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BIOREGIONAL ASSESSMENTS

CSIRO

Impact assessment for the Beetaloo GBA region

Geological and Bioregional Assessment: Stage 3 synthesis

2021

Paddy’s Lagoon, Vermelha Station, Beetaloo GBA extended region © Jenny Davis, Charles Darwin University

Lancewood vegetation near Bullwaddy Nature Reserve © Chris Pavey, CSIRO

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Stuart's Swamp, near Daly Waters in the Beetaloo GBA extended region. © Jenny Davis, Charles Darwin University

At a glance

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

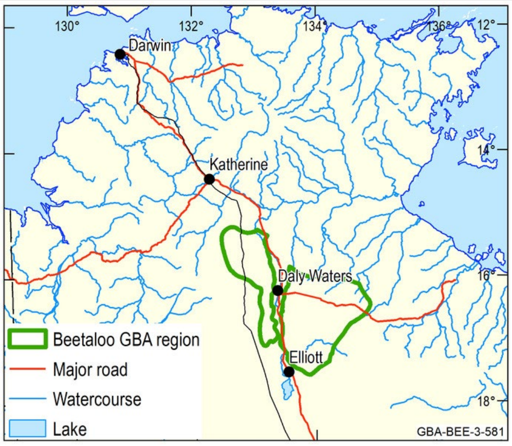
The GBA Program has developed a publicly accessible online tool (the GBA Explorer), which allows anybody to interact with the complex causal network supporting the assessment. The tool lets users focus on the matters of relevance to them and examine the underlying scientific evidence in more detail.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

Key finding: The GBA Program assessed 2,078 pathways for potential impact in the Beetaloo GBA region. The assessment found, with high confidence, that the majority of pathways have low to very low potential for impact. Potential impacts from other pathways can be mitigated through ongoing compliance with existing regulatory and management controls.

Assessment: the Beetaloo GBA region covers an area of about 28,000 km^2 in the Northern Territory (Figure 1).

A resource development scenario of 1,000 tera joules per day was used for this assessment. It included direct disturbance of between 8 and 35 km^2 for infrastructure such as access roads and well pads, within a total project area of between 430 and 7,700 km^2 or 1.5 to 28% of the Beetaloo GBA region. Most potential impacts that could occur are at the surface and can be mitigated by existing controls.

FIGURE 1 The Beetaloo GBA region



Element: GBA-BEE-3-581

Surface water: Where activities are conducted in the vicinity of waterways, a small number of pathways have potential for impact. There is high confidence that existing mitigation strategies will avert these impacts.

Groundwater: Groundwater is the most probable source of water for unconventional gas resource development. The assessment has found that aquifers in the region, such as the Cambrian Limestone Aquifer, can supply this water without adverse regional impacts.

Environment: Invasive plants and broadscale landscape changes due to vegetation removal and vehicle movement have the strongest influence on threatened species and protected areas in the Beetaloo GBA region. There is high confidence that existing management controls can avoid and mitigate these potential impacts.

Protected fauna and flora: The assessment prioritised 6 protected animals based on the importance of the Beetaloo GBA region to each species. Potential impacts involve activities at the surface leading to increased invasive plants and animals, and vegetation removal. There is high confidence that existing management controls can avoid and mitigate these impacts.

Explore this assessment

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

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

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

Supporting information

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

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

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

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

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

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

Executive summary

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

About the region

The Beetaloo GBA region covers an area of 28,000 km^2 about 500 km south of Darwin in the Northern Territory. The climate varies from tropical in the north to semi-arid in the south. Reflecting this climate pattern, tropical savanna species are found in the north with typical Australian desert species dominant in the south. Land use is mainly beef cattle production, with perpetual pastoral leasehold covering 90% of the land area. The region is sparsely populated; the Wubalawun, Mangarrayi, Murranji, Alawa, Gurungu, Marlinja, Dillinya, Karlantijpa and Mambaliya Rrumburriya Wuyaliya Aboriginal Land Trusts are in or near the Beetaloo GBA region.

The Beetaloo GBA region, which is coincident with the Beetaloo Sub-basin, is prospective for significant unconventional gas resources that include shale and tight gas, with potential for liquid hydrocarbons. The gas industry is in the exploration phase of the development life cycle, and there are no existing petroleum developments. A broader region, the Beetaloo GBA extended region, has also been defined to expand data discovery and to allow impacts immediately adjacent to the Beetaloo GBA region to be considered.

About the assessment

The development of unconventional gas resources involves a range of activities including drilling, hydraulic fracturing, construction of roads, well pads, pipelines and processing facilities, extraction of water, and establishment of facilities to manage waste and wastewater. This assessment considers potential impacts from these activities on water, the environment, protected areas and threatened species. This assessment does not replace project-based environmental impact assessments where the location, scale and nature of activities are well delineated.

A resource development scenario for the Beetaloo GBA region was used for this impact assessment with peak production of 365 petajoules per year over a 25-year time period, requiring up to 1,150 wells. The development would directly disturb between 8 and 35 km^2 for infrastructure such as access roads and well pads within a total project area of between 430 and 7,700 km^2. This scenario would require a total of up to 46 gigalitres of water over the 25-year development period, based on an estimate of 40 megalitres for drilling and hydraulic fracturing per well.

Assessment method

A causal network approach was developed for this assessment. The causal network captures the relationships between unconventional gas resource development activities and the complex and interconnected nature of the natural environment in the assessment region. The approach allows for a consistent and systematic evaluation of the cause-and-effect relationships that link nodes in the network, along with an appraisal of the confidence in this evaluation. Mitigation strategies mandated through regulatory controls or operational practices are also considered. The link evaluations are then combined to assess the pathways of potential impact between development activities and the environmental values in the region. The assessment is conducted spatially, which allows identification of areas where impacts are unlikely, as well as areas where potential impacts cannot be ruled out.

Overall results of the impact assessment are reported as levels of concern for pathways, ranging from pathways of 'very low concern', where impacts are not physically possible or are extremely unlikely; 'low concern', where impacts can be avoided by current legislation or because the impact does not represent **a change that exceeds a defined threshold** (material change); 'potential concern', where a pathway could have an impact but the impacts can be minimised or mitigated by existing management controls; to 'potentially high concern' for pathways whose impacts cannot be avoided or mitigated.

The causal network can be accessed in the interactive GBA Explorer that contains the detailed context, node descriptions, link evaluations and spatial information used for the assessment.

There are no pathways of 'potentially high concern' between unconventional gas resource development and water and the environment in the Beetaloo GBA region. All potential impacts can be mitigated through compliance with existing regulatory and management controls, with a high degree of confidence.

The pathways of 'potential concern' identified in this assessment are primarily related to activities that create a disturbance at the surface (transport of materials and equipment, civil construction, decommissioning and rehabilitation, and seismic acquisition). The pathways of 'potential concern' connect these activities with protected matters, protected fauna and terrestrial vegetation. There is high confidence that these potential impacts can be mitigated primarily through existing environmental management practices that are implemented in accordance with activity-specific environmental management plans required under Northern Territory regulations. However, the knowledge base is limited for some cause-and-effect relationships and confidence in the assessment will be improved as knowledge of these relationships and material change thresholds are established.

Pathways associated with subsurface activities (drilling, hydraulic fracturing, production of hydrocarbons) are of 'low concern' or 'very low concern'. The assessment has found stressors of high community concern, such as those involving well integrity or chemical spills, are unlikely to cause material changes to endpoints when existing regulatory and management controls are implemented.

Potential impacts on water

Groundwater is expected to be the source of water for unconventional gas resource development in the Beetaloo GBA region. The assessment found that it is possible to supply this water from the Cambrian Limestone Aquifer without adverse local or regional impacts, including to the Roper River, Mataranka Thermal Pools or to other water users.

Potential impacts to surface water from spills or changes to surface flow are only of 'potential concern' immediately adjacent to surface water features. These impacts are mitigated through buffers to waterways, controls on land disturbance and the regulated storage and handling of chemicals.

Potential impacts due to well integrity are of 'very low concern' to 'low concern'. A small area with particular geological characteristics is of 'potential concern' for contamination due to fluid flow along fractures or faults, although the potential impact is to a deep aquifer that is unlikely to be used by other industries.

There are no permanent streams in the Beetaloo GBA region and flows generally result from wet-season rains. There are a small number of groundwater-dependent ecosystems, most likely supported by perched aquifers and semi-permanent wetlands. The most significant aquifer in the region is the Cambrian Limestone Aquifer, which is an important water resource for agriculture (cattle grazing). Deeper aquifers are used in limited areas where the Cambrian Limestone Aquifer is not present.

There are spring complexes adjacent to the north of the region, most notably the Mataranka Thermal Pools. Lake Woods, an important wetland, lies to the south of the region and receives inflows from the Beetaloo GBA region. Groundwater flow from the Cambrian Limestone Aquifer contributes to baseflow in rivers, such as the Roper and Daly rivers, to the north of the region.

Potential pathways for impacts on water have been considered in terms of those related to water extraction, changes to surface water availability and those that may lead to contamination.

Surface water extraction for petroleum activities is prohibited in the Northern Territory, and groundwater is expected to be the main source of water for petroleum activities. To estimate groundwater drawdown at a local scale, conservative numerical modelling was used (Geological and Bioregional Assessment Program, 2021b) , which found that groundwater drawdown is of 'low concern'. Model outputs did show 'potential concern' for impact if water was extracted within 1 km of existing water bores; however, this impact is mitigated through regulations on the location of extraction bores. The assessment also found that the available water volumes, current allocations and estimates of recharge mean that potential impacts from regional drawdown caused by water extraction for unconventional gas resource development are of 'low concern'. Pathways for impacts on spring flow, baseflow to rivers and groundwater-dependent ecosystems are all of 'very low concern'. The water allocation plan currently being developed for the Daly Roper Water Control District and the requirement for licensing of groundwater extraction for petroleum activities will also assist in mitigating these pathways.

Surface activities may affect the flow of water by diverting or modifying flow paths, causing erosion, or through sedimentation. These impact pathways have been identified as of 'potential concern' to small areas where the activities are conducted in the vicinity of waterways. These pathways are effectively mitigated through buffers to waterways and requirements to manage erosion and runoff.

Leaks and spills have the potential to release chemicals or compounds that are used in, or produced through, unconventional gas resource development to the environment. Any accidental release of contaminants beyond an engineered bunding or control into surface waters is conservatively assumed to be material and is of 'potential concern' for surface water and groundwater-dependent ecosystems, which occupy a small part of the Beetaloo GBA region. Potential impacts on groundwater quality from spills and leaks are of 'potential concern' where groundwater is shallow (less than 14 m). Groundwater is significantly deeper than this in most of the Beetaloo GBA region. The controls used to prevent spills along with buffers to waterways mitigate this risk.

Potential pathways for groundwater contamination through subsurface activities include those related to well integrity and the creation of new fractures or widening of existing faults or fractures during hydraulic fracturing operations. These pathways are assessed as of 'low concern' to 'very low concern' due to existing engineering controls on wells and hydraulic fracturing operations and the vertical separation distances between unconventional gas resources and overlying aquifers. There is a small area (about 4% of the region) of 'potential concern' where the Hayfield sandstone member, a potential target for gas resource development, and overlying Bukalara Sandstone aquifer are relatively close. This pathway is mitigated by existing engineering controls. The Bukalara Sandstone is unlikely to be used as a groundwater resource for other industries as the shallower Cambrian Limestone Aquifer provides a more accessible water resource.

Contamination due to waste disposal is of 'low concern' in the Beetaloo GBA region due to stringent approval and management requirements. Disposal of hydraulic fracturing waste, including wastewater, to surface water or groundwater is prohibited in the Northern Territory.

Potential impacts on the environment

Potential impacts on the environment (vegetation communities) of 'potential concern' are from activities that cause disturbance at the surface (construction of roads and well pads, vehicle movement off road and for seismic acquisition, decommissioning and rehabilitation) as well as transport of equipment and materials into the region. These impacts are likely to be localised to the immediate vicinity of development activities. Existing management controls mitigate these impacts.

For this assessment, the environment of the Beetaloo GBA region, excluding aquatic environments, has been considered in terms of 3 ecosystems based on (i) terrestrial vegetation that is dominated by rainfall dependent open woodlands, (ii) riparian ecosystems that include flora and fauna that are dependent on the presence of rivers and streams and (iii) ephemeral wetlands. Terrestrial vegetation accounts for around 90% of the region.

The pathways of 'potential concern' for impacts on the environment resulting from development activities (such as civil construction, seismic acquisition, transport of materials, and decommissioning and rehabilitation) are from the introduction of invasive plants, vegetation removal and vehicle movement. Potential impacts can occur wherever resource development activities take place; however, they tend to be localised around areas of development activity and warrant detailed local-scale assessment. These impacts can be minimised or mitigated – as required by existing regulations – by locating infrastructure away from sensitive habitats, applying buffers to waterways, minimising vegetation removal, controlling invasive species and minimising vehicle access to undisturbed areas.

Potential impacts on protected fauna

Potential impacts on protected fauna species of 'potential concern' are from similar activities to those for the environment and relate to changes to habitat due to surface activities. Existing management controls mitigate these impacts.

From north to south in the Beetaloo GBA region the climate changes from tropical to semi-arid. Tropical savanna species are found in the north (for example, Gouldian finch) and typical Australian desert species in the south (for example, greater bilby). As the region becomes more widely surveyed, more species may be added to biodiversity records. Six protected matters were prioritised for detailed assessment. Prioritisation of these Commonwealth and Territory protected matters was based on the importance of the Beetaloo GBA extended region to each particular matter (Pavey et al., 2020). Those assessed were:

- 4 bird species: the Australian painted snipe (*Rostratula australis*), crested shrike-tit (northern) (*Falcunculus* (*frontatus) whitei*), Gouldian finch (*Erythrura gouldiae*), grey falcon (*Falco hypoleucos*)
- 1 marsupial: greater bilby (*Macrotis lagotis*)
- 1 aquatic reptile: Gulf snapping turtle (*Elseya lavarackorum*).

Any decline in the survival and maintenance or extension of occupied area of a species in its current habitat (persistence) is assumed to be material.

Pathways of 'potential concern' between activities and the protected fauna species are similar to those that impact on the environment and are primarily related to activities that create a disturbance at the surface (civil construction, decommissioning and rehabilitation, transport of materials and equipment, and seismic acquisition). Threats include increases in invasive plants and animals and vegetation removal, resulting in mortality of native species and decrease in available habitat. The aquatic Gulf snapping turtle is potentially affected by surface water contamination processes and the Gouldian finch, crested shrike-tit (northern), greater bilby and grey falcon are potentially affected by increases in predation by invasive carnivores that may be favoured by access to artificial water sources. Potential impacts can be mitigated by avoiding sensitive habitat; minimising the extent and location of new facilities, roads and pipelines; managing invasive species; and by ensuring rapid and effective remediation of disturbed sites, as well as monitoring.

Monitoring

Monitoring is critical for evaluating changes in a system associated with specific known stressors. The causal network identifies particular points along a pathway where monitoring would be most useful. Results from the impact assessment informed 4 broad monitoring objectives: (i) estimating baseline and trend; (ii) comparing areas of potential impact with areas where no changes occur (control sites); (iii) monitoring compliance with, and effectiveness of, mitigation strategies; and (iv) monitoring to validate and refine the causal network. Future monitoring could reduce uncertainty in critical links along pathways by increasing confidence in the cause-and-effect relationship or providing more information on thresholds of material change.

Conclusion

The impact assessment has provided a thorough, objective and systematic evaluation of potential impact pathways between unconventional gas resource development activities and water and environmental values. The assessment found that there were no potential impact pathways where the risks cannot be mitigated using existing controls. Activities that disturb the surface had the most pathways of 'potential concern', mainly due to changes in habitat through removal or introduction of weeds and predators. Overall confidence in the assessment is high, although there is some uncertainty around the definition of material change thresholds due to the lack of available data for the Beetaloo GBA region. The precautionary principle was applied in this assessment and any improved understanding of thresholds is likely to reduce the number of pathways of 'potential concern'. The assessment could be further refined as more environmental data are collected in the Beetaloo GBA region.

A key aspect of this assessment is that it assumes the existing regulatory controls in place to mitigate potential impacts are complied with by industry and enforced by regulators. The mitigation and management practices are most effective at the activity-to-stressor step of a causal pathway, whereas links from stressors to natural processes and from natural processes to endpoints are often difficult, if not impossible, to mitigate. In the Northern Territory, in addition to regulations that prohibit certain activities (such as extraction of surface water or disposal of wastewater to surface water or groundwater), the primary means of mitigation are environmental management practices. These are set out in Environment Management Plans for petroleum activities as required by the *Petroleum (Environment) Regulations 2016* (NT) and reinforced by mandatory requirements contained in supporting codes of practice and guidelines

Perpetual pastoral leasehold covers over 90% of the Beetaloo GBA region © Jason Kirby, CSIRO

1 About the assessment

1.1 Purpose

The Beetaloo GBA region is estimated to contain significant and technically recoverable unconventional gas resources (Huddlestone-Holmes et al., 2020). The development of these resources involves a range of activities including drilling, hydraulic fracturing, construction of roads, well pads, pipelines and processing facilities, extraction of water, and establishment of facilities to manage waste and wastewater.

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

1.2 Scope

A 'GBA region' is defined for each assessment (Figure 1) to constrain the area of investigation (Section 2). The assessment considers activities associated with the development and production of unconventional gas resources at a regional scale for a 25-year development scenario. The unconventional gas resources that occur in the Beetaloo GBA region, which is coincident with the Beetaloo Sub-basin, include shale gas and tight gas. The Beetaloo Sub-basin may also contain liquid hydrocarbons (condensate and oil). These resource types, referred to throughout as unconventional gas resources, are described further in the Stage 2 petroleum prospectivity technical appendix (Hall et al., 2020). There is no coal seam gas in the Beetaloo GBA region as the rocks do not host coal formations. Assessment findings are for a particular point in time and will change as technology, methods and baseline knowledge advance.

Presented in this synthesis report are the potential impacts on: surface water and groundwater (Section 4.1), the environment (Section 4.3), and protected fauna (Section 4.4) (protected flora were not included in this assessment based on the screening outlined in Pavey et al. (2020)). Strategies for monitoring are also covered (Section 6). **Bold hyperlinked** text denotes where causal network node descriptions provide further detail and can be viewed using the interactive causal network in GBA Explorer.

1.3 Context

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

A Glossary of key terms is provided in this document.

2 About the region

The Beetaloo GBA region and the broader Beetaloo GBA extended region support important landscapes and habitats that have cultural, economic, environmental and social benefits, underpinning the livelihoods of pastoralists, Traditional Owners, tourism operators and other industries. The Beetaloo GBA region is considered to be highly prospective for unconventional gas resources.

2.1 Environmental, cultural, social and economic values

The Beetaloo GBA region is located about 500 km south of Darwin and covers an area of approximately 28,000 km^2 in the Northern Territory (Figure 2). It is located entirely in the tropics of the Northern Territory between Katherine and Tennant Creek, with tropical elements in the north and semi-arid elements in the south (Huddlestone-Holmes et al., 2020). The Beetaloo GBA region has been defined specifically for the purposes of the GBA Program as the geological Beetaloo Sub-basin as defined by the Northern Territory Geological Survey (Department of Primary Industry and Resources (NT), 2017).

