Australian Government
Department of Agriculture, Water and the Environment
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BIOREGIONAL ASSESSMENTS

CSIRO

Geological and environmental baseline assessment for the Isa GBA region

Geological and Bioregional Assessment: Stage 2

2020

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

The Geological and Bioregional Assessment Program

The Geological and Bioregional Assessment Program will provide independent scientific advice on the potential impacts from shale and tight gas projects on the environment. The geological and environmental data and tools produced by the program will assist governments, industry, landowners and the community to help inform decision-making and enhance the coordinated management of potential impacts.

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

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Authorship is listed alphabetically after first author.

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

Cover photograph

The Burketown Bore, drilled in 1897 by the Queensland Government, is a naturally flowing bore that taps the artesian Gilbert River Formation aquifer at a depth of about 700 m below surface. Groundwater within this aquifer naturally contains a variety of dissolved chemical compounds that have deposited around the bore as the hot water (around 68 °C) has evaporated over the years, leading to the formation of a distinctive multi-coloured mound.

Credit: Steven Lewis, Geoscience Australia, July 2018 Element: GBA-ISA-2-264

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At a glance

The $35.4 million Geological and Bioregional Assessment (GBA) Program is assessing the potential environmental impacts of shale and tight gas development to inform regulatory frameworks and appropriate management approaches. The geological and environmental knowledge, data and tools produced by the Program will assist governments, industry, landowners and the community by informing decision making and enabling the coordinated management of potential impacts. Stage 2 baseline data, knowledge and conceptual models for the Isa GBA region (Figure 1) can be used to support impact assessments of future shale gas developments.

Geology and gas resources: Areas of higher prospectivity for the main shale gas plays include the River Supersequence over most of the Isa GBA region and the Lawn Supersequence over the central and western parts of the region (Figure 1).

Groundwater: There are two broad and potentially connected groundwater systems that occur at different depths. The deeper groundwater system contains the targets for shale gas extraction. The shallower system, including part of the Great Artesian Basin, hosts the region's most readily accessible groundwater resources. Groundwater-dependent ecosystems occur along many streams and on nearby floodplains, and also as environmentally and culturally important springs in the south-west of the region.

Figure 1 Isa GBA region
Element: GBA-ISA-2-250

Surface water: The Nicholson River, which rises to the west of the region in the NT and passes near the remote township of Doomadgee, is the major river of interest. Discharging into the Gulf of Carpentaria, it flows through the nationally listed wetlands of the Nicholson Delta and Southern Gulf aggregations.

Water availability: A future shale gas industry will need authorisation to take water from aquifers, watercourses or lakes through the relevant Queensland Government water plans. Produced water from shale gas reservoirs could possibly be used for drilling and hydraulic fracturing, although the volumes available and the economic viability are uncertain.

Potential hydrological connections: There is some evidence of potential existing connectivity between deep and shallow groundwater systems. Considerably more information is needed to understand these potential hydrological connections. Research questions have been devised to address the most important data and knowledge gaps.

Protected matters: Matters of national and state environmental significance include threatened species (plants, reptiles, birds and mammals) and ecological communities and wetlands. Two landscape classes dominate the region: 'floodplain and alluvium' (36% of the region) and 'loamy and sandy plains' (33%).

Eleven Matters of National Environmental Significance and two Matters of State Environmental Significance are recommended for further assessment because of their importance (priority 1). This includes five endangered species and eight vulnerable species, as well as an endangered regional ecosystem and four nationally important wetlands.

Potential impacts: Over 200 individual hazards were systematically identified by considering all the possible ways that activities associated with shale gas development may cause impacts. Hazards were grouped into 14 causal pathways, and then aggregated into three causal pathway groups. Causal pathways connect hazards associated with shale gas development with the values to be protected for each landscape class.

The three causal pathway groups are: (i) landscape management, (ii) subsurface flow paths and (iii) water and infrastructure management. A variety of potential effects were identified across these causal pathways groups, with the highest priority effects including habitat fragmentation and loss, cultural heritage damage or loss, introduction of invasive species, changed groundwater quality and changed surface water flows.

The Geological and Bioregional Assessment Program

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

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

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

The Program aims to:

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

The Program commenced in July 2017 and comprises three stages:

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

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

About this report

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

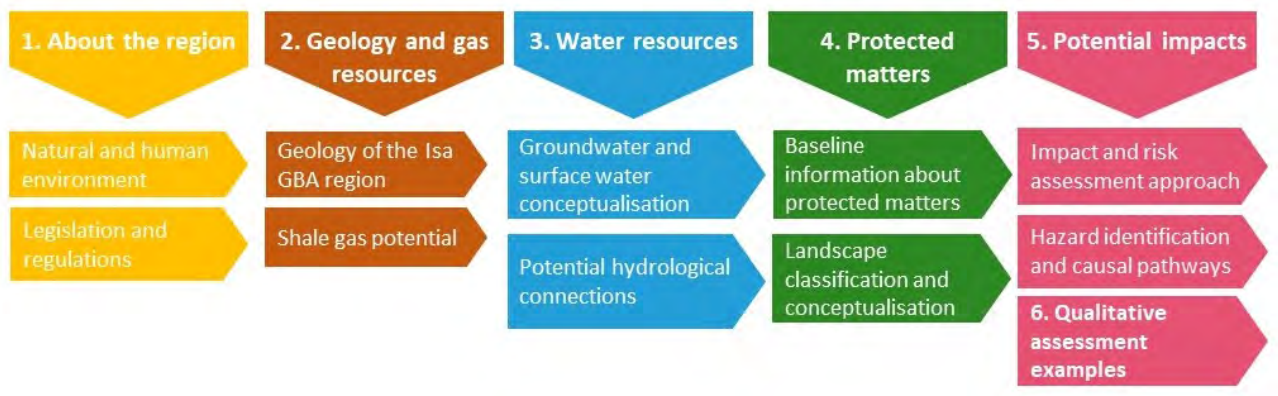

Figure 2 Geological and environmental baseline assessment report structure

Element: GBA-ISA-2-197

1. **'About the region'** briefly introduces the natural and human environments of the Isa GBA region and summarises the legislative and regulatory controls governing water and gas resource development.
2. **'Geology and gas resources'** defines the stratigraphic and structural characteristics that may influence shale gas prospectivity, extraction and potential environmental risks. The spatial extent and relative prospectivity of the resources are assessed.
3. **'Water resources'** describes the current conceptual understanding of surface water and groundwater and water quality, and the surface water – groundwater interactions in the region. This section concludes with an assessment of the availability of water resources for future drilling and hydraulic fracturing for shale gas development.
4. **'Protected matters'** describes the environmental and cultural knowledge in the region, with an emphasis on Matters of National Environmental Significance and Matters of State Environmental Significance. Landscape classification is used to systematically define geographical areas with similar physical and/or biological and hydrological characteristics.
5. **'Potential impacts'** identified by a systematic hazard analysis of the potential hazards associated with all life-cycle stages of shale gas development, definition of a set of causal pathways, which represent the logical chain of events, either planned or unplanned, that may link shale gas development activities with potential impacts on water and the environment (Figure 61) and then aggregated into three causal pathway groups.
6. **'Qualitative assessments'** presents assessments of three important issues to the community, government and industry: hydraulic fracturing, compromised well integrity and screening of drilling and hydraulic fracturing chemicals.

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

User values

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

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

The user panel for the Isa GBA region first met in May 2018, with the second meeting held in August 2019. The user panel has:

- identified sources of additional data and knowledge from government, industry and communities and reinforced the cultural, hydrological and ecological uniqueness of the region
- highlighted the importance of groundwater from the Great Artesian Basin, and surface water from the Nicholson and Gregory rivers, in supporting the characteristic ecosystems of the Isa GBA region, as well as the local communities and multi-million-dollar regional cattle industry
- confirmed broad support for improving the knowledge base around surface water – groundwater interactions, as well as better understanding the ecological and cultural values of the many protected matters within the region.

Technical appendices

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

- Orr ML, Bradshaw BE, Bernardel G, Palu TJ, Hall LS, Bailey AHE, Skeers N, Dehelean A, Reese B and Woods M (2020) Geology of the Isa GBA region.
- Bailey AHE, Bradshaw BE, Palu TJ, Wang L, Jarrett AJM, Orr ML, Lech M, Evenden C, Arnold D, Reese B, Skeers N, Woods M, Dehelean A, Lawson C and Hall LS (2020) Shale gas prospectivity of the Isa GBA region.
- Buchanan S, Dixon-Jain P, Martinez J, Raiber M, Kumar PR, Woods M, Arnold D, Dehelean A and Skeers N (2020) Hydrogeology and groundwater systems of the Isa GBA region.
- MacFarlane CM, Herr A, Merrin LE, O'Grady AP and Pavey CR (2020) Protected matters for the Isa GBA region.
- Kirby JK, Golding L, Williams M, Apte S, Mallants D and Kookana R (2020) Qualitative (screening) environmental risk assessment of drilling and hydraulic fracturing chemicals for the Isa GBA region.
- Kear J and Kasperczyk D (2020) Hydraulic fracturing and well integrity for the GBA regions.

Executive summary

About the region *see Section 1, page 1*

The Isa GBA region is in north-west Queensland and covers about 8223 km^2 (Figure 1). Defined specifically for GBA purposes, the region includes known shale gas systems of the geological Isa Superbasin. Centred on the area around the remote township of Doomadgee, the region contains the north-eastern part of the Isa Superbasin, which is mostly buried at variable depths (commonly greater than 1 km below the surface) beneath younger sedimentary basins, such as the Carpentaria Basin (part of the groundwater system known as the Great Artesian Basin (GAB)).

The Isa GBA region occurs mostly on relatively flat and low-lying savannah country south of the Gulf of Carpentaria, consisting of well-vegetated alluvial and near-coastal plains, with widespread native grasslands and areas of sparse to moderately dense native woodland (Figure 4, Section 1.3). The region experiences summer-dominated rainfall (December to February), hot summers and warm winters. The high inter-annual variability of rainfall is influenced by cyclones and associated low-pressure rainfall events.

