



Advice on unconventional gas

IESC 2024-150: Beetaloo Basin – Unconventional gas exploration and appraisal

Requesting agency	The Australian Government Minister for the Environment and Water
Date of request	5 July 2024
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Advice stage	Advice request

The Independent Expert Scientific Committee on Unconventional Gas Development and Large Coal Mining Development (the IESC) provides independent, expert, scientific advice to the Australian and state government regulators on the potential impacts of unconventional gas and large coal mining proposals on water resources. The advice is designed to ensure that decisions by regulators on unconventional gas or large coal mining developments are informed by the best available science.

The IESC was requested by the Australian Government Minister for the Environment and Water to provide advice on the potential impacts and/or risks to water resources and water-dependent matters of national environmental significance arising from potential unconventional gas exploration and appraisal activities in the Beetaloo Basin, Northern Territory. This advice draws upon available documentation, data and methodologies, together with the expert deliberations of the IESC.

Plain English summary

Exploration and appraisal activities for unconventional gas may expand in the Beetaloo Basin, Northern Territory, likely leading to production. There is concern about the implications of these activities for surface waters, groundwaters and water-dependent plants and animals, some of which are Matters of National Environmental Significance.

Much of the Basin is semi-arid and lacks permanent surface water. However, important groundwater-dependent ecosystems occur in the region, such as the Roper River, Mataranka Springs and numerous springs and perched aquifers.

In July 2024, the Minister for the Environment and Water requested scientific advice from the Independent Expert Scientific Committee on Unconventional Gas Development and Large Coal Mining Development (the IESC) about the potential nature, extent and cumulative impacts of exploration and appraisal activities for unconventional gas on the Basin's water resources.

The IESC considers that the key potential impacts from these activities are loss and fragmentation of native vegetation and altered surface runoff (mainly from constructing access roads to well pads), and groundwater drawdown caused by wells supplying groundwater for use in hydraulic fracturing. Impacts may also arise from accidental spills of chemicals or flowback wastewaters, failure of well integrity and the spread of invasive species. Hydraulic fracturing of the deep shales for exploration and appraisal is not considered to be a major risk to the Basin's groundwaters if conducted according to industry best practice.

Providing mitigation strategies are adopted and correctly implemented, the IESC considers that the potential impacts on the Basin's water resources from initial exploration and appraisal activities for unconventional gas are minor. However, these activities will likely lead to further production, exploration and appraisal which will inevitably intensify impacts, along with those from current and proposed land-uses such as irrigated agriculture (e.g. cotton, mangoes) and from climate change.

Preliminary regional surveys have been undertaken of the Basin's water resources and its native plants and animals but substantial gaps still exist in our knowledge about how these may respond to impacts from unconventional gas development. Detailed local-scale environmental studies are needed to ensure adequate understanding and protection of the Basin's surface and groundwater water resources in areas where unconventional gas development is planned.

Summary

On 5 July 2024, the Minister for the Environment and Water requested scientific advice from the Independent Expert Scientific Committee on Unconventional Gas Development and Large Coal Mining Development (the IESC) on potential impacts and/or risks to water resources and water-dependent Matters of National Environmental Significance (MNES) arising from unconventional gas exploration and appraisal activities in the Beetaloo Basin, Northern Territory. The Minister also requested advice on potential cumulative impacts of these activities and what material gaps exist in current scientific understanding of the Basin that affected the IESC's ability to provide advice.

The IESC notes that the scope of this request is solely on 'exploration and appraisal activities' but considers that subsequent activities associated with production (if approved) would lead to additional impacts not considered here. As in all advice previously provided by the IESC, the term "water resources" is defined as per the *Water Act 2007* (Commonwealth of Australia 2007) and is used here to include all groundwaters and surface waters (permanent and ephemeral), including their organisms, water quality and associated water-dependent ecosystems.

In the context of this advice, the Beetaloo Basin refers to the 86,400-km² Beetaloo Biophysical Study Area (BBSA) used for the Strategic Regional Environmental and Baseline Assessment (SREBA) (DEPWS 2022). This area encompasses known reserves of unconventional gas (the 28,000-km² Beetaloo Sub-basin and 'eastern depocentre'), several catchments (e.g. Lake Woods, southern catchment of the Roper River) and various groundwater-dependent ecosystems (GDEs).

The BBSA is centred around Daly Waters, some 600 km south-east of Darwin (Figure 1). Mean annual rainfall declines from approximately 1,200 mm in the tropical north to approximately 500 mm in the semi-arid south (DEPWS 2022, pp. 11-12) which creates a north-south gradient of decreasing permanence of surface waters and rain-fed groundwater recharge. Regional groundwater occurs within the Cambrian Limestone Aquifer (CLA) (classified as karst in the north) which flows from the southern BBSA north-west to discharge into rivers to the north (e.g. the Roper and Flora rivers, DEPWS 2022, p. 66). Other aquifers occur in strata above and below the CLA, either as localised perched aquifers near the ground surface or as fractured rock (e.g. Antrim Plateau Volcanics) or sandstone (e.g. Bukulara Sandstone) aquifers below the CLA (DEPWS 2022, p. 42). The Mesoproterozoic shales targeted by unconventional gas exploration

are deeper (> 2000 m); in most areas, they are separated from the CLA by one or more aquitards, but there are locations where there is evidence of connection (DEPWS 2022, pp. 63-65).

The surface waters of the BBSA can be broadly divided into (i) largely ephemeral systems in the southern region that drain into Newcastle Creek and ultimately into Lake Woods and (ii) waterways in the north with ephemeral upper reaches but groundwater-fed perennial lower reaches and springs that typically provide diverse aquatic and riparian ecosystems that support MNES species such as Gulf Snapping Turtle (*Eseya lavarackorum*), Largetooth Sawfish (*Pristis pristis*) (DEPWS 2022, p. 272) and Speartooth Shark (*Glyphis glyphis*) (Constance et al. 2024).

To address the Minister's questions, the IESC developed indicative Impact Pathway Diagrams (IPDs) (Commonwealth of Australia 2024) that illustrate how activities associated with exploration and appraisal may impact key water resources. Separate IPDs were derived for sites in the southern and northern parts of the Basin to capture the latitudinal differences in ecohydrology described above. Estimates of the likelihood and consequence of each pathway, the two broad components of risk, are also portrayed on the IPDs.

The IESC has carefully considered the risks to water resources in the Beetaloo Basin from hydraulic fracturing of deep shales during exploration and appraisal, and concludes that infrastructure, transport and surface operations represent greater risks.

Key potential impacts from exploration and appraisal activities in the **southern region** include:

- vegetation removal for new infrastructure (e.g. roads, well pads, temporary accommodation) which may (i) directly impact water-dependent vegetation, (ii) alter catchment drainage and surface runoff patterns, impacting the water regime, water quality and biota of ephemeral reaches of Newcastle Creek and other waterways, including permanent and semi-permanent refugial waters (e.g. Longreach Waterhole) and (iii) promote habitat fragmentation and loss that may reduce the condition and/or persistence of populations of dependent wildlife, impact surface runoff and water quality, alter erosion rates and fire regimes and promote the spread of invasive species;
- alteration of surface water runoff and drainage patterns by roads and seismic lines which may impact the water regime, water quality and biota of ephemeral reaches of Newcastle Creek and other waterways, including permanent and semi-permanent refugial waters (e.g. Longreach Waterhole); and
- in the event of a hazardous chemical or flowback wastewater spill near a waterway or refugial waterhole, impacts on water quality and aquatic and riparian biota.

Key potential impacts from exploration and appraisal activities in the **northern region** include:

- vegetation removal for infrastructure which may (i) directly impact terrestrial GDEs (e.g. *Melaleuca* forests) and other water-dependent vegetation, (ii) alter the water regime, water quality and biota of ephemeral waterways (e.g. Birdum and Western creeks), refugial waters (e.g. permanent waterholes in Western Creek) and aquatic GDEs (e.g. groundwater-fed reaches of the Roper River) and (iii) promote habitat fragmentation and loss that may impact the condition and/or persistence of populations of dependent wildlife, alter fire regimes and promote the spread of invasive species;
- alteration of surface water runoff and drainage patterns by roads and seismic lines which may affect the water regime, water quality and biota of ephemeral waterways and refugial waters;

- extraction of groundwater for water supply from the CLA for hydraulic fracturing and general usage that will cause groundwater drawdown and changes in groundwater flow rates, potentially impacting the lower reaches of the Roper River and other GDEs; and
- in the event of a hazardous chemical or flowback wastewater spill near a waterway, refugial water or sinkhole connected to the CLA, impacts on water quality, aquatic and riparian biota and/or stygofauna.

