deep sands in the south and areas of cracking clays especially in the south.

The range of landforms and the geology, soil and vegetation in the Beetaloo GBA region are incorporated in four physiographic regions (Pain et al., 2011) and three Interim Biogeographic Regionalisation for Australia (IBRA) bioregions identified within the GBA region. Physiographic regions are defined and mapped by landform characteristics that reflect uniformity in landforms, underlying geology and contained regolith materials (Pain et al., 2011). IBRA bioregions are more broadly defined, considering broadscale patterns of distribution of biota.

The Beetaloo GBA region is noteworthy in that, regardless of considering physiographic regions or IBRA bioregions, it is dominated by a single entity: the Sturt Plateau. In terms of the physiographic regions, about 90% of the GBA region is in the Sturt Plateau, with small portions of land in the north and south being in the Gulf Fall and Barkly Tablelands regions, respectively. A very small portion in the south is in the Tanami Sandplain region (Figure 4). That part of the Beetaloo GBA region in the Gulf Fall region is more topographically complex and includes breakaways and tablelands as well as areas dominated by sedimentary rocks. The Barkly Tablelands region is dominated by Mitchell grass on extensive cracking clay soils. In terms of the IBRA bioregions, the Sturt Plateau region again dominates.

The environment of the Beetaloo GBA region is strongly influenced by a steep rainfall gradient that features a sharp decline in average annual rainfall within the region from north to south (see Section 1.3 for details). This gradient influences the biota with more tropical elements in the north and more semi-arid elements in the south.

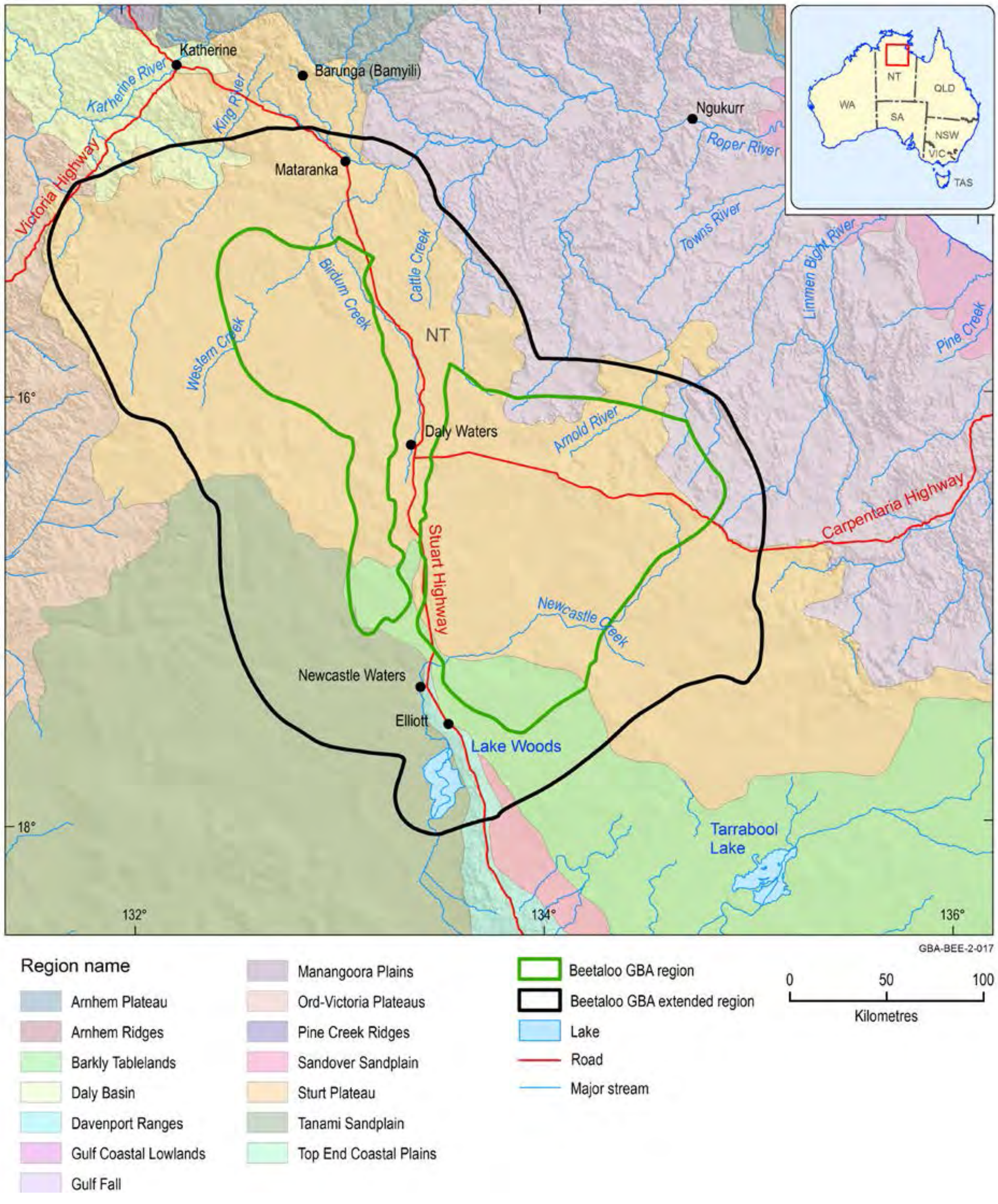

Figure 4 Physiographic regions within the Beetaloo GBA region and the Beetaloo GBA extended region

Data: Geological and Bioregional Assessment Program (2018f)
Element: GBA-BEE-2-017

1.3 Climate

The Beetaloo GBA region is characterised by a tropical climate with distinct wet seasons (November to March) and dry seasons (April to October), hot summers and warm winters as shown by the monthly distribution of rainfall and air temperatures at three sites: Elliott, Mataranka and Ngukurr (Figure 5). For the historical period 1976 to 2005 the mean monthly precipitation was at a maximum in summer, with 163 mm in February at Elliott in the south and 232 mm in February at Mataranka in the north. The minimum rainfall occurred in the winter and was comparable at all three sites, averaging 0 to 3 mm/month in June, July and August.

The average annual rainfall between 1976 and 2005 follows a distinct south-to-north gradient, with lower rainfall of 567 mm/year for Elliott in the south compared with 905 mm/year for Mataranka and 846 mm/year for Ngukurr in the north. The inter-annual variability of rainfall (variation of rainfall from one year to the next) is high; it also varies at different locations – between 1976 and 2005 the maximum annual rainfall was seven times greater than the minimum annual rainfall for Elliott but only three times greater than the minimum for Mataranka (Figure 6).

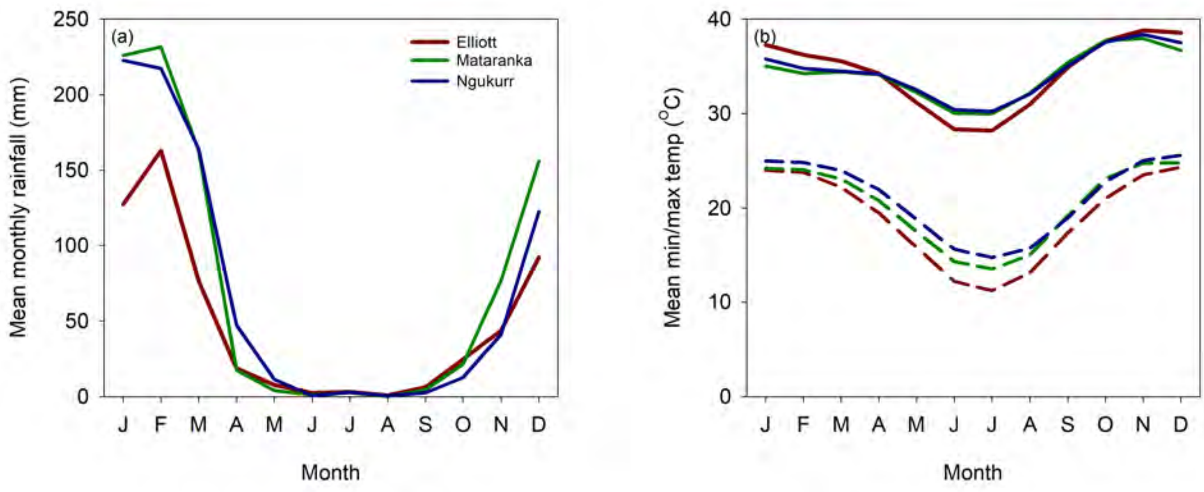

Figure 5 Elliott, Mataranka and Ngukurr: (a) mean monthly rainfall and (b) mean monthly minimum and maximum temperatures for the historical period 1976–2005

The locations for Elliott, Mataranka and Ngukurr are shown in Figure 7.
Data: State of Queensland (2018)
Element: GBA-BEE-2-031

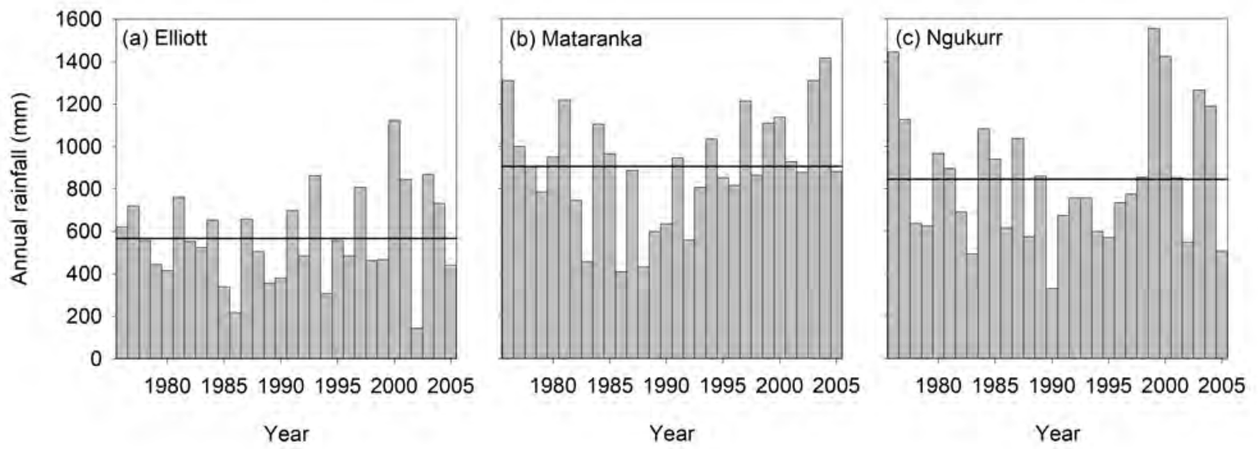

Figure 6 Annual rainfall for the historical period 1976–2005 for (a) Elliott, (b) Mataranka and (c) Ngukurr

The solid line represents the mean annual rainfall for this 30-year period.
Data: State of Queensland (2018)
Element: GBA-BEE-2-032

Methods snapshot: understanding future climates

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

The mean annual rainfall for the Beetaloo GBA region was 709 mm/year, with a maximum in the north-west of 911 mm/year and a minimum of 522 mm/year in the south. This trend is continued in the wider region, with higher rainfall to the north of the GBA region and lower rainfall to the south (Figure 7). There is an increasing trend in rainfall at all three sites over this period and this is consistent with the wider region (CSIRO, 2009). Mean annual rainfall for 2046 to 2075 relative to 1976 to 2005 was projected to have little change in the Beetaloo GBA region for the 50th percentile. The 10th and 90th percentiles give the range of future projections of mean annual rainfall of between a 20% decrease and a 10% increase (Figure 7).

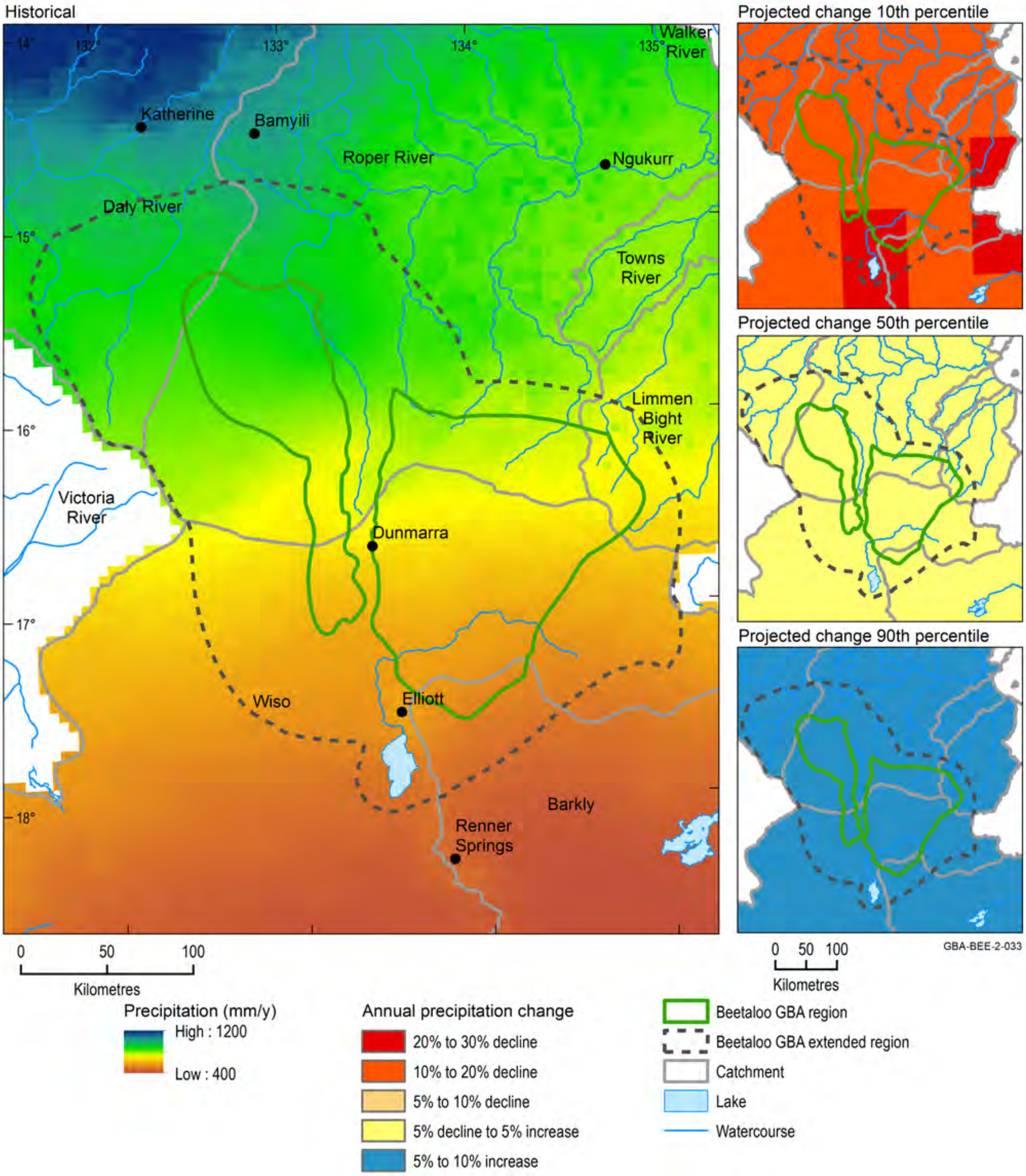

Figure 7 Spatial patterns of mean annual precipitation for the historical period (1976–2005) and 10th, 50th and 90th percentile estimates of projected percentage change in mean annual precipitation from the historical period 1976–2005 to the future period 2046–2075 across the Beetaloo GBA region

Percentiles of projected scenarios are from 42 CMIP5 global climate models under emissions in RCP8.5.
AWRC = Australian Water Resources Council; CMIP5 = Couple Model Intercomparison Project Phase 5
Data: Geological and Bioregional Assessment Program (2018a, 2018c)
Element: GBA-BEE-2-033

Mean annual potential evapotranspiration (PET) for the historical period, calculated using the Morton method (Chiew and McMahon, 1991), was high, with an average of 1905 mm/year across the Beetaloo GBA region (Figure 8). There is little variation across the GBA region, with a range of

1875 to 1936 mm/year. PET is more than double the precipitation across the region, indicating the region is water-limited. Mean annual PET for the future period 2046 to 2075 is projected to increase across the GBA region for the 10th, 50th and 90th percentiles (of the GCMs noted above). Predicted increases vary from 3% to 6% (10th percentile) to 8% to 10% (90th percentile), where increases in evaporative demand may lead to reductions in recharge and runoff.

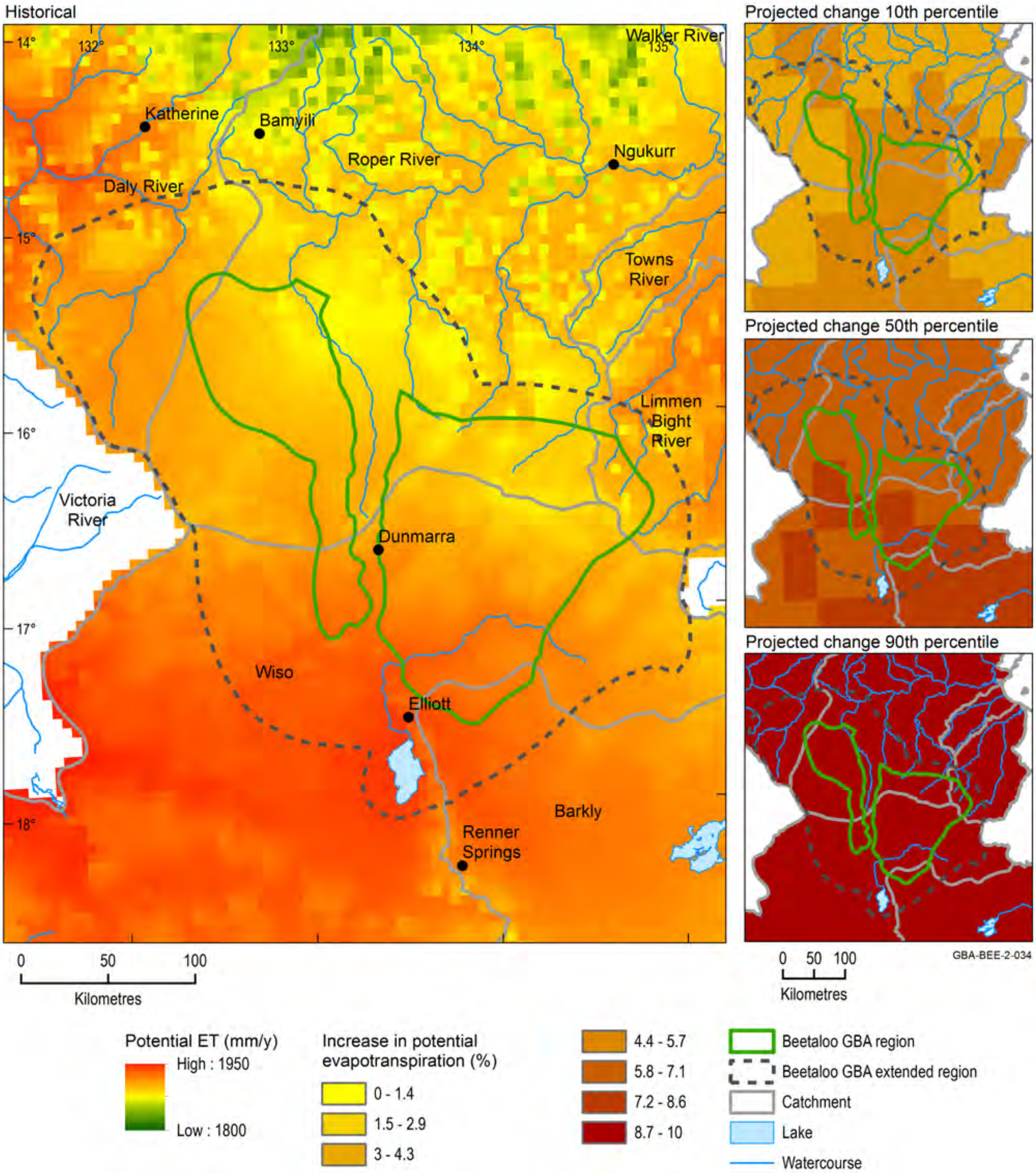

Figure 8 Spatial patterns of mean annual potential evapotranspiration (PET) for the historical period (1976–2005) and 10th, 50th and 90th percentile estimates of projected percentage change in mean annual PET from the historical period 1976–2005 to the future period 2046–2075 across the Beetaloo GBA region

PET was calculated using the Morton method (Chiew and McMahon, 1991).
Percentiles of projected scenarios are from 42 CMIP5 global climate models under emission in RCP8.5.
AWRC = Australian Water Resources Council; CMIP5 = Couple Model Intercomparison Project Phase 5
Data: Geological and Bioregional Assessment Program (2018a, 2018c)
Element: GBA-BEE-2-034

Mean summer maximum air temperatures from 1976 to 2005 ranged from 35 °C to 39 °C and mean minimum air temperatures varied from 22 °C to 25 °C (Figure 9). Winters were warm, with the mean maximum temperature above 28 °C and the mean minimum temperature above 11 °C.

The mean number of hot days (maximum air temperature >35 °C) for 1976 to 2005 across the Beetaloo GBA region varied between 183 days per year in the south and 139 days per year in the north, with an average of 164 days (Figure 9). Mean number of hot days for 2046 to 2075 is projected to increase for the three percentiles across the region consistent with global trends of increasing temperatures. Increases vary from fewer than 30 days under the 10th percentile, up to two additional months above 35 °C under the 50th percentile and up to an additional three months above 35 °C in the north under the 90th percentile.

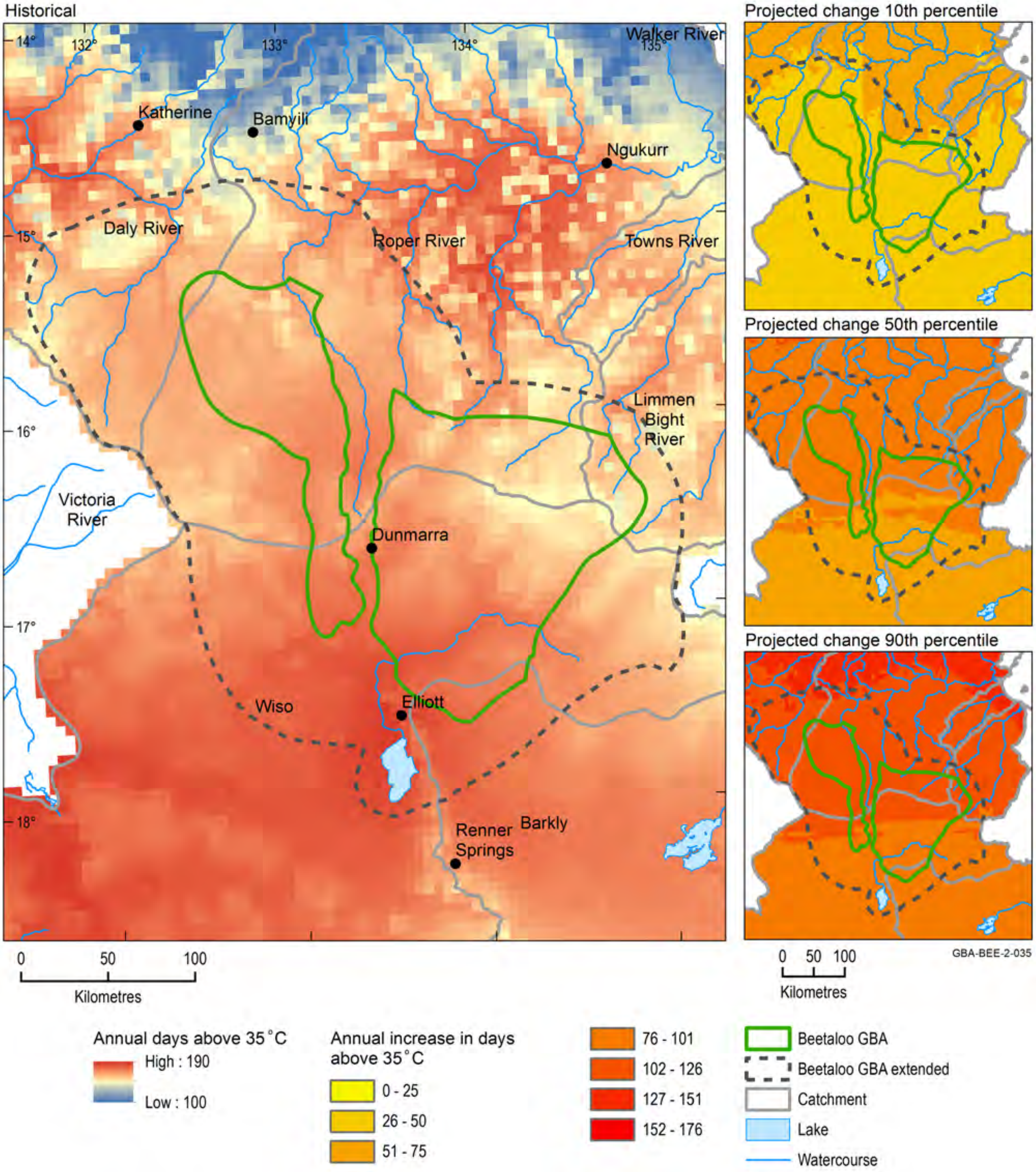

Figure 9 Spatial patterns of mean annual hot days (maximum air temperature >35 °C for the historical period 1976–2005) and 10th, 50th and 90th percentile estimates of projected change in the number of hot days (maximum air temperature >35 °C) from the historical period 1976–2005 to the future period 2046–2075 across the Beetaloo GBA region

Percentiles of projected scenarios are from 42 CMIP5 global climate models under emission in RCP8.5.
AWRC = Australian Water Resources Council; CMIP5 = Couple Model Intercomparison Project Phase 5
Data: Geological and Bioregional Assessment Program (2018a, 2018c)
Element: GBA-BEE-2-035

1.4 Population and land use

The Beetaloo GBA region is sparsely inhabited, with data from the 2016 Australian census indicating that fewer than 500 people live permanently within the region, around 70 of whom are Aboriginal and/or Torres Strait Islander people. There are approximately 1400 people living in the Beetaloo GBA extended region, of which approximately 770 are Aboriginal and/or Torres Strait Islander people. The most significant settlements are:

- Mataranka (310 people, of which 102 are Aboriginal and/or Torres Strait Islander people)
- Jilkminggan (301 people, of which 291 are Aboriginal and/or Torres Strait Islander people)
- Elliott (339 people, of which 299 are Aboriginal and/or Torres Strait Islander people).

There are small settlements at Newcastle Waters (64), Larrimah (47) and Daly Waters (9). Limited information is provided by the Australian Bureau of Statistics for these localities due to the small populations.

Land use within the Beetaloo GBA region is mainly beef cattle production, with perpetual pastoral leasehold covering over 90% of the land area (Figure 10). The Wubalawun, Mangarrayi and Murranji Aboriginal Land Trusts are all partially within the Beetaloo GBA region and the Alawa, Gurungu, Marlinja, Dillinya, Karlantijpa and Mambaliya Rrumburriya Wuyaliya Aboriginal Land Trusts are within, partially within or immediately adjacent to the Beetaloo GBA extended region.

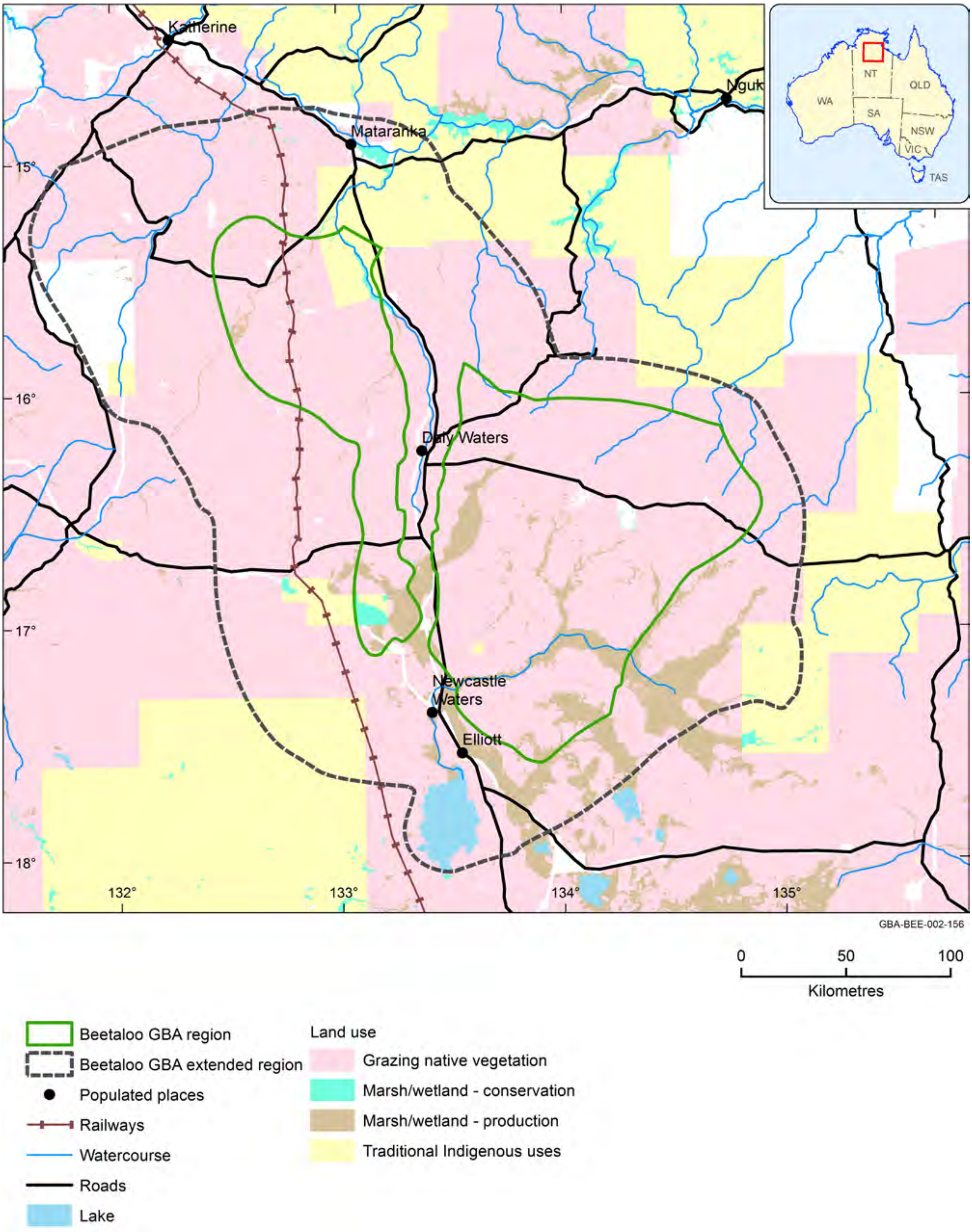

Figure 10 Land use within the Beetaloo GBA region

Land use within the Beetaloo GBA region is predominantly associated with beef cattle industry feeding on native vegetation.
Data: Australian Bureau of Agricultural and Resource Economics and Sciences (2016)
Element: GBA-BEE-2-156

1.5 *Water and resource development legislation and regulations*

The development of shale gas, tight gas and shale oil resources is an emerging industry in Australia and has the potential to impact water resources, biodiversity, social and human capital and other non-renewable natural resources, such as air quality, if not managed appropriately. As such, the industry is regulated at federal, state and local levels to ensure that industry development is sustainable and responsible and minimises impacts on environmental and social values. The following sections outline the Commonwealth and NT regulations that are relevant to the development of shale gas, tight gas and shale oil resources.

1.5.1 Commonwealth legislation

Five key Commonwealth agreements apply to the regulation of the development of shale gas, tight gas and shale oil resources (Table 1). The Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) is discussed in more detail in this section, as this is the primary legislation pertaining to a strategic assessment.

Table 1 Commonwealth legislation relating to the development of petroleum resources

Legislation	Description	Administering department
Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act)	Protects and manages nationally and internationally important flora, fauna, ecological communities, wetlands (e.g. Ramsar) and heritage places. Is the overarching legislation for strategic assessments. Only considers water resources as a Matter of National Environmental Significance in relation to coal seam gas (CSG) and large coal mining developments, which are not found in the Beetaloo GBA region.	Department of the Environment and Energy
Native Title Act 1993 (NT Act)	Recognises and protects native title and the requirements for Indigenous Land Use Agreements.	Attorney-General's Department, Department of the Prime Minister and Cabinet (Indigenous Affairs)
Aboriginal Land Rights (Northern Territory) Act 1976	Regulations related to community and Traditional Owner engagement in application for exploration permits on Aboriginal freehold land. Provides Traditional Owners with an absolute right of veto.	Not applicable
Aboriginal and Torres Strait Islander Heritage Protection Act 1984	Preserves and protects places, areas and objects of particular significance to Aboriginals, where 'Aboriginal' means a member of the Aboriginal race of Australia and includes a descendant of the Indigenous inhabitants of the Torres Strait Islands.	Attorney-General's Department, Department of the Environment and Energy
Industrial Chemicals (Notification and Assessment) Act 1989 (IC Act)	Notifies and assesses the use of industrial chemicals within Australia.	Department of Health (through the National Industrial Chemicals Notification and Assessment Scheme)

Legislation	Description	Administering department
Water Act 2007 (Water Act)	Manages the water within the Murray–Darling Basin. It also provides for the collection, collation, analysis and dissemination of information about Australia's water resources; and the use and management of water in Australia. 'Water information' includes water access rights, water delivery rights or irrigation rights.	Australian Government Department of Agriculture and Water Resources Water information – Bureau of Meteorology

1.5.1.1 Environment Protection and Biodiversity Conservation Act

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

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

The nine MNES are:

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

Generally, proposed activities (e.g. a mine or petroleum field development) are individually submitted to the Department of the Environment and Energy for assessment on an individual project basis. A strategic assessment for an industry type (e.g. shale gas industry in a particular region), however, takes a 'bigger picture' approach over the impacted region. Rather than looking at how a single activity will affect nationally protected matters, a strategic assessment looks at how a group of activities (under a policy, plan or program) will affect these matters regionally. There is currently a strategic assessment underway for offshore petroleum activities in the coastal waters of the NT, for example. As well as helping to protect Australia's unique biodiversity, this type of assessment also benefits the community, developers, industry and government by increasing regulatory efficiency and providing long-term certainty.

The definition of 'environment' under section 528 of the EPBC Act is a comprehensive list of ecological and socio-economic values:

> '(a) ecosystems and their constituent parts, including people and communities; and
>
> (b) natural and physical resources; and
>
> (c) the qualities and characteristics of locations, places and areas; and
>
> (d) Heritage values of places; and
>
> (e) the social, economic and cultural aspects of a thing mentioned in paragraph (a), (b), or (c).'

The meaning of 'water resource' is broad under the Water Act, where it is defined as:

> '(a) surface water or ground water; or
>
> (b) a watercourse, lake, wetland or aquifer (whether or not it currently has water in it); and includes all aspects of the water resource (including water, organisms and other components and ecosystems that contribute to the physical state and environmental value of the water resource).'

Protection of water resources under the EPBC Act only applies where an activity involves coal seam gas development or large-scale coal mining. Shale gas, tight gas and shale oil development in the Beetaloo Sub-basin will not trigger this provision.

Within this context, the GBA Program is designed to provide the underpinning science to facilitate a strategic assessment of future development of shale gas, tight gas and shale oil resources in the Beetaloo Sub-basin and to streamline compliance with the EPBC Act. Strategic assessments (Part 10 of the EPBC Act) offer the opportunity to examine and potentially approve a series of new proposals or developments at a much larger scale and time frame than can be achieved using a project-by-project referral process. They also enable the consideration of cumulative impacts on MNES and seek to explore opportunities for conservation and planning outcomes at a scale that could not be addressed via a project-by-project referral process.

Strategic assessment typically involves two steps:

- assessment and endorsement of a 'policy, plan or program' (the program)

- approval of actions (or classes of actions) that are associated with the program. This step potentially enables the development to proceed across large areas without further need for approval under the EPBC Act.

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

1.5.1.2 Land Rights Act and Native Title Act

The Commonwealth *Aboriginal Land Rights (Northern Territory) Act 1976* (Land Rights Act) guides the consultation and community engagement with Traditional Owners on Aboriginal freehold land. Traditional Owners may consent to or refuse to consent to the grant of a petroleum exploration permit on Aboriginal land and under the Land Rights Act. Also, they have the right to excise culturally significant places from granted petroleum exploration permits. The Traditional Owners are represented in negotiations by their relevant land council.

The Commonwealth's *Native Title Act 1993* establishes Australia's Indigenous people's common law rights to their traditional land and waters. Where native title has been legally recognised, it gives Traditional Owners the right to live and camp in an area, conduct ceremonies, hunt and fish, collect food, build shelters and visit places of cultural importance. Native title can exist over pastoral land but not over NT freehold land or Crown land used for public roads, railways or buildings. Traditional Owners who hold, or have claimed, native title rights over land must be consulted about proposed activities on the land.

1.5.2 Northern Territory

The regulation of petroleum activities in the NT is going through a period of significant change in response to recommendations from the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018). The NT Government is implementing all 135 recommendations of this inquiry and changes have been made to address those recommendations that were required to be completed prior to a recommencement of onshore petroleum exploration activities (Northern Territory Government, 2019a).

The current regulatory framework for petroleum activities in the NT is shown in Figure 11 and key legislation is listed in Table 2. The primary legislative instrument in the NT is the *Petroleum Act 1984*, which covers tenure, resource management, and operational approvals, along with the *Petroleum (Environment) Regulations 2016*, which covers environmental approvals. The *Water Act 1992* (Cth) is also important as it requires licences for extraction of water and prohibits the disposal of hydraulic fracturing wastewater to waters (groundwater and surface water). There are also numerous other NT statutes that apply to onshore petroleum activities for matters such as sacred sites, heritage, management of radioactive material and management of weeds.

Petroleum exploration can only be conducted under an exploration permit, which can only be obtained through a competitive tender as part of an acreage release process by the NT Government or transferred from one entity to another subject to approval. A permit holder has exclusive rights to explore for petroleum resources within the permit area. Permit holders must engage with pastoralists, land managers and other stakeholders regarding planned exploration activities and land access needs. The process for negotiation varies according to the land tenure type (Aboriginal freehold or pastoral lease affected by native title).

An exploration permit holder must obtain activity approvals for any work they intend to conduct (except for activities that involve minimal disturbance, such as reconnaissance). Activity approvals require an approved Environmental Management Plan (EMP) specific to the planned activities.

Upon discovery of a commercially viable petroleum resource, an exploration permit holder may apply for a production licence. A production licence grants the holder exclusive rights to carry out petroleum recovery operations within the licence area, according to a Reservoir Management Plan and individual activity work approvals. EMPs are required for regulated activity approvals. If a project is deemed to have the potential to result in a significant environmental impact, further assessment through an environmental impact statement may also be required under the *Environmental Assessment Act 1982*.

A permit or licence holder also has obligations to decommission all infrastructure and to rehabilitate the site when an exploration permit or production licence is surrendered, expired or cancelled.

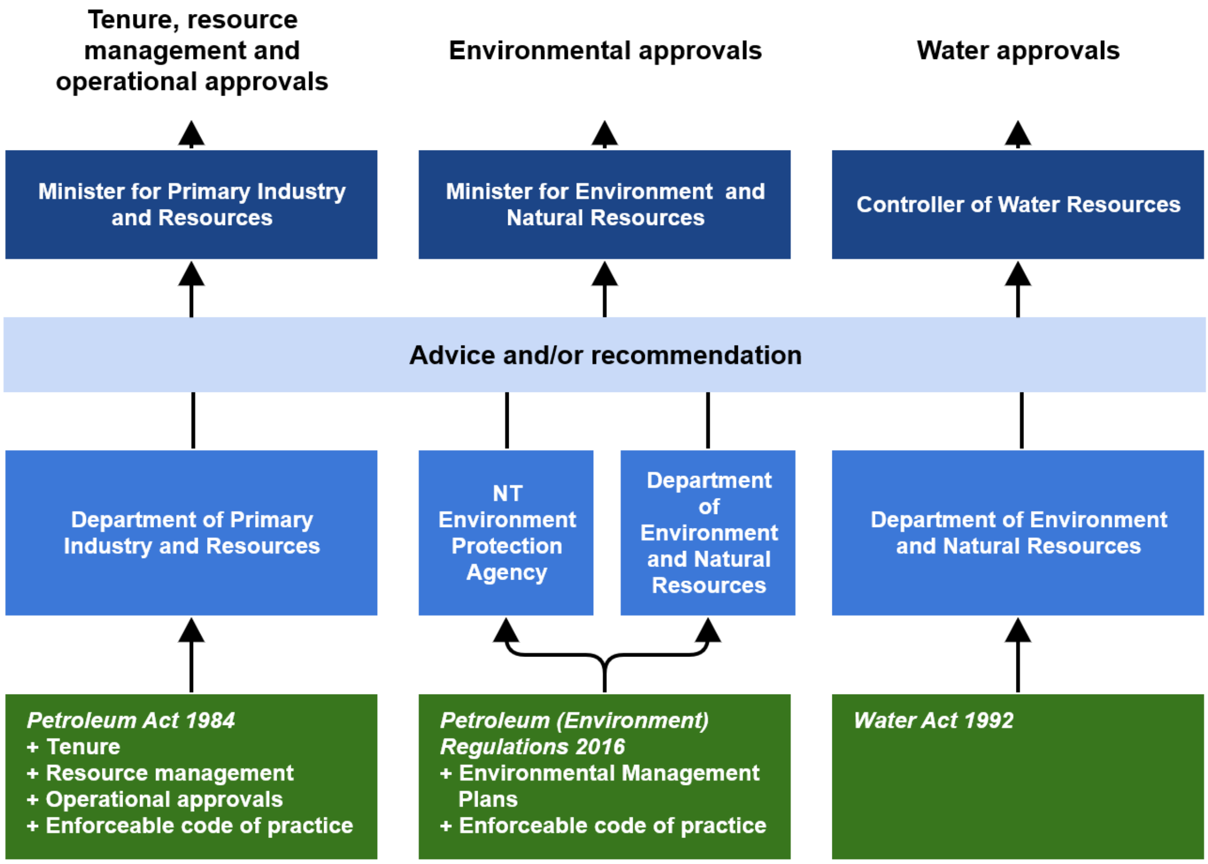

Figure 11 Overview of the petroleum regulatory approvals framework in the Northern Territory

Data: Northern Territory Government (2019a)

Element: GBA-BEE-2-343

Table 2 Primary Northern Territory legislation relating to the development of petroleum resources in the Northern Territory

Legislation	Description	Administering department
Petroleum Act 1984	Primary legislation governing the development of petroleum resources	Department of Environment and Natural Resources in relation to environmental regulation Department of Primary Industry and Resources in relation to other matters
Petroleum (Environment) Regulations 2016	Legislation governing environmental risks and impacts associated with petroleum development	Department of Environment and Natural Resources
Schedule of Onshore Petroleum Exploration and Production Requirements (The Schedule)	Regulation of activities associated with petroleum development Regulation of petroleum resource management	Department of Primary Industry and Resources
Environmental Assessment Act 1982	Assessment of environmental effects of development	NT Environmental Protection Authority
Waste Management and Pollution Control Act 1998	Protection of environment through effective management of waste	NT Environmental Protection Authority
Water Act 1992	Protection, management, use and administration of water resources	Department of Environment and Natural Resources
Northern Territory Aboriginal Sacred Sites Act 1989	Requires an Authority Certificate to be issued to confirm that appropriate requirements will be in place to protect Aboriginal sacred sites The Petroleum (Environment) Regulations require an Authority Certificate to have been issued before an Environmental Management Plan can be granted	Aboriginal Areas Protection Authority

'Once the Minister for Resources has consented to the commencement of negotiations, the minister is no longer involved in the process until the negotiations between the land council and a gas company are completed and there is evidence of an agreement between those two parties. Neither the Government nor the Commonwealth has any involvement in, or control over, the processes outlined below regarding how Land Councils identify and consult with traditional Aboriginal owners or other Aboriginal people' (Pepper et al., 2018).

1.5.2.1 Hydraulic fracturing inquiries

There have been two inquiries into hydraulic fracturing activities in the petroleum industry in the NT over the last five years. They are:

- the independent inquiry into hydraulic fracturing in the Northern Territory (the Hawke inquiry), which was completed in 2014 (Hawke, 2014)
- the Independent Scientific Inquiry into Hydraulic Fracturing of Onshore Unconventional Reservoirs in the Northern Territory (the Pepper inquiry), which was completed in 2018 (Pepper et al., 2018).

These inquiries have resulted in significant changes to the regulation of petroleum activities in the NT; for example, the NT Government is still implementing changes related to the Pepper inquiry.

The Petroleum (Environment) Regulations were implemented in response to recommendations from the Hawke inquiry. They mandate ministerial approval for any activities likely to have a significant environmental impact.

The Pepper inquiry made 135 recommendations and the NT Government has committed to implementing all of them. The Pepper inquiry determined that a number of these recommendations must be completed before exploration activities could occur, and these recommendations have been implemented (Northern Territory Government, 2019a), The key outcomes of implementing the exploration-related recommendations are:

- Environmental management of the petroleum industry has been made the responsibility of the Minister for Environment and Natural Resources (formerly the Minister for Primary Industry and Resources had this responsibility).
- Water use for the onshore petroleum activities is regulated through the Water Act, which includes specific requirements for petroleum activities.
- An enforceable code of practice with defined standards and requirements for the petroleum activities has been put in place.
- A public comment process for draft EMPs related to drilling of petroleum wells and hydraulic fracturing activities has been established.

Additional regulatory reforms will be made as the remaining inquiry recommendations are addressed.

1.5.2.2 Petroleum Act

The objective of the Petroleum Act is to provide the legal framework associated with exploration and development of petroleum resources in the NT such that the optimum value of the resource is returned to the NT. It is supported by the NT's *Petroleum Regulations 1994*, which regulate the fees relating to petroleum activities.

The Petroleum Act:

- grants petroleum interests for exploration and development
- stipulates the role of government following this grant
- promotes active exploration and subsequent development if commercially viable
- assesses proposed technical works and the financial capacity of the developers
- reduces risk to the environment
- provides for the collection and dissemination of information pertaining to exploration and production
- administers the Act and collects royalties
- provides for other matters in connection with exploration for and production of petroleum.

The Minister for Environment and Natural Resources is responsible for administration of matters in relation to environmental regulation, including environmental harm offences. The primary responsibility for approvals for petroleum activities and remaining matters (other than royalties) rests with the Minister for Primary Industries and Resources. Officers in the Department of

Primary Industry and Resources (DPIR) Energy division administer the Petroleum Act and are responsible for compliance and reporting.

1.5.2.3 Petroleum (Environment) Regulations

The objective of the Petroleum (Environment) Regulations is to ensure that development of petroleum resources and its associated regulated activities are:

- consistent with the principles of ecologically sustainable development
- implemented in a manner where environmental impacts and risks are as low as reasonably practical and acceptable.

The regulations provide the framework for the submission and approval of EMPs for regulated activities, which are defined in the regulations. Approval of an EMP is conditional on appropriate stakeholder engagement to the regulated activity specified in the plan. Ministerial approval of an EMP is contingent on the minister being satisfied that the plan will reduce all environmental risks to levels that are as low as practical and acceptable according to the principles of ecologically sustainable development.

The Minster for Environment and Natural Resources has the primary responsibility for EMP approvals. Officers in the Department of Environment and Natural Resources (DENR) administer the Petroleum (Environment) Regulations and are responsible for compliance and reporting. The independent Northern Territory Environmental Protection Authority also advises the Minister for Environment and Natural Resources as part of the approval process for EMPs.

1.5.2.4 Code of Practice: Onshore petroleum activities in the Northern Territory

Petroleum activities in the NT must meet the requirements of the Code of Practice: Onshore petroleum activities in the Northern Territory (the Code) (Northern Territory Government, 2019c). The Code covers four broad areas:

- surface activities
- well operations, including hydraulic fracturing
- well site water management
- methane emissions.

All petroleum activities and EMPs must comply with the requirements of the Code.

1.5.2.5 Schedule of Onshore Petroleum Exploration and Production Requirements

The Schedule of Onshore Petroleum Exploration and Production Requirements (the Schedule) works alongside the Petroleum Act, the Petroleum (Environment) Regulations and the Code to regulate individual activities associated with petroleum exploration and development. The Schedule is enforced through a direction to comply with the terms of the Schedule issued under the Petroleum Act by the Minister for Primary Industries and Resources to each permit or licence holder.

The Schedule was updated when the Code was put in place. The Schedule covers petroleum resource management and operational aspects of petroleum activities, including activity approvals and reporting requirements. A significant inclusion in the recent update was the addition of the requirement for Well Operations Management Plans (WOMPs) for all well activities, including drilling, hydraulic fracturing and decommissioning. This requirement for WOMPs directly addressed a recommendation of the Pepper inquiry.

1.5.2.6 Northern Territory Aboriginal Sacred Sites Act

The *Northern Territory Aboriginal Sacred Sites Act 1989* (Sacred Sites Act) aims to balance the need to preserve and enhance Aboriginal cultural tradition and the economic, cultural and social advancement of the people of the NT. It established the Aboriginal Areas Protection Authority – an independent statutory authority responsible for overseeing the protection of Aboriginal sacred sites in the whole of the NT.

Under the Sacred Sites Act, an Authority Certificate from the AAPA must be issued for any proposed development to confirm that appropriate requirements will be in place to protect Aboriginal sacred sites. The Petroleum (Environment) Regulations require an Authority Certificate to have been issued before an EMP can be granted.

The AAPA, where requested, is now required to carry out surveys and consultations with custodians to determine the constraints imposed by the existence of sacred sites to work on land and waters anywhere in the NT. An Authority Certificate specifying the conditions under which work may be undertaken in the vicinity of a sacred site is then issued. A time limit is placed on the commencement of consultations.

1.5.2.7 Environmental Assessment Act

If a project is deemed to have the potential to result in a significant environmental impact, further assessment through an environmental impact assessment (Correia dos Santos et al., 2012) process may also be required under the *Environmental Assessment Act 1982* (NT). The purpose of the EIA process is to provide for appropriate examination of proposed projects that may cause significant environmental impact.

The Northern Territory Environment Protection Authority (NT EPA) is responsible for administering the Environmental Assessment Act and the results of the EIA process are referred to the Minister for Environment and Natural Resources.

1.5.2.8 Waste Management and Pollution Control Act

The *Waste Management and Pollution Control Act 1998* (NT) does not apply to approved petroleum activities where all waste and contaminants associated with an activity remain within the approved area. However, when waste leaves that site the Act does apply and regulates the collection, transport, storage and disposal of listed wastes, such as chemicals used in hydraulic fracturing or wastewater treatment.

1.5.2.9 Water Act

The *Water Act 1992* (Cth) governs the investigation, allocation, use, control, protection, management and administration of water resources and covers surface water and groundwater resources ('water resource' is not defined in the Water Act, but 'water' means 'water, whether or not it contains impurities'). The Act requires a permit to interfere with water resources, such as drilling bores, polluting water sources, interfering with flow regimes through dam building, and disposal of wastewater underground by means of a bore or extracted water.

Recent amendments in response to recommendations of the Pepper inquiry mean that the Water Act now applies to water extraction for petroleum activities, making it subject to the same considerations as other water users in the NT. Other amendments to the Water Act prohibit the use of surface water for petroleum activities and the discharge of hydraulic fracturing wastewater (treated or untreated) to surface water or groundwater.

1.5.2.10 Strategic Regional Environmental Baseline Assessments

One of the recommendations of the Pepper inquiry was that Strategic Regional Environmental Baseline Assessments (SREBA) be conducted prior to the granting of any further production approvals for onshore gas activities (Pepper et al., 2018). The Pepper inquiry made several recommendations about the purpose of a SREBA and how it should be conducted. The NT Government is developing guidelines for the conduct of a SREBA. There is likely to be overlap between the GBA Program and a SREBA for the Beetaloo Sub-basin, and the GBA Program is engaging closely with the NT Government to maximise the synergies between the two.

2 Geology and petroleum resources

2.1 Regional geological architecture

The Beetaloo Sub-basin is a structural component of the greater McArthur Basin in the NT, located about 500 km south-east of Darwin (Figure 12). It contains the greatest thickness of a Mesoproterozoic sedimentary succession that is distributed broadly across northern Australia. The sub-basin is bounded by several prominent structural highs, and it is divided into eastern and western elements by the Daly Waters High. The Beetaloo Sub-basin is overlain by the Neoproterozoic to Paleozoic Georgina, Wiso and Daly basins, and the Mesozoic Carpentaria Basin, which host major aquifer systems.

This review of the regional structure and stratigraphic architecture of the Beetaloo Sub-basin and overlying sedimentary basins provides the geological framework required to better understand the distribution and properties of stratigraphic sequences hosting both petroleum and water resources.

This section summarises the geology of the Beetaloo GBA region to provide context for the analysis of unconventional hydrocarbons and water resources presented later in this report (Section 2.2 and Section 3). A more detailed review of the region's geological architecture can be found in the accompanying geology technical appendix (Orr et al., 2020).

2.1.1 Geological setting

The Beetaloo Sub-basin is a structural feature of the greater McArthur Basin – a regionally extensive Paleoproterozoic to Mesoproterozoic geological entity covering an area of approximately 550,000 km^2 across the NT and north-western Queensland (Close, 2014; Munson, 2016, 2014). The greater McArthur Basin links the sedimentary rocks of this age across the Birrindudu Basin, Tomkinson Province and McArthur Basin (Close, 2014) (Figure 12).

The greater McArthur Basin contains a thick succession of Paleoproterozoic to Mesoproterozoic sedimentary rocks, which were deposited over a large area of the Australian continent between ca 1800 to 1300 Ma (Betts et al., 2015). The sediments deposited by these systems are grouped as 'packages', which include sedimentary and igneous units that belong to broadly contemporaneous basin phases (Rawlings, 1999). Organic-rich sedimentary rocks, which may have generated hydrocarbons, are known to exist at intervals in these packages. Differences in geological history across the greater McArthur Basin mean that only some basin regions have generated and preserved hydrocarbons.

The Beetaloo Sub-basin is defined as the thickest preserved sequences of the Mesoproterozoic sedimentary rocks and incorporates an area of approximately 28,000 km^2 within the NT (Figure 12). Underlying the Beetaloo Sub-basin, older sedimentary rocks of the Paleoproterozoic Redbank and Glyde and Mesoproterozoic Favenc packages may be present. However, to date (2020) these packages have not been intersected by drilling beneath the Beetaloo Sub-basin.

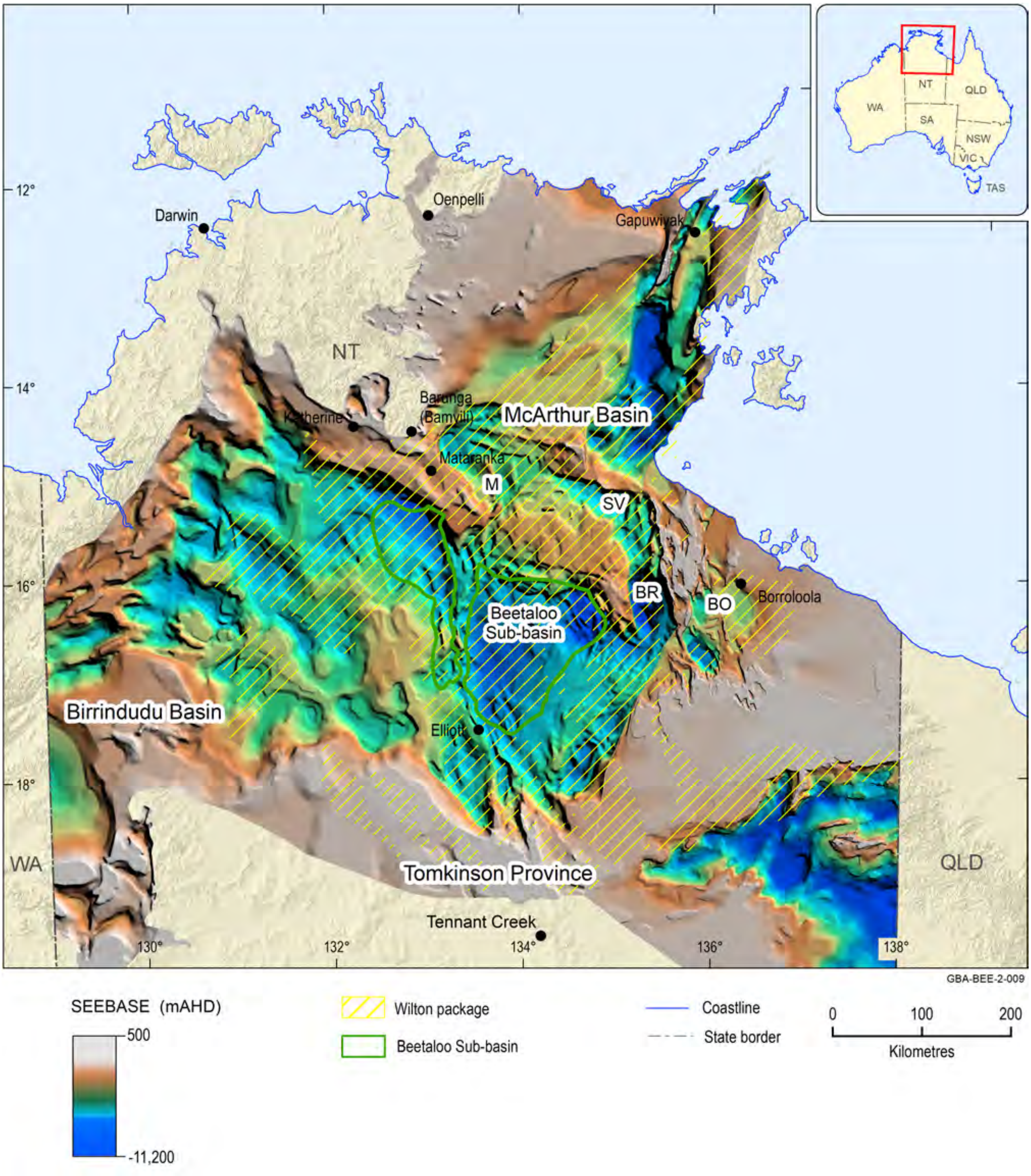

Figure 12 Geological setting of the Beetaloo Sub-basin in the greater McArthur Basin in the Northern Territory

The extent of the modelled depth to basement (SEEBASE®) image corresponds broadly to the greater McArthur Basin extents.
M = Maiwok Sub-basin; SV = Saint Vidgeon Sub-basin; BR = Broadmere Sub-basin; BO = Borroloola Sub-basin;
mAHD = elevation in metres with respect to the Australian Height Datum
Data: depth to basement SEEBASE® model image sourced from Frogtech Geoscience (2018b); Mesoproterozoic Roper Group (Wilton package) distribution from Betts et al. (2015)
Element: GBA-BEE-2-009

The Beetaloo Sub-basin is wholly under the cover of younger basin sediments. Neoproterozoic and Paleozoic sediments of the Centralian A and B superbasins extended over the sub-basin. Regionally, the Georgina, Wiso and Daly basins form parts of these superbasins. Mesozoic marine incursion across the Australian continent resulted in Carpentaria Basin sediment deposition over the sub-basin. Some of the original depths of these sedimentary cover sequences have been eroded in phases over geological time (Section 2.1.3).

Snapshot: Proterozoic versus Phanerozoic Earth

The Beetaloo Sub-basin was deposited during the Mesoproterozoic. The Earth at that time was markedly different from the Phanerozoic Earth of the present day. The planet had cooled to the point where modern-day plate tectonic processes became dominant, allowing for stable continents to form and accrete through significant mountain-building events (Ogg et al., 2016). However, land plants had yet to evolve (Knauth and Kennedy, 2009) and organic matter deposited alongside sediments was derived from simple organisms living in a marine environment, which may have included planktonic algae (Glikson et al., 2006; Glikson et al., 1992) and bacteria (Brocks et al., 2017), or from the growth of microbial mats, such as stromatolites. The conditions under which the organic matter was preserved in the Beetaloo Sub-basin sediments differ substantially from later Phanerozoic marine conditions. Proterozoic organic-rich sediments were deposited under conditions of widespread ocean anoxia in the 1800 to 1000 Ma period (Planavsky et al., 2011). Anoxic conditions in depositional environments are associated with organic matter preservation and can result in enrichment of total organic carbon in sediments.

2.1.2 Structural elements

Sub-basins are sub-divisions of larger geological basins, usually separated by structural highs. The Mallapunyah Fault Zone, for instance, occurs across the north of the Beetaloo Sub-basin (Figure 13) and is associated with major structural highs.

The eastern and western Beetaloo Sub-basin areas are two concealed subsurface volumes of sedimentary rock (Department of Primary Industry and Resources (NT), 2017). Seismic data show that the sediment sequences within the eastern and western sub-basin fill are largely flat-lying and undeformed, with few fault structures connecting the Mesoproterozoic sediments with the younger overlying sedimentary basins (Figure 14).

The Wilton package includes the sedimentary rocks of the Roper Group, which hosts the known petroleum resources in the Beetaloo Sub-basin (Section 2.2). The Roper Group sedimentary fill is as deep as 6700 m below sea level and up to 6000 m thick in the sub-basin (Frogtech Geoscience, 2018b; Orr et al., 2020). The total fill from the base of the Roper Group to the surface is significantly thicker in the sub-basin than the surrounding regions (Figure 13). Further, the base of the Roper Group is generally deeper in the eastern Beetaloo Sub-basin than in the west (Frogtech Geoscience, 2018b).

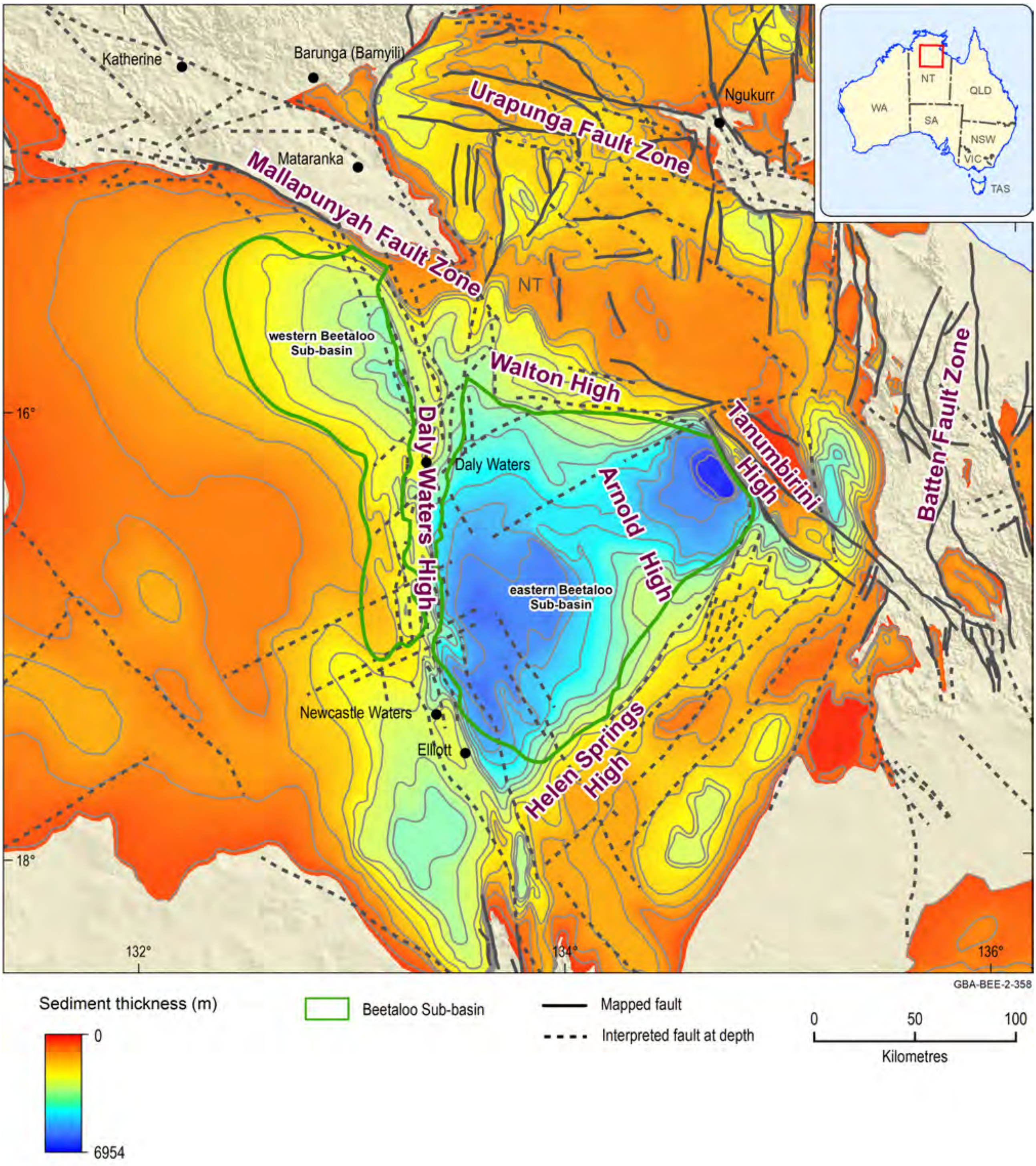

Figure 13 Structural elements map of the Beetaloo Sub-basin showing major faults, overlain on the total sediment thickness from the base of the Mesoproterozoic Roper Group to the surface

The thick black lines show the location of faults mapped from surface outcrop. The dashed lines represent faults and lineaments primarily interpreted from gravity and magnetics data. The extent and nature of these structures is much more uncertain and further work more detailed mapping work using seismic data is required. In addition, it is likely that not all faults intersecting the Beetaloo Sub-basin stratigraphy have yet been mapped and the number of recognised faults in a basin tends to increase substantially as more information (higher resolution and three-dimensional seismic etc.) becomes available over time.

Contour interval (C.I.) = 500 m

Data: major faults and sediment thickness from Frogtech Geoscience (2018b); structural elements from Plumb and Wellman (1987), Silverman et al. (2007) and Munson (2016)

Element: GBA-BEE-2-080

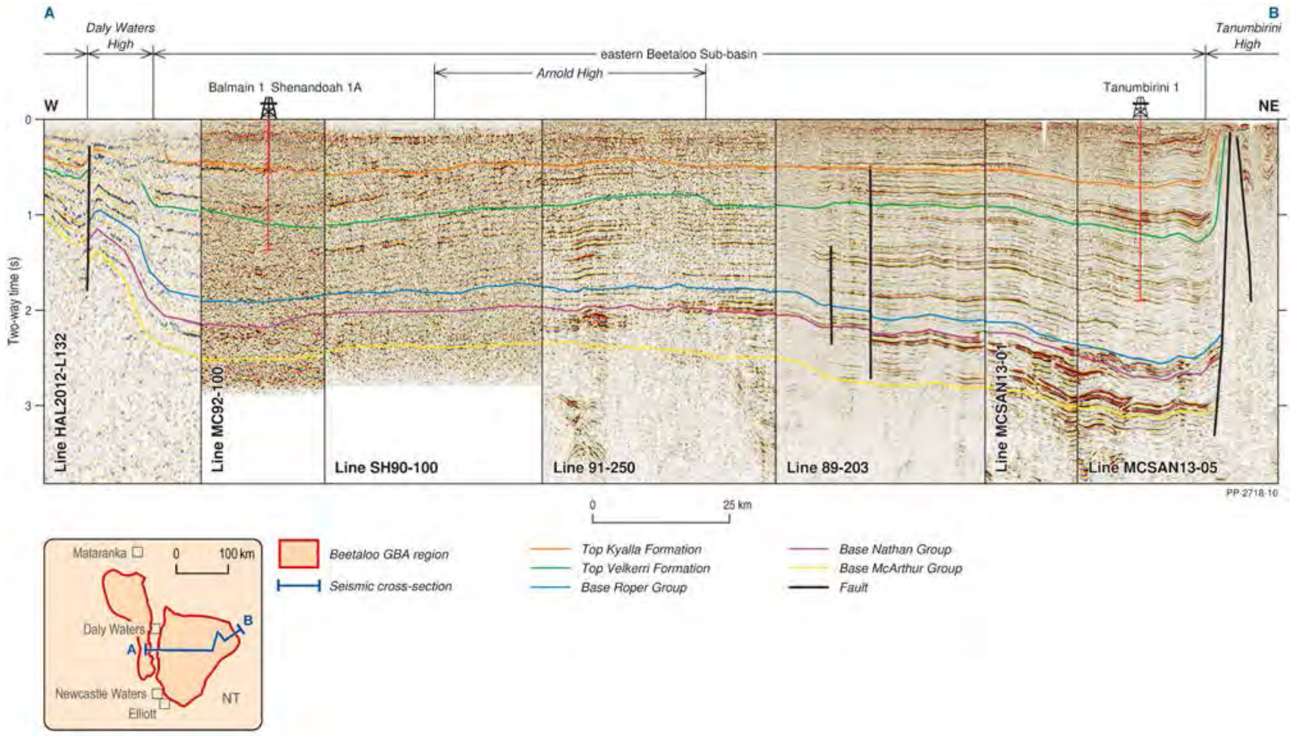

Figure 14 Example interpreted composite seismic section west to east through the Beetaloo GBA region showing the architecture of the eastern Beetaloo Sub-basin

The interpreted stratigraphic intervals belong to the depositional packages indicated in Figure 16; see also the geology technical appendix (Orr et al., 2020) and references therein.
TWT = two-way time (this represents the time taken for a seismic wave to travel from the shot down to a reflector or refractor and back to a receiver at the surface)
Data: interpretation based on Williams (2019)
Element: GBA-BEE-2-083

Structural highs border the eastern Beetaloo Sub-basin, including the Walton High in the north, Helen Springs High in the south and Tanumbirini High in the north-east (Figure 13). The Daly Waters High separates eastern and western sub-basin areas. Typically, these structural highs are deformed and contain major fault structures with large kilometre-scale offsets that have been reactivated several times during the sub-basin's history. The uplift and erosion along sub-basin margins is generally greater than in the central depocentre, potentially affecting the prospectivity of organic-rich sedimentary rocks in these regions. Structural offsets also affect present-day regional groundwater flow and connectivity (Section 3).

At the sub-basin margins, the top of the Roper Group shallows to less than 400 m below the surface and it is this relationship that is used to define the sub-basin's boundaries (see methods snapshot below).

Methods snapshot: defining the Beetaloo Sub-basin

Defining the outline boundary of the Beetaloo Sub-basin is challenging due to the lack of surface outcrop and relatively sparse seismic and well data coverage around the sub-basin margin. As a result, a range of sub-basin outlines exist in the literature. The boundary of the Beetaloo Sub-basin used in this report is that defined by the Northern Territory Geological Survey (Figure 14) (Department of Primary Industry and Resources (NT), 2017). This represents the outline of points defined on seismic data where the Kyalla Formation, the upper member of the Roper Group, shallows to a depth of 400 m below present-day topography or has been truncated by an unconformity. This sub-basin definition covers a smaller area than previous versions and splits the sub-basin into eastern and western elements due to the absence of the Kyalla Formation over the Daly Waters High.

The regional geological architecture of the Beetaloo Sub-basin and overlying sedimentary basins is captured by a three-dimensional geological model produced for this GBA. The model is developed from integration of available public domain datasets (Frogtech Geoscience, 2018b; Fulton and Knapton, 2015; Northern Territory Government, 2018a; Williams, 2019) (Figure 14 and Figure 15). Despite the current exploration activity in the Beetaloo Sub-basin, the area remains relatively data-poor in terms of public domain data, which is a significant limitation in this GBA. Although the coverage of two-dimensional seismic data is sufficient to produce a geological model at regional scale, significant uncertainties remain away from well and seismic data control. In addition, the geological model of the Beetaloo GBA region presented in this Stage 2 report does not include faults; however, this will be addressed in Stage 3. Further details on model construction are in the geology technical appendix (Orr et al., 2020).

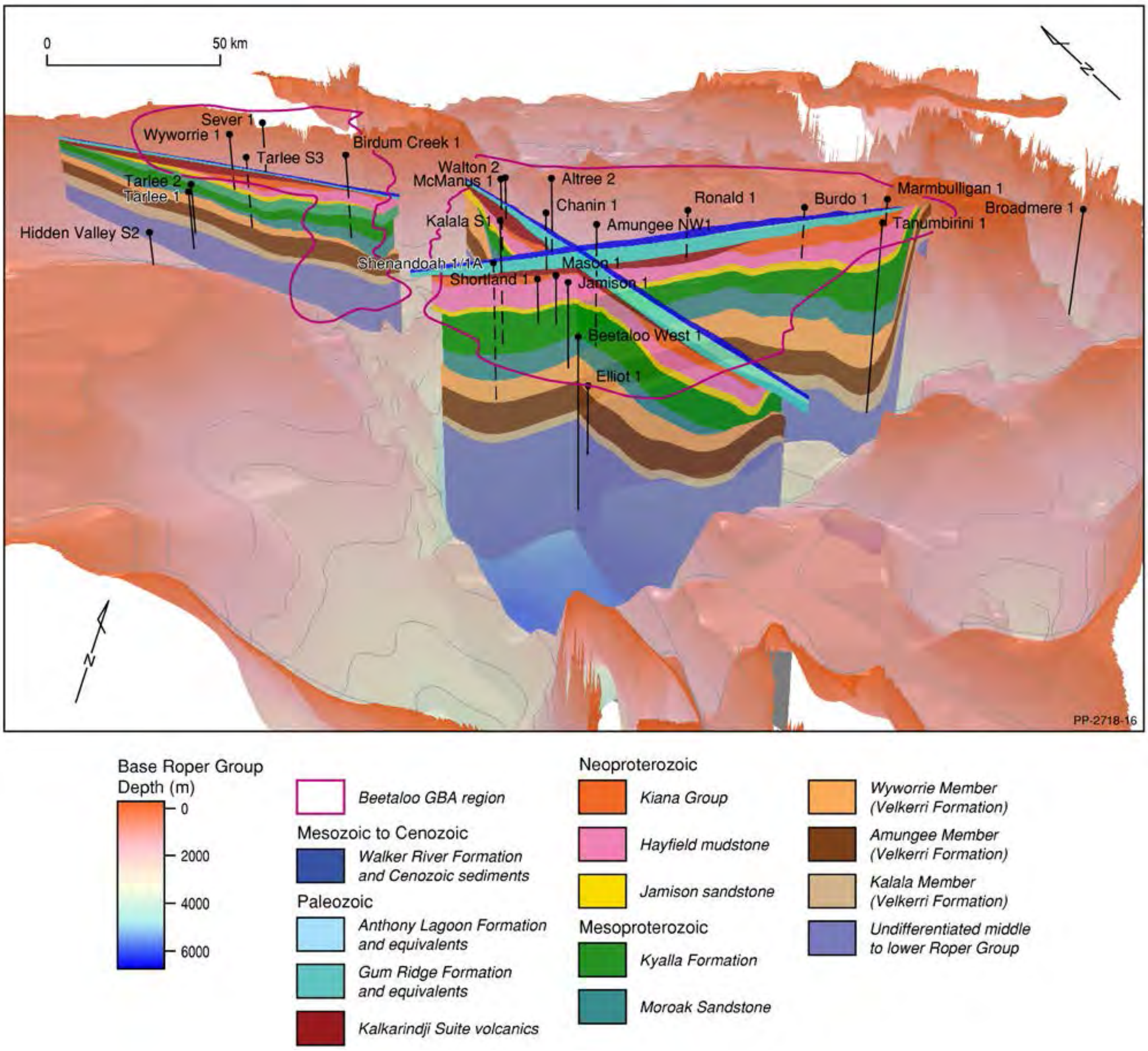

Figure 15 Oblique view of the regional three-dimensional geological model for the Beetaloo GBA region (looking north)

The structural surface shown is the Base Roper Group.
Source: geology technical appendix (Orr et al., 2020) and references therein
Data: base of the Roper Group and basement (SEEBASE®) from Frogtech Geoscience (2018b) and Frogtech Geoscience (2018a). GBA derived dataset: top Velkerri and Kyalla formations modified from Williams (2019), base Anthony Lagoon and Gum Ridge formations (and their equivalents) from the Department of Environment and Natural Resources (NT) (2018), base Walker River Formation from Randal (1973), all other surfaces derived from well completion reports (Northern Territory Government, 2018a)
Element: GBA-BEE-2-072

2.1.3 Basin evolution

The depositional and post-depositional history of sedimentary units controls several factors that affect hydrocarbon prospectivity, groundwater distribution and aquifer connectivity. This section highlights basin evolution events that have implications for hydrocarbon and water resources. A more detailed basin evolution review is provided in the geology technical appendix (Orr et al., 2020).

The following summary includes basin evolution events that affected the Beetaloo Sub-basin and overlying basins from the time of the upper Wilton package onwards. The upper Wilton package has been the focus of hydrocarbon exploration in the Beetaloo Sub-basin. Seismic data show continuous seismic reflectors well below the maximum depth drilled by exploration wells, which most likely represent the older depositional package units (e.g. see Figure 14). The stratigraphy of these older units, described from exposed outcrop elsewhere in the greater McArthur Basin, is reviewed in the geology technical appendix (Orr et al., 2020).

A Proterozoic to Cenozoic stratigraphic chart, which integrates lithostratigraphy and hydrostratigraphy, was compiled for this GBA and it displays the major units confirmed or interpreted to be present in the Beetaloo GBA region (Figure 16).

2.1.3.1 Beetaloo Sub-basin

Mesoproterozoic basin formation and Wilton package deposition were initiated due to rifting and continental breakup (Yang et al., 2018). The Beetaloo Sub-basin was the locus of deposition of the Wilton package and is where it is stratigraphically thickest (Yang et al., 2018).