A broader region, referred to as the 'Beetaloo GBA extended region', has also been defined (Figure 2) to match the area of the Northern Territory Government's Strategic Regional Environmental and Baseline Assessment. This larger region is used to expand additional data discovery and to allow impacts immediately adjacent to the Beetaloo GBA region to be considered. The Strategic Regional Environmental and Baseline Assessment boundary was amended in September 2020 to include the eastern shale depocentre. This change has not been reflected in the Beetaloo GBA extended region and is not included in this assessment.

Surface water systems of the Beetaloo GBA region consist of 5 surface water catchments: the Roper River, Daly River, Limmen Bight River, the Wiso region and the Barkly region (Figure 40 in Huddlestone-Holmes et al. (2020)). The Roper (44%) and Wiso (47%) cover the majority of the region. Most streams in the region are ephemeral and only flow in response to wet-season rains. 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 (Box 2) and baseflow to streams in Elsey National Park.

The landscapes of the Beetaloo GBA region are classified as predominantly loamy and sandy plains with smaller areas of clay plains (Figure 3). Icons in Figure 3 represent stressors on the system that may contribute to an impact due to unconventional gas resource development. A stressor is a physical, chemical or biological agent, environmental condition or external stimulus that might contribute to an impact. The region supports a range of species protected by Australian Government and Northern Territory legislation. Matters of National Environmental Significance 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 an 2 species that are both threatened and migratory. Other protected matters in the Beetaloo GBA extended region comprise 23 listed marine species and 5 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 4 reserves are outside the Beetaloo GBA region but have 100% of their area within the Beetaloo GBA extended region. Also included are 2 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 Northern Territory (but not nationally) have been recorded in the Beetaloo GBA region since 1990 and are considered likely to still occur there (Pavey et al., 2020).

Prioritisation of these Australian Government and Northern Territory protected matters for this assessment was based on the importance of the Beetaloo GBA extended region to each particular matter (Pavey et al., 2020). The following are assessed as endpoints in the causal network (Section 3): 4 bird species (the Australian painted snipe (*Rostratula australis*), crested shrike-tit (northern) (*Falcunculus (frontatus) whitei*), Gouldian finch (*Erythrura gouldiae*) and grey falcon (*Falco hypoleucos*)), 1 marsupial (greater bilby (*Macrotis lagotis*)) and 1 aquatic reptile (Gulf snapping turtle (*Elseya lavarackorum*)), springs and wetlands.

Among groundwater-dependent ecosystems, 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.

Land use within the Beetaloo GBA region is mainly beef cattle production, with perpetual pastoral leasehold covering over 90% of the land area. The region is sparsely populated, with Mataranka, Jilkminggan, Daly Waters and Elliott the most populated settlements, all within the Beetaloo GBA extended region. 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 (Huddlestone-Holmes et al., 2020).

2.2 Unconventional gas resources and hydrogeology

The Beetaloo GBA region is prospective for unconventional gas and is estimated to contain significant technically recoverable unconventional gas resources. To date, there has been limited exploration, with exploration permits currently operated by Origin Energy, Santos and Pangaea Resources (Figure 2). Empire Energy Group Limited entered a binding Sale and Purchase Agreement with Pangaea (NT) Pty Ltd to acquire Pangaea's Beetaloo Sub-basin tenements in April 2021, with the acquisition due to be completed in mid-2021. Hall et al. (2020) present the 5 identified unconventional petroleum plays in the Beetaloo GBA region most likely to be developed within the next 5 to 10 years (after Côté et al. (2018), Figure 4):

- Velkerri Shale (Amungee Member) – dry gas play
- Velkerri Shale (Amungee Member) – liquids-rich gas play
- Kyalla Shale – liquids-rich gas play
- Kyalla Hybrid Lithology – liquids-rich gas play
- Hayfield sandstone member – tight oil/condensate play.

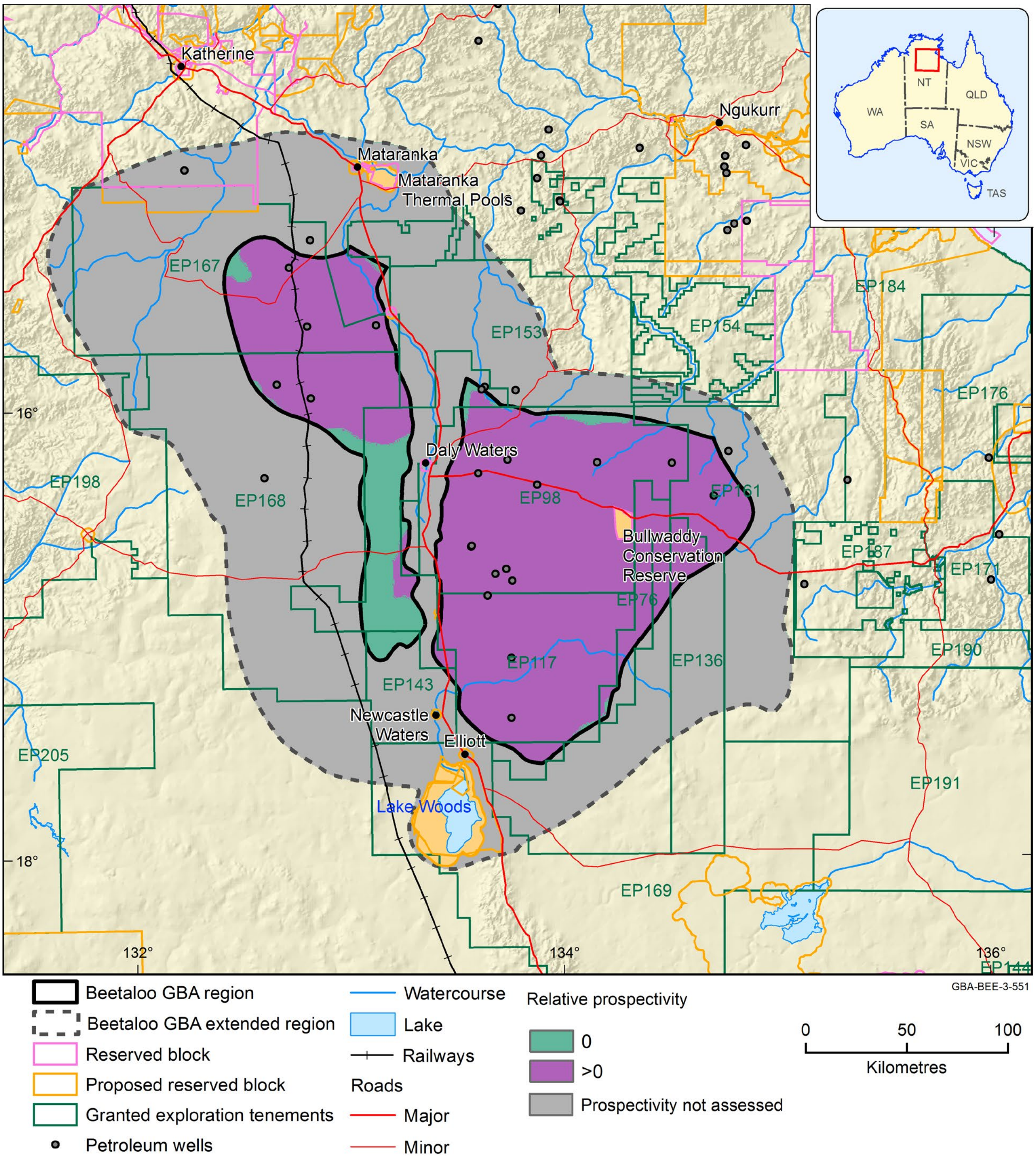
Of these plays, there are only sufficient public domain data available to independently assess the dry and liquids-rich gas plays of the Amungee Member shales of the Velkerri Formation, and the liquids-rich gas in the Kyalla Formation shale.

The current conceptual hydrogeological model for the Beetaloo GBA region consists of 3 individual groundwater subsystems underlain by the Roper Group (the sedimentary package that is host to primary unconventional gas plays of the Velkerri and Kyalla formations). From oldest to youngest, the conceptual model comprises the following components:

- Neoproterozoic rocks and overlying Cambrian Antrim Plateau Volcanics (confined aquifer throughout most of the region)
- Cambrian Limestone Aquifer system (consisting of an upper and lower aquifer sequence) (unconfined aquifer throughout most of the region)
- Undifferentiated Cretaceous Carpentaria Basin and Cenozoic sedimentary rocks (generally unsaturated) (unconfined aquifer).

The Cambrian Limestone Aquifer is the most significant aquifer in the region (in terms of both spatial coverage and use). The deeper, Neoproterozoic fractured rocks also contain 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 2 Relative prospectivity in the Beetaloo GBA region, which is coincident with the Beetaloo Sub-basin, used for the geological and bioregional assessment of the Beetaloo GBA region

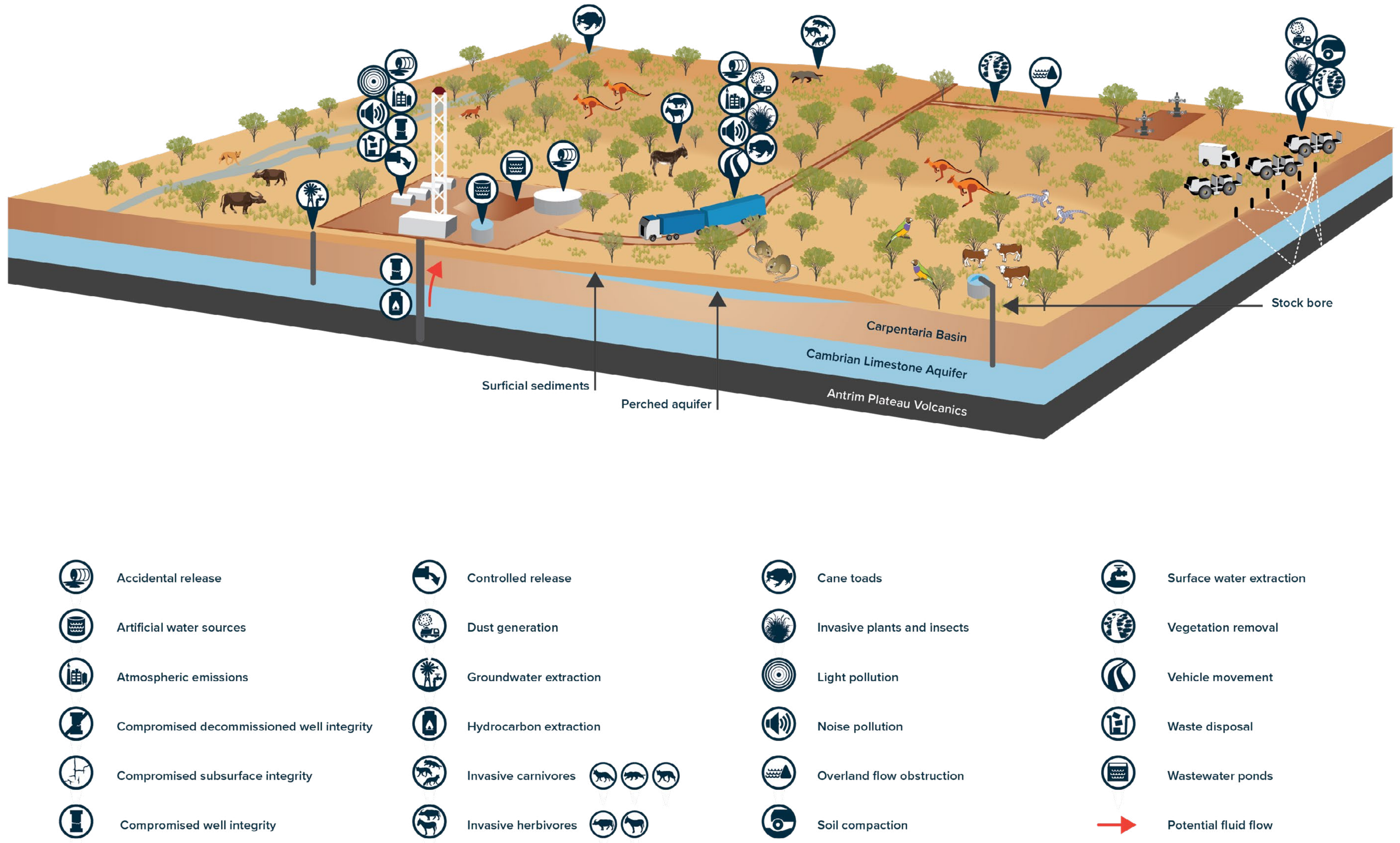


Relative prospectivity determines the relative likelihood of a resource (e.g. oil, gas, groundwater) through analysis of geological properties (e.g. formation depth and extent, rock properties, reservoir characteristics).

Data: Northern Territory Geological Survey (2020)

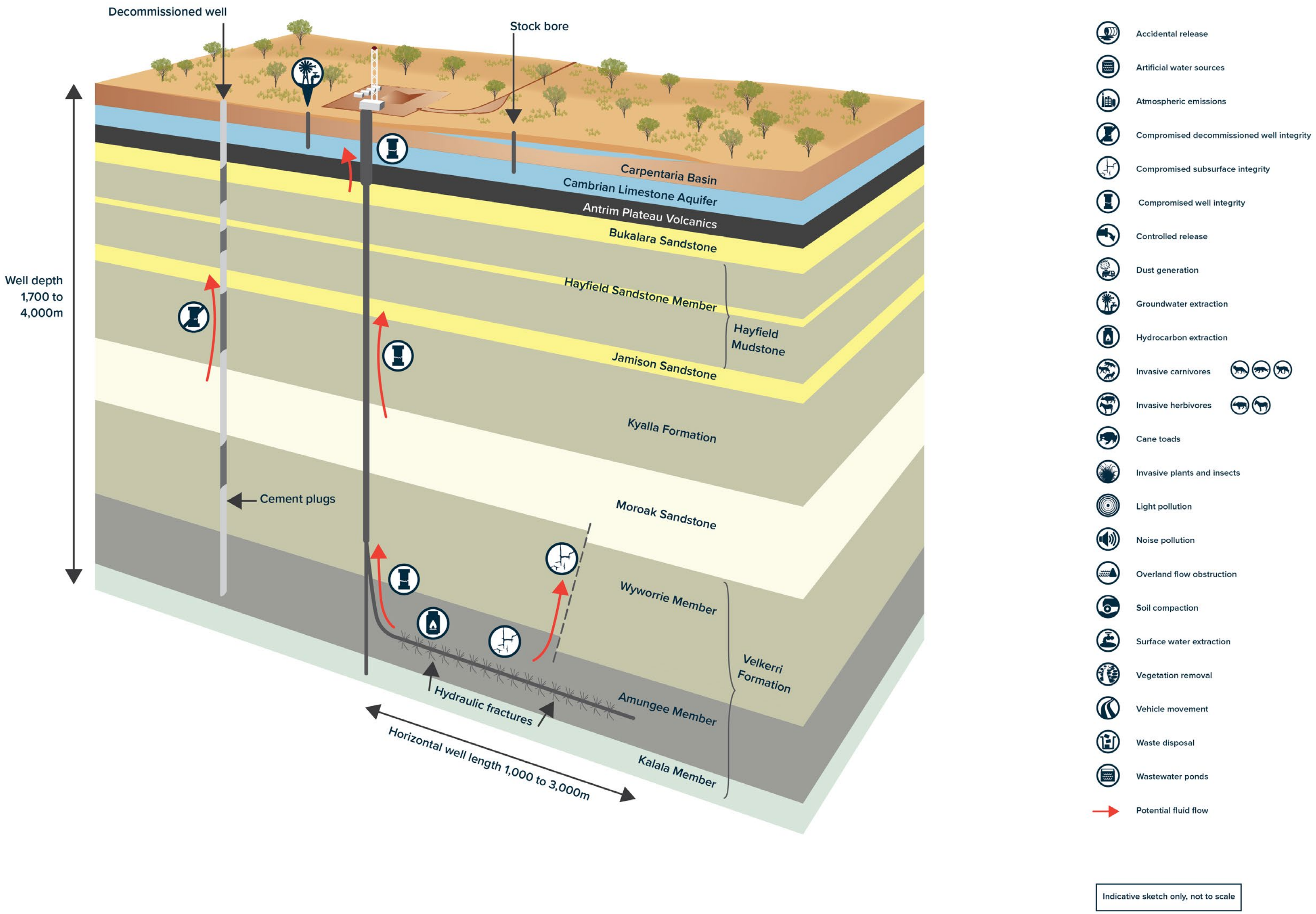
Element: GBA-BEE-3-551

FIGURE 3 Surface and shallow groundwater features of the Beetaloo GBA region



This schematic diagram is not drawn to scale.
Element: GBA-BEE-3-571

FIGURE 4 Conceptual cross-section of the Beetaloo GBA region



The stratigraphy varies across the region. Formation thicknesses and fracture heights are indicative only. Not to scale, for illustrative purposes only. Potential stressors are indicated.
Element: GBA-BEE-3-572

3 Causal network for the Beetaloo GBA region

3.1 Causal networks

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

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

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

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

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

Endpoints are represented in the causal network as 'assessment endpoints' defined as an explicit expression of the ecological, economic and/or social values to be protected, and as 'measurement endpoints' defined as measurable characteristics or indicators related to the valued characteristic chosen as the assessment endpoint (Suter, 1990; US EPA, 2016) (Section 5.1.1 in Stage 2 baseline synthesis and gap analysis (Huddlestone-Holmes et al., 2020)). Endpoints in the causal network for the Beetaloo GBA region represent aquifers such as the Cambrian Limestone Aquifer; landscapes, such as terrestrial vegetation communities; protected areas, such as wetlands; and protected fauna, such as the greater bilby or Gouldian finch listed under territory or national legislation (Table 1).

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

Node type	Description	Examples	Number of nodes
Driver	Major external driving forces (human or natural) that have large-scale influences on natural systems	Resource development	1
Activity	A planned event associated with unconventional gas resource development	Civil construction Transport of materials and equipment	9
Stressor	Physical, chemical or biological agent, environmental condition or external stimulus caused by activities	Dust generation Vehicle movement	23
Process	A naturally occurring mechanism that could change a characteristic of an endpoint	Confined aquifer drawdown Habitat degradation, fragmentation and loss	14
Endpoint	A value pertaining to water and the environment that may be impacted by development of unconventional gas resources	Surface water condition Persistence of Gouldian finch	15

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

The causal network for the Beetaloo GBA region (Figure 6) consists of 62 nodes, 197 links and 2,078 pathways. Nodes are organised from left to right, starting with the driver node resource development. Surface and ecology nodes are in the upper half of the figure, and subsurface and hydrology nodes are in the lower half of the figure. Hazards and causal pathways identified in the Stage 2 baseline synthesis and gap analysis (Huddlestone-Holmes et al., 2020) were refined and incorporated into the causal network.