The human population is sparse, with fewer than 2000 people permanently residing within the region. Doomadgee is the only recognised town in the region, with an estimated population of about 1400 (and 90% of the population is of Indigenous heritage). The multi-million-dollar beef cattle industry is the mainstay of the local economy and large pastoral holdings cover many thousands of square kilometres (Figure 15, Section 1.5). Traditional homelands of the Gangalidda, Garawa and Waanyi peoples are in the Isa GBA region and native title rights have been determined for about 70% of the region (Figure 16, Section 1.5).

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

The Isa Superbasin is a Paleoproterozoic to earliest Mesoproterozoic geological province, the full extent of which is unknown (Figure 18, Section 2.1). Overlying sedimentary basins include the Mesoproterozoic South Nicholson Basin, the Mesozoic Carpentaria Basin and the Cenozoic Karumba Basin. Most of the groundwater for stock and domestic supplies in the region is sourced from aquifers of the Carpentaria and Karumba basins, including the artesian Gilbert River Formation of the GAB.

The Isa Superbasin is an underexplored petroleum province with demonstrated oil and gas shows from previous limited exploration campaigns. Resource development companies are currently pursuing shale gas plays hosted within proven late Paleoproterozoic petroleum systems. Play fairway analysis, used to map the distribution of the Isa Superbasin's key shale gas plays, shows that the River Supersequence is potentially prospective for shale gas exploration over most of the Isa GBA region (Figure 27), whereas the Lawn Supersequence is most likely prospective over central and eastern parts (Figure 28).

Water resources *see Section 3, page 51*

The Isa GBA region is host to two broad and potentially interconnected groundwater systems. The first is a deeper groundwater system associated with the Proterozoic units of the Isa Superbasin and the South Nicholson Basin, where the targets for shale gas extraction lie and where the highest yielding aquifer is the Lady Loretta Formation (Loretta Supersequence) (Figure 30). The overlying groundwater system occurs in the Mesozoic Carpentaria Basin (part of the GAB) and Cenozoic Karumba Basin, where the major aquifers include the basal Gilbert River Formation, the Normanton Formation and the near-surface sediments of the Karumba Basin (Figure 30). The shallower groundwater system hosts the region's most readily accessible groundwater resources. The salinity of groundwater in the Proterozoic units and GAB is typically considered low to moderately saline (Section 3.1.1.5, Section 3.1.2.6).

Most of the Isa GBA region is in the Nicholson River catchment (8020 km^2). The Nicholson River is ephemeral upstream of the confluence of the Nicholson and Gregory rivers and is the major river of interest for this assessment (Figure 36). There is a strong gradient in the runoff generated from south to north (Figure 37) that follows the rainfall gradient (Figure 11), with the highest runoff generated near the coast. Discharging into the Gulf of Carpentaria, the Nicholson River flows through the nationally listed wetlands of the Nicholson Delta and the Southern Gulf aggregations. Surface water quality in the Isa GBA region is variable, although relatively low total dissolved solids mean that the water quality is suitable for drinking water and stock watering (Section 3.2).

The alluvial floodplains in the Isa GBA region have the greatest potential for surface water – groundwater interactions, arising from connectivity between groundwater hosted in the Karumba Basin sediments and surface waters. Groundwater supports aquatic and terrestrial groundwater-dependent ecosystems in the region, including spring ecosystems in the south-west (Section 3.3), nationally important wetlands and strategic environmental areas.

In terms of potential hydrological connections, dissolved gas concentrations within the Gilbert River Formation aquifer and Normanton Formation aquifer provide some evidence of potential existing connectivity between deep and shallow hydrogeological systems (Figure 47). However, this assessment highlights that considerable data and knowledge gaps exist and outlines research questions for future studies to determine the likelihood of these potential hydrological pathways (Table 13, Section 3.4).

There are no existing water licences or allocations for the petroleum and gas industry in the Isa GBA region. Several groundwater and surface water sources are potentially available to supply water requirements for future shale gas development. These include accessing some of the available water reserves from the GAB, as well as surface water or groundwater resources from the Nicholson River catchment. Recycling or reusing flowback or produced water that may be associated with gas production may also be an option, although there is considerable uncertainty around the volumes of produced water likely to be recovered from shale gas wells in the Isa GBA region and the economic feasibility of its reuse.

Protected matters *see Section 4, page 101*

Matters of National Environmental Significance (MNES) in the Isa GBA region include two subspecies of bar-tailed godwit and 24 other vertebrate species listed nationally as threatened (critically endangered, endangered or vulnerable). There are also 32 species that are listed as migratory and 11 species that are both threatened and migratory. Threatened species include the curlew sandpiper (*Calidris ferruginea*), Gouldian finch (*Erythrura gouldiae*) and ghost bat (*Macroderma gigas*). Other protected matters include seven listed marine species (six birds and one reptile). Matters of State Environmental Significance (MSES) include four nationally important wetlands, three state and territory reserves, the Gulf Rivers strategic environmental area and three state-listed threatened species.

The assessment of potential hydrological and environmental impacts due to shale gas development is underpinned by landscape classifications. The key ecological and hydrological features are categorised into ten landscape classes, based mainly on Queensland Land Zones (Figure 52). The Isa GBA region is dominated by the landscape classes ‘floodplain and alluvium’ (36% of the region) and ‘loamy and sandy plains’ (33%). It also contains substantial areas of ‘clay plains’ (15%) and of ‘tablelands and duricrusts’ (12% of the region). There are small areas of ‘undulating country on fine-grained sedimentary rocks’, ‘hills and lowlands on metamorphic rocks’ and ‘sandstone ranges’, as well as two springs (Figure 52, Section 4.3).

To help focus any future impact and risk assessment in the region, protected matters were assigned to one of three priorities. The prioritisation identified 11 MNES and two MSES, the purple-crowned fairy wren (*Malurus coronatus*) and the plant *Solanum carduiforme*, for detailed assessment (priority 1 – importance of the region to the matter warrants a detailed level of assessment). Eight of the ten landscape classes in the Isa GBA region intersect the area likely for resource development (priority 2 – importance of the region to the matter warrants a high level of assessment). Springs and the ‘tidal flats and beaches’ landscape class are also recommended for further assessment due to their potential connections to groundwater systems (priority 2).

Potential impacts of shale gas development *see Section 5, page 131*

The proposed risk assessment approach follows the principles for ecological risk assessment outlined by the United States Environmental Protection Agency (US EPA, 1998) and Hayes (2004) with a view to meeting regulatory processes for the Isa GBA region (Figure 55). The first step of the risk assessment approach identified a total of 222 hazards by considering all the possible ways an activity in the life cycle (Section 5.2.2, Figure 57 and Figure 58) of shale gas development may potentially cause impacts (Section 5.2). Hazards that have similar potential impacts are grouped into causal pathways, and in the Isa GBA region there are 14 causal pathways aggregated into three groups (Figure 61, Section 5.3). Causal pathways (Figure 61) connect hazards arising from existing activities (Section 1.5) and shale gas development activities (Section 5.2) with the values to be protected (Sections 4.1 and 4.2) for each landscape class (Section 4.3).

The prioritised causal pathways recommended for more detailed assessment are mostly in the landscape management (38 of 108) and water and infrastructure management (28 of 92) causal pathway groups, with fewer (two of 22) in the subsurface flow paths causal pathway group. The focus of any future impact and risk assessment in the region is recommended to evaluate how the prioritised causal pathway might affect selected endpoints, including endemic native species, migratory species, ecological communities, wetland ecosystems, cultural heritage and agriculture (Section 5.3).

Qualitative assessments *see Section 6, page 187*

Well integrity and hydraulic fracturing are important issues to industry, government and the community. A qualitative review of recent domestic and international inquiries into onshore gas industry operations, a review of the limited Isa GBA region operations to date and hazard scoring indicated that the likelihood of occurrence of the three impact modes associated with hydraulic fracturing is low (Table 26). While the hazard analysis did not prioritise any of the three impact modes, one impact mode, 'F1: hydraulic fracture growth into aquifer', is recommended for further analysis based on heightened community concerns around hydraulic fracturing and the specific geological characteristics of the Isa GBA region.

Regulated construction of wells for shale gas development aims to ensure that fluid and gas are prevented from flowing unintentionally from the reservoir into another geological layer or to the surface. In this qualitative review, Isa GBA region historical data were compared with findings from international and domestic inquiries to present an initial evaluation of five conceptual impact modes (Table 27). These were compared to the prioritisations from the Isa GBA region hazard analysis (Section 5.2) and are broadly consistent. Two impact modes have been prioritised for more detailed evaluation in the future: 'W3 – migration of fluids between different geological layers along a failure of the well casing' and 'W4 – failure of well integrity after well decommissioning/abandonment' (Section 6.4).

Tier 1 qualitative (screening) assessment found that 116 chemicals were used between 2011 and 2016 for drilling and hydraulic fracturing at shale, tight and deep coal gas operations across the three GBA regions. About a third (42 chemicals) were of 'low concern' and pose minimal risk to aquatic ecosystems. A further 33 chemicals were of 'potentially high concern' and 41 were of 'potential concern'. The identified chemicals of potential concern and potential high concern would require further site-specific quantitative chemical assessments to determine risks from specific gas developments to aquatic ecosystems (Section 6.3).

Natural rock formations contain elements and compounds (geogenic chemicals) that could be mobilised into flowback and produced waters during hydraulic fracturing. Laboratory-based leachate tests and extractions have provided an upper-bound estimate of geogenic chemical mobilisation from target formations in the Isa GBA region. These data may help guide future field-based monitoring, management and treatment options. Laboratory-based tests identified several naturally occurring elements and priority organic chemicals that could potentially be mobilised from formations by hydraulic fracturing fluids (Section 6.3).

Conclusion *see Section 7, page 213*

The baseline data, knowledge and conceptual models (Section 7.1) developed for Stage 2 can be used as the building blocks for any future impact and risk analysis of unconventional gas developments in the Isa GBA region. The impact and risk analysis methodology developed for the GBA program (and applied to the Cooper and Beetaloo GBA regions) can be used to guide future regional-scale impact assessments in the Isa GBA region. Further field-based investigations and targeted hydrological modelling would also help to address key stakeholder questions and prioritised knowledge gaps identified as part of Stage 2 (Section 7.2).