The Wilton package includes the Roper Group sedimentary rocks, which are divided into the lower Collara Subgroup and upper Maiwok Subgroup (Figure 16). Units associated with the Maiwok Subgroup in the Beetaloo Sub-basin are outlined in Table 3.

The Bessie Creek Sandstone and the Moroak Sandstone were deposited under high-energy tide-dominated shoreline to shallow marine shelf settings (Haines et al., 1993; Munson, 2016). The sandstone units are potential reservoirs for tight gas in the Beetaloo Sub-basin (Section 2.2).

The dominantly fine-grained sediments of the Velkerri and Kyalla formations were deposited in deeper marine settings below the base of waves and tides but subject to periodic and regular current activity (Munson, 2016). The organic-rich shale units within the Velkerri and Kyalla formations are the primary unconventional hydrocarbon targets within the Beetaloo Sub-basin. These are discussed further in Section 2.2. A prominent sandstone interval occurs in the Kyalla Formation.

Table 3 Stratigraphy of the Maiwok Subgroup of the Roper Group in the Beetaloo Sub-basin

Formation	Age	Lithological description	Thickness (m)	Depositional environment
Kyalla Formation	Mesoproterozoic	Interbedded claystone and siltstone with minor fine-grained sandstone	<100–786	Storm-dominated marine shelf
Moroak Sandstone	Mesoproterozoic	Medium- to fine-grained quartz sandstone with minor siltstone and conglomerate	Maximum thickness 498	High-energy tide-dominated shoreline to shallow shelf
Velkerri Formation	Mesoproterozoic	Interbedded claystone and siltstone with minor fine-grained sandstone	<50–1483	Shallow to distal marine shelf
Bessie Creek Sandstone	Mesoproterozoic	Fine- to medium-grained, locally coarse, quartz sandstone	Maximum thickness 417	High-energy tide-dominated shoreline to shallow shelf
Corcoran Formation	Mesoproterozoic	Siltstone, mudstone and minor fine-grained sandstone	Approximately 20–550	Fluvial to shallow marine; marine transgression

Source: Abbott et al. (2001) and Munson (2016); see also geology technical appendix (Orr et al., 2020) and references therein

Dyke swarms between 1320 and 1200 Ma marked the final stage of global Mesoproterozoic continental breakup (Goldberg, 2010) and include the Derim Derim Dolerite sill and dyke complex (Figure 16) that intrudes the Beetaloo Sub-basin (Collins et al., 2018). The high temperature of the Derim Derim Dolerite during emplacement has influenced the thermal maturity and petroleum generation history of source rocks immediately adjacent to it.

2.1.3.2 Post-Roper Inversion

For more than 300 million years after the emplacement of the Derim Derim Dolerite sills and dyke complex there was little evidence of sediment deposition over the Beetaloo Sub-basin (Figure 16).

A regionally extensive compressional event – the Post-Roper Inversion (Rawlings et al., 1997) – occurred in the greater McArthur Basin during this time. Kilometre-scale fault offsets occurred along the Mullapunyah Fault Zone, on the northern margin of the Beetaloo Sub-basin and along the Daly Waters High, between the eastern and western sub-basin areas (Frogtech Geoscience, 2018b) (Figure 13). By contrast, faults underlying the central eastern and western Beetaloo Sub-basin record only minor displacement during this period (Frogtech Geoscience, 2018b).

From 1300 to 1050 Ma, a thermal maxima was reached in the Wilton package sedimentary units, associated with an early period of hydrocarbon generation and subsequent hydrocarbon migration (Delle Piane et al., 2019).

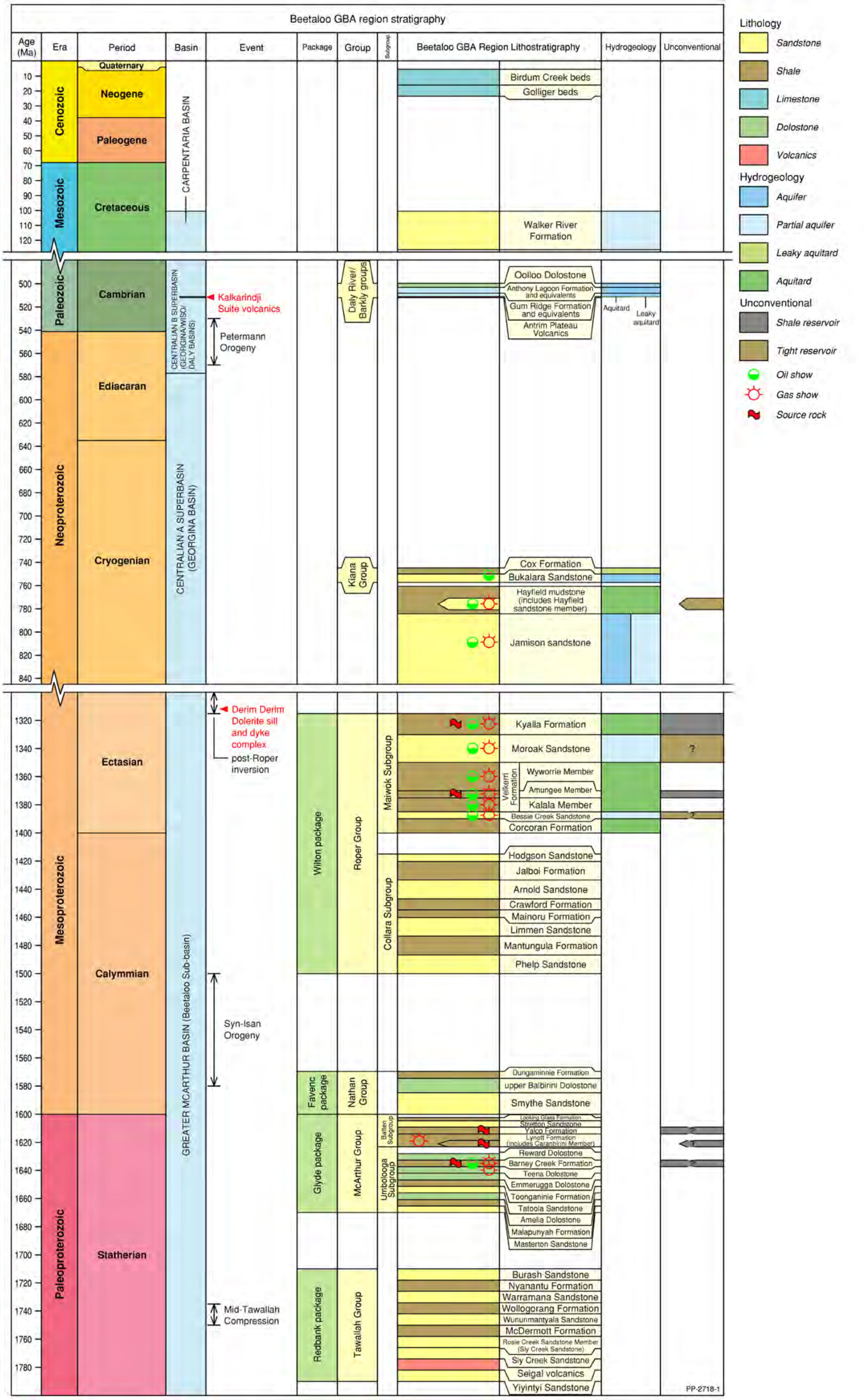

Figure 16 Stratigraphy of the greater McArthur Basin (Beetaloo Sub-basin), Centralian superbasins (Georgina, Wiso and Daly basins) and Carpentaria Basin in the Beetaloo GBA region

Anthony Lagoon Formation equivalents are the Jinduckin Formation, Hooker Creek Formation and Point Wakefield beds. Gum Ridge Formation equivalents are the Top Springs Limestone, Tindall Limestone and Montejinni Limestone. This figure has been optimised for printing on A3 paper (297 mm x 420 mm).

Source: geology technical appendix (Orr et al., 2020), based on Munson (2016), Rawlings (1999), Abbott et al. (2001), Munson and Revie (2018), Munson et al. (2013b), Betts et al. (2015), Jackson et al. (2000), Collins et al. (2018), Page et al. (2000), Ahmad et al. (2013), Kruse et al. (2013); Kruse and Munson (2013b), Munson et al. (2013a), Kruse and Munson (2013a), Edgoose and Ahmad (2013), Munson (2014)

Element: GBA-BEE-2-053

2.1.3.3 Centralian A Superbasin

Deposition was renewed over the Beetaloo Sub-basin with the formation of large depositional systems in northern, central and southern Australia in the Neoproterozoic era – collectively termed the Centralian A Superbasin (Munson et al., 2013b) (Figure 16). Units associated with the superbasin in the Beetaloo GBA region are outlined in Table 4.

The Jamison sandstone and Bukalara Sandstone were deposited under high-energy fluvial, shoreline and shallow marine environments (Munson, 2016; Rawlings, 2006). These predominantly fine- to coarse-grained sandstone units together host one of the main groundwater subsystems in the region (Section 3.1). The sandstone is a potential reservoir for migrated hydrocarbons, and oil and gas shows have been observed in wells intersecting the Jamison sandstone (Silverman et al., 2007).

The Hayfield mudstone and Cox Formation are fine-grained units deposited in sub-tidal shallow marine setting (Haines et al., 1993; Munson, 2016). The Hayfield mudstone acts as a regional aquitard above the units hosting hydrocarbon resources (Section 3.1), whereas the Cox Formation has limited known distribution in the Beetaloo GBA region. A sandstone interval prevalent in the lower part of the Hayfield mudstone, indicative of shallowing to a nearshore environment, is informally termed the 'Hayfield sandstone member' (Munson, 2016). The sandstone member hosts a potential oil/condensate play (Section 2.2) (Côté et al., 2018).

Table 4 Stratigraphy of the Centralian A Superbasin in the Beetaloo GBA region

Formation	Age	Lithological description	Thickness (m)	Depositional environment
Cox Formation	Neoproterozoic	Very fine- to fine-grained sandstone, siltstone and shale	0–203	Storm-influenced subtidal marine shelf
Bukalara Sandstone	Neoproterozoic	Sandstone, with pebble conglomerate and minor shale	0–75	High-energy fluviatile to shallow marine shelf
Hayfield mudstone	Neoproterozoic	Claystone with thinly interbedded siltstone and sandstone; a coarser-grained laterally persistent sandstone interval dominates at the base and has been informally termed the 'Hayfield sandstone member' (Munson, 2016)	94–569	Shallow marine shelf
Jamison sandstone	Neoproterozoic	Fine- to coarse-grained quartz sandstone with minor mudstone interbeds	57–162	High-energy shoreline to shallow marine shelf

Source: Munson (2016) and Kruse et al. (2013); see also the geology technical appendix (Orr et al., 2020) and references therein

2.1.3.4 Kalkarindji Province volcanics

Thick and extensive basaltic lavas were emplaced over much of the region during widespread volcanic eruptions in the Cambrian, associated with the Kalkarindji Large Igneous Province (Figure 16) (Glass et al., 2013). The resulting Kalkarindji Province volcanics (Antrim Plateau Volcanics) in the Beetaloo GBA region (Figure 17) forms a significant regional aquitard, except where the rocks have been subsequently naturally fractured (Section 3.1). The unit is up to 440 m thick in the Beetaloo Sub-basin.

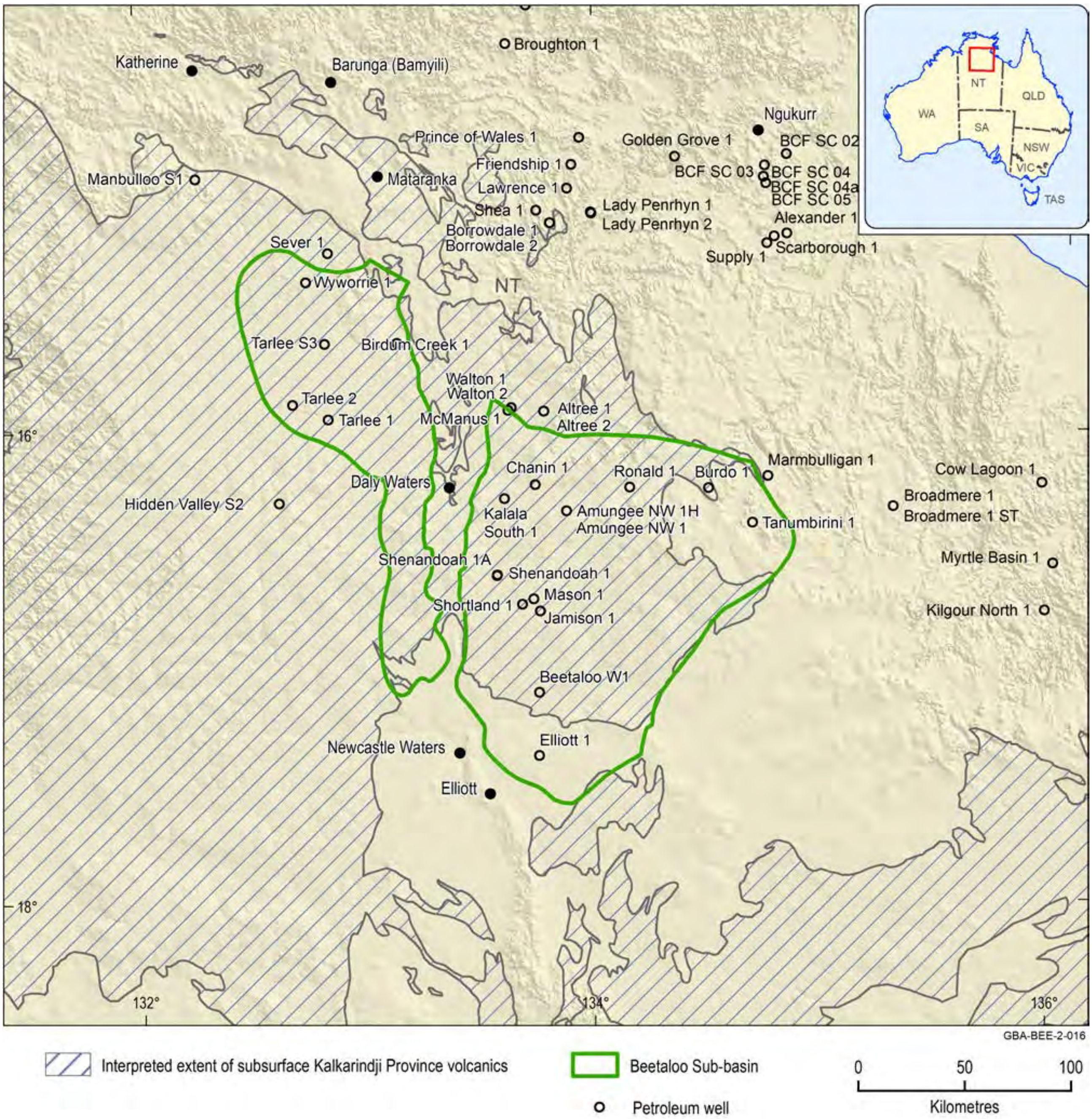

Figure 17 Extent of subsurface volcanics of the Kalkarindji Province

Source: Frogtech Geoscience (2018b); derived from Clifton (2016). Petroleum well distribution from Department of Primary Industry and Resources (NT) (2018a)
Element: GBA-BEE-2-016

2.1.3.5 Centralian B Superbasin

Broad regional subsidence and marine transgression followed the volcanic eruptions, leading to the development of the Centralian B Superbasin (Figure 16) (Munson et al., 2013b). The superbasin includes the Paleozoic sequences of the Georgina, Wiso and Daly basins that overlie the Beetaloo GBA region (Table 5).

Table 5 Stratigraphy of the Centralian B Superbasin in the Beetaloo GBA region

Formation	Age	Lithological description	Thickness (m)
Anthony Lagoon Formation and equivalents	Cambrian	Dolomitic siltstone and interbedded dolostone, dolomitic sandstone and quartz sandstone	0–200
Gum Ridge Formation and equivalents	Cambrian	Limestone, dolostone and minor siltstone and mudstone	0–300

Source: Kruse et al. (2013), Kruse and Munson (2013a) and Kruse and Munson (2013b); see also the geology technical appendix (Orr et al., 2020) and references therein

The Centralian B Superbasin units that are preserved in the Beetaloo GBA region were deposited in peritidal to shallow marine shelf environments and are limestone-rich (Table 5). The limestones host the Cambrian Limestone Aquifer, which forms the principal water resource in the Beetaloo GBA region (Fulton and Knapton, 2015) (Section 3.1).

Deposition is interpreted to have continued through the Paleozoic era until the maximum burial of the Beetaloo Sub-basin was reached by the time of the Triassic period (Duddy et al., 2003). Deep burial in the Paleozoic was apparently of greater magnitude than earlier burial in the Proterozoic (Faiz et al., 2016). The implications of this phase of burial, the associated heating of organic-rich shale units and the generation of hydrocarbons are discussed further in the prospectivity technical appendix (Hall et al., 2020) (see also Section 2.2).

Only some Paleozoic sequences have been preserved in the Beetaloo GBA region (Figure 16; Table 5). Phases of major erosion are interpreted to have occurred during the Mesozoic and Cenozoic eras, which removed parts of the Paleozoic and later Mesozoic sedimentary basins (Duddy et al., 2003; Faiz et al., 2016).

2.1.3.6 Carpentaria Basin

Sediments of the onshore Carpentaria Basin were deposited during a Cretaceous marine incursion across the Australian continent (Figure 16) (Munson et al., 2013a). They form a variably thick veneer (up to 132 m thick) over the entire Beetaloo Sub-basin and include mudstone and siltstone (Fulton and Knapton, 2015).

Erosion of the Carpentaria Basin sediments is evident in much of the NT. The sequence in the Beetaloo GBA region is not deeply incised but it is presently elevated above the regional groundwater surface (Fulton and Knapton, 2015).

2.1.3.7 Cenozoic erosion and deposition

The Oligocene to Miocene collision between Australia and Indonesia resulted in widespread uplift and erosion across northern Australia (Duddy et al., 2003; Frogtech Geoscience, 2018b). While, as a result, Cenozoic rocks of pre-Quaternary age are rarely preserved in outcrop, they have been identified in the Beetaloo GBA region (Figure 16). In the Beetaloo GBA region, these units include the informally named Miocene Golliger and Birdum Creek beds (Table 6) (Edgoose and Ahmad, 2013), undifferentiated Quaternary sediments and other regolith including colluvium, alluvium, talus and scree, calcrete, eluvial soils, aeolian sand, and lake and playa sediments (Edgoose and Ahmad, 2013).

Table 6 Stratigraphy of the Cenozoic cover in the Beetaloo GBA region

Stratigraphic name (informal)	Age	Lithological description	Thickness	Depositional environment
Birdum Creek beds	Middle–late Miocene	Limestone	Unknown	Lacustrine
Golliger beds	Early–middle Miocene	Limestone	Unknown	Lacustrine

Source: Edgoose and Ahmad (2013); see also the geology technical appendix (Orr et al., 2020) and references therein

2.2 *Petroleum prospectivity*

The Beetaloo Sub-basin is prospective for unconventional petroleum and is estimated to contain significant shale gas, tight gas and shale oil resources, particularly within the Kyalla and Velkerri formations within the Mesoproterozoic Roper Group (Revie, 2017b). Production testing at the Amungee NW-1H exploration well in October 2016, which was reported by Origin Energy in 2017, showed that 6.6 trillion cubic feet (Tcf) of contingent gas resources may be present within the organic-rich shales of the Velkerri Formation (Origin Energy, 2016b, 2017). With further exploration, resource assessment and infrastructure development, unconventional oil and gas production is feasible in the Beetaloo Sub-basin within five to ten years (Pepper et al., 2018).

The prospectivity of petroleum resources in the Beetaloo Sub-basin was assessed to underpin further work on understanding likely development scenarios. Key geological properties of the formations hosting petroleum resources were evaluated, and the relative prospectivity of each resource type was mapped at a regional scale across the basin. Results show that the Amungee Member of the Velkerri Formation is potentially prospective for either liquids-rich or dry gas over most of the Beetaloo Sub-basin extent. The Kyalla Formation liquids-rich gas play and the Hayfield sandstone member liquids-rich gas/oil play are primarily restricted to the central part of the eastern sub-basin. Liquids-rich gas resources are currently more favourable to develop from an economic perspective.

The mapped depth and extent of the gas resource inform where the gas resources are more likely to be present within the sub-basin, which in turn aids assessment of potential connectivity to overlying surface water – groundwater systems and associated assets.

2.2.1 Conventional versus unconventional petroleum resources

Conventional natural gas (and oil) occurs in discrete accumulations trapped by a geological structure and/or stratigraphic feature, typically bounded by a down-dip contact with water and capped by impermeable rock (Reservoir type 1 in Figure 18). Conventional petroleum was not formed in situ; it migrated from the deeper source rocks into a trap containing porous and permeable reservoir rocks (Schmoker, 2002; Schmoker et al., 1995).

Unconventional gas and oil are found in a range of geological settings (Reservoir type 2 in Figure 18) and include shale gas, tight gas, shale oil, coal seam gas (CSG) and gas hydrates (Cook et al., 2013). Unlike conventional reservoirs, unconventional reservoirs have low permeabilities and require innovative technological solutions to move the trapped hydrocarbons to the surface.

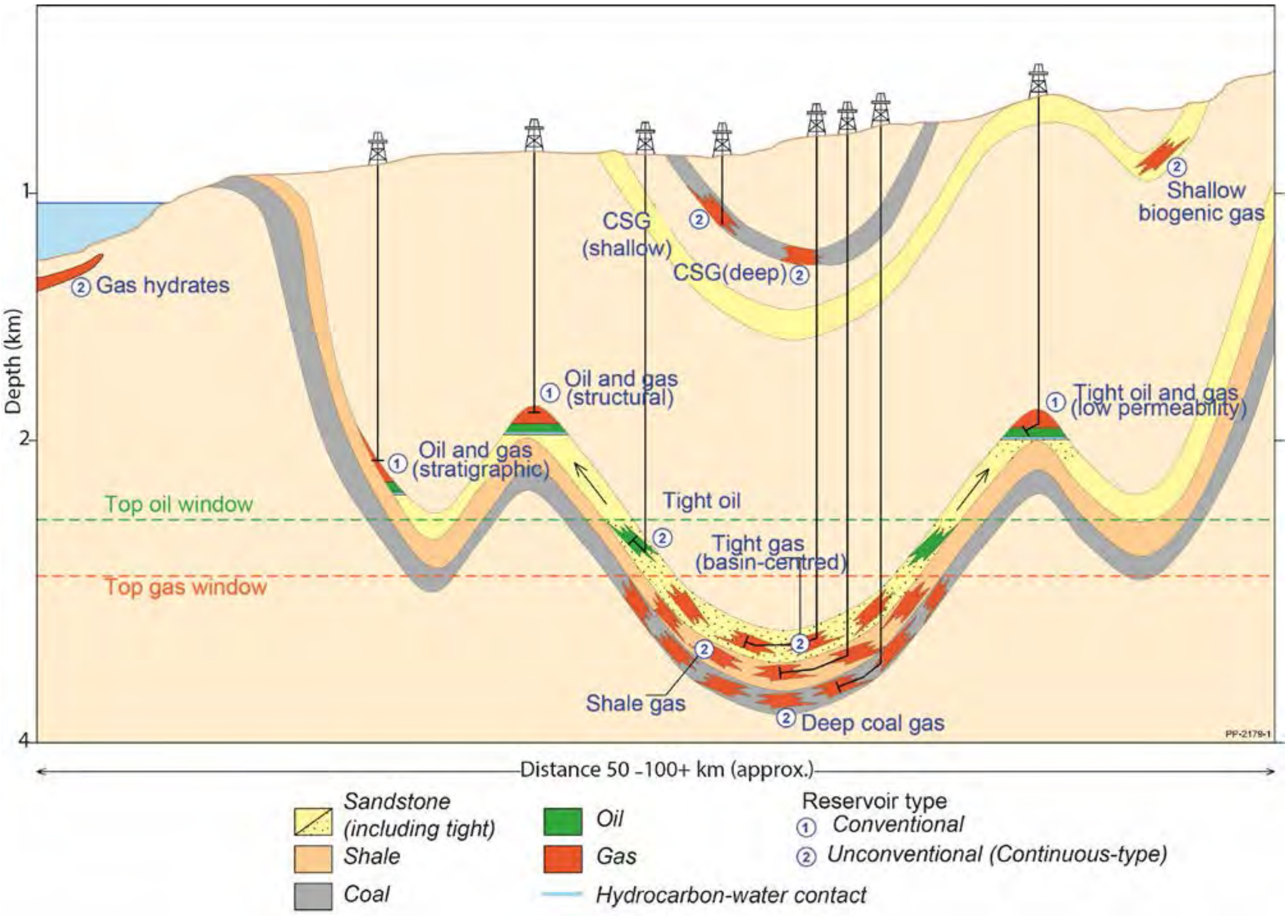

Figure 18 Schematic showing some of the types of oil and gas accumulations

The ‘oil window’ refers to the maturity range in which oil is generated from oil-prone organic matter. Below is the ‘gas window’, which refers to the maturity range in which gas is generated from organic matter.
Source: after Schenk and Pollastro (2002); Cook et al. (2013); Schmoker et al. (1995)
Element: GBA-BEE-2-148

Shale gas is the main type of unconventional gas resource currently being targeted by resource exploration companies in Beetaloo Sub-basin. There are also tight gas resources present within the sub-basin, which may provide an additional target for exploration and development in the next five to ten years.

Shale gas is natural gas hosted in sedimentary rock with low to moderate porosity (with a pore size of 0.005–0.1 µm) and very low permeability. Shale gas usually occurs at depths greater than 1000 to 1500 m. Shales are a common petroleum source rock and may retain more petroleum than they expel during the thermal maturation process of organic matter. The gas remains trapped in the shale and is either absorbed on to the organic matter or is held in a free state in the pores and fractures of the rock. Shale reservoirs occur with significant (10–100 km) lateral continuity and can be of considerable thickness (>100 m). Where shales act as both the petroleum source and reservoir rock, they are sometimes referred to as ‘self-sourcing reservoirs’.

Tight gas is natural gas trapped in reservoirs characterised by low porosity (<8–10%) and permeability (<0.1 mD). There is a range of trapping mechanisms for tight gas. Tight gas may occur in pervasive, distributed basin-centred gas accumulations, where gas is hosted in low-permeability reservoirs, which are commonly abnormally overpressured, apparently lack a down-dip water contact and are continuously saturated with gas (Fall et al., 2002; Law and Curtis, 2002). Tight gas may also occur in discrete reservoirs, where migrated gas accumulates in rocks with very low porosity and permeability, in a similar manner to conventional accumulations (e.g. Shanley and Robinson, 2004).

Gas may be referred to as 'dry gas' or 'liquids-rich gas' depending on its composition. Dry gas is natural gas that is dominated by methane (greater than 95% by volume) with little or no condensate or liquid hydrocarbons. Liquids-rich gas (also known as 'wet gas') contains less methane than dry gas and more ethane and other more complex hydrocarbons (propane, butane, pentane, hexane and heptane). The composition of the gas is important for understanding future development scenarios in the Beetaloo Sub-basin, as liquids-rich gas resources are currently more favourable to develop from an economic perspective.

2.2.2 Petroleum in Beetaloo Sub-basin and surrounds

2.2.2.1 Exploration history

Although the NT is underlain by thick sedimentary rock sequences and large areas are relatively unexplored, the petroleum potential of the Beetaloo Sub-basin and surrounding region has long been recognised (Muir, 1980), with known oil and gas occurrences (Munson, 2014). Oil shows are common, and bitumen and pyrobitumen have been reported from numerous units, including the Paleoproterozoic and Mesoproterozoic sedimentary rocks and the overlying Paleozoic sedimentary rocks (Knutson et al., 1979; Muir, 1980).

Exploration for hydrocarbons in the greater McArthur Basin began in the 1960s but intensified from the 1980s. Interest was further stimulated by the first discovery of oil in the sub-basin, which was made during stratigraphic drilling of the Urapunga 4 well by the Bureau of Mineral Resources (predecessor organisation to Geoscience Australia) in 1985 (Jackson et al., 1986).

Since exploration began, 8818 line km of two-dimensional seismic data have been acquired across the sub-basin; however, there are no publicly available three-dimensional seismic data. Over 30 petroleum wells have been drilled in the greater McArthur Basin, including the Beetaloo Sub-basin and surrounding region (Figure 19). Nineteen of these wells are located within the Beetaloo Sub-basin outline as defined by the Northern Territory Geological Survey (not including side tracks). Five wells are located within the western sub-basin (Birdum Creek 1, Tarlee 1-3 and Wyworrie 1) and 14 are located within the eastern sub-basin (Amungee NW-1H, Balmain 1, Beetaloo W1, Burdo 1, Chanin 1, Elliott 1, Kalala 1, Jamison 1, Mason 1, McManus 1, Ronald 1, Shenandoah 1, Shortland 1 and Tanumbirini 1).

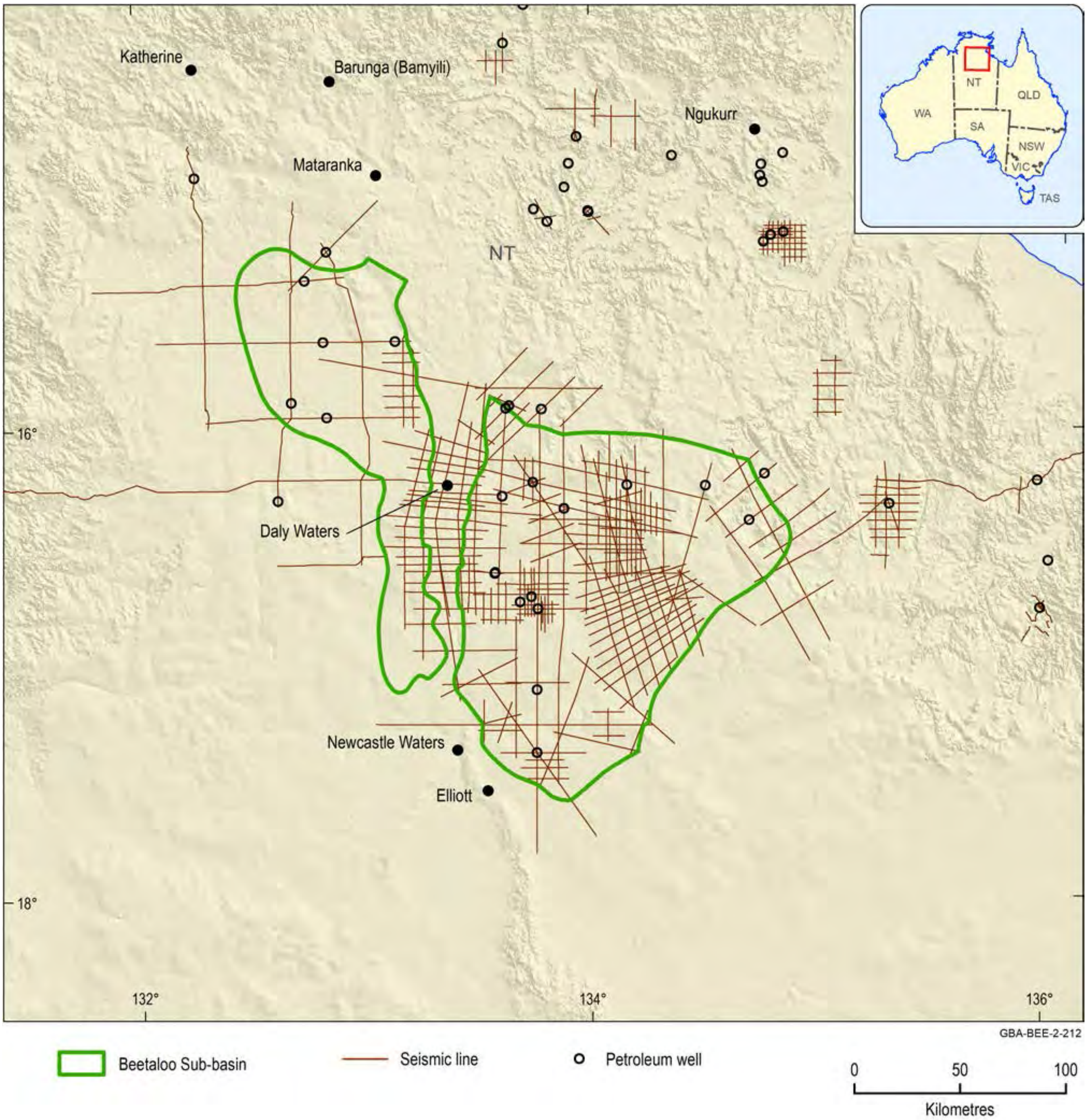

Figure 19 Beetaloo GBA region two-dimensional seismic data coverage

Data: seismic survey lines from Department of Primary Industry and Resources (NT) (2018b), petroleum well distribution from Department of Primary Industry and Resources (NT) (2018a)
Element: GBA-BEE-2-212

While there has been no commercial gas production to date in the Beetaloo Sub-basin, significant exploration activity is underway (Pepper et al., 2018) and Santos, Origin Energy, Falcon Oil and Gas, and Pangaea Resources are continuing to investigate key unconventional targets in the Beetaloo Sub-basin (Figure 20).

In 2017, following completion of extended production testing at the Amungee NW-1H exploration well (Figure 21), Origin Energy reported that 6.6 Tcf of contingent gas resources may be present in their tenure (Figure 20) within the organic-rich 'B shale' unit (Amungee Member) of the Velkerri Formation (Origin Energy, 2016b, 2017). It is important to note these 2C contingent resources have been reported based on the results from one well, assuming homogeneity in the geological characteristics of the play across the region. However, experience in the United States highlights that there is commonly a large degree of heterogeneity in production rates from shale gas plays, even within small areas. In particular, the recovery factor for Amungee NW-1H was reported to be 16% (Revie, 2017b), comparable with well explored shale gas plays in the United States. Nevertheless, further wells are required to increase confidence in the long-term producibility of the play (Revie, 2017b).

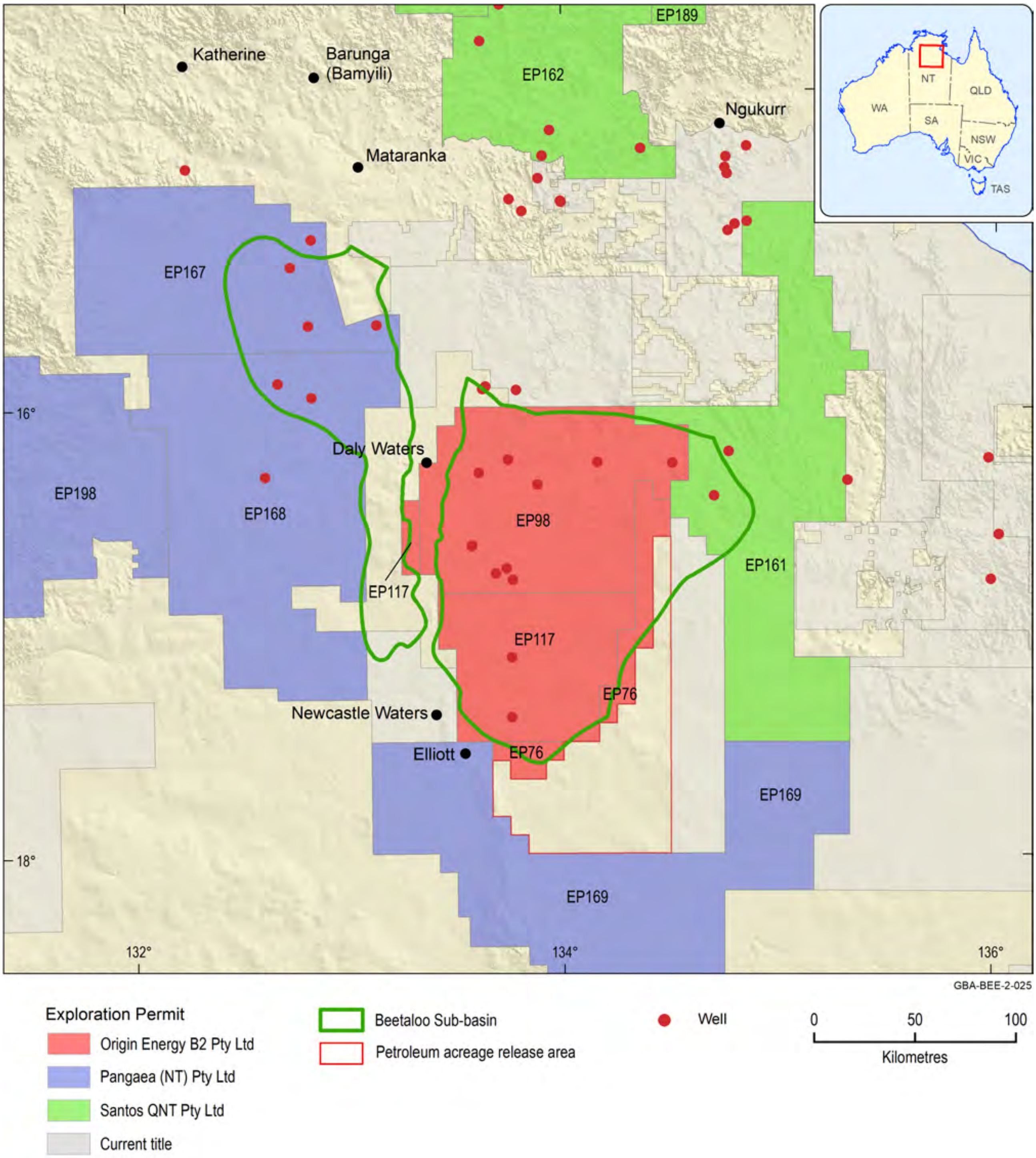

Figure 20 Beetaloo Sub-basin exploration, retention and production permit operators

Data: permit operators and outlines are provided from GPinfo petroleum database – a Petrosys Pty Ltd product (Petrosys Pty Ltd, 2019). Beetaloo Sub-basin outline from Department of Primary Industry and Resources (NT) (2017)
Element: GBA-BEE-2-025

Figure 21 Kyalla 117 N2 well site at the commencement of drilling operations

Credit: Stephanie Stonier and Chris Zipf (Origin Energy)
Element: GBA-BEE-2-379

2.2.2.2 Unconventional gas plays

In geology, a petroleum play, or simply a play, is a group of petroleum accumulations that occur in the same region and are controlled by the same set of geological circumstances (Stoneley, 1995). Five different unconventional play types have been identified within the Beetaloo Sub-basin (Côté et al., 2018), which have the potential to bring petroleum to market within a time frame of five to ten years. Figure 22 and Figure 23 show the location and stratigraphic position of these play types, which are:

- dry gas hosted in the Velkerri Formation shales
- liquids-rich gas hosted in the Velkerri Formation shales
- liquids-rich gas hosted in the Kyalla Formation shales
- the hybrid Kyalla Formation play (including tight sands adjacent to the organic-rich shale intervals)
- tight gas, condensate, and potentially volatile oil, within the Hayfield sandstone member of the Hayfield mudstone in the overlying Neoproterozoic units.

The Velkerri Formation shale dry gas play is the most mature resource play in the Beetaloo Sub-basin (Close et al., 2017b; Côté et al., 2018). A range of regional-scale prospective resource estimates have been published for shale gas in the Velkerri Formation. Most recently, the NT Government has quoted resource numbers from Falcon Energy (Northern Territory Government

(Northern Territory Geological Survey), 2017), which estimates a prospective (P50) in-place gas resource of 496 Tcf in the Amungee Member (Middle Velkerri) 'B' shale, over a prospective area of 16,145 km^2. Although these results highlight the presence of potentially significant petroleum resources, the full extent of these resources is still poorly understood and quantified, and any estimates of potential resources have a high degree of uncertainty associated with them.

Within the Amungee Member of the Velkerri Formation, there are three well-defined target intervals, informally known as the A, B and C shales (Figure 22) (Close et al., 2017b). In 2017, following completion of the extended production testing at the Amungee NW-1H exploration well (Figure 21), Origin Energy reported 6.6 Tcf of contingent gas resources for the organic-rich 'B shale' unit of the Amungee Member (Origin Energy, 2017, 2016b). Although only the B shale has been tested with a horizontal, hydraulically fractured stimulated well, the A and C shales are also viable targets. A liquids-rich gas play has been interpreted for the Velkerri Formation along the northern and south-eastern limits of the eastern Beetaloo Sub-basin, as well as in the western sub-basin (Côté et al., 2018).

The Kyalla Formation has the potential to host both liquids-rich gas and oil plays. Prospective Kyalla Formation oil-in-place resources are estimated at 772 MMbbl (P50) (range: 1163 MMbbl (P10) to 414 MMbbl (P90)) (Revie, 2017b, 2017a; Weatherford Laboratories, 2017). There are three well-defined source rock intervals in the Kyalla Formation. The lower and middle Kyalla Formation shales are identified to be prospective for liquids-rich gas in the deepest sections of both the eastern and western sub-basins (Figure 22) (Côté et al., 2018). Oil is likely to be hosted in the upper shale, as well as in the lower and middle shales towards the basin flanks. In addition, two prospective hybrid target intervals, which host an additional potential liquids-rich gas play (Altmann et al., 2018), have also been identified within the Kyalla Formation. This play is restricted to the south of the eastern Beetaloo Sub-basin (Côté et al., 2018) and is not considered an independent target, but it would most likely be developed as a stacked play in association with the adjacent Kyalla Formation shale intervals.

The Hayfield sandstone member tight gas / condensate play is thought to be a thin but regionally extensive sandstone confined to an area overlying the central part of the eastern Beetaloo Sub-basin, within the Neoproterozoic Hayfield mudstone (Figure 22) (Côté et al., 2018). The play's trapping mechanism is likely to be a structural-stratigraphic trap, containing migrated hydrocarbons from either the Kyalla or Velkerri formation source rocks. Whether this is a gas-condensate, volatile oil or a buoyancy driven play with a gas-condensate cap and a volatile oil leg is still to be determined (Côté et al., 2018). No prospective resource estimates have been published for this play.

Further details on unconventional play types and petroleum resource classifications can be found in the petroleum prospectivity technical appendix (Hall et al., 2020).

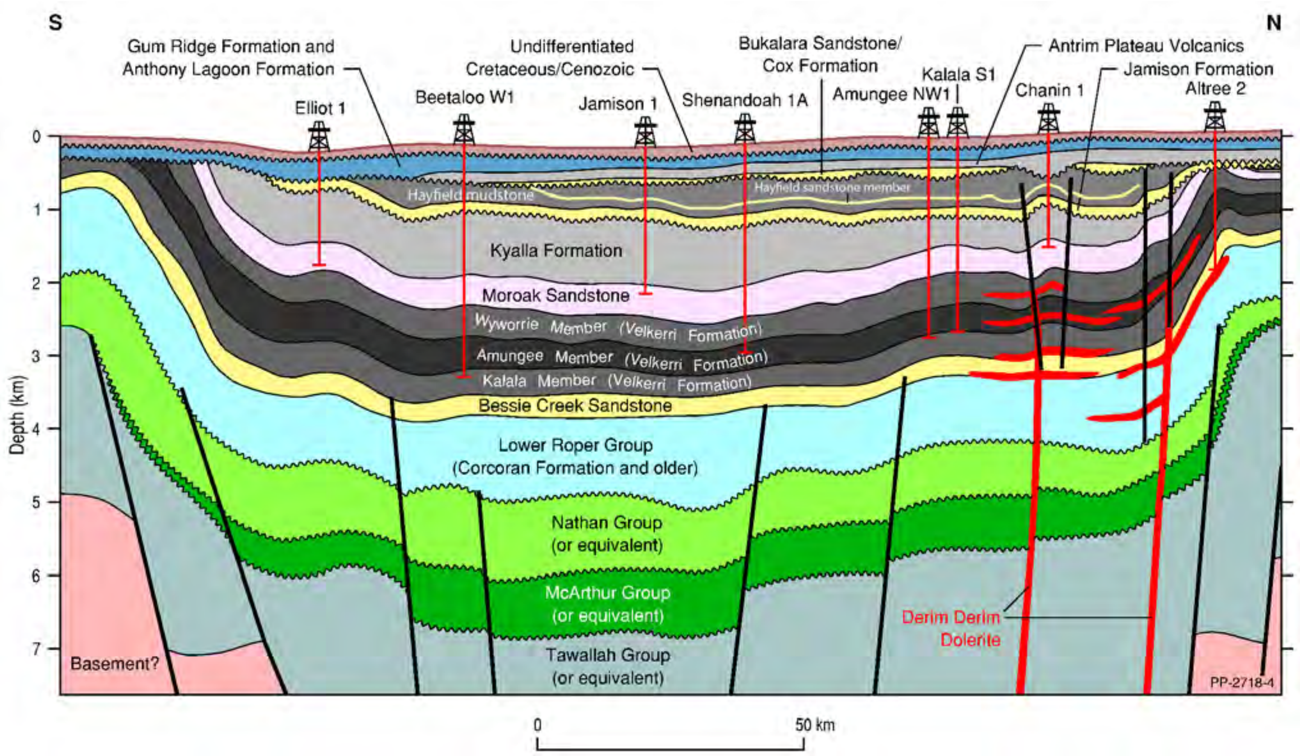

Figure 22 Schematic geological cross-section across the Beetaloo Sub-basin

Unconventional plays are hosted within the Velkerri Formation, Kyalla Formation and Hayfield sandstone member of the Hayfield mudstone.
Source: modified from Altmann et al. (2018)
Element: GBA-BEE-2-056

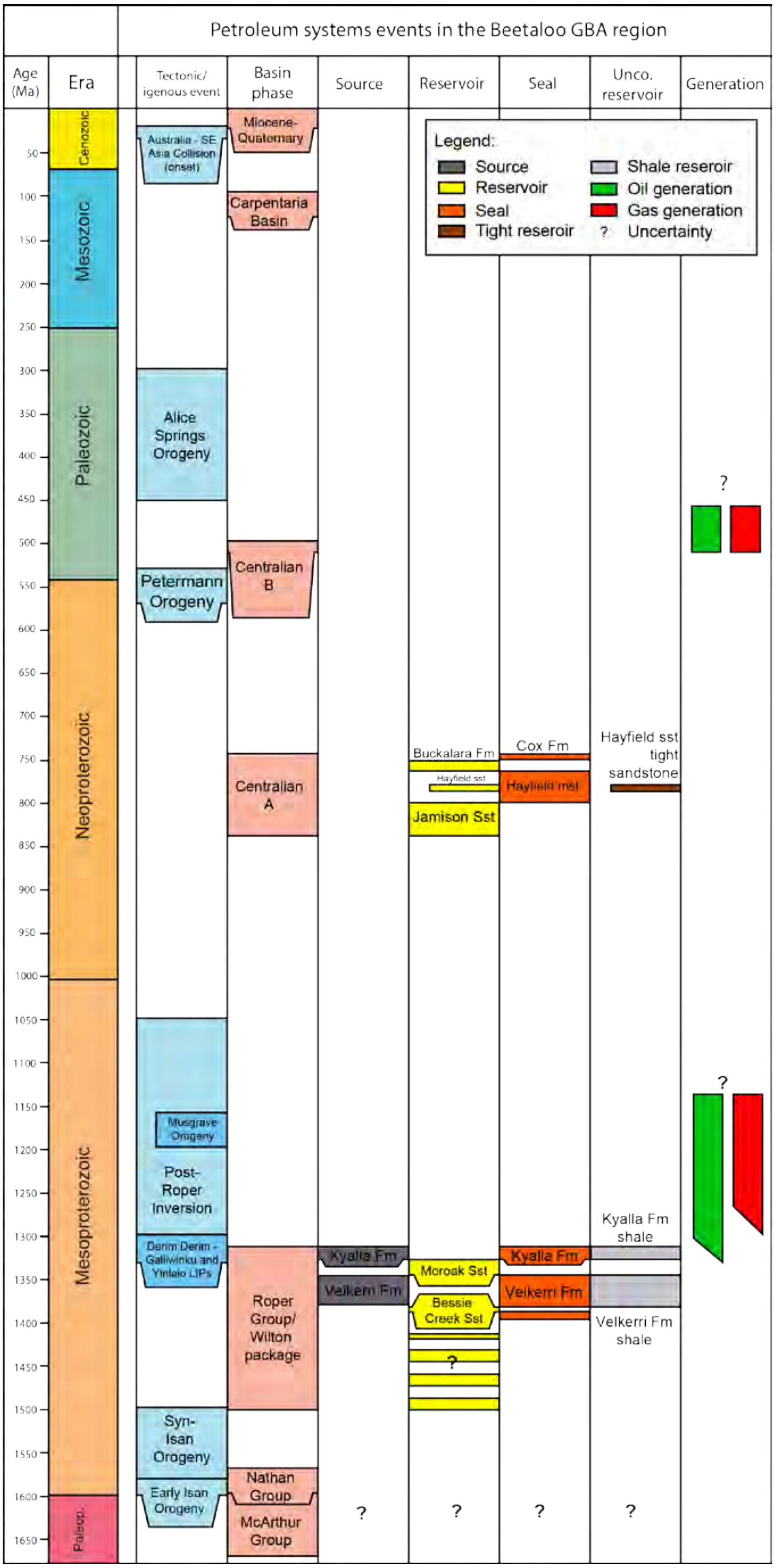

Figure 23 Petroleum systems event chart

Source: petroleum prospectivity technical appendix (Hall et al., 2020) and references therein
Element: GBA-BEE-2-321

Although this study is focused on the petroleum prospectivity within the Beetaloo Sub-basin, the area of potential hydrocarbon prospectivity extends more broadly across the greater McArthur Basin. Figure 24 shows the likely extent of organic-rich shales of the Velkerri Formation in the region surrounding the Beetaloo Sub-basin, as mapped by the Department of Primary Industry and Resources (Pepper et al., 2018). However, as large areas have not been tested by drilling, the petroleum-bearing status has not been confirmed for all regions.

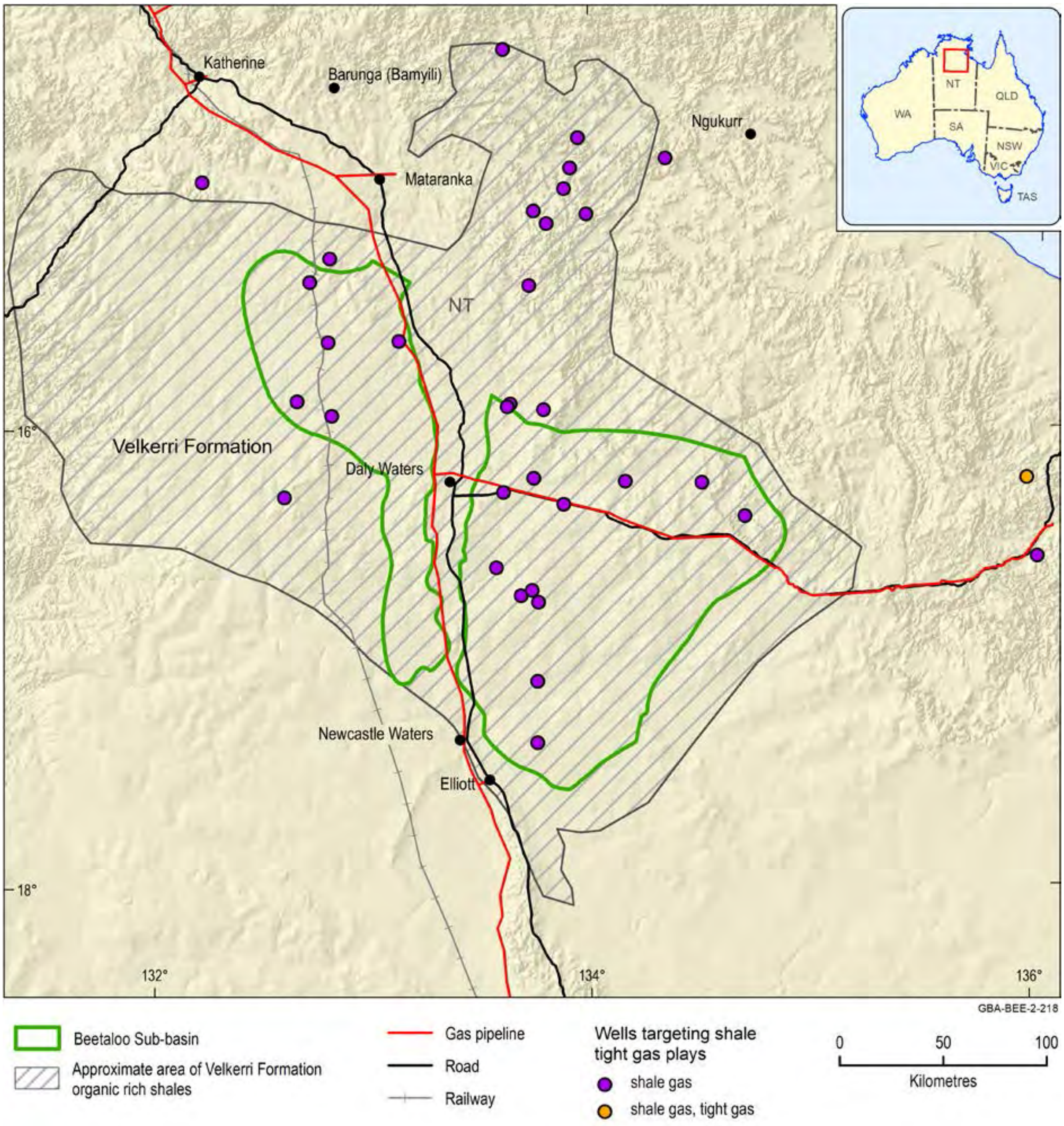

Figure 24 Extent of the organic-rich Velkerri and Barney Creek formation shales in the region surrounding the Beetaloo Sub-basin

Source: adapted from Pepper et al. (2018)
Data: Australian Topographic Base Map (Web Mercator) Web Map Server (WMS) (Geoscience Australia, 2017a). Oil and gas pipelines from the National Oil and Gas Infrastructure WMS (Geoscience Australia, 2014, 2017b). Beetaloo GBA region based on the NT DPIR Beetaloo Sub-basin definition (Department of Primary Industry and Resources (NT), 2017). Approximate extent of the organic-rich Velkerri and Barney Creek formations is based on the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018)
Element: GBA-BEE-2-218

2.2.3 Formation characterisation

The amount of gas (and oil) present within a petroleum accumulation depends on the geological characteristics of both the petroleum source rock and the reservoir rock in which the petroleum is trapped. To underpin further work on understanding likely development scenarios and recovery factors, key geological properties of the Velkerri and Kyalla formations and the Hayfield sandstone member required were characterised, based on available open file domain data. The geological properties evaluated were:

- formation depth and extent (Figure 25)
- source rock properties, including net thickness, total organic carbon content, the type of organic matter (kerogen type) and the quality of the source rock (hydrogen index) (Figure 26). The variation in the type and quality of the source rocks across the sub-basin may be due to differences in depositional environment but remains poorly understood
- source rock thermal maturity, estimated from burial and thermal history models constructed for key wells (example shown in Figure 27). Thermal maturity represents the degree to which a source rock has been heated under the Earth's surface and influences whether the generated petroleum is oil, liquids-rich gas or dry gas (Figure 28)
- reservoir characteristics, including porosity, permeability, gas saturation, mineralogy and brittleness
- regional stress regime and overpressure.

Results are summarised in Table 7 and a full description of this assessment is provided in the petroleum prospectivity technical appendix (Hall et al., 2020).

Table 7 Characteristics of formations hosting petroleum plays assessed for this study

Property	Hayfield sandstone member	Kyalla Formation	Kalala Member – Velkerri Formation	Amungee Member – Velkerri Formation	Wyworrie Member – Velkerri Formation
Top depth (m MSL)	0–964	0–1112	−109–2937		
Thickness (m)	0–569	<30–960	<50–1483		
Net source rock thickness (m) (present day)[a]	Not a source rock	5–93	0–31	52–246	0–34
Total organic carbon (present day) (wt%)	Not a source rock	Mean 1.1 Range 0–9	Mean 0.9 Range 0–7	Mean 3.4 Range 0–30	Mean 0.9 Range 0–11
Hydrogen Index (present day) (mg HC/g TOC)	Not a source rock	6–777	4–133	1–800	8–461
Source rock thermal maturity	Not a source rock	Immature – liquids-rich gas	Immature – dry gas		
Average permeability[b]	No data	Mean 7.9x10^{-5} Range 1.1 x 10^{-5} – 1.1 x 10^{-4}	5.7 x 10^{-5} (1 sample only)	Mean 1.6 x 10^{-5} Range 1.9 x 10^{-5} – 6.3 x 10^{-4}	Mean 8.1 x 10^{-5} Range 1.6 x 10^{-5} – 1.6 x 10^{-4}

Property	Hayfield sandstone member	Kyalla Formation	Kalala Member – Velkerri Formation	Amungee Member – Velkerri Formation	Wyworrie Member – Velkerri Formation
Average porosity[c] (%)	No data	Mean 5.9 Range 3.5–6.1	7.0 (1 sample)	Mean 7.3 Range 4.1–11.0	Mean 8.9 Range 7.7–10.3
Average water saturation[d] (%)	No data	Mean 62 Range 56–71	96.1 (1 sample)	Mean 55.3 Range 33.9–69.9	Mean 58.2 Range 53.2–65.6
Average oil saturation[d] (%)	No data	Mean 5.7 Range 0.9–10.1	1.8 (1 sample)	Mean 5.2 Range 0.5–11.3	Mean 5.0 Range 2.4–8.4
Average gas saturation[e] (%)	No data	Mean: 33 Range 28–34	2.1 (1 sample)	Mean 39.5 Range 28.7–63.7	Mean 36.8 Range 32.0–42.6
Average brittleness[f]	Brittle (0.472)	Brittle (0.406[f])	Brittle (0.475)		
Pressure regime	No data	Overpressured	Overpressured		

[a]Net source rock thickness represents the cumulative thickness of organically rich shale with a present-day TOC content >2 wt% based on available well intersections.
[b]As-received pressure decay permeability by well.
[c]Average porosity represents the dry helium porosity as a % of bulk rock volume by well.
[d]As received saturation as a % of the pore volume by well.
[e]As received gas saturation as a % of pore volume by well.
[f]The brittleness index (BI) was calculated from mineral content using the method of Jarvie DM et al. (2007). However, recent petrophysical, core and geomechanical analyses demonstrate that the Kyalla Formation completion quality is more favourable than that suggested by mineralogy alone (Altmann et al., 2018; Baruch et al., 2018).
HC = hydrocarbons; mD = millidarcy; m MSL = metres with respect to mean sea level; TOC = total organic carbon; wt% = weight %
Source: see the petroleum prospectivity technical appendix (Hall et al., 2020) for full formation descriptions

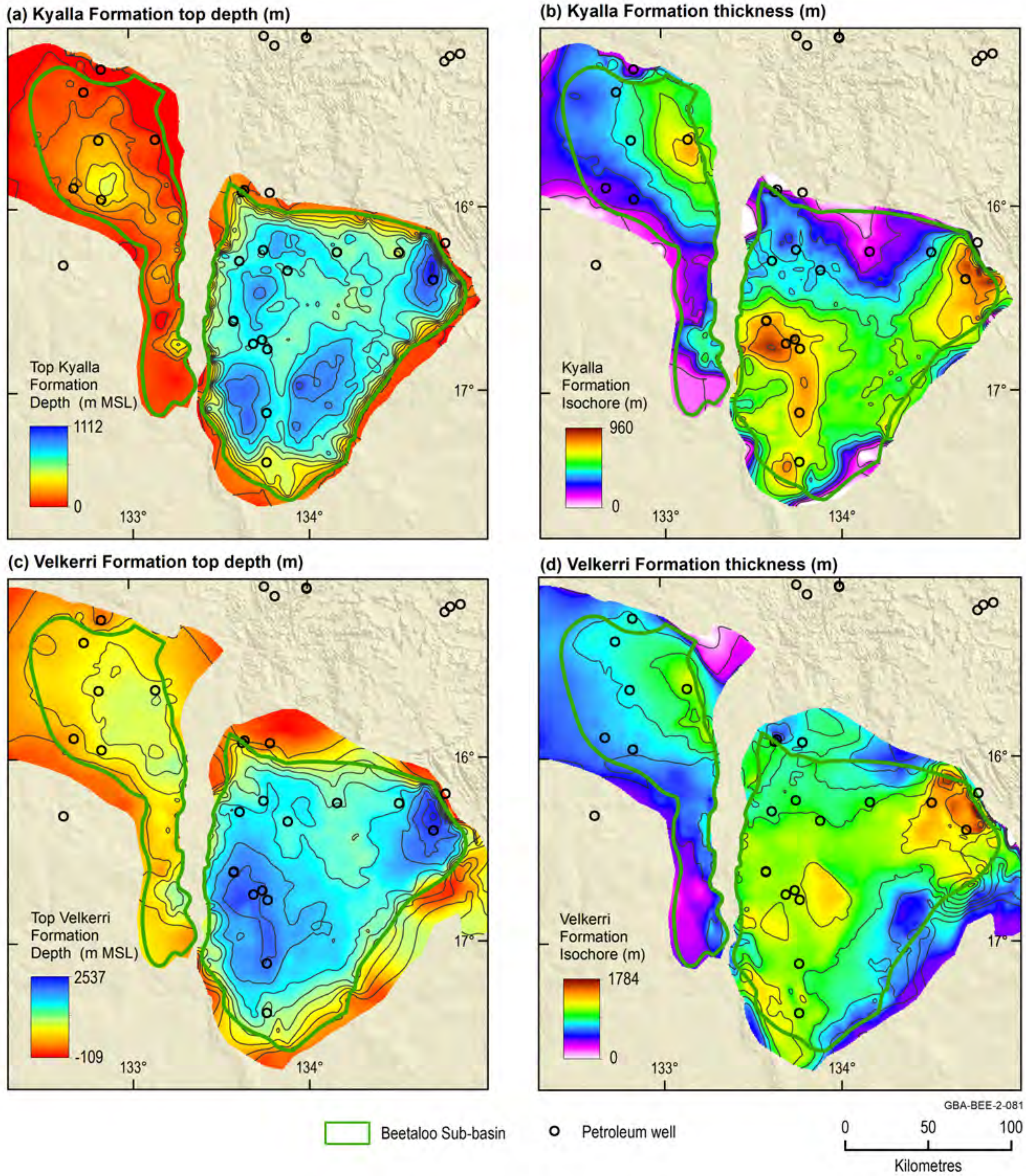

Figure 25 Formation depths and extents (a) Kyalla Formation top depth, (b) Kyalla Formation total vertical thickness, (c) Velkerri Formation top depth and (d) Velkerri Formation total vertical thickness

There are insufficient public domain data to effectively map top Hayfield sandstone member depth and gross formation thickness. Despite the current exploration activity in the Beetaloo Sub-basin, the area remains relatively data-poor in terms of public domain data, which is a significant limitation in this GBA. Although the coverage of two-dimensional seismic data is sufficient to map key formations at a regional scale, significant uncertainties remain in the model away from well control.
Contour interval = 500 m. MSL = mean sea level
Source: geology technical appendix (Orr et al., 2020) and petroleum prospectivity technical appendix (Hall et al., 2020)
Data: GBA derived dataset: top Velkerri and Kyalla formations modified from Williams (2019)
Element: GBA-BEE-2-081

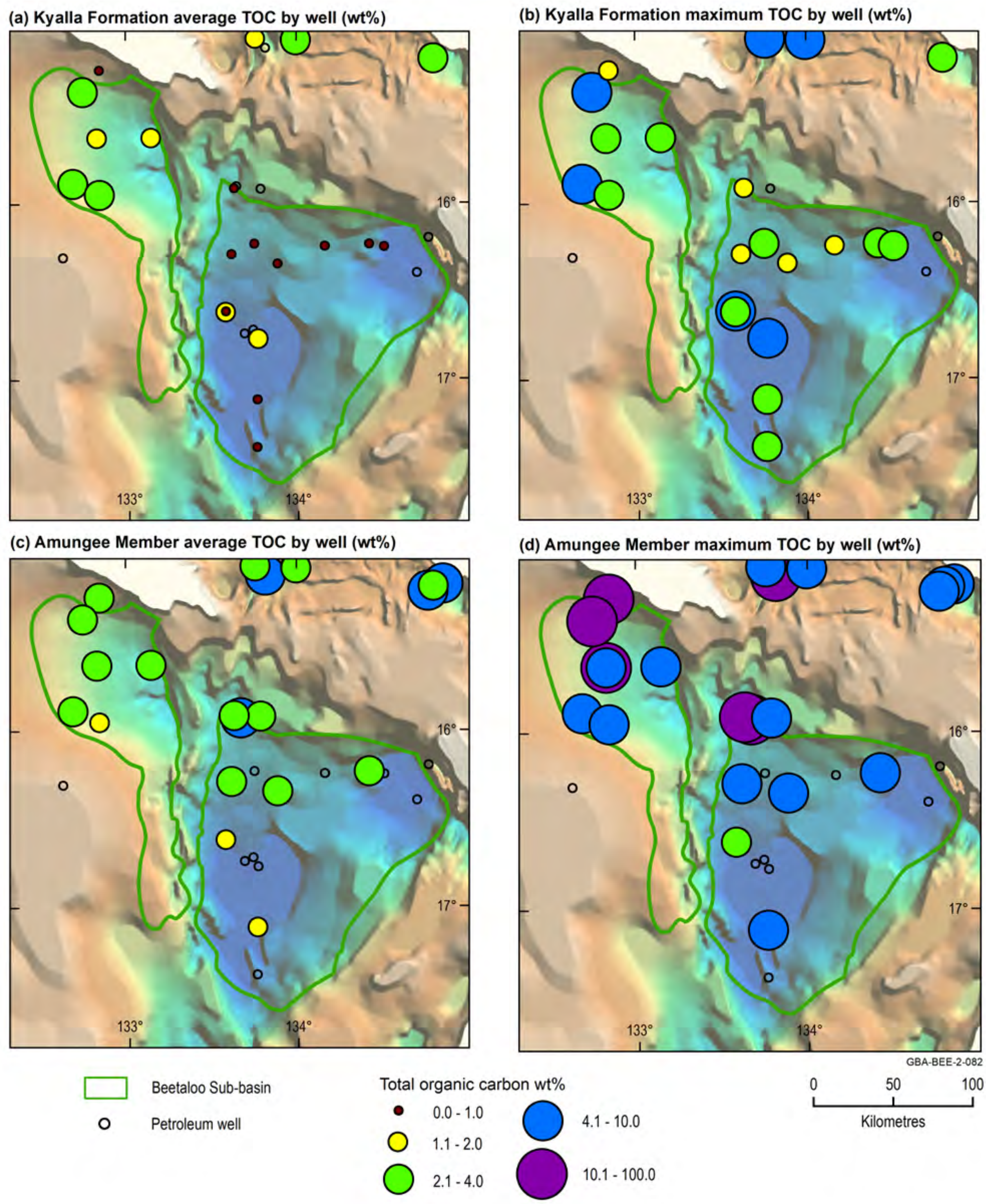

Figure 26 Source rock distribution maps showing the (a) Kyalla Formation average TOC by well, (b) Kyalla Formation maximum TOC by well, (c) Amungee Member average TOC by well and (d) Amungee Member maximum TOC by well

The number of TOC samples by well varies; further information can be found in the petroleum prospectivity technical appendix (Hall et al., 2020).
TOC = total organic carbon; wt% = weight %
Source: modified from Jarrett et al. (2019)
Data: TOC data from Revie and Normington (2018); Pangaea NT Pty Ltd (2019); depth to base Roper Group (Wilton package) sourced from Frogtech Geoscience (2018b)
Element: GBA-BEE-2-082

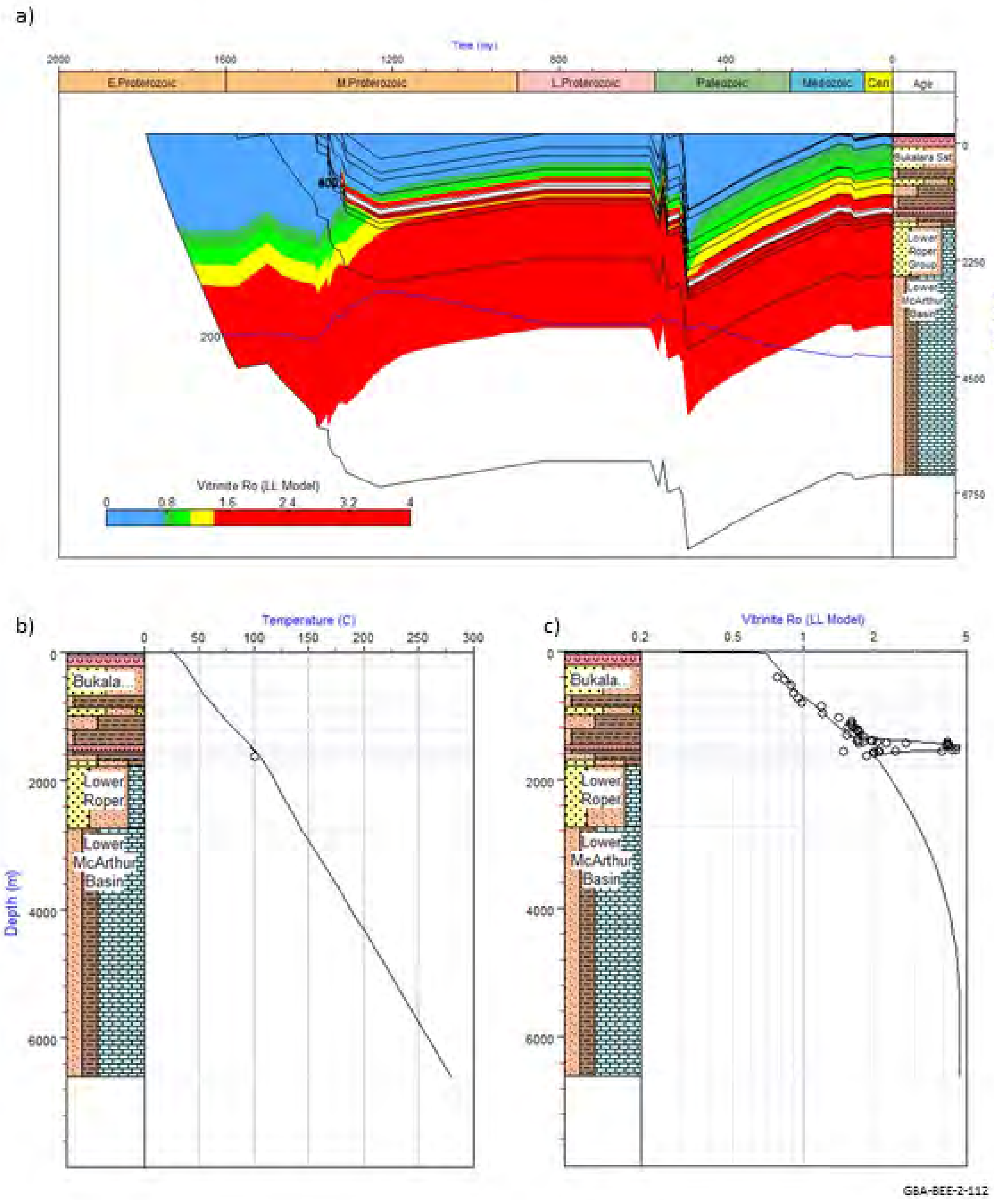

Figure 27 Modelled burial history for Tarlee 3 (a) burial history, showing temperature contours and coloured by thermal maturity; (b) modelled present day temperature-depth profile, with corrected bottom hole temperature measurement; (c) modelled maturity-depth profile, with measured bitumen reflectance data converted to equivalent vitrinite reflectance values using the conversion equation of Jacob (1989)

Source: modified from Hoffman (2015). Refer to the petroleum prospectivity technical appendix for further details (Hall et al., 2020)

Data: Revie and Normington (2018); Pangaea NT Pty Ltd (2019)

Element: GBA-BEE-2-112

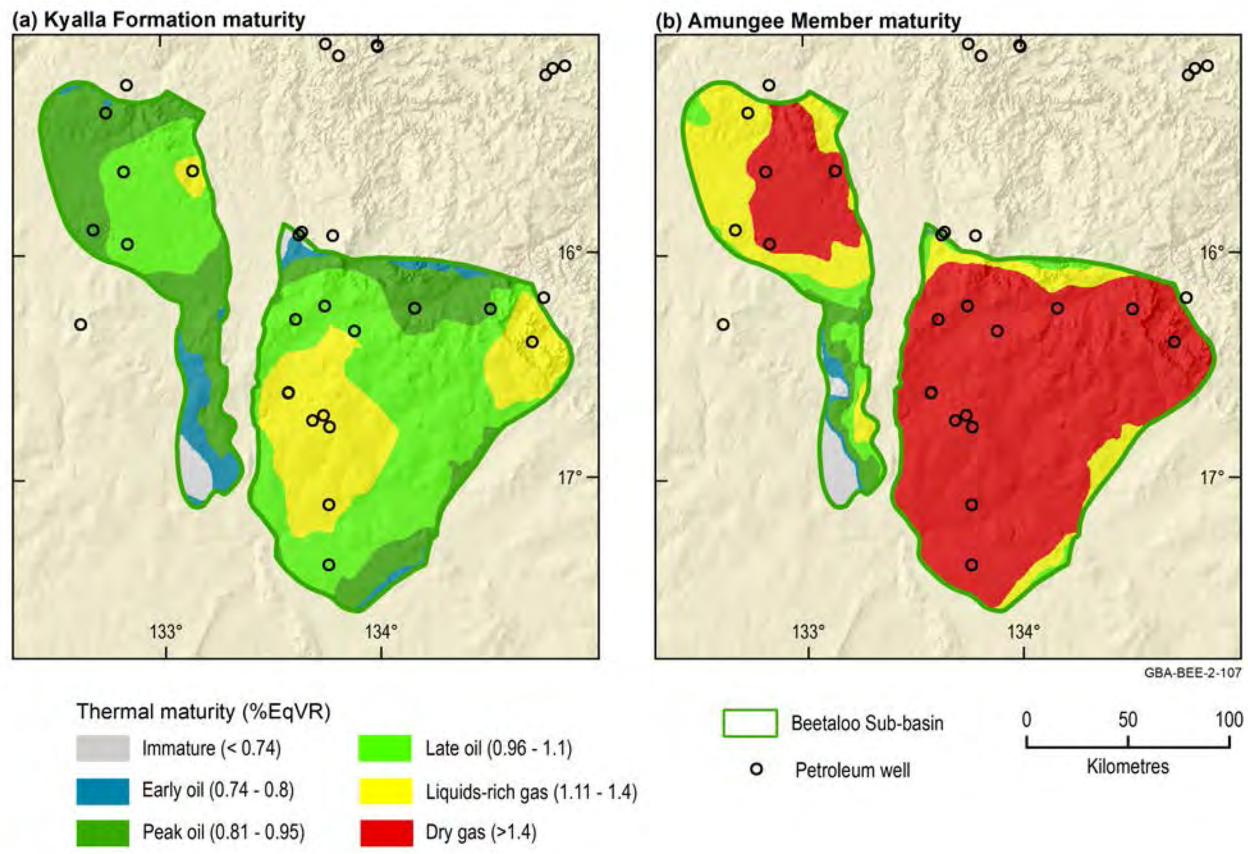

Figure 28 Source rock maturity maps for the mid-depth of the (a) Kyalla Formation and (b) Amungee Member of the Velkerri Formation

Significant uncertainties still remain in our understanding of source rock maturity across the Beetaloo Sub-basin and a more detailed burial and thermal history modelling study, incorporating spatial variations in uplift and erosion and more detailed facies mapping, is required.
%EqVR = vitrinite reflectance equivalent
Source: petroleum prospectivity technical appendix (Hall et al., 2020)
Data: Geological and Bioregional Assessment Program (2019i)
Element: GBA-BEE-2-107

2.2.4 Resource prospectivity maps

The distributions of the different types of gas resource plays were mapped across the Beetaloo Sub-basin. These maps inform where the gas resources are more likely to be present within the sub-basin, which in turn aids assessment of potential connectivity to overlying surface water – groundwater systems and associated assets. The prospectivity assessment workflow is summarised below, and more detail is provided in the petroleum prospectivity technical appendix (Hall et al., 2020).

The potential extent of petroleum resources in the Beetaloo Sub-basin was evaluated for the Velkerri Formation dry- and liquids-rich gas plays and the Kyalla Formation liquids-rich gas play using a process called 'play fairway analysis'. Play fairway analysis was used to identify areas where a specific petroleum resource type is likely to be present, based on the geological characteristics described in Section 2.2.3, and where additional work on a finer scale is warranted to further develop understanding of a prospect.

The key mapped geological properties required for a play to be present were identified. For the Beetaloo GBA region, map data were available for three geological properties: formation depth, net source rock thickness and source rock thermal maturity. Each geological property map was then categorised into three classes (low/absent: 0; medium: 0.5; high: 1) based on the criteria shown in Table 8.

The resulting classified maps were multiplied together to produce an overall relative prospectivity map, which highlights regions with the most favourable geological conditions for this play type (Figure 29). These areas of moderate to high prospectivity form the extent of the play (or ‘play fairway’).