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

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

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

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

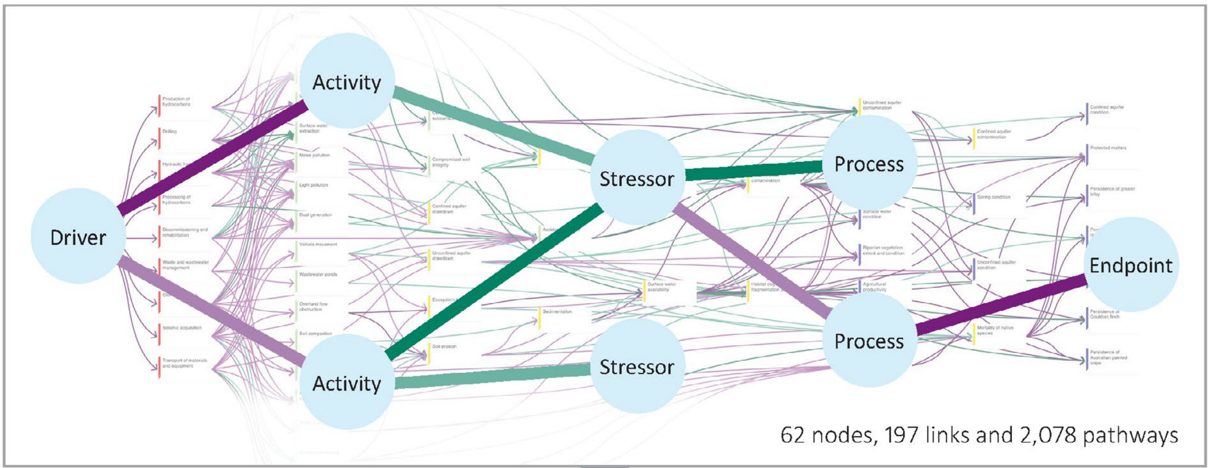
Future studies could extend the causal network to other industries, such as pastoralism or tourism. What is not possible with this method is assessing the cumulative impact of multiple stressors on a baseline. This requires firstly a comprehensive and quantitative baseline assessment and secondly future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

FIGURE 5 The impact assessment for the Beetaloo GBA region explained

CAUSAL NETWORKS

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

Graphical representations and analytical tools of complex systems



Based on a regional resource development scenario

Development time

25 years

Number of wells

4

10

525 wells

1,150 wells

Number of well pads

53 well pads

288 well pads

Energy produced

GALE = 365 PJ/year

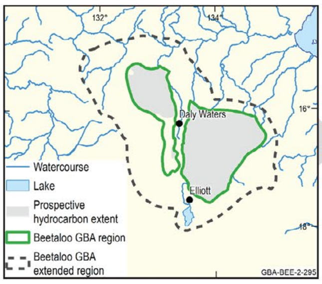
Well numbers: up to 1,150 wells over 25 years with 4 to 10 wells per well pad

Well pads: up to 12 km² or 0.04% of the Beetaloo GBA region

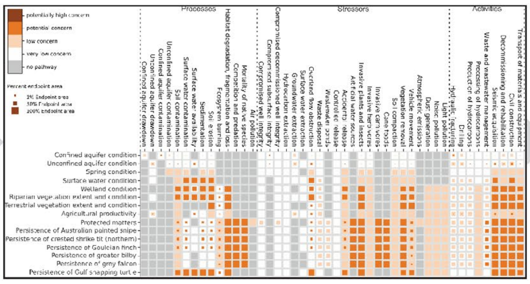
Access roads: up to 22 km² or 0.08% of the Beetaloo GBA region

Three-dimensional seismic area: up to 863 km² or 3% of the Beetaloo GBA region

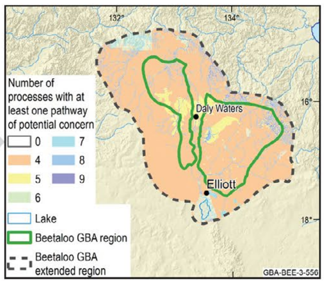
Outputs from the Beetaloo GBA causal network



01 Areas within the 28,000 km² of the Beetaloo GBA region where more detailed local-scale assessments are required



02 Activities, stressors and processes of concern



03 Potential impacts on landscapes, aquifers, wetlands, springs and selected protected fauna

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

Element: GBA-BEE-3-560

3.2 Confidence in the assessment

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

In the causal network, each link evaluation is based on the best available data and knowledge. However, in some cases the knowledge base may be limited for (i) the cause-and-effect relationship, (ii) the threshold of material change, or (iii) the mitigation strategies and whether they are available and effective. Each link evaluation is assigned a confidence score of 'low', 'medium' or 'high' (Table 3). Where the knowledge base is limited, this is reflected in the causal network as uncertainty. Where there is insufficient knowledge to support a robust threshold of material change, links are generally evaluated as material by applying the precautionary principle.

TABLE 3 Confidence assessment of links in the causal network

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

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

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

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

Level of concern	Cause-and-effect relationship (number of causal pathways)		Threshold of material change (number of causal pathways)		Mitigation strategy (number of causal pathways)	
Level of confidence	Low	High	Low	High	Low	High
Very low concern	326	247	529	44	0	573
Low concern	856	242	1,098	0	2	1,098
Potential concern	247	160	401	6	0	407
Potentially high concern	0	0	0	0	0	0

Data: Geological and Bioregional Assessment Program (2021g)

3.3 Assumptions

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

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

- Unconventional gas resource development is restricted to the clearly defined Beetaloo GBA region (Figure 2) and adheres to existing regulations and practices, which are enforced by the relevant regulator. Development of resources adjacent to this region, including within the Beetaloo GBA extended region, is not considered. Effects of activities conducted inside the Beetaloo GBA region and supporting activities in the Beetaloo GBA extended region (transport, civil construction associated with pipelines, access roads) are considered.
- The assessment is based on current and immediately foreseeable technologies. However, unconventional gas resource development technologies and practices are continuously evolving, and so new technologies may result in different stressors on the environment.
- Development activities associated with the 5 life-cycle stages of unconventional gas resource development are correctly represented in the causal network (Huddlestone-Holmes et al., 2020): (i) exploration, (ii) appraisal, (iii) development, (iv) production and (v) rehabilitation. The assessment focuses on potential impacts associated with unconventional gas resource development activities during the exploration to production phases of the resource life cycle where the majority of activity occurs. Characteristics of activities may change throughout the life cycle, typically through the availability of shared infrastructure during the development and production stages. These differences are considered where they are expected to occur.

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

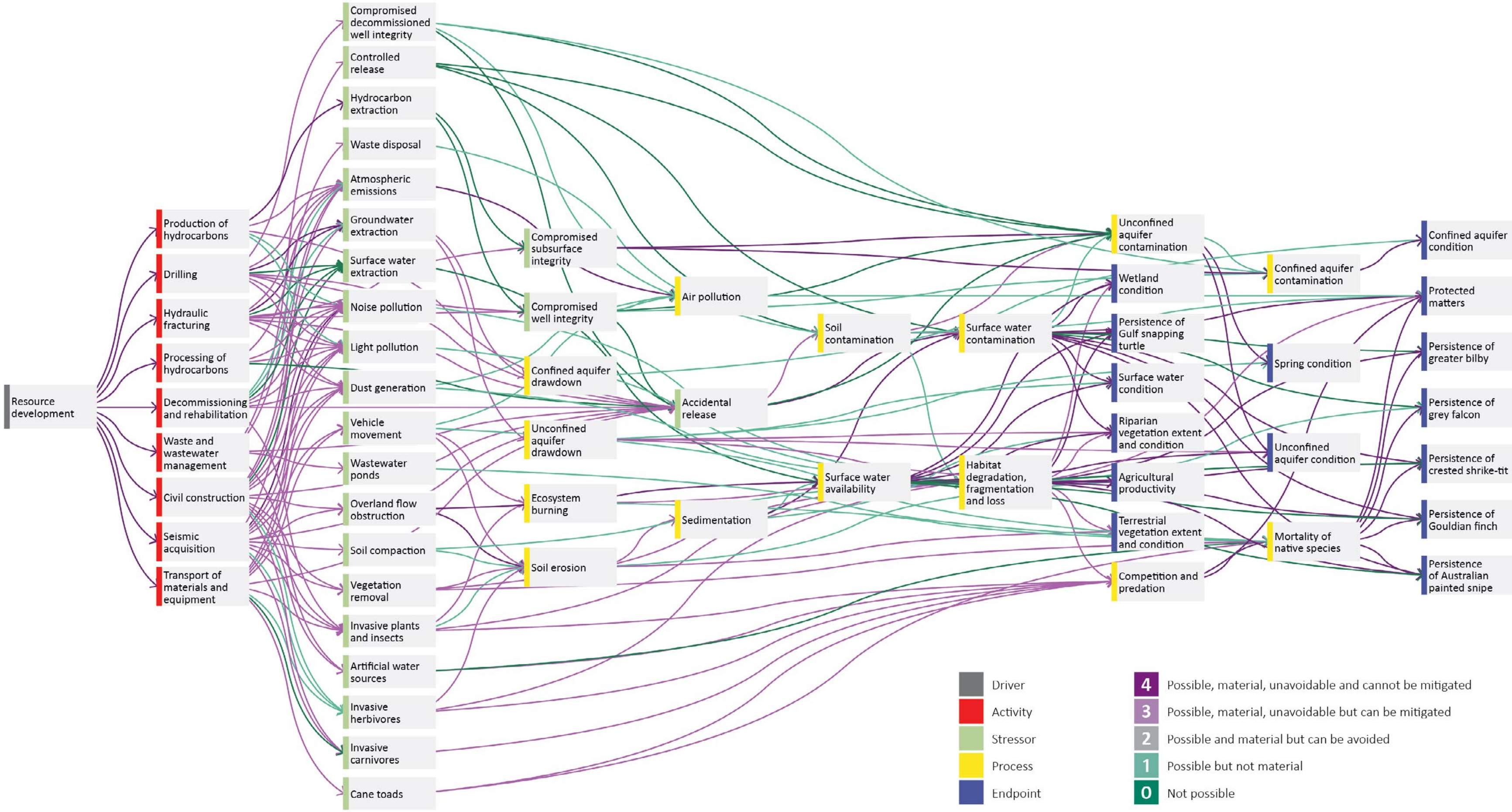
Section 3.4 provides more detail on the assumptions for the resource development scenario that form the foundation of the assessment to estimate what development in the Beetaloo GBA region may look like.

3.4 Resource development scenario

A resource development scenario for the Beetaloo GBA region was used for this impact assessment with peak production of 365 petajoules per year over a 25-year time period, requiring up to 1,150 wells. The development would directly disturb between 8 and 35 km^2 for infrastructure such as access roads and well pads within a total project area of between 430 and 7,700 km^2. This scenario would require a total of up to 46 gigalitres of water over the 25-year development period, based on an estimate of 40 megalitres for drilling and hydraulic fracturing per well.

The unconventional gas resources that are understood to occur in the Beetaloo GBA region include shale gas and tight gas. The Beetaloo Sub-basin may also contain liquid hydrocarbons. Unconventional reservoirs have low permeabilities and require innovative technological solutions to move the trapped resources to the surface (refer Section 2.2 in Stage 2 baseline synthesis and gap analysis (Huddlestone-Holmes et al., 2020)).

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



Interact with the GBA Explorer
Source: Geological and Bioregional Assessment Program (2021g)
Element: GBA-BEE-3-550

This assessment differs from a specific project-based environmental impact assessment where the location, scale and nature of planned activities are well delineated. As there is no certainty of what future development may look like, the resource development scenario is based on the relative prospectivity of unconventional gas plays across the Beetaloo GBA region, as well as potential restrictions prescribed in regulatory frameworks. Relative prospectivity determines the relative likelihood of a resource being present (for example, oil, gas, groundwater) through analyses of geological properties (for example, formation depth and extent, rock properties and reservoir characteristics) (Figure 2).

A resource development scenario based on the GALE scenario used in the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper inquiry) (Pepper et al., 2018) has been adopted. Key characteristics include:

- peak production rate of 365 petajoules per year (or 1,000 terajoules per day)
- project life of 25 years, including 5 years of exploration, appraisal and construction activities
- drilling a maximum of 1,150 wells with 4 to 10 wells per pad (Figure 5).

The estimated area disturbed in this scenario by access tracks and well pads is between 8 km^2 and 35 km^2. The well pad area extends to the limit of surface disturbance where a well is to be drilled and where drill rigs, pumps, engines, generators, mixers and similar equipment are located, as well as fuel, pipes and chemicals. The spatial extent for the entire unconventional gas resource development scenario, which is a combination of development area (such as roads, well pads and seismic lines) as well as the areas between them, is estimated to be contained within a total area between 430 and 7,700 km^2 of the Beetaloo GBA region.

Based on this resource development scenario, a total volume of 21 to 46 gigalitres of water would be required over a 25-year time period (Pan et al., 2021), equivalent to between 0.8 and 1.8 gigalitres per year. Water supply for unconventional gas resource development activities will be governed by a water allocation plan and regulatory conditions overseen by the Northern Territory Government. Potential water sources include groundwater and recycled flowback water from future unconventional resource extraction. As the cost of drilling bores is proportional to the depth, it is assumed that bores will target the shallower unconfined aquifer and if this is not possible, then the deeper confined aquifers. Based on the recommendations of the Pepper inquiry (Pepper et al., 2018) for protection of surface water-dependent wetlands and waterholes, the Northern Territory Government has prohibited the extraction of surface water for petroleum activities (Northern Territory Government, 2019b).

FIND MORE INFORMATION

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

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

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

- *Fact sheet 28:* Development scenarios for unconventional gas resource development (Geological and Bioregional Assessment Program, 2021h)

4 Assessment results

The impact assessment, examining impacts on water, the environment and protected fauna, found that there are no pathways of 'potentially high concern' in the causal network. This means that all potential impacts due to unconventional gas resource development identified by the assessment can be mitigated through ongoing compliance with existing regulatory and management controls.

Pathways of 'potential concern' are primarily related to activities that create a disturbance at the surface (**transport of materials and equipment**, **civil construction**, **decommissioning and rehabilitation**, and **seismic acquisition**) (Figure 7). The pathways of 'potential concern' connect these activities with the protected matters, protected fauna and terrestrial vegetation endpoints, reflecting the potential impact of surface disturbance. The assessment determined that this potential impact can be minimised or mitigated by existing management controls. Protected flora were not prioritised for inclusion in this assessment (Pavey et al., 2020).

Pathways associated with subsurface activities (**drilling**, **hydraulic fracturing**, **production of hydrocarbons**) are linked to pathways of 'low concern' or 'very low concern' (Figure 7). **Compromised well integrity** and **accidental release** are stressors that are of interest to the community. The assessment found that pathways involving these stressors are of 'low concern' or 'very low concern' when existing regulatory and management controls are implemented (Figure 7).

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

A synthesis of key findings for the impact assessment for the Beetaloo GBA region is provided. Key results are presented in Section 4.1 (causal network for the Beetaloo GBA region), Section 4.2 (water), Section 4.3 (environment) and Section 4.4 (protected fauna).

4.1 Causal network for the Beetaloo GBA region

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

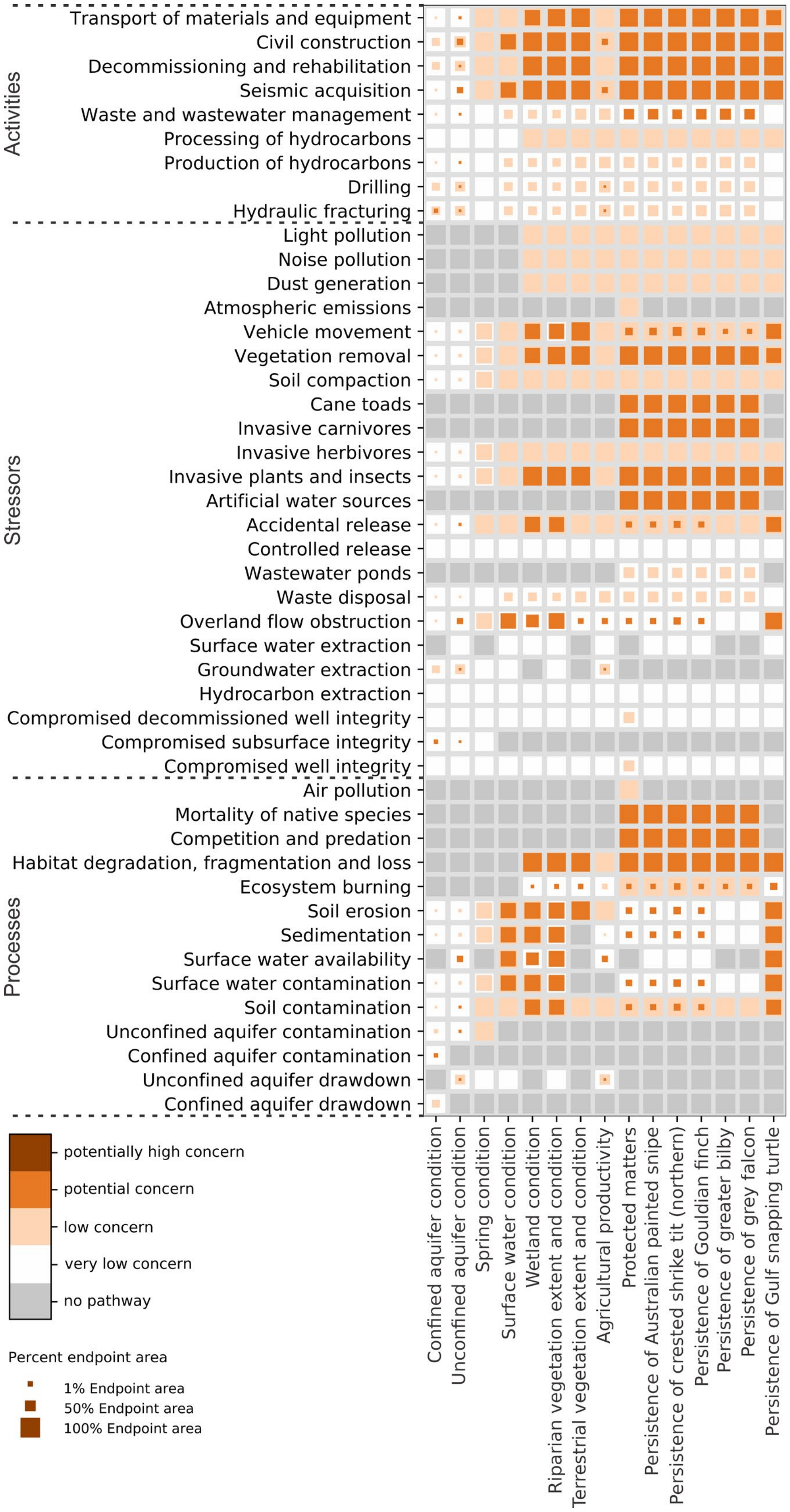
The impact assessment for the Beetaloo GBA region determined (i) areas of concern (how much of an endpoint area is of a particular level of concern), (ii) activities, stressors and processes of concern, and (iii) potential impacts on landscapes, aquifers, springs, wetlands and selected protected fauna.