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

Contents

Figures

Tables

Contributors to the Program

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

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This technical product was reviewed by several groups:

- Activity Leaders: Russell Crosbie (Water Quantity), Lisa Hall (Geology), Jason Kirby (Chemical Assessment), Anthony O'Grady (Protected Matters), Brent Henderson (Impacts), Tim Ransley (Hydrogeology).
- Basin Leaders: Kate Holland (Cooper Basin), Paul Wilkes and Cameron Huddlestone-Holmes (Beetaloo Sub-basin).
- Technical Peer Review Group: Andrew Boulton, Peter McCabe, Catherine Moore, Jenny Stauber and Graeme Batley.
- State Government Science Technical Review: This group includes scientists from various Queensland Government departments.
- Additional reviewers: Sebastien Lamontagne (CSIRO).

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Abbreviations and acronyms

Abbreviation/acronym	Definition
ATP	Authority to prospect
CSG	Coal seam gas
DIWA	Directory of Important Wetlands in Australia
DST	Drill stem test
EA	Environmental authority
EC	Electrical conductivity
EIS	Environmental impact statement
EPBC Act	*Environment Protection and Biodiversity Conservation Act 1999*
ERA	Environmental risk authority
GAB	Great Artesian Basin
GBA	Geological and Bioregional Assessment
GCM	Global climate model
GDE	Groundwater-dependent ecosystem
GMA	Groundwater management area
IBRA	Interim Biogeographic Regionalisation for Australia
IMEA	Impact Modes and Effects Analysis
MNES	Matters of National Environmental Significance
MSES	Matters of State Environmental Significance
PFS	Polygonal fault system
PL	Petroleum lease
RCP	Representative concentration pathway
SEA	Strategic environmental area
TCW	Tasselled Cap Wetness
TDS	Total dissolved solids
TOC	Total organic carbon
WOfS	Water Observations from Space
Surface geology units (as depicted in map legend of Figure 41)	
Qd	Quaternary dunes, sand plains with dunes
Qe	Quaternary estuarine, tidal delta deposits; coastal mud flats
Qs	Quaternary sediments (undivided)
Qt	Quaternary lake and swamp deposits; mud, silt, evaporites, limestone, minor sand
Czc	Cenozoic consolidated siliclastic rocks

Abbreviation/acronym	Definition
Czz	Cenozoic silcrete
Kl	Cretaceous limestone
Ks	Cretaceous mudstone, siltstone, sandstone, conglomerate
JKs	Jurassic–Cretaceous mudstone, siltstone, sandstone, conglomerate
Js	Jurassic mudstone, siltstone, sandstone, conglomerate
El	Cambrian limestone
Lb	Paleoproterozoic mafic to ultramafic volcanic rocks
Lf	Paleoproterozoic felsic volcanic rocks
Lg	Paleoproterozoic felsic intrusive rocks
Ly	Paleoproterozoic low–medium grade siliclastic metamorphic rocks

Units

Unit	Description
bbl	barrels
bbl/mmscf	barrels per million standard cubic feet
Bcf	billion cubic feet
Bcm	billion cubic metres
Gpa	gigapascal
g/cc	grams per cubic centimetre
kPa	kilopascals
Ma	millions of years before the present
ML	megalitres
MPa	megapascals
MPa/km	megapascals per kilometre
m^3	metres cubed
mD	millidarcy
mg HC/g TOC	milligrams of hydrocarbons per gram of total organic carbon
mg/g	milligrams per gram
mg/L	milligrams per litre
mm/y	millimetres per year
mmbbl	million barrels
mmcfd	million cubic feet per day
mmscf	million standard cubic feet
mS/cm	millisiemens per centimetre (= 1000 uS/cm)
mole%	mole (as a percentage)
MW	megawatt
PJ	petajoules – 10^{15} joules
psi	pounds per square inch
psi/ft	pounds per square inch per foot
scc/g	standard cubic centimetres per gram
scf	standard cubic foot
scf/stb	standard cubic foot per stock tank barrel
stb	stock tank barrel
t	tonne (1000 kg)
%TOC	total organic carbon (as a percentage)

Unit	Description
Tcf	trillion cubic feet – 10^{12} cubic feet
%Ro	vitrinite reflectance (as a percentage)
wt%	weight (as a percentage)

1 About the region

1.1 Isa GBA region

The Isa GBA region is the focus area for the geological and bioregional assessment of the Isa Superbasin in north-west Queensland (Figure 3). This region contains part of the Isa Superbasin – a geological feature where previous exploration for petroleum resources, including shale gas, has occurred. For the purposes of this assessment, the Isa GBA region, which is about 8223 km^2 and centred on the remote township of Doomadgee, has been specifically defined as the area that:

- contains an identified unconventional hydrocarbon system (shale gas), hosted in Paleoproterozoic to Mesoproterozoic rocks of the Isa Superbasin
- is the most likely area of the Isa Superbasin where future development of unconventional hydrocarbon resources (shale gas) could result in delivery of gas to the East Coast Gas Market within five to ten years.

The Isa Superbasin is a poorly defined geological entity and is part of the larger North Australian Craton that covers much of north-western Queensland and extends into the NT. The region is a frontier area for hydrocarbon exploration and no gas or oil has ever been commercially produced (Bailey et al., 2020). The most recent exploration campaign, which was undertaken in 2013 and 2014 by Armour Energy Limited, targeted potential shale gas resources hosted within the Isa Superbasin.

Only small rocky outcrops of the Isa Superbasin are exposed at surface in and near the Isa GBA region. Instead, most of the superbasin rocks are buried beneath younger sedimentary basins, commonly at depths greater than 2 km below surface. The overlying basins include the Carpentaria Basin, which is part of Australia's vast groundwater system known as the Great Artesian Basin (GAB). The Australian Geological Provinces database does not currently have a formally agreed outline for the Isa Superbasin, indicative of the overall paucity of geoscientific data presently available to define its extents. Further information about the geology of the Isa Superbasin is in Section 2.1, with a detailed account provided in the geology technical appendix (Orr et al., 2020).

1.2 Area of hydrocarbon potential

Although the Isa Superbasin remains poorly defined, analysis of newly available geoscience data by the GBA team indicates the potential for hydrocarbon resources hosted in various sedimentary basins (i.e. not limited to the Isa Superbasin) to occur across a wider area of north-western Queensland and eastern NT. Consequently, a broader area based on analyses undertaken for this assessment has been defined and is here termed the 'area of hydrocarbon potential' (Figure 3). This area of hydrocarbon potential has been mainly constrained from interpretation of several recently released geoscientific datasets that cover parts of north-western Queensland, as well as the Greater MacArthur Basin area of the NT (refer to the geology technical appendix (Orr et al., 2020) for more information about the datasets used to define the area of hydrocarbon potential).

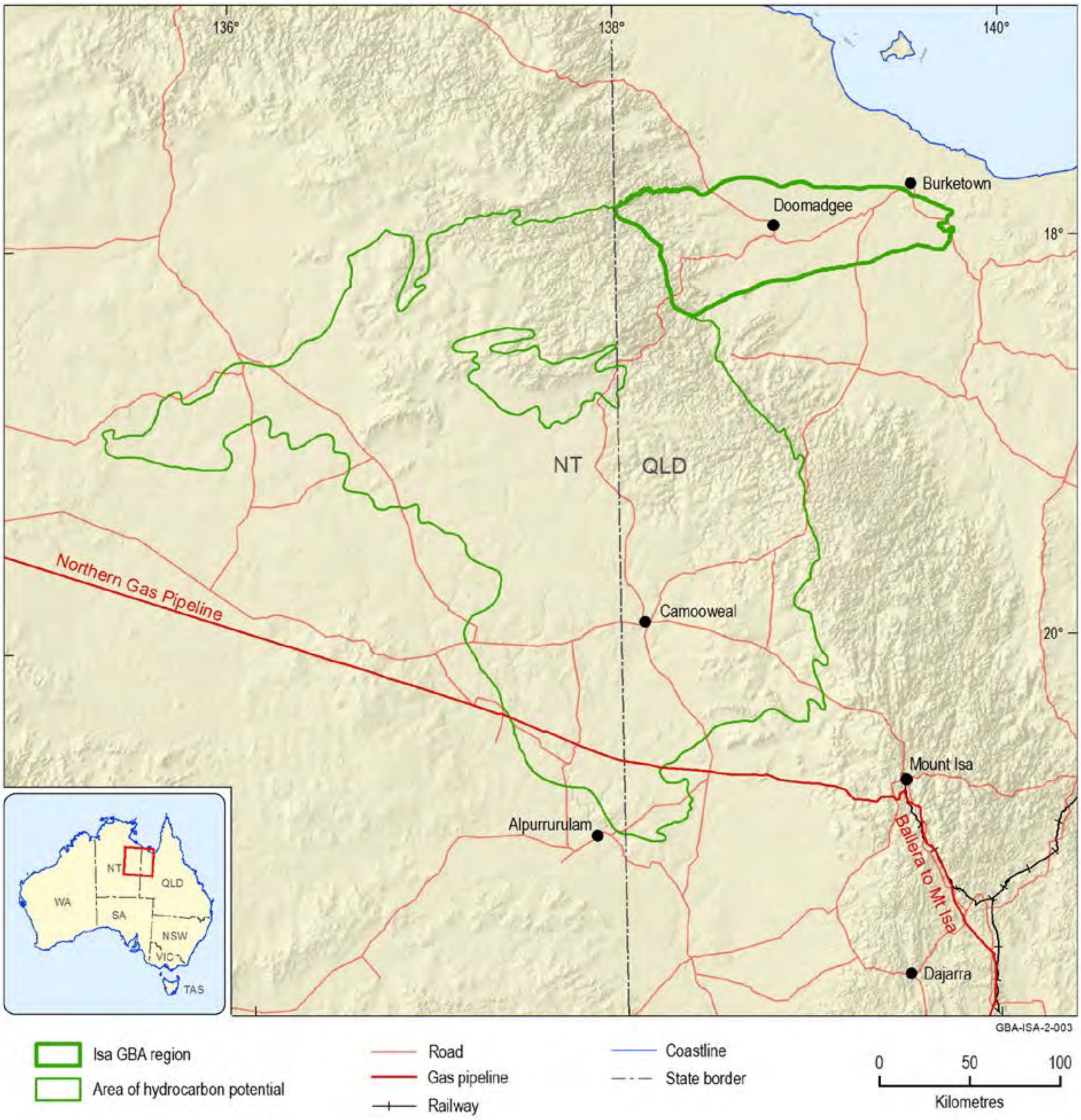

Figure 3 Isa GBA region and the area of hydrocarbon potential defined for the geological and bioregional assessment program

Most maps in this report show only the smaller Isa GBA region, not the broader area of hydrocarbon potential, as the Isa GBA region is the focus of this Stage 2 analysis. The Northern Gas Pipeline from Mount Isa to Tennant Creek was commissioned in late 2018.
Data: Pipeline routes from the GPInfo petroleum database, a Petrosys Pty Ltd product (Petrosys Pty Ltd, 2019)
Element: GBA-ISA-2-003

Although the extent of the 'area of hydrocarbon potential' has been defined for this study, there are scant data presently available to identify if unconventional petroleum reservoirs of the Isa Superbasin exist in this area. For example, there are limited seismic reflection data within the area, and fewer than ten petroleum exploration wells have been drilled (away from the Isa GBA region), with most of these sited near the margins and not the deeper, central part of the area. Consequently, the limited knowledge of unconventional hydrocarbon systems from this broader area effectively means that, for GBA purposes, the baseline assessment (i.e. this Stage 2 report) is restricted to the Isa GBA region.