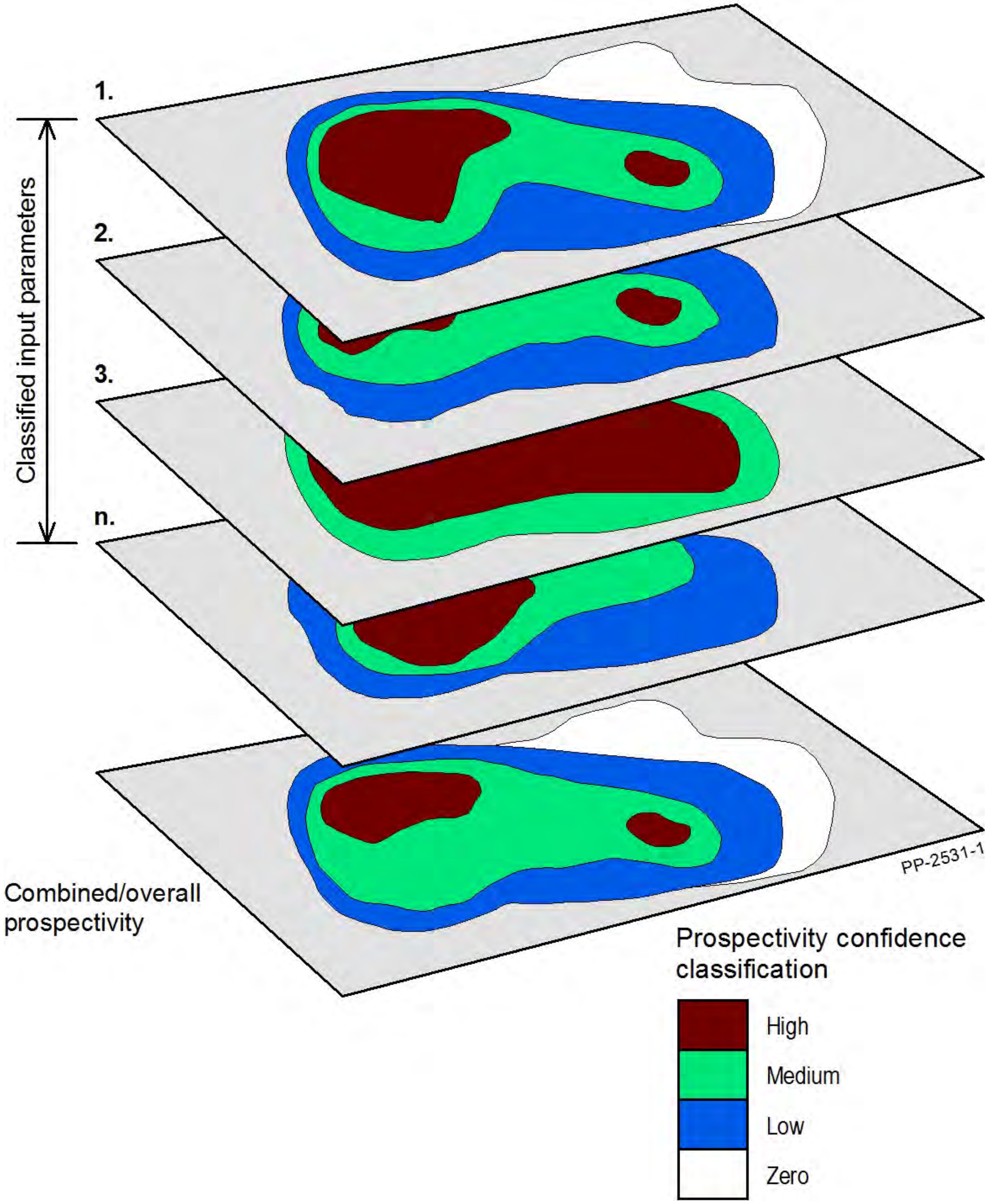

Figure 29 Schematic workflow for combining input parameter maps to develop a play fairway map (relative prospectivity) for a given formation or play

Element: GBA-BEE-2-199

Table 8 Input parameters and classifying criteria used to develop play fairway maps for (a) dry gas and (b) liquids-rich gas

(a) Dry gas

Parameter	Absent/low (0)	Medium (0.5)	High (1)	Map source
Mid formation depth (m)	<700	700–1000	>1000	Three-dimensional geological model (Orr et al., 2020) (Figure 25)
Net source rock thickness (m)[a]	<15	15–30	>30	Gross stratigraphic thickness from three-dimensional geological model (Orr et al., 2020) (Figure 25) multiplied by the net organically rich ratio (Table 7)
Thermal maturity (dry gas) (%EqVR)	<1.4	na	1.4	Source rock maturity map (Figure 28)

(b) Liquids-rich gas

Parameter	Absent/low (0)	Medium (0.5)	High (1)	Map source
Mid formation depth (m)	<700	700–1000 m	>1000	Three-dimensional geological (Orr et al., 2020) (Figure 25)
Net source rock thickness (m)[a]	<15	15–30 m	>30	Gross stratigraphic thickness from three-dimensional geological model (Orr et al., 2020) (Figure 25) multiplied by the net organically rich ratio (Table 7)
Thermal maturity (liquids-rich gas) (%EqVR)	<1.1 or >2	na	1.1–2	Source rock maturity map (Figure 28)

[a]Net source rock thickness represents the cumulative thickness of organically rich shale with a total organic carbon (TOC) content >2 wt%.
na = not applied; %EqVR = vitrinite reflectance equivalent
Source: petroleum prospectivity technical appendix (Hall et al., 2020)

The play fairway analysis results are shown in Figure 30a to Figure 30c.

The Amungee Member has a high relative prospectivity for dry gas plays across most of the eastern sub-basin (Figure 30a). In addition, the Amungee Member is also prospective for dry gas in the central part of the western sub-basin.

The Amungee Member has a high relative prospectivity for liquids-rich gas plays along the northern and south-eastern limits of the eastern sub-basin (Figure 30b). The area of high relative prospectivity for liquids-rich gas also extends around the shallower regions of the western sub-basin. Source rock maturity is the main controlling factor on the Amungee Member play extent in the eastern sub-basin, while net source rock thickness and formation depth restrict play extent in the west.

The Kyalla Formation has a high relative prospectivity for liquids-rich gas plays in the central and western parts of the eastern sub-basin (Figure 30c). Formation depth and maturity are the main controlling factors on extent of the higher prospectivity region.

There were insufficient public domain data available to produce an independent prospectivity map of the Hayfield sandstone tight gas play using play fairway analysis. Instead, the Hayfield sandstone tight gas play presented by Origin Energy in Côté et al. (2018) is used for this assessment, which shows the extent of this resource is primarily restricted to the central part of the eastern sub-basin (Figure 30d).

Results represent the maximum possible area within which each play may be present based solely on regional geological criteria. These maps do not capture any local-scale (<10 km) variations in geology within formations that may influence the prospectivity at a prospect scale. Although liquids-rich gas resources are currently more favourable to develop from an economic perspective, no other factors relating to economics, politics or social issues are incorporated into this assessment.

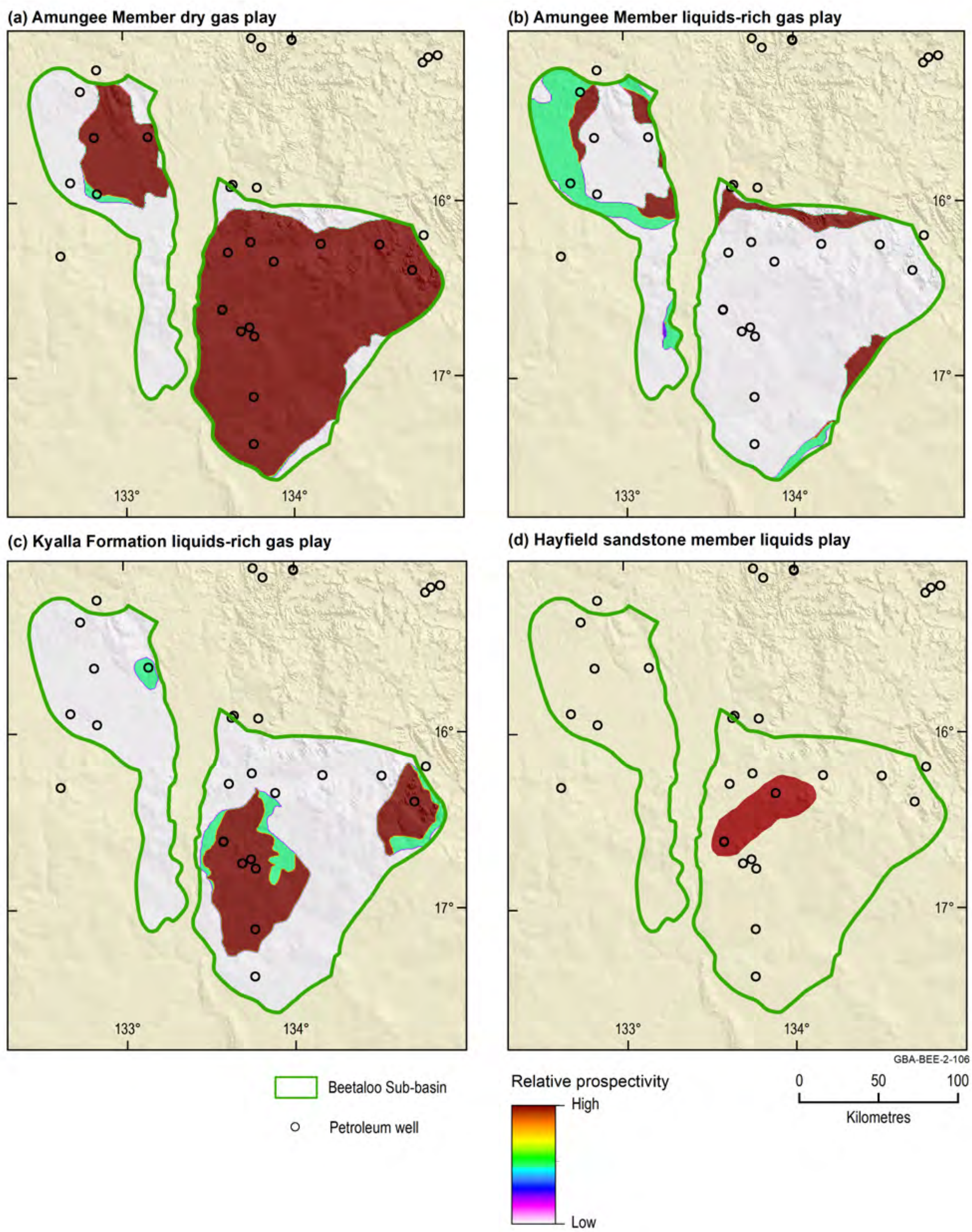

Figure 30 Play fairway maps showing the variation in relative prospectivity of different petroleum resource play types across the Beetaloo Sub-basin (a) Amungee Member dry gas play, (b) Amungee Member liquids-rich gas play, (c) Kyalla Formation liquids-rich gas play and (d) Hayfield sandstone member liquids play

Source: petroleum prospectivity technical appendix (Hall et al., 2020) and Côté et al. (2018)
Data: Geological and Bioregional Assessment Program (2019j)
Element: GBA-BEE-2-106

2.3 Knowledge gaps

Despite the current exploration activity in the Beetaloo Sub-basin, the area remains relatively data-poor in terms of public domain data, which is a significant limitation in this GBA. Although the coverage of two-dimensional seismic data is sufficient to map play intervals at a regional scale, a more detailed analysis would require integrating interpretations from three-dimensional seismic data.

The geological model of the Beetaloo GBA region presented in this report does not include faults (see the geology technical appendix (Orr et al., 2020). To improve understanding of any potential connectivity between the plays and overlying aquifers, the model needs to be updated with fault interpretations and the structural history reviewed in further detail – especially in the areas located close to the sub-basin boundaries. Furthermore, the type and timing of fault movement is important in understanding which faults may be open for fluid migration at the present day or may have been open at certain points back through geologic time. More detailed fault mapping from the available seismic data, development of a conceptual model and local-scale structural and stratigraphic numerical simulations to address these structural/stratigraphic knowledge gaps are a focus for Stage 3.

Play fairway analysis (see the petroleum prospectivity technical appendix (Hall et al., 2020) was undertaken based on the regional-scale geological conceptualisation detailed in the geology technical appendix (Orr et al., 2020). Results identify areas where further data acquisition and geological modelling can be undertaken; however, this regional analysis is not suitable for individual play or prospect-scale evaluations. Due to local geological variations, which may not be captured by the regional-scale input datasets, not all the areas identified as a having a high likelihood of play fairway presence will result in oil or gas discoveries. Although outside the scope for Stage 3 of this assessment, the play fairway analysis results would benefit from further refinement of the available input datasets. For example, the maps of source rock total organic content and maturity could be improved with a more detailed burial and thermal history modelling study, incorporating spatial variations of uplift and erosion and an improved understanding of facies variations across the region. Further data limitations are described in the petroleum prospectivity technical appendix (Hall et al., 2020).

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

The prospectivity maps presented here are only based on the geological factors required for a viable petroleum play to be present. While these results inform where the plays are most likely to be located with respect to overlying assets, they do not provide any economic context and hence are insufficient to effectively inform future development profiles alone. Although outside scope for Stage 3 of this assessment, to place this work in an economic context, the following additional work would be required:

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

3 Water resources

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

3.1 Hydrogeological and groundwater system conceptualisation

The hydrogeology of the Beetaloo GBA region is conceptualised by three individual groundwater systems: (i) Neoproterozoic rocks and overlying Cambrian Antrim Plateau Volcanics, (ii) the Cambrian Limestone Aquifer (CLA), and (iii) Cretaceous Carpentaria Basin and Cenozoic sediments. The Roper Group underlies these sequences and hosts the unconventional hydrocarbons. For the most part, the Roper Group is thought to be an aquitard, except in localised areas where it is naturally fractured in sandstone units. Water recovered from the Roper Group as part of petroleum exploration suggests it is very saline (at least twice as salty as sea water). It is not used as a water supply in the Beetaloo GBA region.

Neoproterozoic aquifers include the Bukalara and the Jamison sandstones. These are separated by the Hayfield mudstone, a thick regional aquitard. The Bukarlara Sandstone is used as a local water resource to the north of the Beetaloo GBA region. Apart from the CLA, these units have potential in the future to be another water supply for petroleum related activities – in particular, in parts of the western Beetaloo GBA region where the CLA is not saturated.

The Antrim Plateau Volcanics is for the most part a regional aquitard, except parts of the western Beetaloo GBA region, where it is used as a local aquifer where the CLA is unsaturated or not there. The Antrim Plateau Volcanics is not present along the southern and eastern extremities of both the eastern and western Beetaloo GBA regions, which potentially allows for hydrogeological connection between the CLA and the underlying Neoproterozoic aquifers in these locations.

The Cambrian Limestone Aquifer (CLA) is the most significant aquifer in the Beetaloo GBA region and is the primary groundwater resource for the pastoral industry and communities. It is composed of two major groundwater flow systems that flow northwards through and out of the Beetaloo GBA region and into the geological Daly Basin, where groundwater discharges to springs and rivers. A distinctive feature of the CLA is the presence of karst (sinkholes, caves solution cavities) that may cause local groundwater flow paths to substantially deviate from the regional flow direction.

The Cretaceous Carpentaria Basin and Cenozoic sediments are for the most part unsaturated and not used as an aquifer. Changes in thickness of this unit influence the amount of recharge to the underlying CLA. Recharge is thought to increase where the overlying Carpentaria Basin is thin and karst features such as sinkholes are near surface.

This section summarises the regional hydrogeology of the Beetaloo GBA region, including the (i) extent of aquifers and aquitards; (ii) groundwater flow dynamics, recharge and discharge processes and rates; (iii) hydrochemistry; and (iv) potential inter-basin connectivity. Full details are provided in the hydrogeology technical appendix (Evans et al., 2020). The hydrogeology of the Beetaloo GBA region draws on information from Fulton and Knapton (2015), Randal (1973), Tickell and Bruwer (2017) and Yin Foo (2002). Additionally, hydrogeological characteristics have been inferred from the Wilton package stratigraphy (Munson, 2016), exploration well completion reports and exploration review papers (Lanigan et al., 1994; Silverman et al., 2007; Silverman and Ahlbrandt, 2011).

The current conceptual hydrogeological model for the Beetaloo GBA region (Figure 31) consists of three individual groundwater subsystems underlain by a sedimentary package containing formations hosting primary unconventional hydrocarbon plays.

From oldest to youngest, the conceptual model comprises the following components:

- Roper Group (the sedimentary package that is host to primary unconventional hydrocarbon plays of the Velkerri and Kyalla formations)
- Neoproterozoic rocks and overlying Cambrian Antrim Plateau Volcanics
- CLA system (consisting of an upper and lower aquifer sequence)
- Undifferentiated Cretaceous and Cenozoic sedimentary rocks (generally unsaturated).

The hydrogeology of the Beetaloo GBA region is characterised by a complex series of stacked sedimentary basins in which several groundwater systems exist. The most significant aquifer in the region (in terms of both spatial coverage and use) is the CLA. There are several, typically deeper, Neoproterozoic fractured rock aquifers within the Beetaloo GBA region, including the Bukalara and Jamison sandstones. Limited supplies of groundwater are also sourced from the aquifers of the Cretaceous Carpentaria Basin and Cenozoic sediments.

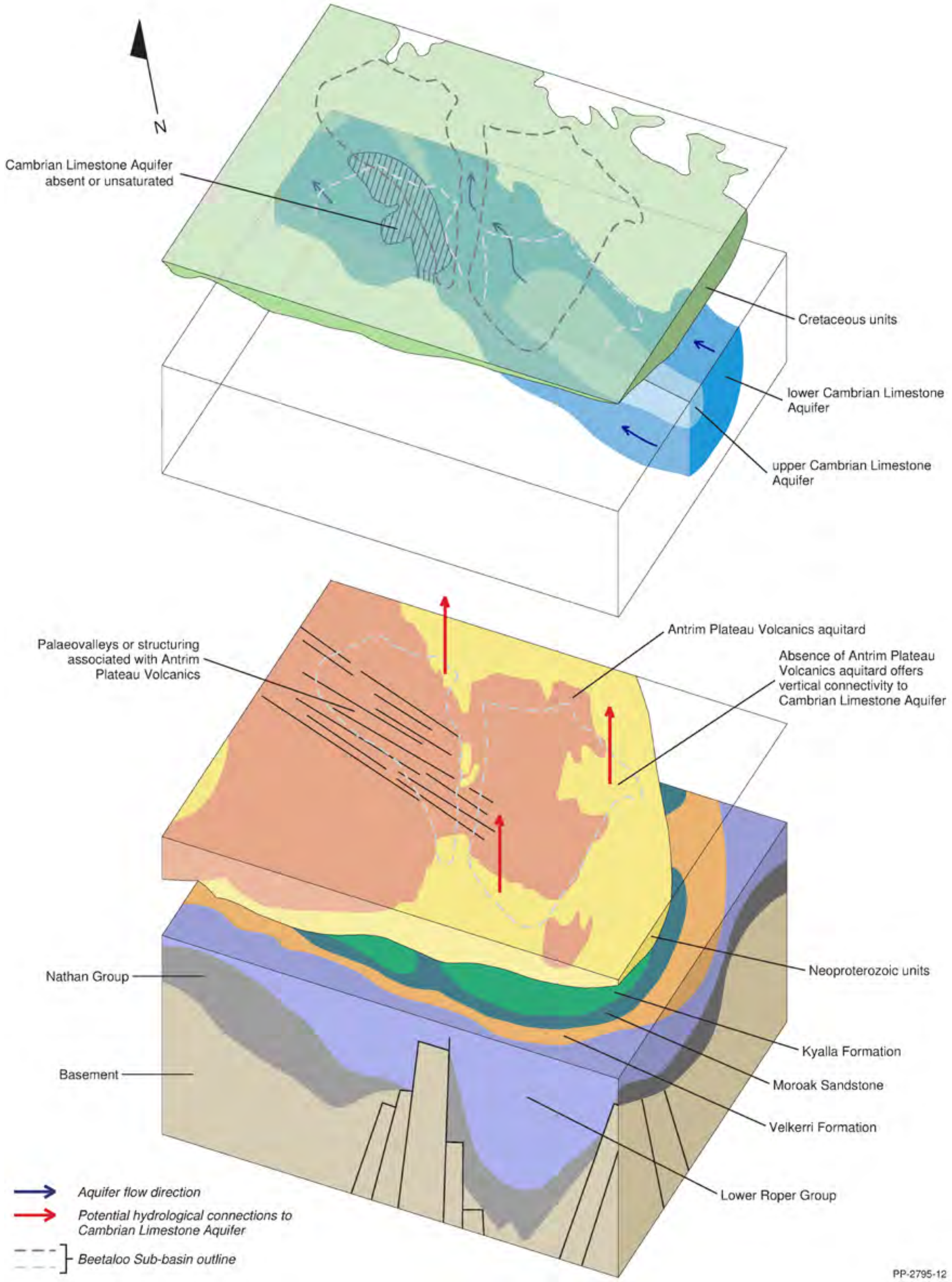

Figure 31 Conceptual hydrogeological model for the Beetaloo GBA region

This conceptual diagram (not to scale) depicts the hydrostratigraphy across the Beetaloo GBA region. The Mesoproterozoic Roper Group hosts two prospective formations for tight gas and shale gas (Velkerri and Kyalla formations), which are separated by the Moroak Sandstone, which is also prospective. Overlying the Roper Group are the Neoproterozoic sequences, of which the Hayfield Mudstone acts as a regional seal (aquitard) for underlying sequences. At shallower levels, another regional aquitard, the Antrim Plateau Volcanics, for the most part separates underlying sequences from the Cambrian Limestone Aquifer. This in turn is overlaid and in places confined the Cretaceous sequence. Cenozoic sediments are not shown.
Source: hydrogeology technical appendix (Evans et al., 2020)
Element: GBA-BEE-2-325

A summary of the key hydrogeological features associated with groundwater systems of the Beetaloo GBA region, other than the CLA system, is provided in the following section. Limited hydrogeological information is available for these systems compared with the CLA, which is the most widely used aquifer within the Beetaloo GBA region. The CLA is considered separately in Section 3.1.2.

3.1.1 Hydrogeology of the Roper Group, Neoproterozoic rocks, Antrim Plateau Volcanics, Carpentaria Basin and Cenozoic units

3.1.1.1 Mesoproterozoic Roper Group

The Roper Group comprises the Collara and Maiwok subgroups (see Figure 32). The Maiwok Subgroup is host to the primary shale and tight gas hydrocarbon plays of the Velkerri and Kyalla formations. Within the Beetaloo GBA region, no bores use the Roper Group as a groundwater source due to the depth of drilling required and poor water quality. With little groundwater data available from petroleum exploration drilling, previous studies have used lithology to infer the hydrogeological characteristics of the formation as either an aquitard (fine-grained clastics) or an aquifer (coarse-grained clastics) (Fulton and Knapton, 2015). Such classification is complicated by other factors, such as the presence of secondary fracture porosity and geological processes that tend to infill and modify original porosity and permeability. The Roper Group is intruded by the Derim Derim Dolerite, which potentially can further compartmentalise the groundwater system in places.

The Roper Group is dominated by low-permeability sandstones and mudstones, which act as aquitards, except the Moroak Sandstone and Bessie Creek Sandstone, which are classified as fractured rock partial aquifers. While these sandstones are not used as a groundwater source, it is important to understand their extent and hydraulic characteristics.

The Bessie Creek Sandstone has only been intersected by a few wells (Orr et al., 2020). However, it has been inferred that at shallower levels, in discrete structural corridors, the unit could contain groundwater and may have enough permeability to act locally as an aquifer (Fulton and Knapton, 2015). Alternatively, where tight gas plays prevail, the sandstone would have low permeability and be more likely to be gas-saturated with little groundwater and thus act as an aquitard.

The Velkerri Formation comprises a thick, upward-coarsening shale succession that would act as an aquitard. Its thickness varies across the Beetaloo Sub-basin, with thickest intersection been recorded in Tanumbirini 1 (1483 m). Seismic sections indicate the Velkerri Formation also extends to the southern margin of the sub-basin, where it is unconformably overlain by the Jamison sandstone (Orr et al., 2020).

The Moroak Sandstone is a partial aquifer of variable character and forms an extensive, basin-wide unit of up to 498 m in thickness (Orr et al., 2020). Porosity and permeability of the Moroak Sandstone is thought to be largely structurally controlled, with better porosity reported on areas such as over structural highs. Elsewhere permeability is low.

The Moroak Sandstone has been eroded away over the north-eastern part of the Walton High (see Figure 13 for location) and remains comparatively thin westwards along this high and into the western Beetaloo Sub-basin (~43 m in thickness). It is also eroded along the southern margin on the Helen Springs High (see Figure 13 for location), where it is unconformably overlain by the Jamison sandstone. Elsewhere in the sub-basin, the Moroak Sandstone is conformably overlain by the Kyalla Formation.

The Kyalla Formation is an extensive regional aquitard found across the Beetaloo GBA region. However, it may have considerable intra-formational variation in its hydrogeological character, due to the occurrence of sandstone inter-beds. The Kyalla Formation is at its thickest in the eastern sub-basin, reaching up to 843 m. However, it is missing over some structures such as the Arnold High (see Figure 13 for location) and the north-eastern end of the Walton High.

Hydraulic heads calculated from drill stem test shut-in pressures suggest that while pressures in the Moroak Sandstone are sub-artesian, it is enough to raise water levels in the sandstone above the Proterozoic unconformity (Evans et al., 2020). Hence, there is potential for groundwater to flow vertically from the Moroak Sandstone aquifer upwards into overlying aquifers if a suitable connective pathway were to exist. Groundwater from the Moroak Sandstone is highly saline (> 100,000 mg/L, at least twice as salty as seawater) with recorded temperatures in the order of 70 °C to 90 °C at depths of 1100 to 1700 m (Evans et al., 2020).

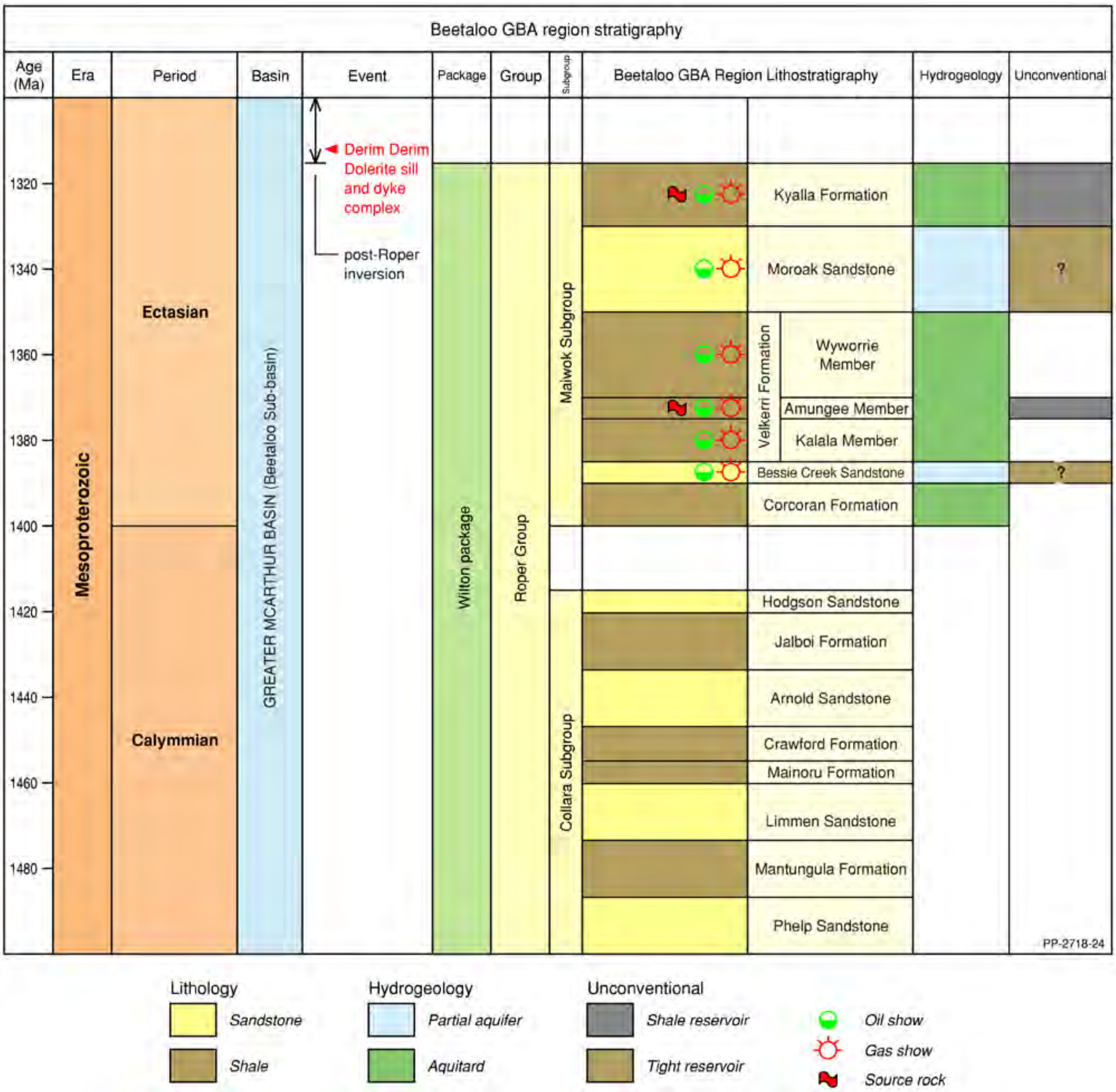

Figure 32 Hydrostratigraphy of Roper Group

Source: Munson (2016), Rawlings (1999), Abbott et al. (2001), Munson and Revie (2018), Munson et al. (2013b), Betts et al. (2015), Jackson et al. (2000), Collins et al. (2018), Page et al. (2000), Ahmad et al. (2013), Kruse et al. (2013), Kruse and Munson (2013b), Kruse and Munson (2013a), Munson et al. (2013a), Edgoose and Ahmad (2013), Munson (2014)
Element: GBA-BEE-2-144

3.1.1.2 Neoproterozoic units

The hydrostratigraphy of Neoproterozoic units is outlined in Figure 33. These rocks were deposited in the Neoproterozoic between 840 to 730 Ma (see Figure 16). Neoproterozoic units, from oldest to youngest, comprise the Jamison sandstone and the Hayfield mudstone as well as the Kiana Group (Bukalara Sandstone and overlying Cox Formation). Within the Beetaloo GBA region the Neoproterozoic units are not used as a groundwater resource thus there is little hydrogeological information available (Evans et al., 2020). Both Jamison and Bukalara sandstones are being considered as potential water supplies for future petroleum operations, particularly in western parts of the Beetaloo GBA region, where the CLA is absent or unsaturated.

The Jamison sandstone is both a regional aquifer and a key reservoir across much of the Beetaloo GBA region. In the western Beetaloo GBA regoin, the sandstone is thickest mid-basin (110 m), thinning northward and southward. In the eastern Beetaloo GBA region the unit reaches a thickness of 163 m in the south-east, thinning to the north-west and eventually pinching out before reaching the Walton High.

The Jamison sandstone is generally confined between the overlying Hayfield mudstone and underlying Kyalla Formation, with a few exceptions (for detail see Fulton and Knapton (2015); Evans et al. (2020)). For example, on the Helen Springs High (see Figure 13 for location), the Jamison sandstone unconformably overlies the Moroak Sandstone, which in turn is directly overlain by either the Antrim Plateau Volcanics or the Tindall Limestone. In areas where regional aquitards are missing, there is potential for hydrogeological connectivity between the Jamison sandstone, the underlying Moroak Sandstone and overlying Tindall Limestone.

The Hayfield mudstone is a regional aquitard, up to 300 m thick, separating the Jamison sandstone and the Kiana Group. The Hayfield mudstone is present across most of the Beetaloo GBA region and is considered to be a regional seal to petroleum systems in underlying sequences (Hall et al., 2020).

The Bukalara Sandstone is up to 390 m thick and comprises quartz feldspathic sandstone, lithic sandstone with pebble conglomerates, and minor shale. It has a discontinuous distribution within and adjacent to the Beetaloo GBA region (Evans et al., 2020). This aquifer is confined by the underlying Hayfield mudstone and, where present, the overlying Antrim Plateau Volcanics.

Outside the Beetaloo GBA region, the Bukalara Sandstone is used as an aquifer, with permeability enhanced by jointing (Fulton and Knapton, 2015). Within the Beetaloo GBA region, groundwater inflows of up to 25 L/second are reported from some petroleum wells (Evans et al., 2020), which suggests that at depth, parts of the Bukalara Sandstone have relatively good hydraulic conductivity and porosity. However, information is limited for the Bukalara Sandstone in the Beetaloo GBA region, with no water quality, water level or hydraulic property data available. While It is not known how connected the Bukalara Sandstone is across the region boundary, its distribution suggests there is likely to be a reasonable degree of disconnect between different parts of the aquifer.

The Cox Formation is recognised in only two petroleum wells in the Beetaloo GBA region. EcOz Environmental Consultants (2015) reports that thin, discontinuous intersections of the Cox Formation occur in the southern part of the western Beetaloo GBA region. It may be that this unit is not widespread or, alternatively, it has not been recognised (as of February 2019) in the stratigraphic logs.

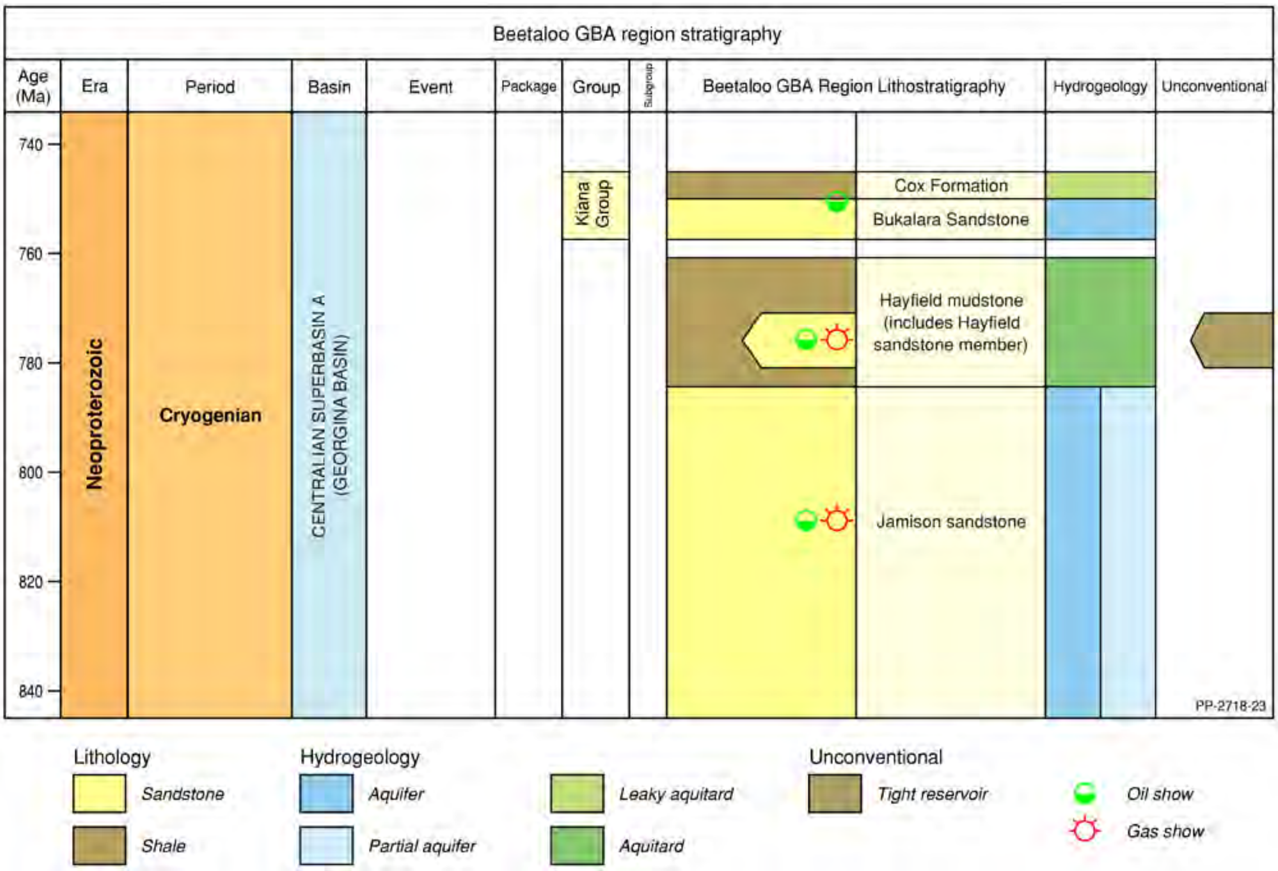

Figure 33 Hydrostratigraphy of Neoproterozoic units

Source: Munson (2016), Rawlings (1999), Abbott et al. (2001), Munson and Revie (2018), Munson et al. (2013b), Betts et al. (2015), Jackson et al. (2000), Collins et al. (2018), Page et al. (2000), Ahmad et al. (2013), Kruse et al. (2013), Kruse and Munson (2013b), Kruse and Munson (2013a), Munson et al. (2013a), Edgoose and Ahmad (2013), Munson (2014)
Element: GBA-BEE-2-143

3.1.1.3 Cambrian Antrim Plateau Volcanics

The hydrostratigraphy of units of Cambrian age is highlighted in Figure 34. Cambrian units encompass the Antrim Plateau Volcanics as well as units that make up the CLA. Due to its importance as the key regional aquifer, the hydrogeology and hydrostratigraphy of the CLA are detailed separately in Section 3.1.2.

The extent of the Antrim Plateau Volcanics is well defined by regional geophysical data and it is found across much of the Beetaloo GBA region. Generally, this unit acts as a regional aquitard, separating the Neoproterozoic aquifers from the overlying CLA. However, in the north-western portion of the western Beetaloo GBA region and beyond, the Antrim Plateau Volcanics locally can act as a fractured rock aquifer with modest groundwater yields.

Depths to groundwater in the Antrim Plateau Volcanics range from 14 to 89 m below ground level (BGL) (average 59 m BGL). Bore depths range from 61 to 240 m BGL, with estimated yields from 0.3 to 5 L/second. Some isolated inflows to petroleum wells are reported from around the northern margin of the Beetaloo GBA region, including intersection of a 1.5-m deep cavity at the base of the volcanics, where an inflow of 28 L/second was recorded (Evans et al., 2020). Relative groundwater elevations within this unit do not indicate a consistent regional flow direction.

A series of south-east oriented lineaments are apparent in the airborne magnetics geophysics over a large portion of the western Beetaloo GBA region (see Figure 13 and Evans et al. (2020)). These lineaments are spaced at 8-km intervals across an area approximately 40 km wide. The cause of them is not clear but they may relate to a mixture of palaeo-topography influencing the thickness of the Antrim Plateau Volcanics or structures.

In some areas of the Beetaloo GBA region the volcanics are absent. In these areas there is potential for hydrogeological connection to exist between the CLA and the underlying Bukalara Sandstone and Jamison sandstone.

Groundwater quality of the Antrim Plateau Volcanics is generally good (average total dissolved solids (TDS) is 715 mg/L). Water chemistry of the Antrim Plateau Volcanics is generally dominated by Mg-Ca-CO_3 ions (Figure 39), which suggests some degree of interaction with waters from the CLA, at least in areas where fracturing/weathering has occurred, where it may yield enough water to act as a local water supply.

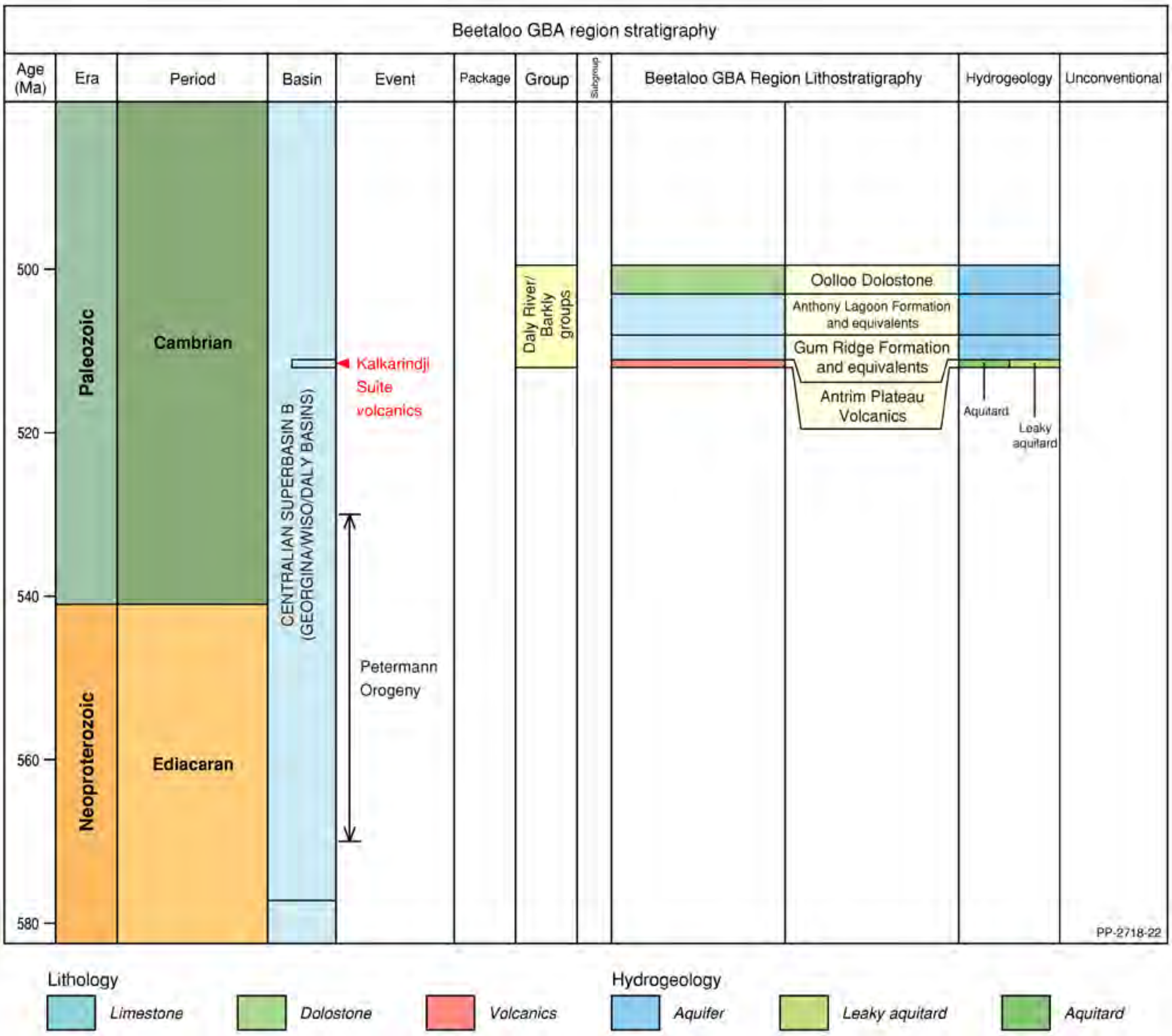

Figure 34 Hydrostratigraphy of Cambrian units

Source: Munson (2016), Rawlings (1999), Abbott et al. (2001), Munson and Revie (2018), Munson et al. (2013b), Betts et al. (2015), Jackson et al. (2000), Collins et al. (2018), Page et al. (2000), Ahmad et al. (2013), Kruse et al. (2013), Kruse and Munson (2013b), Kruse and Munson (2013a), Munson et al. (2013a), Edgoose and Ahmad (2013), Munson (2014)
Element: GBA-BEE-2-142

3.1.1.4 Cretaceous and Cenozoic sediments

The hydrostratigraphy of Cretaceous and Cenozoic units is outlined in Figure 35. The sedimentary rocks that comprise the Cretaceous Carpentaria Basin are generally unsaturated (i.e. contain no usable groundwater) across much of the Beetaloo GBA region (Evans et al., 2020), except in the southern parts of Beetaloo GBA region. Here, several bores exploit a saturated sandstone aquifer found at the base of the sequence, which is likely to be locally hydraulically connected to the underlying CLA. Water quality samples from these bores are limited to the southern portion of the Beetaloo GBA region and to the north of the GBA region near Mataranka Thermal Pools. Salinity levels range from 170 to 8610 mg/L (TDS), with an average of 1548 mg/L (Evans et al., 2020).

The Carpentaria Basin covers the whole of the Beetaloo GBA region. It can be relatively thick (over 100 m) and dominated by fine-grained sediments (mudstone and siltstone) – particularly in the eastern part of the Beetaloo GBA region, which can limit recharge to the CLA. Consequently, for the eastern Beetaloo GBA region, recharge is thought to be only possible beyond the margins of the Carpentaria Basin, where the upper CLA is exposed, or where it is in contact with the Proterozoic basement. In contrast, in the western Beetaloo GBA region the Carpentaria Basin sequence is much thinner and a sandstone at the base of sequence is predominantly exposed, which increases the likelihood of recharge to sinkholes in the underlying CLA. As a result, the western Beetaloo GBA region experiences much higher recharge rates compared with the eastern Beetaloo GBA region.

In overlying surficial Cenozoic units and regolith, a small number of bores within the eastern Beetaloo GBA region intercept saturated units, indicating the presence of perched aquifers. However, beyond these specific sites the distribution and prevalence of such aquifers is unknown. It is possible that perched aquifers act as shallow groundwater sources for vegetation.

While Cenozoic sediments are widespread across the Beetaloo GBA region, very few groundwater samples are available for analysis (Evans et al., 2020). Salinity and hydrochemical signatures are highly varied and not readily interpreted without knowledge of the degree of evaporation of each sample. Groundwater geochemistry shows a Na-K cationic and mixed anionic signature.

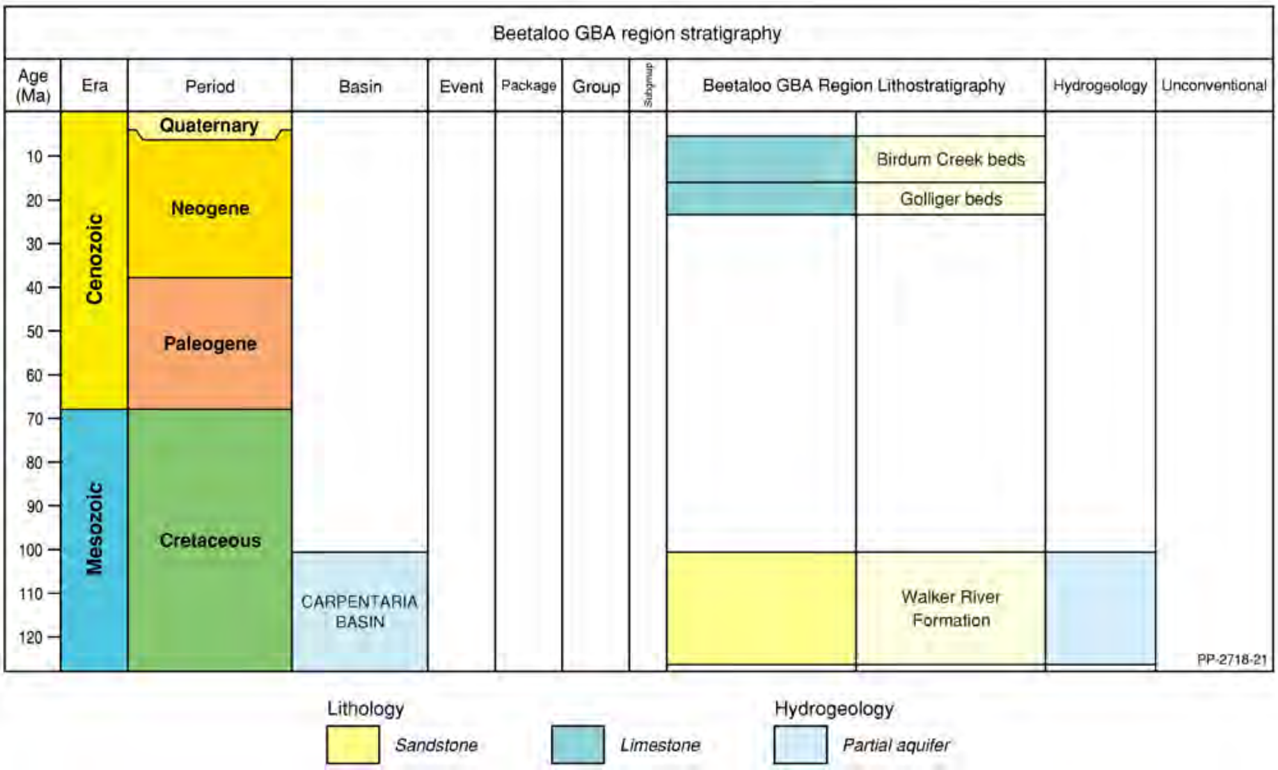

Figure 35 Hydrostratigraphy of Cretaceous and Cenozoic units

Source: Munson (2016), Rawlings (1999), Abbott et al. (2001), Munson and Revie (2018), Munson et al. (2013b), Betts et al. (2015), Jackson et al. (2000), Collins et al. (2018), Page et al. (2000), Ahmad et al. (2013), Kruse et al. (2013), Kruse and Munson (2013b), Kruse and Munson (2013a), Munson et al. (2013a), Edgoose and Ahmad (2013), Munson (2014)
Element: GBA-BEE-2-141

3.1.2 Hydrostratigraphy and hydrogeology of the Cambrian Limestone Aquifer

The CLA is the most extensive and has the most information of all aquifer systems in the Beetaloo GBA region. A distinctive feature of the CLA is the presence of karst (e.g. caves, cavities), which forms where either surface water or groundwater dissolves the limestone matrix. In the CLA, karst is often evident at the surface as sinkholes and other features. Karstic limestone aquifers are characterised by highly variable underground drainage systems that in areas can have very high hydraulic conductivity and surface recharge enhanced by the presence of large conduits (sinkholes) near surface. Within the Beetaloo GBA region, the distribution of near-surface karstic features is poorly known. A summary of available karstic mapping presented in the hydrogeology technical appendix (Evans et al., 2020) suggests that karst is largely found in the north-western portion of the Beetaloo GBA region, where the overlying Carpentaria Basin is relatively thin. It is likely that karst is also present in the eastern Beetaloo GBA region, in the Georgina Basin. However, due to a relatively thick cover of Carpentaria Basin rocks, karst features are not readily evident at the surface in these areas.

The CLA extends across the Georgina, Wiso and Daly basins (Figure 36), both within and beyond the Beetaloo GBA region. The Montejinni Limestone and Hooker Creek Formation in the Wiso Basin; Tindall Limestone, Jinduckin Formation and Oolloo Dolostone in the Daly Basin; and Gum Ridge and Anthony Lagoon formations of the Georgina Basin (Figure 4) comprise the main hydrostratigraphic units of the CLA. The CLA stratigraphy is simplified into upper and lower sequences, which are referred to as the 'Gum Ridge Formation and equivalents' (Gum Ridge Formation, Tindall Limestone, Montejinni Limestone) and the 'Anthony Lagoon Formation and equivalents' (Anthony Lagoon Formation, Jinduckin Formation, Hooker Creek Formation and Point Wakefield beds). Overlying the Jinduckin Formation is the Oolloo Dolostone, which is not present in the Beetaloo GBA region.

The Birdum Creek Fault is a significant fault with an offset of about 200 m. It coincides with a groundwater divide that segregates the Daly Basin into two groundwater systems. Furthermore, connectivity between the upper and lower sequences of the CLA is quite variable and not well understood. Variable water quality and the presence of extensive siltstone units suggest there could be a degree of hydraulic disconnectivity in some areas. Further study of pressure differences in different sequences in nested monitoring wells would assist with understanding the direction of vertical and horizontal groundwater flow in these aquifer sequences.

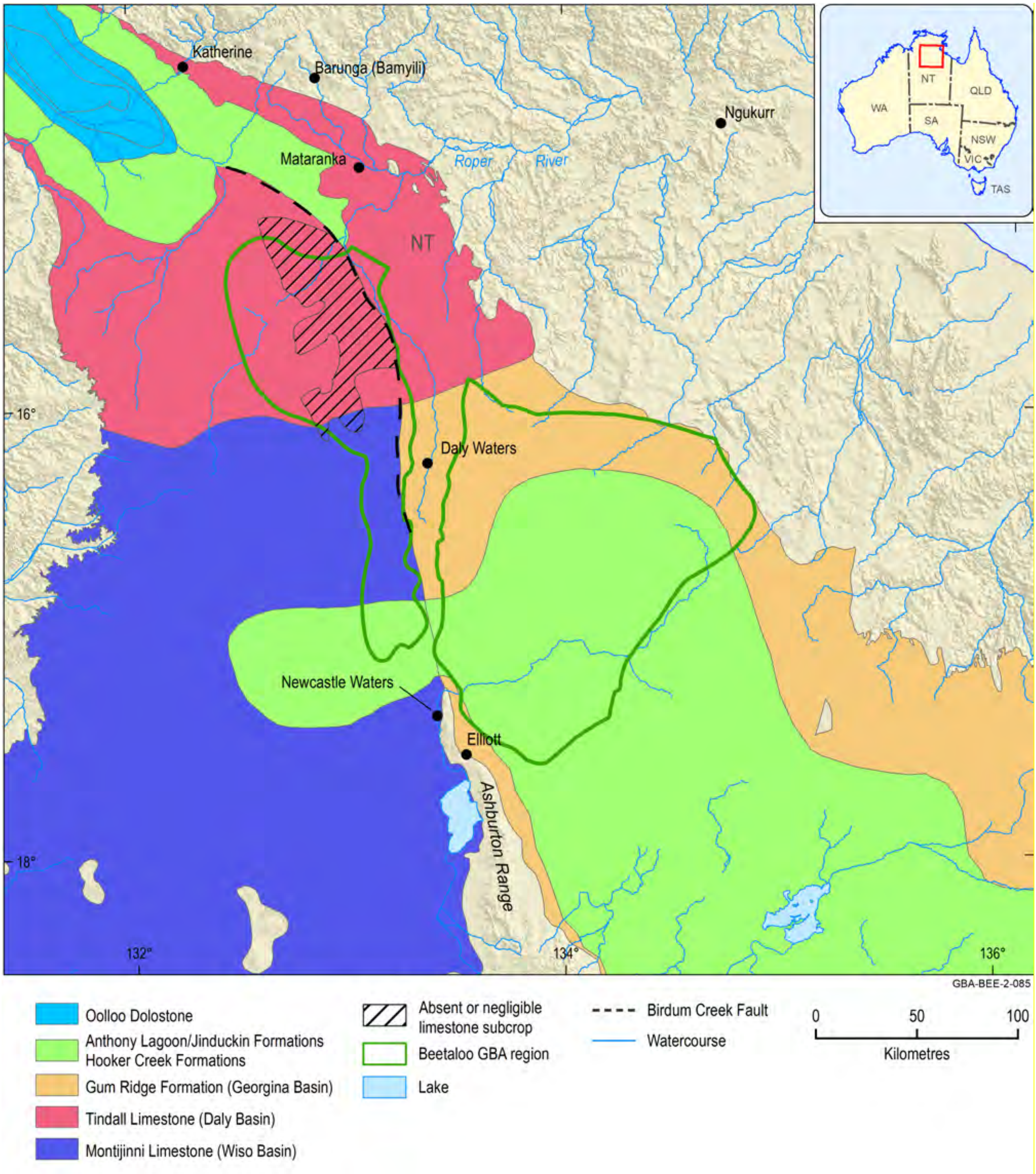

Figure 36 Hydrostratigraphy and near-surface structure in the Cambrian Limestone Aquifer

Source: Munson (2016), Rawlings (1999), Abbott et al. (2001), Munson and Revie (2018), Munson et al. (2013b), Betts et al. (2015), Jackson et al. (2000), Collins et al. (2018), Page et al. (2000), Ahmad et al. (2013), Kruse et al. (2013), Kruse and Munson (2013b), Kruse and Munson (2013a), Munson et al. (2013a), Edgoose and Ahmad (2013), Munson (2014)
Element: GBA-BEE-2-085

3.1.2.1 Hydrodynamics of the Cambrian Limestone Aquifer

Within the Beetaloo GBA region, groundwater bores primarily draw from limestone aquifers in the Georgina, Wiso and Daly basins, enabling measurement of groundwater levels from which the direction of groundwater flow can be inferred. In contrast, older mid-Proterozoic rock sequences such as the Roper Group have poorly constrained hydrodynamics, inferred from sparse petroleum well pressure data and interpretation of geological structures.

The most extensive potentiometric surface map to date for the CLA (Figure 37, derived from work in Fulton and Knapton (2015)) outlines major hydrogeological features, such as groundwater divides. Understanding where large groundwater divides and other potential barriers to flow (e.g. major faults) are located is important for understanding how an aquifer system works. Essentially, these types of boundaries compartmentalise groundwater flow in an aquifer. They can act as a barrier to flow, minimising interactions (and consequently the spread of potential impacts) between different aquifer systems. However, groundwater flow divides can move, if groundwater is pumped excessively in the vicinity of the divide and there is no other physical barrier. Whether they move will depend on other factors, including the geology and the duration of pumping.

There is an apparent discrepancy in the inferred regional groundwater flow patterns along the south-western margin of the CLA, shown in Figure 37, where regional groundwater flow is directed away from springs that occur along the margin of outcrop of the CLA (Evans et al., 2020). This is counterintuitive because a degree of flow towards these springs would be expected, as they are considered to source water from the CLA (Department of Environment and Natural Resources (NT), 2013). However, earlier generations of hydrogeological mapping (Randal, 1973) suggest another groundwater divide occurs along the western margin of the CLA. This would have the effect of compartmentalising groundwater flow to these springs, from groundwater flow in the CLA in the Beetaloo GBA region.

Two groundwater flow systems occur within the Beetaloo GBA region, separated by a major north trending groundwater divide (Figure 37). The eastern system incorporates northerly flow from the Georgina Basin into the Daly Basin, while the western system incorporates northerly flow from the Wiso Basin into the Daly Basin (Figure 36). The eastern system discharges at Mataranka Thermal Pools, some 100 km north of the eastern Beetaloo GBA region and 40 km east of the western part of the Beetaloo GBA region, whereas the closest discharge point for the western CLA groundwater system is thought to be the Flora River springs, which is located approximately 100 km north of the western Beetaloo GBA region. The distance between springs and the GBA region is one factor that may lessen the degree of any potential impacts to springs and spring discharge from developments in the Beetaloo GBA region.

While distance and groundwater divides can assist with decreasing the extent of possible impacts, large karstic pathways (i.e. cave systems and large cavities), where present in the CLA, are likely to act as preferential, relatively high-velocity flow paths. If contaminants (e.g. chemical spills) were to intercept the CLA then potentially they could be transported and dispersed relatively quickly by large pathways. For instance, a study by Tickell (2005) showed groundwater flow velocities of up to 1250 m/day have been noted in the CLA in the vicinity of Katherine, 100 km to the north of the Beetaloo GBA region. High flow rates can exacerbate the spread and dispersion of contaminants. Low levels of contaminants (pesticides) have been detected at Mataranka Thermal Pools (Schult, 2016) and are likely to have come through discharge from springs.

As detailed in Tickell (2005), well-developed cavernous limestone (including sinkholes) occur at the surface around Katherine. These can provide relatively quick pathways for any potential contamination at the surface to reach the CLA aquifer. However, this is less likely to be the case for much of the Beetaloo GBA region, where the CLA is covered by variable thickness of Carpentaria Basin sediments (see Section 3.1.1.4).

While limestone with cavities has been intersected across the Beetaloo GBA region (e.g. see Tickell (2003)), it is not known whether the very large karstic features (and associated flow rates) mentioned previously occur at depth under the Carpentaria Basin cover. Furthermore, groundwater flow paths at more local to semi-regional scales (e.g. at scales of 5 to 20 km) could substantially deviate from the regional northerly flow directions, as outlined in Figure 37, due to the karstic nature of porosity. The occurrence of karstic porosity tends to be controlled by geological features, such as location of the CLA outcrop, structures (e.g. folds, joints or faults) or sedimentological features such as bedding. This can lead to complications in the interpretation of data such as hydrochemistry (as postulated in Suckow et al. (2018)) or understanding how groundwater moves through the CLA.

There is a correlation between topography and groundwater levels measured at the time of drilling, with depth to water increasing from greater than 20 m in the north (where topography is relatively low) to greater than 100 m (where it is relatively elevated) in the eastern Beetaloo GBA region (see Section 3.3 and Figure 43). In many monitoring bores, water levels have increased since at least 1996. Some authors (e.g. Tickell (2009)) report that groundwater levels in the region have been increasing since the 1970s due to increases in rainfall; however, hydrographs are not available in the Beetaloo GBA extended region to confirm this.

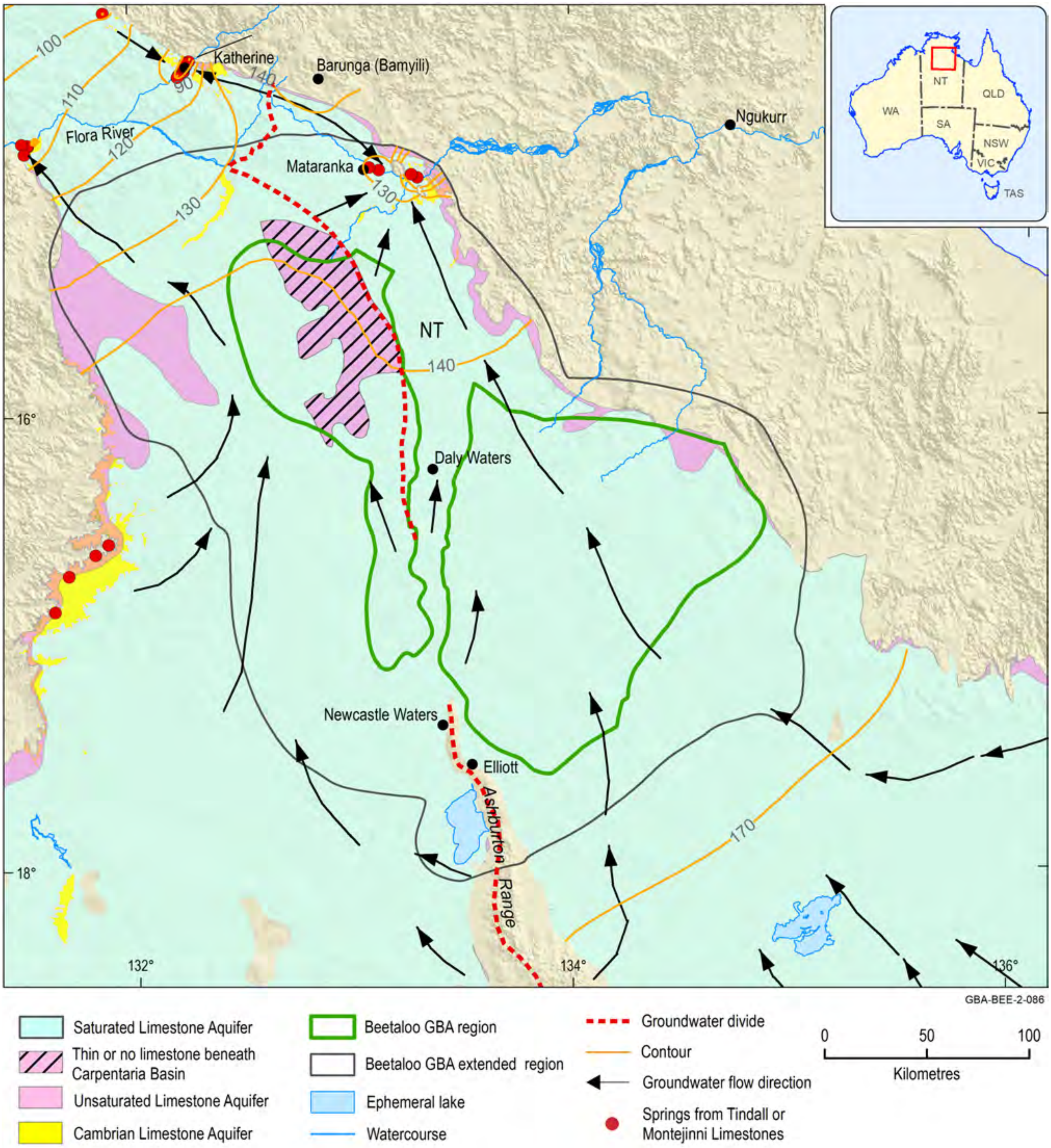

Figure 37 Regional groundwater flow in the Cambrian Limestone Aquifer system

Data: Fulton and Knapton (2015)
Element: GBA-BEE-2-086

3.1.2.2 Recharge and water balances

As outlined in the hydrogeology technical appendix (Evans et al., 2020), recharge differs between the eastern and western Beetaloo GBA region, largely due to variations in limestone permeability and thickness and the lithology of the overlying Carpentaria Basin. Additionally, there is a significant decrease in annual rainfall from north to south across the Beetaloo GBA region. Recharge is generally considered minimal where substantial thicknesses of Cretaceous mudstone are present. Where Cretaceous cover (Carpentaria Basin) is thin or absent and karstic features are present, recharge tends to be higher (Evans et al., 2020), as there are more direct pathways to the CLA. In addition, substantial thicknesses of the upper CLA sequence tend to impede recharge to the lower CLA. While various estimates of recharge are included in the hydrogeology technical appendix (Evans et al., 2020) for the broader Georgina, Daly and Wiso basins, additional work will be undertaken as part of Stage 3 to refine understanding of recharge processes and pathways for the CLA.

For the eastern CLA flow system, throughflow from the Georgina Basin to the south-eastern Daly Basin (see location in Figure 12) is estimated by Tickell and Bruwer (2017) to be approximately 2 GL/year. While no estimate of uncertainty or variance is included in the water balance, it does suggest there is a net gain in both basins. This could be an explanation for the rising groundwater levels described above. However, the hydrograph rises could be due to other factors such as delayed aquifer response to a series of higher than average rainfall years that have occurred since the 1970s. For the western CLA flow system, a water balance or throughflow estimates are not available for groundwater flow from the Wiso Basin into the western Daly Basin (Evans et al., 2020).

3.1.2.3 Hydrochemistry of the Cambrian Limestone Aquifer

Groundwater in the CLA is non-saline to slightly saline (TDS <1500 mg/L – see Figure 38), making it suitable for agricultural, domestic and industrial uses. Average total dissolved solids of the upper and lower CLA are 955 mg/L and 822 mg/L, respectively. Variations in groundwater chemistry (Figure 39) may indicate variations in groundwater processes. They support the hypothesis of an eastern and western groundwater flow system; the western system (Wiso and Daly basins) being generally Ca-Mg-HCO_3 dominant, while the eastern system (Georgina and Daly basins) shows a more mixed groundwater signature. A cluster of higher salinity bores (TDS >1500 mg/L – see Figure 38) is present around the southern boundary of the western Beetaloo GBA region. In this vicinity, the Antrim Plateau Volcanics are absent and the CLA groundwater is dominated by Na-Cl. This may indicate a degree of mixing of groundwater between the CLA and underlying Proterozoic rocks, as groundwater from Proterozoic aquifers can be Na-Cl dominated (Fulton and Knapton, 2015).

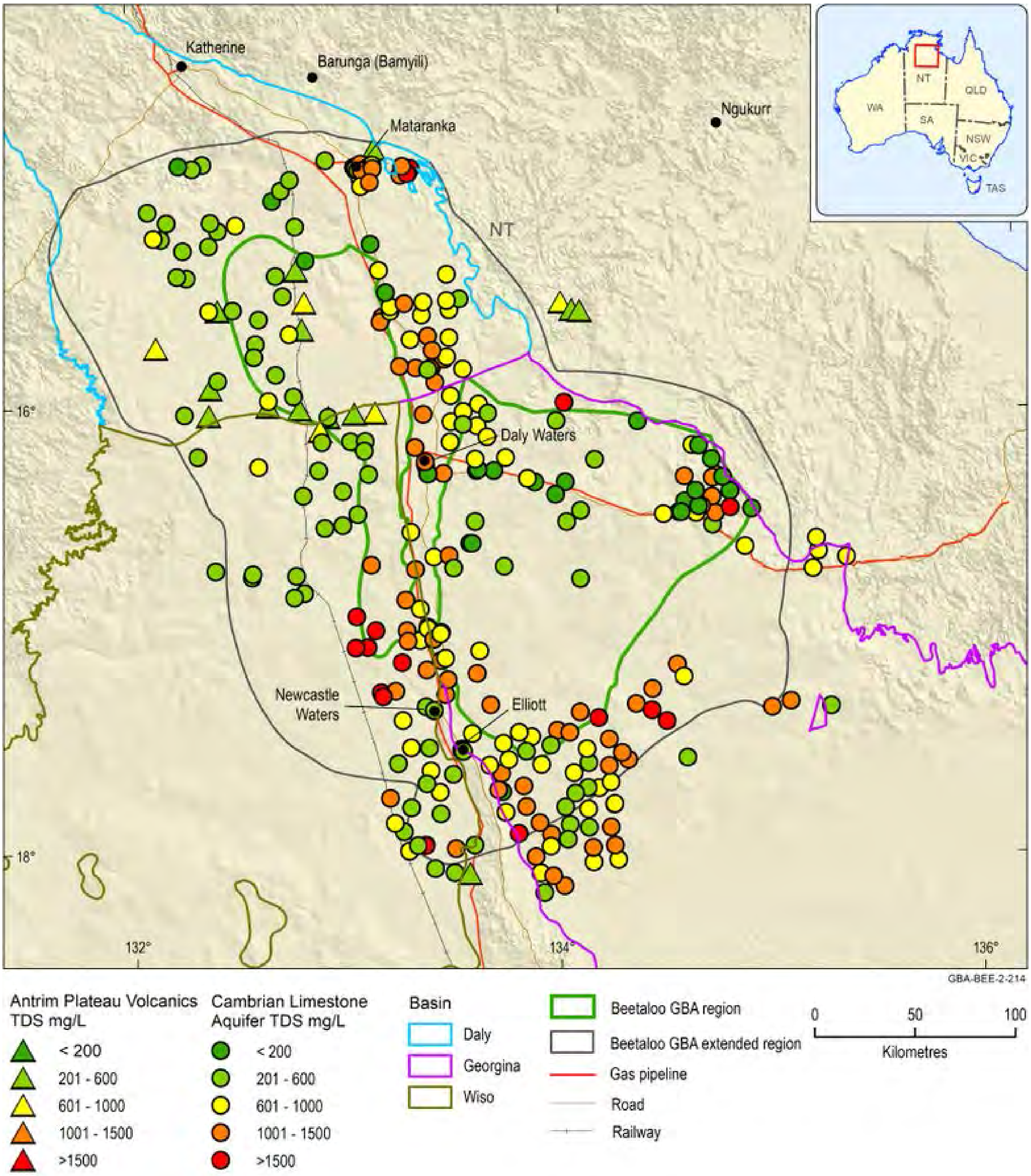

Figure 38 Average total dissolved solids of the Cambrian Limestone Aquifer and Antrim Plateau Volcanics and equivalents

TDS = total dissolved solids
Data: Geological and Bioregional Assessment Program (2019f)
Element: GBA-BEE-2-214

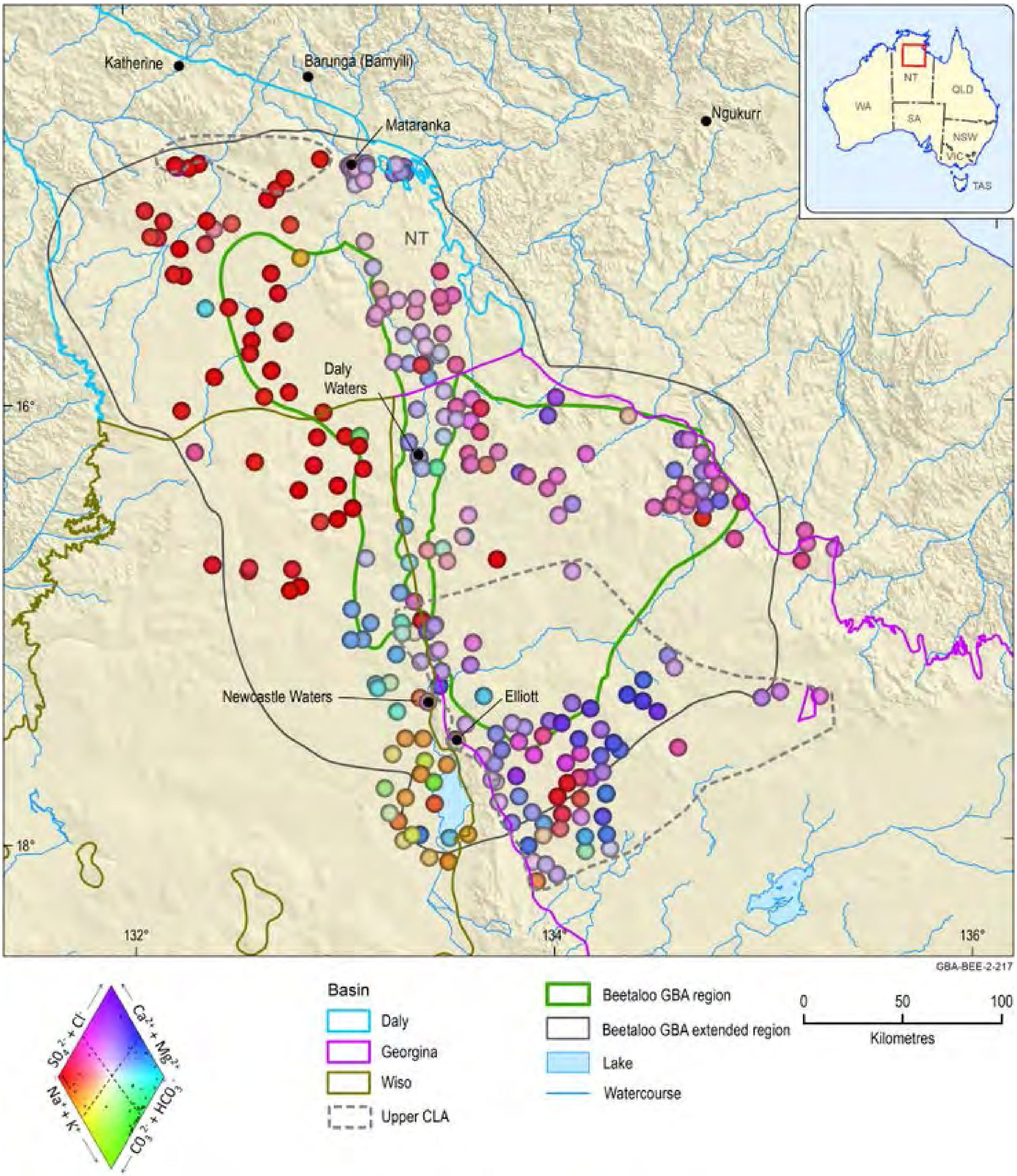

Figure 39 Hydrochemical patterns of the Cambrian Limestone Aquifer spatially visualised with colour Piper plots

CLA = Cambrian Limestone Aquifer

Source: after Peeters (2014)

Data: Geological and Bioregional Assessment Program (2019f)

Element: GBA-BEE-2-217

3.2 Surface water system conceptualisation

The Beetaloo GBA region is intersected by five surface water catchments: Roper River, Daly River, Limmen Bight River, the Wiso region and the Barkly region. The Roper River (44%) and Wiso region (47%) cover most of the region. There are no permanent streams within the Beetaloo GBA region; however, the groundwater discharge from the Beetaloo GBA region supports the perennial flows in the Roper River downstream of the region through the discharge at Mataranka Thermal Pools and baseflow to streams in Elsey National Park.

In the Beetaloo GBA extended region lie wetlands listed in *A directory of important wetlands in Australia* (DIWA) – at Mataranka and Limmen Bight (Port Roper) Tidal Wetland System in the Roper River catchment and at Lake Woods in the Wiso region.

The Beetaloo GBA region is intersected by parts of five river catchments as defined by the Australian Water Resources Council (Figure 40). These comprise 13,392 km^2 of the Wiso region (47%), 12,385 km^2 of the Roper River catchment (44%), 1190 km^2 of the Limmen Bight River catchment (4%), 893 km^2 of the Barkly region (3%) and 244 km^2 of the Daly River catchment (1%). The Roper and Limmen Bight rivers flow to the Gulf of Carpentaria, the Daly River flows to the Timor Sea and Wiso and Barkly regions are internally draining, with Lake Woods being the most prominent receiving body from the Beetaloo GBA region.

The Roper River catchment has a strong north–south rainfall gradient and consequently the southern tributaries that intersect the Beetaloo GBA region (Elsey Creek, Strangeways River and Hodgson River) are the lowest rainfall and runoff tributaries. The flow regime is very strongly seasonal, with 95% of the flow generated during the wet season (CSIRO, 2009). Dry-season flows are sustained by groundwater discharge from the Mataranka Thermal Pools – a DIWA-listed wetland (Environment Australia, 2001) – but most of this flow is lost as evapotranspiration before reaching the coast (Jolly et al., 2004). The middle reaches of the Roper River consist of braided channels across the floodplain. The tidal influence extends 145 km inland before the river discharges into the estuary of the Limmen Bight (Port Roper) Tidal Wetland System – a DIWA-listed wetland (Environment Australia, 2001).

Most of the southward-flowing area of the Beetaloo GBA region is in the Newcastle Creek catchment. Newcastle Creek is an ephemeral creek that flows most years into Lake Woods. Lake Woods is an ephemeral wetland that frequently occupies an area of 350 km^2, but in a big flood year (e.g. 2001) it can reach nearly 1000 km^2. Lake Woods is a DIWA-listed wetland (Environment Australia, 2001).