Overall, the spatial scales of these different impacts vary from local (< 1 km²) for most activities at a single site (e.g. clearing of vegetation for a single well pad or gravel pit) to broad-scale (> 100 km²) impacts from activities such as construction of extensive roads and multiple well pads, groundwater drawdown (assuming that water for multiple hydraulic fracturing operations is sourced from dedicated water bores), and the collective effects of multiple other activities. Impacts from a large spill of chemicals, waste or flowback wastewater near a flowing river or a sinkhole connected to karst systems may also extend over a large area, depending on the volume of the spill and the extent of impact attenuation with distance from the spill site.

The temporal scales of these different potential impacts vary from short (< 1-5 years) for transient activities such as vegetation clearing for well pads and accommodation to longer term (>100 years) for broad-scale activities, legacy effects of roads that continue to be used, or impacts from spills where the contaminants are particularly persistent and cannot be readily cleaned up.

Collective impacts of exploration and appraisal activities on water resources in the Beetaloo Basin could include altered flow regimes, impaired surface water quality and reduced biodiversity and densities of water-dependent biota in ephemeral waterways; increased risks of reduced groundwater availability and water quality leading to loss of groundwater biota; removal or fragmentation of water-dependent vegetation; and changes to hydrological regimes and water quality of perennial waters and aquatic refuges that affect their physicochemistry, biota and ecological processes. These impacts will interact with other processes such as introduction of invasive species and altered fire regimes.

These collective impacts will add to the cumulative impacts of changes in amounts, seasonality and intensity of rainfall and evaporation arising from climate change, and to the changes associated with existing activities such as pastoral uses, irrigated agriculture and urbanisation, and possible future activities such as solar farms.

Material gaps remain in the current scientific understanding of the hydrology, hydrogeology and other aspects of the Beetaloo Basin that affected the IESC's ability to provide advice on potential impacts, impact pathways and risks associated with exploration and appraisal activities. These include:

- geological and hydrogeological characterisation of the aquitards and aquifers, including their inter-connectivity;
- spatial and temporal dynamics of runoff, surface water flows, groundwater recharge and surface water-groundwater connections and how these affect water resources;
- adequate baseline groundwater and surface water quality data; and
- species composition, distribution, groundwater-dependence and condition of subterranean, aquatic and terrestrial GDEs.

Information is needed on where, how much and when exploration and appraisal activities are likely to occur, and their proximity to surface and subterranean water resources in the Basin. Detailed information is also needed on treatment, transport and disposal of flowback wastewaters.

This advice focuses solely on potential impacts to water resources from exploration and appraisal activities associated with unconventional gas development. It does not extend to other activities (e.g. production, decommissioning) or land-uses, other ecosystems not directly associated with water resources, or other impact pathways such as noise, light or greenhouse gas emissions.

Context

Scope of advice and the IESC's remit

On 5 July 2024, the Minister for the Environment and Water wrote to the Chair of the Independent Expert Scientific Committee on Unconventional Gas Development and Large Coal Mining Development (the IESC) requesting scientific advice from the Committee on the likely nature and scale of potential impacts and/or risks to water resources and water-dependent Matters of National Environmental Significance (MNES) resulting from a program of unconventional gas exploration and appraisal activities in the Beetaloo Basin, Northern Territory. The Minister also requested advice on potential cumulative impacts of these activities and what material gaps existed in the current scientific understanding of the hydrology and hydrogeology of the Beetaloo Basin that affected the IESC's ability to provide advice. Recommendations were sought on the research needed to address these gaps at basin and "site" (local) scales.

It is important to note that this request specifies only the activities undertaken during exploration and appraisal. Exploration is defined as locating producible quantities of gas and characterising the gas reservoir. Appraisal is defined as proving and assessing commercially productive gas reserves and their spatial distribution and composition. The IESC acknowledges that these two activities are likely to lead to production (currently out of scope) if prospectivity is confirmed. Production would intensify many of the potential impacts and risks arising from, for example, groundwater drawdown and transport of chemicals and wastes, and would likely be accompanied over decades by ongoing exploration and appraisal.

Consistent with the IESC's remit (<https://www.iesc.gov.au/>), the request relates to advice on 'water resources', which includes all groundwaters and surface waters (permanent and ephemeral), their organisms, water quality and associated water-dependent ecosystems (*Water Act 2007*). The IESC is not a regulatory body and does not decide which projects should proceed or how they should be regulated.

The following advice is a high-level, independent, scientific assessment of the risks of potential impacts on the Basin's water resources from activities associated with exploration and appraisal for unconventional gas and does not address any specific current or proposed projects. Material gaps in the information needed to fully assess these risks (see response to Question 3 below) hamper Basin-scale assessments of these potential impacts and so the IESC has used Impact Pathway Diagrams (described below) to infer and illustrate likely pathways and the nature of their impacts. Although this approach is a useful initial step, the IESC acknowledges that the predictions drawn from these diagrams will not apply to all locations across the Basin and that the likelihood and consequences of particular pathways will vary in space and time. These caveats are discussed in more detail below.

Ecohydrological context

For this advice, the spatial extent of the Beetaloo Basin is considered to comprise the 86,400-km² Beetaloo Biophysical Study Area (BBSA, Figure 1) used for the Strategic Regional Environmental and Baseline Assessment (SREBA, DEPWS 2022). This area encompasses the known reserves of unconventional gas (the 28,000-km² Beetaloo Sub-basin and 'eastern depocentre'), several surface-water catchments (e.g. Lake Woods, southern catchment of the Roper River) and various groundwater-dependent ecosystems (GDEs). The GDEs include springs and perennial river reaches which are likely to be surface expressions of aquifers overlying the prospective gas basins (DEPWS 2022, p. 38).