1.3 Topography and landforms

The Isa GBA region occurs on relatively flat and low-lying savannah country south of the Gulf of Carpentaria in north-western Queensland (Figure 4). Across most of the region the elevation is less than 20 m relative to the Australian Height Datum (AHD) and rises to just over 100 mAHD only near the far western boundary close to the NT border. At its north-eastern boundary near Burketown, the Isa GBA region is less than 50 km from the mangrove-fringed coastline of the Gulf of Carpentaria. The extensive coastal plains in this part of the southern gulf country are part of Australia's largest marine plain environment and are subject to inundation due to the large tidal range, low elevation and frequency of low-pressure (commonly cyclonic) weather systems during the wet season.

The Isa GBA region sits on a broad area of well-vegetated alluvial and near-coastal plains, with widespread native grasslands and areas of sparse to moderately dense native woodlands. The mixed tussock grasslands are dominated by various native and introduced species, including Queensland bluegrass (*Dichanthium sericeum*) and barley Mitchell grass (*Astrebla pectinata*), whereas coolibah (*Eucalyptus microtheca*), whitewood (*Atalaya hemiglauca*) and beefwood (*Grevillea striata*) are common tree species in wooded areas. The alluvial floodplains, which are commonly sand- or loam-rich, are associated with the main streams that flow through the region, including the Nicholson River and the Gregory River, and various smaller tributaries such as Lawn Hill Creek (Figure 4).

Along the far western margin of the Isa GBA region the landscape is more rocky and rugged, with isolated ridges and low undulating hills sweeping down towards the plains. In this area the highly eroded remnants of various Proterozoic sedimentary rocks are dissected by ephemeral streams (such as the Nicholson River) that originate on the tableland country further west. Further information about vegetation and soil types associated with different landscape classes in the Isa GBA region is in Section 4.3, and information on the region's surface water is in Section 3.2.

There are three main landform systems within the Isa GBA region (Figure 5), based on the classification of Australia's physiographic regions (Pain et al., 2011). The Armraynald Plain physiographic region (part of the Carpentaria Lowlands Province) covers about two-thirds of the Isa GBA region, including most of the central, eastern and southern extents (Figure 5). This region is a clay-rich floodplain, with the regolith containing over 50% alluvial sediments and the remainder being either residual sands or highly weathered sedimentary bedrock. The Armraynald Plain covers a much larger area of the southern Gulf country than just the Isa GBA region, extending further south and east into the Leichhardt River catchment.

The western quarter of the Isa GBA region is part of the larger Gulf Fall physiographic region, dominated by ancient weathered bedrock outcrops and residual regolith cover (e.g. colluvial deposits and ferruginous duricrust). The topography, vegetation and regolith characteristics of the Gulf Fall differ from the flatter and lower lying plains that comprise most of the Isa GBA region. To the south-west of the Isa GBA region the Gulf Fall contains the renowned Boodjamulla (Lawn Hill) National Park (Figure 4), with its distinctive ragged sandstone escarpments and spectacular gorges, and the upper reaches of the clear perennial streams of Lawn Hill Creek and the Gregory River.

The smallest physiographic region that overlaps with the Isa GBA region is known as the Manangoora Plains, covering about 10% of the region's northern fringe. The Manangoora Plains largely coincide with the part of the Isa GBA region that occurs within the Settlement Creek catchment (Section 3.2). This physiographic region is characterised by broad, near-coastal alluvial plains that contain meandering rivers and streams contributing large amounts of sediment to the landscape.

A selection of images illustrating typical landscape features of the Isa GBA region is shown in Figure 6 to Figure 9.

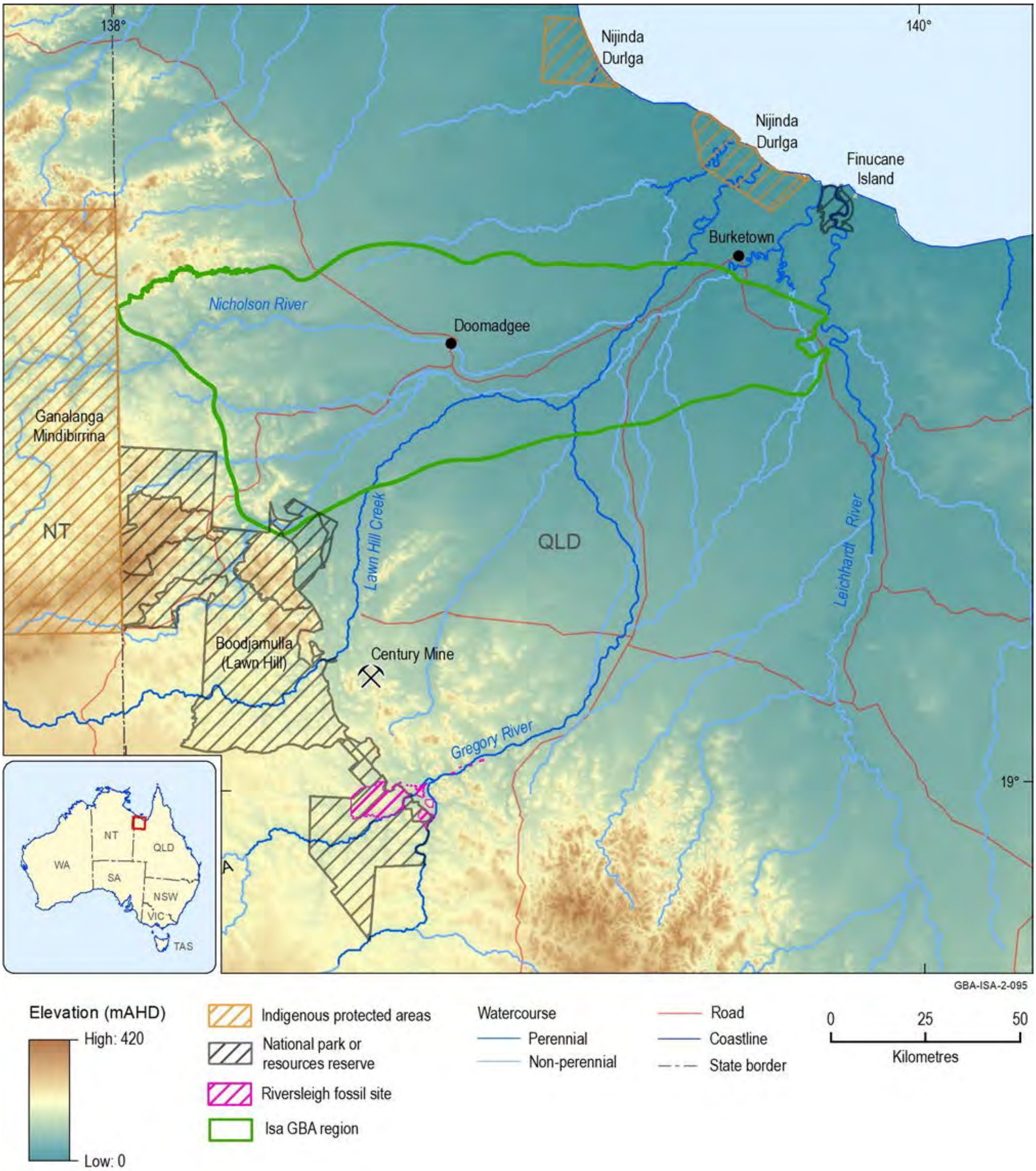

Figure 4 Land surface elevation and selected topographic features of the Isa GBA region

The two national parks labelled here are Boodjamulla (Lawn Hill) and Finucane Island. The Century Mine was one of the world's largest zinc mines during its 16-year operation from 1999 to 2015. New owners restarted operations at Century in 2018, with an initial focus on re-treating the previous mine tailings.
Data: Department of the Environment and Energy (2008); Geoscience Australia (2008)
Element: GBA-ISA-2-095