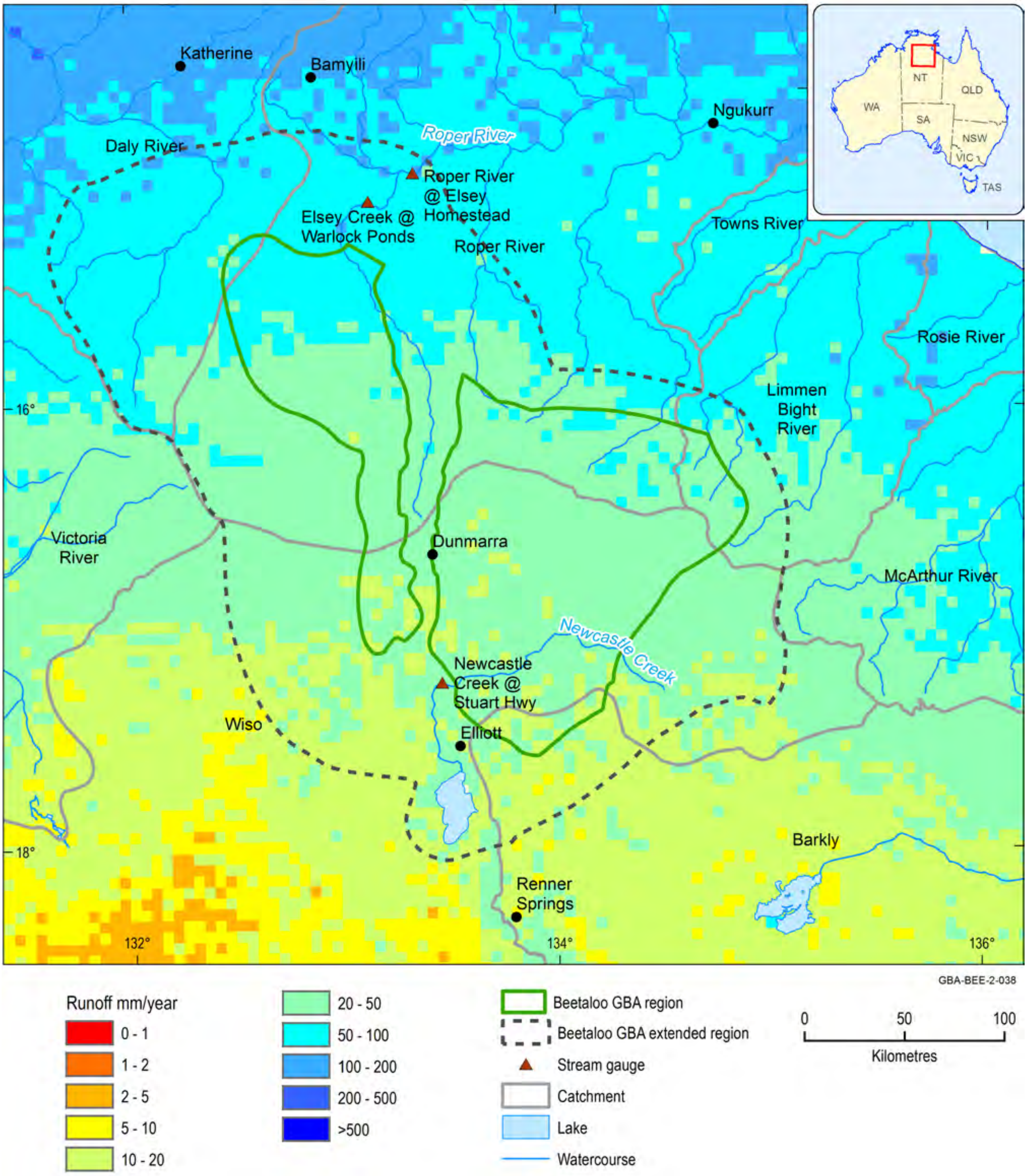

Figure 40 River catchments of the Beetaloo GBA region and modelled mean annual runoff using the Australian Water Resource Assessment (AWRA) model

AWRC = Australian Water Resources Council
Data: CSIRO (2015)
Element: GBA-BEE-2-038

Three gauges were selected to use as examples of streamflow in the Beetaloo GBA region to highlight the surface water conceptualisation (Figure 40). These are Elsey Creek at Warlock Ponds (G903001), which is upstream of the groundwater discharge in Elsey National Park; Roper River at

Elsey Homestead (G9030013), which is the first gauge downstream of Mataranka Thermal Pools; and Newcastle Creek at Stuart Highway (G0280009), which gauges the flow into Lake Woods.

Monthly flows in streams near the Beetaloo GBA region are unevenly distributed throughout the year (Figure 41(a) to (c)) and follow the rainfall distribution (Figure 5). Maximum mean monthly flows occur in March for Elsey Creek (G9030001) and Newcastle Creek (G0280009) and in February for the Roper River (G9030013). Newcastle Creek and Elsey Creek cease to flow through most of the dry season and have the minimum average flows from September to November. The Roper River is sustained by groundwater discharge during the dry season and has a minimum average flow in October.

The interannual variability of flows is very high for these streams near the Beetaloo GBA region (Figure 41(d) to (f)); this flows from the high interannual variation in rainfall (Figure 6).

Most streams within the Beetaloo GBA region are ephemeral and only flow in response to wet-season rains. For example, flow for Newcastle Creek was only recorded 23% of the time (Figure 41f). Downstream from the Beetaloo GBA region Elsey Creek is ephemeral upstream of the Elsey National Park, with flow being recorded 38% of the time (Figure 41g), and becomes perennial closer to the confluence of the Roper River. Flow in the Roper River is perennial downstream of Mataranka Thermal Pools due to groundwater discharge (Figure 41e).

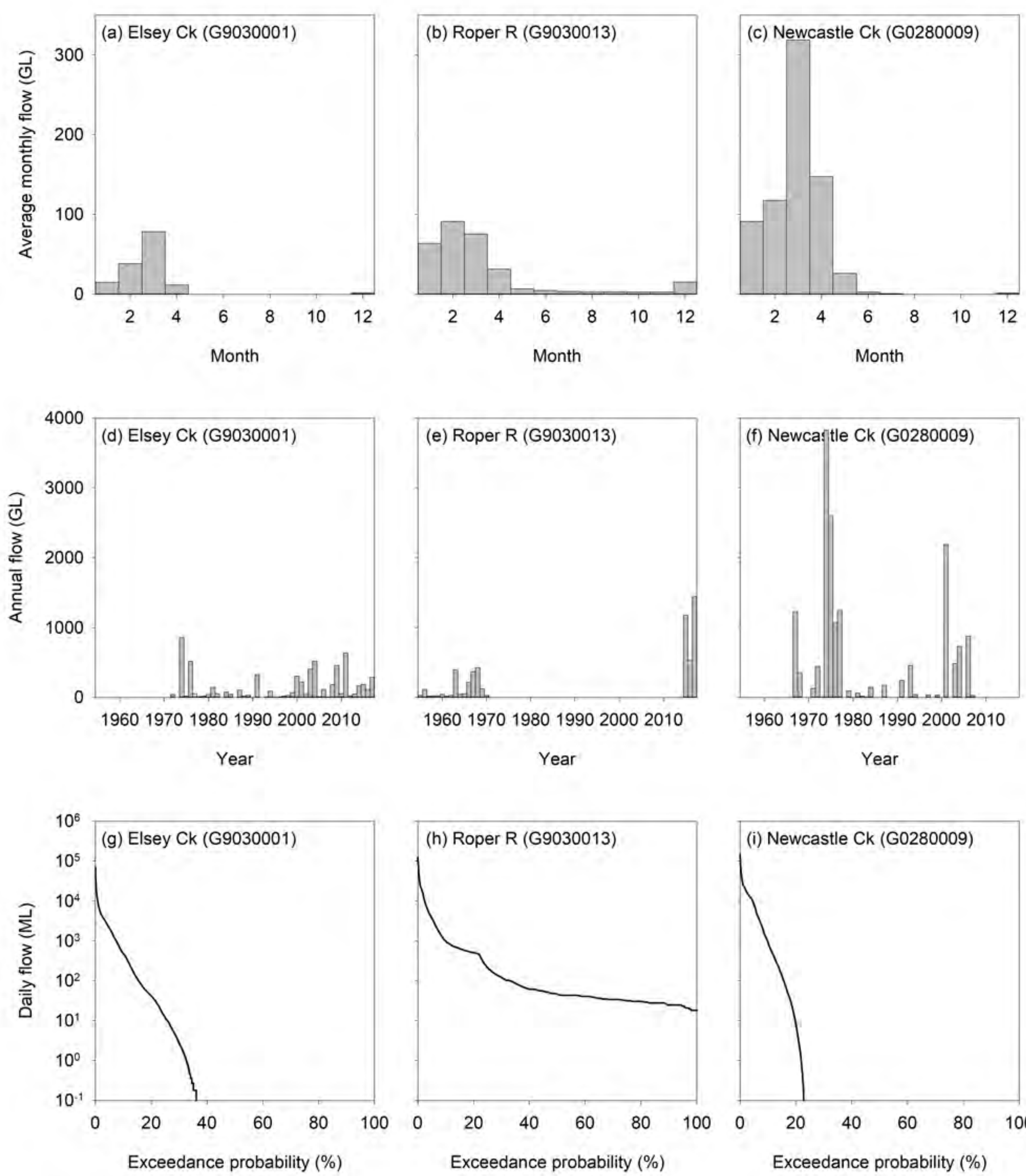

Figure 41 Distribution of mean monthly streamflow ((a), (b) and (c)), annual variability of streamflow ((d), (e) and (f)) and flow duration curves ((g), (h) and (i)) for three gauges near the Beetaloo GBA region: Elsey Creek, Roper River and Newcastle Creek

Ck = creek; R = river
Data: Northern Territory Government (2018b)
Element: GBA-BEE-2-036

There has been some sporadic sampling of the water quality of the surface water system at the gauge network across the NT over past decades, with a current water quality monitoring program in the Roper River catchment associated with the water allocation plan (Shult and Novak, 2017).

For the three gauged sites shown in Figure 40 the median recorded total dissolved solids (TDS) was 860 mg/L for the Roper River at Elsey Homestead, 63 mg/L for the Newcastle Creek at Stuart Highway and 60 mg/L for Elsey Creek at Warlock Ponds (Figure 42). The Roper River has a higher TDS due to being sampled at a time of baseflow where the salt content reflects the groundwater discharge from Mataranka Thermal Pools. At the Roper River gauge site TDS would be considered fair quality for drinking water (NHMRC/NRMMC, 2011), while the other two sites would be considered good quality drinking water. All three sites are suitable for stock watering (ANZECC/ARMCANZ, 2000). There is currently no suitable Environmental Protection Policy (Water) or default ANZGECC/ARMCANZ (2018) water quality guideline value specific for the protection of aquatic biota against extremes of salinity, TDS and nutrients in the Beetaloo GBA region. In the absence of a comparative benchmark, it is useful to look at changes in these parameters over time (Figure 42(a) to (c)). There are no definitive trends of significant increased TDS, total nitrogen and total phosphorus concentrations over time. This suggests that current levels of development have not deteriorated the water quality for aquatic biota but with so few data points it is impossible to say conclusively. The elevated nitrogen and phosphorus in the Roper River is from the groundwater discharge and the concentrations decrease downstream from Mataranka (Shult and Novak, 2017).

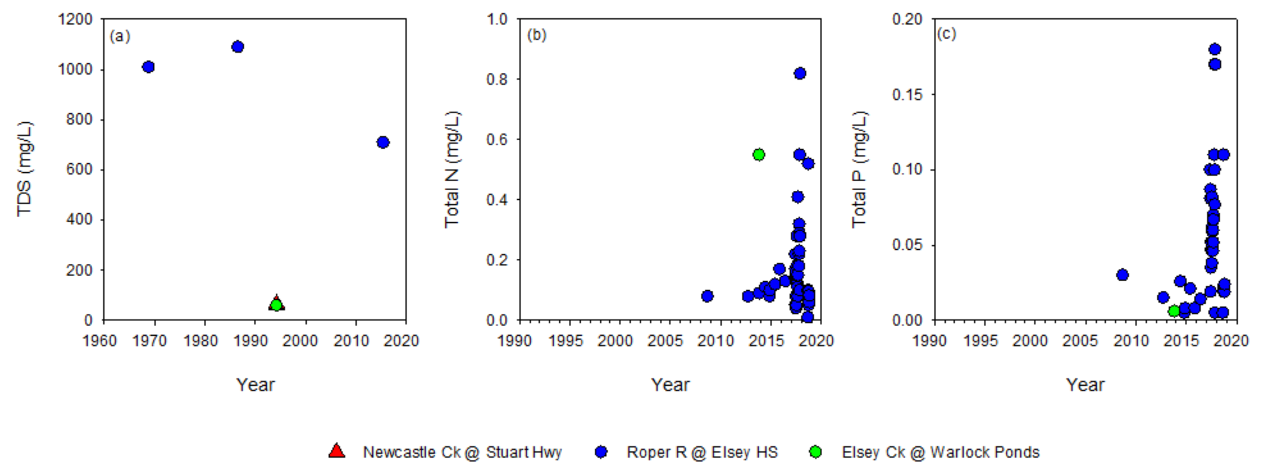

Figure 42 Indicators of water quality for three gauging stations in the Beetaloo GBA region showing (a) total dissolved solids, (b) total nitrogen and (c) total phosphorous

TDS = total dissolved solids; Total N = total nitrogen; Total P = total phosphorus
Data: Northern Territory Government (2019b)
Element: GBA-BEE-2-120

3.3 Surface water – groundwater conceptualisation

Potential groundwater-dependent ecosystems (GDEs) have been identified within the Beetaloo GBA region. However, given that regional groundwater within the GBA region is generally greater than 40 m below the ground surface, the connectivity between the surface water and groundwater is likely to be limited to localised shallow perched aquifer systems, rather than the more regional watertable, as found in the CLA. When inundated, large lakes found to the south in the Beetaloo GBA extended region (e.g. Lake Woods) act as point sources of episodic recharge to the underlying regional watertable in the CLA.

Springs have not been identified within the Beetaloo GBA region. However, some large spring complexes discharge to wetlands and provide significant baseflow to rivers that occur approximately 50 km north of the Beetaloo GBA region. These include Mataranka Thermal Pools and Flora Creek springs. The primary source for these springs is the CLA, and a component of groundwater flow to these springs comes out of the Beetaloo GBA region.

The closest springs to the Beetaloo GBA region are the Beauty Creek and Lagoon Creek springs, situated approximately 10 km to the north-east of the region boundary. These hot springs occur on Roper Group outcrop and discharge hot groundwater from a deep source (probably the Roper Group) in a geologically structurally complex area.

Across much of the Beetaloo GBA region, the regional watertable (Figure 43) lies well below ground surface (generally greater than 40 m), which precludes significant interactions between surface water features, vegetation and the regional watertable. Depth from the surface to regional watertable is much shallower around the north-western margin of the Beetaloo GBA region, as well as north of the region into the Daly and Roper River catchments. This is the case because the CLA is not as deeply buried by rocks belonging to the overlying Carpentaria Basin and also because of the elevation decrease northwards and eastwards (Figure 43) off the Sturt Plateau (Figure 4) into the Daly and Roper river catchments.

Localised shallow aquifers perched above the regional watertable also occur in the Beetaloo GBA region, particularly where Cenozoic sediments overlie less permeable Carpentaria Basin sediments (Fulton and Knapton, 2015). Although the perched aquifers and not used as a groundwater supply, they could potentially interact with surface water or deep-rooted vegetation, particularly on floodplains or black soil plains. Remote sensing investigations that are a part of the Stage 3 of the Beetaloo GBA project could provide further information on distribution of these perched groundwater systems and their potential to interact with vegetation.

The Beetaloo GBA region encompasses several areas classified as GDEs (see Figure 44), some of which have the potential to interact with shallow groundwater that can occur in perched aquifers. GDEs associated with springs have not been identified within the Beetaloo GBA region. However, many do occur to the north and east of the region, as well as in sections of perennially flowing streams (Figure 45). Mataranka Thermal Pools is a major spring complex located approximately 50 km north of the Beetaloo GBA region and forms a major discharge zone for the CLA. This spring complex is situated in the Roper River catchment within the Elsey National Park and include spring pools and large wetlands, all of which contribute baseflow to the Roper River.

Groundwater flow in the Tindall Limestone converges on Mataranka Thermal Pools from the south, north and west (Figure 37). At Mataranka Thermal Pools, Fulton and Knapton (2015) estimated cumulative discharge from the CLA to be around 300 ML/day at the end of dry season. Tickell and Bruwer (2017) estimated discharge of groundwater from the Daly and Georgina basins (i.e. groundwater flow from the south towards the springs) to be 82 ML/day. This suggests around two-thirds of spring discharge could be derived from the north and west of the springs, which are areas that lie outside the Beetaloo GBA region.

Discharge from CLA aquifers in the Wiso Basin and western portions of the Daly Basin occurs 115 km north-west of the Beetaloo GBA region (Figure 45) in the vicinity of Flora River springs (EcOz Environmental Consultants, 2015). Here, at commencement of the wet season, the Flora River gains about 172 to 432 ML/day due to groundwater discharge where it crosses the Tindall Limestone aquifer (Tickell, 2005). This includes discharge from the Flora River springs and will vary depending on how much rain has fallen in the preceding wet season. Springs around Katherine are discharge points for a more local flow system within the CLA. This local system around Katherine is isolated from the Mataranka Thermal Pools groundwater system to the south by an east-trending groundwater divide. This groundwater divide coincides with the catchment divide that separates the Roper and Katherine river basins (Figure 37).

Springs closest to the Beetaloo GBA region are situated approximately 10 km to the north-east of the region boundary, in the headwaters to the Cox River catchment. Here, Beauty Creek springs (in the aptly named Hot Springs Valley) and Lagoon Creek springs discharge groundwater that is up to 60 °C ((Zaar, 2009). The relatively high temperatures at surface would require active groundwater circulation to depths of at least 650 m (Evans et al., 2020), along with good structural permeability. These springs occur on Roper Group outcrop in geologically structurally complex area. The source aquifer(s) for these springs are unknown but, depending on structural control and the geology at depth, they could belong to the Roper Group (e.g. the Hodgson or Bessie Creek sandstones).

Other springs found to the north of the eastern Beetaloo GBA region are predominantly associated with Proterozoic outcrop. Whilst less information is available, a useful reference for these springs is Zaar (2009).

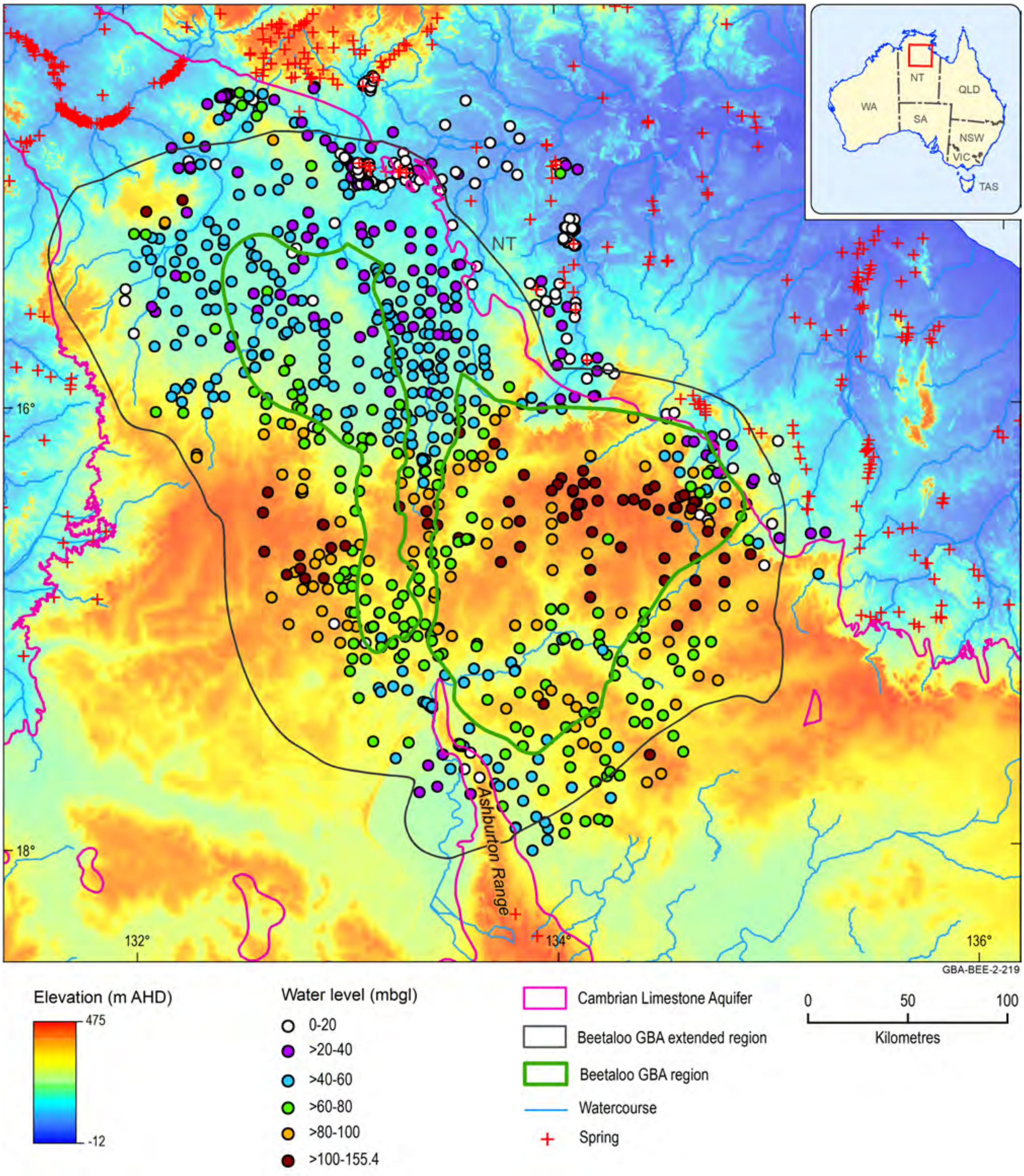

Figure 43 Depth to groundwater in registered groundwater wells

Springs are shown on the map as well as bores because they represent a point where the watertable level is at or higher than the local ground surface.
Data: Geological and Bioregional Assessment Program (2019c)
Element: GBA-BEE-2-219

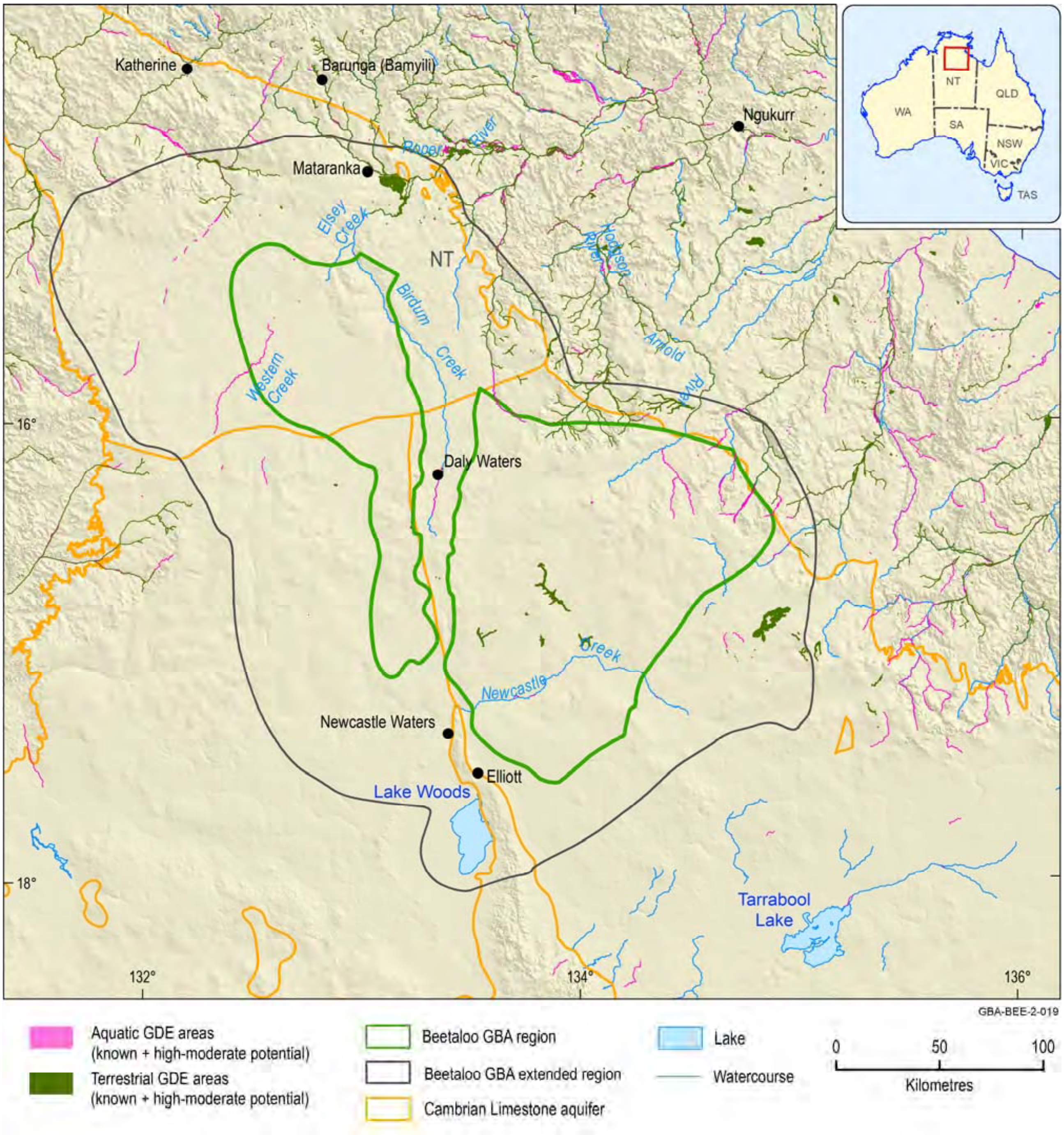

Figure 44 Groundwater-dependent ecosystems in the Beetaloo GBA region and Beetaloo GBA extended region

GDE = groundwater-dependent ecosystem
Data: Bureau of Meteorology (2017)
Element: GBA-BEE-2-019

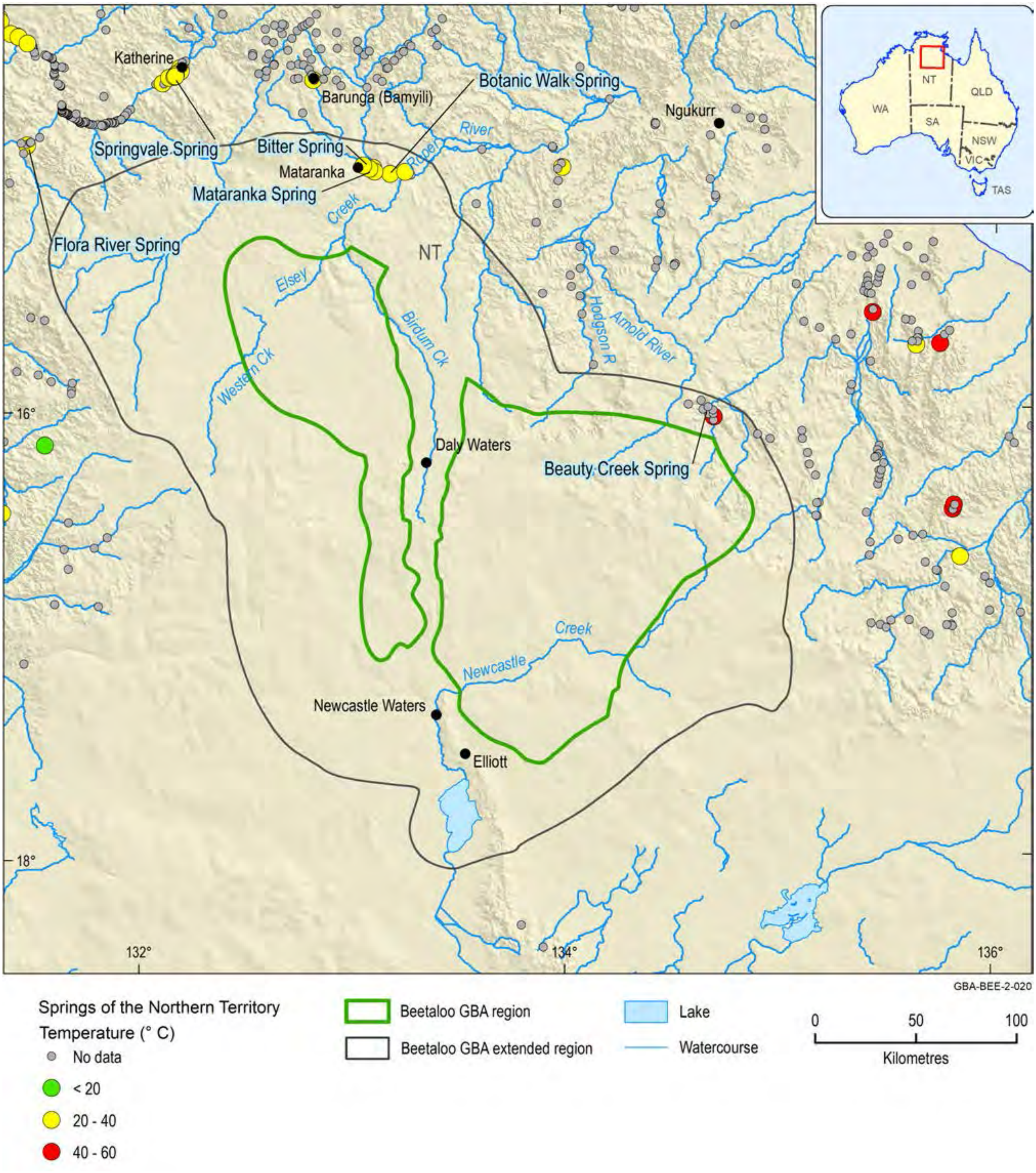

Figure 45 Locations of springs near the Beetaloo GBA region, colour coded by the temperature of groundwater

Data: Department of Environment and Natural Resources (NT) (2013)
Element: GBA-BEE-2-020

3.4 Potential hydrological connections

The nature of the hydrological connection (if any) between deeper groundwaters associated with Proterozoic and younger geological units and surface waters is poorly understood. Five potential hydrological connectivity pathways are postulated for the Beetaloo GBA region related to migration via direct stratigraphic contact and dilation faults; through porous/karstic aquifers, partial aquifers or aquitards; and via discharge from karstic-fractured aquifers into springs. Further investigations in Stage 3 will focus on potential hydrological connections relevant to risks from future shale gas, tight gas and shale oil development.

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

Development of unconventional gas plays in the late Mesoproterozoic Velkerri Formation of the western and eastern Beetaloo Sub-basins (including shale gas, tight gas and shale oil) is a stressor that has the potential to affect migration of groundwater and fluids between deeper formations and assets near the surface (Figure 46). Extraction of water from shallower aquifers (e.g. CLA, basal sandstone of Carpentaria Basin and Cenozoic aquifer) is another stressor that can cause an impact on surface water and groundwater assets. Important assets in the Beetaloo GBA region include:

- **springs**, represented by a series of discharge complexes mapped along the north-north-east and east edges of the Beetaloo GBA extended region but outside of the limits of the Beetaloo Sub-basin, spanning from Katherine to near Borroloola. The closest springs are located approximately 10 km to the north-east of the limits of the eastern Beetaloo Sub-basin (e.g. Lagoon Creek and Beauty Creek Springs) and Mataranka Thermal Pools, located approximately 40 km north of the western Beetaloo Sub-basin
- **GDEs**, including aquatic and terrestrial ecosystems that potentially depend on shallow perched groundwater systems associated with alluvial valleys as well as discharges from deeper systems. Only those GDEs classified as known, high and moderate potential in the *National atlas of groundwater dependent ecosystems* (Bureau of Meteorology, 2017) were considered for the assessment, as shown in Figure 46. Mataranka Thermal Pools, identified as a terrestrial GDE area, for instance, is known to be reliant on baseflow from the CLA
- **streams** and **wetlands**, including Roper, Daly and Limmen Bight rivers, Wiso and the Barkly regions and Lake Woods (south) (see Section 3.2)
- **shallow groundwater bores** used for stock and domestic water supply, as registered in the Department of Environment and Natural Resources (NT) groundwater databases (see Section 3.1).

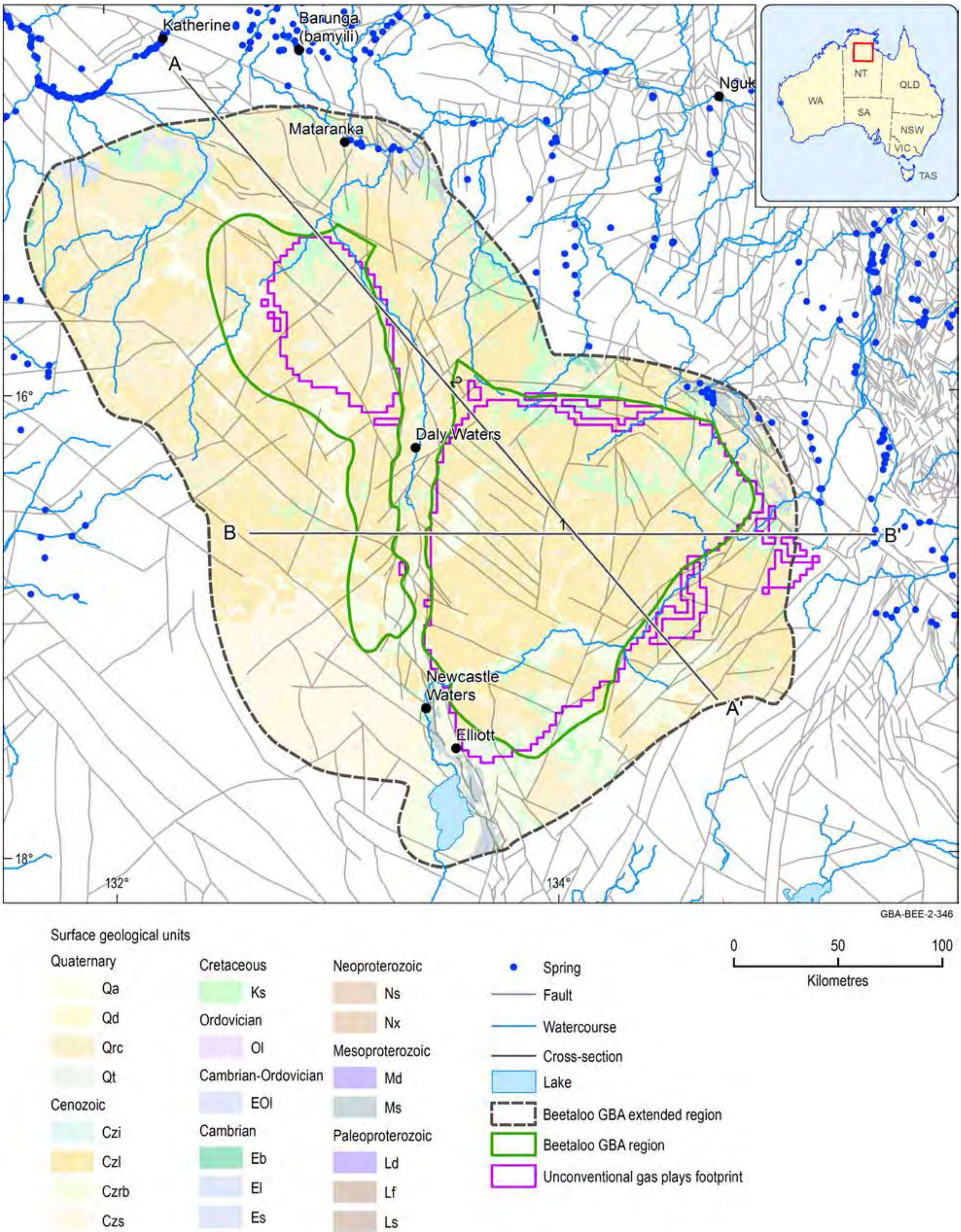

Figure 46 Beetaloo GBA region: surface geology, structures, footprint of unconventional gas plays, environmental assets such as springs and watercourses, and orientation of cross-sections presented in Figure 47 and Figure 49

Data: faults sourced from Betts et al. (2015), unconventional gas plays footprints from Geological and Bioregional Assessment Program (2019d), springs from Department of Environment and Natural Resources (NT) (2013) and geology from Geoscience Australia (2012)
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The connections between stressors and assets that could plausibly affect migration of groundwater and fluids are described below. In the absence of detailed hydrological studies, the evidence supporting these potential hydrological connections includes the conceptual understanding of aquifer and aquitard architecture, proximity of assets to faults, vertical continuity of faults, and geological heterogeneities near the basin margins. The five plausible hydrological connections are:

1. via direct stratigraphic contact
2. via faults
3. through porous/karst aquifers
4. through partial aquifers/aquitards reaching overlying aquifers
5. via groundwater discharge from CLA aquifer to springs.

Connectivity between groundwater systems controls the spread of potential impacts from petroleum resource development and production to environmental assets and groundwater resources. Through the five pathways, key areas of potential concern for groundwater include:

- connectivity issues associated with gas and petroleum production from prospective Roper Group formations, whereby impacts could propagate to overlying groundwater systems (pathways 1 and 2)
- connectivity issues associated with extracting groundwater from units above the Roper Group for use in petroleum resource development, whereby impacts may spread to existing groundwater users and the environment through shallow groundwater systems (pathways 1, 2 and 3)
- connectivity through shallow aquifers (e.g. karst features in the CLA) enabling migration of contamination due to infiltration of surface spills from petroleum development or production. Effects from points 1 and 2 above may also follow this pathway (pathways 3, 4 and 5).

These three connections could occur through five potential hydrological pathways.

Some of the potential connectivity pathways described below are unlikely to occur simultaneously and are also unlikely to create conditions prone to linking the stressors to environmental assets in a human timescale. Nevertheless, considering the current knowledge gaps, it is important to take a precautionary approach when assessing such processes. GBA Stage 3 will conduct a further assessment of the possibility that fluid and/or gas migration from one compartment of the sub-basin to another may occur and the different timescales for these processes.

Methods snapshot: conceptualising potential hydrological connections

Multiple datasets are integrated to develop conceptual models that describe the potential for hydrological connections (if any) between deep unconventional gas plays or water source aquifers (CLA and Cenozoic) and environmental assets (including GDEs) at the surface. Stressors include the development of unconventional shale gas, tight gas and shale oil plays in the Beetaloo Sub-basin (western and eastern) and extraction from shallower aquifers to support development. The geological framework uses key horizons represented in the three-dimensional geological model and fault structures described in the geology technical appendix (Orr et al., 2020). The conceptual models are based on the interpretation of several two-dimensional cross-sections extending from the Paleoproterozoic units of the Beetaloo Sub-basin to the Cenozoic deposits of the Birdum Creek beds (Figure 46). The cross-sections integrate currently available fault-zone architecture information into the context of the regional stratigraphic framework and compare geological architecture and structure with the spatial distribution of assets.

The conceptual models aim to identify areas where there is greater likelihood of hydrological connections based on a combination of factors, including:

- footprint and thickness of the unconventional gas plays intervals (Velkerri and Kyalla formations) and their linear distance (predominantly vertical) to the adjacent Moroak Sandstone aquifer as well as the overlying aquifers hosted in Jamison sandstone, undifferentiated Neoproterozoic (including Bukalara Sandstone), through the karstic/fracture systems of the Cambrian Limestone Aquifer, basal sandstone of Carpentaria Basin, Cenozoic aquifer and near-surface assets
- upwards formation pore pressure (or hydraulic) gradient between the unconventional hydrocarbon plays and the adjacent and overlying hydrostratigraphic units more susceptible to being immediately affected by pressure alternations in the shale gas play intervals
- general stress regime associated with the geological structures conducive to fault reactivation and enhancement
- spatial distribution of thickness and hydraulic properties of the aquitard/seals (e.g. Hayfield mudstone and Antrim Plateau Volcanics) positioned between the unconventional plays and the identified overlying assets
- anomalies identified in physical–chemical, hydrochemical measurements in groundwater, springs and surface water samples (Figure 48) and several gas measurements from water bores
- spatial location and extent of environmental assets, including GDEs, including springs, reaches where baseflow to streams is likely to occur and groundwater bores used for water supply.

① Potential connection via direct stratigraphic contact

Two possible scenarios of hydrological connection may occur where a direct stratigraphic contact exists between the potential unconventional gas plays and adjacent overlying environmental assets (aquifers, springs, GDEs, creeks).

An evident connectivity pathway 'gas plays – asset aquifer' may be represented by the contact between the Velkerri and Kyalla formations with overlying units such as the Moroak Sandstone and Jamison sandstone. Groundwater quality can be relatively poor in these hydrostratigraphic units and they have highly variable hydraulic properties due to predominance of secondary porosity. The Kyalla Formation is also in direct contact with other overlying formations, including the Bukalara Sandstone, Antrim Plateau Volcanics and CLA, in discrete areas near the margins of the Beetaloo GBA region.

The thickness of the Undifferentiated Neoproterozoic – a hydrostratigraphic unit positioned between the shale gas bearing Kyalla Formation and the aquitard Antrim Plateau Volcanics – is significantly reduced (<50 m) in the north-west corner of western portion of the Beetaloo Sub-basin. In fact, the Kyalla Formation is possibly in direct contact with Antrim Plateau Volcanics, which may explain the occurrence of measurable methane (CH_4) in this highly fractured unit and in the overlying lower CLA. Importantly, no mapped faults appear to be in proximity to samples with methane concentrations above 50 µg/L in the western portion of the Beetaloo Sub-basin. This indicates that the dissolved gas in groundwater supports evidence of the direct stratigraphic contact (gas play – aquitard/aquifer), enhanced by the intensely fractured zones in Antrim Plateau Volcanics and karstic conditions in CLA.

As described in Section 3.3.2 of the hydrogeology technical appendix (Evans et al., 2020), there is also evidence of upward hydraulic gradients from the Roper Group towards the overlying sequences. This marks an additional conducive factor to fluid migration along zones where stratigraphic contacts exist. Such connectivity can be further enhanced by the presence of geological structures, as described by pathway 2.

Detection of dissolved methane in aquifers can also be an indicator for the presence of seal bypass systems (further discussed in pathways 2 and 4), and it can be considered a precursor of other organic or even inorganic contaminants derived from organic matter-rich shales or other hydrocarbon sources. However, it can also be due to biogenic processes in shallower formations, and integrated approaches that consider multiple tracers are required to determine the origin of the gas. The presence of dissolved methane in sedimentary basins is not unusual, and concentrations measured in the Eromanga Basin within the Cooper GBA region, for example, ranged from 150 to 216,500 µg/L (Holland et al., 2020) and concentrations of up to approximately 20,000 µg/L are common in productive aquifers of the Surat Basin (Mallants et al., 2016). Measured concentrations of dissolved methane in the Beetaloo GBA region ranged from <0.001 to 2210 µg/L, which is low compared to other sedimentary basins. However, more baseline data including concentrations of dissolved CH_4 and isotopes of CH_4 from different aquifers are required to understand the source of the CH_4 and its implications for the degree of connectivity.

As noted in Section A-A' (Figure 47), the Hayfield mudstone can form an effective aquitard because of its substantial thickness of fine-grained rocks, even though it has thin prospective reservoir sandstones towards its base. However, there are discrete areas near the margins of the Beetaloo GBA region where the regional aquitards are absent (discussed in pathway 4). In these areas Neoproterozoic units may have direct stratigraphic contact with the base of the CLA.

Where sufficient data from the different components of the surface water and groundwater systems are available, hydrochemistry can also be used to determine connectivity between bedrock, alluvia and streams (e.g. Cartwright et al. (2010); King et al. (2014); Martinez et al. (2017); Raiber et al. (2019)). Hydrochemistry in combination with dissolved methane concentrations can also provide additional insights on potential migration pathways.

The multivariate statistical analysis of groundwater and surface water chemistry data using variables such as major ions, pH and electrical conductivity, described in detail in Evans et al. (2020) (Figure 48), shows that there are multiple hydrochemistry clusters with distinct median values for different parameters. For example, the hydrochemical assessment of 857 groundwater bores and 21 surface water samples suggests there are five distinct clusters with median electrical conductivity (EC) values ranging between 118 and 1860 µS/cm and with distinct ionic ratios (Figure 48).

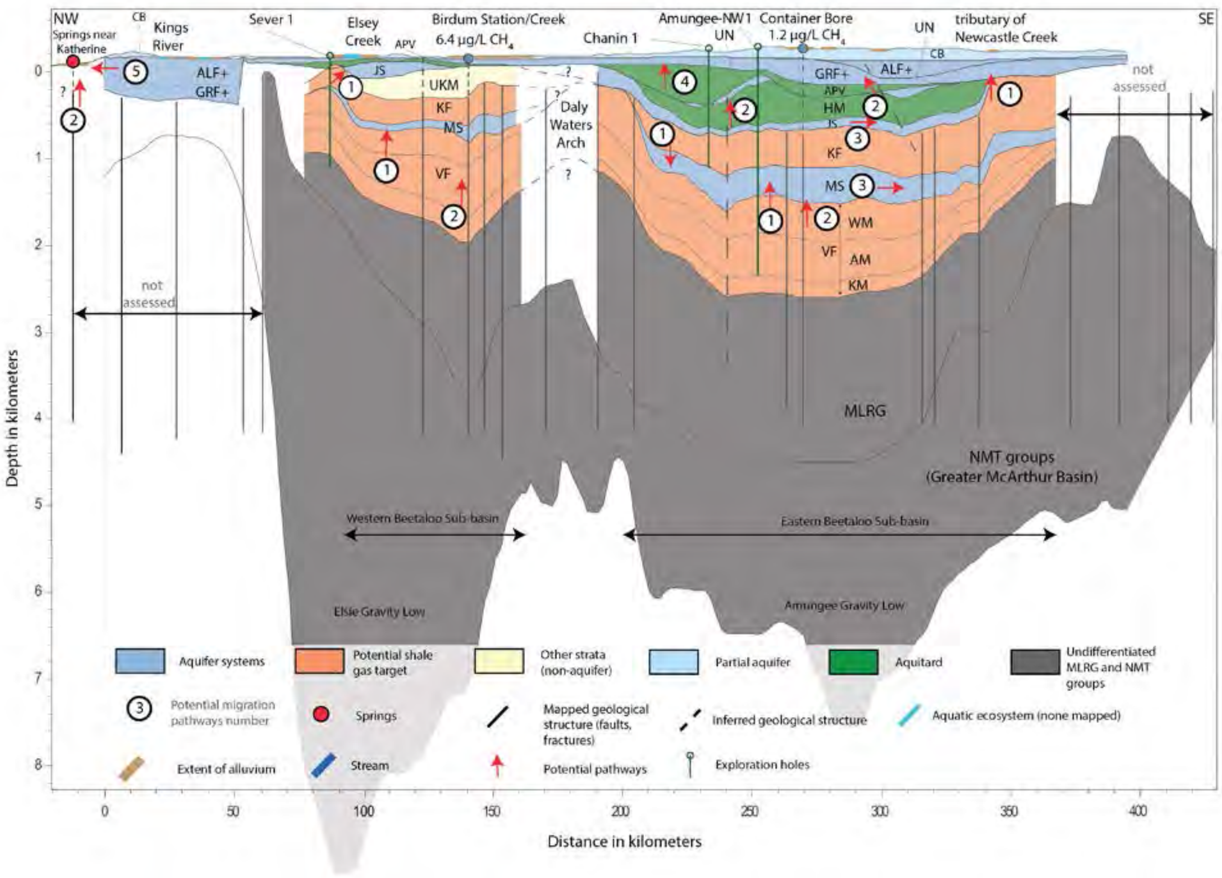

Figure 47 Cross-section A-A' with north-west–south-east orientation through both Elsey and Amungee gravity lows, representing north-eastern and south-western sub-basin margins and major geological structures within the Beetaloo sub-basins, including Daly Water Arch and five potential hydrological connections for water or gas migration

The five potential hydrological connections are: 1. via direct stratigraphic contact, 2. via faults, 3. through porous/karst aquifers, 4. through partial aquifers/aquitards reaching overlying aquifers, 5. via groundwater discharge from CLA aquifer to springs.

NMT = Nathan/McArthur/Tawallah groups; MLRG = Middle to Lower Roper Group; VF = Velkerri Formation (WM = Wyworrie Member; AM = Amungee Member; KM = Kalala Member); MS = Moroak Sandstone; KF = Kyalla Formation; JS = Jamison sandstone; HM = Hayfield mudstone; UKM = Upper Kyalla Member; UN = Undifferentiated Neoproterozoic (including Bukalara Sandstone); APV = Antrim Plateau Volcanics; GRF+ = Gum Ridge Formation and equivalents (lower CLA); ALF+ = Anthony Lagoon Formation and equivalents (upper CLA); CH4 = methane

Data: Faults sourced from Betts et al. (2015), unconventional gas plays footprints from Geological and Bioregional Assessment Program (2019d), springs from Department of Environment and Natural Resources (NT) (2013) and geology from Geological and Bioregional Assessment Program (2019a) and Frogtech Geoscience (2018b); methane data from Wilkes et al. (2019)

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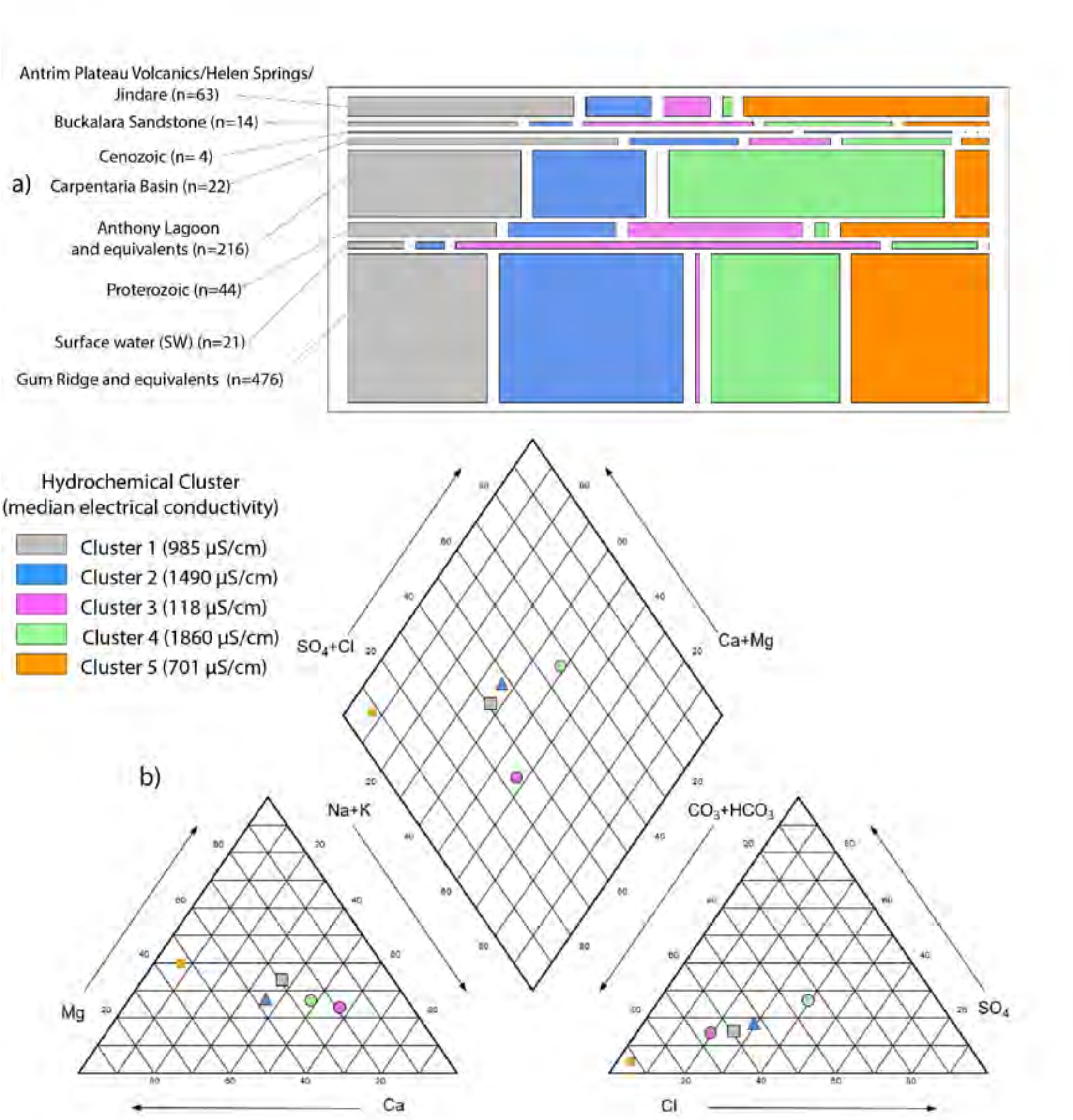

Figure 48 Cluster membership of aquifers and surface water in the Beetaloo GBA region

(a) Width of the bars represents the relative percentage of groundwater and surface water records assigned to each cluster. Numbers in brackets behind the hydrostratigraphic unit correspond to the number of hydrochemical records for each formation.
(b) The Piper plot shows the median concentrations of the different clusters.
Data: Geological and Bioregional Assessment Program (2019h)
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② Potential connection via faults

Fault zones can result in vertical hydraulic connections between different hydrostratigraphic layers and/or where strata are compartmentalised horizontally. This could potentially connect unconventional shale gas plays in the upper Mesoproterozoic Maiwok Subgroup with adjacent and overlying Proterozoic aquifers of Moroak Sandstone, Jamison sandstone and the CLA in the south-east of the eastern Beetaloo Sub-basin. Such structures may extend further up in the vertical stratigraphic profile, potentially reaching the Cretaceous Carpentaria Basin, Cenozoic and alluvial aquifers or surficial assets such as perched watertables, GDEs and springs.

The tectonic and depositional history of the Beetaloo GBA region as described by Orr et al. (2020), is complex and protracted and includes at least three major tectonic events and four major depositional events from 1750 and 300 Ma, highlighting the structural complexity of this region. The Beetaloo Sub-basin is generally bounded by large fault zones, including the Mallapunyah Fault as well as faults associated with Daly Waters High (see Figure 13). According to Frogtech Geoscience (2018b), the fault zones bounding the Beetaloo Sub-basin are prone to fault reactivation, and the Daly Waters High corresponds to an underlying zone of less competent basement.

A combination of the Birdum Creek Fault (Figure 9 in Evans et al. (2020)) and Daly Waters Arch is expected to influence the connectivity and groundwater flow within the CLA, and it is thought to be responsible for a groundwater divide with a north-west trend in the Beetaloo GBA region (as described below) resulting in the Georgina–Daly and Wiso–Daly basin systems.

No springs have been identified within the Beetaloo GBA region. However, the Roper Group (which includes the prospective Velkerri and Kyalla formations) is potentially a source aquifer for springs located just outside the Beetaloo GBA region. Some of these springs are quite hot, with temperatures up to 60 °C. As discussed in Section 3.4.3 in Evans et al. (2020), hot groundwater discharge would require active circulation down to at least 650 m along conduits with relatively good permeability. According to the NT Springs database (Department of Environment and Natural Resources (NT), 2013), the source aquifer of three springs within the Beetaloo GBA region is attributed to Paleoproterozoic units that are associated (closely overlying or underlying) with the gas plays of Velkerri Formation. Moroak Spring, located 76 km north-east of the western Beetaloo Sub-basin, is classified to source water from Roper Group, whereas two springs approximately 30 km east of the eastern Beetaloo Sub-basin are identified to source water from the Bessie Creek Formation and Hodgson Sandstone, both underlying the major gas plays of Velkerri Formation.

Surface geology suggests there is likely to be a high degree of structural control on groundwater flow paths and the degree of connectivity between areas of Roper Group outcrop and Roper Group at depth in the Beetaloo Sub-basin is uncertain. More hydrochemistry data and environmental tracers would be required to determine flow paths and to pinpoint source aquifer(s) for springs in these areas and would assist in determining the degree of connectivity between Roper Group outcrop. It is noticeable in cross-section B-B’ (Figure 49) that the shallowness of the gas plays in the east part of the eastern Beetaloo Sub-basin coincides with a fault zone where a high frequency of mapped faults occurs. This indicates a higher likelihood for connectivity between these springs to the Paleoproterozoic geological units.

Groundwater chemistry evidence also suggests some degree of vertical connectivity. This evidence includes the presence of low levels of dissolved CH_4 (Wilkes et al., 2019), including one outlier sample, with 379.7 µg/L, collected from the upper CLA (Anthony Lagoon Formation) in very close proximity to some faults in the western portion of the Beetaloo GBA region. Whether this minor anomaly relates to migration of gases from depth or alternatively, was generated from organic matter in the CLA is unknown. The chemical and isotopic composition (^{14}C, ^{13}C, total dissolved inorganic carbon, Cl, Na, Mg and Ca) of CLA groundwaters sampled along a 300 km line extending from Mataranka, through Daly Waters and along the Carpentaria Highway (Suckow et al., 2018) are also consistent with the hypothesis that a mixture of young and old waters may be the sources for these groundwaters.

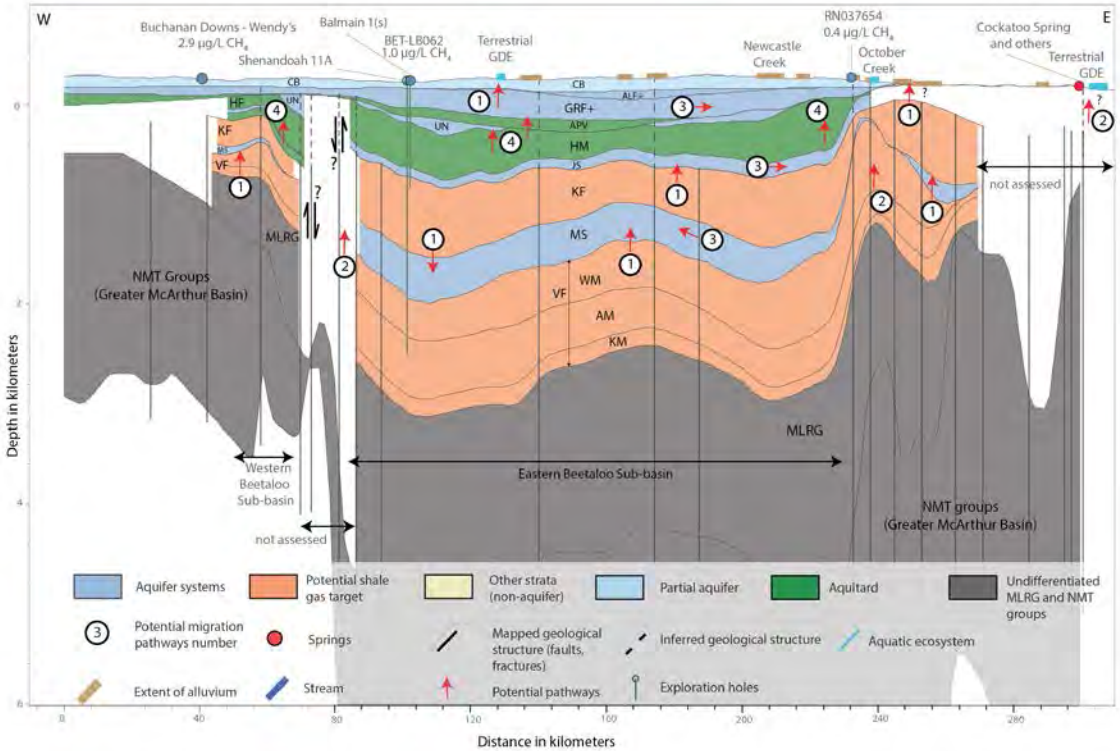

Figure 49 Cross-section B-B', with west–east orientation, representing likely geological structural controlling vertical offsets between western and eastern Beetaloo Sub-basins and eastern margin of the former as well as five potential hydrological connections for water or gas migration

The five potential hydrological connections are: 1. via direct stratigraphic contact, 2. via faults, 3. through porous/karst aquifers, 4. through partial aquitards/aquitards reaching overlying aquifers, 5. via groundwater discharge from CLA aquifer to springs.

NMT = Nathan/McArthur/Tawallah groups; MLRG = Middle to Lower Roper Group; VF = Velkerri Formation (WM = Wyworrie Member; AM = Amungee Member; KM = Kalala Member); MS = Moroak Sandstone; KF = Kyalla Formation; JS = Jamison sandstone; HM = Hayfield mudstone; UKM = Upper Kyalla Member; UN = Undifferentiated Neoproterozoic (including Bukalara Sandstone); APV = Antrim Plateau Volcanics; GRF+ = Gum Ridge Formation and equivalents (lower CLA); ALF+ = Anthony Lagoon Formation and equivalents (upper CLA)

Data: Faults sourced from Betts et al. (2015), unconventional gas plays footprints from Geological and Bioregional Assessment Program (2019d), springs from Department of Environment and Natural Resources (NT) (2013) and geology from Geological and Bioregional Assessment Program (2019a) and Frogtech Geoscience (2018b); methane data from Wilkes et al. (2019)

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③ Potential connection through porous/karst aquifers

Groundwater moving through an aquifer can be a connective pathway that may allow changes to water quality or groundwater pressure to propagate away from a source. The degree to which changes can occur is dependent on many factors including: configuration of the aquifer, its lithology, extent and degree of confinement, hydraulic properties (primarily hydraulic conductivity), hydraulic gradients, flow rates, chemistry and connectivity with other aquifers.

In the Beetaloo GBA region the Roper Group is deeply buried and is not used as a groundwater supply. However, at depth groundwater and fluid/gas flow may occur, particularly in areas that are 'on structure.' Another factor influencing the lateral flow in the Roper Group is the level of induration caused by diagenetic processes and secondary porosity such as fracturing. Groundwater flow in this sequence is unlikely to be extensive, unless through other pathways.

On the other hand, in the CLA, lateral connectivity and groundwater flow is inferred from hydraulic gradients derived from waterlevel data. As previously described in Evans et al. (2020), the porosity and permeability of the CLA is primarily controlled by the formation of karst. Flow rates through karstic porosity and permeability can be extremely variable, including flow rates over 1000 m/day in areas to the north of the Beetaloo GBA region. Two major flow systems in the CLA can be identified within the Beetaloo GBA region, one from the Georgina Basin into the Daly Basin and the other from the Wiso Basin into the Daly Basin. At a local scale, the presence of structures (pathway 2) and karst patterns may cause deviations in the general groundwater flow direction. Figures 14 and 15 of Evans et al. (2020) illustrate the inferred groundwater flow direction of the CLA and groundwater divide formed by the influence of geological structures.

There is direct evidence that groundwater movement occurs in the Kiana Group, labelled in the cross-sections (e.g. Figure 47) as 'Undifferentiated Neoproterozoic'. However, groundwater information from which to infer flow directions is very limited. According to Evans et al. (2020), the Bukalara Sandstone is porous and permeable, with minimum cementation, making this unit a potential horizontal and vertical conduit.

④ Potential connection through partial aquifers/aquitards reaching overlying aquifers

Leakage across aquitards can occur over time. As described for pathway 1, the Hayfield mudstone is deemed an effective aquitard because of its substantial thickness, reaching thicknesses of 449 m (Balmain-1 and Shenandoah-1 petroleum wells) and 569 m (Tanumbirini-1). Where the Hayfield mudstone thins or is compromised by faults (as discussed in Orr et al. (2020)), migration of fluids between petroleum plays in the Kyalla Formation through the Hayfield mudstone to overlying sequences is a possible pathway. All the cross-sections (Figure 47 and Figure 49) show some evidence of extension of deep-seated faults to the surface with creeks coincident with the surface projection of these faults along with the occurrence of dissolved gas (Figure 31 in Evans et al. (2020)) in shallow groundwater in their vicinity (see pathway 2 for further discussion of faults).

The Antrim Plateau Volcanics is classified by Evans et al. (2020) as a thick regional-scale aquitard. However, as shown in Figure 6 in Evans et al. (2020), the unit is absent from the southern and eastern parts of the Beetaloo GBA region and while the Hayfield mudstone is present in these areas, it thins considerably towards the southern and eastern tips of the eastern part of the sub-basin. Again, in these locations, leakage through an aquitard could be possible mechanism that allows vertical connectivity.

The Cox Formation, another leaky aquitard, should be considered a potential connectivity barrier where present. However, knowledge of this unit in the Beetaloo GBA region is sparse and it has not been differentiated in the three-dimensional geological model used for the development of conceptual models in this assessment.

⑤ Potential connection via groundwater discharge from CLA aquifer to springs

Groundwater flow divides segregate the CLA into at least two major groundwater flow systems (Figure 37). One of these systems, the Georgina-Daly system has a northerly regional flow component out of the Beetaloo GBA region towards the Mataranka Thermal Pools and the Roper River. As suggested by Tickell and Bruwer (2017), more localised flowpaths in the Daly Basin are also expected to discharge to the Mataranka Thermal Pools on the Roper River. A possible connectivity pathway is groundwater flow through the CLA and northwards out of the Beetaloo GBA region towards the springs. Whether impacts can actually propagate that far will be determined as part of Stage 3. The relative contributions from different flowpaths (local versus regional) to the springs is likely to lessen the degree of any potential impact.

The carbonate-dominant CLA has a diverse range in permeability, which is difficult to characterise spatially. Some karst systems appear to be influenced by structure but remain localised and are not regionally interconnected. Over parts of the Beetaloo GBA region, the Carpentaria Basin is significantly eroded and only the permeable sandstone of basal 'Unit A' lies at or near ground level enabling localised recharge into the underlying CLA through dolines (see Section 3.3.4 in Evans et al. (2020)). The degree of vertical karst connectivity as well as thickness of the overlying Carpentaria Basin, will influence degree of connectivity from surface to the CLA. This will influence the potnetial for near surface impacts (e.g. spills) to reach the CLA. Where cover is thin and compromised by sinkholes, there is greater potential for spills to reach an aquifer when compared to areas where the cover is thick.

3.4.1 Summary of hydrological connections

The potential connectivity pathways described above and summarised in Table 10 are unlikely to occur simultaneously and are also unlikely to create conditions that link the stressors to environmental assets in a human timescale. Nevertheless, considering the existing knowledge gaps, it is important to take a precautionary approach when assessing such processes and consider the possibility that fluid migration from one compartment of the basin to another may occur at different timescales, eventually impacting assets. This will be further assessed during Stage 3, in which potential impacts of this identified pathway can be determined.

3.5 Potential water sources for drilling and hydraulic fracturing

There are no existing surface water licences for the petroleum industry in the Beetaloo GBA region and the NT Government has prohibited surface water extraction for petroleum activities. Unallocated water reserves and other strategies specified in existing groundwater allocation plans do not currently consider the potential quantity of water that may be taken by the petroleum industry. The potential implications for water plans and other water users will be investigated as part of Stage 3. Produced water from future unconventional resource extraction is a potential water source for hydraulic fracturing and drilling operations that may be used by resource companies in the Beetaloo GBA region.

3.5.1 Surface water

3.5.1.1 Existing water allocation plans

Under the *Northern Territory Water Act 1992* (Northern Territory Government, 1992), water control districts (WCDs) are declared in NT areas where there is a high level of competition for water and/or closer management of the water resources is required. Water allocation plans (WAPs) are declared within a WCD.

Surface water licences under the Daly Roper Beetaloo Water Control District are managed in eight river catchments (i.e. Adelaide River, Daly River, Finniss River, Limmen Bight River, McArthur River, Roper River, Towns River and Victoria River–Wiso), six of which intersect the proposed Beetaloo GBA extended region and four of which intersect the Beetaloo GBA region (Figure 50). Detailed information on surface water management (e.g. WAP, WCD) and accounting (e.g. water licensing) is available from the NT Department of Environmental and Natural Resources.

3.5.1.2 Surface water accounts

Two surface water licences for public water supply, with a total entitlement volume of 112 ML/year, are located within the proposed Beetaloo GBA extended region (Department of Environment and Natural Resources (NT), 2019b). There are no existing surface water licences in the Beetaloo GBA region.

3.5.1.3 Potential future surface water sources used by the gas industry

There are no existing surface water extraction licences for the petroleum and gas industry in the Beetaloo GBA region. Based on the recommendations of the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018) for protection of surface water-dependent wetlands and waterholes, the NT Government has prohibited the extraction of surface water for petroleum activities (Northern Territory Government, 2019a).

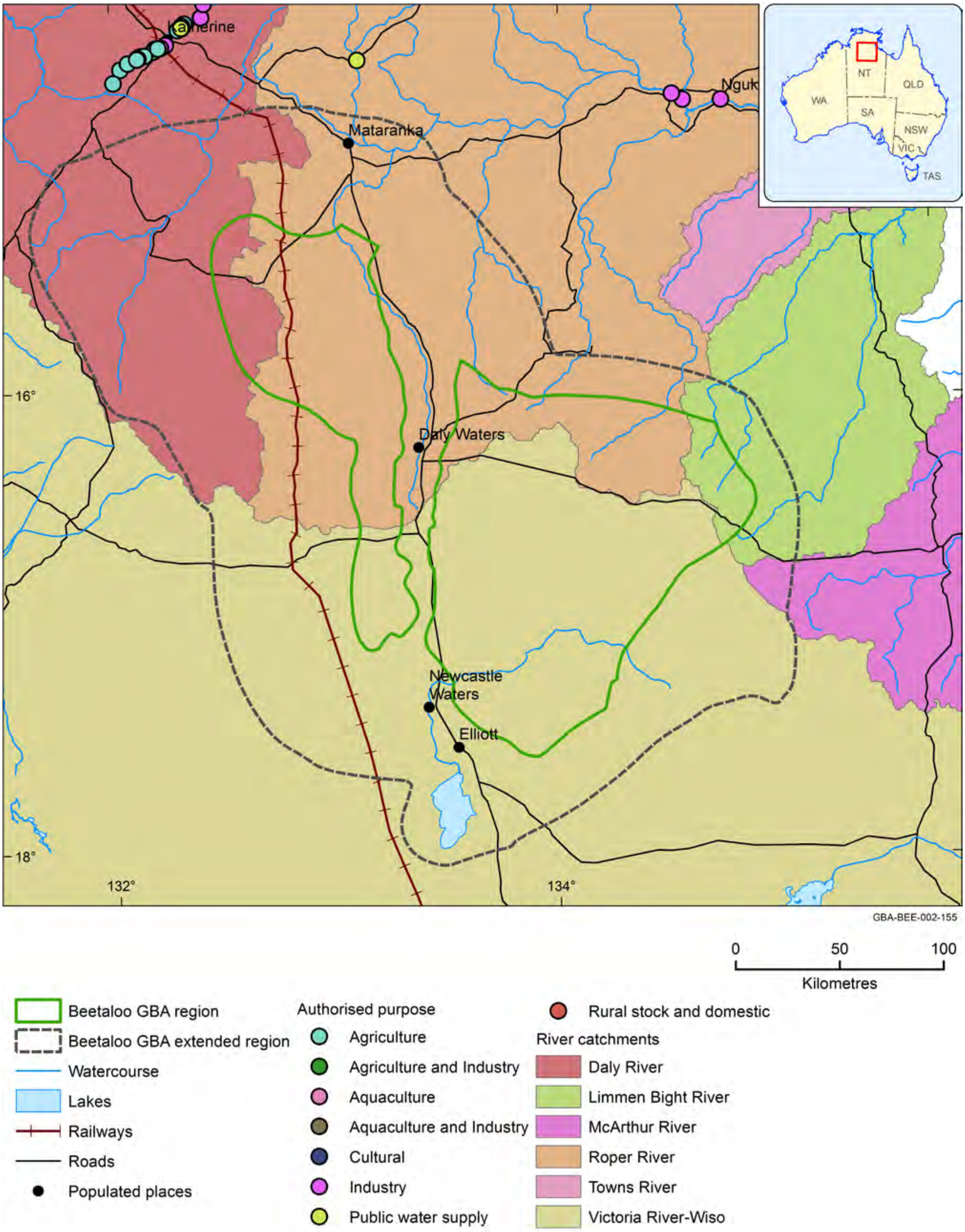

Figure 50 Water management areas and identified purposes of offtake locations in the Beetaloo GBA region

Data: Bureau of Meteorology (2014); Northern Territory Government (2019b)
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3.5.2 Groundwater

3.5.2.1 Existing water allocation plans

Groundwater licences in the Daly Roper Beetaloo Water Control District are granted under its three WAPs: Katherine (Tindall Limestone Aquifer), Draft Oolloo and Draft Tindall Mataranka – Daly Waters (Geological and Bioregional Assessment Program, 2019g). Draft Tindall Mataranka – Daly Waters WAP, an extension of the Draft Tindall Mataranka – Daly Waters WAP, intersects the Beetaloo GBA region (Figure 51). Under the Draft Tindall Mataranka WAP, 36,000 ML/year is reserved for consumptive (agricultural, aquaculture, industry, public water supply and rural stock and domestic) allocation. The Katherine (Tindall Limestone Aquifer) WAP specifies a consumptive allocation of 34,171 ML/year. This WAP area overlaps with the Beetaloo GBA extended region.

3.5.2.2 Groundwater accounts

In the Daly Roper Beetaloo Water Control District, there are 149 water extraction licences with a total entitled extraction volume of 171,117 ML/year from various formations of the CLA (Department of Environment and Natural Resources (NT), 2019b). Licensed uses are agriculture (159,057 ML/year); agriculture, industry and other uses (6,249 ML/year); industry, culture and other uses (1,461 ML/year); and public water supply (4,351 ML/year).

Of this 171,117 ML/year, 28,030 ML/year of groundwater is licensed for extraction in the groundwater management areas intersecting the Beetaloo GBA extended region (Table 9), of which approximately 1,650 ML is licensed from bores located within the Beetaloo GBA region (Department of Environment and Natural Resources (NT), 2019b). This volume does not include 2,108 ML/year of basic water rights for stock and domestic use within the wider WCD area that overlaps the Beetaloo GBA region.

In the NT, groundwater extractions for stock and domestic purposes are non-volumetric and unmetered (Department of Natural Resources, Environment, The Arts and Sport, 2010). Groundwater extraction for livestock water requirements are estimated at 50 L/day per head of cattle, and for domestic use it is estimated to be 5.5 ML/year per bore (Department of Natural Resources, Environment, The Arts and Sport, 2010). There are approximately 1153 stock and domestic bores in the Beetaloo GBA extended region and 343 in the Beetaloo GBA region (Department of Environment and Natural Resources (NT), 2019b). Fulton and Knapton (2015) estimated that in the Beetaloo Sub-basin 6000 ML of groundwater is extracted annually, presumably from the shallow CLA, with most of this used for stock watering. As cattle population data for the Beetaloo GBA region are not readily available, total livestock volume usage for the Beetaloo GBA region has not been estimated. Tickell and Bruwer (2017) estimated that about 13,000 ML/year of water is extracted for livestock purposes from Anthony Lagoon and Gum Ridge formations (part of CLA) in the Georgina Basin. The authorised purpose and number of bores for these licences are shown in Table 9 and their locations are shown in Figure 51.

3.5.2.3 Potential future groundwater sources for the petroleum industry

There are two potential groundwater sources to supply future demand for use in drilling and hydraulic fracturing operations for the unconventional petroleum industry: (i) unused consumptive allocations and (ii) treated formation and produced water.

Hydraulic fracturing of a well would require approximately 10 to 20 ML of water for ten-stage fracturing operations (Pepper et al., 2018). The *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018) has estimated that around 1000 to 1200 unconventional wells will be developed over the next 25 years, resulting in a demand of between 20,000 and 60,000 ML from the aquifer system.

Generally, when reservoir formations are accessed (by drilling a borehole) as part of extraction, water mixed with hydrocarbons (also known as 'produced water') is extracted along with the oil and gas. The *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018) reported that, in the Beetaloo Sub-basin, it is expected that produced water will be treated and that more than 30% of this water will be reused as a water source for hydraulic fracturing and drilling operations as needed. The total volume of produced water depends on the conventional and unconventional oil and gas development scenarios, for which there is a high degree of uncertainty.

In the Beetaloo GBA region, potential unconventional resource producers are likely to seek groundwater from various formations of the CLA during the initial development phase (Pepper et al., 2018). The CLA is used for supplying domestic water for several communities and towns, including Elliott, Newcastle Waters, Daly Waters, Mataranka, Katherine and Larrimah, and is also used for stock water usage for cattle in the Beetaloo GBA region. The consumptive water allocations of the existing WAPs within the Daly Roper Beetaloo Water Control District do not currently account for the volume of water that may be required to support the petroleum industry. However, water allocation under the consumptive pool for the existing WAP within the Daly Roper Beetaloo Water Control District is greater than the expected amount the conventional and unconventional petroleum industry will require, so water supply should not be a limiting factor to industry. The intentional discharge of produced water (wastewater) from shale gas, tight gas and shale oil activities into surface waters is prohibited in the NT and impacts from accidental discharge are discussed in Section 5.3.3. Future water supply demands for the petroleum industry need to be considered while developing the Draft Oolloo and Draft Tindall Mataranka – Daly Waters WAPs for the Daly Roper Beetaloo Water Control District to ensure long-term security of access for other water users and to maintain the flow of water to GDEs (Pepper et al., 2018).

While the CLA is the primary source of groundwater for Beetaloo GBA region, other sources are being considered. These include the Bukalara and Jamison sandstones, particularly in the region underlain by the western Beetaloo Sub-basin (see Section 3.1.1.2).