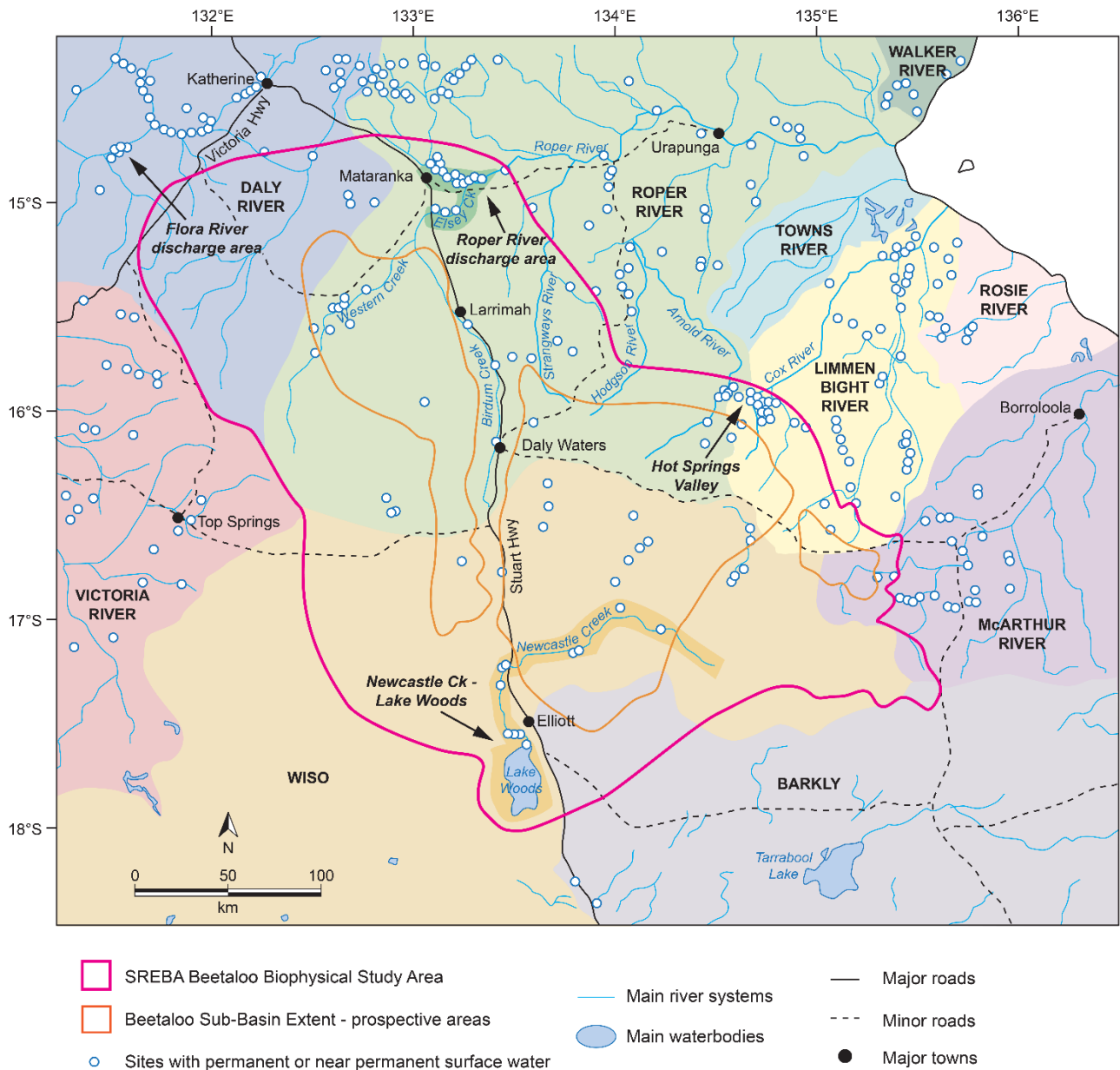


Figure 1. The Beetaloo Basin (represented by the SREBA's Beetaloo Biophysical Study Area (BBSA) in this advice). Different colours depict the surface water catchments labelled in upper case (e.g. BARKLY). Figure adapted from Figure 3-1, Figure 4-21, Figure 5-3 and Figure 10-3 in DEPWS (2022).

The BBSA is centred around Daly Waters, some 600 km south-east of Darwin (Figure 1). Mean annual rainfall declines from approximately 1,200 mm in the Wet-Dry tropical north to approximately 500 mm in the semi-arid south (DEPWS 2022, pp. 11-12), resulting in more permanent surface waters and higher rain-fed groundwater recharge in the north than the south.

Vegetation composition varies across the BBSA following the north-south rainfall gradient, with additional influences from soil type, grazing and fire regime (Young et al. 2022, p. 5). Five broad vegetation groups in the BBSA have high ecological value: three in the north, which are also groundwater-dependent (*Monsoon forest and thicket (riparian rainforest)*, *Melaleuca forests* and *Riparian woodland*), and two more widely distributed ones (*Ephemeral wetland* and *Lignum shrubland*) (Young et al. 2022, p. 6).

Pastoralism, the main industry to date, has not required large-scale clearing of savanna woodland across this region.

Most surface water drainages in the BBSA are ephemeral, particularly to the south and within the Beetaloo Sub-basin. Several of these ephemeral waterways have semi-permanent or permanent pools (e.g. Longreach Waterhole in Newcastle Creek), which provide vital refuges for aquatic biota and key water sources for nearby water-dependent plants and animals. 'Run-on' areas adjacent to ephemeral waterways are flooded after heavy rain and often support distinct vegetation and biodiversity values (DEPWS 2022, p. 162). This area is characterised by a 'boom-and-bust' ecology (Kingsford et al. 1999, Sheldon et al. 2010).

In the northern BBSA, groundwater from aquifers overlying the prospective gas basins provides perennial flows in the lower reaches of the Roper and Flora rivers (DEPWS 2022, p. 12), while their upper reaches are ephemeral. Groundwater-fed springs also occur in the western, northern and eastern margins of the BBSA (Figure 1), many supporting species-rich aquatic ecosystems and fringing vegetation.

The most important groundwater system in the study area is the Cambrian Limestone Aquifer (CLA). This vast, multilayered system includes the Daly, Wiso and Georgina geological basins. In the north, the CLA hosts a highly connected karst system (Tindall Limestone Aquifer). It is the main source of groundwater for extractive use in the region (DEPWS 2022, p. 42). Groundwater in the CLA flows north-west from the southern Beetaloo Basin to discharge into the Flora, Daly and Roper rivers where the Lower CLA outcrops at or near the surface. Groundwater discharge occurs diffusely along riverbeds (e.g. Eley Creek, the Roper River), from springs (e.g. Bitter Springs, Rainbow Spring) and as evapotranspiration, including through groundwater-dependent vegetation (DEPWS 2022, p. 14). Other aquifers occur in strata above and below the CLA. Localised perched aquifers near the ground surface potentially support groundwater-dependent vegetation (Young et al. 2022, p. 6). Below the CLA, there are also fractured rock aquifers (e.g. Antrim Plateau Volcanics) and sandstone aquifers (e.g. Bukulara Sandstone) (DEPWS 2022, p. 42).

The Mesoproterozoic strata targeted by unconventional gas exploration are deeper (> 2000 m). In areas where data are available, they are generally hydraulically disconnected from the CLA by one or more aquitards (low-permeability layers), but there are locations where there is evidence of connection (DEPWS 2022, pp. 63-65). Inter-aquifer connectivity mostly depends on the distribution of sinkholes, aquitards and geological fault zones.

Water-dependent MNES in the region include two Sites of Conservation Significance:

- i. Mataranka Thermal Pools. These lie in the Roper Discharge Zone where groundwater in the Roper flow path discharges to the surface near Mataranka and are considered of 'outstanding value' (DEPWS 2022, p. 272). SREBA surveys (DEPWS 2022) indicate that, compared to other sections of the BBSA, this area has the highest aquatic biodiversity value, the highest number of unique aquatic species and the greatest presence of threatened species, including a significant population of the Gulf Snapping Turtle (*Eiseya lavarackorum*). It also supports most of the terrestrial GDEs in the BBSA and is a breeding locality for the threatened Red Goshawk (*Erythrotriorchis radiatus*).
- ii. Lake Woods and Longreach Waterhole. Lake Woods, when full, is one of the largest temporary freshwater lakes in northern Australia. Compared to other waters of the BBSA, it typically harbours the most waterbirds, and has the highest concentration of migratory shorebird records, including the only record of the Critically Endangered Curlew Sandpiper (*Calidris ferruginea*), and a record of the Endangered Australian Painted Snipe (*Rostratula australis*). Together with Longreach and South Newcastle Waterholes, Lake Woods is listed as a 'Key Biodiversity Area', an 'Important Bird Area' and a 'NT Site of

Conservation Significance' (DEPWS 2022, p. 199) and is also listed on the Directory of Important Wetlands in Australia.

Five aquatic fauna species listed under the *Environment Protection and Biodiversity Conservation Act 1999* occur in the BBSA: Gulf Snapping Turtle (*Eseya lavarackorum*, Endangered), Largetooth Sawfish (*Pristis pristis*, Vulnerable), Mitchell's Water Monitor (*Varanus mitchelli*, Critically Endangered), Mertens' Water Monitor (*Varanus mertensi*, Endangered) (DEPWS 2022, p. 263) and Speartooth Shark (*Glyphis glyphis*, Critically Endangered) (Constance et al. 2024). Other listed MNES fauna in the BBSA (e.g. see Table 6-4, DEPWS 2022, p. 179) are not aquatic but many, such as the Gouldian Finch (*Chloebia gouldiae*, Endangered), require regular access to water and are considered water-dependent.

Systematic surveys by the SREBA at 44 sites across the BBSA identified 291 species of aquatic fauna, including 36 fish species and 11 aquatic and semi-aquatic reptile species (including 7 turtle species) (DEPWS 2022 p. 15). Species richness was greatest along the northern margin of the study area, especially in the perennial reaches of the upper Roper River. At least 28 species of stygofauna (groundwater invertebrates) were recorded, with one or more species collected in 23 of the 66 groundwater bores sampled by the SREBA (DEPWS 2022, p. 264).

Approach to this advice using Impact Pathway Diagrams (IPDs)

Typically, the IESC provides independent scientific advice in response to specific questions from regulators about Environmental Impact Statements for proposed developments (examples in <https://www.iesc.gov.au/advice/scientific-advice>). The current request is very different because the Committee has not been provided with project-specific Environmental Impact Statements to assess and the regional spatial scale substantially exceeds that of any previous request to the Committee. Therefore, the IESC adopted a different approach to this advice, necessitating some explanation.

An extensive literature describes results from regional surveys and high-level risk assessments in the area (e.g. SREBA (DEPWS 2022) and the Geological and Bioregional Assessment (Huddleston-Holmes et al. 2020, 2021)). Rather than reiterate this literature in this advice, the IESC has drawn on relevant material to derive Impact Pathway Diagrams (IPDs, described in Commonwealth of Australia 2024) that portray potential impact pathways from activities associated with exploration and appraisal in the Beetaloo Basin. On an IPD, impact pathways are shown as consecutive links (arrows) between activities to endpoints via one or more components (boxes) that represent various stressors and processes (Commonwealth of Australia 2024). In this advice, the endpoints of each impact pathway have been set as habitats (e.g. ephemeral stream reaches, terrestrial GDEs) rather than, for example, individual species (cf. the causal networks used by the GBA, e.g. Huddleston-Holmes et al. 2021, Figure 6). This simplifies the IPDs but assumes that the main potential impacts on water-dependent MNES species would be those affecting their habitats.