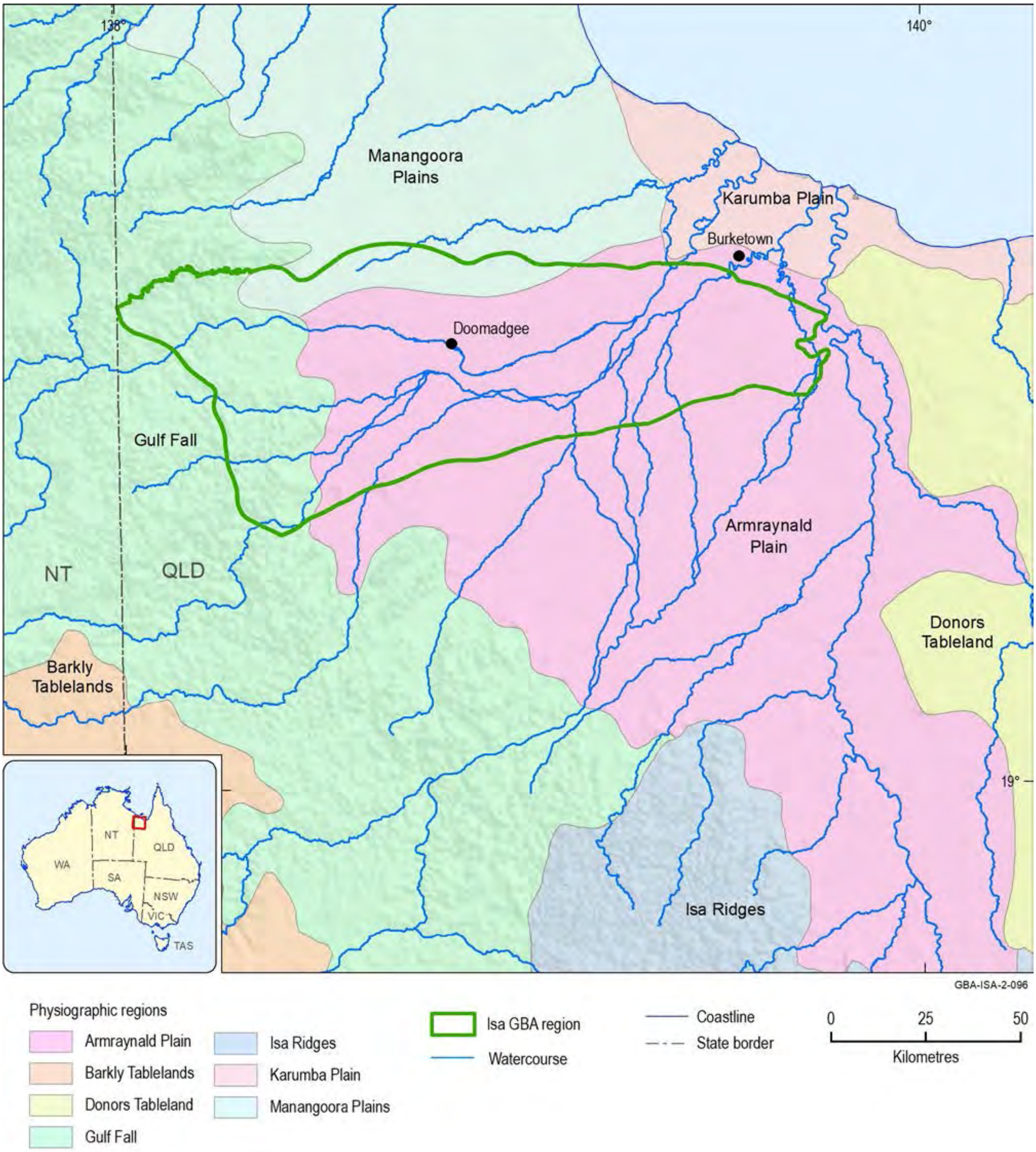

Figure 5 Physiographic regions of north-western Queensland, including the Armraynald Plain, Gulf Fall and Manangoora Plains within the Isa GBA region

Data: CSIRO (2010)
Element: GBA-ISA-2-096

Figure 6 A pastoral station track cuts through moderately forested grassland country south of the Nicholson River in the Isa GBA region, approximately 20 km east of Doomadgee

Source: Geological and Bioregional Assessment Program, Steven Lewis (Geoscience Australia), July 2018
Element: GBA-ISA-2-207

Figure 7 Cattle grazing near the Wills Developmental Road about 50 km south-west of Burketown. Large herds of various tropical breed cattle such as Brahman (*Bos indicus*) are common across the Gulf Savannah country, including the Isa GBA region

Source: Geological and Bioregional Assessment Program, Steven Lewis (Geoscience Australia), November 2018
Element: GBA-ISA-2-208

Figure 8 Agile wallabies (*Macropus agilis*) foraging in grassland on the outskirts of Burketown, during the early morning in the middle of the dry season

Source: Geological and Bioregional Assessment Program, Steven Lewis (Geoscience Australia), July 2018
Element: GBA-ISA-2-209

Figure 9 The Gregory River downstream of its crossing on the Doomadgee – Burketown Road

The Gregory River is one of the only perennial streams in the Isa GBA region. It is maintained by groundwater outflow from limestone aquifers of the geological Georgina Basin, which occur over 50 km upstream of the region.
Source: Geological and Bioregional Assessment Program, Steven Lewis (Geoscience Australia), July 2018
Element: GBA-ISA-2-210

1.4 Climate

The climate of the Isa GBA region is typical of tropical northern Australia and characterised by summer-dominated rainfall (highest rainfall occurs from December to February) with hot summers and relatively warm winters, as shown by the monthly distribution of rainfall and temperature data at three example sites in north-west Queensland: Burketown, Doomadgee and Mount Isa (Figure 10). Mean monthly precipitation in January and February is above 100 mm at Mount Isa in the south and above 200 mm at Burketown in the north. The minimum rainfall occurs through winter to early spring and is comparable at all three sites with less than 10 mm/month from May to September. The yearly mean rainfall at Burketown is about 785 mm, whereas the yearly mean rainfall for Mount Isa is about 460 mm. Mean maximum temperatures in summer range from 34 to 37 °C and mean minimum temperatures vary from 24 to 26 °C (Figure 10). Winter is warm and dry, with mean maximum temperature above 24 °C and mean minimum temperature above 10 °C.

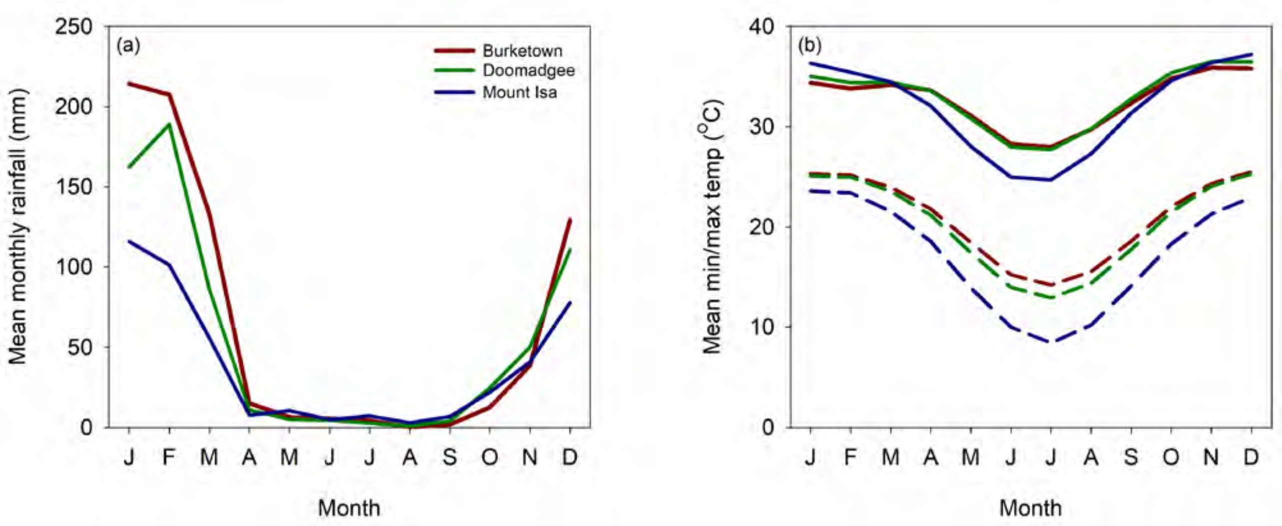

Figure 10 Burketown, Doomadgee and Mount Isa: (a) mean monthly rainfall; and (b) mean monthly maximum and minimum temperatures

The locations for Burketown, Doomadgee and Mount Isa are in Figure 3.
Data: Department of Environment and Science (Qld) (2018b)
Element: GBA-ISA-2-212

The inter-annual variability of rainfall (variation of rainfall from one year to the next) is substantial in the Isa GBA region, particularly due to the unpredictable influence of cyclones and associated low-pressure rainfall events (Figure 11). For example, the highest annual rainfall for the 30-year period 1976 to 2005 (2012 mm in 1998) is about three times the average rainfall at Burketown for the same period (769 mm/year). The average annual rainfall at Doomadgee is slightly lower than Burketown at 651 mm/year over the 30-year period and Mount Isa is lower again at 453 mm/year.

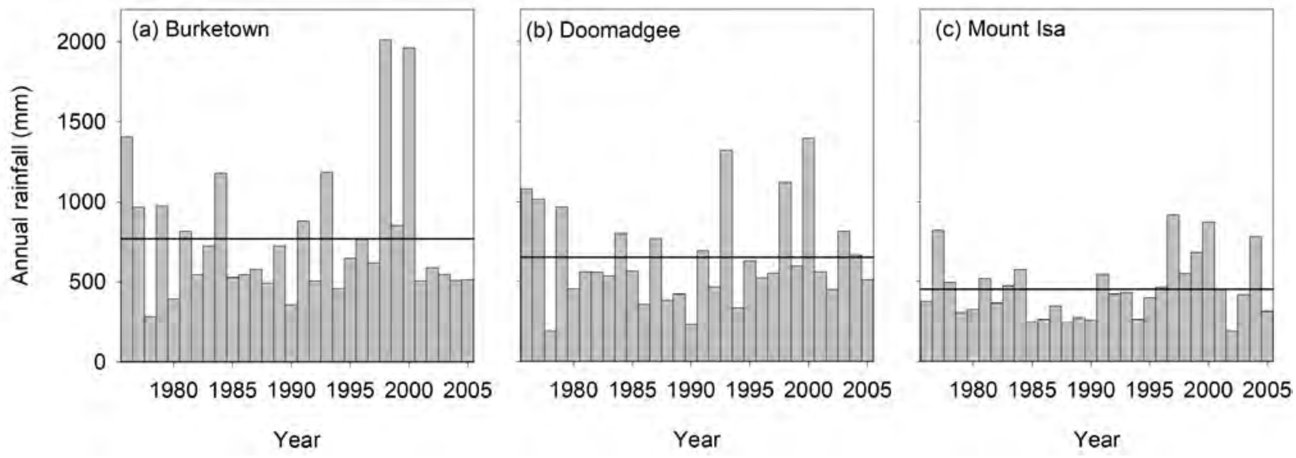

Figure 11 Annual series of rainfall totals for Burketown, Doomadgee and Mount Isa for the period 1976 to 2005

Line represents the mean annual rainfall for the 30-year period 1976 to 2005.
Data: Department of the Environment and Energy (2010)
Element: GBA-ISA-2-211

Methods snapshot: understanding future climates

Future climate projections are typically reported as a percentage change between the period of 1976 to 2005 to the period of 2046 to 2075 for the 10th, 50th and 90th percentiles of the 42 global climate models (GCMs). This report uses the representative concentration pathway (RCP) 8.5 scenario – a worst-case scenario in which emissions continue to rise throughout the 21st century. The projected median global mean temperature of the 42 GCMs is 2.0 °C higher for RCP8.5 in 2046 to 2075 relative to 1976 to 2005.