Table 9 Summary of licensed water allocations in the Beetaloo GBA region and Beetaloo extended GBA region

Authorised purpose	Number of licensed bores in Beetaloo GBA extended region	Total entitlement volume for Beetaloo GBA extended region (ML/y)	Number of licensed bores in Beetaloo GBA region	Total entitlement volume for Beetaloo GBA region (ML/y)
Agriculture	26	27,446	1	1,650
Industry	11	309	0	0
Public water supply	6	275	0	0
Stock and domestic[a]	Various bores[b]	2,108	Various bores[b]	540

[a]Volumes as reported in water allocation plans
[b]There are 1153 and 343 stock and domestic bores located within the Beetaloo GBA extended region and the Beetaloo GBA region, respectively; however, the actual number of bores used for extraction is unknown.
Data: Department of Environment and Natural Resources (2019b)

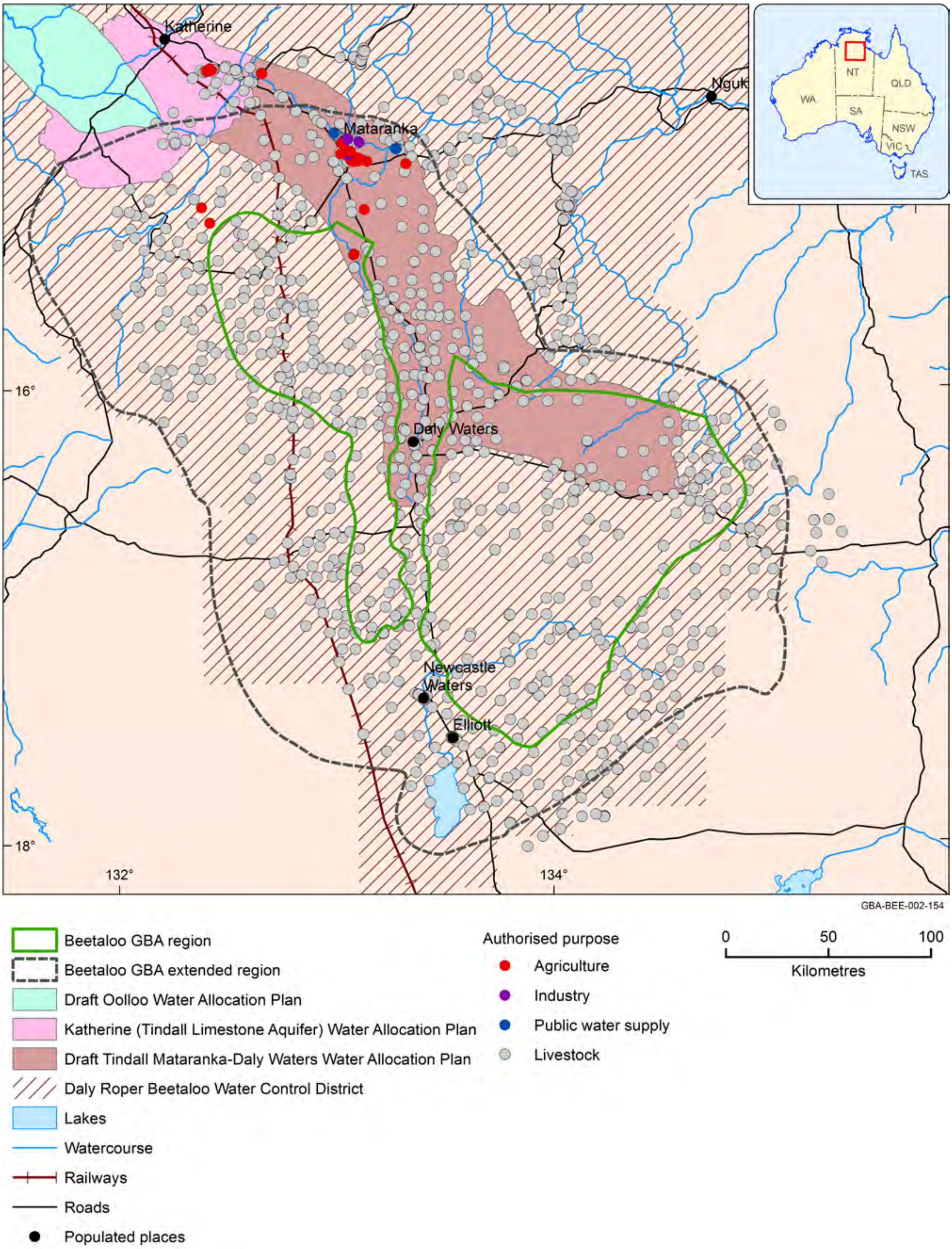

Figure 51 Groundwater management areas and identified purposes of bores in the Beetaloo GBA region

Data: Northern Territory Government (2019b); Geological and Bioregional Assessment Program (2019g)
Element: GBA-BEE-2-154

3.6 Knowledge gaps

3.6.1 Groundwater system conceptualisation

Key data and knowledge gaps identified and potential future work to improve regional hydrogeological conceptualisation of the Beetaloo GBA region are provided below.

3.6.1.1 Baseline data

The amount of available hydrogeological data varies greatly for different groundwater systems in the Beetaloo GBA region. There is also a corresponding variation in the level of understanding for the different groundwater systems. While there are still some significant knowledge gaps, the CLA is a relatively well-studied and understood groundwater system when compared with the limited hydrogeological information available for the deeper Proterozoic groundwater systems.

Identified data and knowledge gaps:

- A significant proportion of groundwater bores with water level and/or hydrochemistry data available have not been assigned to a hydrostratigraphic unit.
- There are limited baseline groundwater level and hydrochemistry data for all aquifers below the CLA – for example, the Bukalara Sandstone.
- There is a lack of fit-for-purpose groundwater data to assess and characterise groundwater flow in aquifers below the CLA.

Stage 3 work:

- Review existing groundwater bores and their screened aquifers to establish if there are any additional bores available for groundwater sampling in the Proterozoic units or Antrim Plateau Volcanics.
- Undertake hydrochemical sampling of selected bores screened in aquifers other than the CLA in the Beetaloo GBA region. Sampling should include environmental tracers as well as hydrochemical parameters to provide hydrochemical baseline and to better understand groundwater recharge mechanisms, groundwater age, flow paths and surface water interactions.
- Characterise groundwater flow paths and sources to Mataranka Thermal Pools using hydrochemistry and environmental tracers.

Future work:

- Review existing groundwater bores and their screened aquifers to establish if there are any additional bores available for groundwater sampling in the Proterozoic (only outside the Beetaloo GBA region) units and Antrim Plateau Volcanics.
- Undertake a systematic groundwater monitoring program for Proterozoic groundwater bores (only available outside the Beetaloo GBA region) and the CLA to help establish baseline conditions, including connectivity and seasonal dynamics.

- Consider drilling monitoring bores into Proterozoic rock aquifers such as Bukalara Sandstone or Jamison sandstone to better understand hydrogeological characteristics in the Beetaloo GBA region.
- Further study of pressure differences using nested monitoring wells would assist with understanding direction of vertical and horizontal groundwater flow and degree of connectivity between different hydrostratigraphic units that comprise the CLA, as well as the degree of connectivity with deeper aquifers (e.g. Bukalara Sandstone).
- As petroleum exploration continues, consideration should be given to including activities that improve understanding of the hydrogeology and geology of the Beetaloo region, above the Roper Group. Activities could include running suites of well logs and extending geological seismic interpretation to relatively shallow depths (e.g. CLA or Antrim Plateau Volcanics) or undertaking formation tests and collecting water samples from prospective deep aquifers, such as Jamison or Bukalara sandstones.

3.6.1.2 Intrabasin and interbasin groundwater connectivity

Identified data and knowledge gaps:

- There is a lack of detailed information on the thickness and structure of the Antrim Plateau Volcanics and Bukalara Sandstone and equivalents in Beetaloo GBA region.
- Thickness and hydraulic properties of Carpentaria Basin units are needed to better understand recharge to the CLA.
- There is poor understanding of the distribution of near-surface karst in the CLA and its role in preferential flow.
- There is limited understanding of structural and stratigraphic connectivity between the Roper Group and overlying aquifers.

Stage 3 work:

- Identify areas where sinkholes are likely to be present near surface (consult with industry where appropriate) and occurrence of preferential recharge in Beetaloo GBA region.
- Indicate thickness of cover (i.e. Carpentaria Basin above the CLA) across the Beetaloo GBA region, including identification of major lithological packages (e.g. the sandstone near the base of the Carpentaria).
- Carry out sampling and environmental tracer studies to investigate groundwater flow patterns both within and between aquifer systems and to identify flow paths.

Suggested future work:

- Update the regional structural and stratigraphic framework using geophysical data such as seismic surveys and ground-calibrated aerial electromagnetic induction.
- Refine the stratigraphy of the Carpentaria Basin in the Beetaloo GBA region by surface mapping, lithological logs and downhole geophysics. Consider drilling monitoring bores targeted into Carpentaria Basin aquifers to better establish hydrogeological characteristics.
- Conduct groundwater sampling and environmental tracer studies to investigate groundwater flow patterns both within and between aquifer systems and to identify flow paths.

- Undertake future work activities as outlined under 'Baseline data' in Section 3.6.1.

3.6.2 Surface water system conceptualisation

The monitoring of the surface water quantity and quality is adequate in the areas of the Roper and Daly river catchments, where there are significant existing users of the water resource. In these areas, the water allocation plan requires this ongoing monitoring. Outside of these areas significant data gaps exist. The *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018) recommended that surface water should not be used as a source of water for drilling and hydraulic fracturing and that wastewater (treated or untreated) should not be disposed of in watercourses. Because these recommendations have now been legislated, there will be little emphasis on improving the surface water conceptualisation as it relates to surface water extraction in Stage3.

3.6.3 Surface water – groundwater conceptualisation

Groundwater discharge to the Mataranka Thermal Pools and nearby streams underpin dry-season flows in the Roper River. This water is sourced from the CLA, but it is not known if there is a minor component from deeper sources. A field study will be conducted in Stage 3 to investigate the potential of any deeper water sources discharging at Mataranka and whether this potential causal pathway presents a greater risk to Mataranka Hot Springs from the development of petroleum resources.

The source of many of the groundwater springs located near the Beetaloo GBA region and associated with outcrop of Proterozoic rocks, such as Beauty Creek springs, remains largely speculative. Future work post Stage 3 could include sampling spring waters for hydrochemical and environmental tracers. These would help identify source aquifers and possible flow paths.

3.6.4 Potential hydrological connections

From the analysis of existing datasets and an integrated assessment of the structural geology and hydrogeological characterisation of the extended Beetaloo GBA region, a set of knowledge and data gaps were identified. Further investigations required to test potential impact pathways from stressors to the assets are summarised in Table 10.

While a number of separate possible flow paths are described, combinations of these flow paths could result in a diffuse connectivity network across hydrogeological sequences. The potential for cumulative impact along multiple flowpaths will be further assessed in Stage.

Table 10 Summary of identified connectivity pathways and potentially impacted assets, supporting evidence based on current data/knowledge, data gaps and recommended future activities

Potential hydrological connections	Potential impacts on water and the environment	Evidence base	Questions	Recommended investigations
① **Direct stratgraphic contact** Potential connection via direct stratigraphic contact between shale and tight gas plays in the Roper Group and adjacent aquifers Jamison sandstone (JS), Bukalara Sandstone, Antrim Plateau Volcanics or the Cambrian Limestone Aquifer (CLA).	Water bores that access Antrim Plateau Volcanics, the CLA and the shallower groundwater systems associated with Carpentaria Basin (CB) and Cenozoic deposits, surface water bodies (including Lake Woods), waterholes (e.g. Grainger Hole, Mungabroom and Chowyung Waterholes), GDEs and springs	Extended zones of direct stratigraphic contact between stressors and the potential assets (aquifers) are identified in cross-sections through both sub-basins (Figure 47, Figure 48, Figure 49) Dissolved methane in groundwater samples from the Antrim Plateau Volcanics and CLA in areas of possible direct contact with underlying Kyalla Formation may confirm the possible connectivity between the hydrocarbon bearing gas play unit and overlying aquifer assets	What is the travel distance and travel time for water and/or gas to migrate from the shale and tight gas reservoirs in the Roper Group into the adjacent/overlying aquifers? Is there evidence of upward hydraulic gradients that would facilitate/drive such processes? Do faults intersecting gas plays in the Roper Group, influence connectivity with adjacent or overlying aquifers that are in direct contact with the reservoir formations?	**Stage 3** • Simple groundwater models to estimate travel times for scenario from the Roper Group through to overlying aquifers. • Collect hydraulic data from both unconventional gas plays and overlying aquifers along the zone of greater connectivity potential (aquitard windows and thinner intervals) to rule out the hypothesis of upward hydraulic gradient • Update regional structural and stratigraphic framework, through additional seismic interpretation • Hydrochemical and isotopic fingerprinting of groundwater and dissolved gases at representative bores in different hydrostratigraphic units (subject to bore availability) for inter-aquifer/ reservoir-aquifer connectivity assessment, including helium, methane, and tracers such as $^{87}Sr/^{86}Sr$ **Future** • Collate and assess borehole image logs from exploration wells to analyse in-situ stress orientations • An assessment using existing water bores located near to each other that target different formations of interest (a proxy for nested wells) could be a first attempt for this hydrochemical and isotopic characterisation • Update the Beetaloo GBA geological model to incorporate faults, to determine areas where aquifers are displaced against aquitards

Potential hydrological connections	Potential impacts on water and the environment	Evidence base	Questions	Recommended investigations
② **Faults** Potential connection through deep-seated faults striking shale gas reservoirs in the Velkerri and Kyalla formations and adjacent /overlying aquifers	Antrim Plateau Volcanics, CLA aquifer, springs and associated surface water bodies	Aquifer source of springs located approximately 10 km east from the Eastern Beetaloo Sub-basin (i.e. Lagoon Creek and Beauty Creek Springs) are inferred to be potentially linked to the Roper Group due to their position near rock outcrops from the Collara Subgroup and Maiwok Subgroup, evidenced by spring water temperature Hydrocarbon shows are reported to occur in the Neoproterozoic units (Jamison sandstone, Hayfield mudstone and Bukalara Sandstone), indicating previous hydrocarbon migration pathways from the underlying source rocks that may act as pathways to assets closer to the surface Hydrochemical clusters spatial distribution are correlated to the location of geological structures, corroborated by dissolved gas in groundwater	What is the likelihood for vertical fluid or gas migration through deep-seated faults from unconventional gas plays to overlying aquifers and near-surface assets? How likely is it that the gas plays are directly connected to the near-surface environmental assets via the mapped/inferred faults considering the proximity between stressors and assets near the Beetaloo GBA region' margins?	**Stage 3** • Simple groundwater models to estimate travel times for scenario from the Roper Group through to overlying aquifers • Update regional structural and stratigraphic framework, through additional seismic interpretation • Hydrochemical and isotopic fingerprinting of groundwater and dissolved gases at representative bores in different hydrostratigraphic units for inter-aquifer connectivity assessment and surface water – groundwater interactions, including helium, methane and tracers such as $^{87}Sr/^{86}Sr$ • Carry out a sampling campaign to constrain the sources of springs located in proximity to mapped faults with a focus on tracers to detect contribution from deeper hydrogeological units (e.g. Helium) • Conduct a synoptic surface water chemistry and tracer survey along Roper River, which exhibits perennial flows to assess surface water – groundwater interactions and alluvium and bedrock connectivity **Future** • Shallow geophysical survey (e.g. time domain electromagnetic (TEM)) to locate and characterise structural elements in the top 100 m near sensitive environmental assets
③ **Aquifers** Potential connection through the porous aquifers of Moroak Sandstone, Jamison sandstone, UN, CB and alluvium and karstic systems of CLA (GRF+ALF)	Water bores that access these aquifers and potentially associated springs	Groundwater flow is confirmed to occur in the CLA system (Figure 16 in Evans et al. (2020) with northward direction	Can this act as a potential hydrological connection between two sub-vertical fault systems?	
④ **Partial aquitards** Migration through aquitards into the CLA and basal sandstone zones of Carpentaria Basin (CB)	Water bores in the aquifer systems Undifferentiated Neoproterozoic (UN e.g. Bukalara Sandstone), CLA and saturated sandstone found in the base of CB	Hydraulic heads measurements in the Moroak Sandstone indicate enough potential to lift water above the top of the Proterozoic. In addition, the higher hydraulic permeability in Moroak Sandstone is inferred to occur near geological structures. The presence of oil shows in the Bukalara Sandstone suggest the occurrence of pathways connected to underlying source rocks	Is there evidence to confirm that fluids or gases migrate vertically and horizontally through the Hayfield mudstone aquitard due to the influence of geological structures?	
⑤ **Groundwater discharge** Migration through the karstic CLA aquifer into springs and associated surface water bodies	Springs that source water from CLA aquifer, including associated surface water bodies and groundwater-dependent ecosystems Users of groundwater from the CLA.	Hydrological connections inferred from subsurface geometry as shown in cross-section C-C' in Figure 44 in Evans et al. (2020) Discharges from CLA aquifer to Mataranka Thermal Pools Sinkholes are known areas of localised recharge where CLA outcrops to the north of the Beetaloo GBA region	Is there sufficient evidence (hydrochemical and environmental tracers) data to confirm connectivity between the CLA system and Mataranka Thermal Pools? What are relative source contributions from different parts of CLA to the Mataranka Thermal Pools? Where are preferential recharge pathways to CLA likely to occur?	**Stage 3** • Carry out a sampling campaign to constrain the aquifer sources and groundwater flow to the Mataranka Thermal Pools • Identify areas where sinkholes are likely to be present near surface in Beetaloo GBA region • Indicate thickness of cover (i.e. Carpentaria Basin above the Cambrian Limestone Aquifer) across the Beetaloo GBA region • Assessment of spill and contaminate transport

ALF = Anthony Lagoon Formation and equivalents (upper CLA); CB = Carpentaria Basin; CLA = Cambrian Limestone Aquifers; GDE = groundwater-dependent ecosystem; GRF = Gum Ridge Formation and equivalents (lower CLA); UN = undifferentiated Proterozoic;

3.6.5 Potential water sources for drilling and hydraulic fracturing

Potential water sources for a future unconventional petroleum industry in the Beetaloo GBA region are unlikely to include surface water, as the NT Government is in the process of prohibiting extraction of surface water for petroleum activities.

Groundwater and produced water extracted during conventional oil and gas development are both potential water sources for a future shale gas, tight gas and shale oil industry in the Beetaloo GBA region. The CLA is the primary source of groundwater for Beetaloo GBA region. Other sources being considered – in particular, in the region underlain by the western Beetaloo Sub-basin – are the Bukalara and Jamison sandstones (see Section 3.1.1.2).

Allocation under the consumptive pool for the existing water allocation plans within the Daly Roper Beetaloo Water Control District do not currently consider the potential magnitude of water that may be taken by the petroleum industry or its potential implications on other water users.

4 Protected matters

The environmental and cultural baseline syntheses identified Matters of National Environmental Significance (MNES) and Matters of Territory Environmental Significance (protected matters) that may potentially be impacted by resource development. Species that are known to occur or potentially occur in the region were identified. Most species were identified as 'likely to occur' or 'may occur' rather than 'known to occur' within the Beetaloo GBA region. Key threatening processes listed under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act) that are relevant to the region were also identified. The key ecological and hydrological systems are conceptualised into landscape classes to underpin the assessment of potential hydrological and other environmental impacts due to shale gas, tight gas and shale oil development in Stage 3.

Throughout this section, the number of matters (usually species) for a given category is presented separately for the Beetaloo GBA region and for the Beetaloo GBA extended region. The reason for this is that at this stage it is unclear whether impacted areas will be restricted to the Beetaloo GBA region. Furthermore, the Beetaloo GBA extended region is also included to understand what additional matters may be of concern should impacts occur adjacent to the Beetaloo GBA region.

MNES that occur, or potentially occur, in the Beetaloo GBA region comprise 14 threatened species, 13 migratory species and one species that is both threatened and migratory. Within the Beetaloo GBA extended region there is potentially one threatened ecological community, 15 threatened species, 15 migratory species and two species that are both threatened and migratory. Other protected matters in the Beetaloo GBA extended region comprise 23 listed marine species and five areas of Commonwealth lands. Within the Beetaloo GBA region there are 21 listed marine species but no areas of Commonwealth lands.

Among Matters of Territory Environmental Significance, one territory reserve – Bullwaddy Conservation Reserve – occurs entirely within the Beetaloo GBA region. A further four reserves are outside the Beetaloo GBA region but have 100% of their area within the Beetaloo GBA extended region. Also included among territory matters of environmental significance are two nationally important wetlands: Mataranka Thermal Pools and Lake Woods. These occur in the Beetaloo GBA extended region. Four species that are classified as threatened in the NT (but not nationally) have been recorded in the Beetaloo GBA region since 1990 and are considered likely to still occur there.

Among groundwater-dependent ecosystems (GDEs), springs do not occur within the Beetaloo GBA region but are present within the Beetaloo GBA extended region to the north–north-east and east as discharge complexes from the major northward flowing groundwater systems of the Cambrian Limestone Aquifer (CLA). The springs at Mataranka Thermal Pools sustain dry-season flows in the Roper River system and support terrestrial and wetland GDEs. Connectivity between surface water and groundwater is limited within the Beetaloo GBA region because of the depth to groundwater (typically >40 m). Terrestrial GDEs are mostly limited to shallow perched aquifer systems that are fed by groundwater.

Key threatening processes identified as operating in the Beetaloo GBA region include competition and land degradation by rabbits and unmanaged goats, predation by European red fox and feral cats, predation, habitat degradation, competition and disease transmission by feral pigs, novel biota and their impact on biodiversity (e.g. feral horses, donkeys and camels) and biological effects, including lethal toxic ingestion, caused by cane toads.

No socio-economic or cultural assets were identified from searches of the EPBC Act on protected matters.

Six landscape classes were classified for the Beetaloo GBA region. The landscape is dominated by loamy and sandy plains, and clay plains. There are also substantial areas of floodplain and alluvium, and undulating country on fine-grained sedimentary rocks.

4.1 *Environmental baseline synthesis*

4.1.1 Matters of National Environmental Significance

MNES within the Beetaloo GBA region, based on a protected matters search in September 2019, are 14 threatened species and 13 migratory species as well as one species that is both threatened and migratory. No other MNES were identified for the Beetaloo GBA region. A summary of each species' biology, distribution and habitat is in Table 11.

MNES identified as potentially occurring in the Beetaloo GBA extended region, based on a protected matters search in September 2019, are one threatened ecological community, 15 threatened species, 15 migratory species and two species that are both threatened and migratory. The threatened and migratory species included all the species identified as MNES in the Beetaloo GBA region plus four additional species: oriental reed-warbler (*Acrocephalus orientalis*), princess parrot (*Polytelis alexandrae*), freshwater sawfish (*Pristis pristis*) and common greenshank (*Tringa nebularia*). A summary of each species' biology, distribution and habitat is in Table 11.

A prioritisation process for MNES as well as other matters protected by the EPBC Act and territory matters of environmental significance is detailed in Section 4 of the protected matters technical appendix (Pavey et al., 2020). The section includes a list of environmental matters that are considered at risk of being impacted by development of shale and other unconventional resources in the Beetaloo GBA region. These matters will be assessed in more detail in Stage 3.

4.1.1.1 Nationally listed threatened species and threatened ecological communities

There are 15 species in the Beetaloo GBA region that are nationally listed as 'threatened' (being critically endangered, endangered or vulnerable). These include eight birds, five mammals and two reptiles. No fish, frogs, invertebrates or plants listed as threatened under the EPBC Act are currently known to occur, or are likely to occur, in the Beetaloo GBA region.

Seventeen species are listed as threatened in the Beetaloo GBA extended region. The total consists of nine birds, five mammals, two reptiles and one freshwater fish. No frogs, invertebrates or plants listed as threatened under the EPBC Act are currently known to occur, or are likely to occur, in the region. The threatened species included all the species identified in the Beetaloo GBA region plus the princess parrot (*Polytelis alexandrae*) and freshwater sawfish (*Pristis pristis*).

The threatened ecological community that potentially occurs within the Beetaloo GBA extended region is the Arnhem Plateau sandstone shrubland complex. This community is situated to the north-east of the Beetaloo GBA region on the Arnhem Plateau (within Djelk and Warddeken Indigenous Protected Areas) and on sandstone outliers at Ubirr, Nawurlandja and Burrunggui in Kakadu National Park and the Marawal Plateau in Nitmiluk National Park. The threatened ecological community has not been recorded in the Beetaloo GBA region. The community may be present in the north-east portion of the Beetaloo GBA extended region, but this has not been confirmed. If it is present, the community will be at the extreme southern edge of its range and is likely to be small in extent.

Details of each of the 17 threatened species are provided in the protected matters technical appendix (Pavey et al., 2020). The protected matters technical appendix provides an overview of the ecology, distribution and status of each species, followed by an assessment of its water dependency and a comment on the hazards associated with shale gas, tight gas and shale oil development that may impact the conservation status of the taxon. A preliminary assessment of the likelihood of the species being impacted by development within the Beetaloo GBA region is also provided.

4.1.1.2 Nationally listed migratory species

Fourteen species are listed as migratory under the EPBC Act and potentially occur in the Beetaloo GBA region. This includes one species – curlew sandpiper (*Calidris ferruginea*) – that is also listed as threatened. The remaining 13 species are not listed as threatened.

Seventeen species are listed as migratory under the EPBC Act and potentially occur in the Beetaloo GBA extended region. This includes two species – curlew sandpiper (*Calidris ferruginea*) and freshwater sawfish (*Pristis pristis*) – that are also listed as threatened. The remaining 15 species are not listed as threatened.

Migratory species are those that are protected under bilateral international agreements. The list of migratory species under the EPBC Act is assembled from four bilateral agreements. These agreements are:

- China–Australia Migratory Bird Agreement (CAMBA)
- Japan–Australia Migratory Bird Agreement (JAMBA)
- Republic of Korea – Australia Migratory Bird Agreement (ROKAMBA)
- Bonn Convention (Convention on Conservation of Migratory Species of Wild Animals).

The classification of the global conservation status of each of the 15 migratory species (IUCN, 2019), which are not classified as threatened in Australia under the EPBC Act, is given in Table 11. Many of these species have both a large global population size and a large population size in Australia. Each of the 15 species has an IUCN global concern status of ‘least concern’ – this is the status with the lowest level of concern in the IUCN classification system.

Table 11 Species classified as Matters of National Environment Significance under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) that protected matters searches have identified as occurring, or potentially occurring, in the Beetaloo GBA extended region together with a summary of biology, distribution and habitat

For those species that are migratory, but not threatened, information is also provided on IUCN global conservation status and global population trend. The fourth column indicates whether protected matters searches have identified the species as occurring, or potentially occurring, in the Beetaloo GBA region (if so, then listed as 'yes') or whether it is restricted to the Beetaloo GBA extended region (listed as 'no').

Status	Scientific name	Common name	Present in GBA region	Biology, distribution and habitat
Critically endangered	*Calidris ferruginea*[a, b]	Curlew sandpiper	Yes	Migratory shorebird. Breeds mainly in Siberian Arctic. Non-breeding migrant during Austral summer to Africa, Asia and Australasia. Large numbers visit Australia mostly on intertidal mudflats in sheltered coastal areas (estuaries, bays, inlets, lagoons). Less common inland on lakes, dams and bore drains. Global population estimate between 1.085 and 1.285 million birds. Numbers declining globally.
Endangered	*Dasyurus hallucatus*	Northern quoll	Yes	Carnivorous marsupial. Nocturnal. Endemic to northern Australia (eastern Queensland, Top End of NT to Kimberley and Pilbara in WA). Occupies savanna woodland and patches of rainforest and favours rocky escarpments. Numbers declining.
	Elseya lavarackorum	Gulf snapping turtle	Yes	Freshwater turtle. Endemic to northern Australia. Limited range covering upper and middle reaches of the Nicholson and Gregory rivers in north-west Queensland / north-east NT and upper reaches of Calvert River, NT. Occurs in deep water pools of permanent spring-fed rivers. Numbers stable. Not considered threatened in the NT (listed as near threatened).
	Erythrura gouldiae	Gouldian finch	Yes	Passerine bird. Endemic to northern Australia from inland north Queensland across Top End of NT to Kimberley in WA. Occupies open woodland close to water; it feeds on seeding grasses and nests in hollows in eucalypts. Mounting evidence that numbers are recovering and that status should be downgraded (Garnett et al., 2011).
	Pezoporus occidentalis	Night parrot	Yes	Parrot. Nocturnal, terrestrial. Endemic to arid zone; records in south-west Queensland, north-east SA and northern WA. Occupies mature spinifex grassland feeding on short-lived herbs and grasses. Trends in abundance unknown.
	Rostratula australis[c]	Australian painted snipe	Yes	Resident shorebird. Endemic to Australia. Occupies shallow freshwater wetlands. Recorded across mainland but its area of occupancy is comparatively small, estimated at about 2000 km^2. Numbers appear to be stable.

Status	Scientific name	Common name	Present in GBA region	Biology, distribution and habitat
Vulnerable	*Acanthophis hawkei*	Plains death adder	Yes	Venomous snake. Endemic to northern Australia from north-east of WA across Top End and Barkly Tableland of NT–Queensland border and Mitchell Grass Downs in south-west Queensland. Occupies floodplains with cracking clay soils. Numbers may be declining due to consumption of cane toads.
	Erythrotriorchis radiates	Red goshawk	Yes	Bird of prey. Endemic to Australia with patchy range across coastal and interior regions of Queensland, NT and north-east of WA and north-east NSW. Occurs in open forest and woodland and along rainforest edges. Numbers appear to be stable.
	Falcunculus frontatus whitei	Crested shrike-tit (northern)	Yes	Passerine bird. Occurs in northern Australia across Top End of NT to Kimberley in WA. Populations fragmented. Forages for invertebrates on trees within woodland. Numbers stable. Not considered threatened in the NT (listed as near threatened).
	Grantiella picta	Painted honeyeater	Yes	Passerine bird. Specialised on fruit of mistletoes. Wide distribution across eastern Australia extending to the tropics in north-west Queensland and north-east NT. Exhibits seasonal movement in response to food availability. Occupies acacia-dominated woodlands, preferring those with mature trees. Numbers appear to be stable.
	Macroderma gigas	Ghost bat	Yes	Bat (largest insectivorous bat in Australia with body mass up to 165 g). Endemic to tropical northern Australia from Rockhampton, central Queensland across Top End of NT to Kimberley and Pilbara in WA. Daytime roosts in caves and disused mines, forages in woodland. Recent declines in numbers. Listed as threatened in 2016.
	Macrotis lagotis	Greater bilby	Yes	Ground-dwelling marsupial. Nocturnal. Endemic to arid Australia in south-western Queensland and across western deserts of NT and WA. Occurs in variety of habitats favouring spinifex sandplains and paleodrainage areas in NT. Numbers appear to be stable, although they fluctuate naturally as resources fluctuate.
	Phascogale pirate	Northern brush-tailed phascogale	Yes	Carnivorous marsupial. Nocturnal. Endemic to Top End of NT. Occurs mostly in tall open forest dominated by eucalypts. Little is known about this species. Numbers may be declining.

Status	Scientific name	Common name	Present in GBA region	Biology, distribution and habitat
	Polytelis alexandrae	Princess parrot	No	Parrot. Endemic to the western arid zone of Australia occurring in north-west SA and across the western deserts of NT and WA. Forages on flowers, seeds and other plant material on spinifex sandplains and woodlands and nests in hollows of large trees. Exhibits nomadic movements in response to pulses in primary productivity. Numbers appear to be stable.
	Pristis pristis[a]	Freshwater sawfish	No	Freshwater fish (largest freshwater fish in Australia, reaching maximum body length of 5.82 m). Occupies river (up to 400 km inland) and estuarine environments and up to 100 km offshore in northern and western Australia as well as in North America, South America, Africa, Asia and New Guinea. In Australian rivers during the dry season, habitat is a series of isolated waterholes. Numbers appear to be declining.
	Saccolaimus saccolaimus nudicluniatus	Bare-rumped sheath-tailed bat	Yes	Insectivorous bat. Occurs in northern Australia (Townsville to Iron Range in Queensland and Top End of NT) and in New Guinea, Timor, Indonesia and elsewhere in south-east Asia. Forages in open space above woodland and roosts during day in colonies of up to 100 bats in tree hollows. Recent status change from critically endangered because of new information on distribution.
	Tyto novaehollandiae Kimberli	Masked owl (northern)	Yes	Owl. Occurs across northern Australia from the coast of north Queensland across Top End to Kimberley in WA. Forages in tall open eucalypt forest and along margins of agricultural fields. Nests and roosts in hollows in large trees within forest patches. Numbers appear to be stable.
Migratory	*Acrocephalus orientalis*[b]	Oriental reed-warbler	No	Passerine bird. Breeds in Russia, Mongolia and northern Asia. Non-breeding migrant to equatorial areas during the Austral summer. Very rare vagrant in Australia. IUCN global status is least concern; however, numbers may be decreasing.
	Actitis hypoleucos[b]	Common sandpiper	Yes	Shorebird. Global population estimated at 2.6 to 3.2 million birds. Breeds in Europe and Asia. Non-breeding migrant in Austral summer in large numbers along all coastlines and in many inland areas of Australia. Mapped extent of potential habitat covers entire Australian continent. IUCN global status is least concern; however, numbers may be decreasing.

Status	Scientific name	Common name	Present in GBA region	Biology, distribution and habitat
	Apus pacificus[b]	Fork-tailed swift	Yes	Swift. Breeds in south-east China and adjacent countries. Non-breeding migrant in Austral summer across Australia. Mapped extent of potential habitat covers most of Australia. IUCN global status is least concern and numbers are stable.
	Calidris acuminata[b]	Sharp-tailed sandpiper	Yes	Shorebird. Breeds in northern Siberia. Non-breeding migrant in Austral summer in large numbers along all coastlines and in inland areas of Australia. Population estimated at up to 140,000 birds (global population estimate is >160,000 birds). Mapped extent of potential habitat covers entire continent. IUCN global status is least concern and numbers are stable.
	Calidris melanotos[b]	Pectoral sandpiper	Yes	Shorebird. Breeds in northern Russia and North America. Non-breeding migrant in Austral summer in low numbers along coastlines and inland areas of Australia. Global population estimate is 25,000 to 100,000 birds. Mapped extent of potential habitat covers entire continent. IUCN global status is least concern and numbers are stable.
	Cecropis daurica[b]	Red-rumped swallow	Yes	Passerine bird. Widespread and abundant (global population estimate of between 10 and 50 million). Breeds in Russia, Mongolia, western Asia, northern Africa, Middle East and southern Europe. Non-breeding migrant to the tropics in the Austral summer. A vagrant in Australia, with less than ten birds typically present in any given year. IUCN global status is least concern and numbers are stable.
	Charadrius veredus[b]	Oriental plover	Yes	Shorebird. Breeds in Mongolia and adjacent Russia. Approximately 90% of global population migrates to Australia in Austral summer occupying coastal and inland areas. Non-breeding in Australia. There were 144,000 birds at Eighty Mile Beach, WA, in February 2010. Occupies a wide range of marine, freshwater and terrestrial habitats. IUCN global status is least concern. The population trend is unclear.

Status	Scientific name	Common name	Present in GBA region	Biology, distribution and habitat
	Crocodylus porosus[b]	Saltwater crocodile	Yes	Aquatic reptile. Occurs in Bangladesh, Brunei, Cambodia, India, Sri Lanka, Malaysia, Myanmar, Papua New Guinea, Philippines, Solomon Islands, Vanuatu, Vietnam, Timor and Indonesia. Occupies inland lakes, swamps and marshes and coastal brackish waters and tidal sections of rivers. In Australia occupies rivers and estuarine areas from Kimberley across northern Australia to southern coastal Queensland. IUCN global status is least concern, with numbers increasing.
	Cuculus optatus	Oriental cuckoo	Yes	Cuckoo. Large global distribution, including breeding range across the Palearctic region. Non-breeding migrant to the Top End of NT and eastern Australia in the Austral summer. Global population is estimated at between 5 and 15 million birds. IUCN global status is least concern and numbers are stable.
	Glareola maldivarum[b]	Oriental pratincole	Yes	Shorebird. Breeds in eastern China and Russia and parts of south-east Asia. Non-breeding migrant in Austral summer, mainly in the north of WA and across Top End of NT to north-west Queensland. Occupies a wide range of marine, freshwater and grassland habitats. IUCN global status is least concern; however, numbers may be decreasing.
	Hirundo rustica[b]	Barn swallow	Yes	Passerine bird. One of the world's most widespread birds (global population estimate between 290 and 500 million birds) occurring across all continents except Antarctica. Rare summer visitor across north of Australia. IUCN global status is least concern. The population trend is unclear.
	Motacilla cinerea [b]	Grey wagtail	Yes	Passerine bird. Widespread in the Northern Hemisphere and tropics, with some populations breeding in Europe and Asia then migrating to tropical Africa and Asia. Global population estimate of 6.9 to 19.8 million birds. A non-breeding vagrant in Australia. Occupies riverine areas. IUCN global status is least concern and numbers are stable.
	Motacilla flava[b]	Yellow wagtail	Yes	Passerine bird. Extremely large range from Europe to Siberia to west Asia and China south to Egypt. Global population estimate of 64 to 107 million birds. A non-breeding vagrant in Australia. Occupies terrestrial and freshwater habitat. IUCN global status is least concern. The population trend is unclear.

Status	Scientific name	Common name	Present in GBA region	Biology, distribution and habitat
	Pandion haliaetus[b]	Osprey	Yes	Bird of prey. Occurs in all continents except Antarctica. Breeding resident along the entire coast of mainland Australia (but not Tasmania). The global population is between 100,000 and 499,999 birds and is increasing. IUCN global status is least concern and numbers are increasing.
	Tringa nebularia[b]	Common greenshank	No	Shorebird. Breeds in Scandinavia and across Russia. Non-breeding migrant in Austral summer in small numbers along most coastlines and in many inland areas of Australia. Australian population estimated at 18,000 to 19,000 birds (global population estimate of 440,000 to 1.5 million). Occupies a range of wetland types. IUCN global status is least concern with numbers stable.

[a]Also listed as migratory
[b]Also listed as marine
[c]Listed as marine under the name *Rostratula benghalensis*

4.1.2 Other matters protected under the Environment Protection and Biodiversity Conservation Act

The EPBC Act protected matters search identified 23 listed marine species as occurring or potentially occurring in the Beetaloo GBA extended region. Twenty-one of these listed marine species were identified for the Beetaloo GBA region. In addition, the Beetaloo GBA extended region hosts five areas of Commonwealth lands.

4.1.2.1 Listed marine species

Listed marine species are those that occur in Commonwealth marine areas. Twenty-three listed marine species were identified as occurring or potentially occurring in the Beetaloo GBA extended region. Of the 23 species, 16 species have already been identified as MNES (Table 11). The curlew sandpiper (*Calidris ferruginea*) is threatened and migratory, the painted snipe (*Rostratula benghalensis*) is threatened (although listed as the Australian painted snipe – see Table 11) and 14 other species are migratory (all migratory species in Table 11 except the oriental cuckoo (*Cuculus optatus*). Only seven of the species that are listed marine species are not migratory or threatened or both (i.e. they are not MNES).

A brief profile of each of these seven listed marine species is given in Table 12, together with information on each species' biology, distribution, habitat, IUCN global conservation status and global population trend. Each species occurs in the Beetaloo GBA region and has an IUCN global concern status of 'least concern' – the status with the lowest level of concern in the IUCN classification system.

4.1.2.2 Commonwealth lands

Five areas of Commonwealth land are located within the Beetaloo GBA extended region but outside of the Beetaloo GBA region. These areas are not managed for conservation; four locations are managed by the Department of Defence for defence purposes. These assets are the Delamere Weapons Range, Willeroo Station Radar Site, Killarney Station Radar Site and an un-named site adjacent to the Delamere Weapons Range. These four sites are in the extreme north-west portion of the Beetaloo GBA extended region. The final area is an un-named property within the town of Elliott. Because of the location of these areas, none are considered to be at risk from the development of a shale gas industry.

Table 12 Listed marine species classified as other matters protected under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) that occur, or potentially occur, in the Beetaloo GBA region and extended region together with a summary of biology, distribution, habitat, IUCN global conservation status and global population trend

Species that are also Matters of National Environmental Significance are not covered in this list.
Information is sourced from IUCN (2019). Refer to Table 11 for a list of threatened species and migratory species.

Scientific name	Common name	Biology, distribution, habitat and IUCN status
Anseranas semipalmata	Magpie goose	Waterbird. Occurs in Australia and southern regions of the island of New Guinea. Nomadic, congregating in large numbers in wetlands or wet grasslands. In Australia occurs from Kimberley, WA across the Top End of NT down east coast to northern NSW. Also recorded from southern Victoria and SA. Populations appear to be stable and IUCN conservation status is least concern.
Ardea alba	Great egret	Waterbird. Massive global distribution, including North America, South America, Africa, Asia and Europe. Global population estimated at 41.5 to 69.9 million birds. Occupies wide range of inland and coastal wetlands. Mapped extent of potential habitat covers entire Australian continent. IUCN conservation status is least concern.
Ardea ibis	Cattle egret	Waterbird. Massive global distribution, including North America, South America, Africa, Asia and Europe. Global population estimated at 4 to 9.85 million birds. Occupies open grassy areas and some wetlands. Mapped extent of potential habitat covers most of Australian continent. Populations appear to be increasing and IUCN conservation status is least concern.
Chrysococcyx osculans	Black-eared cuckoo	Cuckoo. Breeding resident in Australia, southern regions of the island of New Guinea and in Timor and Indonesian islands. Occupies woodland and shrubland, mostly in inland Australia, although mapped extent of potential habitat covers most of Australian continent. Populations appear to be stable and IUCN conservation status is least concern.
Haliaeetus leucogaster	White-bellied sea-eagle	Bird of prey. Range includes coastal India, Sri Lanka, south-east Asia, Philippines, Indonesia and Papua New Guinea. In Australia, occurs along coasts and extends inland along some of the larger rivers. Australian population size estimated at >500 pairs. Populations appear to be decreasing but IUCN conservation status is least concern.
Merops ornatus	Rainbow bee-eater	Bee-eater. Outside Australia occurs in Indonesia, Timor-Leste, Papua New Guinea and Solomon Islands. The population is estimated to be at least 1 million birds. Mapped extent of potential habitat covers entire Australian continent. Populations appear to be stable and IUCN conservation status is least concern.

Scientific name	Common name	Biology, distribution, habitat and IUCN status
Crocodylus johntsoni	Freshwater crocodile	Aquatic reptile. Endemic to northern Australia, where it occurs in the Kimberley region of WA across the Top End of the NT across northern Queensland. It occupies freshwater wetlands. Populations appear to be stable and IUCN conservation status is least concern.

4.1.3 Matters of Territory Environmental Significance

Three categories of important environmental assets listed under NT legislation or otherwise regarded as being of territory-level environmental significance occur in the Beetaloo GBA extended region: nationally important wetlands, territory reserves and territory-listed threatened species. A single territory reserve occurs within the Beetaloo GBA region.

4.1.3.1 Nationally important wetlands

Two wetlands that occur in the Beetaloo GBA extended region are listed as nationally important wetlands (Department of the Environment and Energy, 2010): Lake Woods and Mataranka Thermal Pools.

Lake Woods is a temporary freshwater wetland located south of the Beetaloo GBA region. It typically occupies an area of 350 km^2 but has expanded up to 850 km^2 during major floods (1993, 2001). When inundated the Lake Woods system consists of a diversity of wetland environments, including open water and large areas of lignum (*Duma florulenta*) swamp, and holds over 100,000 waterbirds.

Mataranka Thermal Pools is a series of perennial spring wetlands fed by groundwater in the upper Roper River system. The area has ten species of plants endemic to the NT. It lies 40 km to the north of the boundary of the Beetaloo GBA region.

4.1.3.2 State and territory reserves

One territory reserve, Bullwaddy Conservation Reserve, occurs entirely within the Beetaloo GBA region (Table 13). A further four reserves are outside the Beetaloo GBA region but have 100% of their area within the Beetaloo GBA extended region (Table 13). Three of these reserves protect the nationally important wetlands outlined in Section 4.1.3.1.

Table 13 Reserves located in the Beetaloo GBA region and the Beetaloo GBA extended region listed under the *Territory Parks and Wildlife Conservation Act* (NT), together with a summary of key attributes

Location	Name of reserve	Details
Beetaloo GBA region	Bullwaddy Conservation Reserve	Only reserve within the Sturt Plateau IBRA region Contains significant stands of bullwaddy, *Macropteranthes kekwickii*
Beetaloo GBA extended region	Elsey National Park	Protects Mataranka Thermal Pools. Refugium for endemic plants
	Frew Pond	A waterhole along the former route of the Overland Telegraph Line named by explorer John McDouall Stuart in 1862
	Lake Woods Conservation Covenant	Covers Lake Woods A significant wetland
	Longreach Waterhole Protected Area Conservation Covenant	Part of the Lake Woods system

4.1.3.3 Territory-listed threatened species

Four species of vertebrate animal, that have been classified as threatened in the NT but not nationally have been recorded within the Beetaloo GBA region since 1990 and are considered to possibly still occur there (Table 14). These species are the grey falcon (*Falco hypoleucos*), pale field-rat (*Rattus tunneyi*), Mertens' water monitor (*Varanus mertensi*) and floodplain monitor (*Varanus panoptes*). A further two species have been recorded from the Beetaloo GBA extended region since 1990: Mitchell's water monitor (*Varanus mitchelli*) and the land snail, *Trachiopsis victoriana*. Each of these species is classified as vulnerable in the NT.

Table 14 Fauna species recorded from the Beetaloo GBA extended region that are listed as threatened under the *Territory Parks and Wildlife Conservation Act* (NT), but not listed under the EPBC Act, also indicating if recorded within the Beetaloo GBA region

Scientific name	Common name	Conservation status	Present in GBA region
Falco hypoleucos	Grey falcon	Vulnerable	Yes
Rattus tunneyi	Pale field-rat	Vulnerable	Yes
Trachiopsis victoriana	Land snail	Vulnerable	No
Varanus mertensi	Mertens' water monitor	Vulnerable	Yes
Varanus mitchelli	Mitchell's water monitor	Vulnerable	No
Varanus panoptes	Floodplain monitor	Vulnerable	Yes

4.1.3.4 Groundwater-dependent ecosystems

Springs do not occur within the Beetaloo GBA region but are present to the north-north-east and east as discharge complexes from the major northward flowing groundwater systems of the CLA (Figure 45). These springs are present within the Beetaloo GBA extended region. There are 78 likely or confirmed spring locations in the GBA extended region. The closest springs to the boundary of the Beetaloo GBA region are Lagoon Creek and Beauty Creek Springs, approximately 10 km to the north-east, and at Mataranka Thermal Pools, located 40 km to the north. The springs at Mataranka Thermal Pools sustain dry-season flows in the Roper River system.

The depth of regional groundwater in the Beetaloo GBA region, usually at depths greater than 40 m (Figure 43), means that connectivity between surface water and groundwater is limited. Within the Beetaloo GBA region terrestrial GDEs are typically limited to shallow perched aquifer systems that are fed by groundwater. These occur at locations such as north of Newcastle Creek (Figure 44).

Other GDE systems within the Beetaloo GBA extended region include 33 km^2 of lake ecosystems (e.g. at Craven Creek), 49 km^2 of river ecosystems (e.g. Roper River system), and 33 km^2 of wetlands, including Theresa Creek and Stuart Swamp.

4.1.4 Threatening processes with potential to impact species

Key threatening processes identified under the EPBC Act relevant to the Beetaloo GBA region include:

- competition and land degradation by rabbits
- competition and land degradation by unmanaged goats
- invasion of northern Australia by gamba grass and other introduced grasses
- novel biota and their impact on biodiversity (e.g. feral horses, donkeys and camels)
- predation by European red fox
- predation by feral cats
- predation, habitat degradation, competition and disease transmission by feral pigs
- biological effects, including lethal toxic ingestion, caused by cane toads (*Bufo marinus*).

4.2 Cultural baseline synthesis

Socio-economic and cultural assets were considered by carrying out searches of the EPBC Act for protected matters.

No socio-economic or cultural assets were identified in the EPBC Act protected matters searches. The searches did not identify any world heritage properties, national heritage places or Commonwealth heritage places in the Beetaloo GBA extended region.

Methods snapshot: identifying cultural assets

Cultural assets were searched for in EPBC Act protected matters searches run by the Department of the Environment and Energy. Two separate searches were run: one for the Beetaloo GBA region (carried out on 16 September 2018) and another for the Beetaloo GBA extended region (carried out on 15 March 2019 and 23 September 2019).

The Beetaloo GBA region has supported Indigenous cultures for millennia, and communities maintain an ongoing connection to the region. Assessment of impacts on Indigenous values are also managed under Commonwealth (see Section 1.5.1.2) and Northern Territory (see Section 1.5.2.6) legislation.

4.3 Landscape classification and ecohydrological conceptualisation

To determine how hydrological and other changes caused by shale and tight gas development may affect ecosystems at a landscape scale, six landscape classes have been identified, based on Queensland's Land Zones. The Beetaloo GBA region is dominated by loamy and sandy plains and by clay plains. There are also substantial areas of floodplain and alluvium, and undulating country on fine-grained sedimentary rocks. There are only traces of tablelands and duricrusts; and basalt plains and hills.

Methods snapshot: developing the landscape classification

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

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

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

Inputs into the landscape classification were based on existing classification schemes wherever possible and can be purely physical, biological or predictive (Linke et al., 2011). Choice of approach depends on the availability of data at an appropriate scale, as well as the expertise and resources for undertaking the assessment. Landscape classifications should be credible, transparent, logical and consistently applied; where possible, match other classifications (or at least some of their classes); and be feasible within available resourcing.

The landscape classification developed for the Beetaloo GBA region is based on the Queensland Land Zones (Wilson and Taylor, 2012). Consistent with the principles outlined above, it sought to use existing data sources and classifications and to leverage the extensive effort already expended by the Queensland Government to develop highly relevant conceptual models at both landscape scale and wetland scale through the Queensland Wetlands Program (Department of Environment and Science (Qld), 2017).

A detailed landscape classification, based on Queensland's Land Zones, was provided by the Department of Environment and Natural Resources (Department of Environment and Natural Resources (NT), 2019a). The areas of each landscape class in the Beetaloo GBA region and corresponding land zone (Queensland) are given in Table 15, along with geological descriptions of the landscape classes.

Table 15 Landscape classes within the Beetaloo GBA region and corresponding Queensland Land Zones

Landscape class	Queensland Land Zones	Geological description	Area (km^2)	Area (%)
Loamy and sandy plains	Tertiary – early Quaternary loamy and sandy plains and plateaus	Tertiary – early Quaternary extensive, uniform near-level or gently undulating plains with sandy or loamy soils. Includes dissected remnants of these surfaces. Also includes plains with sandy or loamy soils of uncertain origin; and plateau remnants with moderate to deep soils usually overlying duricrust. Excludes recent Quaternary alluvial systems, exposed duricrust, and soils derived from underlying bedrock. Soils are usually Tenosols and Kandosols, also minor deep sandy surfaced Sodosols and Chromosols. There may be a duricrust at depth.	19,979	70
Clay plains	Tertiary – early Quaternary clay plains	Tertiary – early Quaternary clay deposits, usually forming level to gently undulating plains not related to recent Quaternary alluvial systems. Excludes clay plains formed in-situ on bedrock. Mainly Vertosols with gilgai microrelief but includes thin sandy or loamy surfaced Sodosols and Chromosols with the same paleo-clay subsoil deposits.	4,937	17
Floodplain and alluvium	Recent Quaternary alluvial systems	Recent Quaternary alluvial systems, including closed depressions, paleo-estuarine deposits currently under freshwater influence, inland lakes and associated wave-built lunettes. Excludes colluvial deposits such as talus slopes and pediments. Includes a diverse range of soils, predominantly Vertosols and Sodosols; also with Dermosols, Kurosols, Chromosols, Kandosols, Tenosols, Rudosols and Hydrosols; and Organosols in high rainfall areas.	1,809	6
Undulating country on fine-grained sedimentary rocks	Fine-grained sedimentary rocks	Fine-grained sedimentary rocks, generally with little or no deformation and usually forming undulating landscapes. Siltstones, mudstones, shales, calcareous sediments, and labile sandstones are typical rock types, although minor interbedded volcanics may occur. Includes a diverse range of fine-textured soils of moderate to high fertility, predominantly Vertosols, Sodosols and Chromosols.	1,406	5

Landscape class	Queensland Land Zones	Geological description	Area (km^2)	Area (%)
Tablelands and duricrusts	Cenozoic duricrusts[a]	Cainozoic duricrusts formed on a variety of rock types, usually forming mesas or scarps. Includes exposed ferruginous, siliceous or mottled horizons and associated talus and colluvium, and remnants of these features – for example, low stony rises on downs. Soils are usually shallow Rudosols and Tenosols, with minor Sodosols and Chromosols on associated pediments, and shallow Kandosols on plateau margins and larger mesas.	383	1
Basalt plains and hills	Cainozoic igneous rocks	Cainozoic igneous rocks, predominantly flood basalts forming extensive plains and occasional low scarps. Also includes hills, cones and plugs on trachytes and rhyolites, and associated interbedded sediments, and talus. Excludes deep soils overlying duricrust. Soils include Vertosols, Ferrosols and shallow Dermosols.	7	0
Total			**28,521**	**100**

[a]Also referred to as Cainozoic duricrusts in some publications
na = not applicable
Source: Geological and Bioregional Assessment Program (2018e) adapted from Wilson and Taylor (2012)

The total area of the Beetaloo GBA region is 28,521 km^2 (Table 15). It is dominated by loamy and sandy plains (19,979 km^2) and by clay plains (4,937 km^2), mainly associated with the Sturt Plateau Interim Biogeographic Regionalisation for Australia (IBRA) region (Table 16), although the southern-most clay plains are associated with Mitchell Grass Downs IBRA region (Table 16).

The 1809 km^2 of floodplain and alluvium is mainly within the Sturt Plateau IBRA region but also in headwaters of the Nicholson River within the Gulf Fall Uplands IBRA region (Table 16). The Sturt Plateau watercourses are generally short and braided and include Western and Birdum creeks in the north-west of the region and Newcastle Creek in the south.

Undulating country on fine-grained sedimentary rocks comprise 1406 km^2, and Cenozoic duricrusts 383 km^2, of the Beetaloo GBA region. These are headwaters of modern creeks and rivers in both the Gulf Fall and Uplands and Sturt Plateau IBRA regions (Table 16).

There are only very small areas of basalt plains and hills (7 km^2) in the Beetaloo GBA region. Sandstone ranges, and hills and lowlands on metamorphic rocks, occur just outside the Beetaloo GBA region (Figure 52). No springs occur in the Beetaloo GBA region; however, Mataranka Hot Springs is situated in the Roper River catchment in Elsey National Park, some 50 km north of the Beetaloo GBA region, and other springs occur outside but in the groundwater assessment area (Evans et al., 2020).

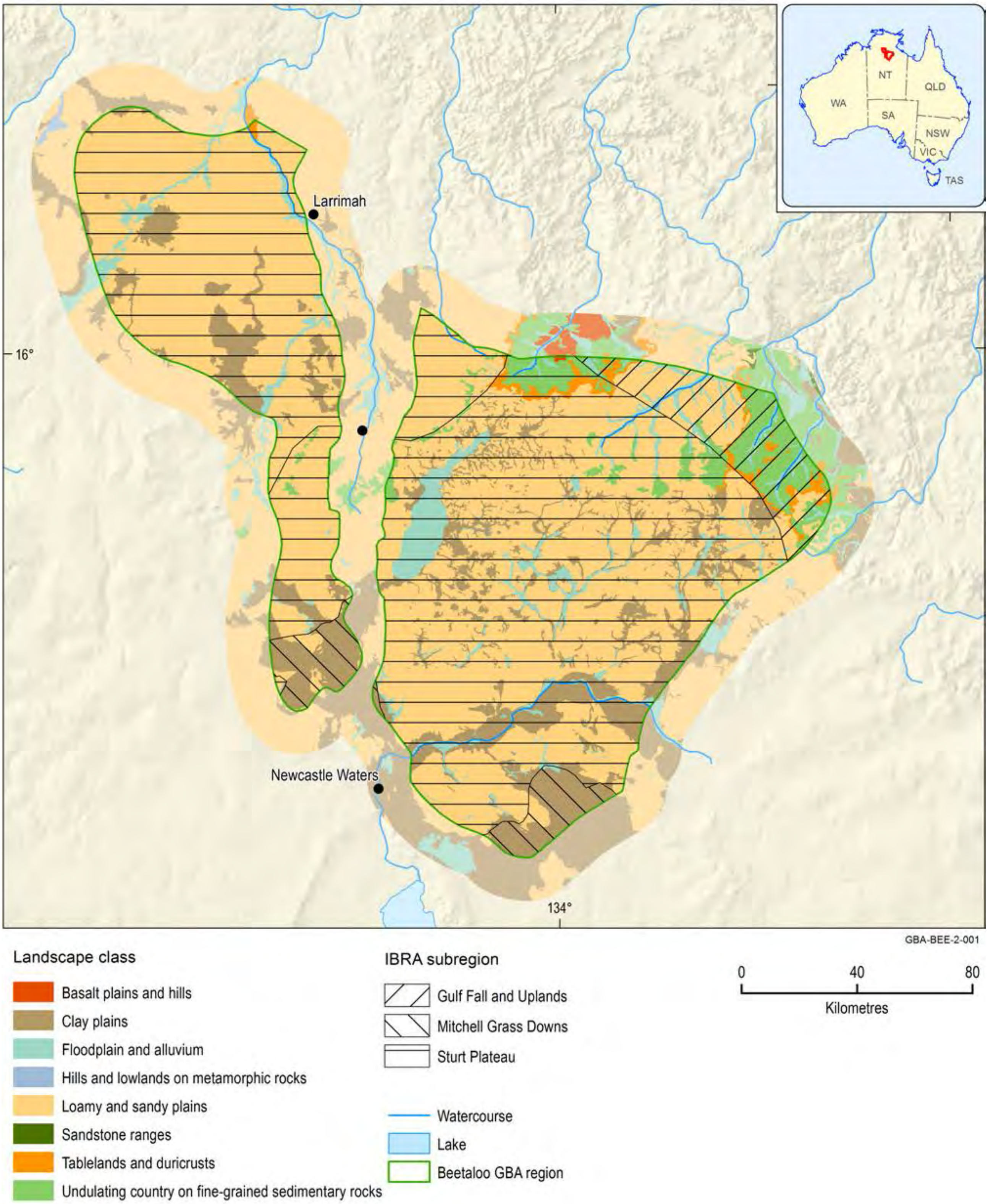

Figure 52 Landscape classes and IBRA regions within the Beetaloo GBA region

IBRA regions are also indicated. Note that the landscape classification extends slightly outside the GBA boundary for context.
Data: Department of Environment and Natural Resources (NT) (2019a)
Element: GBA-BEE-2-001

Table 16 IBRA regions in the Beetaloo GBA region

IBRA region	Area (km²)
The **Sturt Plateau** region mostly comprises a gently undulating plain on lateritised Cretaceous sandstones. Soils are predominantly neutral sandy red and yellow earths. The most extensive vegetation is eucalypt woodland with tussock grass or Triodia understorey, but there are also large areas of lancewood (*Acacia shirleyi*) thickets, and bullwaddy (*Macropteranthes kekwickii*) woodlands. Elevation ranges from 100 to 300 m above sea level and falls gently from south to north. The Sturt Plateau lies over the Dunmurra, Daly, Wiso and McArthur basins, where Tertiary formed laterites of the Birdum Creek Beds and Cainozoic deposited sands occur. There are two major catchment areas: the Roper drainage system captures all streams east of, and including, the Western Creek system, while the Dry River catchment in the west eventually contributes to the Daly River. The drainage systems are weakly developed. Channel incision is poor in the southern and central areas and it is not until the lower reaches of the Dry River and Elsey Creek are approached that some maturity is observed. Generally, less than 5% of rainfall will contribute eventually to streamflow as a result of the flat terrain, the apparent high storage capacity of waterholes and swamps and the existence of sinkholes.	25,155
The Barkly Tableland subregion of the **Mitchell Grass Downs** region is dominated by *Astrebla pectinata* grasslands on the extensive Tertiary clay plains overlying limestone beds. A variety of mulga (*Acacia aneura*), eucalypt and chenopod open woodland to shrubland communities occur on swamps or sand sheets associated with deposits from the adjacent Northwest Highlands bioregion. Intermittent drainage lines and associated alluvial plains supporting eucalypt woodland, grasslands or open herblands are scattered across the Barkly Tableland (as they are across all provinces in the Mitchell Grass Downs bioregion).	1,338
The McArthur subregion of the **Gulf Fall and Uplands** region is composed almost entirely of low hills and plateaus on gently deformed pre-Cambrian sediments, overlain in places by Mesozoic sediments of the Carpentaria Basin forming residual plateaus and scarps. Folded pre-Cambrian sediments underlie most of the subregion and outcrop mainly along its eastern margin. These low hills are essentially outliers of the Mount Isa Inlier subregion. Sandy alluvia are common along the larger watercourses. Sandstone areas sometimes contain springs and other areas of permanent or near-permanent water. This is a remote subregion and its biology is poorly known. It drains largely into the Nicholson River and the lower reaches of Lawn Hill Creek, and then into the Gulf of Carpentaria.	2,027

Source: Sattler and Williams (1999)

4.3.1 Description of landscape classes

4.3.1.1 Loamy and sandy plains

There are extensive areas of loamy and sandy plains within the Beetaloo GBA region, mainly associated with the Sturt Plateau IBRA subregion, which is characterised by undulating plain on lateritised Cretaceous sandstones (Table 16). Loamy and sandy plains may be formed by redeposition of colluvium or be formed in-situ from 'old' alluvial processes (Wilson and Taylor, 2012). They may also result from prolonged, intense, deep weathering of parent rock material high in iron and/or aluminium oxides and kaolin clays. Landforms are flat to gently undulating plains, plateaus and dissected tablelands.

Within the Beetaloo GBA region, the vegetation is dominated by woodlands and open forests of *Corymbia* and *Acacia*, with some areas of *Macropteranthes* woodlands and tussock grasslands.

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

4.3.1.2 Clay plains

Clay plains are mainly associated with the Sturt Plateau IBRA region although the southernmost clay plains are associated with Mitchell Grass Downs IBRA region. Clay plains are either on relict drainages or associated with modern creeks such as Newcastle Creek.

Clay plains are typically gently undulating plains, with clay soils and texture-contrast soils derived from fine-grained sediments. Clay plains includes paleo-clay unconsolidated sediments originating from 'old' alluvial processes and aeolian clays forming predominantly level to gently undulating plains but includes lesser rises and low hills, particularly in arid areas. These paleo-clay deposits are now elevated above and usually isolated from the alluvial valleys and floodplains (Wilson and Taylor, 2012). As a result, this is now an erosional landscape with poorly defined drainage. These clay soils have been extensively cleared for introduced pastures and cropping in higher rainfall areas due to their relatively high soil water availability and high fertility. Soils are dominated by Vertosols with gilgai microrelief. Larger gilgai may provide ephemeral wetland habitat due to ponding of rainfall. Soils usually have restricted rooting depth due to the adverse effects of high sodium levels.

Within the Beetaloo GBA region, vegetation is dominated by *Eucalyptus* and *Corymbia* woodlands, by tussock grasslands, and by *Acacia* open forest. There are also areas of *Melaleuca* low woodland.

This landscape class is represented by the 'high-level alluvia' conceptual model ((Queensland Government, 2017b); protected matters technical appendix (Pavey et al., 2020)). The term 'high-level alluvia' refers to alluvia deposited in ancestral valleys that are located above the channels in the current landscape in a form of inverted relief. Over time a channel will erode through older alluvial deposits, resulting in older alluvia appearing in the banks above the channel.

4.3.1.3 Floodplain and alluvium

The floodplain and alluvium landscape class is associated with numerous creeks (Birdum, Sunday, Western, Elsey, Cow, Middle, Bucket, Ross, Newcastle in the Sturt Plains IBRA region), several rivers (Arnold, Hodgson, Cox) and the creeks that feed them in the Gulf Fall and Uplands IBRA region, along with their associated floodplains.

The floodplain and alluvium landscape class includes a wide variety of landforms including, but not limited to, fans, plains, flats, banks, benches, bars, channels and streams, depressions, lakes, playa, swamps and terraces (Wilson and Taylor, 2012). For these landforms, there may be frequent active erosion and aggradation by channelled and overbank streamflow or the landforms may be relict from these processes (National Committee on Soil and Terrain, 2009).

Floodplain and alluvium landforms are mostly flat to gently undulating with levees, bars, streambed and banks creating minor local relief (Wilson and Taylor, 2012). Soils are very diverse and are dominated by Vertosols and Sodosols but include a diverse range of other soils. They are usually fertile and often cleared or developed for agriculture or pastoralism. Riparian vegetation adjacent to watercourses is generally more biodiverse than that of the surrounding landscape and is often denser due to greater water availability.

Within the Beetaloo GBA region, vegetation is dominated by *Melaleuca*, *Eucalyptus* and *Corymbia* woodlands and low woodlands.

This landscape class is represented by the 'alluvium' conceptual model ((Queensland Government, 2017b); protected matters technical appendix (Pavey et al., 2020)).

4.3.1.4 Undulating country on fine-grained sedimentary rocks

Undulating country on fine-grained sedimentary rocks in the Beetaloo GBA region is found mainly in the Gulf Fall and Uplands IBRA subregion, which is composed almost entirely of low hills and plateaus on gently deformed pre-Cambrian sediments, overlain in places by Mesozoic sediments of the Carpentaria Basin forming residual plateaus and scarps.

Fine-grained sedimentary rocks include siltstones, mudstones and shales. Depending on the lithology (mineral composition) of the lithic fragments, these fine-grained sedimentary rocks form clayey soils or soils with clay subsoils (Wilson and Taylor, 2012). Due to the generally 'soft' nature of the sedimentary rocks and the readily weathered nature of the lithology, the landforms are dominated by gently undulating plains and rises, many of which have been extensively developed or cleared for pasture. Soils are predominantly Vertosols, Sodosols and Chromosols.

The vegetation in the Beetaloo GBA region is dominated by *Eucalyptus* and *Corymbia* woodland, with areas of tussock grassland, *Melaleuca* low woodland and *Acacia* open forest.

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

4.3.1.5 Tablelands and duricrusts

Tablelands and duricrusts occur in the north-west of the Beetaloo GBA region, mainly in the Gulf Fall and Uplands IBRA subregion (Table 15).

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

Within the Beetaloo GBA region, the vegetation is dominated by *Acacia* woodland and low woodlands, with some areas of *Corymbia*, *Eucalyptus* and *Melaleuca* woodland, and some areas of tussock grassland.

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

4.3.1.6 Basalt plains and hills

Basalt plains and hills are lava plains and associated volcanic cones and plugs (Wilson and Taylor, 2012). The extensive undulating plains are broken occasionally by low scarps, hills and plateaus.

Vegetation on basalt plains and hills in the Beetaloo GBA region is dominated by *Melaleuca* low woodland.

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

4.4 Protected matters prioritisation

In order to focus the assessment in Stage 3, protected matters were prioritised based on how important the Beetaloo GBA extended region is to each matter. Detailed assessments will focus on five protected species (four nationally listed, one territory listed), two nationally important wetlands, and all GDEs (priority 1).

A prioritisation and screening process was adopted to identify the individual protected matters that were considered most likely to be impacted by potential shale gas, tight gas and shale oil development in the Beetaloo GBA extended region. Each identified protected matter was reviewed by the process in relation to its extent and distribution within the region.

Each of the protected matters was assigned to one of three categories:

- **Priority 1** – importance of the region to the matter warrants a detailed level of assessment
- **Priority 2** – importance of the region to the matter warrants a high-level assessment
- **Priority 3** – importance of the region to the matter does not warrant further assessment.

Following the initial categorisation, protected matters categorised as priority 1 or 2 were further screened using the significant impact guidelines (Commonwealth of Australia, 2013). Where the protected matter was a *place* (e.g. a wetland of national significance) the matter was retained as priority 1 or 2 if the area:

- partially or wholly intersected with areas licenced for exploration and within areas deemed to be prospective for shale gas, tight gas and shale oil development
- could be considered hydrologically connected to these areas from a surface water or groundwater perspective
- was thought to contain habitat for a species identified through the protected matters screening and prioritisation process.

Protected matters that were not retained were assigned to priority 3. Landscape classes were assessed using the same criteria as for *place* protected matters.

Where the protected matter was a species, an assessment of its exposure to causal pathways associated with development of shale gas, tight gas and shale oil resources was made. This assessment included reference to likelihood of occurrence in the region, listed threatening processes and existing literature, which included species recovery plans, conservation advices and threat abatement plans.

The proportion of each species' occurrence (known records and predicted distributions) within the Beetaloo GBA extended region was assessed against its national distribution. Within the region the spatial data were assessed in relation to the extent of the protected matter within areas deemed likely to be prospective for shale gas, tight gas and shale oil development. If, in conjunction with an understanding of the species habitat requirements, the species or its habitat was likely to occur in the region, then that species was retained as priority 1. Matters that were not retained were assigned to priority 3.

Those protected matters that occurred or potentially occurred in the Beetaloo GBA extended region but not in the Beetaloo GBA region were given priority 3. However, if in Stage 3 (impact analysis and management) of this work the impacts from shale gas, tight gas and shale oil development are predicted to extend beyond the Beetaloo GBA region – for example, based on hydrological flow information for groundwater systems discharging at Mataranka Thermal Pools – these assessments will be reconsidered.

Four species of national environmental significance were identified as being potentially at risk from future unconventional gas development. These species will be considered further in the next stage (Stage 3, impact analysis and management) of this GBA. These include:

- the endangered species
    - *Erythrura gouldiae* (Gouldian finch)
    - *Rostratula australis* (Australian painted snipe).
- the vulnerable species
    - *Falcunculus frontatus whitei* (Crested shrike-tit (northern))
    - *Macrotis lagotis* (greater bilby).

In addition, one species, *Falco hypoleucos* (grey falcon) that is a Matter of Territory Environmental Significance was identified as being potentially at risk from future unconventional gas development and will be assessed as a priority 1 matter in Stage 3. It is listed as vulnerable in the NT.

The two nationally important wetlands – Mataranka Thermal Pools and Lake Woods – were assessed as priority 1 matters. Although they are outside the Beetaloo GBA region, there is sufficient evidence, for both these wetlands, of hydrological connectivity to areas within the Beetaloo GBA region that are deemed to be prospective for shale and tight gas development to warrant their inclusion as priority 1 matters. Mataranka Thermal Pools show evidence of groundwater connectivity and Lake Woods of surface water connectivity to areas within the Beetaloo GBA region. Several NT parks, reserves and conservation covenants are included within the area of these two wetlands. Specifically, Elsey National Park covers Mataranka Thermal Pools and Lake Woods includes Lake Woods conservation covenant and Longreach Waterhole protected area. Hence, these three matters will not be assessed separately.

In addition to these matters, all GDEs were identified as priority 1 matters for assessment in Stage 3.

4.5 Knowledge gaps

Adequate understanding of the geographic distribution and ecology, including diet, habitat use and breeding season, of MNES and other protected matters and Matters of Territory Environmental Significance are key knowledge gaps for the study area. The knowledge gaps in this case represent understanding of both where matters occur in relation to potential unconventional petroleum resource development and how the ecological requirements of species and ecological communities may be impacted by the resource development pathway. Currently, the majority of protected matters are identified as ‘likely to occur’ or ‘may occur’ rather than ‘known to occur’ within the Beetaloo GBA region. Resolving whether individual matters occur (or did occur) within the GBA region and, if so, when and where is necessary to identify those matters that may be impacted by future unconventional petroleum resource development. Likewise, understanding the ecological requirements (including diet, habitat use and breeding season) and life histories of individual species is essential for assessing how each will respond to environmental change resulting from the unconventional petroleum development pathway in a region. This is an important knowledge gap.

Another important knowledge gap relates to the interaction between existing key threatening processes in the region and causal pathways that will eventuate during resource development. As an example, road construction during the establishment phase of unconventional petroleum resource development may facilitate the movement of invasive species (both animals and plants) into new areas. Knowledge of the nature and extent of these interactions and how they may differ across landscape classes is scarce.

The landscape classification is limited by the quality of available datasets, including surface geology, elevation, vegetation and landform mapping, and extent and quality of ground observations. Additional information of this type will assist in refining and increasing the accuracy of the landscape classification.

5 Potential impacts due to shale gas, tight gas and shale oil development

The time frame and extent of future shale gas, tight gas and shale oil development in the Beetaloo GBA region are currently unknown. This is due to factors such as the limited understanding of the shale gas resources and uncertainty about the commercial viability of gasfield development in this remote area. As noted in Section 2.2, a considerable amount of additional exploration and reservoir appraisal work is needed to enhance the shale gas knowledge base in the region, which is a fundamental requirement before any long-term investment decisions are made. This type of fundamental work is primarily the responsibility of the petroleum exploration lease holder and would likely require significant capital investment to fund further data acquisition, including additional seismic reflection data, and to drill and hydraulically fracture new petroleum wells. Santos and Origin Energy recommenced their exploration activities in the area in late 2019.

As a consequence of the limited understanding of the shale gas resources and the nature of a likely pathway to commercial operations, the assessment of potential impacts of shale gas, tight gas and shale oil development presented in this report is, by necessity, a preliminary exercise aimed at providing initial insights into the potential effects of this industry within the region. Several assumptions have been made about the types of development activities that would likely be undertaken, based on knowledge of how shale gas developments have occurred in other locations; for example, the recognition of the ten major activities in shale gas operations which are explained in Section 5.2.2. This approach provides an initial indication of the types of development-related hazards that may occur in the region, as well as the most likely causal pathways that could link various activities with impacts on water and the environment. Further, more detailed qualitative assessments of three key features of shale gas development that were raised as key concerns by the user panel for the Beetaloo GBA region– namely, an assessment of potential impacts of hydraulic fracturing, compromised well integrity and the nature of the chemicals commonly used in drilling and fracturing of shale gas wells – are also provided (Section 6).

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

The focus through Stage 2 is on identifying the causal pathways that may affect ecological, economic and/or social values in the Beetaloo GBA region. This has involved a preliminary consideration of standard management and mitigation measures to control these risks. Causal pathways ranked the lowest (priority 3) are not considered further in the assessment. All other causal pathways will be evaluated in some way as part of the impact and risk analysis undertaken in Stage 3. Overall, this approach is precautionary, as it is expected that many of the causal pathways identified for further analysis will present lower risks when the available management and mitigation measures are considered more extensively in the risk assessment process.

5.1 Impact and risk assessment approach

The risk assessment approach follows the principles for ecological risk assessment to meet regulatory requirements for the NT. Stage 2 establishes the context for the impact and risk assessment, including a regional description of geological, hydrological and ecological aspects and conceptualising how they work and interact. It also identifies and prioritises causal pathways based on an appraisal of hazards. Much of the impact and risk assessment will occur in Stage 3 and the causal pathways and endpoints identified in Stage 2 – the key building blocks for the impact and risk assessment – will be refined and finalised.

The assessment will take the form of a risk assessment and follows the principles for ecological risk assessment outlined by the US EPA (1998) and Hayes (2004) with a view to meeting regulatory requirements for petroleum activities in the NT. At the highest level it seeks to evaluate the likelihood and consequence of adverse environmental impacts as a result of the development of unconventional hydrocarbon resources.

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

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

Components of the risk assessment occur in Stage 2 and Stage 3, as summarised in Figure 53.

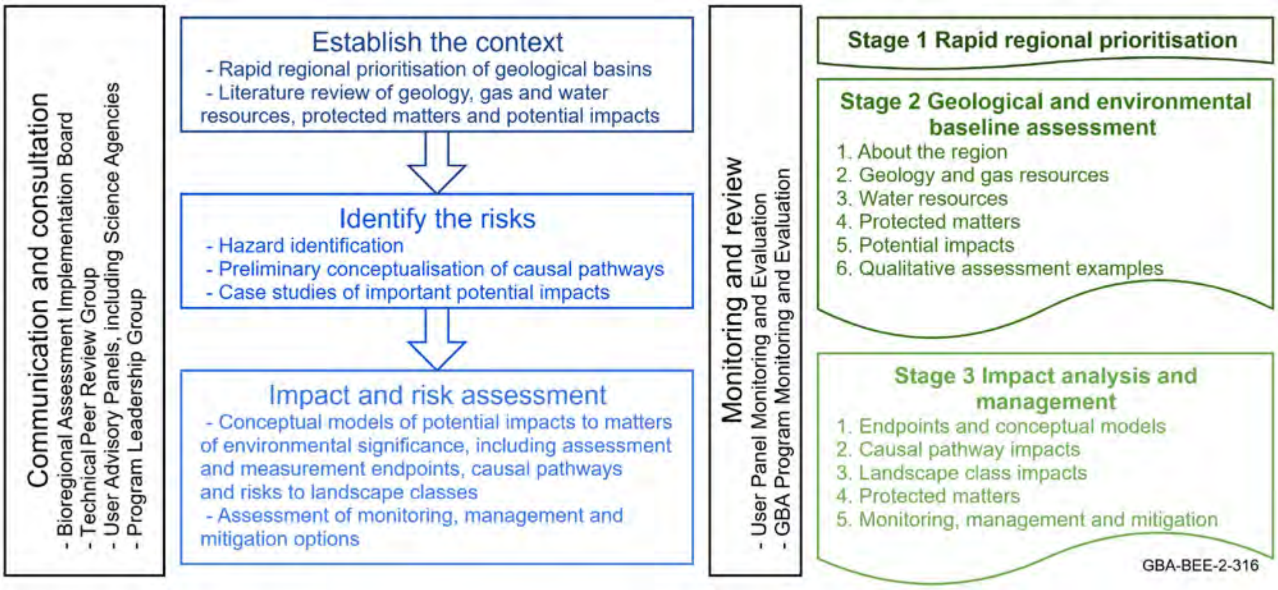

Figure 53 Impact and risk assessment approach (blue boxes) and staged reporting structure (green boxes with curved bases) for the GBA Program

Data: Geological and Bioregional Assessment Program (2019a)
Element: GBA-BEE-2-316

Section 5.2 describes a systematic hazard analysis applied in Stage 2 that (i) identifies potential changes that may stem from the development of unconventional hydrocarbon resources; aggregates individual hazards to a smaller set of causal pathways; and (iii) uses hazard scores to prioritise the causal pathways to be considered further in Stage 3. It also presents preliminary conceptual models for each causal pathway from hazards to potential impacts on landscape classes and values assessed as endpoints. Endpoints include assessment endpoints – an explicit expression of the ecological, economic and/or social values to be protected; and measurement endpoints – measurable characteristics related to the assessment endpoint. Potential impacts include changes to endpoints caused by potential effects, which are specific types of impacts or changes to water or the environment.