The north-south gradient in hydrogeology and hydrology across the BBSA must be considered in regional assessments of the potential impacts of unconventional gas exploration and appraisal activities on water resources. Consequently, this advice discusses two sets of potential impact pathways – one for the southern BBSA where surface waters are ephemeral and groundwater is deep below the surface, and one for the northern BBSA where groundwater in the CLA is closer to the surface and supports multiple GDEs. The IESC derived two indicative IPDs based on information from two localities in the BBSA: Newcastle Creek and Lake Woods in the south and the Roper Discharge Zone in the north. The IPDs are intended to illustrate the impact pathways from exploration and appraisal activities in the prospective areas (Figure 1) that may affect water resources in the broader catchments of Lake Woods and the Roper River, respectively.

Each IPD is accompanied by a narrative that explains the nature and scale of key pathways and qualitatively assesses two components of risk: likelihood and consequence. Potential likelihood for a given link (i.e. an arrow) between components was assessed as 'low' if it was considered unlikely to occur

across most of the broader catchment during initial exploration and appraisal activities. However, where a link was inevitable or likely to occur, the likelihood was assessed as 'high'. This high-level qualitative rating attempts to 'average out' the relative likelihood of a given link across the catchment represented by the IPD but will not represent all locations within the catchment. When considering cumulative impacts, the IESC assumed that the likelihood of many pathways and their links would likely increase, especially in locations where intensive activities occur near potential receiving waters.

The potential consequences of a given link between components were assessed as 'low' if, on average across the catchment, there would not be a material and/or lasting change in the receiving component (box) that could be reasonably predicted to arise from that link alone. Conversely, if a link could reasonably be expected to propagate impacts causing a material and/or lasting change in the receiving component, it was rated 'high'. Again, these predicted ratings of consequence are high-level, qualitative and spatially variable. When making these assessments for both IPDs, the IESC was constrained by material information gaps (see response to Question 3). Therefore, the predicted likelihoods and consequences of the impact pathways and their constituent links should be considered as indicative and in need of testing and validation with site- or project-specific monitoring data and modelling.

It is important to reiterate that both of the IPDs and their narratives presented below are simply examples of inferred impact pathways for contrasting localities in the BBSA. Other pathways (and risks) may exist in other parts of the Basin. For example, gas leakage into aquifers from loss of well integrity may pose potential impacts to surface-expression GDEs such as springs in the Hot Springs Valley, north-east of the Beetaloo Sub-basin.

The IPDs assume that the impact pathways portrayed reflect 'best available practice' in the mitigation, monitoring and management of potential impacts, but the IESC acknowledges that sometimes these may fail such as during extreme weather events or as a result of human error. This means that for many links, the qualitative assessments of likelihood and/or consequences are lower than if no mitigation options were applied. However, some links may be almost impossible to mitigate or manage such as contamination of springs due to groundwater transporting contaminants through the karstic CLA aquifer, and the IESC considered this when assessing relative consequences.

Response to questions

The IESC's advice in response to the Minister's specific questions is provided below.

Question 1: What would be the likely nature and scale of potential impacts and/or risks to water resources and water-dependent MNES from the range of activities conducted during an unconventional gas exploration and appraisal program in the Beetaloo Basin?

1. An exploration and appraisal program for unconventional gas in the Beetaloo Basin would be expected to involve most or all of the following activities:
 - construction of surface infrastructure including roads, temporary accommodation, gravel pits, temporary water pipelines and well pads,
 - acquisition of geophysical and seismic data,
 - drilling of exploration and appraisal gas wells,
 - drilling of groundwater supply bores and construction of temporary water storages,
 - hydraulic fracturing,
 - transport of personnel, equipment and materials (including wastewater, drilling waste and chemicals) by road and potentially pipelines,

- storage of flowback wastewater, solid waste and chemicals, and
 - decommissioning and restoration.
2. Each of these activities potentially poses risks of impacts to water resources and water-dependent MNES in the Beetaloo Basin. The nature of these impacts largely depends on the:
- a. likelihood of the impact pathways between these activities and the endpoints (in this advice, water resources represented by aquatic habitats, including their water quality and biota) and,
 - b. vulnerability of each endpoint to individual and collective impacts. Vulnerability is a complex characteristic of each endpoint and is influenced by the endpoint's proximity to the source of the impact(s) and inherent features of the endpoint (e.g. resilience to disturbance, sensitivity to specific impact(s), condition/integrity).

Both these parameters will vary spatially and temporally across the BBSA which makes it difficult to specify the precise scales of potential impacts at a site, or their cumulative impacts (see response to Question 2).

3. In the following paragraphs, we use IPDs (Commonwealth of Australia 2024) and brief supporting narratives to describe the likely nature of impacts and their pathways between the activities listed in Paragraph 1 and aquatic habitats in two contrasting localities in the BBSA. The narrative for each IPD concludes with a high-level description of the likely spatial and temporal scales of the potential impacts in each locality, reiterating the caveat that these scales will vary spatially and temporally across the Basin for each endpoint. Although other impact pathways (and risks) to water resources may exist in other parts of the Basin, the IESC considers that the extent and scale of impacts arising from exploration and appraisal activities for unconventional gas are largely captured in the following two examples.

Likely nature and scales of potential impacts in the Newcastle Creek-Lake Woods catchment (southern region)

4. Impacts that arise from vegetation removal for construction of infrastructure and possibly seismic lines may include (Figure 2):
- a. direct impacts on water-dependent vegetation (e.g. riparian vegetation where stream crossings are built),
 - b. alterations of catchment drainage patterns and surface runoff that impact the water regime, water quality and biota of Newcastle Creek and other waterways, including permanent and semi-permanent refugial waters (e.g. Longreach Waterhole), and
 - c. fragmentation and loss of vegetated habitats, including groundwater-dependent vegetation, that may reduce the condition and/or persistence of populations of dependent wildlife, and possibly impact surface runoff patterns and water quality, alter erosion and sedimentation rates and promote the spread of invasive species, some of which (e.g. Gamba Grass *Andropogon gayanus*) may also change fire regimes.
5. Roads and, if constructed, seismic lines and/or pipelines, are likely to permanently alter catchment drainage patterns and surface runoff, causing on-going impacts to water regimes, water quality and biota of receiving surface waters. Most of these waters are ephemeral creeks whose flow regimes are strongly influenced by catchment runoff. Changes to ecologically relevant components (e.g. frequency and durations of low- and zero-flow periods, flow pulses and overbank inundation) of these flow regimes are likely to have impacts on the species composition and persistence of aquatic and riparian biota of these creeks as well as some aspects of their

water quality (e.g. dissolved oxygen) and ecological processes (see chapters in Datry et al. 2017).

- Waste includes drilling muds and flowback wastewater which contains hydraulic fracturing chemicals and natural compounds from the shale rock (geogenics), including naturally occurring radioactive materials (NORM). Where wastewater, drilling muds and chemicals are transported or stored, there is a risk of spillage which, if it occurs near a creek line or refugial waterhole, may impact water quality and aquatic and riparian biota (Figure 2). For this advice, the IESC assumed that wastewater will not be discharged into local waterways or stored in open ponds but will be transported off site by road.