The climate data presented here are for the four surface water catchments that intersect the Isa GBA region and cover the areas investigated in this report. These are the Nicholson River, Leichhardt River, Settlement Creek and Morning Inlet catchments (see Section 3.2 for further information about the region's surface water). The broader focus on the regional climate provides greater context for the climate analysis of the Isa GBA region. The historical mean annual rainfall across the four catchments has a distinctive south-to-north trend in which rainfall increases from around 400 mm/year in the south-west to over 1000 mm/year at the coast in the Settlement Creek catchment. This trend is also evident at the smaller scale of the Isa GBA region, with about 570 mm/year rainfall in the south and up to 780 mm/year in the north. The historical rainfall mean for the Isa GBA region is 680 mm/year (Figure 12). Mean annual rainfall for the period 2046 to 2075 is projected to have little change under 50th percentile estimates, a decrease of up to 20% for the 10th percentile and an increase of up to 20% under the 90th percentile.

Mean annual potential evapotranspiration (PET) calculated using the Morton method (Chiew and McMahon, 1991) is high across all catchments, ranging from less than 1800 mm/year in the south to above 1900 mm/year in the north (Figure 13). PET for the Isa GBA region is relatively consistent, ranging from 1870 mm/year in the south to 1930 mm/year in the north with a mean of 1920 mm/year. PET is approximately 2.8 times greater than precipitation across the Isa GBA region. Mean annual PET for the period 2046 to 2075 is projected to increase for the three percentiles analysed across the Isa GBA region (Figure 13). Increases vary from 3% under the 10th percentile to 9% under the 90th percentile.

The number of hot days (maximum air temperature >35 °C) for the historical period of 1976 to 2005 across the Settlement Creek, Nicholson River, Leichhardt River and Morning Inlet catchments decreases from about five months in the Leichhardt River catchment in the east to about two months in the Settlement Creek catchment in the north. The Isa GBA region has an average of 130 days a year above 35 °C. The mean number of hot days for the period 2046 to 2075 is projected to increase for the three percentiles across the Isa GBA region (Figure 14). Increases vary: less than an additional 30 days under the 10th percentile, 40 to 80 days under the 50th percentile and potentially an extra 120 days under the extreme 90th percentile.

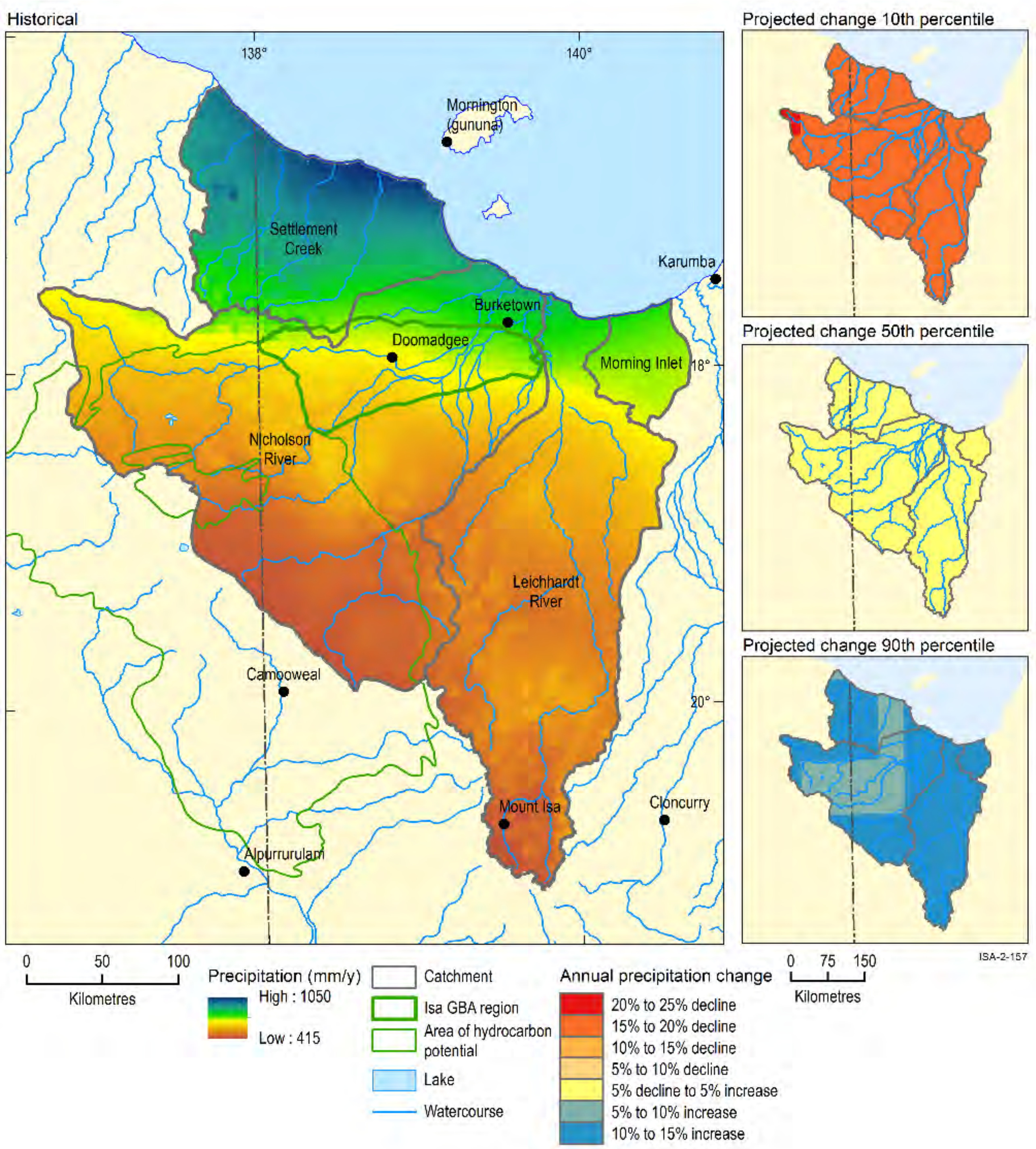

Figure 12 Spatial patterns of mean annual precipitation for the historical period (1976–2005) and 10th, 50th and 90th percentile estimates of projected percentage change in mean annual precipitation from the periods of 1976–2005 to 2046–2075 across the Settlement Creek, Nicholson River, Leichhardt River and Morning Inlet catchments

Percentiles of projected scenarios are from 42 CMIP5 global climate models under emission in RCP8.5.
AWRC = Australian Water Resources Council; CMIP5 = Coupled Model Intercomparison Project Phase 5
Data: Geological and Bioregional Assessment Program (2018a); Geological and Bioregional Assessment Program (2018c)
Element: GBA-ISA-2-157

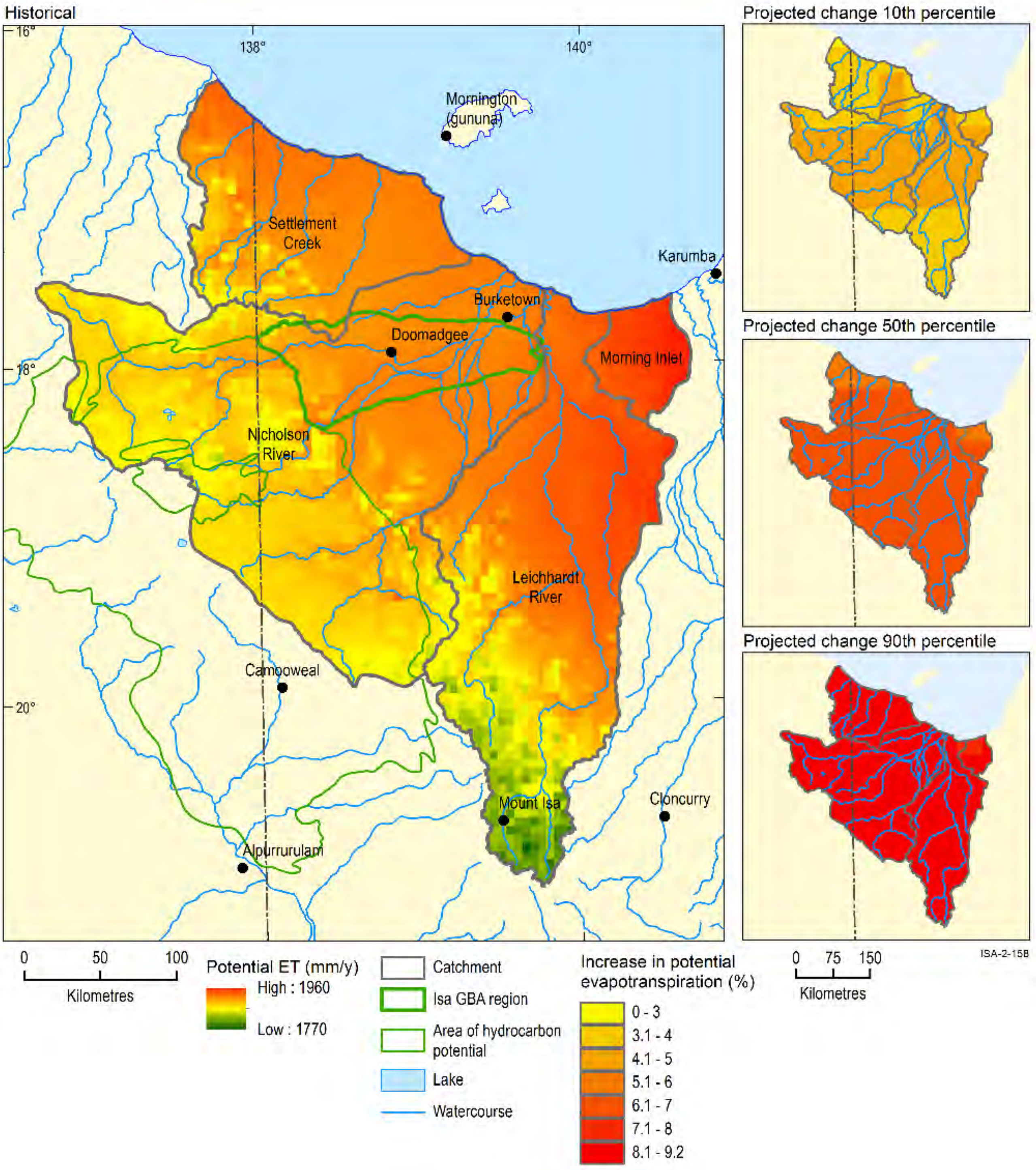

Figure 13 Spatial pattern of mean annual potential evapotranspiration (PET) (1976–2005) and 10th, 50th and 90th percentile estimates of projected percentage change in mean annual PET from the periods of 1976–2005 to 2046–2075 across the Settlement Creek, Nicholson River, Leichhardt River and Morning Inlet catchments