The causal network for the Beetaloo GBA region consists of 1 driver node, 9 activity nodes, 23 stressor nodes, 14 process nodes and 15 endpoints (Table 1). Potential impacts due to stressors associated with unconventional gas resource development on water, the environment and selected protected matters are conceptualised in Figure 3 and Figure 4.

The selected 15 endpoints in the causal network for the Beetaloo GBA region represent values pertaining to water and the environment that may be impacted by development of unconventional gas resources. These endpoints represent: (i) landscapes – agricultural productivity, terrestrial vegetation, riparian vegetation, wetlands and springs; (ii) water – surface water and subsurface water (aquifers); and (iii) protected fauna – 4 bird species (Australian painted snipe, crested shrike-tit (northern), Gouldian finch and grey falcon), 1 marsupial (greater bilby) and 1 aquatic reptile (Gulf snapping turtle). Impact assessment results include a spatial assessment that shows how much of the endpoint's extent may be affected by pathways of concern (Figure 7). This spatial assessment does not distinguish between the relative importance of different components of the extent of an endpoint (for example, characteristics of the breeding and foraging habitats of Gouldian finch) or where any future potential impacts (for example, loss of critical food sources) may be more important to an individual endpoint.

Road to Bullwaddy Nature Reserve in the Beetaloo GBA region © Chris Pavey, CSIRO

FIGURE 7 Results of the impact assessment for the Beetaloo GBA region based on the causal network



Each cell in the figure represents the highest level of concern for the endpoint from all the pathways that pass through the activity, stressor or process node. Endpoints are ordered from subsurface to surface and then protected fauna.

Data: Geological and Bioregional Assessment Program (2021g)

Element: GBA-BEE-3-548

4.2 Potential impacts on water

Potential impacts on water due to unconventional gas resource development are considered based on 2 sets of impact pathways. The first set are those impact pathways related to water extraction for resource development. The second set of impact pathways relate to potential impacts on surface water and groundwater systems, including springs, that result in changes to water availability or quality. Findings from targeted investigations based on user panel concerns and priority knowledge gaps identified in the baseline synthesis and gap analysis (Section 7.2 (Huddlestone-Holmes et al., 2020)) are featured in Box 1, Box 2, Box 3, Box 4, Box 5, Box 6).

Potential impacts related to water extraction for resource development

Groundwater is expected to be the source of water for unconventional gas resource development in the Beetaloo GBA region. The resource development scenario adopted in this assessment – up to 1,150 wells drilled over 25 years – requires an average of between 0.8 and 1.8 gigalitres per year. Groundwater modelling results indicate that it is possible to supply this water from the Cambrian Limestone Aquifer without adverse regional impacts, including to the Roper River or Mataranka Thermal Pools.

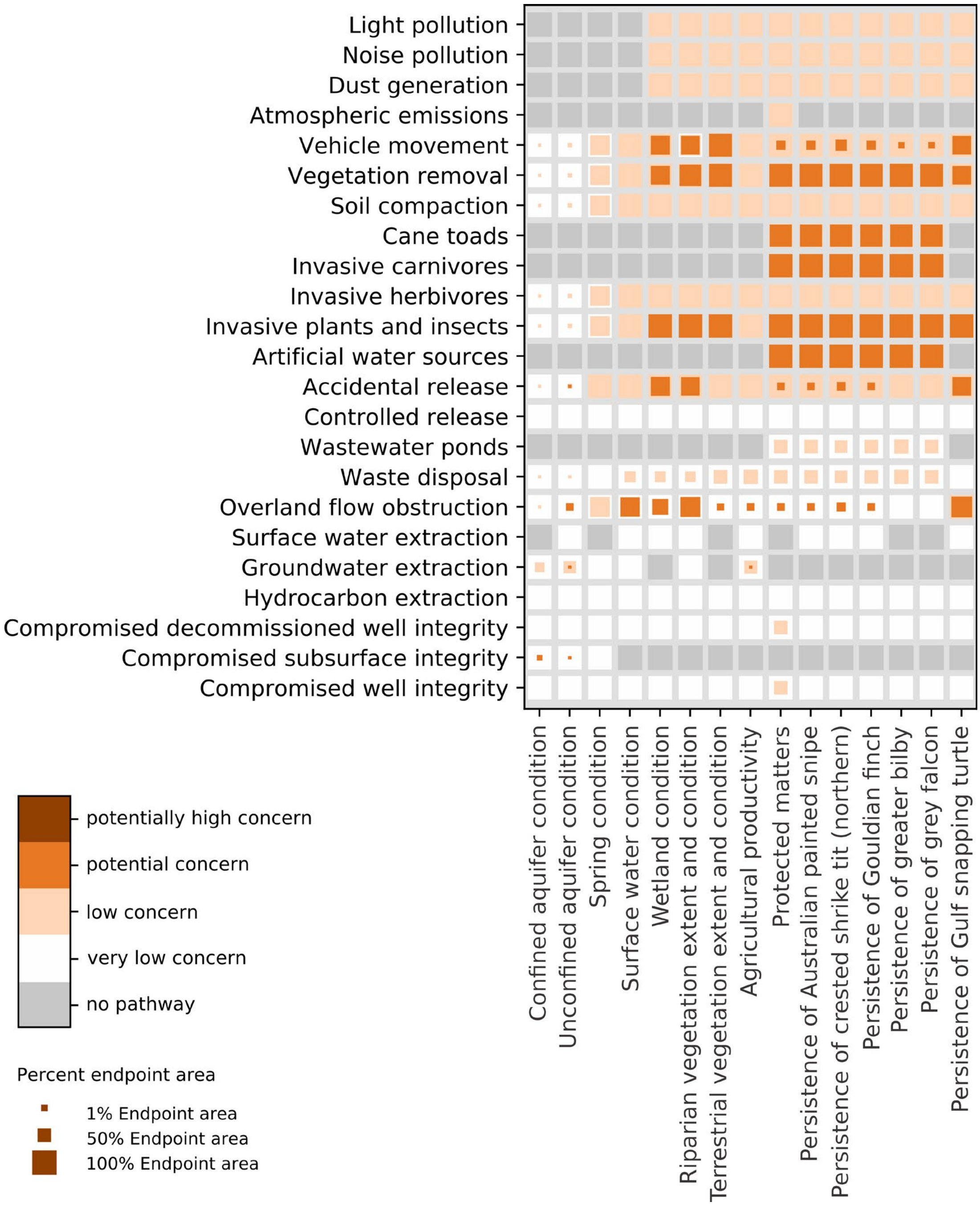
At a local scale, conservative numerical modelling (Geological and Bioregional Assessment Program, 2020b, 2021b) was used to estimate groundwater drawdown. Groundwater drawdown is of 'low concern', except within 1 km of existing bores sourced from the Cambrian Limestone Aquifer where there is 'potential concern' for unconfined aquifer drawdown leading to impacts on those bores. This impact is mitigated through regulations on the extraction of water within 1 km of an existing water bore. Reductions in spring flow and baseflow, and impacts on groundwater-dependent ecosystems are of 'very low concern' due to groundwater extraction.

A Northern Territory Government groundwater modelling study assessed the impacts of groundwater extraction from the Cambrian Limestone Aquifer on flow in the Roper River. Results show it is possible to extract an additional 40 gigalitres per year over the current extraction from an area between the Beetaloo GBA region and Mataranka (Bruwer and Tickell, 2015). This suggests that the 1.8 gigalitres per year required under the resource development scenario may be supplied from the Cambrian Limestone Aquifer without significant impact. The water allocation plan currently being developed for the Daly Roper Water Control District and the requirement for licensing of groundwater extraction for petroleum activities will also assist in mitigating these pathways.

Estimating water demand is difficult without knowing the design of hydraulic fracturing operations, the amount of flowback that may be reused or recycled from hydraulic fracturing operations, or the rate of development. The 1.8 gigalitres per year estimate is an average over the 25-year life of the development scenario and annual rates may be higher during the construction phase of a development. The estimate is conservative in that it assumes 40 megalitres of water required for drilling and hydraulic fracturing for each well with no reuse or recycling.

Groundwater extraction from aquifers causes a decrease in pressure and groundwater levels in the pumped aquifer in the vicinity of the production bores and may cause a decrease in groundwater pressure or groundwater levels in over or underlying aquifers. To protect sensitive ecosystems, such as groundwater-dependent ecosystems, prevention or mitigation options are required where predicted drawdown is greater than 0.2 m (DENR, 2020). To ensure groundwater resources are used sustainably, a separate 1 m drawdown threshold was used for aquifer interference with existing water users based on the recommendation in the Pepper inquiry (Pepper et al., 2018).

FIGURE 8 Level of concern for causal pathways from stressors to endpoints for the Beetaloo GBA region



Endpoints are on the x axis and stressors are on the y axis. The colour of the squares shows the level of concern for the pathway, and the size of the squares shows the percentage of the endpoint area potentially impacted. Where a square has multiple colours, it indicates that there are different levels of concern spatially for the endpoint. Stressors are ordered from surface to subsurface and endpoints are ordered from subsurface to surface.

Data: Geological and Bioregional Assessment Program (2021g)

Element: GBA-BEE-3-554

Among the water-related endpoints, increased drawdown due to **groundwater extraction** that exceeds these thresholds is only of 'potential concern' for **agricultural productivity** and **unconfined aquifer condition** endpoints within 1 km of existing bores sourced from the Cambrian Limestone Aquifer where drawdown may exceed the 1 m threshold (Methods snapshot, Figure 8). This impact is mitigated through regulations (*Water Act 1992*) that stipulate authorisation for water extraction for hydraulic fracturing purposes cannot be given within 1 km of an existing bore without landholder agreement or scientific investigation. Groundwater drawdown due to groundwater extraction is of 'low concern' for **confined aquifer condition** and **riparian vegetation extent and condition** endpoints (Figure 8). Reductions in spring flow and baseflow are of 'very low concern' due to groundwater extraction (Figure 8).

Overall, there is high confidence in the assessment of impacts on water. Potential impacts due to groundwater extraction are gleaned from conservative groundwater modelling in the unconfined and confined aquifers based on local information; therefore, there is high confidence in the assessment (Table 3). A water allocation plan currently being developed for the Beetaloo region will regulate groundwater extraction; therefore, there is high confidence in the ability to mitigate potential impacts. Studies on groundwater recharge will inform the development of the water allocation plan (Box 1, Box 2, Box 3).

Licensing of the extraction of surface water for any unconventional gas extraction activities in the Northern Territory is prohibited under the *Water Act 1992.* Furthermore, surface water is an unreliable source of water for hydraulic fracturing in the Beetaloo GBA region as there are no permanent streams within the Beetaloo GBA region.

Methods snapshot: groundwater modelling

The assessment of **groundwater extraction** and groundwater drawdown (**unconfined aquifer drawdown** and **confined aquifer drawdown**) is based on analysis of local datasets and analytical modelling (Geological and Bioregional Assessment Program, 2020b, 2021b). These are models that directly estimate groundwater drawdown by considering 3 mechanisms: (i) drawdown from groundwater extraction in the same aquifer, (ii) drawdown from groundwater extraction in an over or underlying aquifer, and (iii) drawdown from depressurisation of an underlying gas reservoir. As detailed scenarios of groundwater extraction locations and volumes are not available, the models simulate groundwater extraction everywhere in the Beetaloo GBA region for 200 megalitres extraction in one year for a single groundwater extraction bore. The predicted quantity of water required to hydraulically fracture 5 wells without any recycling or reuse is 200 ML. The models use local information on layer thicknesses and the presence of faults. They use conservative estimates of hydraulic properties based on regional measurements as local information is not available at the scale required.

Box 1 Investigation into geological controls on recharge

An investigation was conducted to improve understanding of how the Carpentaria Basin (one of the 4 sedimentary basins in the Beetaloo GBA region) may influence recharge and groundwater connectivity to underlying aquifers. Stage 2 of the assessment for the Beetaloo GBA region found that while the extent of the Carpentaria Basin is well known, the thickness and distribution of rock types are poorly defined (Evans et al., 2020). The type of rock and its thickness are geological factors that have a bearing on how much recharge from the surface can reach underlying aquifers, such as the Cambrian Limestone Aquifer.

In the eastern Beetaloo GBA region, the Carpentaria Basin sequence was found to consist primarily of clay rich rocks (mudstone and siltstone) and can be over 100 m thick. Clay rich rocks are aquitards and recharge is likely to be impeded due to thickness of rocks with low permeability. However, in north-western Beetaloo GBA region the Carpentaria Basin sequences thins to less than 40 m thick and contains higher proportions of sandstone. Thin sequences of sandstone are more likely to allow recharge to occur due to higher permeability of rock and shorter recharge pathways (Geological and Bioregional Assessment Program, 2021i).

Sinkholes are pipelike features that form when soil and rock have collapsed into subsurface cavities, leaving either an open hole or a depression at surface (Figure 9). Where the Cambrian Limestone Aquifer outcrops, open sinkholes can provide more rapid recharge pathways than might otherwise occur. The Cambrian Limestone Aquifer does not outcrop in the Beetaloo GBA region. However, sinkholes and circular depressions are also developed in Carpentaria Basin rocks. These sinkholes and depressions constitute a part of the surface drainage in areas away from stream channels and have a tendency to divert runoff to form waterholes. Sinkholes and waterholes are particularly prevalent in the western portion of the Beetaloo GBA region and there is potential that some sinkholes may allow for rapid recharge to subsurface or that the waterholes leak (Geological and Bioregional Assessment Program, 2021j).

The Beetaloo GBA region was sub-divided into domains that outline areas with similar geological controls on recharge (Geological and Bioregional Assessment Program, 2021k) . Defining the distribution of geological recharge pathways will improve the understanding of the hydrogeology and potential for any impacts to propagate from the surface.

FIGURE 9 Sinkhole near the Buchanan Highway in the Beetaloo GBA extended region

Credit: Michael Short (NT, Department of Environment, Parks and Water Security)
Element: GBA-BEE-3-576

Box 2 Investigation into the source of water to Mataranka Thermal Pools

Mataranka Thermal Pools lie in the north-east of the Beetaloo GBA extended region and were highlighted for their significance by the Beetaloo user panel (Figure 10). To confirm the origin of the water at Mataranka Thermal Pools complex, spring and groundwater samples were collected in October 2019 (at the end of the dry season). Using environmental tracers – either compounds dissolved in groundwater or some property of the water molecule – the origin of the water and how and when this water entered the groundwater system was investigated.

Findings for springs that make up the Mataranka Thermal Pools, indicate the Daly flow path from the north of the Cambrian Limestone Aquifer is a major source of water for Rainbow Spring and the Georgina flow path from the south is a major source of water for Bitter Spring. Other smaller springs in the complex (Warloch Pond and Fig Tree) had chemical signatures similar to the Georgina flow path.

With the exception of Fig Tree Spring, there was limited evidence for 'young' (post-1950), locally recharged groundwater contributing to the springs, demonstrating that much of the groundwater originated from farther away in the Cambrian Limestone Aquifer. Fig Tree Spring shows seasonal variations in nearly all measured parameters and is at least partly fed by a quick local flow system. High amounts of radiogenic helium-4 in Rainbow Spring, Bitter Spring and many nearby groundwater bores demonstrated an additional older, deeper source (or sources) of groundwater to the complex that would require further investigation to identify. See Geological and Bioregional Assessment Program (2021l) for further information.

FIGURE 10 Bitter Springs at Mataranka Thermal Pools in the Beetaloo GBA extended region

Source: Geological and Bioregional Assessment Program, Clare Brandon (CSIRO)
Element: GBA-BEE-3-420

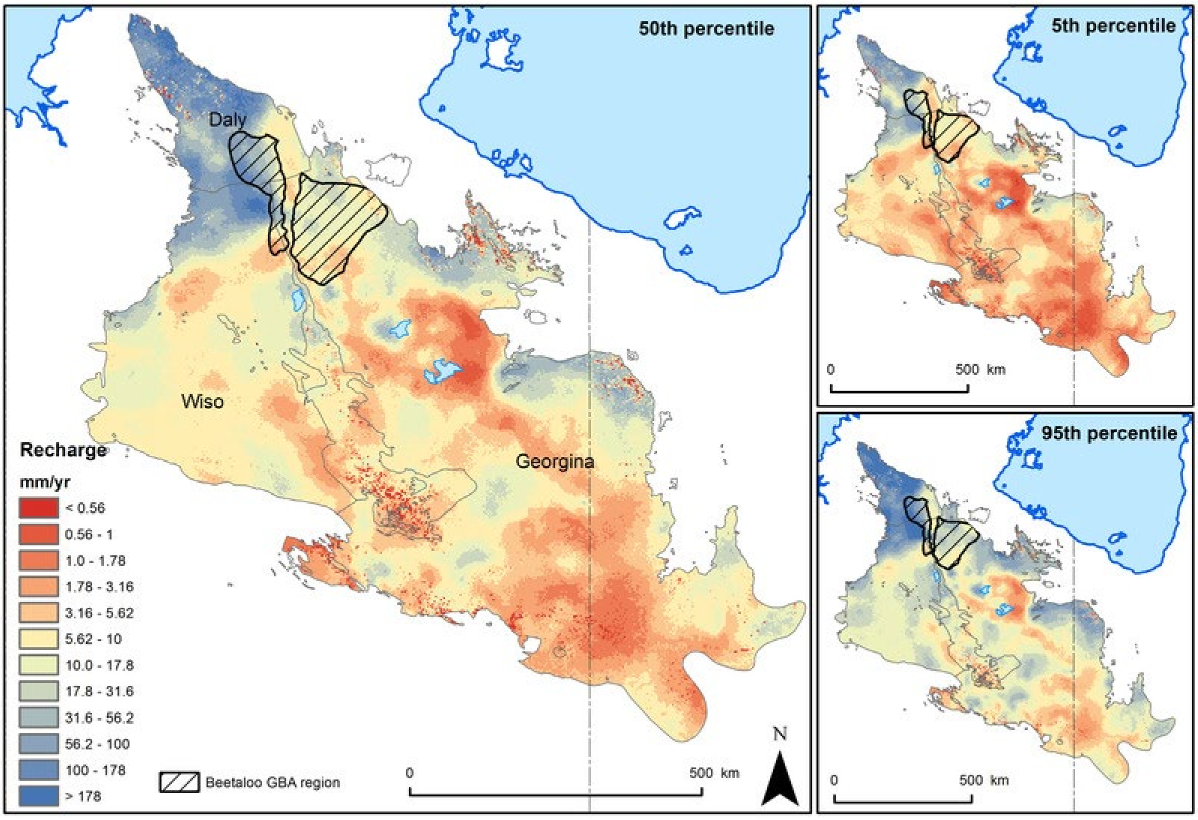
Box 3 Quantifying recharge in the Cambrian Limestone Aquifer

The hydrogeology of the Cambrian Limestone Aquifer is complex owing to a strong decrease in rainfall from north to south, extensive karst features (for example, caves, cavities and sinkholes), a thick unsaturated zone and partial confinement of the aquifer.