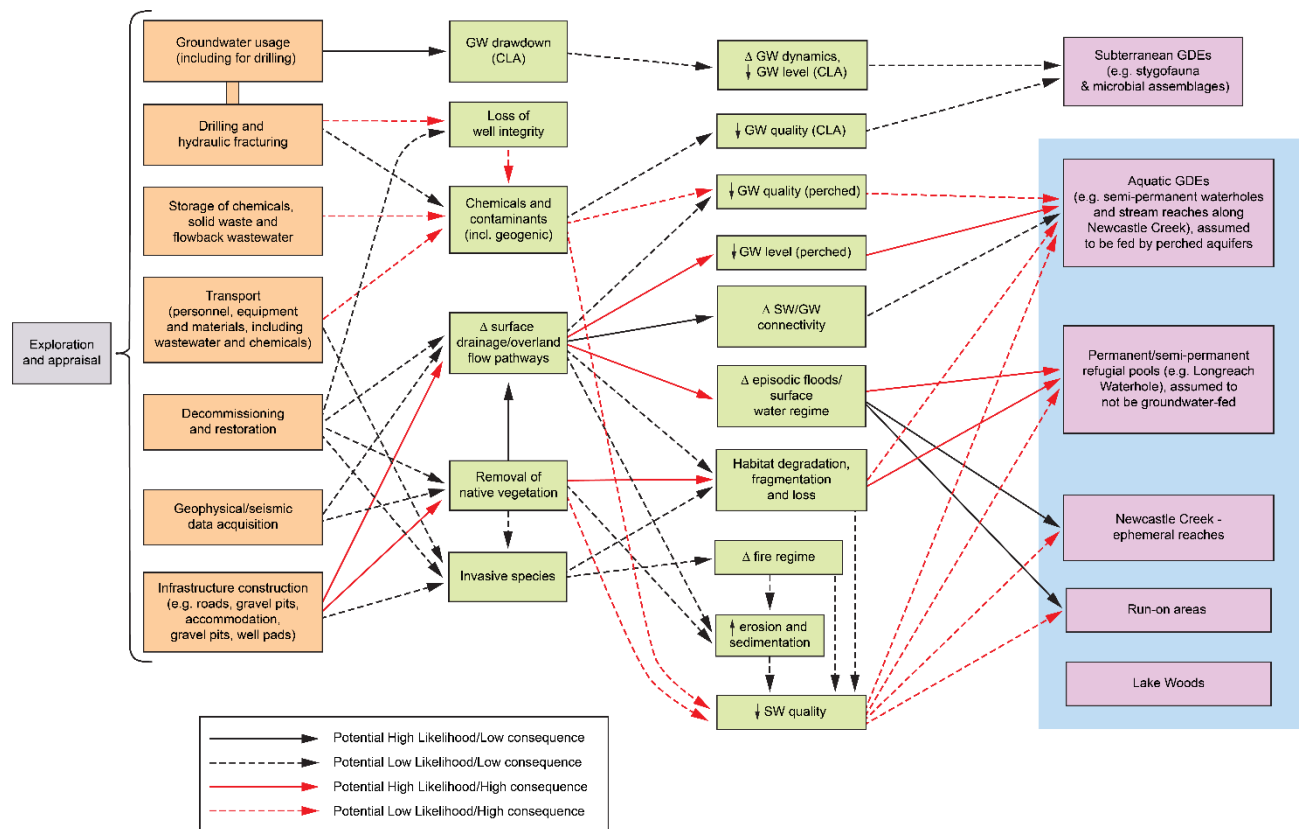


Figure 2. IPD of the potential impacts of exploration and appraisal activities on water resources in the Newcastle Creek-Lake Woods catchment. Activities are shaded in apricot, intermediate components (stressors and processes) in green, and endpoints in pink. The endpoints are grouped in a blue box to indicate that they are hydrologically connected. Potential likelihood and potential consequence (risk) are indicated by lines of different colour and style (see legend). Within the green boxes, Δ represents 'change in'; \uparrow represents 'increase' and \downarrow represents 'decrease'. SW and GW refer to surface water and groundwater respectively.

- Groundwater is typically at least 20 m below the surface and there is no evidence for springs or other surface-expression GDEs in this locality (DEPWS 2022, Figure 5.9, p. 44). Consequently, activities involving groundwater usage from the CLA (e.g. water supply for hydraulic fracturing, drilling of exploratory bores through the CLA to deeper strata) may cause localised drawdown (Figure 2) but not affect surface-expression GDEs, and would be unlikely to pose material risks to subterranean GDEs (e.g. stygofauna) in this locality. When inundated, Newcastle Creek and its terminus, Lake Woods, both potentially recharge the CLA (ELA 2022, Figure 37, p. 81).

Therefore, reductions or alterations of inundation patterns of these surface waters may have a minor impact on groundwater levels in the CLA.

8. Perched aquifers support permanent and semi-permanent refugial waters (e.g. Newcastle Waters) along Newcastle Creek (DEWPS 2022, p. 100). If terrestrial GDEs occur in the area, they are likely to also rely on perched aquifers. Recharge of these perched aquifers may be impacted by altered surface water/groundwater connectivity (Figure 2) and their water quality could be affected by a spill of flowback wastewater or chemicals in their recharge area (Figure 2).
9. Many of the links in Figure 2 were predicted to have 'low' likelihoods and consequences (black dashed lines). These include all the links from activities associated with acquiring seismic data and with decommissioning and restoration, all the links associated with groundwater levels and quality in the CLA, invasive species, fire regime and erosion and sedimentation, and all the links to the subterranean GDE endpoint (Figure 2). This implies that many of the activities associated with exploration and appraisal are less likely to result in impacts on the endpoints, although this may change under a maximum development scenario (see response to Question 2). Some of the links, such as between invasive species and fire regime, were rated as 'low' likelihood and consequence because they may already occur, have occurred or would be difficult to attribute purely to exploration and appraisal activities. Only one full impact pathway (chemicals and contaminants from hydraulic fracturing altering groundwater quality in the CLA and affecting subterranean GDEs) has low-likelihood links throughout (Figure 2).
10. It is important not to dismiss the links qualitatively predicted to have a low likelihood or consequence because there may be specific locations and/or times during the exploration and appraisal activities in the Lake Woods catchment when these links are more likely and/or consequential than shown on the IPD. Nonetheless, the IESC considers that the impacts propagated along impact pathways with one or more black dashed links are, on average, less material than, for example, impact pathways where likelihood and/or consequence are high (e.g. removal of native vegetation during construction of infrastructure that could degrade, fragment or remove vegetation fringing refugial pools along Newcastle Creek) (Figure 2).
11. The spatial and temporal scales of these impacts (Paragraphs 4 to 10) in this southern locality are likely to be dictated by the extent and duration of the exploration and appraisal activities and their cumulative impacts (including production, other land-uses and consequences of predicted climate change, see response to Question 2). Spatially, collective impacts resulting from clearing native vegetation, constructing roads and altering surface runoff and drainage patterns may be substantial (>100 km²). This is because in addition to localised impacts of direct clearing for infrastructure construction, there may be large areas affected by roads that fragment vegetation (including 'edge effects' that may extend hundreds of metres from the road, e.g. Pocock and Lawrence 2005) and alter natural dynamics of runoff and sediment, especially when roads traverse floodplains and run-on areas. These impacts may also be long-lasting (decades), especially if the infrastructure is not decommissioned after exploration and appraisal. Impacts arising from the spillage of flowback wastewater or hazardous chemicals may persist for decades if large volumes are involved and if the contaminants are particularly toxic, persistent and cannot be readily cleaned up.

Likely nature and scale of potential impacts in the Roper River catchment (northern region)

12. In contrast to the previous example, GDEs are more prevalent, diverse and ecologically important in the northern region which means that the likely nature and scale of some of the potential impacts of exploration and appraisal will be different. In addition, exploration and appraisal activities are unlikely to occur across much of the north-eastern Roper River catchment because of its limited overlap with the areas of prospectivity (Figure 1). Nonetheless, surface and subsurface flow paths provide potential routes for propagation of impacts and some GDEs

outside the prospective areas may be vulnerable to altered groundwater volumes and water quality arising from exploration and appraisal.

13. Where the Roper River catchment overlaps the prospective area (Figure 1), impacts arising from removal of vegetation for construction of infrastructure and possibly seismic lines may include (Figure 3):
 - a. direct impacts on terrestrial GDEs (e.g. *Melaleuca forests*) and other water-dependent vegetation (e.g. riparian vegetation where stream crossings are built),
 - b. changes to the water regime and water quality that have impacts on the aquatic and riparian biota of ephemeral waterways (e.g. Birdum and Western creeks), refugial waters (e.g. permanent waterholes in Western Creek) and aquatic GDEs (e.g. groundwater-fed reaches of the Roper River), and
 - c. fragmentation and loss of vegetated habitat that may impact the condition and/or persistence of populations of dependent wildlife, alter fire regimes and promote the spread of invasive species. Altered fire regimes and habitat fragmentation are likely to impact on terrestrial GDEs and, potentially, fringing vegetation around refugial waters in the ephemeral upper reaches of the Roper River.

As seen for the previous example, roads and any seismic lines or pipelines are likely to permanently alter catchment drainage patterns and surface runoff (especially if gas production commences), causing on-going impacts to water regimes, water quality and biota of receiving surface waters.

14. Where flowback wastewater, solid waste and chemicals are transported or stored, there is a risk of spillage which, if it occurs near a creek line, refugial waterhole or groundwater recharge area, may impact on surface and/or groundwater water quality and biota (Figure 3).