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

Much of the impact and risk assessment will occur in Stage 3. The causal pathways and endpoints – the key building blocks for the impact and risk assessment – are identified and prioritised based on a ranking process in Stage 2. These causal pathways will be finalised in Stage 3, with a focus on higher priority pathways. Figure 54 emphasises the central role of the causal pathways in the assessment, connecting hazards arising from unconventional gas resource development activities, as well as existing threatening processes (see Section 4.1.4), to potential impacts on the values to be protected represented in the assessment by endpoints. The assessment of potential impacts on ecological, economic and/or social values represented by endpoints will account for conceptual differences between landscape classes.

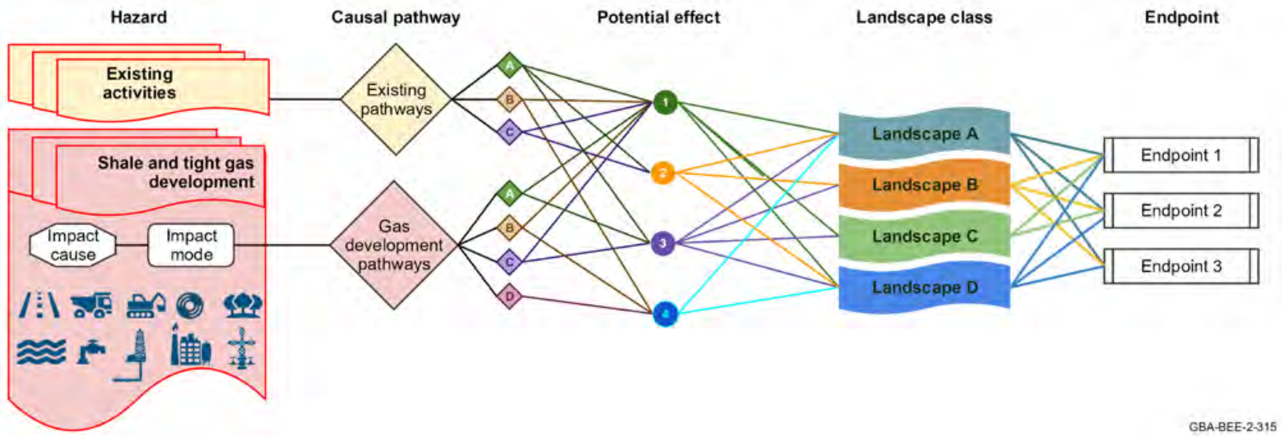

Figure 54 Overview of GBA impact and risk assessment approach, connecting hazards from existing and future development through causal pathways to potential effects on landscape classes and values that can be assessed as endpoints

Links along the conceptual pathway are shown by coloured lines.
'Hazard' = an event, or chain of events, that might result in an effect; 'impact cause' = an activity (or aspect of an activity) that initiates a hazardous chain of events; 'impact mode' = the manner in which a hazardous chain of events (initiated by an impact cause) could result in an effect (change in the quality or quantity of surface water or groundwater); 'causal pathway' = the logical chain of events, either planned or unplanned, that link unconventional gas resource development and potential impacts on water and the environment; 'potential effect' = specific types of impacts or changes to water or the environment, such as changes to the quantity and/or quality of surface water or groundwater or to the availability of suitable habitat; 'landscape class' = a collection of ecosystems with characteristics that are expected to respond similarly to changes in groundwater and/or surface water due to unconventional gas resource development; 'endpoint' = includes 'assessment endpoints' – an explicit expression of the ecological, economic and/or social values to be protected; 'measurement endpoints' = measurable characteristics or indicators related to the assessment endpoint.
Data: Geological and Bioregional Assessment Program (2019a)
Element: GBA-BEE-2-315

5.1.1 Defining endpoints

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

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

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

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

Table 17 presents examples of assessment endpoints for different categories of MNES, water resources and agriculture. The approach taken here is consistent with Beckett (2019) and reduces the criteria used in the significant impact guidelines (Commonwealth of Australia, 2013) for each category of threatened species into a single set of assessment endpoints. It then applies these endpoints to all sets of native species regardless of their listed status. These examples are intended to provide context for the direction of the impact and risk assessment in Stage 3.

Table 17 Examples of assessment endpoints

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

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

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

The potential for 'significant impacts' for each measurement endpoint (Table 17) will be described using thresholds to more precisely quantify the aspects of tolerance, resilience and persistence of the asset to be protected, how cumulative impacts interact and the spatial and temporal scales of the response. For instance, Butcher and Hale (2011) use limits of acceptance change for Coongie

Lakes to specify thresholds for indicators beyond which there may be material change to aspects of the ecological character.

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

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

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

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

5.2 Hazard identification

Hazards were systematically identified by considering all the possible ways an activity in the life cycle (Figure 55) of shale gas, tight gas and shale oil development may impact ecological, economic and/or social values. The range of severity and likelihood scores for each hazard was developed based on equivalent work in the Cooper and Isa GBA regions. Stage 3 of the GBA Program will assess the likelihood and consequences of the identified risks (risk analysis and risk evaluation phases).

Hazards were prioritised by the highest hazard score (severity + likelihood), allowing low-priority hazards to be ruled out for future analysis in Stage 3. The hazard prioritisation was then used to prioritise the causal pathways, which will be the focus of Stage 3. Of the 13 causal pathways identified, five causal pathways were prioritised for a detailed level of assessment in Stage 3 (priority 1), a further six were prioritised for a moderate level of assessment (priority 2), and two were ruled out from requiring further assessment. Important potential impacts to be assessed in Stage 3 are changes to groundwater quality; changes to surface water flows; cultural heritage damage or loss; habitat fragmentation and loss;

introduction of invasive species; and contamination of soil, groundwater and or surface water. Most of the priority hazards are in the landscape management and water and infrastructure management causal pathway groups, with fewer in the subsurface flow paths causal pathway group.

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

Hazard identification is a key component of the *Identification and formulation* step of the GBA impact and risk assessment approach outlined in Section 5.1. As part of this stage, the hazards are prioritised based on a high-level assessment of their likelihood and consequence based on expert opinion. At this stage no quantitative determination of the probability of any single hazard occurring or its impacts on endpoints has been conducted. A more detailed assessment, including the role of industry standards and environmental and operation regulations in mitigating these hazards, will be conducted in Stage 3.

5.2.1 Impact Mode and Effects Analysis

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

IMEA is a ‘bottom-up’ hazard analysis tool. It begins with a thorough description of the overall system and its subsystems, individual components and activities. It then identifies all the possible ways in which each activity can have an impact (the ‘impact modes’) and assesses the severity of the impact on the ecological, economic and/or social values (the ‘endpoints’). It considers the ‘impact modes’, which are the manner in which a hazardous chain of events (initiated by an ‘impact cause’) could result in a ‘potential effect’ (Figure 54). An ‘impact cause’ is an activity (or aspect of an activity) that initiates a hazardous chain of events. ‘Potential effects’ are specific types of impacts or changes to water or the environment, such as changes to the quantity and/or quality of surface water or groundwater or to the availability of suitable habitat. Multiple impact modes and potential effects may be associated with each activity. The range of severity and likelihood of the potential effect is scored on an interval (minimum to maximum) for each hazard. Current controls that are in place are identified and considered in the scoring, and they are thus part of the hazard prioritisation. These controls, and additional mitigation or management options that may reduce the severity and/or likelihood of potential impact, will be considered in detail in the analysis of causal pathways in Stage 3. The IMEA used in the GBA Program differs from the IMEA used in the Bioregional Assessment Program (Ford et al., 2016) in that it does not score the detectability of the impact. Detectability can be useful for weighting more highly those hazards that are harder to detect. In this context these are often subsurface hazards which may take years to present. This was assessed as more important for bioregional assessments given the subsurface causal pathways are typically nearer to assets at the surface for coal seam gas (CSG) and coal mining compared with deeper shale gas, tight gas and shale oil resources.

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

5.2.2 Typical shale gas, tight gas and shale oil development activities

Activities that typically occur during shale gas, tight gas and shale oil development have been grouped into ten major activities (Figure 55) that span five life-cycle stages (Figure 56). The ten major activities are:

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

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

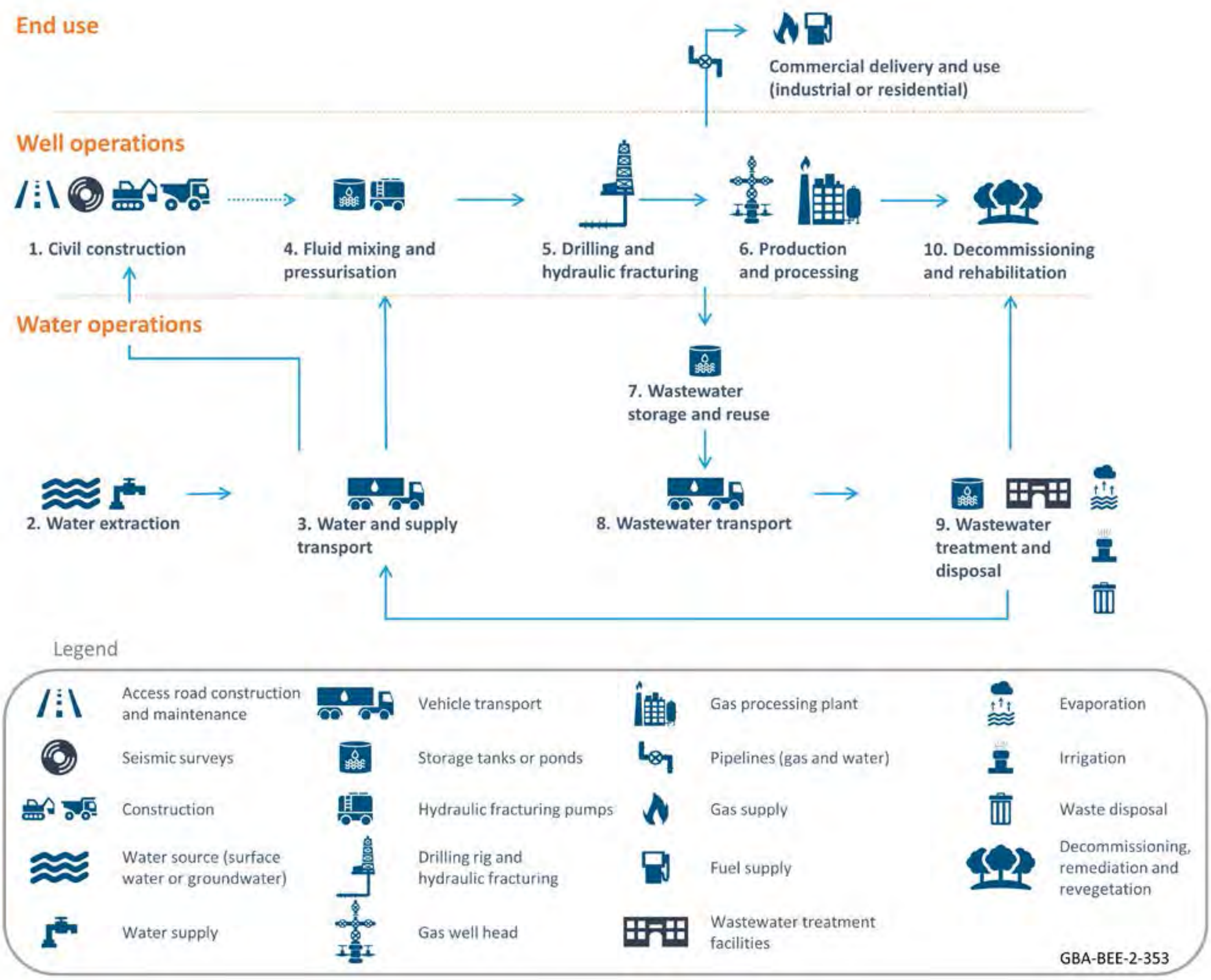

Figure 55 Ten major activities involved in typical shale gas, tight gas and shale oil resource development

Source: adapted from Litovitz et al. (2013)
Element: GBA-BEE-2-353

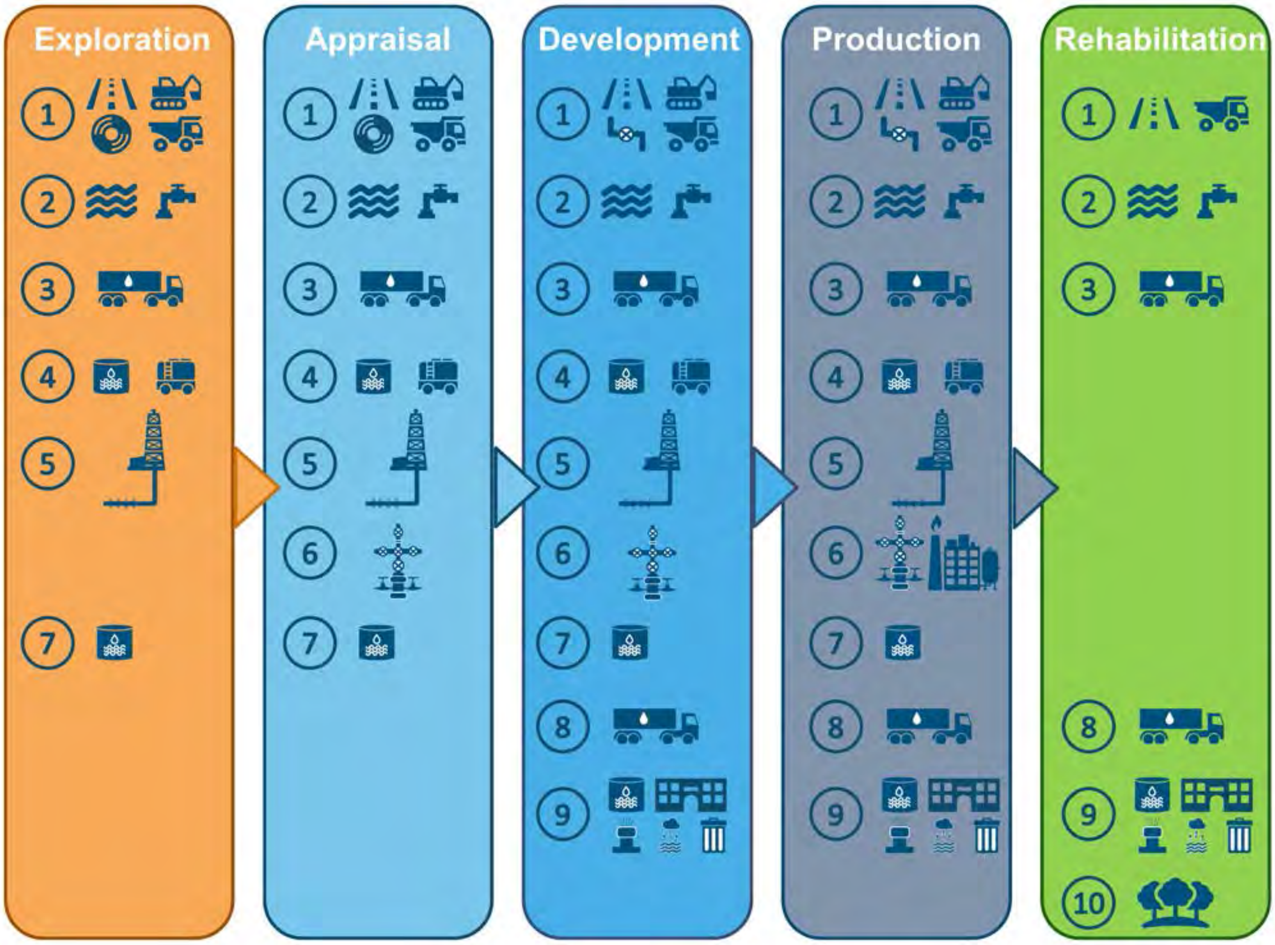

Figure 56 Life-cycle stages and major activities expected for future unconventional gas resource development in the Beetaloo GBA region

Symbols for each of the ten major activities (1. Civil construction; 2. Water extraction; 3. Water and supply transport; 4. Fluid mixing and pressurisation; 5. Drilling and hydraulic fracturing; 6. Production and processing; 7. Wastewater storage and reuse; 8. Wastewater transport; 9. Wastewater treatment and disposal; and 10. Decommissioning and rehabilitation) are defined in Figure 55.
Element: GBA-BEE-2-352

1. Civil construction

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

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

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

2. Water extraction

Water is extracted for site operations, which include access road construction, drilling and hydraulic fracturing (Huddlestone-Holmes et al. (2018) and Section 5.3). For this hazard identification process, it was assumed that approximately 15 to 20 ML/well are needed for drilling and hydraulic fracturing during the exploration, appraisal and development stages. Water use will be highest in the development stage, when drilling intensity is highest relative to the exploration and appraisal stages. During the production stage, approximately 10 ML/well will be required for well workovers, intervention and refracturing to extend gas production. Huddlestone-Holmes et al. (2018) note that low-salinity water is preferred because high-salinity water may damage equipment and target formations.

Extraction of surface water for petroleum activities in the NT is prohibited under the *Water Act 2007* (Cth). Beetaloo GBA region water for drilling and hydraulic fracturing will need to be extracted from groundwater bores, and recycling or reuse of water may also be important in reducing total volumes extracted. Groundwater extraction can affect groundwater levels or pressures and/or groundwater quality in source aquifers.

3. Water and supply transport

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

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

4. Fluid mixing and pressurisation

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

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

5. Drilling and hydraulic fracturing

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

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

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

6. Production and processing

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

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

Processing and compression of gas, including flaring or venting of gas, can affect air quality or light and noise levels, which may alter natural habitat and species distributions if not appropriately managed. Failure of surface infrastructure may cause emissions of natural gas leaks from equipment or pipelines, affecting air quality. Unconventional gas extraction may alter groundwater pressures, which can lead to fault reactivation and induced seismicity.

7. Wastewater storage and reuse

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

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

Soil, surface water and/or groundwater contamination may arise from leaks, spills or overflows due to integrity failure or uncontrolled releases (e.g. during floods).

8. Wastewater transport

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

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

9. Wastewater treatment and disposal

The intentional discharge of wastewater (treated or untreated) from shale gas, tight gas and shale oil activities into surface waters or groundwater is prohibited in the NT. Wastewater, or residue from wastewater treated onsite, must be transported offsite for disposal. It may also be recycled or reused within petreoleum activities. Evaporation ponds may be used to reduce volumes, and treatment technologies such as thermal distillation or reverse osmosis may be used to separate the water streams leaving the site for disposal at appropriate waste disposal facilities. Wastewater (treated sewage) from camps or other supporting infrastructure will produce small volumes that may be released to environment if it meets appropriate quality standards.

10. Decommissioning and rehabilitation

Partial rehabilitation of land disturbed for temporary access tracks, well pads and pipelines occurs as soon as those activities are complete. Final decommissioning and rehabilitation primarily occurs after production operations cease and includes the decommissioning of surface infrastructure (e.g. water treatment plants, pipes, gas processing plant, compression stations, water/fluid storage facilities, offices and workshops), decommissioning wells by plugging with cement prior to abandonment, and the remediation of impacted land by revegetation and landscaping. Some of the decommissioned infrastructure and materials will be transported offsite by trucks for disposal and reuse. In some cases, rehabilitation may occur sequentially, particularly with revegetation and landscaping during production to minimise visual impact and to mitigate erosion.

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

5.2.3 Hazard identification process

The hazard identification process for the Beetaloo GBA region leveraged the results of the earlier hazard analysis work done for the Cooper and Isa GBA regions, which provide a consistent program-wide framework for hazard evaluation (Holland et al., 2020; Lewis et al., 2020). For the Cooper and Isa GBA regions, participants at a series of hazard identification workshops systematically identified and ranked over 200 hazards associated with petroleum activities in the respective basins. The hazard identification dataset describes the activity, current control, impact cause, impact mode, major activity, peak life-cycle stage and potential effect, as well as the upper and lower estimates for severity, likelihood and hazard score, for each individual hazard (Geological and Bioregional Assessment Program, 2019b). This dataset was then reviewed by staff from CSIRO for its applicability to the Beetaloo GBA region considering the nature of the region's petroleum resources, water resources and ecology and the NT's regulatory framework. The risk assessment conducted by the Pepper inquiry (Pepper et al., 2018) was also reviewed to ensure the list of potential hazards was consistent. Experts from industry were also consulted to gain further insight into the potential hazards and to identify and score any hazards that were not initially considered.

IMEA assumes that relevant control measures, such as standard Australian gas industry operating procedures and regulatory requirements, are met. However, at this preliminary stage it is not possible to provide a thorough assessment of the effectiveness of these controls in mitigating identified hazards. A closer examination will be conducted as part of the detailed assessment in Stage 3 that will be guided by development scenarios. The resulting dataset (Geological and Bioregional Assessment Program, 2019a) provides a range of scores associated with each hazard, which allows the uncertainty in the severity and likelihood of potential impacts to be expressed. Potential hazards were then prioritised using the highest score for each interval, which meant that low-priority hazards can be 'ruled out'.

The severity of potential effects ranges from 'no impact' (severity score = 3) through to 'catastrophic impact' (severity score = 9), where there is an order of magnitude or a tenfold change in the degree of impact, its spatial extent and reversibility (Table 18). For example, the severity of potential effects is considered 'minor' (severity score = 6) if the impacts are moderate, contained within the petroleum lease and reversible in five to ten years. The severity score considers potential impacts from each hazard for ecological, sociocultural and economic values.

The likelihood of potential environmental impacts ranges from 'extremely rare' or one event in 1000 years (likelihood score = –3) through to 'every day' or 365 events in one year (likelihood score = 2.5) (Table 18). A one-unit increase (or decrease) in the likelihood score indicates a tenfold increase (or decrease) in the probability of occurrence. This is in effect a first-pass assessment of risk based on the opinions of those consulted throughout the process to allow prioritisation for Stage 3 where a more comprehensive assessment will be conducted.

Table 18 Categories, descriptions and scores for severity of environmental impact and likelihood of recurrence

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

Source: Geological and Bioregional Assessment Program (2019a)

5.2.4 Causal pathway prioritisation

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

Hazards are ranked using their upper hazard score, which ranges from a maximum of 7.5 to a minimum of 1.0. Lower hazard scores range from a maximum of 4.0 to a minimum of 0.5. Ranked upper hazard scores (Figure 57) decrease rapidly for high scores (upper hazard scores between

7.5 and 5.5) and moderately for medium scores (between 5.0 and 4.0) and lower ranked scores (between 3.5 and 1.0).

The top 7% of hazard scores (12 hazards) are prioritised for a detailed level of assessment in Stage 3 (priority 1) (Table 19). Severity of potential impact estimates range from 'minimal' (moderate impact on ecosystem; contained within petroleum lease; reversible in one to five years) to 'major' (significant harm or irreversible impact (e.g. to a World Heritage Area); widespread, catchment-scale; long-term impacts, >10 years). Likelihood estimates range from 'very unlikely' (one event in 33 years) to 'almost certain' (three events in one year). Five causal pathways are included in the priority 1 hazards:

- altering cultural heritage
- altering natural habitat and species distributions
- altering surface water hydrology
- failure of surface infrastructure (ponds, tanks, pipelines, etc.)
- introduction of invasive species.

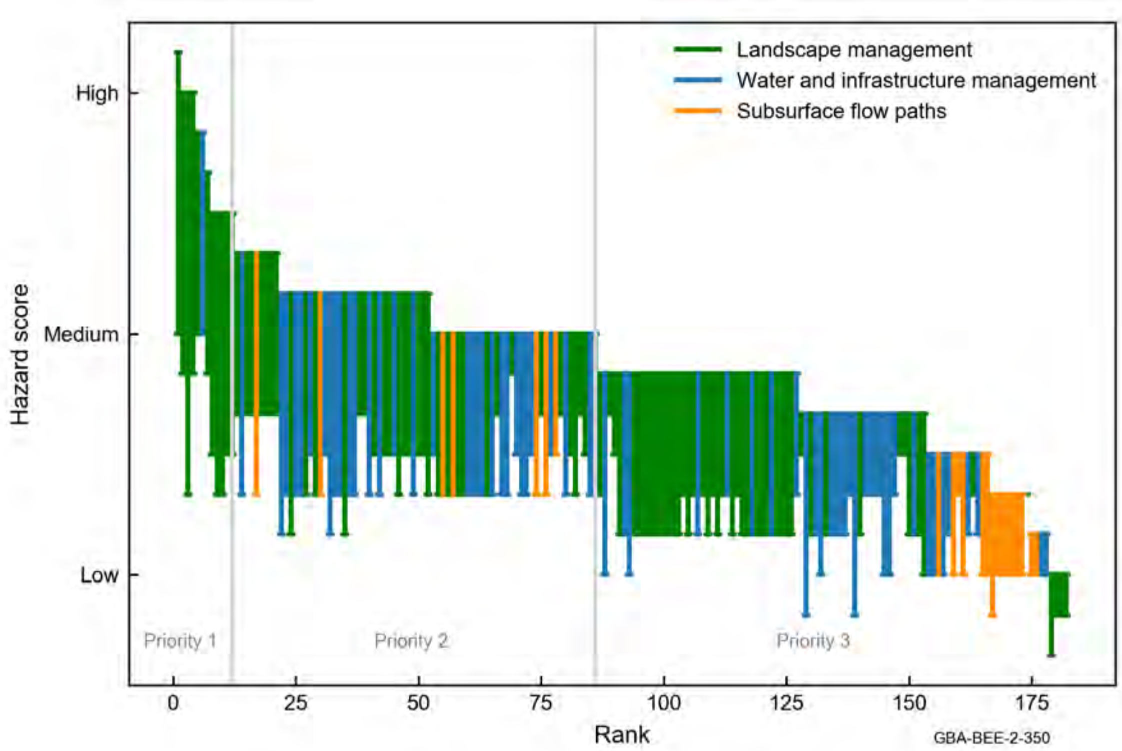

Figure 57 Hazard score ranges (upper and lower for each hazard) ranked by upper hazard score for the Beetaloo GBA region

Hazard score = severity + likelihood scores
Source: Geological and Bioregional Assessment Program (2019a)
Element: GBA-BEE-2-350

The next 41% of ranked hazard scores (75 hazards) were also prioritised for assessment in Stage 3 (priority 2) (Table 19). Severity of potential impact estimates range from 'none' to 'minor' (moderate impact on ecosystem; contained within petroleum lease; reversible in five to ten years).

Likelihood estimates range from 'rare' (one event in 100 years) to 'most certain' (ten events in one year). The six causal pathways identified for assessment in Stage 3 as priority 2 are:

- altering natural and agricultural productivity
- compromised well integrity
- disposal and storage of site materials
- gas extraction altering groundwaters
- processing and using extracted water
- sourcing water for site operations.

The severity and likelihood of the remaining 95 hazards does not warrant further assessment (priority 3) (Table 19). Severity of potential impact estimates for these hazards range from 'none' to 'minimal' (moderate impact on ecosystem; contained within petroleum lease; reversible in one to five years) and likelihood estimates range from 'very rare' (one event in 333 years) to 'almost certain' (three events in one year). The two causal pathways identified as priority 3 are:

- discharging into surface waters
- hydraulic fracturing.

The hydraulic fracturing causal pathway will have additional assessment in response to concerns raised by the user group and general community concern (see Section 6).

Table 19 Prioritisation of causal pathways for the Beetaloo GBA region

The numbers refer to the number of hazards and their priority effects identified for each causal pathway.

Causal pathway	Priority 1	Priority 2	Priority 3
Landscape management causal pathway group	**11**	**35**	**48**
Altering cultural heritage	2	3	2
Altering natural and agricultural productivity	0	4	18
Altering natural habitat and species distributions	2	21	18
Altering surface water hydrology	3	6	3
Introduction of invasive species	4	1	7
Subsurface flow paths causal pathway group	**0**	**7**	**15**
Compromised well integrity	0	6	5
Gas extraction altering groundwaters	0	1	2
Hydraulic fracturing	0	0	8
Water and infrastructure management causal pathway group	**1**	**33**	**32**
Discharging into surface waters	0	0	1
Disposal and storage of site materials	0	7	10
Failure of surface infrastructure (ponds, tanks, pipelines, etc.)	1	17	15
Processing and using extracted water	0	7	1
Sourcing water for site operations	0	2	5
Total	**12**	**75**	**95**

Source: Geological and Bioregional Assessment Program (2019a)

Six potential effects are prioritised for a detailed level of assessment in Stage 3 (priority 1) (Table 20):

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

Eight additional potential effects are prioritised for assessment in Stage 3 (priority 2) (Table 20):

- bank instability and erosion
- changed air quality
- changed groundwater levels or pressures
- changed groundwater quality
- damage to infrastructure
- increased mortality of native species

- increased soil erosion
- reduced soil productivity.

Fault reactivation and induced seismicity are not considered priorities and do not warrant further assessment in Stage 3 (priority 3) (Table 20).

Table 20 Prioritisation of potential effects for the Beetaloo GBA

The numbers refer to the number of hazards and their priority effects identified for each causal pathway.

Potential effect	Priority 1	Priority 2	Priority 3
Bank instability and erosion	0	2	0
Changed air quality	0	3	11
Changed groundwater levels or pressures	0	3	7
Changed groundwater quality	0	5	6
Changed surface water flows	1	5	4
Changed surface water quality	2	0	0
Cultural heritage damage or loss	2	3	2
Damage to infrastructure	0	2	0
Fault reactivation and induced seismicity	0	0	2
Habitat fragmentation and loss	2	13	8
Increased competition and predation	4	1	7
Increased mortality of native species	0	4	2
Increased soil erosion	0	3	10
Reduced soil productivity	0	1	8
Soil, groundwater and/or surface water contamination	1	30	28
Total	**17**	**76**	**113**

Source: Geological and Bioregional Assessment Program (2019a)

5.3 Causal pathways

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

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

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

Three groups of causal pathways were identified for the Beetaloo GBA region: (i) landscape management; subsurface flow paths; and (iii) water and infrastructure management, as shown in Figure 58 and described in Table 21.

Section 5.3.1 describes the preliminary conceptualisation of the five causal pathways in the landscape management causal pathway group in greater detail, which reflects the greater number of hazards identified as priority 1 (11 hazards) or as priority 2 (35 hazards) in this group (Table 19). The preliminary conceptualisation for the five causal pathways in the water and infrastructure management causal pathway group is described in less detail (Section 5.3.2), which reflects the smaller number of hazards identified as priority 1 (one hazard) or as priority 2 (33 hazards) in this group (Table 19). Section 5.3.3 provides a brief overview of the preliminary conceptualisation for the three causal pathways in the subsurface flow paths causal pathway group, which reflects that no hazards were identified as priority 1 and only seven hazards were identified as priority 2 (eight hazards) in this group (Table 19).

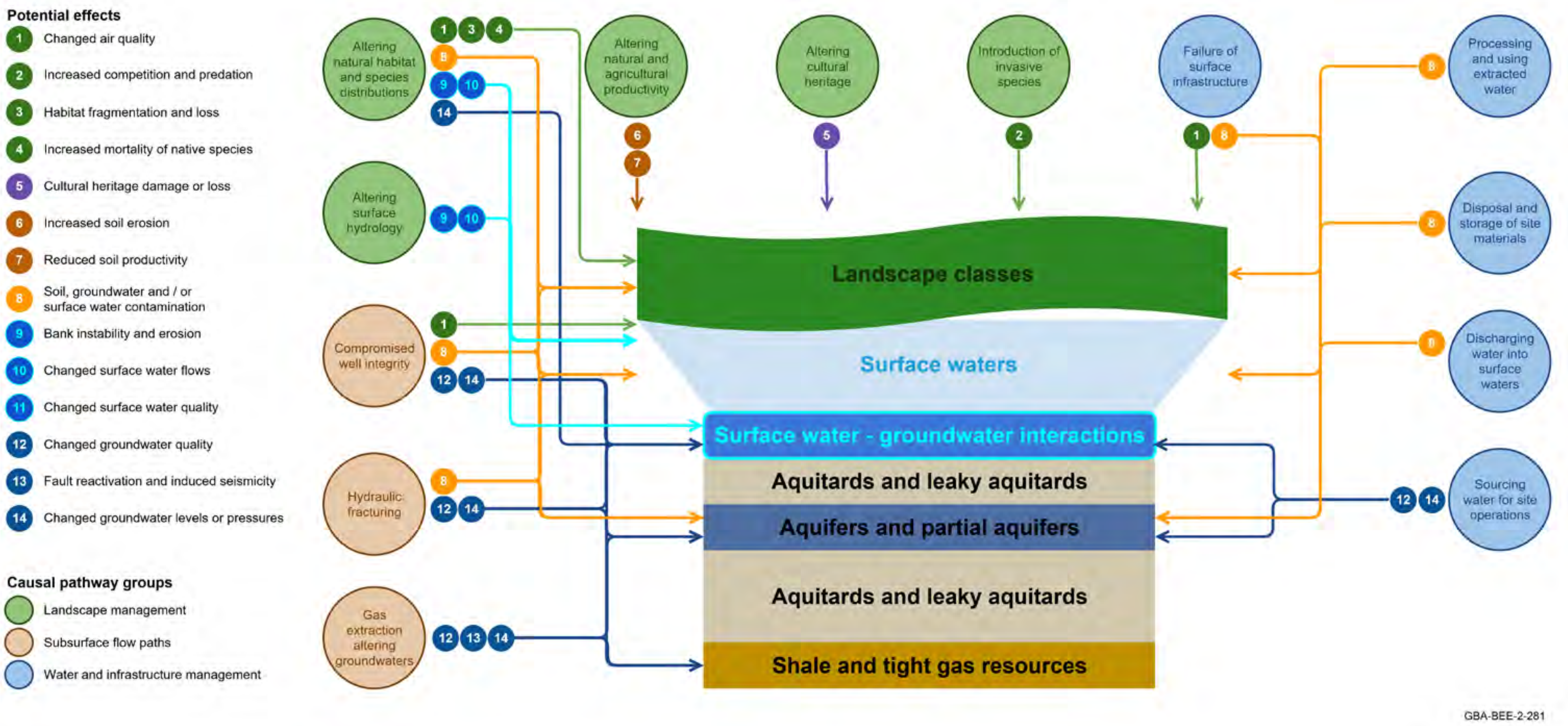

Figure 58 Causal pathways, causal pathway groups and potential effects identified for the Beetaloo GBA region

Arrows show how the causal pathways interact with key components: aquifers and partial aquifers; aquitards and leaky aquitards; landscape classes; shale gas, tight gas and shale oil resources; surface water – groundwater interactions; and surface waters. This figure has been optimised for printing on A3 paper (297 mm x 420 mm).
Typology and punctuation are consistent with the hazard identification dataset (Geological and Bioregional Assessment Program, 2019a).
Element: GBA-BEE-2-281

Table 21 Description of potential effects arising from hazards grouped by causal pathway and causal pathway group

Number of hazards in each causal pathway or causal pathway group is indicated in the brackets.

Causal pathway group	Causal pathway	Potential effects and approaches to mitigation
Landscape management (94 hazards)	Altering cultural heritage (7 hazards)	Construction of access roads and surface infrastructure may diminish cultural values through alteration, damage, disturbance, diminution and removal or restriction of use of cultural artefacts, ceremonial objects, rock art and cultural values. Cultural heritage clearances, training and site-based protocols manage potential impacts to cultural heritage.
	Altering natural and agricultural productivity (22 hazards)	Construction and rehabilitation of access roads, seismic surveys, surface infrastructure and well pads can cause increased soil erosion, reduced soil productivity and changed vegetation composition. Site management protocols aim to avoid sensitive areas (such as slopes, sensitive vegetation and fragile landscapes), minimise extent and timing of vegetation disturbance and earthworks and use progressive clearing and reinstatement practices to restore natural topsoil, contours and seedstock during rehabilitation.
	Altering natural habitat and species distributions (41 hazards)	Changed air quality, groundwater levels or pressures and surface water flows; soil erosion; habitat fragmentation and loss; increased mortality of native species; and exposure to soil, groundwater and/or surface water contamination can affect natural habitat and species distributions. Habitat fragmentation and loss can arise through direct impacts, such as alteration of natural fire regime, excavation and site vegetation removal; and by indirect impacts, such as light and noise impacts on fauna. Mortality of native species can arise by entrapment; increased road mortality; and changes to vegetation, groundwaters and surface water bodies. Natural habitat and species distributions can also be affected by the 'introduction of invasive species' causal pathway. Site management protocols aim to avoid, minimise or mitigate potential impacts on natural habitat and species distributions.
	Altering surface hydrology (12 hazards)	Civil construction and rehabilitation can alter the topography of the landscape, as well as the distribution of vegetation, which can change surface water flows and potentially cause bank instability and erosion. Subsurface fluid production and groundwater extraction can cause subsidence of land surface, creating artificial topographic lows where surface water may pool, altering surface water flows.
	Introduction of invasive species (12 hazards)	Construction of access roads and surface infrastructure can increase competition and predation on native species by invasive species. Invasive plants may displace or reduce cover of native vegetation, reducing available habitat and food sources (e.g. seeds) for native species such as some threatened birds. Dispersal associated with vehicle transport, landscape modification and ecosystem disturbance are managed by site-based conditions and rules. Other dispersal mechanisms associated with agricultural activities, stock movements and natural methods (via wind, water and dispersal activities by fauna) are managed by Commonwealth, territory and local government regulations.

Causal pathway group	Causal pathway	Potential effects and approaches to mitigation
Subsurface flow paths (22 hazards)	Compromised well integrity (11 hazards)	Failure of well barriers may create a direct fluid pathway between the target formation and overlying aquifers or the surface; or between non-target formations. Well barriers may be compromised by exposure to high fluid pressure, mechanical stresses, poor well construction, degradation of the cement or steel casing or thermal cycling. Changes to air quality; groundwater composition, levels or pressures; and soil, groundwater and/or surface water contamination may arise from compromised well integrity. After well decommissioning, abandoned wells may act as preferential pathways for fluid movement between geological layers. Well barriers ensure that control of the well is maintained during all life-cycle phases.
	Gas extraction altering groundwaters (3 hazards)	Subsurface fluid production and migration may change groundwater composition, levels or pressures and may cause fault reactivation and induced seismicity due to pressure changes in the target formation. Unlike conventional oil and gas production, the shale formations in the Beetaloo Sub-basin are unlikely to yield large volumes of produced water. These target formations are 'gas-charged' units, as the high pressure of the gas in the target formations has expelled much of the groundwater. In addition, water-sharing plans regulate access and provide an upper limit for water use.
	Hydraulic fracturing (8 hazards)	Hydraulic fracturing increases the productivity of petroleum wells by propagating hydraulic fractures that increase the effective permeability of the reservoir. Potential impacts that may arise following hydraulic fracturing include changed groundwater levels or pressures and groundwater composition, as well as fault reactivation and induced seismicity due to pressure changes. Potential impacts may arise from unplanned fracture growth into non-target geological layers, faults or wells that have higher permeability than the natural geological layers. Potential impacts are managed to a suitably low level by regulatory controls, sufficient understanding of the baseline geological and environmental systems, and acceptable industry practices.
Water and infrastructure management (66 hazards)	Discharging into surface waters (1 hazard)	Discharge of wastewater from hydraulic fracturing activities is prohibited in the NT. Discharge of treated sewage from camps and other infrastructure may occur, but volumes are likely to be small and there are regulatory controls on the quality of water that is released to the environment.
	Disposal and storage of site materials (17 hazards)	Soil, groundwater and/or surface water contamination may arise from disposal and storage of materials during construction, drilling and hydraulic fracturing, decommissioning, rehabilitation, vehicle transport, waste disposal and wastewater treatment. Potential spills from storage areas are contained by bunding and hardstand within designated facilities. Typical waste streams include cement; contaminated soils; drill cuttings; drilling and hydraulic fracturing chemicals; fluids; fertilisers and herbicides used for rehabilitation; sand; and residual waste from water treatment facilities, including biosolids, brines and sludge. Disposal and storage of site materials is a regulated activity governed by specific conditions and rules, particularly for waste that is stored onsite or taken offsite for disposal in an approved facility.

Causal pathway group	Causal pathway	Potential effects and approaches to mitigation
	Failure of surface infrastructure (ponds, tanks, pipelines, etc.) (33 hazards)	Leaks, spills or overflow from surface infrastructure during construction, drilling and hydraulic fracturing, natural hazards such as floods or bushfires, water management and rehabilitation can affect air quality and lead to soil, groundwater and/or surface water contamination. Ponds, tanks and pipelines are designed and managed to maintain integrity and operability. Management protocols include the mandated use of enclosed tanks for hydraulic fracturing wastewater in the NT, leak detection, corrosion mitigation, overpressure protection and fencing to exclude native fauna and livestock. Leaks, spills and overflow from surface infrastructure are regulated activities governed by specific conditions and rules, but (less commonly) they may be unregulated – for example, due to extreme flood inundation, natural hazards or failure of storages.
	Processing and using extracted water (8 hazards)	Reuse of extracted water can lead to soil, groundwater and/or surface water contamination. Beneficial or productive reuse of water is a regulated activity that aims to protect the environment and maximise the productive use of water. Reused water must meet relevant water quality guidelines for the end use and receiving environment. Potential beneficial reuse options include aquaculture, construction, dust suppression, industrial and manufacturing operations, landscaping and revegetation, and stock and domestic water supplies.
	Sourcing water for site operations (7 hazards)	Water is extracted from groundwaters for onsite operations. This may change groundwater composition, groundwater levels or pressures. Extraction of water must be licensed in the NT.

Source: Geological and Bioregional Assessment Program (2019a)

5.3.1 Landscape management causal pathways

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

- altering cultural heritage (seven hazards)
- altering natural and agricultural productivity (22 hazards)
- altering natural habitat and species distributions (41 hazards)
- altering surface hydrology (12 hazards)
- introduction of invasive species (12 hazards).

The individual hazards and potential effects associated with these causal pathways in the Beetaloo GBA region are illustrated conceptually in Figure 59. Each causal pathway includes a range of different impact modes and potential effects identified through the IMEA process, most of which are focused on impacts at the land surface, such as habitat fragmentation and loss, increased competition and predation from invasive species, changed surface water flows and increased mortality of native species.

Priority 1 and 2 hazards were identified in all five causal pathways:

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

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

- habitat fragmentation and loss (15 out of 23 hazards)
- changed surface water flows (three out of nine hazards)
- cultural heritage damage or loss (five out of seven hazards)
- increased mortality of native species (four out of six hazards)
- increased competition and predation (five out of 12 hazards)
- increased soil erosion (three out of ten hazards)
- changed air quality (three out of nine hazards)
- bank instability and erosion (two out of two hazards)
- reduced soil productivity (one out of nine hazards).

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

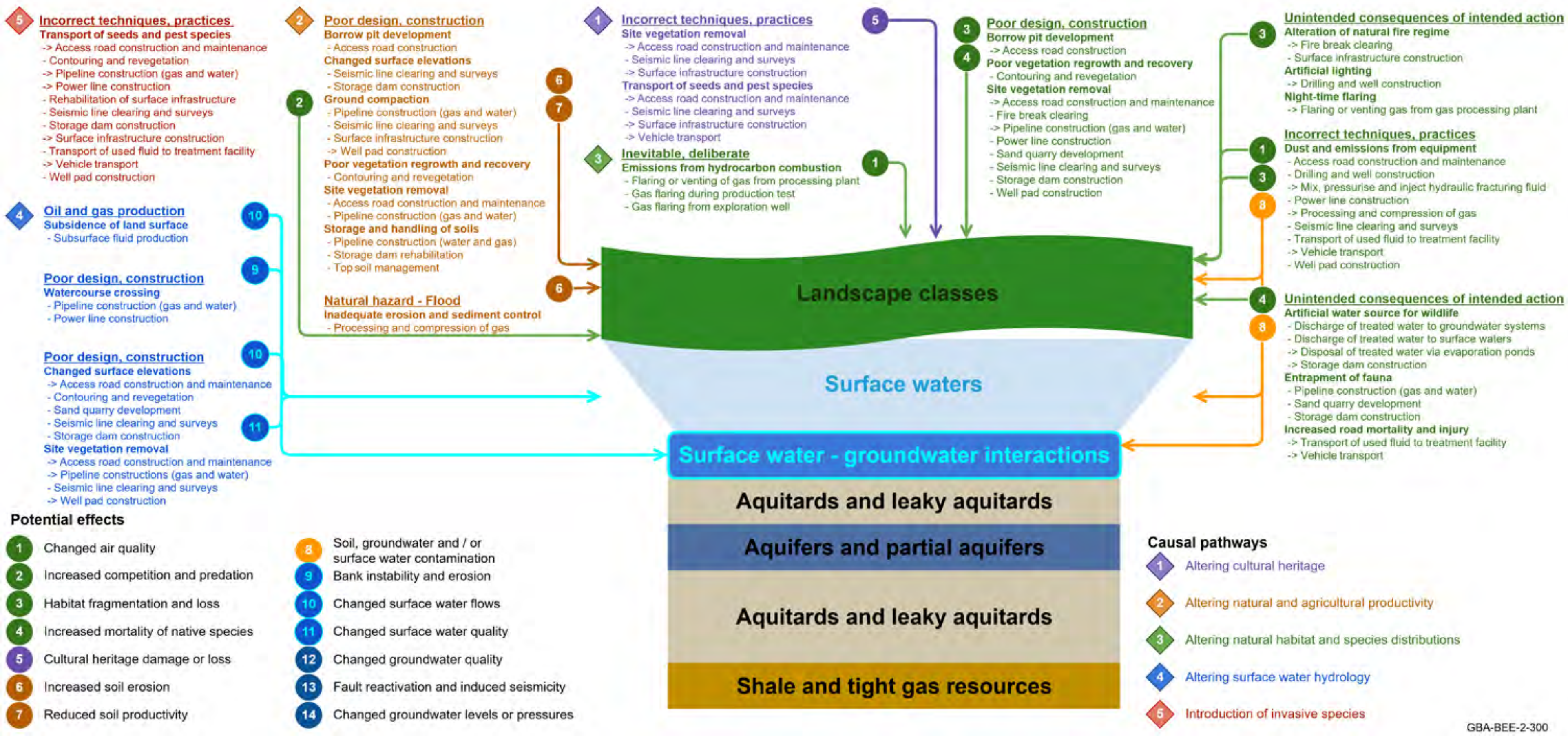

Figure 59 Hazards (impact causes, impact modes and activities) and associated effects in the 'landscape management' causal pathway group identified for shale gas, tight gas and shale oil development in the Beetaloo GBA region

Impact causes are underlined, impact modes are bold, activities are bullet points (low-priority hazards = '-' and priority hazards = '->'). An individual activity may lead to more than one hazard if multiple potential effects are associated with an activity. Arrows show how the individual hazards interact with key components: aquifers and partial aquifers; aquitards and leaky aquitards; landscape classes; shale gas, tight gas and shale oil resources; surface water – groundwater interactions; and surface waters. Causal pathways are identified by number and text colour. This figure has been optimised for printing on A3 paper (297 mm x 420 mm).
Typology and punctuation are consistent with the hazard identification dataset (Geological and Bioregional Assessment Program, 2019a).
Element: GBA-BEE-2-300

5.3.1.1 Altering cultural heritage

Cultural heritage sites can be physically, socially and spiritually linked to ecologically significant areas and archaeological or historic sites across the region (Figure 60). Risks to cultural heritage in the Beetaloo GBA region are related to site vegetation removal and transport of seeds and pest species, which may alter values associated with water resources, vegetation and wildlife that have strong connections with cultural traditions (Constable et al., 2015). Traditional Owners value their country and have good knowledge of ecosystem function and the physico-chemical and biological processes that drive an ecosystem and sustain life (Trivedi et al., 2018), particularly the links between water, vegetation and wildlife in arid landscapes. Damage or loss of cultural heritage values may permanently diminish cultural values for a community or group. Waterholes, lakes, rivers and aquifers have spiritual values, with many sites attached to creation stories. Traditional Owners are concerned about damage to sacred sites that may restrict or inhibit use as a cultural or ceremonial site. This includes waterholes associated with customary rituals, such as women's business and historic burial sites (Constable et al., 2015).

Risks to cultural heritage values in the region include potential changes to water resources or shrinkage of spring-fed waterholes from groundwater. Construction activities and changes to water regimes may also facilitate the introduction and establishment of invasive species that can diminish cultural heritage values.

Vegetation removal for the development of roads and surface infrastructure could potentially remove food and medicinal plants and may also affect cultural values associated with natural habitat and species distributions. Site vegetation removal that causes minor to moderate damage or loss to cultural heritage (reversible in ten years or less) is a priority hazard in the Beetaloo GBA region. Changes to cultural heritage can affect food supply and cultural connectedness of Traditional Owners. Introduction or facilitation of invasive weeds and pests could also upset the natural balance, potentially affecting cultural values (Figure 60). Incorrect techniques or practices used during development may remove, damage or substantially disturb cultural artefacts, archaeological deposits, Indigenous built structures or ceremonial objects. This includes resource areas, paintings, engravings, scar trees, quarries, shell middens, dwellings, burial sites, landscape features, artefact scatters, stone arrangements, hearth ovens, pathways and important story places (Constable et al., 2015).

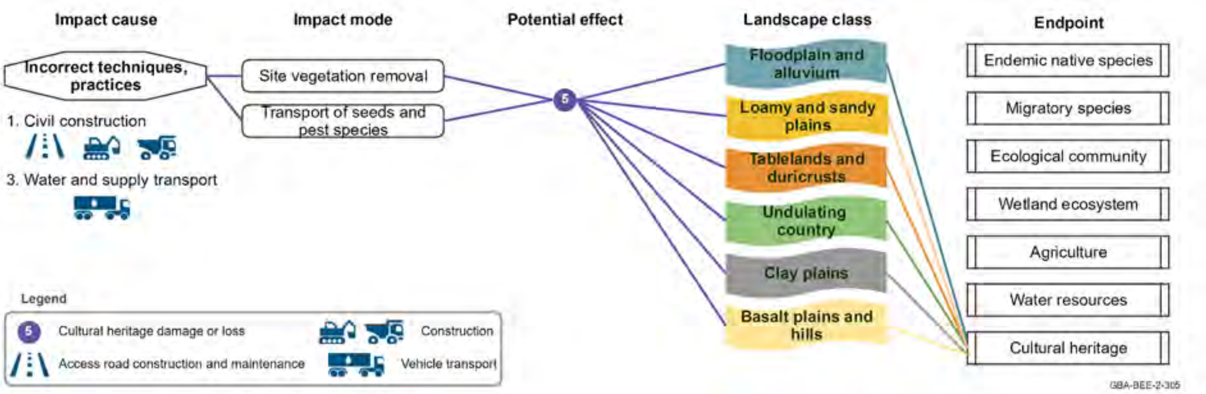

Figure 60 Preliminary conceptualisation of hazards associated with future shale gas, tight gas and shale oil development in the Beetaloo GBA region for the 'altering cultural heritage' causal pathway

Numbered items refer to the ten major activities described in Figure 55 (e.g. '1. Civil construction').
Data: Geological and Bioregional Assessment Program (2019a)
Element: GBA-BEE-2-305

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

5.3.1.2 Altering natural and agricultural productivity

Risks to natural and agricultural productivity in the Beetaloo GBA region include increased soil erosion and reduced soil productivity. Increased soil erosion is caused by disturbance to the soil structure by natural (such as flooding) or mechanical means, which causes removal of rocks and soil particles and changes in landform. Poor design and construction of access roads, borrow pits, pipelines (gas and water), seismic surveys, surface infrastructure and well pads can alter drainage pathways, increase soil erosion and reduce soil productivity. Increased soil erosion due to ground compaction during well pad construction is a priority 2 hazard.

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

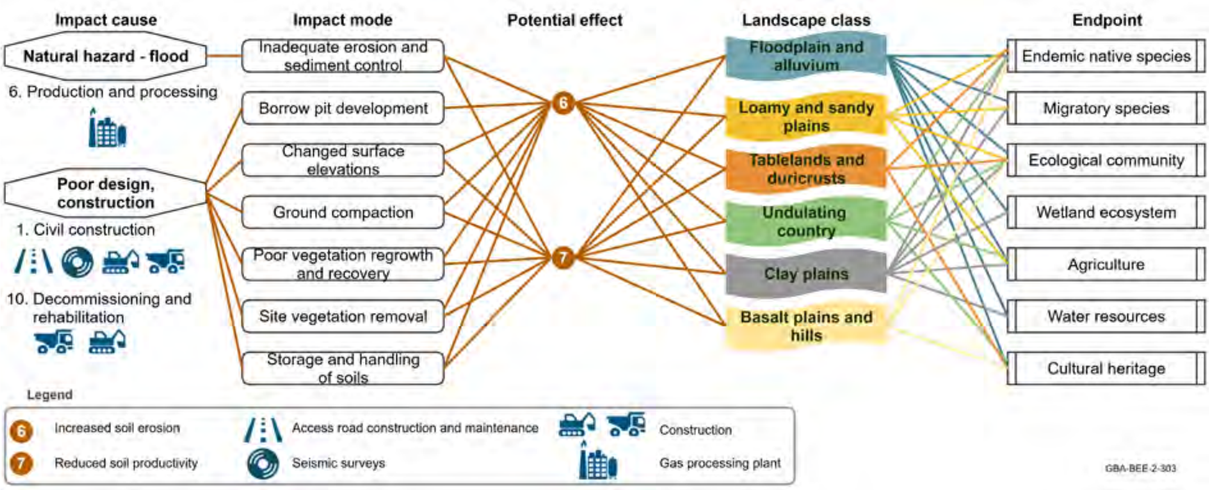

Figure 61 Preliminary conceptualisation of hazards associated with shale gas, tight gas and shale oil development in the Beetaloo GBA region in the 'altering natural and agricultural productivity' causal pathway

Numbered items refer to the ten major activities described in Figure 55 (e.g. '1. Civil construction').
Data: Geological and Bioregional Assessment Program (2019a)
Element: GBA-BEE-2-303

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

5.3.1.3 Altering natural habitat and species distributions

Natural habitat and species distribution may be affected in a number of ways, including habitat fragmentation and loss; increased mortality or reduced productivity of native species; changed air quality; contamination of soil, groundwater and/or surface water; changed groundwater levels or pressures (one hazard); and changed surface water flows (Figure 62). In particular, land clearance is a key threatening process identified under the EPBC Act. Vegetation removal can potentially affect both terrestrial and aquatic environments, as well as removing ground cover that is important natural habitat.

Suitable habitat for threatened species can also be reduced following disturbance when invasive species out-compete native vegetation, creating monocultures (see the 'introduction of invasive species' causal pathway, Figure 64). Introduced plant species, such as invasive grasses, can also increase the severity and likelihood of fire, which can be detrimental to fire-sensitive plant communities and less mobile native wildlife.

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

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

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

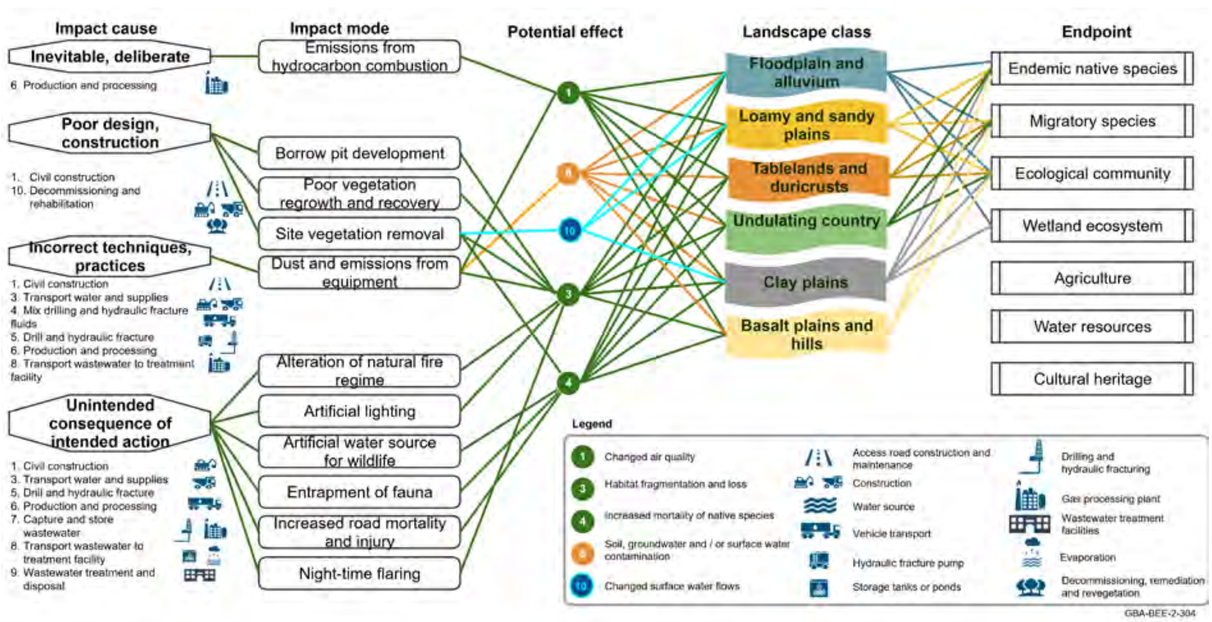

Figure 62 Preliminary conceptualisation of hazards associated with shale gas, tight gas and shale oil development in the Beetaloo GBA region in the 'altering natural habitat and species distribution' causal pathway

Numbered items refer to the ten major activities described in Figure 55 (e.g. '1. Civil construction').
Data: Geological and Bioregional Assessment Program (2019a)
Element: GBA-BEE-2-304

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

Construction and maintenance of roads, pipelines and seismic survey lines can lead to habitat fragmentation and loss through removal of vegetation. Historically, methods used to clear vegetation for seismic surveys permanently fragmented the landscape. New acquisition methods used for recent seismic surveys result in more rapid vegetation recovery.

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

5.3.1.4 Altering surface hydrology

Surface water hydrology may be affected by bank instability and erosion, as well as changed surface water flows (Figure 63). This is most likely to occur on floodplains and clay plains but can also occur anywhere in the landscape where surface water flows occur. Activities that can alter surface hydrology identified as priority 1 or 2 hazards include construction of access roads and well pads that could affect the magnitude, duration, timing and frequency of surface water flows.

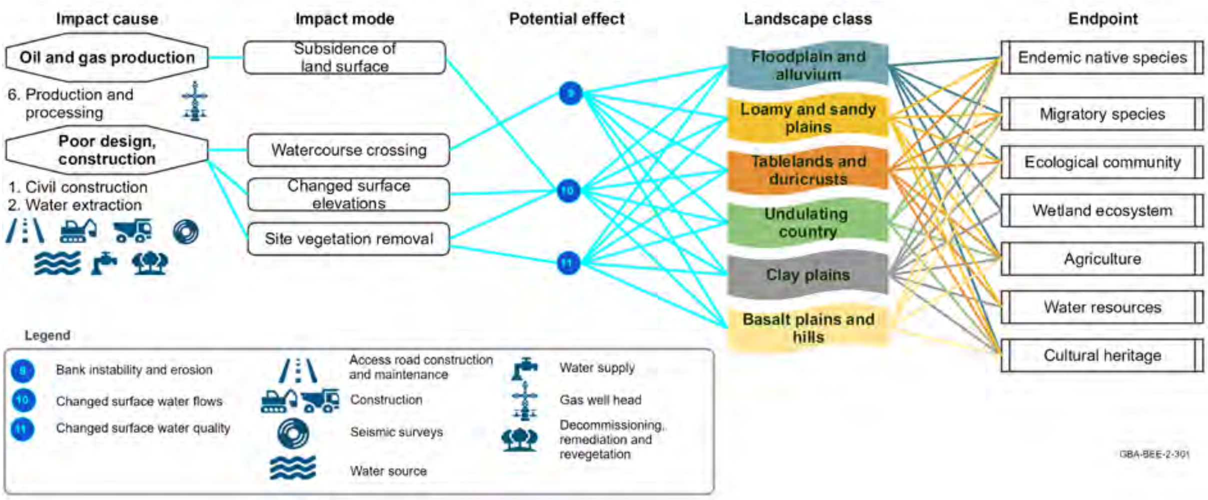

Figure 63 Preliminary conceptualisation of hazards associated with future shale gas, tight gas and shale oil development in the Beetaloo GBA region in the 'altering surface hydrology' causal pathway

Numbered items refer to the ten major activities described in Figure 55 (e.g. '1. Civil construction').
Data: Geological and Bioregional Assessment Program (2019a)
Element: GBA-BEE-2-301

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

Management protocols to minimise the impact of road construction on surface waters include ensuring that roads and access tracks are constructed in accordance with applicable Australian standards, guidelines and codes of practice. Erosion control measures are installed where required.

5.3.1.5 Introduction of invasive species

Invasive species can be introduced, or the spread of those already in a region facilitated, through incorrect techniques or practices throughout development (Figure 64). Transport of seeds and pest species during construction of access roads, pipelines, powerlines and surface infrastructure, as well as transport of water and supplies, may have a moderate to major impact on ecosystems. Priority hazards identified in the 'introduction of invasive species' causal pathway include construction and maintenance of access roads, pipelines (gas and water), power lines and other surface infrastructure. Introduction of invasive species via vehicle transport is a priority 2 hazard.

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

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

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

Pest species can also take advantage of artificial water points, such as water tanks and leaking pipes, as well as storage dams, and this can allow pests to become established. Artificial water points can attract introduced species, such as feral goats (*Capra hircus*) and cane toads (*Rhinella marina*), that can be detrimental to local wildlife (Letnic et al., 2014).

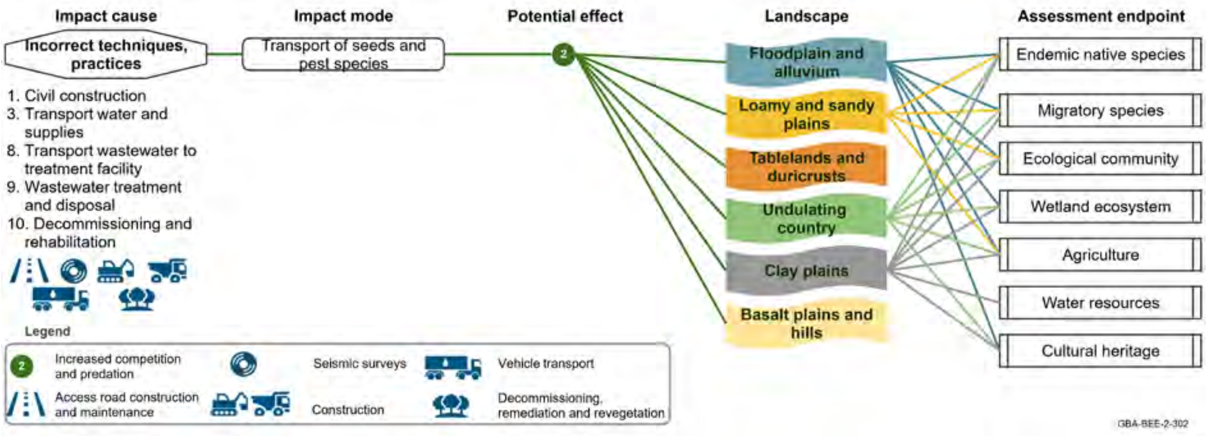

Figure 64 Preliminary conceptualisation of hazards associated with future shale gas, tight gas and shale oil development in the Beetaloo GBA region in the 'introduction of invasive species' causal pathway

Numbered items refer to the ten major activities described in Figure 55 (e.g. '1. Civil construction').
Data: Geological and Bioregional Assessment Program (2019a)
Element: GBA-BEE-2-302

Site-based protocols include vehicle and machinery cleaning, when arriving and leaving sites, to remove all seeds or plant material – particularly washdown of all vehicles for interstate movement and in some cases for movement of vehicles between properties.

Most introduced plants in the Beetaloo GBA region are naturalised or widespread species of limited concern. However, there is a number of species of invasive plants that are of particular concern in the region. These species include buffel grass (*Cenchrus ciliaris*), Parkinsonia (*Parkinsonia aculeata*), Parthenium (*Parthenium hysterophorus*) and rubber bush (*Calotropis procera*). Other species of invasive plants are currently not a major pest in the Beetaloo GBA region, but they have the potential to invade or increase in abundance in the future. These species include Noogoora burr (*Xanthium strumarium*). Management protocols target the detection and assessment of the spread of pest plants and animals.

5.3.2 Subsurface flow paths causal pathways

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

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

Subsurface flow paths causal pathways are focused on water-related impacts that may occur at various depths below the surface, such as changes to groundwater quality or groundwater pressures in an aquifer (Figure 65).

Priority hazards are identified in two of the causal pathways:

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

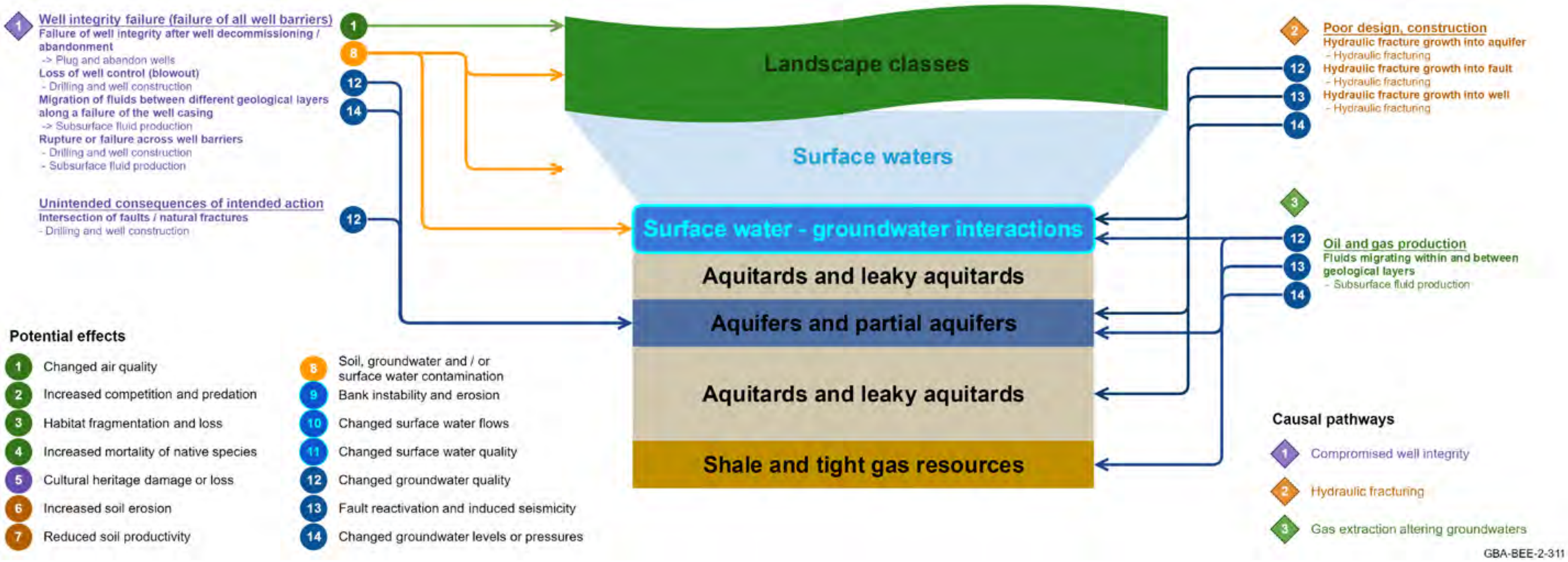

Figure 65 Hazards (impact causes, impact modes and activities) and associated effects in the 'subsurface flow paths' causal pathway group identified for shale gas, tight gas and shale oil development in the Beetaloo GBA region

Impact causes are underlined, impact modes are bold, activities are bullet points (low-priority hazards = '-' and priority hazards = '->'). An individual activity may lead to more than one hazard if multiple potential effects are associated with an activity. Arrows show how the individual hazards interact with key components: aquifers and partial aquifers; aquitards and leaky aquitards; landscape classes; shale gas, tight gas and shale oil resources; surface water – groundwater interactions; and surface waters. Causal pathways are identified by number and text colour. This figure has been optimised for printing on A3 paper (297 mm x 420 mm).
Typology and punctuation are consistent with the hazard identification dataset (Geological and Bioregional Assessment Program, 2019a).
Element: GBA-BEE-2-311

5.3.2.1 Compromised well integrity

The effective maintenance of well integrity throughout all life-cycle stages of a petroleum well is critical for its safe operation and to ensure the protection of water resources and the environment. This includes wells drilled to explore for, appraise or produce hydrocarbons from the types of unconventional gas reservoirs in the Beetaloo Sub-basin that are the focus of the GBA Program (shale gas, tight gas and shale oil plays). If the integrity of a well is compromised at any stage in its life cycle (including for decommissioned wells), it may create an unintended pathway for fluids to flow either out of or into the well or between different geological formations (potentially including aquifers) or even to the surface. For these reasons, well integrity is of paramount importance to the oil and gas industry, service companies and regulatory organisations and is also commonly recognised as a key concern of local communities in areas of unconventional gas development. Current regulations in the NT require industry to proactively manage risks associated with drilling, installation and operation of gas wells (Northern Territory Government, 2019c, 2019d). These regulatory requirements draw on the many international standards that exist for managing well integrity.

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

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

Hazards associated with compromised well integrity are most likely to have a localised impact on groundwater systems, with the potential to affect groundwater quality (five hazards) and groundwater levels or pressures (one hazard). However, if well integrity failure results in uncontrolled release of gas and/or fluids to the surface, there is also potential for changes to air quality (e.g. escape of methane to the atmosphere – three hazards), as well as contamination of soils, surface waters or shallow groundwaters (two hazards). In situations where gas and fluids are released at surface due to compromised well integrity, the most severe impacts are likely to be localised to the immediate vicinity of the well, although effects may extend further – for example, due to airborne dispersal of natural gas (Figure 66).

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

Failure of integrity after decommissioning of a well is a priority 2 hazard for the Beetaloo GBA region. It can affect groundwater quality, potentially leading to similar effects on aquifers as noted above.

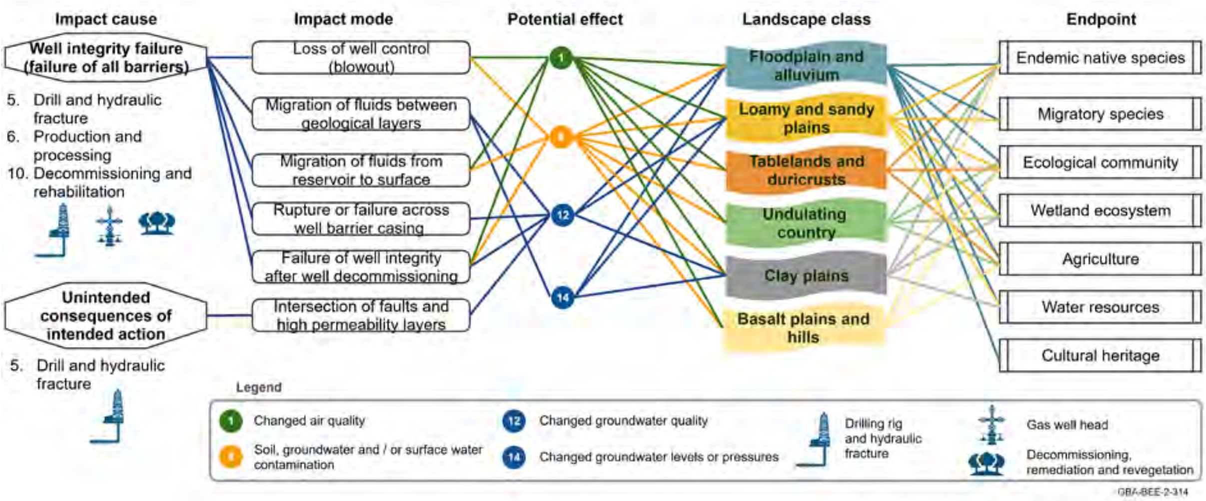

Figure 66 Preliminary conceptualisation of hazards associated with shale gas, tight gas and shale oil development in the Beetaloo GBA region in the 'compromised well integrity' causal pathway

Numbered items refer to the ten major activities described in Figure 55 (e.g. '1. Civil construction').
Data: Geological and Bioregional Assessment Program (2019a)
Element: GBA-BEE-2-314

Prior to the drilling and operation of a shale gas, tight gas or shale oil well, considerable planning is required to ensure that the well can be installed and operated safely and efficiently. For example, it is critical to understand key geological parameters of the gas reservoir and the surrounding rock formations so that the well is designed to withstand the local geological conditions. Good knowledge of local geology that guides the installation of an appropriately designed well is essential in ensuring that well integrity is maintained throughout all life-cycle stages. Well barriers and operational practices are designed to prevent the uncontrolled release of fluids – between the well and geological formations, between geological formations or to the surface. Well barriers are the main features of the well that ensure its integrity. They include well barrier elements such as drilling muds, steel drill casing, high-quality cement, well heads and blowout preventers. There are also various operational, administrative and regulatory aspects to successfully maintaining well integrity (Huddlestone-Holmes et al., 2018; Northern Territory Government, 2019c, 2019d).

In addition to the IMEA hazard identification, a more detailed qualitative analysis of well integrity and hydraulic fracturing was undertaken in Stage 2 of the GBA Program for the Beetaloo GBA region, leading to a supporting technical appendix (see Kear and Kasperczyk

(2020), with a summary provided in Section 6.2). The specific focus on these aspects of unconventional gas resource development was considered appropriate given the high level of community concern raised about these issues at user panel meetings for the Beetaloo GBA region. This review focused in detail on summarising the findings from nine domestic and international inquiries, as well as analysing Beetaloo Sub-basin data relating to well integrity.

5.3.2.2 Hydraulic fracturing

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

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

Potential effects that may arise during hydraulic fracturing (Figure 67) of shale gas, tight gas and shale oil wells include changes to the groundwater quality of an aquifer and changes to groundwater pressures in confined aquifers. These effects arise due to the unplanned release of hydraulic fracturing fluids into subsurface formations beyond the extent of the target gas reservoir. There is also potential for hydraulic fracturing to intersect other petroleum or water supply wells that could contaminate soil, groundwater or surface waters. Growth of a fracture into a fault that could lead to fault reactivation and induced seismicity was also considered. Limited information is available on natural background seismicity in the region due as the coverage from the existing seismic monitoring is not able to detect small seismic events. Elevated cyclical pressures applied to wells during hydraulic fracturing could also affect the integrity of the well (Huddlestone-Holmes et al., 2018), which is addressed by the ‘compromised well integrity’ causal pathway (Figure 66).

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

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

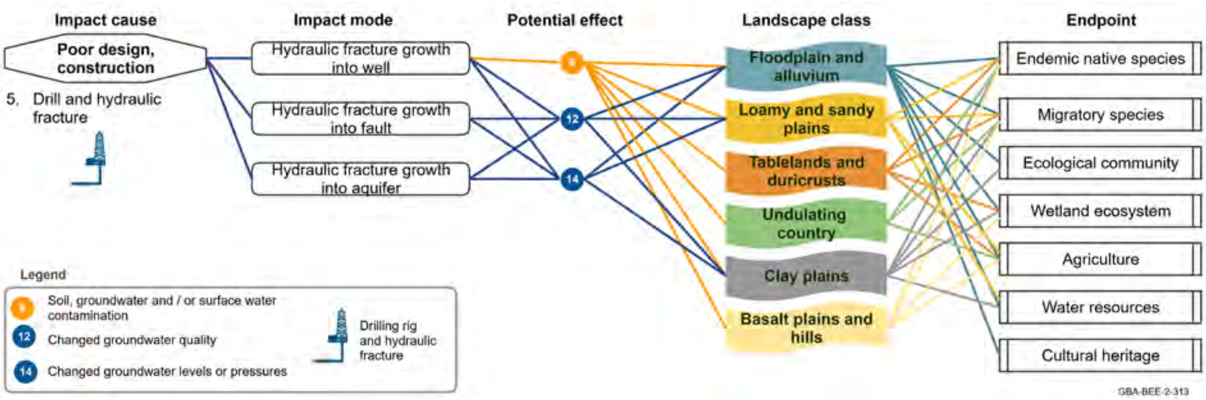

Figure 67 Preliminary conceptualisation of hazards associated with shale gas, tight gas and shale oil development in the Beetaloo GBA region in the ‘hydraulic fracturing’ causal pathway

Numbered items refer to the ten major activities described in Figure 55 (e.g. ‘1. Civil construction’).
Data: Geological and Bioregional Assessment Program (2019a)
Element: GBA-BEE-2-313

Effective planning, design and implementation of each hydraulic fracturing stage are critical to ensuring that the risks to groundwater associated with hydraulic fracturing are adequately managed. Given adherence to existing regulatory controls and guidelines (Northern Territory Government, 2019c, 2019d) designed to safeguard the process, the risks posed by hydraulic fracturing are generally regarded as acceptable to both the gas industry and government regulators. Indeed, the IMEA ranked all hazards associated with the hydraulic fracturing causal pathway as priority 3 hazards – the lowest tier of hazards classified in this assessment. However, due to heightened community concern related to hydraulic fracturing impact modes, the qualitative assessment outlined in Section 6.2 recommends undertaking analysis in Stage 3 of the Beetaloo GBA to further evaluate the potential for hydraulic fracture growth into overlying aquifers specific to the unconventional gas target reservoirs in the Beetaloo GBA region.

5.3.2.3 Gas extraction altering groundwaters

Production of gas from unconventional reservoirs may cause changes in reservoir pressures as gas is extracted during the life of the well (typically ten to 20 years), with potential effects on the quality and/or pressure of groundwaters (Figure 68). Another potential effect relates to changes in reservoir pressures, which may lead to fault reactivation and potentially induced seismic activity.