Understanding recharge processes in the Cambrian Limestone Aquifer is important for quantifying groundwater recharge and for assessing potential risks to groundwater from unconventional gas resource development. Groundwater recharge was measured over the entire 570,000 km^2 Cambrian Limestone Aquifer footprint using a method for estimating recharge called 'chloride mass balance'.

There is a considerable gradient in recharge in the Cambrian Limestone Aquifer that follows the climate gradient, the highest recharge is in the Daly River catchment to the north of the Beetaloo GBA region and the lowest recharge is in the Georgina River catchment to the south of the Beetaloo GBA region (Figure 11). Preferential recharge areas were associated with limestone outcrops (including sinkholes) and around the large ephemeral water features. This study found the recharge over the footprint of the eastern Beetaloo GBA region (not recharge to the entire Beetaloo GBA region) was 12 mm per year and the western side was considerably higher at 48 mm per year. Further details of this investigation can be found in Crosbie and Rachakonda (2021) and Geological and Bioregional Assessment Program (2021m, 2021n).

FIGURE 11 Constrained recharge across the Cambrian Limestone Aquifer in the Beetaloo GBA region



Main image shows 50th percentile estimates, top right shows 5th percentile estimates, bottom right shows 95th percentile estimates.
Data: Geological and Bioregional Assessment Program (2020a)
Element: GBA-BEE-3-585

Potential impacts related to water quality and availability

Surface activities may affect surface water flows by diverting or modifying flow pathways, causing erosion or through sedimentation. **Overland flow obstruction** and **vegetation removal** may result in reduced surface water availability or an increase in surface water contamination (via erosion and sedimentation) and is of 'potential concern' to small areas of the **agricultural productivity** endpoint (only near existing surface water features), and **riparian vegetation extent and condition**, **wetland condition**, **surface water condition**, and **unconfined aquifer condition** endpoints. There is high confidence that regulations and mitigation strategies can mitigate potential impacts on water-related endpoints.

Overland flow obstruction includes complete, partial or minor impediment to the movement of water over the landscape. Obstructions can act as a dam or diversion that may partially or completely change the flow path of water. Altered flow paths may lead to impacts on water-related endpoints through a reduction in flow to streams, wetlands, waterholes and sinkholes (a recharge mechanism).

Vegetation removal involves the destruction of above-ground native vegetation. **Overland flow obstruction** and **vegetation removal** stressors may both impact on water-related endpoints through increased soil erosion and sedimentation, leading to surface water contamination. These stressors may lead to impacts on endpoints that rely on surface water availability and water quality. These include **agricultural productivity** (only in the vicinity of existing surface water features provide water for stock), **riparian vegetation extent and condition**, **wetland condition**, **surface water condition** where surface water availability and quality are important for the endpoint function, and **unconfined aquifer condition**, which may be impacted by decreased recharge through existing surface waterways. There is high confidence that impacts due to **overland flow obstruction** and **vegetation removal** can be mitigated by adhering to regulations and mandatory requirements such as site selection for surface activities listed in the *Code of practice: Onshore petroleum activities in the Northern Territory* (the Code) (Northern Territory Government, 2019c).

Potential impacts related to accidental spills

Spills and leaks due to **accidental release** could lead to **unconfined aquifer contamination**. This is of 'potential concern' in very limited parts of the Beetaloo GBA region where the depth to groundwater is less than 14 m (Geological and Bioregional Assessment Program, 2021f, 2021p). Direct pathways for contamination of unconfined aquifers from the land surface, for example via sinkholes or open karsts, are mitigated by the chemical handling requirements stipulated in the Code (Northern Territory Government, 2019c).

Any **accidental release** of contaminants beyond an engineered bunding or control into surface waters is conservatively assumed to be material and is of 'potential concern' for **wetland condition** and **riparian vegetation extent and condition** endpoints. However, compliance reporting of spills and leaks from the Northern Territory and other jurisdictions indicates that existing avoidance and mitigation strategies prescribed in the Code (Northern Territory Government, 2019c) and other Northern Territory regulations are effective in mitigating this pathway. These pathways have been evaluated as 'low concern' to 'very low concern' for springs.

Community and government consultation during the initial stages of the GBA Program identified potential impacts on water quality — particularly groundwater — from the use, handling, and storage of chemicals and flowback waters during extraction of unconventional gas in the Northern Territory as an area of community concern. Chemicals or compounds used or produced in unconventional gas resource development may be unintentionally released to the environment through spills and leaks if they escape any engineered bunding or control (**accidental release**). **Hydraulic fracturing**, **drilling**, **waste and wastewater management**, **production of hydrocarbons** and **processing of hydrocarbons** all involve material volumes of chemicals and compounds.

The pathway from **accidental release** to surface waters is of 'potential concern' for **wetland condition** and **riparian vegetation extent and condition** endpoints. This is based on the conservative assumption that any spill into surface waters, should it occur, is material. There are limited options to avoid or remediate surface water contamination once it has occurred due to rapid spreading of chemicals through surface water and partitioning to, and accumulation in, sediments (National Research Council, 2000; Eggleton and Thomas, 2004; Jaffé, 1991). Existing controls prescribed in the Code (Northern Territory Government, 2019c) and other Northern Territory regulations can effectively mitigate this pathway.

Unconfined aquifer contamination from **accidental release** at the land surface is of 'very low concern'. Where unconfined aquifers are greater than 14 m deep, conservative chemical transport modelling shows that concentrations of contaminants will have dispersed and diluted to levels that are not material (Geological and Bioregional Assessment Program, 2021f, 2021p). Areas where the depth to unconfined aquifers is less than 14 m are limited to the vicinity of Western Creek, where the watertable is shallow within the Antrim Volcanics (the Cambrian Limestone Aquifer is absent or unsaturated), and along Lagoon Creek in the north-east of the Beetaloo GBA region where the watertable sits in the Bukulara Sandstone (and the Cambrian Limestone Aquifer is absent). The vast majority of the area of 'potential concern' is outside the Beetaloo GBA region and within the Beetaloo GBA extended region where unconventional gas resource development activities will be limited to major transport corridors and accidental release incidents are less likely.

The Beetaloo GBA region includes karstic formations such as caves, cavities and sinkholes, which may allow for increased vertical flow rates. It is considered unlikely that well pads, storage tanks or other infrastructure will be constructed over undetected shallow karst features due to site characterisation and precautionary testing requirements outlined in the Code (Northern Territory Government, 2019c). Similarly, the likelihood of a truck roll-over into a sinkhole leading to unconfined aquifer contamination is considered very unlikely. Pathways from **accidental release** to springs (**spring condition**) have also been evaluated as 'low concern' as activities will not occur close enough to the springs to have an impact.

Potential impacts due to **accidental release** are primarily managed through existing avoidance and mitigation strategies prescribed in the Code (Northern Territory Government, 2019c) that prevent **accidental release** occurring in the first place. This includes requirements to store chemicals and compounds within secondary containment (engineered controls), operators to have spill management plans and regular monitoring of chemical storage, compounds and wastewater. Confidence in existing mitigation strategies that reduce the chance of accidental release is high, whereas confidence in pathways leading to surface water contamination is low due to the limited knowledge base available to establish thresholds of material change for each endpoint.

Investigations related to accidental release

Two GBA Program investigations have added to the knowledge base for increasing understanding of the chemicals in flowback water and natural attenuation (natural processes that reduce contaminants in soil or groundwater) of hydraulic fracturing chemicals (Box 4, Box 5).

Box 4 Assessment of hydraulic fracturing chemicals and chemicals in flowback water

A qualitative risk assessment for the GBA Program evaluated potential chemical impacts on water quality from the use, handling and storage of hydraulic fracturing chemicals and chemicals in flowback water from the target shale formation (geogenic chemicals). Field studies were conducted at Tanumbirini-1 and Kyalla-117 well sites in the Beetaloo GBA region (Geological and Bioregional Assessment Program, 2021h; Kirby et al., 2020). Investigations included pre- and post-hydraulic fracturing groundwater quality monitoring to assess the effectiveness of controls in protecting water quality in the region.

Direct toxicity assessment of flowback tank storage waters (chemical mixtures) were used to derive site-specific 'safe dilutions' to protect 95% of freshwater organisms. This information was used for site-specific modelling scenarios of possible events such as spills and leaks, and the catastrophic failure of storage tanks (Box 5) (Geological and Bioregional Assessment Program, 2021q, 2021r).

There is a risk to water quality from the use, handling and storage of chemicals and flowback waters at gas activities in the Beetaloo GBA region. However, the release of chemicals and flowback waters, and impacts to surface waters and groundwaters is, an 'impact unlikely to occur' (Geological and Bioregional Assessment Program, 2021s) if all controls and management actions are implemented effectively, comply with Northern Territory Government procedures, practices and policies, and are in accordance with the Code (Northern Territory Government, 2019c). Further information on this investigation can be found in Geological and Bioregional Assessment Program (2021h).

Box 5 Environmental fate of chemicals in flowback water in the event of a spill

Flowback water from unconventional gas operations is known to contain a mixture of metals, radionuclides and organics. While accidental releases of flowback waters from storage tanks into the environment is an unlikely event due to multiple containment barriers, leak detection, and routine inspections, they cannot be entirely excluded.

Predictive modelling was used for a scenario involving a possible leak (0.1 megalitres) from a storage pond. Actual chemical concentrations in flowback water collected from the Tanumbirini-1 shale gas well served as input for simulating chemical transport through the zone in soils and rocks occurring above the watertable, where there is some air within the pore spaces (unsaturated soil and the deep unsaturated zone). Simulations accounted for the long-term effects of typical dry or wet seasonality of the Beetaloo GBA region. A 3 dimensional analytical transport model was used to assess transport and chemical attenuation in groundwater should chemicals reach the watertable and be transported.

If accidental release of flowback water from storage tanks occurs, the findings suggest it is unlikely to impact groundwater quality due to slow migration and natural attenuation processes in the soil.

Scenario modelling of spills or leaks using direct toxicity assessment data provides additional evidence that chemical mixtures in flowback are unlikely to impact freshwater organisms due to slow migration and natural attenuation processes in the soil.

Spills and leaks are regulated by Northern Territory and Australian Government law. Gas companies are required to implement a range of risk controls, mitigation and management strategies and actions to protect groundwater quality from use, handling and storage of chemicals and flowback waters. If contamination is detected, cleanup and remediation is required to commence as soon as practical in accordance with the spill management plan, emergency response plan (if applicable) and the Code (Northern Territory Government, 2019c). Further information on this investigation can be found in Geological and Bioregional Assessment Program (2021f, 2021p).

As the disposal of hydraulic fracturing waste to surface water or groundwater is prohibited in the Northern Territory, it is not possible for **controlled release** of wastewater from hydraulic fracturing activities to impact surface water or aquifers in the Beetaloo GBA region.

Stringent approval and management requirements, including national guidelines, Northern Territory regulations and industry waste management plans, give confidence that contamination due to **waste disposal** is of ‘low concern’ in the Beetaloo GBA region.

Controlled release of wastewater is the intentional release of treated or untreated water into the environment. The release of hydraulic fracturing wastewater to surface waterways or groundwater is not permitted in the Northern Territory so this stressor is not possible. Wastewater is disposed of through evaporation to reduce volumes, with the residual material (including brines and pond liners) disposed of as regulated waste at a licensed waste facility according to the *Waste Management and Pollution Control Act 1998 (NT).* The Code (Northern Territory Government, 2019c) requires all wastewater to be accounted for along with the methods for monitoring of storages, any reuse or recycling and ultimate disposal.

Waste disposal is the handling, storage, transport and disposal of solid waste materials – excluding wastewater – that result from unconventional gas resource development. Any waste that leaves the site of a petroleum activity must be managed in accordance with the *Waste Management and Pollution Control Act 1998 (NT)*. Waste that cannot be reused, recycled or treated is disposed of in designated waste management facilities. Solid waste includes drill cuttings, which can only be disposed of onsite if strict conditions set out in the Code (Northern Territory Government, 2019c) are followed, including independent certification that on site disposal plans meet required standards.

The stringent approval and management requirements for waste disposal are based on established guidelines (Commonwealth of Australia, 2013b) and the Code (Northern Territory Government, 2019c), which ensure there is high confidence that any contamination can be effectively managed and/or mitigated; therefore, waste disposal is of 'low concern'.

Potential impacts related to subsurface activities

The 1,204 km^2 where the Hayfield sandstone member is prospective for unconventional resources is also the area where there is potential connection with the Bukalara Sandstone, a confined aquifer. In this 4% of the Beetaloo GBA region, aquifer contamination due to creation of new fractures or widening of existing faults or factures (**compromised subsurface integrity**) is of 'potential concern'. The Bukalara Sandstone aquifer is not currently used for water in this area as the shallower Cambrian Limestone Aquifer provides a better resource. Outside this small area, the distance separating unconfined aquifers and unconventional gas resources and avoidance and mitigation measures in the Code (Northern Territory Government, 2019c) reduce the level of concern for potential unconfined and confined aquifer contamination to 'low concern' and 'very low concern'. Subsurface activities are of 'low concern' for springs.

Longreach Waterhole near Elliott, Beetaloo GBA extended region. © Jenny Davis, Charles Darwin University

Creation of new fractures or the widening of existing faults or fractures may lead to **compromised subsurface integrity** due to hydraulic fracturing or through changes in subsurface stress from gas extraction. There is potential that this could result in **confined aquifer contamination** and **unconfined aquifer contamination**.

For an aquifer to be contaminated, there must be a flow path between it and the underlying unconventional gas resource that is the source of contaminants. This flow path may be a fault or fracture. The distance between the aquifer and the reservoir will determine the time it takes for contaminants to reach the aquifer and whether they will be of a concentration to have an impact. Conservative modelling shows that a separation distance of less than 139 m between an aquifer and reservoir may allow contamination of the aquifer by fluid flow up a fault or fracture (see **compromised subsurface integrity** node description). In the Beetaloo GBA region, the area where the Hayfield sandstone member is prospective for unconventional resources, is also an area where there is less than 139 m separation from the Bukalara Sandstone, a confined aquifer. This aquifer is not currently accessed in this area as the shallower Cambrian Limestone Aquifer provides a better resource. This pathway can be mitigated through industry practices in the design and operation of hydraulic fracturing activities, including geotechnical modelling and monitoring (Kear and Kasperczyk, 2020). There is high confidence that the mitigation strategies required through regulations in the Code (Northern Territory Government, 2019c), including requirements for detailed geotechnical modelling where the interval between the formation being hydraulically fractured and overlying aquifers is less than 600 m, is adequate to avoid, mitigate and manage this risk. Outside this small area, the distance separating unconfined aquifers and unconventional gas resources, and the avoidance and mitigation measures in the Code (Northern Territory Government, 2019c), reduce the level of concern for potential unconfined and confined aquifer contamination to 'low concern' and 'very low concern.'

Causal pathways between subsurface activities and the **spring condition** endpoint are of 'low concern'. The springs are too far from the Beetaloo GBA region to be affected by these activities.

There is high confidence that groundwater contamination due to **compromised well integrity** or **compromised decommissioned well integrity** is of 'low concern' to 'very low concern'.

Due to government and community concerns about potential impacts of well integrity on water, well integrity throughout resource extraction and once wells are decommissioned was considered in the impact assessment. Well integrity is a fundamental component of petroleum well design and is the main focus of the Schedule (Northern Territory Government, 2019a) and the Code (Northern Territory Government, 2019c). Pathways related to **compromised well integrity** and **compromised decommissioned well integrity** are evaluated as having 'low concern' to 'very low concern'. These evaluations are supported by the findings of multiple domestic and international inquiries (for example, Pepper et al. (2018) as summarised in Section 2 of Stage 2 hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020)).

Compromised well integrity refers to the possibility of breaches of a well system that allow the unintended movement of fluids (gas, liquid hydrocarbons and water) into or out of the well. Well integrity is a fundamental component of petroleum well design, and is the main focus of regulations (Northern Territory Government, 2019a, 2019c). Confidence in regulatory process is increased through inclusive participation of stakeholders, implementation of transparent processes and open communication (Huddlestone-Holmes et al., 2017). One of the ways the Northern Territory Government is addressing transparency and open communication is through the publication of documents such as Well Barrier Integrity Verification reports for wells through the POINT website.

Following international best practice, a minimum of 2 independent well barriers – are required by regulation (International Organization for Standardization, 2017; Department of Natural Resources, Mines and Energy (Qld), 2019; Northern Territory Government, 2019c) to provide redundancy; such that a failure in one well barrier does not lead to unintended fluid infiltration into geological layers or to the surface. **Compromised decommissioned well integrity** refers to breaches of a well system after it has been decommissioned. After a well has been decommissioned the requirements for 2 independent well barriers and isolation of the surface and aquifers from each other and hydrocarbon-bearing formations continue to apply. The well barriers must be designed to maintain integrity of the well in perpetuity (Northern Territory Government, 2019c).

Investigations related to subsurface stressors

The amount of available hydrogeological data and understanding varies greatly between different groundwater systems in the Beetaloo GBA region. Investigations undertaken for the GBA Program fill some of these knowledge gaps (Box 2, Box 6).

Box 6 Hydrological connections through faults

Greater understanding of the potential natural connections between the unconventional gas resources, the aquifers and the surface across the Beetaloo GBA region improves assessment of potential impacts from resource development.

Faults have the potential to provide a flow path that connects deeper layers with the shallow unconfined aquifers. The spring complexes of Mataranka Thermal Pools and Beauty Creek may be surface expressions of these pathways in the Beetaloo GBA extended region. Within the Beetaloo GBA region, there is no evidence that faults are connecting the deeper layers with the Cambrian Limestone Aquifer.

Within the Beetaloo GBA extended region there is evidence that suggests north to north–north-west trending geological faults have been reactivated in recent geological history, controlling post-Cambrian sediment deposition at the edges of the Beetaloo GBA region, outside of the area prospective for unconventional gas resources. The Hot Spring Valley springs and Mataranka Thermal Pools are associated with this system. These faults have the potential to connect shallow unconfined aquifers with deeper gas or fluid sources at a local scale, without involving regional connections within the Beetaloo GBA region. There is no evidence within the Beetaloo GBA region that north-west trending faults have been reactivated in recent geological ages (post-Cambrian) in areas prospective for unconventional gas resources. Analysis of faults elsewhere in the Beetaloo GBA region is limited to interpretation of 2-dimensional seismic data and aeromagnetic and electromagnetic surveys. While this data is sparse, there is no evidence of vertical fluid movement in recent geological time. Further information on this investigation can be found in Geological and Bioregional Assessment Program (2021o).

FIND MORE INFORMATION

GBA Stage 2 hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020)

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

- *Fact sheet 3:* Assessment of groundwater quality from a possible leak of a flowback storage tank from shale gas operations (Geological and Bioregional Assessment Program, 2021f)
- *Fact sheet 19:* Recharge processes in the Beetaloo Sub-basin (Geological and Bioregional Assessment Program, 2021n)
- *Fact sheet 23:* Structural flow implications for unconventional resources exploration, Beetaloo Sub-basin case study (Geological and Bioregional Assessment Program, 2021o)
- *Fact sheet 24:* Water quality risk assessment from use, handling, and storage of chemicals and flowback at onshore gas operations in the Beetaloo Sub-basin (Geological and Bioregional Assessment Program, 2021s)
- *Fact sheet 25:* Groundwater sources to the Mataranka Springs Complex (Geological and Bioregional Assessment Program, 2021l)

4.3 Potential impacts on the environment

For this assessment, the environment of the Beetaloo GBA region, excluding aquatic environments, has been considered in terms of 3 ecosystems based on (i) terrestrial vegetation that is dominated by rainfall dependent open woodlands, (ii) riparian ecosystems that include flora and fauna that are dependent on the presence of rivers and streams and (iii) ephemeral wetlands. Terrestrial vegetation accounts for around 90% of the region.