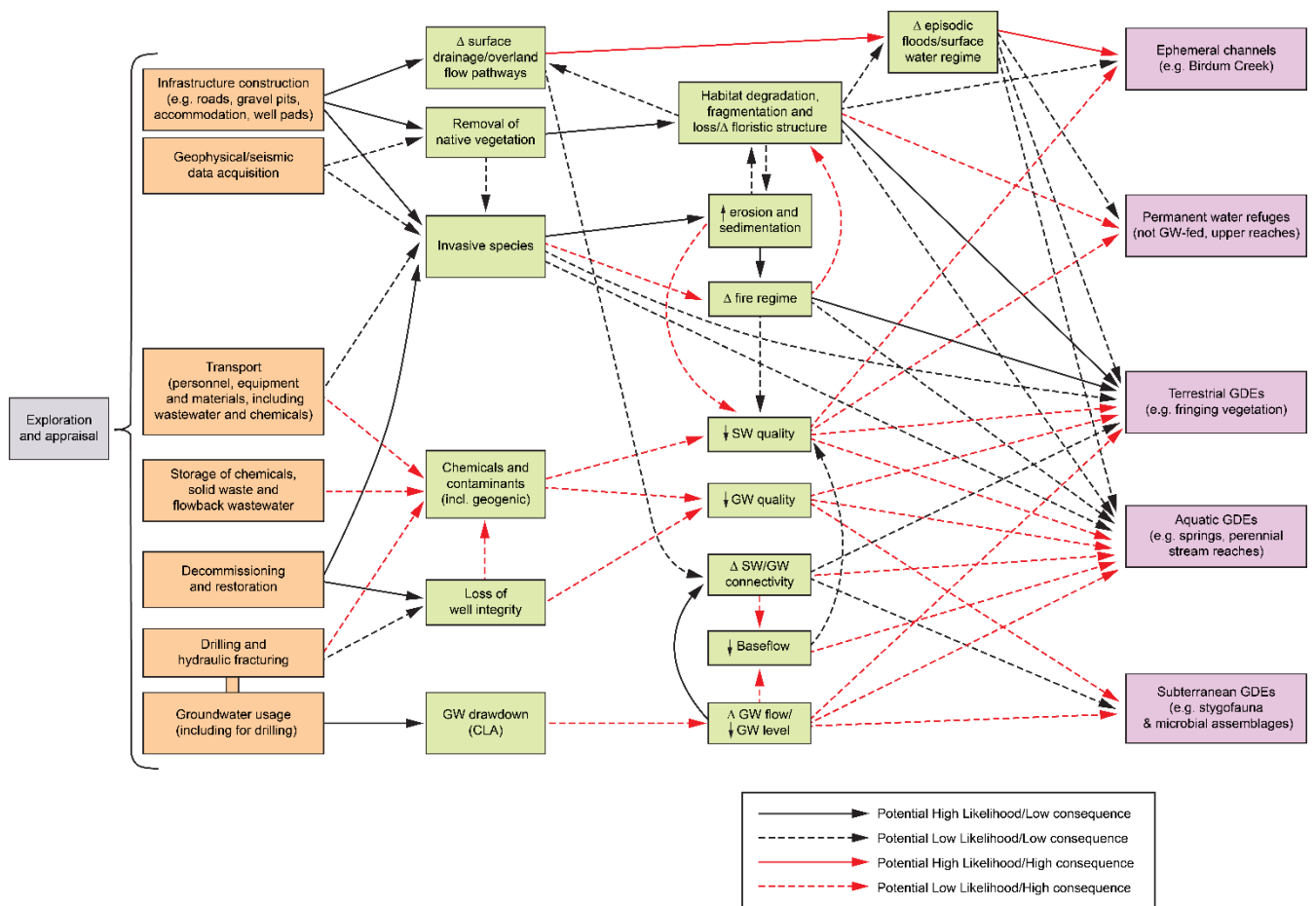


Figure 3. IPD of the potential impacts of exploration and appraisal activities on water resources in the Roper River catchment. Activities are shaded in apricot, intermediate components (stressors and processes) in green, and endpoints in pink. Potential likelihood and consequence (risk) are indicated by lines of different colour and style (see legend). Within the green boxes, Δ represents ‘change in’; ↑ represents ‘increase’ and ↓ represents ‘decrease’. SW and GW refer to surface water and groundwater respectively.

- Usage of groundwater from the CLA, including for drilling exploratory wells and for hydraulic fracturing, may cause drawdown leading to reductions in baseflow and changes to surface water/groundwater connectivity that impact subterranean, aquatic and terrestrial GDEs (Figure 3). These GDEs are also potentially vulnerable to impacts arising from reduced water quality caused by spills (Paragraph 14) and unsuccessful well decommissioning (Figure 3). Much of the groundwater discharging into the upper Roper River and the springs in Elosey National Park and Elosey Creek appears to come from a recharge area between Mataranka and Larrimah which is largely replenished each wet season (Pepper et al. 2018, p. 126). This groundwater moves more rapidly through the system than groundwater from further south (Pepper et al. 2018, p. 127). This recharge zone in the northern CLA with its fast-moving groundwater may be especially vulnerable to accidental spills of flowback wastewater or hazardous chemicals that could affect GDEs downstream in the Roper and Daly rivers.
- Almost half of the links in Figure 3 were predicted to have ‘low’ likelihoods and consequences (black dashed lines), including all the links from activities associated with acquiring seismic data. However, unlike the previous IPD for the Lake Woods catchment, there are no components or endpoints of this IPD that are solely linked by low-likelihood arrows. Several complete impact pathways (e.g. from transport and geophysical/seismic data acquisition via invasive species to

terrestrial and aquatic GDEs) are qualitatively rated as low likelihood (Figure 3). As discussed earlier, links qualitatively predicted to have a low likelihood or consequence should not be dismissed because there may be specific locations and/or times during the exploration and appraisal activities in the Roper catchment when these links are more likely and/or consequential than shown on the IPD.

17. As in the example from the southern region, the spatial and temporal scales of the impacts of exploration and appraisal in this northern locality are likely to be dictated by the extent and duration of the activities and their cumulative impacts (including production, other land-uses and consequences of predicted climate change, see response to Question 2). However, in contrast to the previous example, high-value GDEs are more prevalent.
18. Spatially, collective impacts resulting from clearing native vegetation, constructing roads and altering surface runoff and drainage patterns, and alterations of groundwater dynamics (e.g. drawdown, water quality) may be substantial (>100 km²) but largely occurring outside the Roper catchment. Nonetheless, because of the direction of groundwater flow paths, and high rates and volumes of groundwater movement (Paragraph 15), there may be multiple impacts on high-value GDEs in the Roper River and these impacts may occur over large areas and for decades. In particular, spillage of wastewater or hazardous chemicals near groundwater recharge zones may persist for decades if large amounts are involved and if the contaminants are particularly toxic, persistent and cannot be readily cleaned up. Material gaps still exist in our understanding of the likely spatial and temporal scales of most of the impacts and impact pathways shown in Figures 3, the response thresholds of different water resources (e.g. aquatic habitats and their biota) to predicted impacts on water regimes and water quality, and even the species composition and structure of most of the aquatic, riparian and groundwater assemblages of this locality and the wider BBSA (see response to Question 3).

Question 2: What are the potential cumulative impacts that may occur as a result of this range of exploration and appraisal activities, including an increase in scale and frequency of activities or multiple exploration and appraisal programs?

19. To infer potential cumulative impacts on the Basin's water resources, the IESC assumed a 'maximum development scenario' (MDS) and that in addition to successful exploration and appraisal, production would occur. This MDS is based on the 'GALE scenario' used by Pepper et al. (2018) and was also used in the Stage 3 impact assessment by the Geological and Bioregional Assessment Program (<https://www.bioregionalassessments.gov.au/34-resource-development-scenario>). It assumes a peak production rate of 365 petajoules per year (or 1,000 terajoules per day), a project life of 25 years (including five years of exploration and appraisal activities) and the drilling of a maximum of 1,150 wells with 4 to 10 wells per pad. The Geological and Bioregional Assessment Program inferred that this scenario would directly disturb 8-35 km² for infrastructure such as access roads and well pads, and require a total of up to 46 gigalitres of water over the 25-year development period (assuming 40 megalitres for drilling and hydraulic fracturing per well).
20. As in the response to Question 1, it was also assumed that exploration and appraisal activities would only take place in the Beetaloo Sub-basin and eastern depocentre considered prospective for unconventional gas. Therefore, when using IPDs to infer potential collective impacts from exploration and appraisal activities alone, it was assumed that many of the 'low likelihood' links in Figures 2 and 3 would now become more likely under an MDS. IPDs can only show collective rather than cumulative impacts because some combinations of impact pathways are not simply additive but may be synergistic or antagonistic (Commonwealth of Australia 2024). Material gaps in current understanding of these synergistic and antagonistic processes (see response to Question 3) constrains the IESC's predictions of likely cumulative impacts in this advice.