Potential evapotranspiration was calculated using the Morton method (Chiew and McMahon, 1991).
Percentiles of projected scenarios are from 42 CMIP5 global climate models under emission in RCP8.5.
AWRC = Australian Water Resources Council; CMIP5 = Coupled Model Intercomparison Project Phase 5; ET = evapotranspiration
Data: Geological and Bioregional Assessment Program (2018a); Geological and Bioregional Assessment Program (2018c)
Element: GBA-ISA-2-158

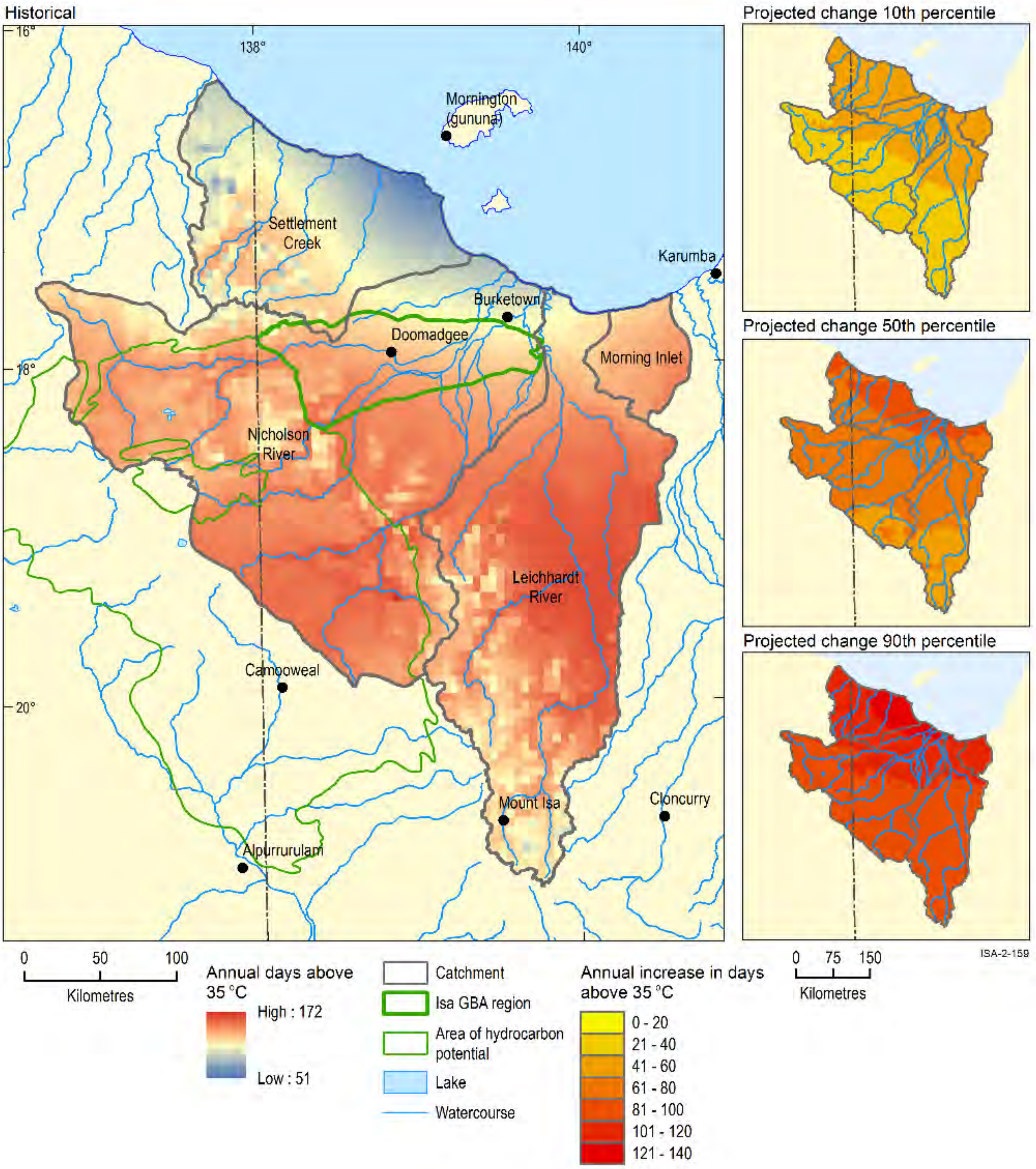

Figure 14 Spatial patterns of mean annual hot days (maximum air temperature >35 °C for 1976–2005) and 10th, 50th and 90th percentile estimates of projected change in hot days from the periods of 1976–2005 to 2046–2075 across the Settlement Creek, Nicholson River, Leichhardt River and Morning Inlet catchments

Percentiles of projected scenarios are from 42 CMIP5 global climate models under emission in RCP8.5.
AWRC = Australian Water Resources Council; CMIP5 = Coupled Model Intercomparison Project Phase 5
Data: Geological and Bioregional Assessment Program (2018a); Geological and Bioregional Assessment Program (2018c)
Element: GBA-ISA-2-159

1.5 Population and land use

Like much of Outback north-west Queensland the Isa GBA region is very sparsely populated. The 2016 Australian census indicated that fewer than 2000 people live permanently within the region (Australian Bureau of Statistics, 2016a). Doomadgee, which has an estimated population of about 1400 (of which about 90% are of Indigenous heritage), is centrally located and the only recognised town within the Isa GBA region (Figure 4). Further east, Burketown sits just outside the northern boundary of the region and has a population of around 160 (Australian Bureau of Statistics, 2016b). Burketown is an important regional centre in the southern gulf country, providing goods and services to pastoralists, Indigenous people and visiting tourists. Tourist numbers typically swell in the cooler dry season months from May to September, with visitors active in a range of outdoor pursuits such as camping, sightseeing and fishing.

The main local government area in the Isa GBA region is the Shire of Burke, which covers over 40,000 km^2 of far north-western Queensland stretching along the southern Gulf of Carpentaria to the NT border. In 2010, the Doomadgee Aboriginal Shire Council was established within the central part of the Burke Shire as a stand-alone council by the Queensland Government (under a Deed of Grant in Trust). The Doomadgee Aboriginal Shire is about 1860 km^2, with the southern half of the shire within the Isa GBA region (Figure 15).

The mainstay of the local economy in the Isa GBA region is the multi-million-dollar beef cattle industry (Figure 7), active across many large-scale leasehold properties across the Gulf country. Ten pastoral stations, including Lawn Hill, Bowthorn and Armraynald, intersect the Isa GBA region. Collectively, these large pastoral holdings cover many thousands of square kilometres. The latest version of the Australian Land Use and Management Classification dataset (version 8) indicates that almost 90% of the land within the Isa GBA region is classed as grazing native vegetation (Figure 15). This dataset also highlights the variable extent of tidal inundation that occurs across the flat near-coastal plains north of Burketown.

The traditional homelands of the Gangalidda, Garawa and Waanyi peoples occur within and around the Isa GBA region. The Traditional Owners of the region have inhabited this land for many thousands of years and continue to maintain strong cultural connections – for example, through ceremonial occasions and by harvesting a variety of native plants and animals. Approximately 70% of the Isa GBA region has had native title rights determined, including about 2600 km^2 under the Waanyi people's determination to the south and west of Doomadgee (determined in December 2010) and a further 2445 km^2 under the Gangalidda and Garawa peoples' determination from April 2015 (north and east of Doomadgee). More recently, the Gangalidda People (Pendine) Claim, which covers about 710 km^2 to the north-east of Doomadgee, was determined in March 2019. There is also part of the Waanyi People #2 registered native title application area within the Isa GBA region. To the north of the region there are several designated areas along the coastline that are part of the Gangalidda Indigenous Protected Area known as Nijinda Durlga (Figure 4).