Potential impacts on terrestrial vegetation

Rain-fed open woodlands dominate the Beetaloo GBA region. Activities at the surface such as civil construction, seismic acquisition, transport of materials and equipment and decommissioning and rehabilitation (Figure 13) may cause changes in **terrestrial vegetation extent and condition**. Pathways that are of 'potential concern' and warrant more detailed local-scale assessment are related to **invasive plants and insects**, **vegetation removal** and **vehicle movement**. Existing management controls can avoid and mitigate these potential impacts.

Potential impacts on areas of rainfall-dependent vegetation in the Beetaloo GBA region are explored through the **terrestrial vegetation extent and condition** endpoint. Terrestrial vegetation encompasses the largest portion of the Beetaloo GBA extended region and provides habitat for a wide range of species, including 4 of the threatened fauna species assessed: greater bilby (*Macrotis lagotis)*, crested shrike-tit (northern) (*Falcunculus (frontatus) whitei*), Gouldian finch (*Erythrura gouldiae*) and grey falcon (*Falco hypoleucos*). The area is predominantly open woodlands over a grassy understorey, although it does include several landscape classes and a range of vegetation communities (see Figure 12 for an example of typical terrestrial vegetation).

FIGURE 12 Bullwaddy vegetation, near the Bullwaddy Conservation Reserve in the Beetaloo GBA region, one of the vegetation types within the terrestrial vegetation endpoint

Source: Geological and Bioregional Assessment Program, Chris Pavey (CSIRO)
Element: GBA-BEE-3-540

Impacts from activities such as **civil construction**, **seismic acquisition**, **transport of materials and equipment** and **decommissioning and rehabilitation** are unavoidable in resource development (Figure 13). However, impacts can be avoided, minimised or mitigated through adherence to strategies outlined in the *Land clearing guidelines* for the Northern Territory (Northern Territory Government, 2020) and the Code (Northern Territory Government, 2019c). Mitigation strategies include locating infrastructure away from potentially sensitive habitats to avoid vegetation removal in their vicinity, control of invasive species (weeds and carnivores) and minimisation of vehicle access to previously undisturbed areas.

Potential impacts on wetlands and riparian vegetation

The Beetaloo GBA extended region has small areas of wetlands (3%) and riparian vegetation (2%) that have high ecological value and provide habitat for many species. Key potential impacts for **wetland condition** and **riparian vegetation extent and condition** are from civil construction (for example, roads, well pads or laydown yards) and any activity that requires vehicle movement beyond designated roads, such as seismic acquisition.

The **wetland condition** endpoint covers a relatively small area, representing just 3% of the Beetaloo GBA extended region. It includes ephemeral lakes, swamps and channel environments that are inundated less than 70% of the time, including the *Directory of important wetlands*-listed Lake Woods. Lake Woods is the largest receiving lake in the Beetaloo GBA extended region (Environment Australia, 2001) and a significant open water environment and lignum swamp that supports breeding sites for 23 species of waterbird. Wetlands and the vegetation they support, provide important habitats for the Australian painted snipe (*Rostratula australis*).

The **riparian vegetation extent and condition** endpoint includes vegetation associated with areas mapped as watercourses and all terrestrial groundwater-dependent ecosystems, whose occurrence is mostly confined to the north of the Beetaloo GBA region and makes up around 2% of the land area in the Beetaloo GBA extended region. Riparian areas adjacent to watercourses typically have higher species richness than the surrounding landscape and vegetation is often denser due to greater water availability (Woinarski et al., 2000). Riparian areas are known to support species such as the Gouldian finch, which needs to drink daily during breeding (Dostine et al., 2001; O'Malley, 2006), and the grey falcon, which can use tall trees including river red gums along watercourses as nesting sites (Marchant and Higgins, 1993).

Pathways of 'potential concern' for **wetland condition** and **riparian vegetation extent and condition** are the same as those for **terrestrial vegetation extent and condition**, primarily involving disturbance at the surface (Figure 13). The *Land clearing guidelines* for the Northern Territory (Northern Territory Government, 2020) and the Code (Northern Territory Government, 2019c) require that activities in these vegetation communities be minimised or avoided. Therefore the pathways for impact for these endpoints are indirect.

Potential impacts related to accidental spills

Accidental release of chemicals is of 'potential concern for **wetland condition** and **riparian vegetation extent and condition** through surface water contamination. However, there is high confidence that existing regulations and mitigation strategies related to accidental release can mitigate potential impacts on wetlands and riparian vegetation.

As surface water is a component of both wetlands and riparian vegetation, there is potential for surface water contamination to affect their condition. Spills onto the land surface outside of bunded areas (**accidental release**) is of 'potential concern' for wetlands and riparian vegetation through **surface water contamination**. **Accidental release** may result from any activity that involves the transport, handling, storage and use of chemicals. Australian and international literature indicates that spills are infrequent, although rates are highly variable (depending on local conditions and practices) and difficult to define (Huddlestone-Holmes et al., 2017). The spatial extent of spills beyond containment is likely to be limited to a scale of tens of square metres over a short duration. Infrequent chemical discharge to the environment through accidental release may briefly exceed guideline values and harm aquatic species and other biota. However, there is high confidence that existing regulations and mitigation strategies related to accidental release can mitigate potential impacts on wetlands and riparian vegetation.

4.4 Potential impacts on protected fauna

Six protected matters were prioritised for more detailed assessment based on the importance of the Beetaloo GBA extended region to the continued persistence of each species (Huddlestone-Holmes et al., 2020). 'Persistence' is the survival and maintenance or extension of occupied area of a species in its current habitat, in the Beetaloo GBA extended region over a time frame much longer than the unconventional gas resource development life cycle. Those assessed were:

- 4 bird species: the Australian painted snipe (*Rostratula australis*), crested shrike-tit (northern) (*Falcunculus (frontatus) whitei*), Gouldian finch (*Erythrura gouldiae*), grey falcon (*Falco hypoleucos*)
- 1 marsupial: greater bilby (*Macrotis lagotis*)
- 1 aquatic reptile: Gulf snapping turtle (*Elseya lavarackorum*).

The Beetaloo GBA region changes from tropical in the north to semi-arid in the south. Tropical savanna species are found in the north (for example, the Gouldian finch) and typical Australian desert species are found in the south (for example, the greater bilby). As the region becomes more widely surveyed, more species are expected to be added to biodiversity records. As water controls the ecology and movements of the 6 protected fauna quite differently, these species were selected to better understand the potential impacts of unconventional gas resource development. Any decline in persistence is assumed to be material.

Pathways between activities and fauna endpoints of 'potential concern' are primarily related to activities that create a disturbance at the surface (**civil construction**, **decommissioning and rehabilitation**, **transport of materials and equipment** and **seismic acquisition**). The pathways of 'potential concern' connect these activities with key stressors, namely **invasive plants and insects** and **vegetation removal** that result in **mortality of native species** and **habitat degradation, fragmentation and loss**. Common processes within these pathways that are of 'potential concern' are **competition and predation**, and **ecosystem burning**. The aquatic Gulf snapping turtle may be affected by **surface water contamination** processes while the Gouldian finch, crested shrike-tit (northern), greater bilby and grey falcon may be affected by increases in invasive carnivores as a result of **artificial water sources**.

Gulf snapping turtle

The Gulf snapping turtle lives near permanent water bodies, occupying deep water pools along permanently flowing spring-fed rivers. However, it is also dependent on riparian vegetation that fringes its aquatic habitat to provide stable banks, where the species breeds by laying eggs in the soil, and to provide habitat for the plants that provide its food. It has been noted that densities of Gulf snapping turtle are lower adjacent to riparian vegetation that is degraded by invasive plants and/or fire. As the food plants of the turtle occupy fire-sensitive riparian vegetation, fire is seen as a process that opens the canopy and facilitates weed invasion during seasonal flooding. Therefore, the Gulf snapping turtle is vulnerable to disturbances that impact both freshwater condition and availability, and the condition and availability of riparian vegetation.

Potential impacts for the Gulf snapping turtle due to unconventional gas resource development relate to **civil construction**, **decommissioning and rehabilitation**, and **transport of materials and equipment** (Figure 13) activities. The aquatic habitat of the species is potentially affected by **surface water contamination** generated by the stressors of **accidental release** (directly or via a pathway through soil contamination), **overland flow obstruction**, **soil compaction** and **vehicle movement** (via a pathway through soil erosion and sedimentation). Riparian vegetation on which the species depends is potentially affected by **habitat degradation, fragmentation and loss** generated by the stressors of **invasive plants and insects** (directly or via a pathway through ecosystem burning), **vegetation removal** and **vehicle movement** (via a pathway through ecosystem burning).

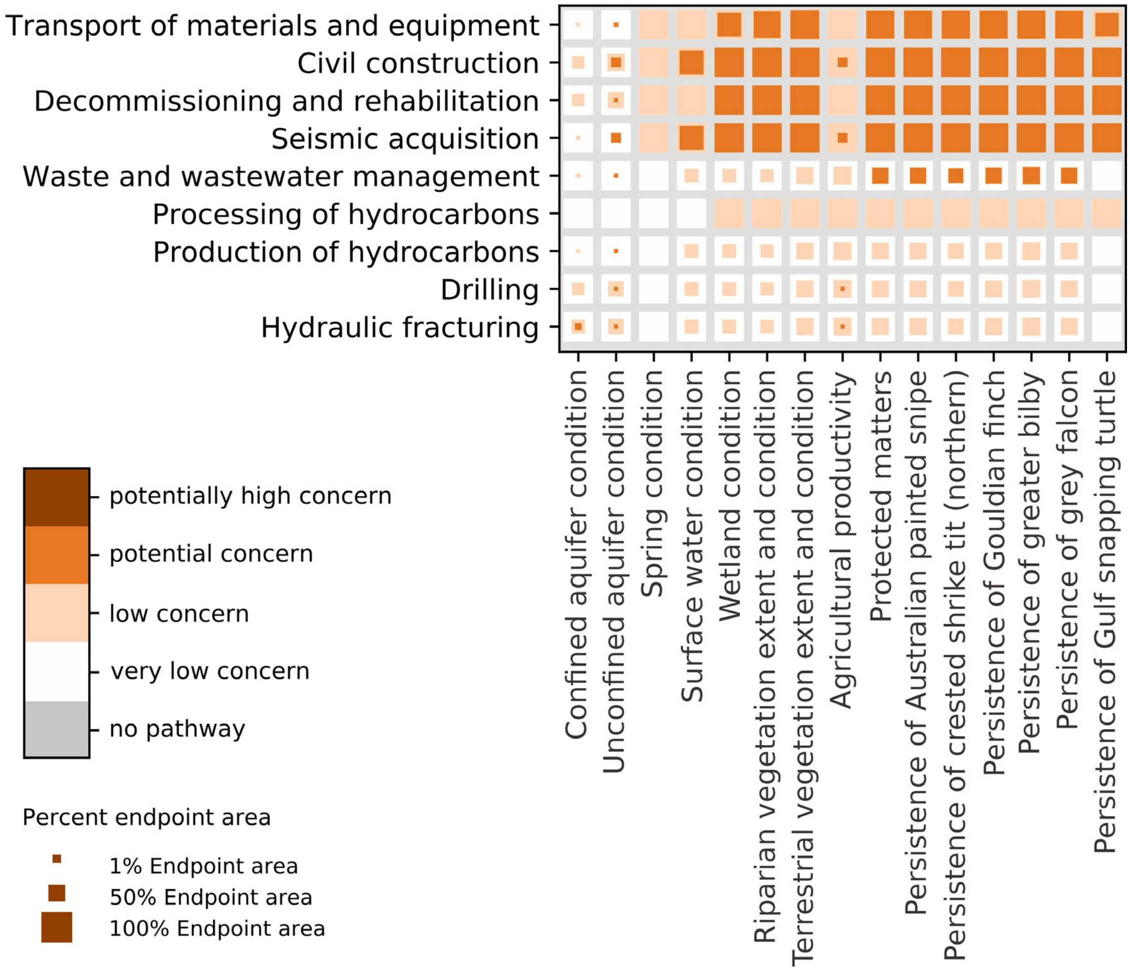
Australian painted snipe

The semi-aquatic Australian painted snipe is also considered to be water dependent but does not live in water. It shelters among vegetation adjacent to wetlands and forages during twilight hours in shallow, brackish or freshwater wetlands including lakes, swamps, claypans, inundated or waterlogged grassland and saltmarsh and artificial wetlands. It forages by probing the soft mud with its bill, consuming seeds and invertebrates.

Potential habitat for the Australian painted snipe in the Beetaloo GBA region consists of small and shallow ephemeral wetlands. These appear infrequently in the region in response to rainfall. The species is nomadic and does not occupy an area if suitable wetlands are not available. It leaves once wetlands dry.

Potential impacts for the Australian painted snipe due to unconventional gas resource development relate to **civil construction**, **decommissioning and rehabilitation**, **transport of materials and equipment**, **waste and wastewater management**, and **seismic acquisition** (Figure 13) activities. The majority of pathways involve **invasive plants and insects** as the key stressor. **Vegetation removal** is also an important stressor for the species. The pathways from invasive plants and insects and vegetation removal conclude either in **mortality of native species** or **habitat degradation, fragmentation and loss**. **Competition and predation** and **ecosystem burning** feature as processes in some of these pathways. Pathways involving stressors related to water availability and condition such as **surface water availability** and **surface water contamination** are not considered to be of 'potential concern' for the Australian painted snipe.

FIGURE 13 Level of concern for causal pathways from activities to endpoints for the Beetaloo GBA region



Endpoints are on the x axis and activities on the y axis. The colours of the squares show the level of concern for the pathway, and the size of the squares shows the percentage of the endpoint area potentially impacted. Where a square has multiple colours, it indicates that there are different levels of concern spatially for the endpoint. Activities are ordered from surface to subsurface and endpoints are ordered from subsurface to surface.

Source: Geological and Bioregional Assessment Program (2021g)

Element: GBA-BEE-3-547

Gouldian finch

The Gouldian finch, although a terrestrial species, is reliant on daily access to water to drink. This reliance on water influences its movement, ecology and activities throughout the year. In addition, the Gouldian finch has distinct nesting and foraging habitat. It breeds in the hollows of eucalypt species on rocky hills and feeds on grass seed. As a result it has a complex life cycle that involves the use of discrete environments across the annual cycle. The Gouldian finch is vulnerable to disturbances that impact the availability and condition of specific aspects of the terrestrial vegetation in which it nests and feeds.

Potential impacts for the Gouldian finch due to unconventional gas resource development relate to **civil construction**, **decommissioning and rehabilitation**, **transport of materials and equipment**, and **waste and wastewater management** activities (Figure 13). The majority of pathways involve **invasive plants and insects** as the key stressor. **Vegetation removal** is also an important stressor for the Gouldian finch. The pathways from invasive plants and insects and vegetation removal conclude either in **mortality of native species** or **habitat degradation, fragmentation and loss**. Important processes in these pathways are **competition and predation**, and **ecosystem burning**. **Vehicle movement** can also result in ecosystem burning. Overall, confidence that these pathways are of 'potential concern' or 'low concern' is medium based on available literature and local assessment of potential invasive plant species, although the knowledge base for thresholds of material change is limited.

Artificial water sources from civil construction and waste and wastewater can increase competition and predation through facilitating spread of **invasive carnivores** resulting in **mortality of native species**. This pathway is of 'low concern' but confidence is low owing to a lack of local studies or data and an inadequate knowledge base to define and evaluate a material change.

Gulf snapping turtle © Scott Thomson, CC BY-NC 4.0

Crested shrike-tit (northern) © JJ Harrison, CC BY-SA 4.0

Crested shrike-tit (northern)

The water requirements of the crested shrike-tit (northern) are unknown. It may require daily access to water like the Gouldian finch or it may be able to obtain all (most) of its water requirements from its prey. The species is arthropodivorous, that is it feeds on invertebrates, mostly insects and spiders, in the foliage, branches, trunk and bark of trees. The potential geographic range of the crested shrike-tit (northern) overlaps with that of the Gouldian finch. Both species are characteristic of savanna woodlands in the north of the Beetaloo GBA region. The crested shrike-tit (northern) occurs in woodland and open woodland dominated by a range of *Eucalyptus* and *Corymbia* species. It also breeds in this habitat, constructing a cup-shaped nest from fibre, bark and other materials, near the top of a eucalypt, bloodwood or paperbark tree.

The crested shrike-tit (northern) is very similar to the Gouldian finch in terms of the potential impacts posed by unconventional gas resource development. Potential impacts due to unconventional gas resource development relate to **civil construction**, **decommissioning and rehabilitation**, **transport of materials and equipment**, and **waste and wastewater management** activities (Figure 13). The majority of pathways involve **invasive plants and insects** as the key stressor. **Vegetation removal** is also an important stressor for crested shrike-tit (northern). The pathways from invasive plants and insects and vegetation removal conclude either in **mortality of native species** or **habitat degradation, fragmentation and loss**. Important processes in these pathways are **competition and predation**, and **ecosystem burning**. **Vehicle movement** can also result in ecosystem burning. **Artificial water sources** from civil construction and waste and wastewater management can increase competition and predation through facilitating spread of **invasive carnivores,** resulting in mortality. This pathway can also happen directly without artificial water sources being involved.

Overall, confidence that these pathways are of 'potential concern' or 'low concern' is low to medium based on available literature and limited local evidence. The knowledge base for thresholds of material change is also limited.

Greater bilby

The greater bilby is a ground-dwelling marsupial occurring across the western deserts of the Northern Territory and Western Australia. The south-west of the Beetaloo GBA region is at the extreme north-east edge of its range. Bilbies are nocturnal, sheltering during the day in burrows. The species has an omnivorous diet. Invertebrates, especially termites, are relied upon when plant food is scarce. The greater bilby does not require daily access to water.

Although the greater bilby differs from the Gouldian finch in not having a requirement for regular access to water, the pathways of 'potential concern' for the bilby are the same as for the Gouldian finch. These pathways relate to **civil construction**, **decommissioning and rehabilitation**, **transport of materials and equipment**, and **waste and wastewater management** activities (Figure 13). Most pathways involve **invasive plants and insects** as the key stressor. **Vegetation removal** is also an important stressor. The pathways from invasive plants and insects and vegetation removal conclude either in **mortality of native species** or **habitat degradation, fragmentation, and loss**. Important processes in these pathways are **competition and predation**, and **ecosystem burning**. **Vehicle movement** is a stressor that can result in ecosystem burning. **Artificial water sources** from civil construction and waste and wastewater management can increase competition and predation by facilitating spread of **invasive carnivores,** resulting in mortality. This pathway can occur directly without artificial water sources being involved. The greater bilby is at more risk than the other fauna species from pathways involving predation by introduced carnivores because it is in the weight range of mammals with a heightened probability of extinction from predation by cats and foxes.