21. Although Question 2 only specifies exploration and appraisal activities, it is important to acknowledge that other land-uses exist in the area or are planned. These include irrigated agriculture (e.g. cotton, mangoes, melons), pastoral activities (e.g. cattle), domestic use (e.g. stations, communities), solar farms and wind farms (Northern Territory Government 2024). The two land-uses considered most likely to have potential cumulative impacts on water resources in addition to exploration and appraisal activities are irrigated agriculture and pastoral developments.
22. Finally, the cumulative impacts of all these activities and land-uses on water resources in the Beetaloo Basin will be in addition to, and modified by, the current and predicted changes in climate. Heavy rainfalls are projected to increase by 8%-15% per degree of global warming (Wasko et al. 2024), and while the frequency of cyclones is likely to decrease, their intensity will increase (Walsh et al. 2016). There will be considerably more days above 40°C, and evapotranspiration will potentially increase (NESP 2020). Projected change in average annual rainfall is unclear, where both wetter and drier futures are plausible depending on the degree of global warming.

Potential cumulative impacts that may occur as a result of exploration and appraisal activities under maximum development

23. Under an MDS, all of the predicted impacts described in the response to Question 1 could reasonably be expected to occur. However, many of the links and impact pathways shown in Figures 2 and 3 are now more likely and their collective impacts may extend further and persist for longer. For example, in the Lake Woods-Newcastle Waters catchment (Figure 2), exploration and appraisal activities under an MDS would likely increase the risk of introducing invasive species that could directly impact surface waters (e.g. trampling and rooting by feral pigs), increase fire frequency and intensity via increased spread of flammable weeds such as Gamba Grass and Buffel Grass (*Cenchrus ciliaris*) and exacerbate rates of erosion and sedimentation. These may all combine with existing and potentially greater alterations in surface runoff patterns and native vegetation removal (Figure 2) to have collective and possibly cumulative impacts on the water quality, biota and ecological processes of the connected surface waters of Newcastle Creek and Lake Woods (blue box in Figure 2). However, it is unlikely that increased exploration and appraisal activities will materially impact subsurface GDEs in the CLA.
24. In the Roper River catchment (Figure 3), increased exploration and appraisal activities under an MDS are likely to increase the potential collective impacts on GDEs via impact pathways that affect either groundwater quality, groundwater dynamics or both. For example, greater numbers of exploratory wells increase the likelihood of drawdown and failed well integrity that, in combination with increased risks of chemical or flowback wastewater spills, may have cumulative impacts on GDEs through reduced groundwater quality, volumes or both. Increased exploration and appraisal activities also enhance the likelihood of introducing or spreading invasive species that may directly impact surface water resources and/or alter fire regimes and erosion/sedimentation dynamics that will, in turn, potentially have cumulative impacts on the water quality, biota and ecological processes in surface-expression aquatic and terrestrial GDEs.

Potential cumulative impacts that may occur as a result of exploration, appraisal and production activities, additional land-use activities and predicted climate change

25. It is highly likely that exploration and appraisal activities will continue after production commences as operators seek to locate and prove further gas reserves. As an example, Figure 4 shows how drilling of exploration and appraisal wells has continued for coal seam gas (CSG) projects in Queensland concurrently with production from 2000 to 2024.

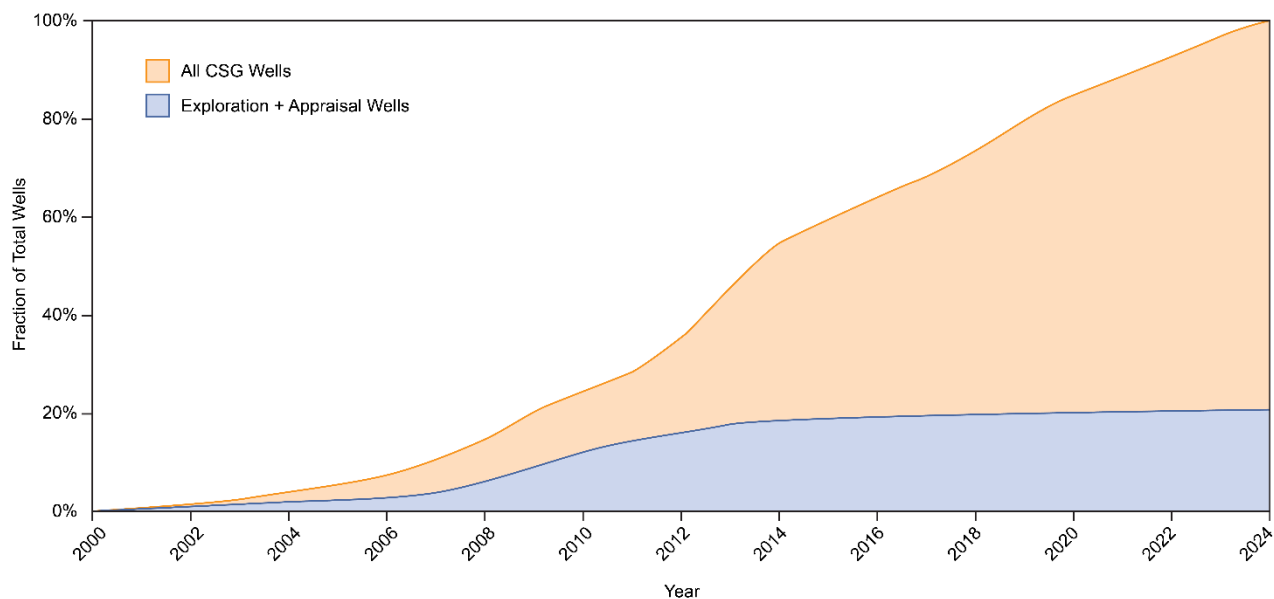


Figure 4. Exploration and appraisal wells as a fraction of total coal seam gas (CSG) wells in Queensland developed from 2000 to 2024. Data source: [Queensland Spatial Catalogue](#).

26. The cumulative impacts of production under an MDS will likely arise from the combination of increased usage of groundwater, greater likelihood of spills and inter-aquifer leakage from well integrity failure and potential groundwater contamination (cf. Shanfield et al. 2019).
27. In addition to those impacts described in Paragraph 4, the main impacts of additional activities are likely to be potential salinisation associated with irrigated agriculture in the Beetaloo Basin, and the use of fertilisers, herbicides, fungicides and pesticides.
28. Projected climate change in the area (Paragraph 22) will likely exacerbate the following cumulative impacts: increased erosion and sedimentation associated with more intense rainfall, or recharge of groundwater that may increase or decline. Additionally, predicted changes under climate-change scenarios, particularly increasing numbers of very hot days and increasing evapotranspiration rates, may reduce the resilience of water-dependent MNES such as Gouldian Finch and species with a requirement for persistent water or climate-buffering habitats (DEPWS 2022, p.18). In general, the rate and nature of the impacts of climate change on temperatures, rainfalls and climatic variability in the region are subject to deep uncertainty, which confounds attempts to assess climate-related changes to cumulative impacts. This uncertainty is unlikely to be reduced with basin and local-scale modelling.

Question 3: Are there material gaps in the current scientific understanding of the hydrology and hydrogeology of the Beetaloo Basin that affect the IESC's ability to provide advice on potential impacts, impact pathways and risk assessment associated with exploration and appraisal activities? If so, what are these and what research is needed to address these gaps at basin and site scale?

29. Regional surveys and high-level risk assessments such as SREBA (DEPWS 2022) and the Geological and Bioregional Assessment (Huddlestone-Holmes et al. 2020, 2021) have contributed substantially to knowledge of the Beetaloo Basin. However, material gaps remain in the current scientific understanding of the hydrology, hydrogeology and other aspects of the Beetaloo Basin that affected the IESC's ability to provide advice on potential impacts, impact pathways and risks associated with exploration and appraisal activities. These gaps fall into two groups: the first where information is needed and the second where further data and research are required.