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

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

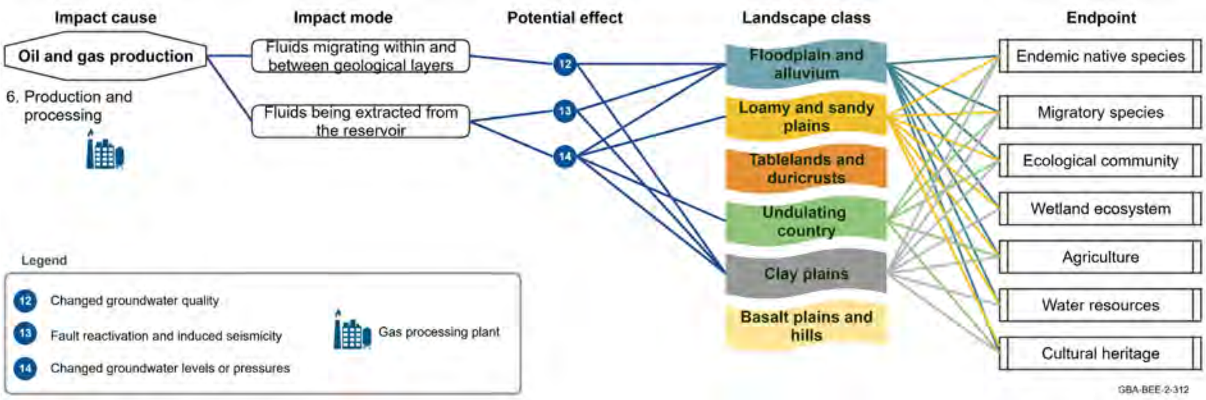

Figure 68 Preliminary conceptualisation of hazards associated with shale gas, tight gas and shale oil development in the Beetaloo GBA region in the 'gas extraction altering groundwaters' causal pathway

Numbered items refer to the ten major activities described in Figure 55 (e.g. '1. Civil construction').
Data: Geological and Bioregional Assessment Program (2019a)
Element: GBA-BEE-2-312

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

5.3.3 Water and infrastructure management causal pathways

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

- discharging water into surface waters (one hazard)
- disposal and storage of site materials (17 hazards)
- failure of surface infrastructure (ponds, tanks, pipelines, etc.) (33 hazards)
- processing and using extracted water (eight hazards)
- sourcing water for site operations (seven hazards).

The individual hazards and potential effects associated with these causal pathways in the Beetaloo GBA region are illustrated conceptually in Figure 69. The impact modes and potential effects are mostly focused on impacts to surface waters or groundwaters, including changes to levels, pressures or flows and water quality.

Priority hazards were identified for four of the causal pathways:

- failure of surface infrastructure (ponds, tanks, pipelines, etc.) (18 out of 33 hazards)
- sourcing water for site operations (one out of seven hazards)
- disposal and storage of site materials (seven out of 17 hazards)
- processing and using extracted water (seven out of eight hazards).

Potential effects associated with priority hazards are:

- soil, groundwater and/or surface water contamination (30 out of 55 hazards)
- changed groundwater levels or pressures (one out of five hazards)
- damage to infrastructure (two out of two hazards).

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

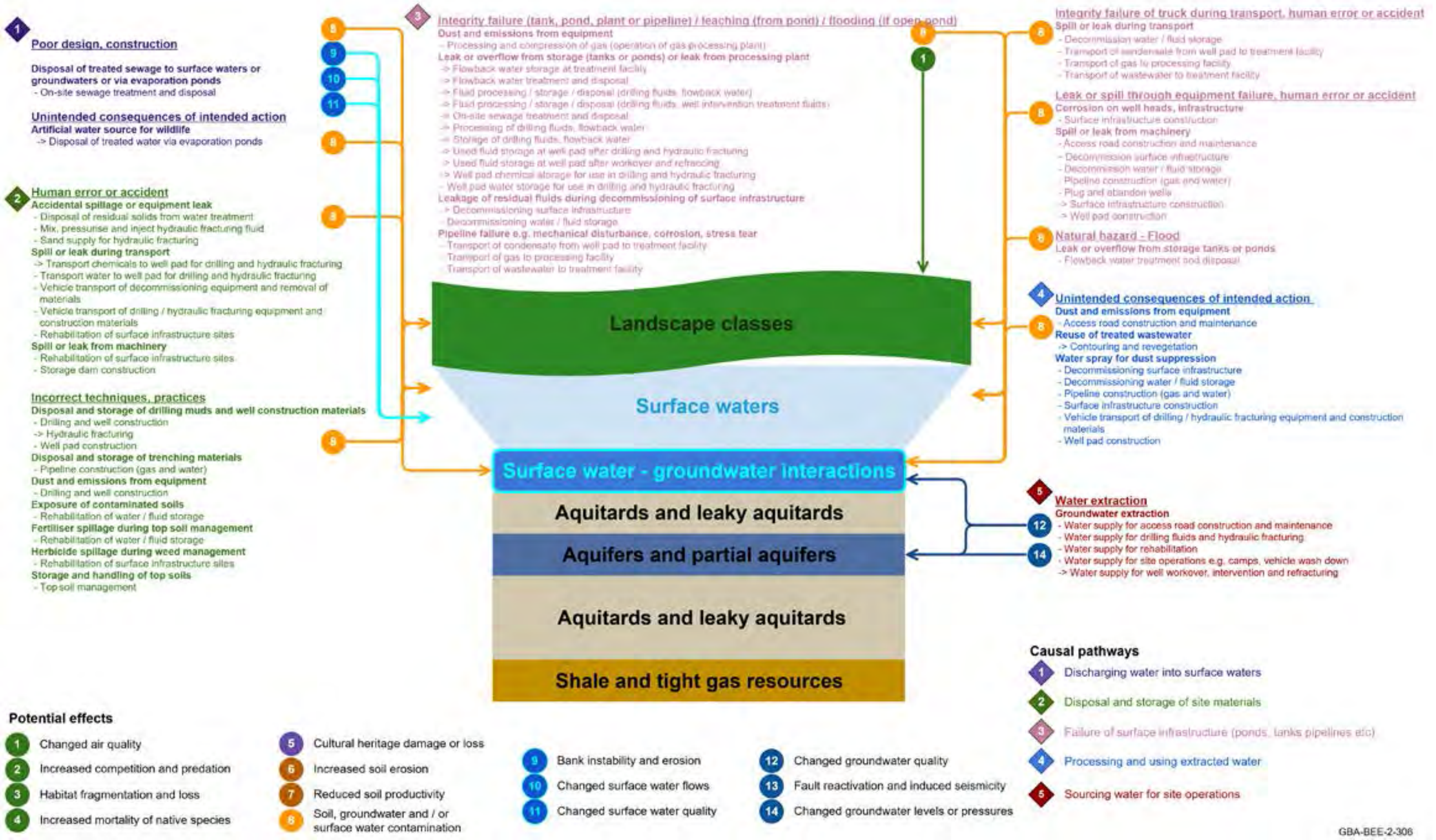

Figure 69 Hazards (impact causes, impact modes and activities) and associated effects in the 'water and infrastructure management' causal pathway group identified for shale gas, tight gas and shale oil development in the Beetaloo GBA region

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

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

Element: GBA-BEE-2-306

5.3.3.1 Discharging into surface waters

The intentional discharge of wastewater from shale gas, tight gas and shale oil activities into surface waters is prohibited in the NT. The only hazard identified for this causal pathway is from the discharge of wastewater (treated sewage) from camps or other supporting infrastructure and is considered to be low priority. Any volumes are likely to be low and the wastewater would be treated to meet minimum standards. No priority hazards have been identified for this causal pathway. Potential effects of this hazard are the contamination of soil, groundwater and/or surface waters (Figure 70). An unintended consequence of discharging treated water into streams is the creation of artificial water sources for wildlife. While this may be positive for some species, it can have negative consequences for native species if the additional water source favours introduced species.

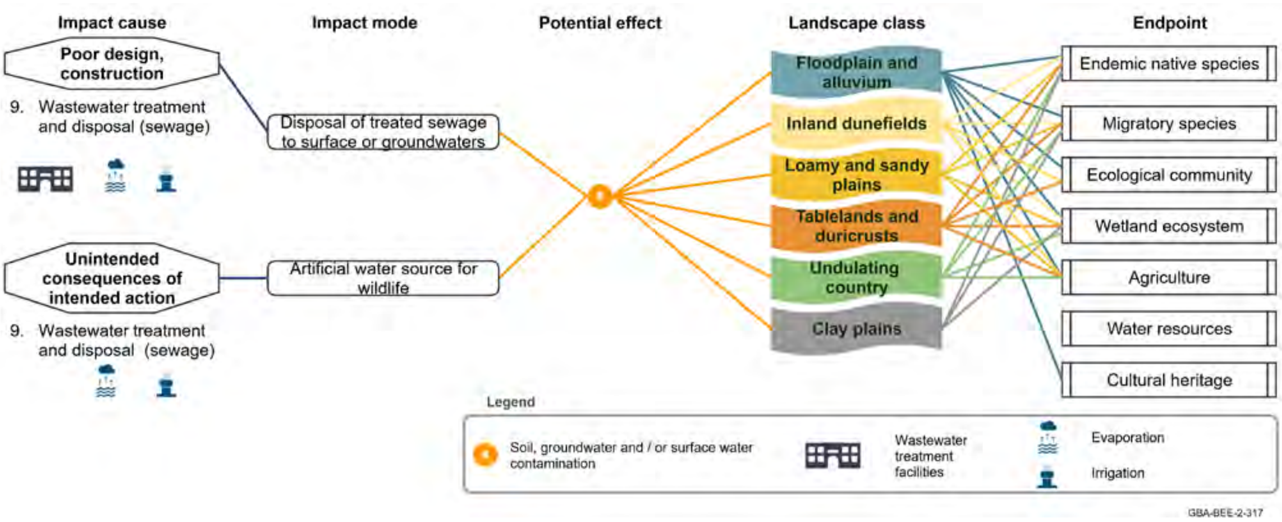

Figure 70 Preliminary conceptualisation of hazards associated with shale gas, tight gas and shale oil development in the Beetaloo GBA region in the 'discharging into surface waters' causal pathway

Only wastewater from sewage is considered due to the prohibition on the discharge of hydraulic fracturing wastewater to surface waters in the Northern Territory.
Numbered items refer to the ten major activities described in Figure 55 (e.g. '1. Civil construction').
Data: Geological and Bioregional Assessment Program (2019a)
Element: GBA-BEE-2-317

Several management protocols are in place to reduce the impact of discharge of wastewater. These include the requirement to treat water to an acceptable level before discharge; water quality testing; and fencing to minimise the potential for access by native fauna and livestock.

5.3.3.2 Disposal and storage of site materials

Soil, groundwater and/or surface water contamination may arise due to human error or accident or when incorrect techniques and practices are used for the disposal and storage of site materials (Figure 71). Spills in chemical storage areas are contained by bunding and hardstand within designated facilities. Typical waste streams include cement; contaminated soils; drill cuttings; drilling and hydraulic fracturing chemicals; fluids; fertilisers and herbicides used for rehabilitation; sand; and waste from water treatment facilities, including biosolids, brines and sludge. Disposal and storage of site materials is a regulated activity governed by specific conditions and rules, particularly for waste that is stored onsite or taken offsite for disposal in an approved facility. Spills and accidents involving chemicals could occur during all phases of operation (e.g. well casing failures, spills during fluid transport) and could potentially lead to contamination of soils, surface water and/or shallow groundwater. Changes to water quality may increase stress and/or mortality of aquatic species, riparian zone vegetation and non-aquatic wildlife using surface waters to drink.

Potential impacts associated with this causal pathway are typically localised to the landscape class where disposal and storage operations occur. In the Beetaloo GBA region this is most likely to be in the 'loamy and sandy plains' and 'clay plains' landscape class, although the other landscapes could also be affected to a lesser degree (Figure 71). A variety of endpoints linked to the potentially affected landscapes may be affected by hazards associated with disposal and storage of materials.

Accidental spills or leaks during transport of drilling and hydraulic fracturing equipment that contaminate soil, groundwater and/or surface waters due to human error or accident are considered a priority hazard. Similarly, it is possible that incorrect techniques and practices used in the disposal and storage of drilling muds and well construction materials during drilling and hydraulic fracturing, and exposure of contaminated soils, fertiliser or herbicide spillage during decommissioning and rehabilitation, may lead to similar impacts and so is also considered a priority hazard.

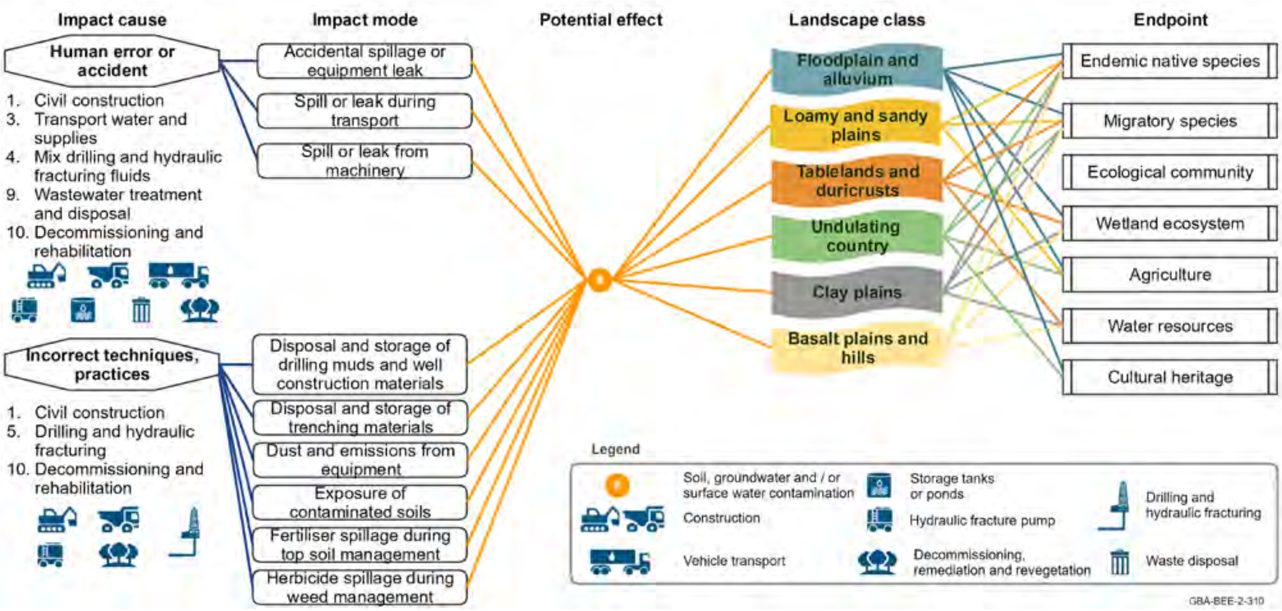

Figure 71 Preliminary conceptualisation of hazards associated with shale gas, tight gas and shale oil development in the Beetaloo GBA region in the 'disposal and storage of site materials' causal pathway

Numbered items refer to the ten major activities described in Figure 55 (e.g. '1. Civil construction').
Data: Geological and Bioregional Assessment Program (2019a)
Element: GBA-BEE-2-310

Risks associated with transportation, storage and handling of chemicals, fuels and oils are managed in accordance with relevant standards and guidelines.

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

Failure of surface infrastructure may result in changes to air quality or contamination of soil, groundwater and/or surface water (Figure 72). Surface infrastructure includes pipelines, storage tanks, evaporation ponds, transport vehicles, machinery (civil construction equipment, drilling and hydraulic fracturing equipment) and operating plant. Fluids that may be released from infrastructure include produced hydrocarbon gas and liquids, produced water, flowback water, hydraulic fracturing fluids, fuels and lubricants in machinery and plant, and process chemicals that are used in some infrastructure.

The hazards associated with failure of surface infrastructure can range from having a localised impact (e.g. minor leak of fuel or lubricant) through to having more widespread impacts (e.g. failure of wastewater transfer pipe). Consequently, there is potential in the Beetaloo GBA region for all of the landscape classes and many of their associated endpoints to be affected by these hazards, particularly where soil, shallow groundwater or surface water systems may be contaminated (Figure 72).

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

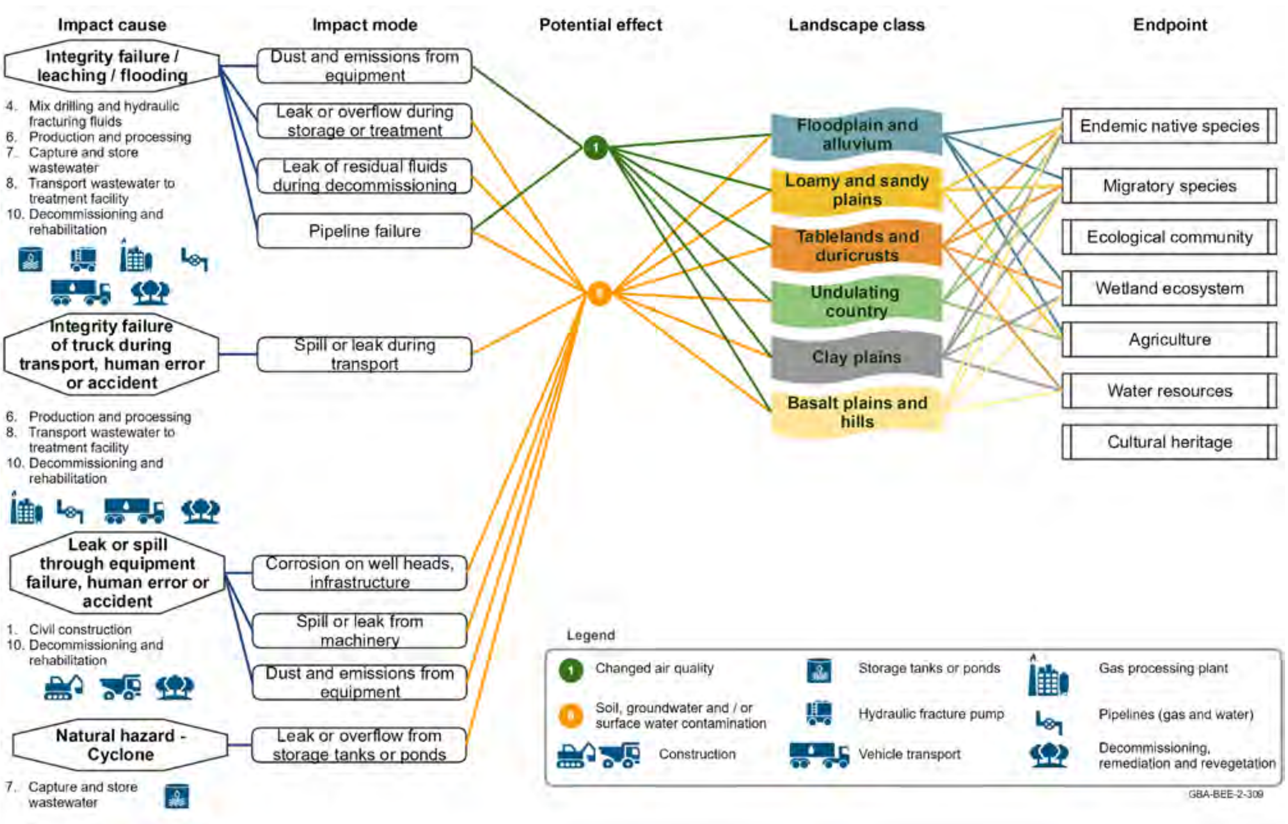

Figure 72 Preliminary conceptualisation of hazards associated with shale gas, tight gas and shale oil development in the Beetaloo GBA region in the 'failure of surface infrastructure' causal pathway

Numbered items refer to the ten major activities described in Figure 55 (e.g. '1. Civil construction').
Data: Geological and Bioregional Assessment Program (2019a)
Element: GBA-BEE-2-309

Ponds, tanks and pipelines are designed and managed to maintain integrity and operability. In the NT, all hydraulic fracturing wastewater must be stored in enclosed tanks with secondary containment (Northern Territory Government, 2019c). Management protocols include leak detection, maintenance, corrosion mitigation, overpressure protection, and fencing to exclude native fauna and livestock. Leaks, spills or overflow from surface infrastructure is a regulated activity governed by specific conditions and rules but (less commonly) may be unregulated – for example, due to extreme flood inundation, natural hazards or failure of storage dams.

5.3.3.4 Processing and using extracted water

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

Priority hazards identified from processing and use of extracted water (Figure 73) relate primarily to unintended consequences from the use of water for dust suppression during civil construction, transport of water and supplies, and irrigation for remediation and revegetation activities. Reuse of extracted water can lead to soil, groundwater and/or surface water contamination, which is not limited to particular landscape classes (Figure 73).

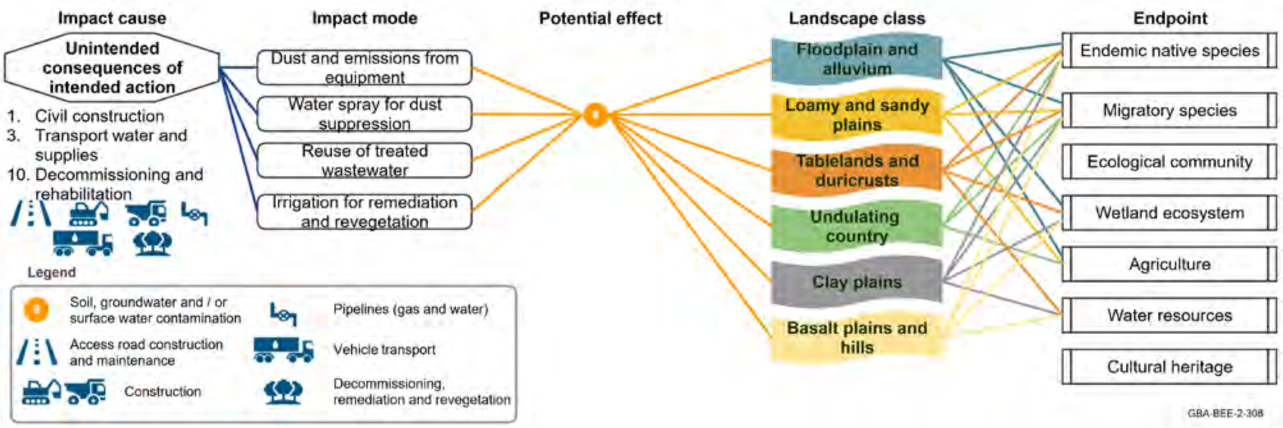

Figure 73 Preliminary conceptualisation of hazards associated with shale gas, tight gas and shale oil development in the Beetaloo GBA region in the 'processing and using extracted water' causal pathway

Numbered items refer to the ten major activities described in Figure 55 (e.g. '1. Civil construction').
Data: Geological and Bioregional Assessment Program (2019a)
Element: GBA-BEE-2-308

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

5.3.3.5 Sourcing water for site operations

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

Potential effects from water extraction for site operations are changes to groundwater levels or pressures and groundwater quality (Figure 74). Groundwater extraction from aquifers that changes groundwater levels or pressures is typically localised near production borefields and will begin to recover to pre-development levels once pumping ceases. Extraction of groundwater from one aquifer may induce inter-aquifer flow, thereby affecting water quality in the source aquifer. The preliminary conceptualisation for the 'sourcing water for site operations' causal pathway also considers indirect effects to groundwater levels, pressures or flows and quality (Figure 74). Water supply for drilling, hydraulic fracturing, well workover, intervention and refracturing during the production life-cycle stage that changes groundwater levels or pressures (groundwater extraction) are considered to be priority hazards. The two landscape classes identified in (Figure 74) are those considered most likely to interact with groundwater.

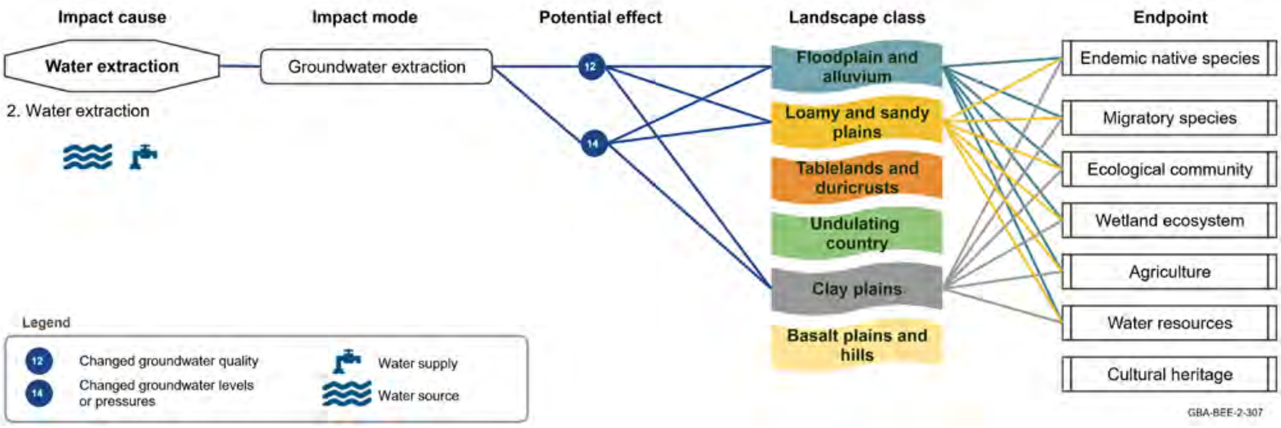

Figure 74 Preliminary conceptualisation of hazards associated with shale gas, tight gas and shale oil development in the Beetaloo GBA region in the 'sourcing water for site operations' causal pathway

Numbered items refer to the ten major activities described in Figure 55 (e.g. '1. Civil construction').
Dotted line indicates indirect potential effects to groundwater and surface water levels, pressures or flows and quality.
Data: Geological and Bioregional Assessment Program (2019a)
Element: GBA-BEE-2-307

Water supply for petroleum activities is regulated under the Water Act in the NT. The extraction of surface waters for petroleum activities is prohibited and petroleum companies are required to obtain a permit to construct water bores in water control districts and a groundwater extraction licence for water used in petroleum activities (Northern Territory Government, 2019a). The Beetaloo Sub-basin is covered by the Daly Roper Beetaloo Water Control District. Water allocation plans are being developed for the Beetaloo Sub-basin as part of this water control district.

Relevant water allocation plans and water accounts for the Beetaloo GBA region are summarised in Section 3.5.2 (groundwater) and Section 3.5.1 (surface water).

5.4 Knowledge gaps

The future development profiles for the Beetaloo GBA region are a knowledge gap that affects the assessment of potential impacts from the development of shale gas, tight gas and shale oil resources in the region. A better understanding of future shale gas, tight gas and shale oil development will reduce uncertainty in the nature of hazards and the associated risks elucidated through this study – particularly the spatial and temporal scales of potential impacts and causal pathways, including changes over time (if relevant) and how they may be affected by the pulsed nature of flows and water inputs at and near the surface in the context of the local ecosystems of the Beetaloo GBA region. The causal pathways have been characterised at a high level, sufficient for prioritisation for GBA Stage 3. Further work to characterise the causal pathways and associated risks is a necessary component of a detailed risk assessment that will assess the impacts on specific endpoints within the landscape classes identified, along with their likelihood and consequences. Existing approaches to mitigate these impacts also need to be assessed.

There is also a lack of understanding about how the various causal pathways presented here may interact with each other and what the potential cumulative effects of such interactions may be. For example, could the interaction of several causal pathways result in more severe and/or less reversible impacts to landscape classes and endpoints?

A range of possible development profiles and the spatial and temporal distribution of their activities will be developed in Stage 3 to provide constraints for the assessment of the priority causal pathways and their potential impacts identified in this report. The focus of Stage 3 will be to build upon the preliminary conceptual models developed here that link activities and hazards identified in the possible development profiles with landscape classes and endpoints specific to the region. Further work in Stage 3 will seek to better identify how risks from shale gas development may affect protected matters within the environment, including how shale gas development may interact with existing threatening processes such as changing climate patterns, grazing, land clearing and biodiversity impacts due to introduced pests, such as weeds and feral animals. Stage 3 will also assess the effectiveness of existing mitigation and management approaches in more detail than has been conducted in Stage 2, allowing gaps to be identified.

Conceptualisation of the regional geology and hydrogeology, as well as the potential hydrological connections from stressors to assets, includes a number of uncertainties and alternative conceptual models. These uncertainties will be captured, represented and tested in Stage 3 using simple, screening numerical models. Uncertainty will be propagated through models used for the assessment in Stage 3 by basing predictions upon plausible distributions of model parameters rather than fixed values. The preliminary conceptualisations presented here for each causal pathway will be updated in Stage 3 using a range of approaches, including expert elicitation.

6 Qualitative assessment examples

Potential impacts from (i) chemicals used for drilling and hydraulic fracturing and (ii) two causal pathways – hydraulic fracturing and compromised well integrity – are assessed in greater detail because of their importance to government, the community and industry.

6.1 Screening of drilling and hydraulic fracturing chemicals

A total of 116 chemicals have been identified as being associated with drilling and hydraulic fracturing at shale, tight and deep coal gas operations in the three regions (Cooper, Isa and Beetaloo) of the GBA Program between 2011 and 2016. Of the 116 chemicals, nine were drilling chemicals, 99 were hydraulic fracturing chemicals and eight were chemicals used for both drilling and hydraulic fracturing. Fifty-eight percent of the chemicals identified in the current study were not assessed in the National Assessment of Chemicals Associated with Coal Seam Gas (CSG) extraction in Australia (NICNAS, 2017).

A Tier 1 qualitative (screening) environmental risk assessment (ERA) of these chemicals found that (i) 42 chemicals were of 'low concern' and considered to pose minimal risk to aquatic ecosystems, 33 chemicals were of 'potentially high concern' and (iii) 41 were of 'potential concern'. The identified chemicals of potential concern and potentially high concern would require further site-specific quantitative chemical assessments to be performed to determine risks from specific gas developments to aquatic ecosystems.

Natural rock formations contain elements and compounds (geogenic chemicals) that could be mobilised into flowback and produced waters during hydraulic fracturing. Laboratory-based leachate and extraction tests were undertaken to provide an upper-bound estimate of geogenic chemical mobilisation from target formations in the Beetaloo GBA region. They were intended to guide future field-based monitoring, management and treatment options. Leachate tests on powdered rock samples identified several elements that could be substantially mobilised into solutions by hydraulic fracturing fluids: aluminium, cadmium, cesium, cobalt, iron, lanthanum, manganese, neodymium, nickel, lead, silver, yttrium, and zinc. Priority organic chemicals such as phenol, polycyclic aromatic hydrocarbons (PAHs) and total recoverable hydrocarbons (TRHs) were detected in extracts of powdered rock samples. Targeted analysis of PAHs represented a small fraction of the total organic geogenic compounds present in the sample extracts. Hence, the majority of organic compounds in sample extracts (as TRHs) were unidentified and their risk (individual and mixtures) to aquatic environments is unknown.

The Stage 3 chemical assessment project will undertake water quality monitoring of future shale gas operations in the Beetaloo GBA region. The project will provide open and transparent reporting of water quality monitoring data before, during and after hydraulic fracturing to improve community and government understanding in the ERA process (for chemical assessments), controls and monitoring of chemicals; and inform wastewater management and treatment options.

6.1.1 Identification of chemicals associated with shale gas, tight gas and shale oil operations

Industrial chemicals are required in shale, tight and deep coal gas operations for activities such as drilling, cementing, well construction and completion, well clean-up, hydraulic fracturing, and waste treatment. The composition and concentration of chemicals will depend on site-specific conditions such as the geology and mineralogy of formations, environmental conditions such as temperature and pressure, and requirements to maintain well integrity and production. The managed use or accidental release of chemicals (industrial and geogenic (natural)) may have negative impacts on local and regional water quality (surface water and groundwater) and water-dependent ecosystems if not adequately controlled or managed.

Companies undertake an ERA process of gas operations (in consultation with government agencies) that includes identifying potential hazards (e.g. chemical transport and storage, hydraulic fracturing fluid injection, flowback and produced water storage), determines the likelihood and consequence of a risk event occurring, identifies and evaluates control and mitigation measures (e.g. what controls are in place or need to be in place to address the identified risk and how effective are these controls), and develops a monitoring program to ensure controls and management strategies are adequate/effective and for compliance.

6.1.1.1 Drilling chemicals

Shale, tight, and deep coal gas operations will require the construction of a well to access formations at depths to liberate the gas reserves. The wells are constructed to provide the necessary integrity and isolation (e.g. from groundwater) during the operational phase and post-decommissioning. As the well is being drilled, a series of metal casings are installed and cemented to provide the well stability, integrity, and isolation from aquifers and formations. The target formation(s) for gas production are accessed at specific well depths by perforating (creating small holes) the well casing and cement using small explosive charges or guns. Well pressure is tested at different stages during drilling and completion prior to hydraulic fracturing to monitor and confirm the well integrity. Industrial chemicals are used to support the effectiveness and efficiency of drilling and maintenance of well integrity. The chemical additives are used for roles such as (i) mobilise and remove cuttings; lubricate and support the drill bit and assembly; (iii) reduce friction; (iv) facilitate cementing; (v) minimise damage to formations; (vi) seal permeable formations; and (vii) prevent corrosion and bacterial growth.

6.1.1.2 Hydraulic fracturing chemicals

Hydraulic fracturing involves the injection of fluids with chemical additives under high pressure into target formations to fracture the rock to create high-conductivity gas flow paths to the well. Common chemical additives in hydraulic fracturing fluids for shale, tight and deep coal gas operations are listed in Table 22.

Table 22 Common hydraulic fracturing fluid chemical additives used in shale, tight and deep coal gas operations

Chemical additive	Purpose
Acid/solvent	Removes mineral scales and deposits and cleans the wellbore prior to hydraulic fracturing stimulation; dissolves minerals and initiates fractures in formations
Buffer/acid	Adjusts pH to maintain the effectiveness of fluid components and iron control
Biocide	Prevents or limits bacterial growth that can result in clogging, unwanted gas production, and corrosion
Clay stabiliser	Prevents swelling or shifting in formations
Crosslinking agent	Used to link polymers or gelling agent to improve cohesion, adhesion and thermal stability and maintain fluid viscosity
Inhibitor mineral scales and deposits	Prevents build-up of material on sides of well casing and surface equipment; iron control agent to prevent precipitation of metal oxides, such as iron oxides and hydroxides
Friction reducer	Minimises friction of the hydraulic fracturing fluid
Corrosion inhibitor	Prevents damage to the wellbore and corrosion of pipes
Surfactant	Allows for increased matrix penetration and aids in recovery of water used during hydraulic fracturing
Proppant	Holds open fractures to allow gas flow
Gelling agent/viscosifier	Adjusts fluid viscosity and thickens fluid in order to suspend the proppant
Breaker/deviscosifier	Degrades or breaks down the gelling agent/viscosifier

In general, the majority of hydraulic fracturing fluid consists of water (>97%), with smaller proportions of proppant (e.g. sand) and chemical additives (Figure 75).

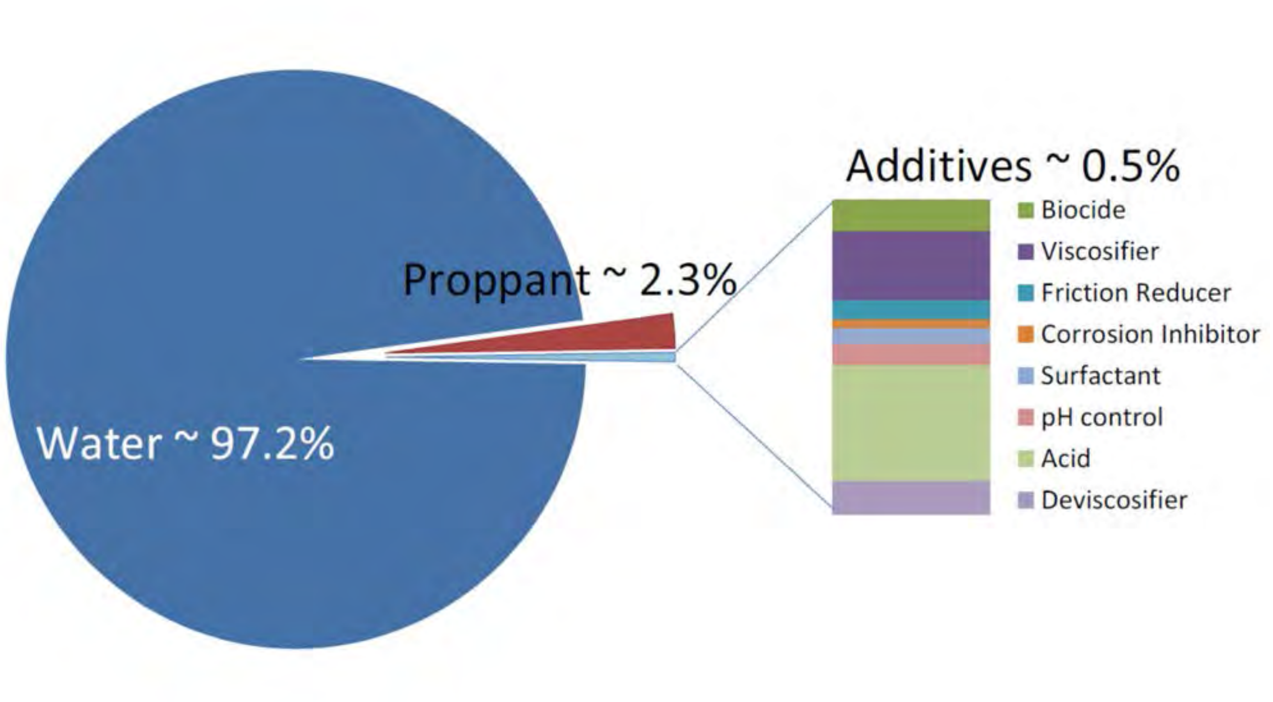

Figure 75 An example of overall percentages of water, proppant and chemical additives in hydraulic fracturing fluid in a deep shale gas well fracturing operation in the Cooper Basin

Source: figure reproduced from Beach Energy and RPS (2012)
Element: GBA-BEE-2-282

The well pressure and volume of hydraulic fracturing fluids added and recovered are routinely monitored in wells during stimulation to assess well integrity and optimise gas production. Typically, flowback and produced water, and liquid from the gas separator, are directed to storage locations/ponds/tanks (above or below ground), which have specifications dependent on the environmental conditions and requirements at the well site. Depending on the water quality, environmental conditions and treatment/management costs, the stored wastewater could be (i) treated onsite (e.g. reverse osmosis); reused or recycled onsite (e.g. dust suppression); (iii) used for beneficial purposes by the company or a third party (e.g. irrigation pending the necessary approvals and it being fit for purpose); (iv) evaporated onsite in ponds to a solid waste or brine for storage in a controlled manner; (v) reinjected to deep aquifers (pending the necessary approvals); or (vi) transported and disposed off-site at an approved treatment/disposal facility.

6.1.1.3 Geogenic chemicals

Natural rock formations contain geogenic (natural) chemicals (compounds and elements) that could be mobilised into flowback and produced waters during hydraulic fracturing. These geogenic chemicals (compounds and elements) include nutrients, salinity (e.g. chlorides), carbonates, organics (e.g. PAHs and phenols), metals and metalloids (e.g. arsenic, manganese, barium, boron and zinc) and naturally occurring radioactive materials (NORMs) (e.g. isotopes of radium, thorium, and uranium). The composition and concentration of geogenic chemicals in flowback and produced waters will depend on many factors, including (i) geology and mineralogy of formations; surface area of the fracture network exposed to hydraulic fracturing fluids; (iii) composition and concentration of chemicals used in hydraulic fracturing; (iv) residence time of hydraulic fracturing fluids in formations; (v) operational and environmental conditions (e.g. volumes added and recovered, temperature, pressure); and (vi) chemical reactions (e.g. adsorption, complexation, precipitation, aggregation, degradation and transformations).

Aim, objectives and methods

The aim of the Stage 2 chemical screening study was to gain a better understanding of risks of chemicals to surface water and groundwater quality and aquatic ecosystems from shale, tight and deep coal gas operations in Australia. The assessment did not include chemicals used in shale oil development. The objectives were:

1. to conduct a Tier 1 qualitative (screening) ERA for chemicals identified associated with shale, tight and deep coal gas operations in the three GBA regions in Australia
2. to identify geogenic chemicals (compounds and elements) that could be mobilised into flowback and produced waters from powdered rock samples sourced from shale gas target formations in the Beetaloo GBA region due to hydraulic fracturing.

An ERA provides for a systematic and transparent approach for evaluating the likelihood and consequences that adverse ecological effects may occur due to exposure to one or more stressors (e.g. chemicals) (US EPA, 1992; Norton et al., 1992). The Australian Government Department of the Environment and Energy has outlined a framework for performing an ERA of chemicals associated with CSG extraction in Australia (Department of the Environment and Energy, 2017). This framework provides a sound basis for undertaking an ERA of chemicals associated with shale, tight and deep coal gas operations in Australia. A tiered approach to ERA is often used to provide a systematic way of evaluating risk that is proportional to resources, complexity and cost (Department of the Environment and Energy, 2017; US EPA, 2004). The tiers progress in complexity and refinement from Tier 1 to Tier 3. In this study, a Tier 1 qualitative chemical screening was undertaken as an initial step in the ERA chemical assessment process (on chemical data sourced at the time of the study) to determine if a potential risk to aquatic ecosystems exists from the use of chemicals. If a potential risk was identified from chemicals, a site-specific quantitative chemical assessment would need to be undertaken to determine risks from specific gas development to aquatic ecosystems.

A Tier 1 qualitative (screening) ERA was undertaken on identified drilling and hydraulic fracturing fluid chemicals used in shale, tight and deep coal gas activities across the three regions in the GBA Program (Cooper, Isa and Beetaloo) during 2011 to 2016 (chemical screening technical appendix (Kirby et al., 2020)). The main exposure pathway for chemicals, if released during shale, tight and deep coal gas operations, will likely occur through water (surface water and groundwater); hence, this assessment focused on the potential effects to aquatic organisms. The Tier 1 assessment used a decision tree framework that evaluates sourced data for chemicals in relation to their persistence (P), bioaccumulation (B) and toxicity (T) to aquatic organisms (Geological and Bioregional Assessment Program, 2018d). A conservative (precautionary) approach (e.g. P, B, T data sourced only from standard testing protocols and international recognised ERA organisations/agencies and models, and assessments did not make assumptions based on chemical classes or groups) was applied to the evaluation of chemical and ecotoxicity data and Tier 1 qualitative ERA.

Laboratory-based leachate tests on powdered rock samples from formations in the Beetaloo GBA region were undertaken to examine potential mobilisation of geogenic chemicals (compounds and elements) into solution from exposure to a hydraulic fracturing fluid (chemical screening technical appendix (Kirby et al., 2020)). The laboratory-based tests were designed to provide an upper-bound estimate of geogenic chemical mobilisation from target formations in the Beetaloo GBA region and intended to guide future field-based monitoring, management and treatment options. The powdered rock samples (<70 µm) were sourced from formations based on their potential as targets for shale gas developments in the Beetaloo GBA region: Kyalla and Velkerri. For inorganic elements, the leachate test solutions comprised a synthetic groundwater, dilute hydrochloric acid and an in-house hydraulic fracturing fluid at 80 °C. Leachate tests were also conducted at an elevated pressure (18,400 KPa) to ascertain if pressure had an effect on geogenic chemical (element) mobilisation. A wide range of inorganic elements were quantified in leachates using inductively coupled plasma-atomic emission spectrometry (ICP-AES) and inductively coupled plasma-mass spectrometry (ICP-MS). For organic compounds, powdered rock samples were extracted using an accelerated solvent extraction (ASE) system and a combination of hydrophilic and hydrophobic solvents. The extracts were analysed for a range of targeted priority organics compounds: 14 substituted phenols, and 15 PAHs and TRH fractions (C10-C40).

Additional information on the experimental design, methodology, findings and conclusions can be found in the chemical screening technical appendix (Kirby et al., 2020).

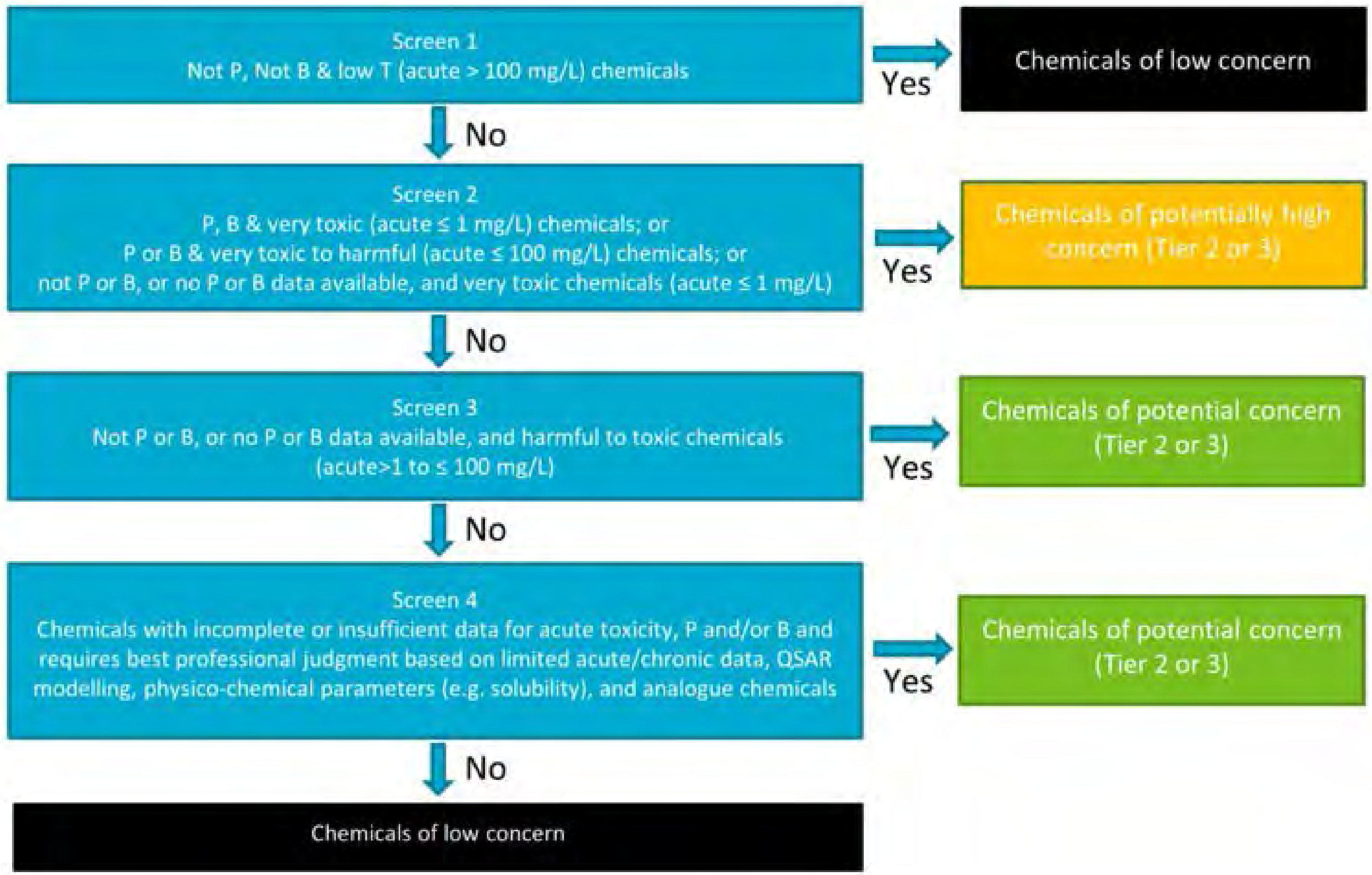

Figure 76 Decision tree framework for Tier 1 qualitative (screening) ERA of chemicals associated with shale, tight and deep coal gas operations

P = persistent; B = bioaccumulative; T = toxic; QSAR = quantitative structure–activity relationship
Element: GBA-BEE-2-283

6.1.2 Chemical screening assessment

6.1.2.1 Chemicals associated with shale, tight and deep coal gas operations in the three GBA regions of Australia

A total of 116 chemicals were identified for use in drilling and hydraulic fracturing at shale, tight and deep coal gas operations between 2011 and 2016 (chemical screening technical appendix (Kirby et al., 2020)). Of the 116 chemicals identified, nine were drilling chemicals, 99 were hydraulic fracturing chemicals and eight were chemicals used for both activities. An additional 32 proprietary chemicals (contained within products) were identified as being used for drilling and hydraulic fracturing but are not assessed here due to limitations in public disclosure of information.

A similar number of chemicals (n=113) were identified as being used with CSG extraction in Australia (NICNAS, 2017). Fifty-eight percent of the chemicals (n=67) identified in the current study were not assessed in the National Assessment of Chemicals Associated with CSG extraction (NICNAS, 2017). Of the 67 chemicals not previously assessed, a Tier 1 qualitative ERA found 16 chemicals were of 'low concern', 28 chemicals were of 'potential concern' and 23 chemicals were of 'potentially high concern'. The additional chemicals identified in this study for shale, tight and deep coal gas operations may be due to site-specific requirements needed for higher temperatures and pressures, geology and mineralogy of the specific formations, scale and biofilm build-up, fluid stability and viscosity, proppant transport, improved gas extraction and efficiency, and the move by industry towards 'greener-safer' options.

The Tier 1 screening of 116 chemicals identified 42 of 'low concern' (Screen 1 (13) and Screen 4 (29)), 33 of 'potentially high concern' (Screen 2), and 41 of 'potential concern' (Screen 3 (18) and Screen 4 (23)) (Figure 77). Data on persistence, bioaccumulation and ecotoxicity for individual chemicals and screening categories are reported in the chemical properties and ecotoxicity database (Geological and Bioregional Assessment Program, 2018d) and chemical screening technical appendix (Kirby et al., 2020).

Of the 33 chemicals identified as being of 'potentially high concern', five chemicals (one biocide and four defoaming agents) are not likely to be easily degraded (persistent), are bioaccumulative (potentially can accumulate in aquatic organisms) and exhibit very high acute toxicity to aquatic organisms (normally P, B, T chemicals) (Table 23; Figure 77) (chemical screening technical appendix (Kirby et al., 2020)). Such chemicals are considered a high concern/risk to the environment, as they can pose serious harm to aquatic ecosystems if released. They require specific controls to prevent their release into the environment.

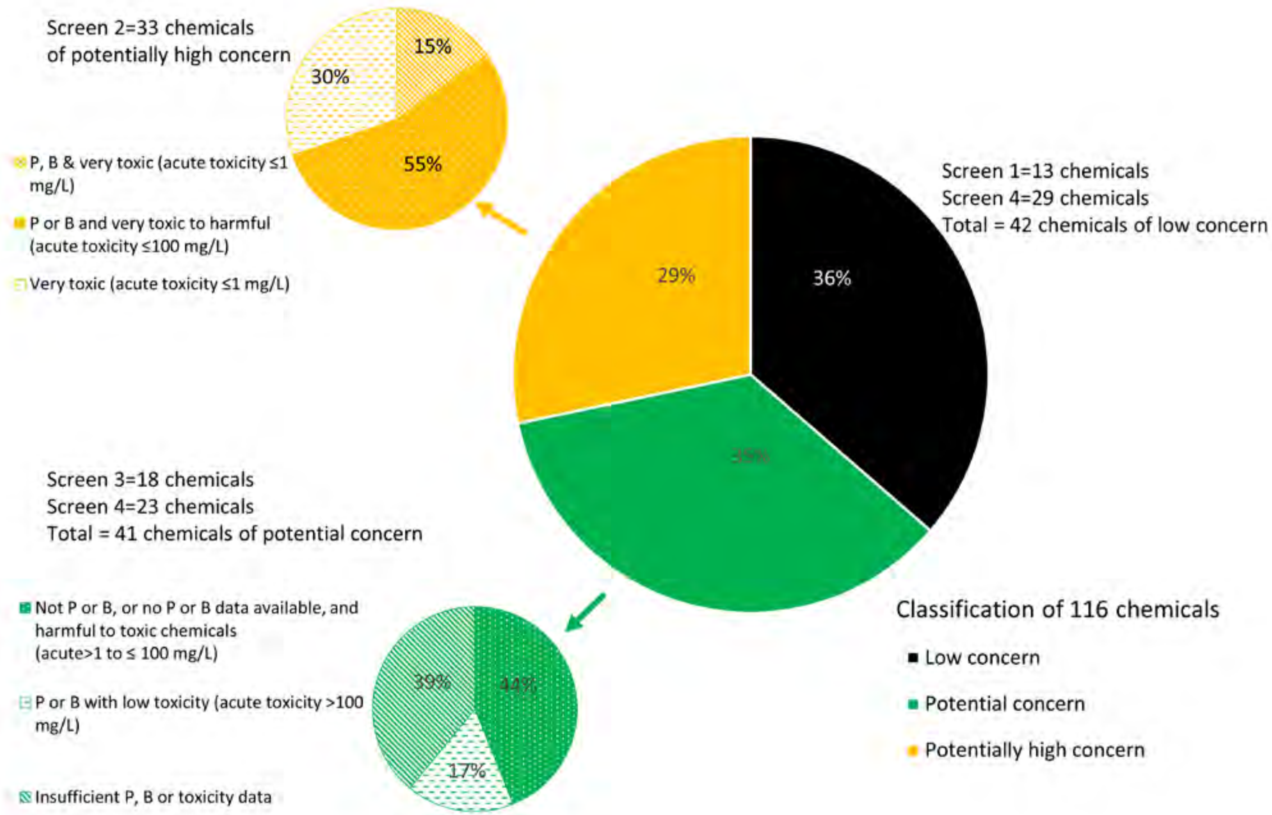

Figure 77 Tier 1 qualitative ERA of chemicals associated with shale, tight and deep coal gas operations in Australia

Refer to Figure 72 for screens 1 to 4 details. Percentages of chemicals in each category are shown in each segment. Further breakdown of chemicals in each category are shown in each segment. Further breakdown of chemicals of 'potential concern' and 'potentially high concern' are shown in the smaller coloured circles.

P = persistent; B = bioaccumulative; T = toxic

Data: (Geological and Bioregional Assessment Program, 2018d)

Element: GBA-BEE-2-284

Table 23 Chemicals of 'potentially high concern' that are persistent (P) and bioaccumulative (B) and exhibit very high acute toxicity (T)

Chemical	CAS RN	Use	P1[a]	B2[b]	T3[c]
Dicoco dimethyl ammonium chloride	61789-77-3	Biocide/surfactant	##	‡‡	***
Decamethylcyclopentasiloxane (D5)	541-02-6	Defoaming agent/surfactant	##	‡‡	***
Silicone oil (poly(dimethyl siloxane)	63148-62-9	Defoaming agent/surfactant	##	‡‡	***
Dodecamethylcyclohexasiloxane (D6)	540-97-6	Defoaming agent/surfactant	##	‡‡	***
Octamethylcyclotetrasiloxane (D4)	556-67-2	Defoaming agent/surfactant	##	‡‡	***

[a]Persistence = half-life >60 days (##)
[b]Bioconcentration factor = BCF >2000 or octanol/water partition coefficient = Log Kow ≥ 4.2 (‡‡)
[c]Toxicity = ≤1 mg/L (***)
CAS RN = Chemical Abstracts Services Registry Number
Data: Geological and Bioregional Assessment Program (2018d)

The remaining 28 chemicals identified as being of 'potentially high concern' are persistent or bioaccumulative and harmful to very toxic chemicals (n=18) (Table 24; Figure 77) or not persistent or bioaccumulative (or no data available) and very toxic (n=10) chemicals (Table 25;Figure 77) to aquatic organisms. These chemicals can pose serious harm to aquatic ecosystems if released and require specific controls to prevent their release into the environment. Persistent and bioaccumulative chemicals are generally considered of high concern in the environment due to the potential for organisms to be exposed for longer time periods (chronic effects). There were limited aquatic chronic toxicity data available (using standard tests) for most of the 116 chemicals associated with shale, tight and deep coal gas operations in Australia.

The 41 chemicals identified as 'potential concern' are not persistent and not bioaccumulative (or no persistence and bioaccumulative data could be sourced) but are toxic or harmful chemicals (n=18) (Screen 3) and are chemicals with incomplete data that require professional judgment (n=23) (Screen 4) (Figure 77). These chemicals have the potential to harm aquatic ecosystems if released and may require specific control and management measures to prevent their release into the environment.

For Screen 4 (Figure 77), seven of the 52 chemicals identified were found to be persistent or bioaccumulative and have low toxicity. These seven chemicals are (i) 1-benzyl quinolinium chloride; sodium acryloyldimethytaurate; (iii) Amaranth (acid red 27); (iv) alcohols, C6-12 ethoxylated propoxylated; (v) ethylene glycol butyl ether; (vi) poly(ethylene glycol); and (vii) tall oil (fatty acids). Since the Tier 1 qualitative ERA used mainly acute toxicity data, these chemicals are considered to be of 'potential concern' due to their unknown effects on organisms that may occur due to long-term exposure (chronic toxicity).

Table 24 Chemicals of 'potentially high concern' that are persistent (P) or bioaccumulative (B), and are harmful to very toxic (T)

Chemical	CAS RN	Use	P1[a]	B2[b]	T3[c]
1,2,4-Trimethylbenzene	95-63-6	Solvent	##	‡	**
1-Benzyl methyl pyridinium chloride	68909-18-2	Corrosion inhibitor	##	‡	***
5-Chloro-2-methyl-4-isothiazolol-3-one	26172-55-4	Biocide	##	‡	***
2-Mercaptoethyl alcohol	60-24-2	Surfactant	##	‡	***
2-Methyl-4-isothiazol-3-one	2682-20-4	Biocide	##	‡	***
Acrylamide	79-06-1	Friction reducer/gelling agent	##	‡	*
Alcohols, C10-16, ethoxylated propoxylated	69227-22-1	Surfactant	##	‡	***
Alcohols, C12-C16, ethoxylated	68551-12-2	Surfactant	##	‡	***
Amines, tallow alkyl, ethoxylated	61791-26-2	Surfactant	##	‡	***
C12-18-alkyldimethylbenzyl ammonium chlorides	68391-01-5	Biocide	##	‡	***
Coco alkyldimethyl oxide	61788-90-7	Surfactant	#	‡‡	***
Dipentene terpene hydrocarbon byproducts	68956-56-9	Friction reducer/gelling agent	#	‡‡	**
Naphthalene	91-20-3	Friction reducer/gelling agent	##	‡	***
Naphthenic acids, ethoxylated	68410-62-8	Friction reducer/gelling agent	##	‡	*
Polyethylene glycol monohexyl ether	31726-34-8	Non emulsifier	##	‡	*
Pontacyl carmine 2B (acid violet 12)	6625-46-3	Tracking dye	##	‡	*
Heavy aromatic solvent naphtha (petroleum)	64742-94-5	Friction reducer/gelling agent	##	‡	**
Hydrotreated light distillate (C13-C14 isoparaffin)	64742-47-8	Friction reducer/gelling agent	##	‡	***

[a]Persistence = half-life >60 days (##); half-life ≤60 days (#)
[b]Bioconcentration factor = BCF >2000 or octanol/water partition coefficient = Log Kow ≥4.2 (‡‡); BCF ≤2000 or octanol/water partitioning coefficient = Log Kow < 4.2 (‡)
[c]Toxicity = ≤1 mg/L (***), >1 to ≤10 mg/L (**), >10 to ≤100 mg/L (*)
CAS RN = Chemical Abstracts Services Registry Number
Data: Geological and Bioregional Assessment Program (2018d)

Table 25 Chemicals of 'potentially high concern' that are not persistent (P) or bioaccumulative (B), and are very toxic (T)

Chemical	CAS RN	Use	P1[a]	B2[b]	T3[c]
2-Bromo-2-nitro-1,3-propanediol	52-51-7	Biocide	#	‡	***
Chromium (VI)	18540-29-9	Breaker	na	na	***
Cupric sulfate	7758-98-7	Biocide/breaker	na	na	***
Glutaraldehyde	111-30-8	Biocide	#	‡	***
Hydrochloric acid	7647-01-0	Scale remover	na	na	***
Sodium chlorite ($NaClO_2$)	7758-19-2	Biocide/breaker	na	na	***
Sodium hypochlorite	7681-52-9	Biocide/breaker	na	na	***
Sodium iodide	7681-82-5	Breaker/breaker	na	na	***
Tetrakis (hydroxymethyl) phosphonium sulfate	55566-30-8	Biocide	#	‡	***
Tributyl-tetradecylphosphonium chloride	81741-28-8	Biocide	na	na	***

[a]Persistence = half-life ≤60 days (#), not applicable (na)
[b]Bioconcentration = BCF ≤2000 or octanol/water partition coefficient = Log Kow<4.2 (‡), not applicable or no data (na)
[c]Toxicity = ≤1 mg/L (***)
Data: Geological and Bioregional Assessment Program (2018d)

Biocides are used in drilling and hydraulic fracturing to prevent excess biofilm production in wells and formations, which may lead to clogging, unwanted gas production (e.g. hydrogen sulfide gas), and corrosion of underground casing/tubing and equipment (Kahrilas et al., 2016; Kahrilas et al., 2015). Biocide selection will depend on factors including (i) the mineralogy and biogeochemistry of the formation, compatibility with environmental conditions (e.g. temperature, pressure, salinity and organic matter contents), (iii) abiotic transformations, (iv) sorption reactions, (v) performance against specific microbial species (mode of action) and (vi) cost.

Biocides are inherently toxic and are, therefore, of 'potentially high concern' if released into the environment. Four biocides identified are water-soluble, persistent and highly toxic to aquatic organisms (Geological and Bioregional Assessment Program, 2018b): (i) dicoco dimethyl ammonium chloride (CAS RN 61789-77-3), 2-methyl-4-isothiazol-3-one (CAS RN 2682-20-4), (iii) 5-chloro-2-methyl-4-isothiazolol-3-one (CAS RN 26172-55-4) and (iv) C12-18-alkyldimethylbenzyl ammonium chlorides (CAS RN 68391-01-5). The effect on biota in the receiving aquatic environment is likely to be dependent on the release scenario (e.g. surface spills, pond overflow to soil and surface water or well leakage to groundwater, etc.), exposure concentrations, fate and behaviour in environments (e.g. rate of degradation and transformation, partitioning and complexation), bioavailability and sensitivity of aquatic organisms.

Biocides such as glutaraldehyde (CAS RN 111-30-8) and tetrakis (hydroxymethyl) phosphonium sulfate (CAS RN 55566-30-8), which are very toxic to aquatic organisms, may pose a lower risk to aquatic organisms due to their expected rapid (i.e. ≤60 days) degradation in aquatic environments (Geological and Bioregional Assessment Program, 2018d). However, degradation products of some biocides have been reported to be more toxic and/or persistent than their parent compounds (Kahrilas et al., 2016; Kahrilas et al., 2015). This highlights the need for the development of sensitive and selective analytical methods to detect parent and transformation products in wastewaters and receiving waters to assess impacts on aquatic ecosystems.

Siloxanes can be added to hydraulic fracturing fluids as defoaming agents and surfactants. These chemicals have low water solubility (soluble/miscible in solvents), are hydrophobic and, in the case of cyclic siloxanes, are volatile. The siloxanes are of 'potentially high concern' to aquatic organisms due to their persistence and bioaccumulative and highly toxic nature (Geological and Bioregional Assessment Program, 2018d). The three cyclic siloxanes, octamethylcyclotetrasiloxane (CAS RN 556-67-2), decamethylcyclopentasiloxane (CAS RN 541-02-6) and dodecamethylcyclohexasiloxane (CAS RN 540-97-6), are likely to volatilise or degrade in water (via hydrolysis) but, due to their hydrophobic nature, are also likely to strongly associate with sediments/suspended solids where they can persist. Furthermore, there are currently conflicting ERAs on the cyclic siloxanes due to difficulties in conducting aquatic toxicity tests because of their volatility, making the toxicity assessments highly uncertain (ECHA, 2018; Environment Canada and Health Canada, 2008; Fairbrother et al., 2015; Fairbrother and Woodburn, 2016; Government of Canada, 2012b, 2012a). The National Industrial Chemicals Notification and Assessment Scheme (NICNAS, 2018) conducted a Tier 2 ERA on these chemicals and found all three to be persistent, two to be bioaccumulative (octamethylcyclotetrasiloxane and decamethylcyclopentasiloxane) and one (octamethylcyclotetrasiloxane) to have 'uncertain toxicity'. These chemicals, therefore, if used at shale, tight and deep coal gas operations, will require a more detailed quantitative ERA to be undertaken with realistic exposure scenarios in which the quantitative ERA assesses and models the likelihood and consequence of a risk event occurring, identifies and evaluates control and mitigation measures (e.g. what controls are in place to address the identified risk and how effective are these controls), and monitors to ensure controls and management strategies are adequate to prevent impacts on the environment.

6.1.2.2 Laboratory-based leachate tests on powdered rock samples from the Beetaloo GBA region – geogenic chemicals

Leachate tests conducted with dilute hydrochloric acid and synthetic hydraulic fracturing fluid mobilised the highest element concentrations into solutions compared with synthetic groundwater (SGW) (chemical screening technical appendix (Kirby et al., 2020)). This demonstrates the role that acidity and chemical constituents of hydraulic fracturing fluids (e.g. chelating agents, surfactants, solvents, etc.) can play in mobilising elements from powdered rocks in formations. The elements showing substantial mobilisation (>50-fold median increase compared to SGW) in hydraulic fracturing fluids included aluminium, cadmium, cesium, cobalt, iron, lanthanum, manganese, neodymium, nickel, lead, silver, yttrium and zinc. It was noted that there was variability between rock types in formations in terms of both the total content of elements and concentrations of elements mobilised into solution. Further studies are needed to determine the underlying relationships between element content and physico-chemical properties of the formations and fate of chemicals in the hydraulic fracturing fluid.

Higher pressure led to increased mobilisation into solutions using hydraulic fracturing fluids of elements such as thorium, cobalt, uranium, lithium, copper, silver, calcium and zinc; and decreased mobilisation for elements such as vanadium, boron, antimony, molybdenum, barium, and lead (chemical screening technical appendix (Kirby et al., 2020)). The findings highlight the important role pressure can play in the mobilisation of geogenic chemicals from powdered rocks in formations during hydraulic fracturing. Further work is required to determine the relationship between pressure (and temperature) on the hydraulic fracturing fluids and mobilisation of geogenic chemicals from powdered rocks in shale gas formations in the Beetaloo GBA region.

Targeted priority organic chemicals such as phenols, PAHs and TRHs were detected in extracts of powdered rock samples from formation in Beetaloo GBA region (chemical screening technical appendix (Kirby et al., 2020)). Phenols were detected only in powdered rock sample extracts from Shenandoah 1/1A drill core (Lower Kyalla and Velkerri B Shale) (two of seven sample extracts). Targeted PAHs were detected only in powdered rock sample extracts from Altree-2 drill core (Upper and Middle Velkerri) (three of seven sample extracts). Other targeted phenols and PAHs were below their respective concentrations of reporting in sample extracts. The most common identified PAHs in sample extracts were benzo(ghi)perylene, chrysene, indeno-(1,2,3-cd)-pyrene, and phenanthrene (three of seven extracts). The Altree-2 Upper Velkerri sample contained the highest number of PAHs (n=5) and concentrations in sample extracts e.g. anthracene = 10.5 µg/kg, benzo(ghi)perylene = 7.2 µg/kg, indeno-(1,2,3-cd)-pyrene = 7.2 µg/kg, and phenanthrene = 45.9 µg/kg (except chrysene = 64.8 ug/kg in the Middle Velkerri sample (764m) from Altree-2).

The highest concentration of TRHs were found to be associated with the >C16-C34 NEPM TRH (21 to 277 mg/kg; 39 to 43% TRHs) and TRH C15-C28 (17 to 225 mg/kg; 32 to 35% TRHs) fractions for powdered rock samples (chemical screening technical appendix (Kirby et al., 2020)). Targeted analysis of phenols and PAHs represented a small fraction of the total organic geogenic compounds identified in the sample extracts (i.e. 0.02 to 0.07%). The absence of volatile compounds in sample extracts from this study may be due to the long-term storage of the sourced rocks in dry, non-climate controlled conditions. Hence, most geogenic organic compounds (as TRHs) in sample extracts were unidentified and their potential risk (individuals and mixtures) to aquatic environments is unknown.

6.1.2.3 Fate and behaviour of chemicals in the environment

The ecotoxicity of chemicals released during shale, tight and deep coal gas operations will likely be affected by reactions and processes in environments that can modify their fate and bioavailability (e.g. exposure concentrations) (Adriano, 2001; ANZECC/ARMCANZ, 2000; Neilson, 1994). Organic chemicals can be volatilised, photodegrade, undergo abiotic and biotic degradation and transformations, and complex/adsorb to a range of solid phases (e.g. organic matter). Inorganic chemicals can undergo neutralisation, displacement, ionisation, redox and precipitation reactions, undergo biotransformation (e.g. arsenic methylation), and complex/partition to a range of solid phases (e.g. clays, oxides/hydroxides and organic matter). These reactions and processes will be influenced by the physical and chemical properties of the receiving environment such as pH, salinity, redox conditions, microbial populations and organic matter content.

Chemical additives used in hydraulic fracturing fluids may also be lost in wells and formations to solid surfaces and/or degrade or be transformed, leading to lower concentrations than what was initially added. For example, polymers can degrade or decompose, biocides can degrade and complex with or adsorb onto solid surfaces, and surfactants can be adsorbed onto solid surfaces in formations. In addition, chemical concentrations from source zones can be attenuated in surface water and groundwater through dilution and volatilisation processes.

The Tier 1 qualitative (screening) ERA used aquatic acute ecotoxicity data representing three trophic levels – a freshwater alga, a water flea and a fish species using standard testing protocols (Geological and Bioregional Assessment Program, 2018b). Acute toxicity data may not be sufficient in assessing the environmental risk of persistent and bioaccumulative chemicals that could result in effects on biota due to long-term exposure (chronic effects) in the environment. Chronic toxicity data on aquatic organisms from a range of trophic positions (and sensitive species) are needed to accurately assess effects due to long-term exposure of these chemicals to aquatic organisms. In addition, the approach of single-chemical acute toxicity test data provides a highly uncertain assessment when there is limited detailed knowledge on the interactions that modify toxicity and on the modes of toxicity of the chemicals to aquatic biota. A direct toxicity approach where aquatic biota are exposed to dilutions of a complex chemical mixture (e.g. a hydraulic fracturing fluid, flowback and produced water) would provide a more relevant environmental exposure assessment that incorporates chemical interactions/mixtures. Further, these assessments do not consider pulse discharges and dispersion of chemicals (individual and mixtures) into aquatic ecosystems.

6.1.3 Conclusions

A total of 116 chemicals were identified for use in drilling and hydraulic fracturing at shale, tight and deep coal gas operations between 2011 and 2016. A Tier 1 qualitative (screening) ERA of the identified chemicals found that 42 chemicals are of ‘low concern’ and considered to pose minimal risk to surface water and groundwater aquatic ecosystems; 33 chemicals are of ‘potentially high concern’; and 41 are of ‘potential concern’. The identified chemicals of potential concern and potential high concern would require further site-specific quantitative chemical assessments to be performed to determine risks to aquatic ecosystems from specific gas operations.

The chemicals used in drilling and hydraulic fracturing are expected to change with time as the gas industry adapts to site-specific conditions, improves gas extraction efficiency, and endeavours to use ‘greener-safer’ options. A Tier 1 qualitative (screening) ERA should be undertaken on new chemicals (and chemical not previously assessed) used in shale, tight and deep coal operations in Australia to determine if a potential environmental risk exists (‘yes/no’). If a risk exists, the questions will change to ‘what’, ‘where’ and ‘how great’ is the risk (i.e. Tier 2 and 3 quantitative ERAs).

Laboratory-based leachate tests on powdered rock samples collected from formations in the Beetaloo GBA region identified several elements that could be substantially mobilised into solutions by hydraulic fracturing fluids, including aluminium, cadmium, cesium, cobalt, iron, lanthanum, manganese, neodymium, nickel, lead, silver, yttrium and zinc. Priority organic chemicals such as phenol, PAHs and TRHs were detected in extracts of powdered rock samples. Results of targeted analysis of PAHs accounted for only a small fraction of the total organic geogenic compounds present in the sample extracts. Hence, the majority of organic compounds in sample extracts (as TRHs) were unidentified and their risk (individual and mixtures) to aquatic environments is unknown. The composition and concentration of geogenic chemicals in flowback and produced waters will depend on many factors, including (i) geology and mineralogy of formations; surface area of the fracture network exposed to hydraulic fracturing fluids; (iii) composition and concentration of chemicals used in hydraulic fracturing; (iv) residence time of hydraulic fracturing fluids in formations; (v) operational and environmental conditions (e.g. volumes added and recovered, temperature, pressure); and (vi) chemical and physical reactions (e.g. adsorption, complexation, precipitation, aggregation, degradation and transformations).

Companies undertake an ERA process of gas operations (in consultation with government agencies) that identifies potential hazards (e.g. chemical transport and storage, hydraulic fracturing fluid injection, flowback and produced water storage), determines the likelihood and consequence of a risk occurring, identifies and evaluates control and mitigation measures (e.g. what controls are in place or need to be in place to address the identified risk and how effective are these controls), and develops a monitoring program to ensure controls and management strategies are adequate/effective and for compliance. Despite undertaking these detailed ERAs, there is still public concern surrounding the potential environmental impacts of hydraulic fracturing – particularly the threats posed by the mixture of industrial chemicals used and geogenic chemicals that could be mobilised and their impacts on water quality.

6.1.4 Knowledge gaps

The chemical assessment identified the following knowledge gaps:

- Chemicals used in drilling and hydraulic fracturing are expected to change with time as industry adapts to site-specific conditions, improves gas extraction efficiency and endeavours to use ‘greener-safer’ options. A Tier 1 qualitative (screening) ERA should be undertaken on new chemicals (and chemicals not previously assessed) used in shale, tight and deep coal operations in Australia to determine if a potential environmental risk exists (‘yes/no’). If a potential risk exists, the questions should change to ‘what’, ‘where’ and ‘how great’ is the risk (Tier 2 and 3 quantitative ERAs). The chemical assessments should be undertaken in the context of the risk management framework that determines the likelihood and consequence of a risk event occurring, identifies and evaluates control and mitigation measures (e.g. what controls are in place or need to be in place to address the identified risk and how effective are these controls), and develops a monitoring program to ensure controls and management strategies are adequate/effective and for compliance.
- The Tier 1 qualitative ERA relied mainly on aquatic acute ecotoxicity data representing three trophic levels – a freshwater alga, a water flea and a fish species. Acute toxicity data may not be sufficient for assessing the environmental risks of persistent and bioaccumulative chemicals that could have effects on aquatic organisms due to long-term exposure. Chronic toxicity data using a range of aquatic organisms and trophic levels are needed to accurately assess the effects of long-term exposure of chemicals to aquatic organisms. In addition, ecotoxicity data on drilling and hydraulic fracturing chemicals for Australian species are limited and ecotoxicity endpoints are currently not available for groundwater organisms (e.g. stygofauna).

- Comprehensive baseline surface water and groundwater quality data used for targeted aquifers, irrigation and drinking water, and groundwater-dependent ecosystems should be collected prior to shale, tight and deep coal gas developments.
- Publicly available data on the composition and concentration of chemicals in hydraulic fracturing fluids, flowback and produced water, and wastes (e.g. muds, brines) from shale, tight and deep coal operations in Australia are limited. The fate, transformations and toxicity of chemicals present in hydraulic fracturing fluids, and flowback and produced water (individual chemicals and mixtures) in the environment, are also unknown.
- Leachate tests did not include analysis for naturally occurring radioactive materials (NORMs). Further research needs to be undertaken to understand the mobilisation of NORMs from formations in the Beetaloo GBA region and their fate and behaviour during hydraulic fracturing, storage and treatment.
- The majority of organic compounds present in sample extracts from powdered rock samples were unidentified and their potential risk (if present in flowback and produced waters) to aquatic environments is unknown.
- Despite the very low likelihood of a well integrity failure or failure of surface infrastructure (ponds, tanks, pipelines, etc.) associated with shale, tight and deep coal gas operations in Australia (i.e. constructed to highest industry standards, high level of government regulation and compliance), there is still public concern about the consequences to water quality (drinking, livestock, aquatic ecosystems and cultural) if fluids are released. Surface water and groundwater monitoring and modelling using site-specific conditions and exposure scenarios would improve public understanding of potential impacts and consequences to water quality (i.e. localised event) and the adequacy of control and management plans to prevent environmental impacts.

6.2 Hydraulic fracturing and compromised well integrity

Hydraulic fracture stimulation is used to create hydraulic fractures in the target petroleum reservoir to maximise the flow of gas to the well. Potential environmental risks of hydraulic fracturing have been the focus of active discussion across industry, government and academic agencies for the past decade and have led to several significant domestic and international inquiries into onshore gas industry operations. A review of the findings of these inquiries, along with a review of Beetaloo GBA region operations to date and GBA hazard identification workshop data and scoring (refer Section 5), provide an initial assessment of the relative likelihood of occurrence of three impact modes in the Beetaloo GBA region (Table 26). While this initial assessment did not highlight any of the three hydraulic fracturing impact modes as a priority 1 impact mode, ‘F1 – Hydraulic fracture growth into aquifer’ will be included in Stage 3 analysis to address heightened community concern about hydraulic fracturing in the context of the regional geology for the Beetaloo GBA region.

Compromised well integrity is a concern for industry, government and the community. Regulated construction of wells aims to ensure that fluid and gas are prevented from flowing unintentionally from the reservoir into another geological layer or to the surface. In this qualitative review, Beetaloo GBA region data were compared with findings from international and domestic inquiries and specifically the findings from the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018) to present an initial evaluation of five conceptual impact modes (Table 27). These were compared with the prioritisations from GBA hazard identification workshops (Section 5) and are broadly consistent. Two impact modes have been prioritised for inclusion in Stage 3 analysis: ‘W3 – Migration of fluids along casing between geological layers’ and ‘W4 – Migration of fluids along decommissioned or abandoned wells’ (Section 6.2.2).