Overall, confidence that these pathways are of 'potential concern' or 'low concern' is medium based on available literature and local evidence, although the knowledge base for thresholds of material change is limited.

Grey falcon

The grey falcon is a predatory bird endemic to Australia. It is well known for being the only species among the world's 39 species of falcons that is confined to arid and semi-arid regions (although occasional vagrants move outside this area). The grey falcon is unique among the 6 species of protected fauna prioritised for the Beetaloo GBA region in that it uses space at a large scale. The grey falcon is generally nomadic although individuals can occupy specific areas for prolonged periods of time. Non-breeding birds undertake wide-ranging trips of up to several hundred kilometres whereas breeding birds typically remain within a radius of around 20 km of the nest. Grey falcons also make use of human structures (telecommunication towers, repeater stations) as nesting sites and can capture their preferred prey (birds, especially pigeons, doves, parrots and finches) around artificial water sources.

The pathways of 'potential concern' for grey falcon are similar to those of the greater bilby. Most pathways involve **invasive plants and insects** as the key stressor. **Vegetation removal** is also an important stressor. The pathways from invasive plants and insects and vegetation removal conclude either in **mortality of native species** or **habitat degradation, fragmentation, and loss**. Important processes in these pathways are **competition and predation**, and **ecosystem burning**. **Vehicle movement** is a stressor that can result in ecosystem burning. **Artificial water sources** from civil construction and waste and wastewater management can increase competition and predation by facilitating spread of **invasive carnivores** resulting in mortality. This pathway can also be direct without artificial water sources being involved – for example, predation by cats and foxes is an emerging threat for grey falcons.

Overall, confidence that these pathways are of 'potential concern' or 'low concern' is medium based on available literature and local evidence, although the knowledge base for thresholds of material change is limited.

5 Additional studies

The GBA Program was extended through allocated additional funding in the 2019–20 federal budget for activities to support the delivery of the Beetaloo GBA region assessment and the Northern Territory's Strategic Regional Environmental and Baseline Assessment. These activities were:

- Baseline ecological surveys to undertake regional ecosystem-scale vegetation mapping, to improve understanding of terrestrial and aquatic ecosystems in the region and to test sampling methodologies and processes to support the roll-out of Strategic Regional Environmental and Baseline Assessments. The surveys also targeted threatened species providing new records and improved understanding of habitat of the Gouldian finch, crested shrike-tit (northern) and greater bilby. The occurrence of the Gulf snapping turtle in the region was also established during these surveys. The final report for this project will be available on the Geological and Bioregional Assessment Program website.
- Water characterisation and discharge studies from the Cambrian Limestone Aquifer. This work investigated the relative significance of different hydrogeological processes that contribute to water flows in the Cambrian Limestone Aquifer and at Mataranka Thermal Pools through tracer studies (Box 2). This will help to improve understanding of the contribution of regional and local recharge pathways, karst processes and whether there is any deep groundwater contribution to the Cambrian Limestone Aquifer. A large number of fact sheets and datasets are associated with this work (Geological and Bioregional Assessment Program, 2021k, 2021e, 2021j, 2021a, 2021r, 2021n, 2021c, 2021l).

Australian painted snipe © Department of Agriculture Water and the Environment

Greater bilby © Bernard DUPONT, CC BY-SA 2.0

- A study that used a range of remote sensing approaches, including terrestrial and spaceborne LiDAR (Light Detection and Ranging), to develop approaches to monitoring changes in condition of habitat of selected protected matters: especially the Gouldian finch and crested shrike-tit (northern). This study sought to develop long-term approaches for remote monitoring of changes in extent and condition of habitat of key species (Geological and Bioregional Assessment Program, 2021d) .
- The Beetaloo Sub-basin Seismic Monitoring Project, undertaken by Geoscience Australia, to install a seismic monitoring network in the Beetaloo GBA region. This network will detect and locate natural seismic activity (for example, earthquakes) in the area, as well as monitoring for any human-induced seismicity that could potentially result from unconventional gas activities. This information will be used by Geoscience Australia, the public and other organisations to build knowledge about potential human-induced seismic activity in the region that may be associated with activities such as hydraulic fracturing.
- Development of a data management platform for the Northern Territory Government to support management and storage of Strategic Regional Environmental and Baseline Assessment data.

Gouldian finch © Roger Smith, CC BY-NC 2.0

Grey falcon © Christopher Watson CC BY-SA 3.0

6 Monitoring

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

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

Specific monitoring objectives define the attributes to be measured, the spatial domain, timeframe of monitoring and detection of the magnitude of change. Selection of attributes for each of the monitoring objectives is based on 'measurement endpoints' and 'environmental condition indicators' associated with the causal network. As defined in Section 3.1, a measurement endpoint is a measurable attribute of the 'assessment endpoint' associated with a link from a process to an endpoint. An example is the 'number of mature Australian painted snipe individuals', which is a measurement endpoint for the assessment endpoint **persistence of Australian painted snipe**. Persistence of Australian painted snipe is linked to processes in the causal network, such as **mortality of native species** and **habitat degradation, fragmentation and loss**.

Bore sampling near Mataranka, Beetaloo GBA region © Sébastien Lamontagne, CSIRO

Environmental condition indicators are attributes of stressors or processes that are relevant to, but not directly related to or linked to, an endpoint. An example of an environmental condition indicator is the area burned by bushfire, which is an attribute of the **ecosystem burning** process node. Ecosystem burning links to the endpoint 'persistence of Australian painted snipe' through changes to **habitat degradation, fragmentation and loss**. Environmental condition indicators are often measured at a regional scale and relate to many endpoints.

Estimating baseline and trend

Baseline data establishe the condition of endpoints related to water and the environment prior to unconventional gas resource development. Regional-scale data were compiled in the baseline synthesis and gap analysis for the Beetaloo GBA region (Huddlestone-Holmes et al., 2020). Future unconventional gas resource development proposals would require additional monitoring to provide local-scale baseline data on measurement endpoints and environmental condition indicators, which can include the extent and condition of the endpoint.

Protected flora and fauna endpoints have measurement endpoints that relate to the abundance of the species and are based on the criteria for listing outlined in the EPBC Act. These are supplemented by environmental condition indicators, such as habitat extent, surface water quality and streamflow.

Aquifer condition endpoints have measurement endpoints that relate to groundwater chemistry and aquifer levels or pressures. These are supplemented by environmental condition indicators, such as soil chemistry to detect soil contamination that could spread into unconfined aquifers.

Environment-related endpoints pertaining to landscape classes have measurement endpoints that relate to vegetation extent or condition. Relevant environmental condition indicators include vegetation cover, streamflow, surface water quality, soil chemistry, area of bare ground and area affected by bushfire

Comparing impact versus control sites

For areas where multiple stressors overlap, the true impact of resource development can only be measured by comparing areas that are affected with areas that are not directly affected (control sites). Control sites are ideally those that are almost identical in nature to the sites that are affected (with the same habitat and environmental pressures). In the absence of specific development proposals, it is not possible to provide local advice on which areas would be suitable for impact monitoring and which would be suitable as control sites. At a regional scale, locations where no or few processes lead to pathways of 'potential concern' are prime locations to establish regional control sites. Locations potentially affected by multiple stressors of 'potential concern' are preferred locations to establish regional impact sites. The final location of control and impact sites for any local monitoring design will depend on the location and footprint of the proposed unconventional gas resource development.

Monitoring compliance with and effectiveness of mitigation strategies

Monitoring for compliance evaluates operator adherence to legal requirements. Australian Government and Northern Territory Government regulators monitor this compliance. For example, the *Petroleum (Environment) Regulations 2016* requires reporting against environmental performance standards, the *Monitoring and compliance strategy for onshore petroleum* (DPIR and DENR, 2019) sets out schedules for monitoring of compliance, the Code (Northern Territory Government, 2019c) has specific monitoring requirements for many aspects of resource development and the Australian Government's *Industrial Chemicals Act 2019* requires notification and assessment for the use of industrial chemicals.

Monitoring for effectiveness of specific mitigation strategies to ensure they are achieving their environmental protection objectives is also regulated. For example, Schedule 1 of the *Petroleum (Environment) Regulations 2016* outlines what an environmental management plan must contain, including an implementation strategy where monitoring '…can be audited against the environmental performance standards and measurement criteria specified in the plan…'. This monitoring is done and reported on by the operator, with compliance checks conducted by the regulator. In the causal network, monitoring for effectiveness of mitigation strategies can be identified for the links along pathways. Mitigation strategies are based on existing gas industry controls and regulatory approval conditions, effective planning and design, and adherence to best-practice international standards and procedures. Site management protocols aim to avoid or mitigate potential impacts on natural habitat and species distributions. However, wherever development occurs – particularly in the vicinity of protected species – monitoring of compliance with, and effectiveness of, mitigation strategies associated with activities and stressors is needed. Here, rather than focusing on extrapolating inference to the broader region, the intention is to closely monitor targeted sites at a local level where an impact or change is most likely to occur.

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

Monitoring to validate and refine the causal network

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

FIND MORE INFORMATION

Impact assessment summary for the Beetaloo GBA region

7 Conclusion

7.1 Key findings

For the impact assessment in Stage 3 of the GBA Program, a causal network was used to assess the potential impacts of unconventional gas resource development on water and the environment in the Beetaloo GBA region. This assessment was informed by the Stage 2 baseline synthesis and gap analysis that presented knowledge about the geology, and prospectivity for unconventional gas resources, water resources, protected matters and potential impacts to water and the environment in the Beetaloo GBA region.

The impact assessment identifies pathways of 'very low concern' where impacts are not physically possible or are extremely unlikely (having an estimated probability of less than 1 in 1,000), 'low concern' where impacts can be avoided by current legislation or because the impact does not represent a material change. If impacts can be minimised or mitigated by existing management controls, pathways are evaluated as of 'potential concern'. Impacts from pathways of 'potentially high concern' cannot be avoided or mitigated at the scale of the GBA region (Table 2).

The impact assessment, based on current knowledge, found that there are no pathways of 'potentially high concern' in the Beetaloo GBA region. Furthermore, all potential pathways to impacts due to unconventional gas resource development identified in the Beetaloo GBA region can be mitigated when existing regulatory and management controls are implemented.

The pathways of 'potential concern' are primarily related to activities that create a disturbance at the surface (transport of materials and equipment, civil construction, decommissioning and rehabilitation, and seismic acquisition) (Figure 3, Figure 13). The pathways of 'potential concern' connect these activities with the protected matters, protected fauna and terrestrial vegetation endpoints, reflecting how surface disturbance has the potential to impact these endpoints. These potential impacts are mitigated through environmental management plans that are intended to ensure that appropriate environmental management practices are identified and implemented during the various stages of an activity. There is high confidence that there are mitigation strategies in place for these potential impacts.

Pathways associated with subsurface activities – such as drilling, hydraulic fracturing, production of hydrocarbons – are of 'low concern' or 'very low concern' (Figure 4, Figure 7). The assessment has found stressors of high community concern, such as those involving well integrity or chemical spills, are unlikely to cause material changes to endpoints when existing regulatory and management controls are implemented.

Water extraction

Groundwater is expected to be the source of water for unconventional gas resource development in the Beetaloo GBA region. Conservative groundwater modelling results indicate that it is possible to supply this from the Cambrian Limestone Aquifer without any adverse regional impacts, including to the Roper River or Mataranka Thermal Pools. There is a high degree of confidence for this finding. At a local scale, pathways leading to groundwater drawdown are of 'low concern', except where an extraction bore is situated within 1 km of an existing bore. This impact is mitigated through regulations on the extraction of water within 1 km of an existing water bore. Reductions in spring flow, baseflow and impacts upon groundwater-dependent ecosystems due to groundwater extraction are of 'very low concern'.

Water quality and availability

Surface activities may affect the flow of water by diverting or modifying flow pathways, causing erosion or through sedimentation. Overland flow obstruction and vegetation removal may result in reduced surface water availability or an increase in surface water contamination and is of 'potential concern' to small areas where the activities are conducted in the vicinity of waterways. There is high confidence that mitigation strategies related to civil construction will limit any potential impacts on water-related endpoints.

Conservative chemical transport modelling of spills and leaks due to accidental release leading to unconfined aquifer contamination showed 'potential concern' only where the depth to groundwater is less than 14 m, which only occurs in very limited parts of the Beetaloo GBA region. Accidental release, which requires a spill to enter the environment beyond containment, is of 'potential concern' for water-related endpoints if a spill reaches them. However, evidence suggests that accidental releases of material volumes are very unlikely because of existing avoidance and mitigation strategies.

As the disposal of hydraulic fracturing waste to surface water or groundwater is prohibited in the Northern Territory, it is not possible for controlled release of wastewater from hydraulic fracturing activities to generate impacts on surface water or aquifers. Stringent approval and management requirements, including national guidelines, Northern Territory Government regulations and industry waste management plans, mean that contamination due to waste disposal is of 'low concern' in the Beetaloo GBA region.

Aquifer contamination due to creation of new fractures or widening of existing faults or factures (compromised subsurface integrity) is of 'low concern' to 'very low concern' throughout the Beetaloo GBA region except in the area where the Hayfield sandstone member is prospective. In that case, there is potential for development to impact on confined aquifers, below the Cambrian Limestone Aquifer, that can be mitigated through existing engineering controls.

Environment

Terrestrial vegetation (predominantly rain-fed open woodlands) dominates the Beetaloo GBA region. Activities at the surface such as civil construction, seismic acquisition, transport of materials and equipment and decommissioning and rehabilitation (Figure 13) may cause material changes in vegetation extent and condition. Certain pathways are of 'potential concern' and warrant more detailed, local-scale assessment, in particular, those pathways involving invasive plants and insects, vegetation removal and vehicle movement leading to impacts on environment and fauna endpoints. Existing management controls can avoid and mitigate these potential impacts.

The Beetaloo GBA extended region has small areas of wetlands (3%) and riparian vegetation (2%) that have high ecological value and are habitat for many species. The key potential impacts for wetland condition and riparian vegetation extent and condition are from civil construction (for example, roads, well pads or storage tanks) and any activity that requires vehicle movement beyond designated roads, such as seismic acquisition. However, the likelihood of impacts in these ecosystems are mitigated by limiting the amount of activity that occurs within them.

Protected fauna

From north to south in the Beetaloo GBA region the climate changes from tropical to semi-arid. Tropical savanna species are found in the north (for example, the Gouldian finch) and typical Australian desert species in the south (for example, the greater bilby). As the region becomes more widely surveyed, more species are expected to be added to biodiversity records. Any decline in persistence of the 6 species assessed is assumed to be material.

Water controls the ecology and movements of the 6 protected fauna quite differently. Pathways of 'potential concern' between activities and the protected fauna species are primarily related to activities that create a disturbance at the surface (civil construction, decommissioning and rehabilitation, transport of materials and equipment, and seismic acquisition, Figure 13). The pathways of 'potential concern' connect these activities with key stressors, namely invasive plants and animals and vegetation removal, resulting in mortality of native species and habitat degradation, fragmentation and loss. Common processes within these pathways that are of 'potential concern' are competition and predation, and ecosystem burning.

Causal network for the Beetaloo GBA region

The causal network illustrates the complex and interconnected nature of the natural environment and unconventional gas resource development activities in the region to be assessed (Figure 5, Figure 6). The network allows evaluation of how undertaking these activities may cause potential stress on the environment. The evaluation considers how the existing regulatory controls and operational practices can mitigate potential impacts. Mitigation and management practices are most effective at the activity–to–stressor step of a causal pathway, whereas links from stressors to natural processes and from natural processes to endpoints are often difficult, if not impossible, to mitigate.

The causal network assessment is supported by the systematic and transparent evaluation of confidence. Confidence in the assessment is generally high where the available knowledge base supports the (i) cause-and-effect relationship, (ii) threshold of material change and (iii) availability or effectiveness of mitigation strategies along a pathway. Where there is insufficient knowledge to support a robust and meaningful evaluation of the cause-and-effect relationship or threshold of material change, the precautionary principle is applied so that uncertainty about potentially serious hazards does not lead to underestimation of impacts. Potential impacts to water and the environment from unconventional gas resource development are identified but only adverse impacts are assessed.

A key assumption in the causal network assessment is that the complex ecological and hydrological systems in the region are adequately represented by the causal network. An advantage of the causal network is that it allows experts in unconventional gas resource development activities, environmental risk assessment, ecology, geology and hydrology to interact in a common framework. This reduces the chance of omission of important parts of the assessed system. The causal network for the Beetaloo GBA region has 62 nodes, connected by 197 links, with 2,078 causal pathways.

The causal network for the Beetaloo GBA region uses a development scenario to provide activity- or scale-dependent inputs to the network. The scenario assumes peak production of 365 petajoules per year (or 1,000 terajoules per day), over a 25-year time period, with a maximum of 1,150 wells (at 4 to 10 wells per pad). The estimated maximum area disturbed in this scenario by access tracks and well pads is between 8 and 35 km^2, contained within an area between 430 and 7,700 km^2. This scenario would require 21 to 46 gigaliters of water over the 25-year time period, based on an estimate of 40 megalitres for drilling and hydraulic fracturing per well. The impact assessment for the Beetaloo GBA region considers activities associated with the development and production of unconventional gas resources in a generic way and at a regional scale for the duration of the development scenario.

Using causal networks for impact assessment

The causal network approach to environmental impact assessment provides a comprehensive and clearly identified set of deduced direct and indirect pathways where unconventional gas resource development activities may impact on environmental values (endpoints in the network). Consistent and systematic evaluation of likelihood, consequence and mitigation strategies allows integration of qualitative and quantitative information, even when the available knowledge base is limited. The evaluation of the causal network is based on the understanding of the individual nodes and the links between them. All nodes and links are evaluated independently and individually before being combined to assess the pathways between development activities and the endpoints. Detailed context, evaluation and assessment accessed in GBA Explorer produce a robust assessment and improve objectivity. Changes in knowledge can be incorporated in the causal network. The assessment is a spatial evaluation, allowing areas where impacts on water and the environment are unlikely to be identified, as well as where potential impacts cannot be ruled out.

GBA Explorer

The GBA Program has developed an innovative way to allow stakeholders to visualise and interact with the assessments' evidence base and evaluations; through the GBA Explorer. This unique tool allows the possibility for the causal network and its assessment to be readily updated as new information becomes available.

Mitigation

Mitigation of potential impacts identified in the causal network assessment occurs through environmental management practices (for example, activity-specific Environmental Management Plans required under the *Petroleum Act 1984* (NT)). Environmental Management Plans are intended to ensure that appropriate environmental management practices are identified and implemented during the various stages of an activity. Once approved, an Environmental Management Plan becomes an enforceable or statutory document. The Environmental Management Plan must also incorporate the requirements prescribed in the Code (Northern Territory Government, 2019c). Additional regulation of petroleum activities, particularly related to drilling and hydraulic fracturing operations, are contained in the *Schedule of Onshore Petroleum Exploration and Production Requirements* (Northern Territory Government, 2019a). For example, Well Operations Management Plans that include requirements to identify and manage well integrity risks throughout the life of a well. Well Operations Management Plans must also incorporate the requirements prescribed in the Code (Northern Territory Government, 2019c).