- a. Information is needed on:
 - i. where, when and the scale of exploration and appraisal activities that are likely to occur, and their proximity to surface and subterranean water resources in the Basin;
 - ii. water requirements of current and future land uses, and their likely changes under projected climate change and population pressure in the Basin;
 - iii. planned storage, transport and treatment of flowback, drilling muds and other wastes, as well as wastewater treatment (acknowledging that there will be no controlled releases of flowback water to the environment); and
 - iv. which combinations of impact pathways are synergistic or antagonistic, and the conditions under which these interactions occur in the Beetaloo Basin (see response to Question 2).
30. Along with the research proposed below, there remains a need for site- and project-specific investigations including collection of baseline data and subsequent modelling. Guidelines and suggested methods for these are provided on the IESC website (<https://www.iesc.gov.au/>).
31. Research, including collection of relevant baseline data and other information, is needed to address material gaps in the following broad topics.

Geological framework of the basin

32. There is a need for a substantially improved geological framework of the Beetaloo Basin as this is critical to understanding the groundwater and groundwater-surface water connections as well as the risks associated with potential gas development. This requires a refined stratigraphy, including facies distribution of key aquifers and aquitards and an improved structural framework, and should include the following work.
- a. To inform the improved structural framework and identify potential impact pathways, further borehole and geophysical investigations are needed. For example, there is geological uncertainty near the northern boundary with the upper Roper catchment (Jarrett et al. 2022), in the north-east near the Hot Springs Valley (Evans et al. 2020, p. 90), and in the relationship between the Bukalara and Gum Ridge strata (DEWPS 2022, Figure 4.6, p. 59).
 - b. The characteristics of complex fault-zones, another potential impact pathway, are uncertain near the boundaries of the Beetaloo Basin. For example, the east-west Mallapunyah fault zone near the northern boundary with the upper Roper catchment is largely undefined (Jarrett et al. 2022). Investigations are needed to map complex fault-zones (Murray and Power 2021), including the possible offset of aquitard strata that could compartmentalise groundwater. These investigations could help verify the modelling estimate that Beetaloo Basin groundwater is a small contribution to the water balance of the Tindall limestone and Mataranka springs (<10% of total groundwater in Tindall limestone, Knapton 2020).

Groundwater

33. Building from the refined geological framework (Paragraph 32), detailed characterisation is needed of aquifer and aquitard geometries, hydraulic properties, groundwater levels, hydraulic gradients and flow pathways, including their temporal variability. This information will address gaps in understand how groundwater supports GDEs (subterranean, aquatic and terrestrial), including perched systems, and will improve conceptualisation, water balances, models and site-specific evaluations of the potential impact pathways. To achieve this, the following research is recommended:

- a. The regional multi-level bore monitoring network needs to be extended to better characterise basin-wide groundwater systems, fault-zones and local inter-aquifer connectivity (e.g. between the Bukalara and Gum Ridge strata). Investigations are also needed to confirm the extent and properties of aquitards that disconnect CLA aquifers from deeper shales in the Beetaloo Basin.
- b. This bore monitoring network should be used to obtain site-specific values of hydraulic conductivity (e.g. Valois et al. 2023) and to identify different types of aquifers and values of groundwater storage (Chowdhury et al. 2022).
- c. Site-specific geophysical surveys and tracer studies (e.g. Office of Water Science 2020) should investigate the potential for groundwater flow through preferential paths that may be undercover (e.g. karst channels without surface sinkholes, perched aquifers) and contribute to the risk of rapid migration of contaminants and their discharge to surface waters.
- d. For the regional water balance (see Paragraph 36) further research is needed into groundwater recharge, particularly on its spatial and temporal variability (e.g. Lee et al. 2024), on episodic recharge events and to quantify focused recharge mechanisms through preferential paths.
- e. Quantify groundwater through-flow from the south-east Beetaloo Basin to the Tindall limestone (i.e. the CLA in the Roper River catchment) using multiple lines of evidence e.g. geophysics, drilling, multi-level piezometers, environmental tracers (see Paragraph 32b).

Surface water

34. Further baseline data are needed on concurrent sub-daily rainfalls and streamflows for catchments covering a range of spatial scales, catchment types and climatic conditions. These data should include high-flow gaugings (and associated hydrodynamic modelling to help inform stage-discharge relationships) which will address material gaps in the characterisation of the high flows that contribute to surface runoff, extended inundation events and recharge of perched and near-surface aquifers.
35. Given the very flat topography, high-quality topographic data (e.g. Light Detection and Ranging (LiDAR) data) are needed to model surface runoff and flood inundation behaviour. Local-scale rainfall-runoff models will be required to address project-specific impacts.

Surface water and groundwater connectivity

36. There is the large uncertainty in how rainfall is partitioned into evapotranspiration, recharge to groundwater systems, losses to surface and depression stores, and surface runoff. To reduce this uncertainty in water balance components, data assimilation techniques should be applied that combine ground-based observations, remote-sensing data and model outputs (e.g. Doble and Crosbie 2017, Kalu et al. 2024).
37. In the flat terrain typical of much of the Beetaloo Basin, the spatial and temporal distributions of episodic runoff are governed by small differences in elevation that influence recharge to near-surface groundwaters used by terrestrial GDEs. High-quality topographic information is needed to better inform our understanding of the recharge dynamics in such areas (see Paragraph 35).
38. To better understand the connectivity and hydrological pathways between groundwater and surface water systems, data are needed to develop a range of suitable trigger values for maintaining groundwater discharge to the surface at major springs such as those in Hot Springs Valley. This needs to be done in conjunction with geophysical studies and tracers (e.g. Campbell

et al. 2025) to ensure that potential contamination pathways are identified and incorporated into environmental risk assessments.

Water quality

39. Further baseline groundwater and surface water quality monitoring across the Beetaloo Basin is required to assess impacts from any accidental chemical or flowback wastewater spills and from which site-specific criteria may need to be developed if production goes ahead (Golding et al. 2022). Monitoring should include background physico-chemical parameters, nutrients, dissolved methane, naturally occurring radioactive materials and organic and inorganic contaminants in both surface and groundwaters prior to and during exploration and appraisal activities. Baseline groundwater monitoring should also include environmental isotopes (Office of Water Science 2020) to characterise groundwater and dissolved gases.
40. Recent research (Golding et al. 2022) has shown that concentrations of naturally occurring radioactive materials, such as radium, in flowback may exceed guidelines. These isotopes may precipitate at the surface, with potential increases in daughter isotopes. Information on these isotope species and concentrations are required to ensure appropriate protection of aquatic ecosystems in the Basin (Lauer et al. 2018, Campin 2019, p. 260).

Ecology

41. Although Question 3 asks specifically about material gaps in hydrology and hydrogeology, there are several gaps in the current scientific understanding of ecology of water-dependent biota that constrained the IESC's advice and where research is needed. These gaps include:
 - a. Species composition, distribution, degree of groundwater-dependence and current condition of aquatic and terrestrial GDEs in different parts of the Basin, and what and how native species (especially MNES) are supported by them. Survey techniques for assessing these GDEs are well-established (e.g. Doody et al. 2019) and include remote-sensing methods (e.g. Brim Box et al. 2022) that can be used in a multiple-lines-of-evidence approach (e.g. Fildes et al. 2023) appropriate for site- and Basin-scale assessments. In some areas where diverse GDEs occur (e.g. the Roper River discharge area) or where perched aquifers may be at risk (e.g. Lake Woods catchment), detailed field assessments of seasonal groundwater use and potential sources of groundwater are needed to confirm suspected impact pathways.
 - b. Species composition and distribution of subterranean GDEs (stygofauna and microbial assemblages). The initial studies by Oberprieler et al. (2021) and DEPWS (2022) need to be extended to fully describe the components and processes that characterise the subterranean GDEs of the Basin. Determination of the spatial and temporal variability exhibited by the groundwater biota is needed to develop thresholds indicating irreversible change and to provide a baseline for future monitoring.
 - c. Species composition, distribution and current condition of water-dependent native plants and animals (especially MNES) that may be affected by unconventional gas development (including production), climate change and other existing and future water-uses in the Basin. Appropriate methods (e.g. Geological and Bioregional Assessment Program 2021, DEPWS 2022) should be used to provide further baseline data, supplemented by targeted research assessing water use and seasonal dependency so that thresholds (see next point) can be assessed.
 - d. Thresholds ('tipping points') for the vulnerability of different GDEs to changes in groundwater drawdown and water quality across the Basin. Field and laboratory research is needed to quantify these thresholds to identify whether they may be exceeded by maximum

unconventional gas development (including production), informing assessment of cumulative impacts due to climate change and other ongoing water-uses in the Basin.

Date of advice	16 December 2024
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Acknowledgement	We thank Belinda Cale for drafting the figures in this advice.
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