6.2.1 Hydraulic fracturing

Hydraulic fracture stimulation is used to increase the productivity of petroleum wells and is critical to the performance of wells in low-permeability ‘unconventional’ formations. Fluid is injected at sufficient pressure and flow rate to propagate hydraulic fractures into the target formation. After the fluid pressure is released, proppant (sand or artificial ceramics) remains in the created fracture to increase the effective permeability in the target formation and ultimately increase the flow of gas to the well. Wells are usually fractured in stages, where isolated sections are fractured individually. The number of hydraulic fracturing stages depends on the length of the well and can range from one up to 50 stages per well.

The Beetaloo GBA region is in the early stages of a resurgence of exploration and appraisal, which includes hydraulic fracture stimulation activities. Two hydraulic fracture stimulations have been conducted in the Beetaloo GBA region to date. The first hydraulic fracture stimulation of a petroleum well in the Beetaloo GBA region was in 2011 in the Shenandoah 1A exploration well in the Velkerri Formation. The Velkerri Formation was targeted by a second exploration well in the Beetaloo GBA region, Amungee NW-1H, which was stimulated with hydraulic fracturing in August 2016. The hydraulic fracture stimulation of the Amungee NW-1H well was completed in accordance with industry standards and best practices issued by the American Petroleum Institute (Origin Energy, 2016a) and as documented in Close et al. (2017a). The stimulation was completed successfully with no environmental incidents.

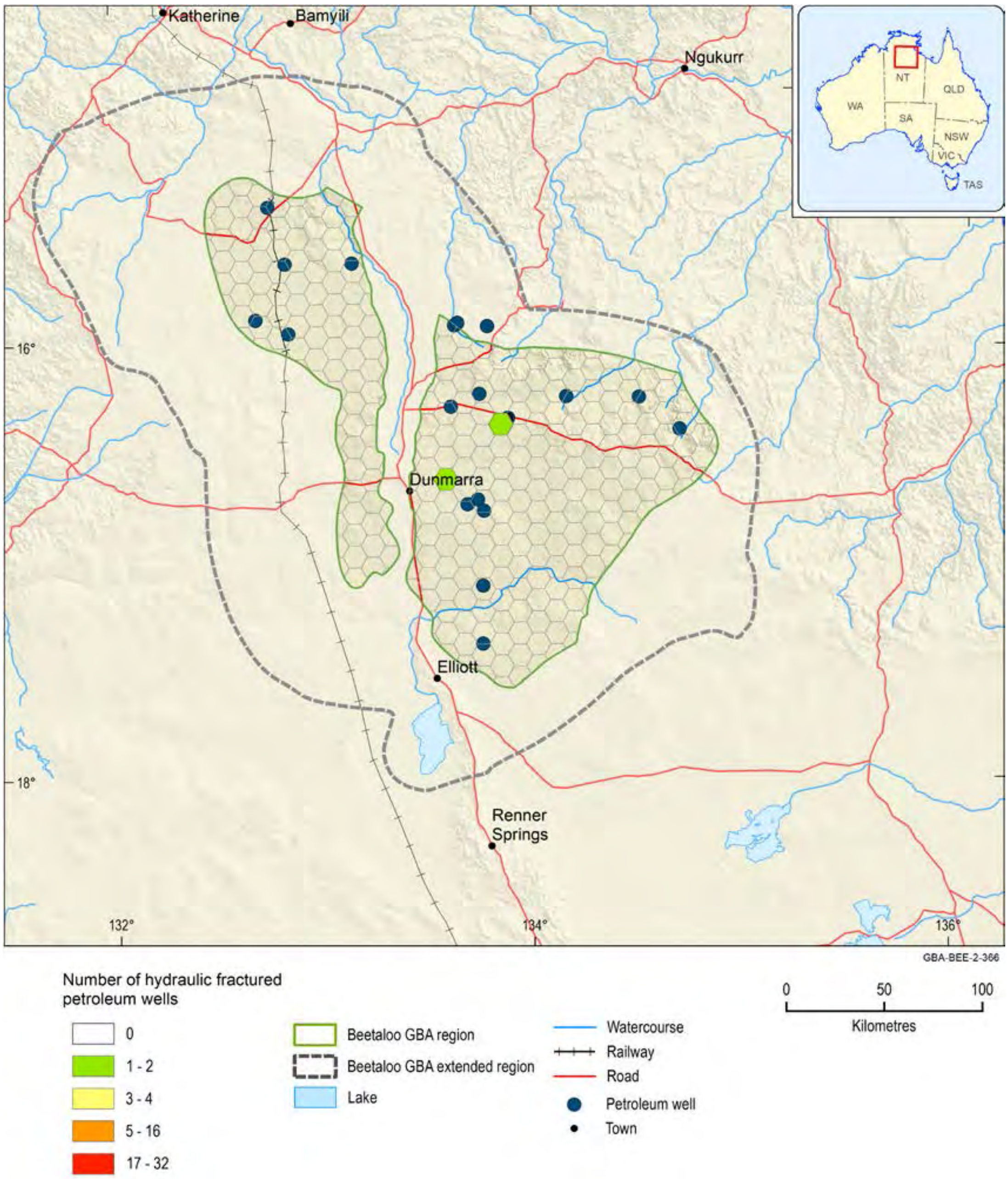

Figure 78 Map of petroleum wells in the Beetaloo GBA region and surrounding area (with the location of the hydraulic fracture stimulations in the Shenandoah 1A and Amungee NW-H1 exploration wells shown in green)

Data: hydraulically fractured locations from Geological and Bioregional Assessment Program (2019e)
Element: GBA-BEE-2-366

Over the last decade, the potential environmental risks of hydraulic fracturing have been the focus of active discussion and investigation across industry, government and academic agencies (e.g. Davies (2011); Atherton et al. (2014); Vengosh et al. (2014); Wright (2014); Dusseault and Jackson (2014); Hawke (2014); US EPA (2016b); Pepper et al. (2018); Hatton et al. (2018)). In response to this heightened public interest in the risks associated with hydraulic fracturing, international and domestic inquiries have been conducted to assess hydraulic fracturing activities, including considering the potential likelihoods of many of the impact modes in their local contexts. Specifically, the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018) considered the nature and extent of the risks associated with hydraulic fracturing of onshore unconventional shale gas reservoirs and associated activities on the environmental, social, cultural and economic conditions of the NT.

While there are several impact modes by which hydraulic fracturing operations could potentially dilate or create a pathway for fluid migration between subsurface geological layers or to the surface, the Pepper et al. (2018) inquiry found that, if all recommendations were adopted and implemented in their entirety, 'not only should the risks associated with an onshore shale gas industry be minimised to an acceptable level, in some instances, they could be avoided altogether'. This finding is consistent with the findings of the eight other international and domestic inquiries reviewed in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020), which state that the likelihood of the considered impact modes occurring is generally considered manageable to a suitably low level given appropriate regulatory controls, sufficient understanding of the baseline geological and environmental systems, and acceptable industry practices (US EPA, 2016b; Hawke, 2014; Cook et al., 2013; The Royal Society and The Royal Academy of Engineering, 2012; Wright, 2014; Council of Canadian Academies, 2014; Atherton et al., 2014; Pepper et al., 2018; Hatton et al., 2018). The findings from Pepper et al. (2018), along with the eight other reviewed international and domestic inquiries, have been interpreted to distil, where possible, a relative likelihood of occurrence for each impact mode. The findings from each of the nine reviewed inquiries are summarised in Table 26. Further details are available in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020).

However, several sources (US EPA, 2016b; Council of Canadian Academies, 2014; Vidic et al., 2013; Jackson et al., 2013) note that due to the difficulty in observing potential impacts – especially to groundwater resources – it is difficult to validate many of the estimates of rates of these occurrences. The uncertainty caused by the lack of validation data cannot be fully overcome within the scope of the GBA Program.

The qualitative review in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020) compares data from the operations in the Beetaloo GBA region to date with findings from international and domestic hydraulic fracturing inquiries. It presents an initial qualitative evaluation of the likelihood of three impact modes by which hydraulic fracturing could conceivably cause contaminants to impact assessment endpoints in the Beetaloo GBA region.

The three impact modes relating to hydraulic fracture stimulation considered in the hazard analysis and qualitative review (Kear and Kasperczyk, 2020) are:

- F1 – Hydraulic fracture growth into aquifer
- F2 – Hydraulic fracture growth into well
- F3 – Hydraulic fracture growth into fault.

Each of the above impact modes was evaluated against the findings of significant domestic and international inquiries, historical data from the Beetaloo GBA region and the findings from the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018). The evaluation results are shown in Table 26, with details of the review presented in the accompanying hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020).

The causal pathway appraisal for the Beetaloo Sub-basin (see Section 5) did not highlight any of the three hydraulic fracturing impact modes as a priority based on estimated severity and likelihood of the potential impacts. This finding is broadly consistent with the findings of the qualitative review of the domestic and international inquiries.

The analysis of the historical and geological data for the Beetaloo GBA region showed there is substantial physical separation between the Kyalla and Velkerri formations and the closest overlying aquifers. Therefore, a qualitative analysis of the Beetaloo GBA region indicates the potential likelihood is low of a hydraulic fracture extending into an aquifer unit or exhibiting excessive vertical height growth though intersection with a fault. This finding is similar to other international shale gas developments (Rare) where there is significant (>1000 m) distance between the target interval and the closest aquifer. This also reflects the findings of the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018).

The qualitative assessment of the likelihood of hydraulic fractures impacting assessment endpoints though intersection of another petroleum well in the Beetaloo GBA region is lower than other international shale gas developments due to the low density of legacy petroleum wells in the region.

Although the likelihood of this occurrence is considered low and the hazard score is not sufficient to warrant prioritisation, the impact mode ‘Hydraulic fracture growth into aquifer’ will be included in Stage 3 analysis on the basis of the heightened community concern around hydraulic fracturing.

Table 26 Summary of likelihoods for hydraulic fracturing impact modes

Generalised likelihood definitions are as follows: Very rare – Near-zero chance of occurring in the inquiry's area of study; Rare – Very improbable to occur in the inquiry's area of study given local geological, existing operational controls and/or regulatory conditions; Very unlikely – Very unlikely to occur in the inquiry's area of study given local geological, operational and/or regulatory conditions; Unlikely – Possible but unlikely to occur in the inquiry's area of study given local geological, operational and/or regulatory conditions; Likely – Expected to occur in some activities in the inquiry's area of study. Specific likelihood definitions for each impact mode and further details of the qualitative review are available in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020).

Likelihood estimates	F1 – Hydraulic fracture growth into aquifer	F2 – Hydraulic fracture growth into well	F3 – Hydraulic fracture growth into fault
GBA hazard identification workshops (Geological and Bioregional Assessment Program, 2019b)	Rare – Very unlikely	Very unlikely – Unlikely	Rare – Very unlikely
Likelihood estimated from historical Beetaloo Basin data (Kear and Kasperczyk, 2020)	Rare	Rare	Rare
Overall qualitative likelihood from the nine inquiries	Rare	Unlikely	Rare
Range of inquiry qualitative likelihood ratings	Rare – Unlikely	Rare – Unlikely	Rare – Unlikely
Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory (Pepper et al., 2018)	Rare	Not assessed	Rare
Hydraulic fracturing for oil and gas: impacts from the hydraulic fracturing water cycle on drinking water resources in the United States (US EPA, 2016b)	Unlikely	Unlikely	Rare
Report of the independent inquiry into hydraulic fracturing in the Northern Territory (Hawke, 2014)	Rare	Not assessed	Unlikely
Engineering energy: Unconventional gas production. report for the Australian council of learned academics (Cook et al., 2013)	Unlikely	Not assessed	Unlikely
Shale gas extraction in the UK : a review of hydraulic fracturing (The Royal Society and The Royal Academy of Engineering, 2012)	Rare	Not assessed	Unlikely
Drilling for oil and gas in New Zealand: Environmental oversight and regulation (Wright, 2014)	Not assessed	Not assessed	Not assessed
Environmental impacts of shale gas extraction in Canada (Council of Canadian Academies, 2014)	Rare	Unlikely	Rare
Report of the Nova Scotia Independent Panel On Hydraulic Fracturing (Atherton et al., 2014)	Rare	Unlikely	Not assessed
Independent scientific panel inquiry into hydraulic fracture stimulation in Western Australia (Hatton et al., 2018)	Rare	Rare	Unlikely

6.2.2 Compromised well integrity

Petroleum wells are constructed to have integrity such that fluid and gas are prevented from flowing unintentionally from the reservoir into another stratigraphic layer or to the surface. The components that prevent this fluid movement are known as 'well barrier elements' and form 'well barriers'. The well barriers are pressure containment envelopes and a minimum of two independent well barriers is required in the NT by the *Code of Practice: Onshore Petroleum Activities in the Northern Territory* ((Northern Territory Government, 2019c) and is recommended under international standards for industry practice and regulations (e.g. ISO 16530 (International Organization for Standardization, 2013), NORSOK Standard D-010 (Norwegian Petroleum Industry, 2004) and ANSI/API RP 100-1 and 100-2 (2015b, 2015a). The *Code of Practice: Onshore Petroleum Activities in the Northern Territory* (Northern Territory Government, 2019c) also sets a minimum standard for well construction that is the equivalent of what Stone et al. (2016) defined as a Category 9 well (defined to incorporate external cementing of all casing from the shale formation to the surface). By having multiple well barriers, a failure within one well barrier element does not result in the loss of integrity of a well (US EPA, 2016b).

If the integrity of a well were to be compromised, there could be a potential pathway for fluids to flow vertically between geological layers and to the surface. Huddlestone-Holmes et al. (2017) provide a summary of well integrity considerations. While there are several impact modes by which loss of well integrity could potentially cause the well to act as a conduit for fluid migration, the likelihood of those impact modes occurring is generally considered manageable to a suitably low level given appropriate regulatory controls, sufficient understanding of the baseline geological and environmental systems, and acceptable industry practices (US EPA, 2016b; Hawke, 2014; Cook et al., 2013; The Royal Society and The Royal Academy of Engineering, 2012; Wright, 2014; Council of Canadian Academies, 2014; Atherton et al., 2014; Pepper et al., 2018; Hatton et al., 2018). However, data limitations make it difficult to assess the rates at which well integrity failures have impacted groundwater resources (Council of Canadian Academies, 2014; Jackson et al., 2013; Vidic et al., 2013; US EPA, 2016b). The uncertainty caused by the lack of validation data cannot be fully overcome within the scope of the GBA Program.

The qualitative review in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020) compares historical data for the Beetaloo GBA region with findings from international and domestic inquiries to present an initial evaluation of the likelihood of five impact modes by which well integrity failures could conceivably cause contaminants to impact assessment endpoints in the Beetaloo GBA region.

Three of the reviewed well integrity failure impact modes relate to the production phase of a well:

- W1 – Rupture or failure across well barriers that allows fluids to move between the inside and the outside of the well
- W2 – Migration of fluids from the reservoir to the surface along a failure of the well casing
- W3 – Migration of fluids between different geological layers along a failure of the well casing.

Two of the reviewed impact modes relate to well integrity failure during construction, workover and decommissioning operations:

- W4 – Failure of well integrity after well decommissioning / abandonment
- W5 – Loss of well control (blowout).

Each of the five reviewed well integrity failure impact modes has been evaluated against the findings of significant domestic and international inquiries, with particular weighting given to the findings of the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018) and the results from the GBA hazard screening workshop. The evaluation results are shown in Table 27, with detail available in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020).

Table 27 Summary of likelihoods for compromised well integrity impact modes

Generalised likelihood definitions are as follows: Very rare – Near-zero chance of occurring in the inquiry's area of study; Rare – Very improbable to occur in the inquiry's area of study given local geological, existing operational controls and/or regulatory conditions; Very unlikely – Very unlikely to occur in the inquiry's area of study given local geological, operational and/or regulatory conditions; Unlikely – Possible but unlikely to occur in the inquiry's area of study given local geological, operational and/or regulatory conditions; Likely – Expected to occur in some activities in the inquiry's area of study. Specific likelihood definitions for each impact mode and further details of the qualitative review are available in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020).

Likelihood estimates	W1 – Well rupture or failure across barriers	W2 – Migration of fluids to the surface along a failure of the well	W3 – Migration along casing between geological layers	W4 – Migration along decommissioned / abandoned wells	W5 – Loss of well control
GBA hazard identification workshops (Geological and Bioregional Assessment Program, 2019b)	Rare – Unlikely	Rare – Unlikely	Rare – Possible	Unlikely – Possible	Rare – Unlikely
Likelihood estimated from historical Beetaloo Sub-basin data (Kear and Kasperczyk, 2020)	Rare	Rare	Unlikely	Unlikely	Not assessed
Overall qualitative likelihood from the nine inquiries	Rare	Rare	Unlikely	Unlikely	Not assessed
Range of inquiry qualitative likelihood ratings	Vary rare – Rare	Rare – Unlikely	Very rare – unlikely	Unlikely – Likely	Not assessed
Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory (Pepper et al., 2018)	Rare	Rare	Unlikely	Unlikely	Not assessed
Hydraulic fracturing for oil and gas: impacts from the hydraulic fracturing water cycle on drinking water resources in the United States (US EPA, 2016b)	Rare	Unlikely	Unlikely	Unlikely	Not assessed
Report of the independent inquiry into hydraulic fracturing in the Northern Territory (Hawke, 2014)	Rare	Rare	Vary rare	Unlikely	Not assessed
Engineering energy: unconventional gas production. Report for the Australian Council of Learned Academics (Cook et al., 2013)	Rare	Not assessed	Unlikely	Unlikely	Not assessed

Likelihood estimates	W1 – Well rupture or failure across barriers	W2 – Migration of fluids to the surface along a failure of the well	W3 – Migration along casing between geological layers	W4 – Migration along decommissioned / abandoned wells	W5 – Loss of well control
Shale gas extraction in the UK: a review of hydraulic fracturing (The Royal Society and The Royal Academy of Engineering, 2012)	Not assessed	Rare	Not assessed	Unlikely	Not assessed
Drilling for oil and gas in New Zealand: environmental oversight and regulation (Wright, 2014)	Rare	Rare	Not assessed	Unlikely	Not assessed
Environmental impacts of shale gas extraction in Canada (Council of Canadian Academies, 2014)	Rare	Unlikely	Unlikely	Unlikely	Not assessed
Report of the Nova Scotia Independent Panel on Hydraulic Fracturing (Atherton et al., 2014)	Vary rare	Rare	Rare	Likely	Rare
Independent scientific panel inquiry into hydraulic fracture stimulation in Western Australia (Hatton et al., 2018)	Vary rare	Not assessed	Rare	Unlikely	Not assessed

The scoring from the GBA hazard screening workshops (see Section 5) identified two of the five compromised well integrity impact modes as priorities for assessment in Stage 3 on the basis of the assessed severity and likelihood of the potential impacts. The two priority compromised well integrity impact modes are:

- W3 – Migration of fluids along casing between geological layers
- W4 – Migration of fluids along decommissioned or abandoned wells.

These prioritisations are broadly consistent with the findings of the qualitative review of the domestic and international inquiries as summarised in Table 27, with detail presented in the accompanying hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020). Therefore, the two above prioritised impact modes are recommended for inclusion in Stage 3 analysis.

6.2.3 Knowledge gaps

Qualitative assessments of hydraulic fracturing and compromised well integrity for the Beetaloo GBA region identified knowledge gaps including:

- Potential environmental risks from hydraulic fracture stimulation are generally considered manageable to a suitably low level, but there is heightened community concern about hydraulic fracturing. Inclusion of a spatial analysis in Stage 3 could serve to address the identified knowledge gap between engineering risk assessments and community concerns of the risks in the Beetaloo GBA region. Therefore, one impact mode, 'Hydraulic fracture growth into aquifer', is recommended for inclusion in Stage 3 analysis based on the heightened community concern around hydraulic fracturing and the regional geology of the Beetaloo GBA region.

- Quantification of the likelihood and potential rate of subsurface flow of fluids along compromised wells in the Beetaloo GBA region was identified as a priority impact mode and knowledge gap. Stage 3 investigation of two impact modes – 'Migration of fluids along casing between geological layers' and 'Migration of fluids along decommissioned or abandoned wells' – is designed to address this knowledge gap. Spatial analysis of potential flow along compromised wells will improve understanding of the likelihood of environmental impacts of well integrity failure in the Beetaloo GBA region.
- The challenges of observing and validating potential impacts from hydraulic fracture stimulation and compromised well integrity remain a source of uncertainty for future assessments. Numerical modelling of hydraulic fracturing and groundwater flow will provide quantitative estimates of fracture heights and fluid flow between aquifer units in the Beetaloo GBA region in Stage 3 to improve confidence in the assessment of risks.

7 Conclusion

The geological and environmental baseline assessment for the Beetaloo GBA region provides a synthesis of the geology and prospectivity of future shale gas, tight gas and shale oil resources, water resources and protected matters (environmental and cultural). Causal pathways for impacts to water (quantity and quality) and the environment are identified and prioritised for further investigation and assessment in Stage 3. The insights and needs emanating from informal discussions with governments, industry, landowners and the community at GBA workshops and user panel meetings are incorporated in this report.

7.1 Key findings

About the region

The Beetaloo GBA region is the focus of the Stage 2 geological and environmental baseline assessment and covers about 28,000 km^2 in the NT. The region has been defined for the GBA Program as the geological Beetaloo Sub-basin defined by the Northern Territory Geological Survey. This region is currently explored for shale gas, tight gas and shale oil resources by the petroleum companies Origin Energy, Pangaea Resources and Santos. The development and regulation of a petroleum industry targeting onshore unconventional resources has been a contentious matter in the NT and the regulation of the industry is undergoing a period of reform in response to the recommendations of the *Scientific inquiry into hydraulic fracturing in the Northern Territory* (which delivered its final report in 2018 (Pepper et al., 2018)).

Tropical and sparsely populated, this region has low agricultural potential and the land is mainly used for grazing of beef cattle. The landscapes mostly support eucalypt woodlands over a grassy understorey and a steep rainfall gradient strongly influences the environment, with more tropical elements in the north and more semi-arid elements in the south. The region is deeply weathered and overlays a thick Cambrian aquifer.

Geology and unconventional petroleum resources

The Beetaloo Sub-basin is a structural component of the greater McArthur Basin in the NT, located about 500 km south-east of Darwin. It contains a succession of Mesoproterozoic Roper Group sediments more than 5000 m thick. Overlying sedimentary basins include the Neoproterozoic to Paleozoic Georgina, Wiso and Daly basins and the Mesozoic Carpentaria Basin. The Beetaloo Sub-basin is prospective for unconventional hydrocarbons and is estimated to contain significant technically recoverable unconventional petroleum resources. Plays most likely to be developed in a five- to ten- year time frame include shale plays in the Kyalla Formation and Amungee Member of the Velkerri Formation, along with a tight sandstone play in the Hayfield sandstone member of the Hayfield mudstone.

The regional review of geological architecture, stratigraphic framework and accompanying three-dimensional geological model presented in this report provides an integrated baseline framework for the development of conceptual models.

To underpin further work on understanding likely development scenarios and recovery factors, the key physical formation properties required for each of these plays to be successful were characterised. The physical properties (Orr et al., 2020) vary by play type and include formation depths and extents, source rock properties (net thickness, total organic carbon (TOC), quality and maturity), reservoir characteristics (porosity, permeability, gas saturation and brittleness), regional stress regime and pressure gradient).

Areas with the highest potential for unconventional petroleum development were assessed by mapping the relative prospectivity of each play across the basin. Results show that the Amungee Member of the Velkerri Formation is potentially prospective for either liquids-rich or dry gas over most of the Beetaloo Sub-basin extent, whereas the Kyalla Formation is primarily prospective for liquids-rich gas. The Hayfield sandstone member liquids-rich gas/oil play is primarily restricted to the central part of the eastern sub-basin. Liquids-rich gas resources are currently more favourable to develop from an economic perspective.

As this analysis was based on geological constraints only, these results need to be integrated with information on likely economic outcomes, as well as other environmental and cultural considerations, before they can be used to fully inform future development scenarios.

The geology and prospectivity will be used as a constraint for understanding likely development scenarios in Stage 3. For example, liquids-rich gas resources are considered to be more favourable to develop from an economic perspective. The development scenarios will inform the characteristics, scale, and plausible locations for development, which are key inputs for the risk assessment in Stage 3.

Water resources

The NT Government has prohibited surface water extraction for petroleum activities. Groundwater is the most likely source of water for petroleum activities and the Cambrian Limestone Aquifer (CLA) is the most likely target, although other aquifers are potential sources and this will be investigated further in Stage 3. The NT Government requires the extraction of groundwater for petroleum activities to be licensed. Produced water from future unconventional resource extraction are potential water sources for hydraulic fracturing and drilling.

The key unconventional resources targeted for exploration are contained in ancient Proterozoic rocks (>540 My) that are mostly composed of low-permeability sedimentary formations. Those rocks are overlaid by a series of stacked geological basins in which several groundwater systems exist. The hydrogeology of the Beetaloo GBA region is conceptualised by three individual groundwater subsystems: (i) Neoproterozoic fractured rock aquifers and overlying Cambrian Antrim Plateau Volcanics, which regionally act as an aquitard; the CLA system, which is the most significant aquifer in the region; and (iii) Cretaceous Carpentaria Basin and Cenozoic sediments, which are mostly unsaturated.

The CLA system is the most documented and is used as a resource for the pastoral industry and communities. It is composed of two major groundwater flow systems that incorporate northerly flow into the Daly Basin and discharge at a spring located toward the north of the Beetaloo GBA region. A distinctive feature of the CLA is the presence of karst systems that may cause local groundwater flow paths to substantially deviate from the regional flow directions.

Potential for connection exists between the CLA and the underlying Neoproterozoic aquifers in the north-western portion of the western Beetaloo GBA region and along the southern and eastern extremities of both the eastern and western parts of the region where the Antrim Plateau Volcanics are fractured or absent. The CLA can also be connected to overlying upper Cenozoic sediments within the southern portion of the eastern Beetaloo GBA region where the Cretaceous Carpentaria Basin sediments do not act as a regional aquitard.

The Roper (44%) and Wiso (47%) catchments are the main catchments in the Beetaloo GBA region. There are no permanent streams within the region, but the groundwater discharge at Mataranka Hot Springs and baseflow to streams in Elsey National Park from the region support the perennial flows in the Roper River. Downstream of the Beetaloo GBA region there are wetlands listed in *A directory of important wetlands in Australia* (DIWA) at Mataranka and Limmen Bight (Port Roper) Tidal Wetlands System in the Roper River catchment and Lake Woods in the Wiso region.

Several groundwater-dependent ecosystems (GDEs) have been identified within the Beetaloo GBA region. However, given that regional groundwater is typically greater than 20 m deep, GDEs are likely to rely on shallow perched groundwater systems.

There are no mapped springs within the Beetaloo GBA region, but a number are recorded in surrounding areas. To the north, significant springs discharging groundwater from the Beetaloo GBA region include those near Mataranka and Flora River. South of the Beetaloo GBA region, several lakes (including Lake Woods) are likely recharge points to the CLA.

Protected matters

Two separate protected matters searches under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) EPBC Act were conducted to establish a baseline assessment for protected matters for the Beetaloo GBA region: one for the Beetaloo GBA region and another for the Beetaloo GBA extended region.

Within the Beetaloo GBA region, 14 threatened species, 13 migratory species and one species that is both threatened and migratory were identified. Other protected matters consist of 21 listed marine species.

Within the Beetaloo GBA extended region there is one threatened ecological community, 18 threatened species, 15 migratory species and two species that are both threatened and migratory. There are two nationally important wetlands: (i) Mataranka Thermal Pools and Lake Woods. These wetlands are also listed as Matters of Territory Environmental Significance; other listed matters for the NT include six territory reserves – one in the Beetaloo GBA region and the remaining five in the extended region. Five species of vertebrate animals are listed as threatened under the *Parks and Wildlife Conservation Act* (NT). No socio-economic or cultural assets were identified in searches for protected matters under the EPBC Act.

A landscape classification was developed to describe the key ecological and hydrological systems in the Beetaloo GBA region. The ecohydrological conceptualisation for the Beetaloo GBA region underpins the assessment of potential hydrological and other environmental impacts due to shale gas, tight gas and shale oil development in Stage 3. The Beetaloo GBA region was categorised into six landscape classes, dominated by the 'loamy and sandy plains' and 'clay plains' landscape classes.

Prioritisation of protected matters for further investigation in Stage 3 centred on how important the Beetaloo GBA extended region was to each matter. Detailed assessment will focus on five protected species (four nationally listed, one territory-listed), two nationally important wetlands and GDEs (priority 1).

Potential impacts

Stage 2 establishes the context for the impact and risk assessment of environmental and hydrological changes due to shale gas, tight gas and shale oil development that may affect protected matters, landscapes and other assessment endpoints in the Beetaloo GBA region. A desktop analysis of all the possible ways an activity in the life cycle of shale gas, tight gas and shale oil development may cause impact identified and scored individual hazards. Hazards that have similar potential impacts were categorised into 13 causal pathways and aggregated into three causal pathway groups:

- landscape management group
  - altering cultural heritage (priority 1)
  - altering natural and agricultural productivity (priority 2)
  - altering natural habitat and species distributions (priority 1)
  - altering surface hydrology (priority 1)
  - introduction of invasive species (priority 1)
- subsurface flow paths group
  - compromised well integrity (priority 2)
  - gas extraction altering groundwaters (priority 2)
  - hydraulic fracturing
- water and infrastructure management group.
  - discharging into surface waters
  - disposal and storage of site materials (priority 2)
  - failure of surface infrastructure (ponds, tanks, pipelines, etc.) (priority 1)
  - processing and using extracted water (priority 2)
  - sourcing water for site operations (priority 2).

Causal pathways are used in this assessment as a way of connecting hazards arising from existing activities and shale gas, tight gas and shale oil resource development with potential impacts on protected matters, landscape classes and other assessment endpoints. Five causal pathways were prioritised for a detailed level of assessment in Stage 3 (priority 1). Another six causal pathways were prioritised for assessment (priority 2).

The process of aggregating and prioritising hazards, and understanding the causal pathways that may arise from shale gas, tight gas and shale oil development, helps to focus the attention for Stage 3 by ruling out hazards deemed to be of low concern. It also ensures that future modelling and investigations are targeted towards the highest priority hazards that are likely to be of greatest severity and highest likelihood.

The impact and risk assessment in Stage 3 will further characterise these causal pathways and assess how each of them might impact on the suite of endpoints – endemic native species, migratory species, ecological communities, wetland ecosystems, water resources, cultural heritage and agriculture – for the range of development profiles to be developed in Stage 3. Development profiles will represent the range of activities required across the landscape and over time for shale gas, tight gas and shale oil resource development. In Stage 3 the assessment will identify the likely mitigation and management measures, assess the likelihood and consequence of potential impacts for each pathway, identify risk factors that amplify or diminish potential impacts, describe confidence in existing knowledge, address knowledge gaps identified in Stage 2, and identify any knowledge gaps that remain.

Preliminary conceptual models have been produced for each landscape class to consider how changes to the environment or hydrology from shale gas, tight gas and shale oil development may impact key system processes. In Stage 3, control and stressor conceptual models for each landscape class will be used to consider causal pathways in relation to key system processes (shale gas, tight gas and shale oil processes) and other threatening processes relevant to each landscape class. Protected matters (e.g. threatened species, threatened ecological communities, Ramsar-listed wetlands) will be investigated through individual asset-level assessments that consider the potential exposure of that asset to causal pathways for each landscape class (and how this may vary between landscape classes) and the impacts to the asset that may stem from that exposure. As an example, Figure 79 is a preliminary conceptualisation of potential linkages between existing drivers, threatening processes and causal pathways leading to potential impacts from future shale and tight gas development on the Gouldian finch (*Erythrura gouldiae*) – a species listed as endangered under the EPBC Act. Mitigation and management options that could be considered in an abatement plan for individual assets and that are relevant for specific causal pathways will also be identified. Monitoring recommendations, including design principles, possible measurement endpoints and relative monitoring emphases, that could validate (or invalidate) the risk predictions and underpin a baseline will be provided.

Additional to identifying and prioritising hazards and causal pathways, GBA Stage 2 has also examined in greater detail some of the most contentious issues raised by the Isa GBA user panel in relation to shale gas development:

- industrial chemicals associated with drilling and hydraulic fracturing of shale gas wells
- hydraulic fracturing and compromised well integrity.

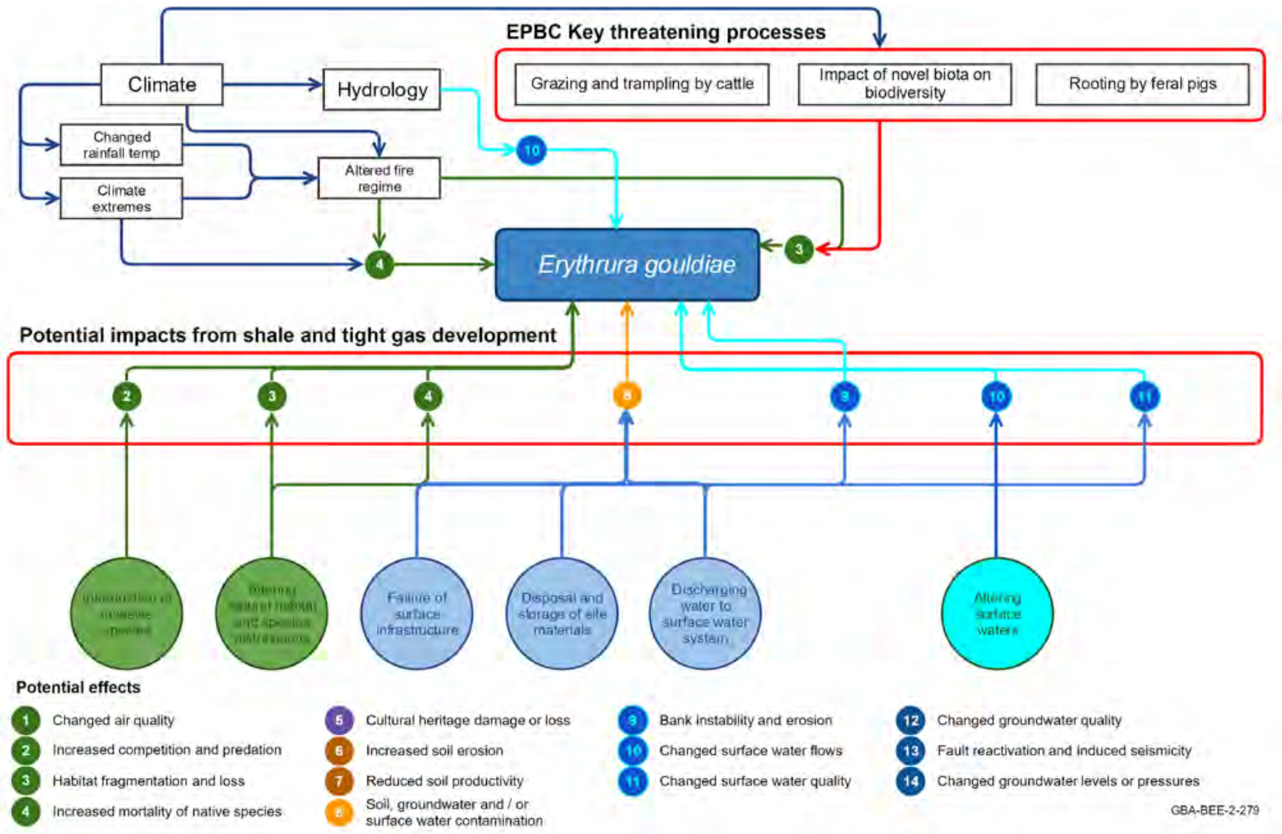

Figure 79 Preliminary conceptualisation of linkages between existing drivers, threatening processes and causal pathways leading to potential impacts from future shale and tight gas development on the Gouldian finch (*Erythrura gouldiae*)

The upper part of the conceptual model represents the ‘control model’ and represents system drivers and existing threatening processes currently impacting on the Gouldian finch. The full model, which includes the casual pathways associated with shale gas, tight gas and shale oil development, represents the stressor model.
Element: GBA-BEE-2-279

Screening of drilling and hydraulic fracturing chemicals

A total of 116 chemicals were identified for use in drilling and hydraulic fracturing at shale, tight and deep coal gas operations between 2011 and 2016. A Tier 1 qualitative (screening) environmental risk assessment (ERA) of the identified chemicals found that 42 chemicals are of ‘low concern’ and considered to pose minimal risk to surface water and groundwater aquatic ecosystems; 33 chemicals are of ‘potentially high concern’; and 41 are of ‘potential concern’. The identified chemicals of potential concern and potential high concern would require further site-specific quantitative chemical assessments to be performed to determine risks from specific gas operations to aquatic ecosystems.

Laboratory-based leachate tests on powdered rock samples collected from formations in the Beetaloo GBA region identified several elements that could be substantially mobilised into solutions by hydraulic fracturing fluids, including aluminium, cadmium, cesium, cobalt, iron, lanthanum, manganese, neodymium, nickel, lead, silver, yttrium and zinc. Priority organic chemicals such as phenol, polycyclic aromatic hydrocarbons (PAHs) and total recoverable hydrocarbons (TRHs) were detected in extracts of powdered rock samples. Targeted analysis of PAHs represented a small fraction of the total organic geogenic compounds present in the sample extracts. Hence, the majority of organic compounds in sample extracts (as TRHs) were unidentified and their risk (individual and mixtures) to aquatic environments is unknown.

Companies undertake an ERA process of gas operations (in consultation with government agencies) that identifies potential hazards (e.g. chemical transport and storage, hydraulic fracturing fluid injection, flowback and produced water storage), determines the likelihood and consequence of a risk occurring, identifies and evaluates control and mitigation measures (e.g. what controls are in place or need to be in place to address the identified risk and how effective are these controls), and develops a monitoring program to ensure controls and management strategies are adequate/effective and for compliance. Despite undertaking these detailed ERAs, there is still public concern surrounding the potential environmental impacts of hydraulic fracturing – particularly the threats posed by the mixture of industrial chemicals used and geogenic chemicals that could be mobilised and their impacts on water quality.

Hydraulic fracturing and compromised well integrity

Initial estimates of the relative likelihood of occurrence of any hydraulic fracturing and compromised well integrity impact modes were considered low. However, their importance to government and the community warrants further assessment of the ‘Hydraulic fracture growth into aquifer’ impact mode in Stage 3 as well as compromised well integrity impact modes – ‘Migration of fluids along casing between geological layers’ and ‘Migration of fluids along decommissioned or abandoned wells’.

7.2 Gaps, limitations and opportunities

Geology and unconventional petroleum resources

The geological model of the Beetaloo GBA region presented here does not include faults (Orr et al., 2020). To improve understanding of potential connectivity between the plays and overlying aquifers, the model needs to be updated with fault interpretations and the structural history reviewed in further detail, especially in the areas located close to the sub-basin boundaries. A conceptual model, as well as local-scale structural and stratigraphic numerical simulations, needs to be developed to address these structural/stratigraphic knowledge gaps. This work is being conducted in preparation for Stage 3.

The regional-scale prospectivity analysis identifies areas where more detailed work can be undertaken but is not suitable for individual play or prospect-scale evaluations. Due to local geological variations not captured by the regional input datasets, not all areas identified as having a high relative prospectivity confidence will result in gas discoveries. In addition to cultural and environmental considerations, the large capital expenditure required to extract unconventional resources (i.e. if and how a play is developed) is dependent on its economic viability. Therefore, future development profiles and impact and risk analysis should consider development of each play in the context of likely economic outcomes. Additional work to place the prospectivity analysis in an economic context includes:

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

Water resources

Groundwater knowledge gaps and future work are detailed in Section 3.6. The hydrogeological and groundwater system assessment of the GBA Beetaloo region shows that the amount of available hydrogeological data varies greatly between groundwater systems in the Beetaloo GBA region, and the deeper Proterozoic groundwater systems have limited hydrogeological data with identified gaps on the stratigraphy, baseline groundwater, hydrochemistry, flow direction, and recharge and water balance estimates.

Work undertaken as part of Stage 3, including further work on the stratigraphic model and fault interpretation and updating thickness maps of the Carpentaria Basin in the Beetaloo GBA region, aims to improve the understanding of groundwater connectivity, recharge pathways and processes. A field study will be conducted to investigate the potential of any deeper water sources discharging at Mataranka and whether this potential causal pathway presents a greater risk to Mataranka Thermal Pools and the CLA in general from the development of the petroleum industry.

Beyond the GBA Program, consideration should be given to including in exploration programs activities that will improve the knowledge base and understanding of the hydrogeology and geology of the Beetaloo region above the Roper Group. Activities could include running suites of well logs and extending geological seismic interpretation to relatively shallow depths (e.g. CLA or Antrim Plateau Volcanics) or undertaking formation tests and collecting water samples from prospective deep aquifers, such as Jamison or Bukalara sandstones.

Protected matters

The knowledge gaps for the Beetaloo GBA region represent understanding of both where matters occur in relation to potential unconventional petroleum resources development and how the ecological requirements of species and ecological communities may be impacted by the unconventional petroleum resource development pathway. Further work is needed to develop conceptual models that explicitly link risks due to shale gas, tight gas and shale oil development with individual threatened species and other important ecological assets.

The landscape classification is limited by the quality of available datasets, including surface geology, elevation, vegetation and landform mapping, and extent and quality of ground observations. Additional information of this type will assist in refining and increasing the accuracy of the landscape classification.

Potential impacts

The focus of Stage 3 will be on building upon the preliminary conceptual models of causal pathways developed in Stage 2 that link development-related activities and hazards with landscape classes and endpoints specific to the region. Stage 3 will also seek to better identify how risks from shale gas, tight gas and shale oil development may affect protected matters within the environment, including how shale gas, tight gas and shale oil development may interact with existing threatening processes such as changing climate patterns, land clearing and biodiversity impacts due to introduced pests, such as weeds and feral animals.

Conceptualisation of the regional geology and hydrogeology, as well as the potential hydrological connections from shale gas, tight gas and shale oil reservoirs to near-surface assets such as the regional watertable aquifer, includes several uncertainties and alternative conceptual models. These uncertainties will be captured, represented and tested using simple, screening numerical models (some of the additional work being conducted in Stage 3 will address and reduce some of these uncertainties). Uncertainty will be propagated through models used for the assessment in Stage 3 by basing predictions on plausible distributions of model parameters rather than fixed values. The preliminary conceptualisations presented here for each causal pathway will be updated in Stage 3 using a range of approaches, including expert elicitation. The conceptual models reflect the beliefs that experts hold about the ways in which development might affect ecological, economic and sociocultural values. More detailed analysis, based on development scenarios, will produce more robust conceptual models for the causal pathways that are also informed by an appraisal of current regulatory controls and industry practices.

Additional GBA Beetaloo Sub-basin work

As part of the 2019 budget, the Australian Government committed an additional $5.022 million to the GBA Program to align the delivery of the assessment of the Beetaloo Sub-basin with the NT Government's Strategic Regional Environmental Baseline Assessment (SREBA). The additional funds will be used to undertake terrestrial and aquatic biodiversity surveys, additional water sampling to improve the understanding of groundwater flow and water quality, baseline seismic monitoring and development of data delivery systems. The additional activities have been developed with input from the NT Government, GBA Program partners and members of the Beetaloo Technical Working Groups.

The majority of activities will occur during the 2019–20 and 2020–21 financial years, with minor carryover into 2021–22.

Screening of drilling and hydraulic fracturing chemicals

Public concern about potential environmental impacts on water quality from hydraulic fracturing remains heightened. In particular, the community is concerned about potential impacts on water quality from the mixture of industrial chemicals used and geogenic chemicals that could be mobilised during shale, tight and deep coal gas resource developments. The Stage 3 chemical assessment project will undertake water quality monitoring of future shale gas operations in the Beetaloo GBA region. The project will provide open and transparent reporting of water quality monitoring data before, during and after hydraulic fracturing to improve community and government understanding in the ERA process (for chemical assessments), controls and monitoring of chemicals; and inform wastewater management and treatment options. Specifically, the project aims to:

1. assess the concentration of industrial and geogenic chemicals in flowback and produced waters resulting from hydraulic fracturing operations to determine safe dilutions and treatment options
2. check compliance of chemical concentrations in nearby surface water and groundwater bores with relevant Australian water quality guideline values (i.e. Australian drinking water quality criteria, Australian livestock watering quality criteria, ANZECC/ARMCANZ (2000) criteria for the protection of aquatic ecosystems)
3. quantify the site-specific surface water and groundwater-related risks of chemicals used in hydraulic fracturing in the event of unlikely release of fluids – for example, due to compromised well integrity or leakage from storage dams. Residual risk reduction of unlikely events will have minimal consequence on water quality (localised event) and treatment, remediation and management plans are adequate to prevent impacts.

Hydraulic fracturing and compromised well integrity

Potential environmental risks from hydraulic fracture stimulation are generally considered manageable to a suitably low level. However, there are heightened community concerns around the use of hydraulic fracturing in many places, including the local communities of the Beetaloo

GBA region. To help address these concerns and improve knowledge of regional geology, the impact mode 'hydraulic fracture growth into aquifer' will be further analysed in Stage 3.

Quantification of the likelihood and potential rate of subsurface flow of fluids along compromised wells in the Beetaloo GBA region was identified as a priority impact mode and knowledge gap for government and the community. Spatial analysis, using a simple model potential flow along compromised wells that incorporates key geological characteristics for the basin and well construction standards, will improve understanding of the likelihood of environmental impacts of well integrity failure in the Beetaloo GBA region.

Finally, the challenges of observing and validating potential impacts from hydraulic fracture stimulation and compromised well integrity remain a source of uncertainty for future assessments. In place of observations, numerical modelling of hydraulic fracturing and groundwater flow gives quantitative estimates of potential fracture heights and fluid flow between aquifer units in the Beetaloo GBA region to contribute to knowledge and management of these risks.

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Glossary

The register of terms and definitions used in the Geological and Bioregional Assessment Program is available online at https://w3id.org/gba/glossary (note that terms and definitions are respectively listed under the 'Name' and 'Description' columns in this register). This register is a list of terms, which are the preferred descriptors for concepts. Other properties are included for each term, including licence information, source of definition and date of approval. Semantic relationships (such as hierarchical relationships) are formalised for some terms, as well as linkages to other terms in related vocabularies.

2C: best estimate of contingent resources

abandonment: a process which involves shutting down the well and rehabilitating the site. It includes decommissioning the well.

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

activity: for the purposes of Impact Modes and Effects Analysis (IMEA), a planned event associated with unconventional gas resource development. For example, activities during the exploration life-cycle stage include drilling and coring, ground-based geophysics and surface core testing. Activities are grouped into ten major activities, which can occur at different life-cycle stages.

adsorption: the capability of all solid substances to attract to their surfaces molecules of gases or solutions with which they are in contact

aeolian: relating to or arising from the action of wind

anticline: an arch-shaped fold in rock in which rock layers are upwardly convex. The oldest rock layers form the core of the fold and, outward from the core, progressively younger rocks occur.

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

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

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

asset: an entity that has value to the community and, for the purposes of geological and bioregional assessments, is associated with a GBA region. An asset is a store of value and may be managed and/or used to maintain and/or produce further value. An asset may have many values associated with it that can be measured from a range of perspectives; for example, the values of a wetland can be measured from ecological, sociocultural and economic perspectives.

barrel: a standard unit of measurement for all production and sales of oil. It has a volume of 42 US gallons [0.16 m^3].

baseflow: the portion of streamflow that comes from shallow and deep subsurface flow, and is an important part of the groundwater system

basement: the oldest rocks in an area; commonly igneous or metamorphic rocks of Precambrian or Paleozoic age that underlie other sedimentary formations. Basement generally does not contain significant oil or gas, unless it is fractured and in a position to receive these materials from sedimentary strata.

basin-centred gas: a type of tight gas that occurs in distributed basin-centred gas accumulations, where gas is hosted in low permeability reservoirs which are commonly abnormally overpressured, lack a down dip water contact and are continuously saturated with gas. This is also sometimes referred to as 'continuous' and 'pervasive' gas.

bed: in geosciences, the term 'bed' refers to a layer of sediment or sedimentary rock, or stratum. A bed is the smallest stratigraphic unit, generally a centimetre or more in thickness. To be labeled a bed, the stratum must be distinguishable from adjacent beds.

bioaccumulation: a process by which chemicals are taken up by a plant or animal either directly through exposure to a contaminated medium (soil, sediment, water) or by consuming food or water containing the chemical

biogenic gas: hydrocarbon gases (which are overwhelmingly (greater than or equal to 99%) methane) produced as a direct consequence of bacterial activity

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

brittleness: a material is brittle if, when subjected to stress, it breaks without significant plastic deformation

casing: a pipe placed in a well to prevent the wall of the hole from caving in and to prevent movement of fluids from one formation to another

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

causal pathway group: causal pathways with similar attributes (e.g. landscape management) that are grouped for further analysis

cementing: the application of a liquid slurry of cement and water to various points inside and outside the casing

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

clastic: sedimentary rock that consists of fragments or clasts of pre-existing rock, such as sandstone or shale cleat: the vertical cleavage of coal seams. The main set of joints along which coal breaks when mined.

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

coal seam gas: coal seam gas (CSG) is a form of natural gas (generally 95% to 97% pure methane, CH4) extracted from coal seams, typically at depths of 300 to 1000 m. Also called coal seam methane (CSM) or coalbed methane (CBM).

compression: lateral force or stress (e.g. tectonic) that tends to decrease the volume of, or shorten, a substance

conceptual model: an abstraction or simplification of reality that describes the most important components and processes of natural and/or anthropogenic systems, and their response to interactions with extrinsic activities or stressors. They provide a transparent and general representation of how complex systems work, and identify gaps or differences in understanding. They are often used as the basis for further modelling, form an important backdrop for assessment and evaluation, and typically have a key role in communication. Conceptual models may take many forms, including descriptive, influence diagrams and pictorial representations.

condensate: condensates are a portion of natural gas of such composition that are in the gaseous phase at temperature and pressure of the reservoirs, but that, when produced, are in the liquid phase at surface pressure and temperature

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

consequence: synonym of impact

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

contingent resources: those quantities of petroleum which are estimated, on a given date, to be potentially recoverable from known accumulations but which are not currently considered to be commercially recoverable

conventional gas: conventional gas is obtained from reservoirs that largely consist of porous sandstone formations capped by impermeable rock, with the gas trapped by buoyancy. The gas can often move to the surface through the gas wells without the need to pump.

Cooper Basin: the Cooper Basin geological province is an Upper Carboniferous – Middle Triassic geological sedimentary basin that is up to 2500 m thick and occurs at depths between 1000 and 4400 m. It is overlain completely by the Eromanga and Lake Eyre basins. Most of the Cooper Basin is in south-west Queensland and north-east SA, and includes a small area of NSW at Cameron Corner. It occupies a total area of approximately 130,000 km^2, including 95,740 km^2 in Queensland, 34,310 km^2 in SA and 8 km^2 in NSW.

crude oil: the portion of petroleum that exists in the liquid phase in natural underground reservoirs and remains liquid at atmospheric conditions of pressure and temperature. Crude oil may include small amounts of non-hydrocarbons produced with the liquids.

crust: the outer part of the Earth, from the surface to the Mohorovicic discontinuity (Moho)

cumulative impact: for the purposes of geological and bioregional assessments, the total environmental change resulting from the development of selected unconventional hydrocarbon resources when all past, present and reasonably foreseeable actions are considered

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

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

deep coal gas: gas in coal beds at depths usually below 2000 m are often described as 'deep coal gas'. Due to the loss of cleat connectivity and fracture permeability with depth, hydraulic fracturing is used to release the free gas held within the organic porosity and fracture system of the coal seam. As dewatering is not needed, this makes deep coal gas exploration and development similar to shale gas reservoirs.

deformation: folding, faulting, shearing, compression or extension of rocks due to the Earth's forces

delta: a low, nearly flat area near the mouth of a river, commonly forming a fan-shaped plain that can extend beyond the coast into deep water. Deltas form in lakes and oceans when sediment supplied by a stream or river overwhelms that removed by tides, waves, and currents

depocentre: an area or site of maximum deposition; the thickest part of any specified stratigraphic unit in a depositional basin

deposition: sedimentation of any material, as in the mechanical settling of sediment from suspension in water, precipitation of mineral matter by evaporation from solution, and accumulation of organic material

depositional environment: the area in which, and physical conditions under which, sediments are deposited. This includes sediment source; depositional processes such as deposition by wind, water or ice; and location and climate, such as desert, swamp or river.

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

development: a phase in which newly discovered oil or gas fields are put into production by drilling and completing production wells

disconformity: see unconformity

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.

dolomite: a rhombohedral carbonate mineral with the formula $CaMg(CO_3)_2$

dolostone: a carbonate sedimentary rock that contains over 50% of the mineral dolomite [$CaMg(CO_3)_2$]

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)

drill bit: a drilling tool that cuts through rock by a combination of crushing and shearing

drill stem test: an operation on a well designed to demonstrate the existence of moveable petroleum in a reservoir by establishing flow to the surface and/or to provide an indication of the potential productivity of that reservoir. Drill stem tests (DSTs) are performed in the open hole to obtain reservoir fluid samples, static bottomhole pressure measurements, indications of productivity and short-term flow and pressure buildup tests to estimate permeability and damage extent.

drilling fluid: circulating fluid that lifts rock cuttings from the wellbore to the surface during the drilling operation. Also functions to cool down the drill bit, and is a component of well control.

dry gas: natural gas that is dominated by methane (greater than 95% by volume) with little or no condensate or liquid hydrocarbons

economic values: values associated with agriculture, aquaculture, drinking water supply, industry or intensive development and tourism activities

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

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

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

endpoint: for the purposes of geological and bioregional assessments, an endpoint is a value pertaining to water and the environment that may be impacted by development of unconventional gas resources. Endpoints include assessment endpoints – explicit expressions of the ecological, economic and/or social values to be protected; and measurement endpoints – measurable characteristics or indicators that may be extrapolated to an assessment endpoint as part of the impact and risk assessment.

Eromanga Basin: an extensive geologic sedimentary basin formed from the Early Jurassic to the Late Cretaceous that can be over 2500 m thick. It overlies several older geological provinces including the Cooper Basin, and is in part overlain by the younger Cenozoic province, the Lake Eyre Basin. The Eromanga Basin is found across much of Queensland, northern SA, southern NT, as well as north-western NSW. The Eromanga Basin encompasses a significant portion of the Great Artesian Basin.

erosion: the wearing away of soil and rock by weathering, mass wasting, and the action of streams, glaciers, waves, wind, and underground water

exploration: the search for new hydrocarbon resources by improving geological and prospectivity understanding of an area and/or play through data acquisition, data analysis and interpretation. Exploration may include desktop studies, field mapping, seismic or other geophysical surveys, and drilling.

exploration approvals: all operational approvals under the Schedule and all environmental approvals under the Petroleum Environment Regulations granted on an exploration permit for an exploration activity

extraction: the removal of water for use from waterways or aquifers (including storages) by pumping or gravity channels. In the oil and gas industry, extraction refers to the removal of oil and gas from its reservoir rock.

facies: the characteristics of a rock unit that reflect the conditions of its depositional environment

fairway: a term used in geology to describe a regional trend along which a particular geological feature is likely to occur, such as a hydrocarbon fairway. Understanding and predicting fairways can help geologists explore for various types of resources, such as minerals, oil and gas.

fault: a fracture or zone of fractures in the Earth’s crust along which rocks on one side were displaced relative to those on the other side

field: in petroleum geoscience, a 'field' refers to an accumulation, pool, or group of pools of hydrocarbons or other mineral resources in the subsurface. A hydrocarbon field consists of a reservoir with trapped hydrocarbons covered by an impermeable sealing rock, or trapped by hydrostatic pressure.

floodplain: a flat area of unconsolidated sediment near a stream channel that is submerged during or after high flows

flowback: the process of allowing fluids and entrained solids to flow from a well following a treatment, either in preparation for a subsequent phase of treatment or in preparation for cleanup and returning the well to production. The flowback period begins when material introduced into the well during the treatment returns to the surface following hydraulic fracturing or refracturing. The flowback period ends when either the well is shut in and permanently disconnected from the flowback equipment or at the startup of production.

flowback water: the fluids and entrained solids that emerge from a well during flowback

fluvial: sediments or other geologic features formed by streams

fold: a curve or bend of a formerly planar structure, such as rock strata or bedding planes, that generally results from deformation

footwall: the underlying side of a fault, below the hanging wall

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

formation fluid: any fluid within the pores of the rock. It may be water, oil, gas or a mixture. Formation water in shallow aquifers can be fresh. Formation water in deeper layers of rock is typically saline.

formation water: water that occurs naturally in sedimentary rocks

fracking: see hydraulic fracturing

fracture: a crack or surface of breakage within rock not related to foliation or cleavage in metamorphic rock along which there has been no movement. A fracture along which there has been displacement is a fault. When walls of a fracture have moved only normal to each other, the fracture is called a joint. Fractures can enhance permeability of rocks greatly by connecting pores together, and for that reason, fractures are induced mechanically in some reservoirs in order to boost hydrocarbon flow. Fractures may also be referred to as natural fractures to distinguish them from fractures induced as part of a reservoir stimulation or drilling operation. In some shale reservoirs, natural fractures improve production by enhancing effective permeability. In other cases, natural fractures can complicate reservoir stimulation.

free gas: the gaseous phase present in a reservoir or other contained area. Gas may be found either dissolved in reservoir fluids or as free gas that tends to form a gas cap beneath the top seal on the reservoir trap. Both free gas and dissolved gas play important roles in the reservoir-drive mechanism.

gas cap: part of a petroleum reservoir that contains free gas

gas hydrate: naturally occurring 'ice-like' combinations of natural gas and water that have the potential to provide an immense resource of natural gas from the world’s oceans and polar regions. Gas hydrates are known to be widespread in permafrost regions and beneath the sea in sediments of outer continental margins. It is generally accepted that the volume of natural gas contained in the world's gas hydrate accumulations greatly exceeds that of known gas reserves.

gas-in-place: the total quantity of gas that is estimated to exist originally in naturally occurring reservoirs gas saturation: the relative amount of gas in the pores of a rock, usually as a percentage of volume

geogenic chemical: a naturally occurring chemical originating from the earth – for example, from geological formations

geological architecture: the structural style and features of a geological province, like a sedimentary basin

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

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

groundwater-dependent ecosystem: ecosystems that require access to groundwater on a permanent or intermittent basis to meet all or some of their water requirements

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

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

groundwater system: see water system

hanging wall: the overlying side of a fault, above the footwall

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

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

horizontal drilling: drilling of a well in a horizontal or near-horizontal plane, usually within the target hydrocarbon-bearing formation. Requires the use of directional drilling techniques that allow the deviation of the well on to a desired trajectory.

hydraulic fracturing: also known as 'fracking', 'fraccing' or 'fracture simulation'. This is a process by which geological formations bearing hydrocarbons (oil and gas) are 'stimulated' to increase the flow of hydrocarbons and other fluids towards the well. In most cases, hydraulic fracturing is undertaken where the permeability of the formation is initially insufficient to support sustained flow of gas. The process involves the injection of fluids, proppant and additives under high pressure into a geological formation to create a conductive fracture. The fracture extends from the well into the production interval, creating a pathway through which oil or gas is transported to the well.

hydraulic fracturing fluid: the fluid injected into a well for hydraulic fracturing. Consists of a primary carrier fluid (usually water or a gel), a proppant such as sand and chemicals to modify the fluid properties.

hydraulic fracturing stage: hydraulic fracture stimulation conducted at a defined interval along a well. Hydraulic fracture stimulation of horizontal wells will often involve multiple hydraulic fracture stages so as to create hydraulic fractures at multiple locations along the length of the well.

hydrocarbons: various organic compounds composed of hydrogen and carbon atoms that can exist as solids, liquids or gases. Sometimes this term is used loosely to refer to petroleum.

hydrogen index: the amount of hydrogen relative to the amount of organic carbon present in kerogen (organic matter). Gross trends of hydrogen indices (HIs) can be used as an indication of maturity.

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

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

hydrostatic pressure: equal pressure in all direction, equivalent to the pressure which is exerted on a portion of a column of water as a result of the weight of the fluid above it

impact: the difference between what could happen as a result of activities and processes associated with extractive industries, such as shale, tight and deep coal gas development, and what would happen without them. Impacts may be changes that occur to the natural environment, community or economy. Impacts can be a direct or indirect result of activities, or a cumulative result of multiple activities or processes.

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

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

Impact Modes and Effects Analysis: a systematic hazard identification and prioritisation technique based on Failure Modes and Effects Analysis injection: the forcing or pumping of substances into a porous and permeable subsurface rock formation. Examples of injected substances can include either gases or liquids.

kerogen: insoluble (in organic solvents) particulate organic matter preserved in sedimentary rocks that consists of various macerals originating from components of plants, animals, and bacteria. Kerogen can be isolated from ground rock by extracting bitumen with solvents and removing most of the rock matrix with hydrochloric and hydrofluoric acids.

kerogen type: kerogens are classified into five types: I, II, IIS, III, and IV

known accumulation: the term accumulation is used to identify an individual body of moveable petroleum. The key requirement to consider an accumulation as known, and hence contain reserves or contingent resources, is that each accumulation/reservoir must have been penetrated by a well. In general, the well must have clearly demonstrated the existence of moveable petroleum in that reservoir by flow to surface or at least some recovery of a sample of petroleum from the well. However, where log and/or core data exist, this may suffice, provided there is a good analogy to a nearby and geologically comparable known accumulation.

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, a collection of ecosystems with characteristics that are expected to respond similarly to changes in groundwater and/or surface water due to unconventional gas resource development. Note that there is expected to be less heterogeneity in the response within a landscape class than between landscape classes. They are present on the landscape across the entire GBA region and their spatial coverage is exhaustive and non-overlapping. Conceptually, landscape classes can be considered as types of ecosystem assets.

leaky aquitard: a semi-permeable geological material that can transmit groundwater. Although regionally non-productive, it may be classed as a very low yielding aquitard that is sometimes used to produce groundwater where no other source is available.

life-cycle stage: one of five stages of operations in unconventional gas resource development considered as part of the Impact Modes and Effects Analysis (IMEA). These are exploration, appraisal, development, production, and rehabilitation. Each life-cycle stage is further divided into major activities, which are further divided into activities.

likelihood: probability that something might happen

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

lithology: the description of rocks, especially in hand specimen and in outcrop, on the basis of characteristics such as colour, mineralogic composition and grain size major activity: for the purposes of Impact Modes and Effects Analysis (IMEA), a group of activities associated with a common part of the shale, tight or deep coal gas resource development process. There are ten major activities used in geological and bioregional assessments ranging from 'construction' through to 'well abandonment and rehabilitation'. Major activities may occur across different life cycles, though often with differing levels of intensity; for example, drilling may occur in the exploration, appraisal, development and production life cycles but is at its peak during development.

marl: a sedimentary rock containing calcareous clay

material: pertinent or relevant

mature: a hydrocarbon source rock that has started generating hydrocarbons

metamorphic rock: a rock formed from pre-existing rock due to high temperature and pressure in the Earth's crust, but without complete melting

methane: a colourless, odourless gas, the simplest parafin hydrocarbon, formula CH_4. It is the principal constituent of natural gas and is also found associated with crude oil. Methane is a greenhouse gas in the atmosphere because it absorbs long-wavelength radiation from the Earth's surface.

migration: the process whereby fluids and gases move through rocks. In petroleum geoscience, 'migration' refers to when petroleum moves from source rocks toward reservoirs or seep sites. Primary migration consists of movement of petroleum to exit the source rock. Secondary migration occurs when oil and gas move along a carrier bed from the source to the reservoir or seep. Tertiary migration is where oil and gas move from one trap to another or to a seep.

Moho: the Mohorivicic discontinuity (seismic reflector) at the base of the crust

mudstone: a general term for sedimentary rock made up of clay-sized particles, typically massive and not fissile

natural gas: the portion of petroleum that exists either in the gaseous phase or is in solution in crude oil in natural underground reservoirs, and which is gaseous at atmospheric conditions of pressure and temperature. Natural gas may include amounts of non-hydrocarbons.

naturally occurring radioactive materials: radioactive elements and their decay products found in the environment that have been generated from natural processes

net thickness: the accumulated thickness of a certain rock type of a specified quality which is found within a specific interval of formation

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

oil-in-place: the total quantity of oil that is estimated to exist originally in naturally occurring reservoirs

oil-prone: organic matter that generates significant quantities of oil at optimal maturity organic matter: biogenic, carbonaceous materials. Organic matter preserved in rocks includes kerogen, bitumen, oil and gas. Different types of organic matter can have different oil-generative potential.

outcrop: a body of rock exposed at the surface of the Earth

overpressure: occurs when the pore pressure is higher than the hydrostatic pressure, caused by an increase in the amount of fluid or gas in the rock, or changes to the rock that reduce the amount of pore space. If the fluid cannot escape, the result is an increase in pore pressure. Overpressure can only occur where there are impermeable layers preventing the vertical flow of water, otherwise the water would flow upwards to equalise back to hydrostatic pressure.

P10: in terms of petroleum resource classification, P10 indicates a 10% probability that this volume of oil or gas will be found or exceeded

P50: in terms of petroleum resource classification, P50 indicates a 50% probability that this volume of oil and gas will be found or exceeded

P90: in terms of petroleum resource classifications, P90 indicates a 90% probability that at least this much oil or gas can be found in place

partial aquifer: a permeable geological material with variable groundwater yields that are lower than in an aquifer and range from fair to very low yielding locally

peak life-cycle stage: the life-cycle stage when impacts from unconventional gas resource development are expected to be greatest. The five life-cycle stages are: (i) exploration, appraisal, (iii) development, (iv) production and (v) rehabilitation.

percentile: a specific type of quantile where the range of a distribution or set of runs is divided into 100 contiguous intervals, each with probability 0.01. An individual percentile may be used to indicate the value below which a given percentage or proportion of observations in a group of observations fall. For example, the 95th percentile is the value below which 95% of the observations may be found.

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

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

petroleum system: the genetic relationship between a pod of source rock that is actively producing hydrocarbon, and the resulting oil and gas accumulations. It includes all the essential elements and processes needed for oil and gas accumulations to exist. These include the source, reservoir, seal, and overburden rocks, the trap formation, and the hydrocarbon generation, migration and accumulation processes. All essential elements and processes must occur in the appropriate time and space in order for petroleum to accumulate.

play: a conceptual model for a style of hydrocarbon accumulation used during exploration to develop prospects in a basin, region or trend and used by development personnel to continue exploiting a given trend. A play (or group of interrelated plays) generally occurs in a single petroleum system.

play fairway analysis: sometimes referred to as play fairway mapping, play fairway analysis is used to identify areas where a specific play is likely to be successful, and where additional work on a finer scale is warranted in order to further develop an understanding of a prospect. The phrasing 'fairway' is used as prospective areas on the map are often visually similar to fairways on a golf course. Play fairway maps are created at a regional scale, often tens to hundreds of kilometres in scale, from multiple input sources that vary based on what information is available and relevant based on the requirements of the creator.

plug: a mechanical device or material (such as cement) placed within a well to prevent vertical movement of fluids

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

potential effect: specific types of impacts or changes to water or the environment, such as changes to the quantity and/or quality of surface water or groundwater, or to the availability of suitable habitat

produced water: a term used in the oil industry to describe water that is produced as a by-product along with the oil and gas. Oil and gas reservoirs often have water as well as hydrocarbons, sometimes in a zone that lies under the hydrocarbons, and sometimes in the same zone with the oil and gas. The terms 'co-produced water' and 'produced water' are sometimes used interchangeably by government and industry. However, in the geological and bioregional assessments, 'produced water' is used to describe water produced as a by-product of shale and tight gas resource development, whereas 'co-produced water' refers to the large amounts of water produced as a by-product of coal seam gas development.

producing: a well or rock formation from which oil, gas or water is produced

production: in petroleum resource assessments, 'production' refers to the cumulative quantity of oil and natural gas that has been recovered already (by a specified date). This is primarily output from operations that has already been produced.

production activity: any physical activity associated with drilling and hydraulic fracturing (which may include clearing and/or well construction) pursuant to the granting of production approvals for onshore shale gas on a production licence

production approvals: all operational approvals granted under the Schedule and all environmental approvals granted under the Petroleum Environment Regulations on a production licence for a production activity

production well: a well used to remove oil or gas from a reservoir progradation: movement of the shoreline into a sedimentary basin when clastic input exceeds the accommodation space, as might occur due to reduced basinal subsidence or increased erosion and sediment supply

proppant: a component of the hydraulic fracturing fluid system comprising sand, ceramics or other granular material that 'prop' open fractures to prevent them from closing when the injection is stopped

prospectivity assessment: the assessment of an area to determine the likelihood of discovering a given resource (e.g. oil, gas, groundwater) by analysing the spatial patterns of foundation datasets. The key objective is to identify areas of increased likelihood of discovering previously unrecognised potential. Sometimes referred to as 'chance of success' or 'common risk segment' analysis.

prospectivity confidence: the relative certainty of hydrocarbons being found (on a scale of zero to one) based on prospectivity mapping

prospectivity mapping: mapping or visualisation component of a prospectivity analysis which is used to determine the likelihood of discovering a given resource within a chosen area. See prospectivity assessment.

recharge: see groundwater recharge

regression: the retreat or contraction of the sea from land areas, and the consequent evidence of such withdrawal (such as enlargement of the area of deltaic deposition). Also, any change (such as fall of sea level or uplift of land) that brings nearshore, typically shallow-water environments to areas formerly occupied by offshore, typically deep-water conditions, or that shifts the boundary between marine and nonmarine deposition (or between deposition and erosion) toward the center of a marine basin.

reserves: quantities of petroleum anticipated to be commercially recoverable in known accumulations from a given date forward under defined conditions. Reserves must further satisfy four criteria: they must be discovered, recoverable, commercial and remaining (as of the evaluation date) based on the development project(s) applied.

reservoir: a subsurface body of rock having sufficient porosity and permeability to store and transmit fluids and gases. Sedimentary rocks are the most common reservoir rocks because they have more porosity than most igneous and metamorphic rocks and form under temperature conditions at which hydrocarbons can be preserved. A reservoir is a critical component of a complete petroleum system.

reservoir rock: any porous and permeable rock that contains liquids or gases (e.g. petroleum, water, CO_2), such as porous sandstone, vuggy carbonate and fractured shale

reverse fault: a fault in which the hanging wall appears to have moved upward relative to the footwall. Common in compressional regimes.

ridge: a narrow, linear geological feature that forms a continuous elevated crest for some distance (e.g. a chain of hills or mountains or a watershed) riparian: within or along the banks of a stream or adjacent to a watercourse or wetland; relating to a riverbank and its environment, particularly to the vegetation

risk: the effect of uncertainty on objectives (ASNZ ISO 3100). This involves assessing the potential consequences and likelihood of impacts to environmental and human values that may stem from an action, under the uncertainty caused by variability and incomplete knowledge of the system of interest.

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

sandstone: a sedimentary rock composed of sand-sized particles (measuring 0.05–2.0 mm in diameter), typically quartz

seal: a relatively impermeable rock, commonly shale, anhydrite or salt, that forms a barrier or cap above and around reservoir rock such that fluids cannot migrate beyond the reservoir. A seal is a critical component of a complete petroleum system.

sediment: various materials deposited by water, wind or glacial ice, or by precipitation from water by chemical or biological action (e.g. clay, sand, carbonate)

sedimentary rock: a rock formed by lithification of sediment transported or precipitated at the Earth's surface and accumulated in layers. These rocks can contain fragments of older rock transported and deposited by water, air or ice, chemical rocks formed by precipitation from solution, and remains of plants and animals.

sedimentation: the process of deposition and accumulation of sediment (unconsolidated materials) in layers

seismic survey: a method for imaging the subsurface using controlled seismic energy sources and receivers at the surface. Measures the reflection and refraction of seismic energy as it travels through rock.

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

severity: magnitude of an impact

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

shale: a fine-grained sedimentary rock formed by lithification of mud that is fissile or fractures easily along bedding planes and is dominated by clay-sized particles

shale gas: generally extracted from a clay-rich sedimentary rock, which has naturally low permeability. The gas it contains is either adsorbed or in a free state in the pores of the rock.

shear: a frictional force that tends to cause contiguous parts of a body to slide relative to each other in a direction parallel to their plane of contact sill: a small body of intrusive igneous rock injected between layers of sedimentary rock

siltstone: a sedimentary rock composed of silt-sized particles (0.004 to 0.063 mm in diameter)

sociocultural values: values associated with aesthetic, cultural and spiritual beliefs, human health and recreation or amenity values

source rock: a rock rich in organic matter which, if heated sufficiently, will generate oil or gas. Typical source rocks, usually shales or limestones, contain about 1% organic matter and at least 0.5% total organic carbon (TOC), although a rich source rock might have as much as 10% organic matter. Rocks of marine origin tend to be oil-prone, whereas terrestrial source rocks (such as coal) tend to be gas-prone. Preservation of organic matter without degradation is critical to creating a good source rock, and necessary for a complete petroleum system. Under the right conditions, source rocks may also be reservoir rocks, as in the case of shale gas reservoirs.

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

stratigraphy: the study of the history, composition, relative ages and distribution of stratified rock strata, and its interpretation to reveal Earth’s history. However, it has gained broader usage to refer to the sequential order and description of rocks in a region.

stress: the force applied to a body that can result in deformation, or strain, usually described in terms of magnitude per unit of area, or intensity

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

strike-slip fault: a type of fault whose surface is typically vertical or nearly so. The motion along a strike-slip fault is parallel to the strike of the fault surface, and the fault blocks move sideways past each other. A strike-slip fault in which the block across the fault moves to the right is described as a dextral strike-slip fault. If it moves left, the relative motion is described as sinistral.

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

subsidence: the sudden sinking or gradual downward settling of the Earth's surface with little or no horizontal motion. The movement is not restricted in rate, magnitude, or area involved.

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

thermal maturity: the degree of heating of a source rock in the process of transforming kerogen (derived from organic matter) into hydrocarbon. Thermal maturity is commonly evaluated by measuring vitrinite reflectance or by pyrolysis.

tight gas: tight gas is trapped in reservoirs characterised by very low porosity and permeability. The rock pores that contain the gas are minuscule, and the interconnections between them are so limited that the gas can only migrate through it with great difficulty.

total organic carbon: the quantity of organic matter (kerogen and bitumen) is expressed in terms of the total organic carbon (TOC) content in mass per cent. The TOC value is the most basic measurement for determining the ability of sedimentary rocks to generate and expel hydrocarbons.

toxicity: inherent property of an agent to cause an adverse biological effect

transgression: any change (such as rise of sea level or subsidence of land) that brings offshore, typically deep-water environments to areas formerly occupied by nearshore, typically shallow-water conditions, or that shifts the boundary between marine and nonmarine deposition (or between deposition and erosion) outward from the center of a marine basin.

trap: a geologic feature that permits an accumulation of liquid or gas (e.g. natural gas, water, oil, injected CO_2) and prevents its escape. Traps may be structural (e.g. domes, anticlines), stratigraphic (pinchouts, permeability changes) or combinations of both.

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

unconformity: a surface of erosion between rock bodies that represents a significant hiatus or gap in the stratigraphic succession. Some kinds of unconformities are (a) angular unconformity – an unconformity in which the bedding planes above and below the unconformity are at an angle to each other; and (b) disconformity – an unconformity in which the bedding planes above and below the stratigraphic break are essentially parallel.

unconventional gas: unconventional gas is generally produced from complex geological systems that prevent or significantly limit the migration of gas and require innovative technological solutions for extraction. There are numerous types of unconventional gas such as coal seam gas, deep coal gas, shale gas and tight gas.

vitrinite: one of the primary components of coal and most sedimentary kerogen. Vitrinite is a type of maceral, where 'macerals' are organic components of coal analogous to the 'minerals' of rocks. It is derived from the cell-wall material or woody tissue of plants.

vitrinite reflectance: a maturation parameter for determining organic matter in fine-grained rocks

volatile oil: type of crude oil that contains a significant portion of dissolved gasses and typically is lower viscosity than other types of crude oil. When produced, dissolved gases separate from the liquid and, hence, volatile oil reservoirs can produce mainly gas with a relatively low liquid content.

water allocation: the specific volume of water allocated to water access entitlements in a given season, defined according to rules established in the relevant water plan

water-dependent asset: an asset potentially impacted, either positively or negatively, by changes in the groundwater and/or surface water regime due to unconventional gas resource development water system: a system that is hydrologically connected and described at the level desired for management purposes (e.g. subcatchment, catchment, basin or drainage division, or groundwater management unit, subaquifer, aquifer, groundwater basin)

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

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

weathering: the breakdown of rocks and other materials at the Earth's surface caused by mechanical action and reactions with air, water and organisms. Weathering of seep oils or improperly sealed oil samples by exposure to air results in evaporative loss of light hydrocarbons.

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

well barrier: envelope of one or several dependent barrier elements (including casing, cement, and any other downhole or surface sealing components) that prevent fluids from flowing unintentionally between a bore or a well and geological formations, between geological formations or to the surface.

well barrier failure: when a single, specific barrier fails to contain fluids (remaining barriers maintaining containment)

well integrity: maintaining full control of fluids (or gases) within a well at all times by employing and maintaining one or more well barriers to prevent unintended fluid (gas or liquid) movement between formations with different pressure regimes, or loss of containment to the environment

well integrity failure: when all well barriers have failed and there is a pathway for fluid to flow in or out of the well

well pad: the area of land on which the surface infrastructure for drilling and hydraulic fracturing operations are placed. The size of a well pad depends on the type of operation (for example, well pads are larger during the initial drilling and hydraulic fracturing than at production).

workover: well procedure to perform one or more remedial or maintenance operations on a producing well to maintain or attempt production increase. Examples of workover operations are downhole pump repairs, well deepening, plugging back, pulling and resetting liners, squeeze cementing and re-perforating.

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