In the impact assessment these environmental management requirements for mitigation, along with those required through other Northern Territory Government and Australian Government regulatory instruments, and industry practices, were used when evaluating the cause-and-effect relationships. There is a high degree of confidence in the overall assessment that there are no causal pathways in the Beetaloo GBA region that cannot be mitigated.

7.2 Knowledge gaps and limitations

At a point in time where industry is still building its understanding of the unconventional gas resources in the Beetaloo GBA region, distinct characteristics of any future development, and potential impacts on water and the environment, cannot be known. Using a causal network to assess impacts (Section 3.1) helps to address some of this uncertainty and increase understanding of the potential implications of development. However, knowledge gaps do remain. These range from overarching knowledge gaps about the resource development through to specific knowledge gaps about aspects of activities, stressors, processes and endpoints, and the links between them.

Overarching knowledge gaps

The overarching knowledge gaps relate to the lack of certainty about what a future resource development entails and the associated impacts to water and the environment, particularly at a local scale. The aspects of resource development where there are significant knowledge gaps are:

- The scale, location and timing of future development. Economic viability for industry dictates that the scale must warrant the level of infrastructure investment required to connect the resource to market (such as production of hundreds of terajoules per day with hundreds of wells over the development lifetime). Location will influence the environmental, economic, cultural and social values with which development potentially interacts. The timing of future development influences rate-dependent potential impacts, such as water use and rates of vegetation removal.
- The characteristics and impacts of drilling and hydraulic fracturing activities that are ultimately used in a development. These technologies will depend on the nature of the resource and the decisions made by operators. The overall footprint of the development and amount of water used will be influenced by the development approach.
- Future interactions with other industries. High-resolution quantitative information on both the state of the environment and the processes acting on the landscape is needed to assess interactions with other drivers of system change (for example, agriculture, tourism, infrastructure development and climate change), which are not in scope for this assessment.
- How thresholds of material change will be altered due to any modification to the environment and ecological processes due to climate change.

Other aspects of the impact assessment where there are overarching knowledge gaps relate to the baseline for environmental values. The current understanding of all aspects of the ecosystems of the Beetaloo GBA region is limited; for example, which native species occur in the Beetaloo GBA region, where and how they use the area, and how these species respond to and interact with each other, invasive species and other potential stressors. These knowledge gaps will be partly addressed by the baseline ecological and groundwater information that is being collected by the Northern Territory Government's Strategic Regional Environmental and Baseline Assessment program.

The nature of these overarching knowledge gaps primarily relates to the specifics of future development. Most, if not all, gaps will be addressed via project-specific environmental impact assessments required by the *Environmental Assessment Act 1982* (NT). The causal network and causal pathways, along with the knowledge gaps identified, may provide useful input into the terms of reference for these.

Specific knowledge gaps

Specific knowledge gaps are recorded in the descriptions of the nodes and links of the causal network. The evaluation of each link in a causal pathway is based on best available data and knowledge. There are cause-and-effect relationships in the network for which the knowledge base is limited. This can pertain to limited data on the cause-and-effect relationship itself, its direction, the existence of any potential 'tipping points' for thresholds where the relationship suddenly alters markedly, the definition of material change, or the availability or effectiveness of mitigation strategies. This uncertainty is captured in the confidence score assigned to each link, as well as the confidence in the existence of the link, its materiality and the effectiveness of mitigation methods, reflecting the knowledge base underpinning the evaluation

Specific knowledge gaps relating to extraction of unconventional gas resources include the following:

- It is not known what chemicals will be used in future petroleum activities as the technology in this area develops. There are also aspects of ecotoxicity and the fate of chemicals in the environment that are not fully understood. As more knowledge becomes available more sophisticated approaches to understanding potential impacts of chemicals could be used than the conservative modelling used in this assessment.
- Information on how a single spill at a local scale impacts a protected matter over a large scale (for example, species population persistence and fitness or wetland health). New data and information may potentially change thresholds of material change for species or functional groups of species.

There are also specific knowledge gaps related to the understanding of ecological processes and how sensitive they are to the stressors that may be imposed on them by resource development activities. They include:

- Understanding of the occurrence and distribution for water, environment and protected matters endpoints in the Beetaloo GBA region. From a biodiversity perspective, the region is one of the least surveyed in Australia. The Beetaloo GBA region Strategic Regional Environmental and Baseline Assessment studies should provide much of this baseline information.
- The characteristics of groundwater resources below the Cambrian Limestone Aquifer are not well understood. Improving this knowledge will assist in understanding its suitability as a water supply and for any potential connections between these groundwater resources and the Cambrian Limestone Aquifer.
- Habitat requirements of species, including activities (for example, breeding and foraging), are not fully understood. The impact of seemingly minor stressors (for example, noise and light pollution) on suitability of critical habitat for specific species is not known in the Beetaloo GBA region. Additional knowledge would allow nuanced assessment of the impacts of these stressors on critical habitat.

- Estimates of the population size of species in the Beetaloo GBA region and how that varies seasonally, interannually and over time. This is baseline information that will assist in determining potential impact from future resource development activities. Demographic data have been identified as being an important knowledge gap for Gouldian finch and Gulf snapping turtle.
- The reliance of certain species on surface water, how much and when, and the water quality required.
- Understanding of the potential impacts of changes in fire regime resulting from a future unconventional gas resource development. A better understanding of optimum fire management, particularly for Gouldian finch, crested shrike-tit (northern) and greater bilby is required.
- The role of artificial water sources from unconventional gas resource development in increasing predation by invasive carnivores. The key questions are whether predation by introduced carnivores is a threat for each species and, if so, whether this threat is facilitated by the presence of artificial water sources and what are the options for mitigation.

Limitations

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

- Non-linear effects or time-varying cause-and-effect relationships that capture the boom-and-bust dynamics of a region. It is a complicated exercise to represent the complex reality of ecological and hydrological systems in a directional acyclic graph (the graphical causal network, Figure 6). One of the most challenging aspects is that feedback loops cannot be represented. Feedback loops are an essential feature of complex natural systems. When represented in a graph, however, it is no longer possible to unequivocally establish causal pathways between starting and ending nodes.
- Adverse impacts and benefits. In line with guidelines under the EPBC Act (Commonwealth of Australia, 2013a), where an action may have both adverse and beneficial impacts, only adverse impacts are assessed. However, positive effects are also evident. For example, while new roads in a landscape may increase bushfires due to an increased likelihood of accidental ignition, roads can also act as firebreaks, limiting the spread of bushfires. To determine net benefits of an action, a more quantitative estimate of the likelihood and magnitude of positive and negative effects is needed.
- Ecological, economic and/or social values to be protected. Environmental values are represented in the assessment by key ecological and hydrological systems in the Beetaloo GBA region. The 6 protected fauna listed under territory or national legislation were prioritised for assessment based on the importance of the Beetaloo GBA region to the continued persistence of each species. However, while the assessment takes a values-based perspective, more detailed assessment of potential impacts on cultural heritage values are beyond the scope of the GBA Program and are not directly represented in the causal network.

- Cumulative impacts of multiple stressors from multiple industries. Future studies could extend the causal network to other industries, such as pastoralism or tourism, to assess the impacts of multiple activities and stressors on processes and endpoints. A quantitative assessment of the magnitude and likelihood of cumulative impacts is not possible without detailed baseline and future development scenarios.
- Ecological processes and interactions. Links between activities, stressors, processes and endpoints are unable to capture all of the nuance of more detailed ecological conceptual models, which may cause unintended assessment outcomes.

7.3 Opportunities

This assessment has identified that activities that create a disturbance at the surface (transport of materials and equipment, civil construction, decommissioning and rehabilitation and seismic acquisition) lead to a number of pathways of 'potential concern'. While the assessment has identified that the impacts from these activities can be mitigated, there may be opportunities to look at ways to further minimise and/or mitigate these impacts from these causal pathways. For example, industry relevant application of *Land clearing guidelines* and coordinated industry-wide approaches to the management of invasive species.

Other opportunities that arise from this assessment are related to the knowledge gaps and limitations that have been identified. The causal network can be updated for the Beetaloo GBA region as more knowledge becomes available through:

- The baseline ecological surveys conducted through the additional GBA funding provided (Section 5).
- The Northern Territory Government's Strategic Regional Environmental and Baseline Assessment program that is collecting baseline ecological, surface water and groundwater information.
- Provision of information from ongoing exploration and appraisal activities by industry to understand resource potential, develop prospective resource estimates, identify areas most likely to be developed, and investigate extraction technologies. Thereby, improving the understanding of future resource development scenarios and their footprints.
- As more hydraulic fracturing operations are conducted, the probable designs of future hydraulic fracturing operations (including fluid composition and volumes) and the amounts of flowback fluid and its quality will be better understood. This has important implications for overall water use and wastewater management options
- The results of research conducted by programs such as the CSIRO's Gas Industry Social and Environmental Research Alliance that may be relevant to adding to the causal network.

The Strategic Regional Environmental and Baseline Assessment program ecological baseline data will be useful in helping to further differentiate the landscape classes and vegetation communities within the Beetaloo GBA region. A better understanding of the importance of these vegetation communities to habitat requirements is likely to emerge from these baseline surveys. This would allow refinement of the assessment of the causal pathways of 'potential concern' identified in this assessment.

The causal network could be further refined to consider various scenarios. These could include:

- Further differentiation of the various phases in the gas resource development life cycle. While this assessment considers all phases, the causal network could be refined to consider each phase separately.
- Evaluation of the causal network considering different climatic or weather conditions. For example, considering the effects of climate change, comparing the impacts during drier and wetter periods.
- Consideration of regional cumulative impacts by incorporating the activities of other industries (for example tourism, large-scale solar and pastoralism).

The assessment focused on the types of events and impacts that happen as a normal part of unconventional gas resource development. While this assessment did consider accidents and inadvertent incidents, it did not consider low-likelihood, high-consequence events. Examples of these are a major well blowout, a catastrophic failure at a processing plant, the impacts of a cyclonic weather event, or major pipeline failure. Assessing these events would require a significant amount of speculation about the specifics of the infrastructure and the environmental setting. Risk assessments for low-likelihood, high-consequence events are a routine component of infrastructure design – due to the risk to human life and financial impacts – the causal network method could be applied for assessment of the environmental impacts of these events.

The conservative modelling of the fate of chemicals in the environment used in this assessment could be augmented by more detailed assessment. Further consideration of how chemicals break down in the environmental conditions found in the Beetaloo GBA region would increase confidence in the assessment of the risks these chemicals pose.

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

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

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Glossary

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

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

activity: for the purposes of geological and bioregional assessments, an activity is a planned event associated with unconventional gas resource development. For example, activities during the exploration life-cycle stage include drilling and coring, ground-based geophysics and surface core testing.

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

asset: an entity that has value to the community and, for the purposes of geological and bioregional assessments, is associated with a GBA region. An asset is a store of value and may be managed and/or used to maintain and/or produce further value. An asset may have many values associated with it that can be measured from a range of perspectives; for example, the values of a wetland can be measured from ecological, sociocultural and economic perspectives.

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

baseflow: the portion of streamflow that comes from shallow and deep subsurface flow, and is an important part of the groundwater system

bed: in geosciences, the term 'bed' refers to a layer of sediment or sedimentary rock, or stratum. A bed is the smallest stratigraphic unit, generally a centimetre or more in thickness. To be labelled a bed, the stratum must be distinguishable from adjacent beds.

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

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

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

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

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

conceptual model: an abstraction or simplification of reality that describes the most important components and processes of natural and/or anthropogenic systems, and their response to interactions with extrinsic activities or stressors. They provide a transparent and general representation of how complex systems work, and identify gaps or differences in understanding. They are often used as the basis for further modelling, form an important backdrop for assessment and evaluation, and typically have a key role in communication. Conceptual models may take many forms, including descriptive, influence diagrams and pictorial representations.

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

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

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

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

conventional gas: conventional gas is obtained from reservoirs that largely consist of porous sandstone formations capped by impermeable rock, with the gas trapped by buoyancy. The gas can often move to the surface through the gas wells without the need to pump.

cumulative impact: for the purposes of geological and bioregional assessments, total impact on endpoints from multiple stressors, and their interactions, due to multiple developments in multiple industries.

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

depocentre: an area or site of maximum deposition; the thickest part of any specified stratigraphic unit in a depositional basin.

development: a phase in which newly discovered oil or gas fields are put into production by drilling and completing production wells.

dome: a type of anticline where rocks are folded into the shape of an inverted bowl. Strata in a dome dip outward and downward in all directions from a central area.

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

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

dry gas: natural gas that is dominated by methane (greater than 95% by volume) with little or no condensate or liquid hydrocarbons

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

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

endpoint: for the purposes of geological and bioregional assessments, an endpoint is a value pertaining to water and the environment that may be impacted by development of unconventional gas resources. Endpoints include assessment endpoints – explicit expressions of the ecological, economic and/or social values to be protected – and measurement endpoints – measurable characteristics or indicators that may be extrapolated to an assessment endpoint as part of the impact and risk assessment.

erosion: the wearing away of soil and rock by weathering, mass wasting, and the action of streams, glaciers, waves, wind, and underground water.

exploration: the search for new hydrocarbon resources by improving geological and prospectivity understanding of an area and/or play through data acquisition, data analysis and interpretation. Exploration may include desktop studies, field mapping, seismic or other geophysical surveys, and drilling.

extraction: the removal of water for use from waterways or aquifers (including storages) by pumping or gravity channels. In the oil and gas industry, extraction refers to the removal of oil and gas from their reservoir rock.

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 clean up 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 start up of production.

flowback water: the fluids and entrained solids that emerge from a well during flowback.

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

fracture: a crack or surface of breakage within rock not related to foliation or cleavage in metamorphic rock along which there has been no movement. A fracture along which there has been displacement is a fault. When walls of a fracture have moved only normal to each other, the fracture is called a joint. Fractures can enhance permeability of rocks greatly by connecting pores together and for that reason, fractures are induced mechanically in some reservoirs in order to boost hydrocarbon flow. Fractures may also be referred to as natural fractures to distinguish them from fractures induced as part of a reservoir stimulation or drilling operation. In some shale reservoirs, natural fractures improve production by enhancing effective permeability. In other cases, natural fractures can complicate reservoir stimulation.

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.

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

hydraulic fracturing: also known as 'fracking', 'fraccing' or 'fracture simulation'. This is a process by which geological formations bearing hydrocarbons (oil and gas) are stimulated to increase the flow of hydrocarbons and other fluids towards the well. In most cases, hydraulic fracturing is undertaken where the permeability of the formation is initially insufficient to support sustained flow of gas. The process involves the injection of fluids, proppant and additives under high pressure into a geological formation to create a conductive fracture. The fracture extends from the well into the production interval, creating a pathway through which oil or gas is transported to the well.

hydraulic fracturing fluid: the fluid injected into a well for hydraulic fracturing. Consists of a primary carrier fluid (usually water or a gel), a proppant such as sand and chemicals to modify the fluid properties.

hydrocarbons: various organic compounds composed of hydrogen and carbon atoms that can exist as solids, liquids or gases. Sometimes this term is used loosely to refer to petroleum.

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

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

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

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

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

likelihood: the chance that something might happen.

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

marl: a sedimentary rock containing calcareous clay

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

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

mudstone: a general term for sedimentary rock made up of clay-sized particles, typically massive and not fissile

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

operator: the company or individual responsible for managing an exploration, development or production operation

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

play: a conceptual model for a style of hydrocarbon accumulation used during exploration to develop prospects in a basin, region or trend and used by development personnel to continue exploiting a given trend. A play (or group of interrelated plays) generally occurs in a single petroleum system.

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

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

production: in petroleum resource assessments, ‘production’ refers to the cumulative quantity of oil and natural gas that has been recovered already (by a specified date). This is primarily output from operations that has already been produced.

recharge: see groundwater recharge.

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.

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

risk: the effect of uncertainty on objectives (AS/NZS ISO 31000:2009). This involves assessing the potential consequences and likelihood of impacts to environmental and human values that may stem from an action, under the uncertainty caused by variability and incomplete knowledge of the system of interest.

sandstone: a sedimentary rock composed of sand-sized particles (measuring 0.05–2.0 mm in diameter), typically quartz.

sediment: various materials deposited by water, wind or glacial ice, or by precipitation from water by chemical or biological action (for example, clay, sand and carbonate).

sedimentary rock: a rock formed by lithification of sediment transported or precipitated at the Earth's surface and accumulated in layers. These rocks can contain fragments of older rock transported and deposited by water, air or ice, chemical rocks formed by precipitation from solution, and remains of plants and animals.

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.

shale: a fine-grained sedimentary rock formed by lithification of mud that is fissile or fractures easily along bedding planes and is dominated by clay-sized particles.

shale gas: generally extracted from a clay-rich sedimentary rock, which has naturally low permeability. The gas it contains is either adsorbed or in a free state in the pores of the rock.

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

stress: the force applied to a body that can result in deformation or strain, usually described in terms of magnitude per unit of area, or intensity.

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

structure: a geological feature produced by deformation of the Earth's crust, such as a fold or a fault; a feature within a rock, such as a fracture or bedding surface; or, more generally, the spatial arrangement of rocks.

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

tight gas: tight gas is trapped in reservoirs characterised by very low porosity and permeability. The rock pores that contain the gas are minuscule and the interconnections between them are so limited that the gas can only migrate through it with great difficulty.

toxicity: inherent property of an agent to cause an adverse biological effect.

trap: a geologic feature that permits an accumulation of liquid or gas (e.g. natural gas, water, oil, injected 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.

unconventional gas: unconventional gas is generally produced from complex geological systems that prevent or significantly limit the migration of gas and require innovative technological solutions for extraction. There are numerous types of unconventional gas such as coal seam gas, deep coal gas, shale gas and tight gas.

water allocation: the specific volume of water allocated to water access entitlements in a given season, defined according to rules established in the relevant water plan.

water 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.

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

well barrier: envelope of one or several dependent barrier elements (including casing, cement, and any other downhole or surface sealing components) that prevent fluids from flowing unintentionally between a bore or a well and geological formations, between geological formations or to the surface.

well integrity: maintaining full control of fluids (or gases) within a well at all times by employing and maintaining one or more well barriers to prevent unintended fluid (gas or liquid) movement between formations with different pressure regimes, or loss of containment to the environment

well pad: the area of land on which the surface infrastructure for drilling and hydraulic fracturing operations are placed. The size of a well pad depends on the type of operation (for example, well pads are larger during the initial drilling and hydraulic fracturing than at production).

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

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- Geoscience Australia – Merrie-Ellen Gunning, Steven Lewis, David Robinson, Baskaran Sundaram.

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Northern Territory Government Science Technical Review:

- Northern Territory Department of Environment, Parks and Water Security and Northern Territory Department of Industry, Tourism and Trade

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Back cover credit: Grassland on the dry northern bed of Lake Woods © Jenny Davis, Charles Darwin University

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