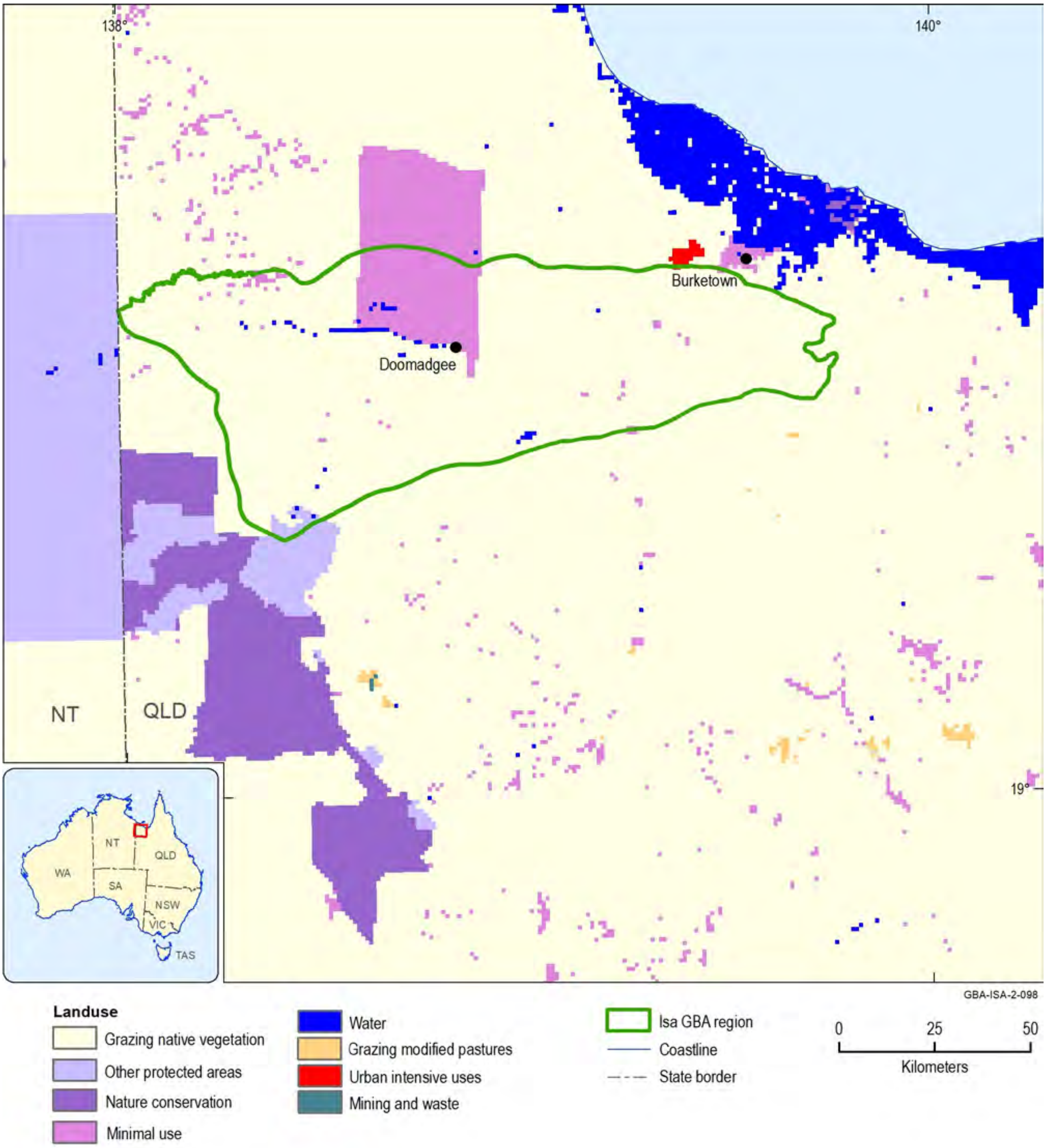

Figure 15 Land use within the Isa GBA region

Land use within the Isa GBA region is predominantly associated with grazing of native vegetation, reflecting the strong economic reliance on the beef cattle industry in this area. The area classed as 'minimal use' north of Doomadgee coincides with the Doomadgee Aboriginal Shire Council.
Data: Australian Bureau of Agricultural and Resource Economics and Sciences (2016)
Element: GBA-ISA-2-098

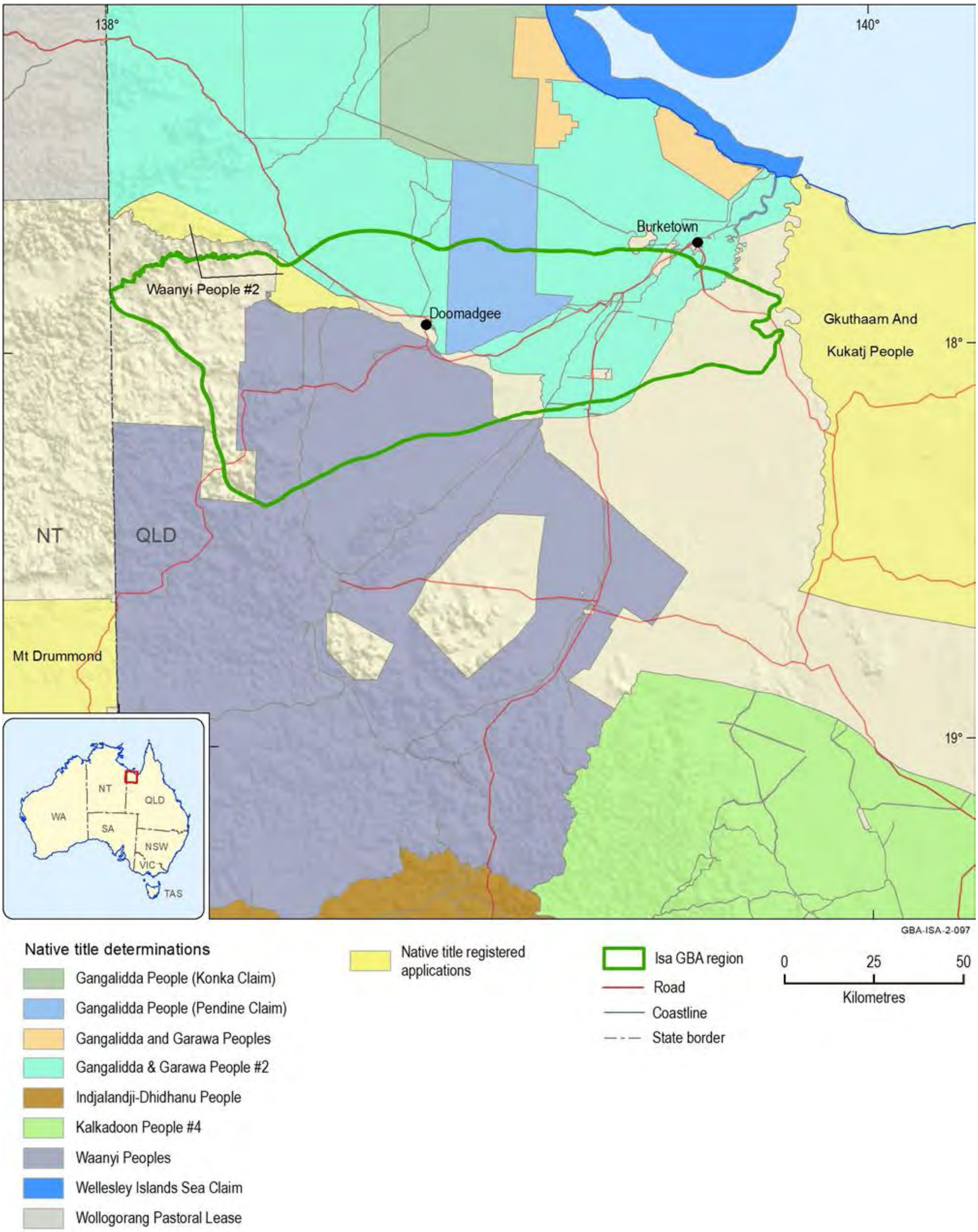

Figure 16 Areas of native title determinations and applications in north-western Queensland

Data: National Native Title Tribunal (2019)
Element: GBA-ISA-2-097

1.6 *Water and resource development legislation and regulations*

The development of unconventional gas resources, including shale gas, is an emerging industry in Australia that has raised community concerns over potential impacts on water resources, biodiversity, social and human capital and other non-renewable natural resources, such as air quality and the depletion of the target resource. As such, the industry is regulated at federal, state and local levels to ensure that industry development is undertaken in a sustainable and responsible manner that minimises impacts on environmental and social values. The following sections outline the Commonwealth and Queensland regulations relevant to the development of shale gas resources in the Isa GBA region.

1.6.1 Commonwealth legislation

Five main pieces of Commonwealth legislation regulate the development of shale gas resources in Australia (Table 1). The *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) specifically relates to Matters of National Environmental Significance (MNES) and is discussed in more detail below.

Table 1 Commonwealth legislation that may relate to the development of petroleum resources

Legislation	Description	Administering department
Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act)	Protects and manages nationally and internationally important flora, fauna, ecological communities, wetlands (e.g. Ramsar) and heritage places. The EPBC Act is the overarching legislation for strategic assessments and has a specific trigger related to water resources associated with coal seam gas and coal mine development.	Department of the Environment and Energy
Aboriginal and Torres Strait Islander Heritage Protection Act 1984	Preserves and protects places, areas and objects of significance to Aboriginals, where 'Aboriginal' means a member of the Aboriginal race of Australia and includes a descendant of the Indigenous inhabitants of the Torres Strait Islands. This act sits under and complements the EPBC Act.	Attorney-General's Department, Department of the Environment and Energy
Native Title Act 1993	Establishes and provides the framework for recognition and protection of native title.	Attorney-General's Department, Department of the Prime Minister and Cabinet (Indigenous Affairs)
Industrial Chemicals (Notification and Assessment) Act 1989	Provides for notification and assessment of the use of industrial chemicals within Australia.	Department of Health (through the National Industrial Chemicals Notification and Assessment Scheme)

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

1.6.1.1 Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999*

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

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

The nine MNES are:

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

Generally, proposed activities are individually submitted to the Department of the Environment and Energy for assessment. A strategic assessment for an industry type (e.g. petroleum resource industry), however, takes a bigger picture approach over the impacted region. Rather than looking at how a single activity will affect nationally protected matters, a strategic assessment looks at how a group of activities (under a policy, plan or program) will affect these matters regionally. As well as helping to protect Australia's unique biodiversity, strategic assessments also benefit the community, developers, industry and government by cutting red tape and providing greater long-term certainty.

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

Within this context, the GBA Program aims to facilitate and support integration with the Queensland Government's strategic assessment of proposed development of shale gas resources in the Isa GBA region and to streamline compliance with the EPBC Act. Strategic assessments (Part 10 of the EPBC Act) may offer the opportunity to examine and potentially approve a series of new proposals or developments at a much larger scale and time frame than can be achieved using a project-by-project referrals process. Strategic assessments enable the consideration of cumulative impacts on MNES and seek to explore opportunities for conservation and planning outcomes at a scale that could not be addressed via a project-by-project referral process.

Strategic assessment typically involves two steps:

1. assessment and endorsement of a 'policy, plan or program' (the program)
2. approval of actions (or classes of actions) that are associated with the program. This step potentially enables the resource development to proceed across large areas without need for further approval under the EPBC Act.

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

1.6.2 Queensland legislation

Shale gas development is subject to the same regulatory conditions that govern the exploration and development of coal, oil and gas resources in Queensland. These requirements have been previously reviewed by the Queensland Competition Authority (2014) and by Huddlestone-Holmes et al. (2018) and are summarised here. Regulation is achieved via a nested hierarchy of primary legislation, subordinate legislation, administrative decisions or discretions and quasi-regulation (Figure 17).

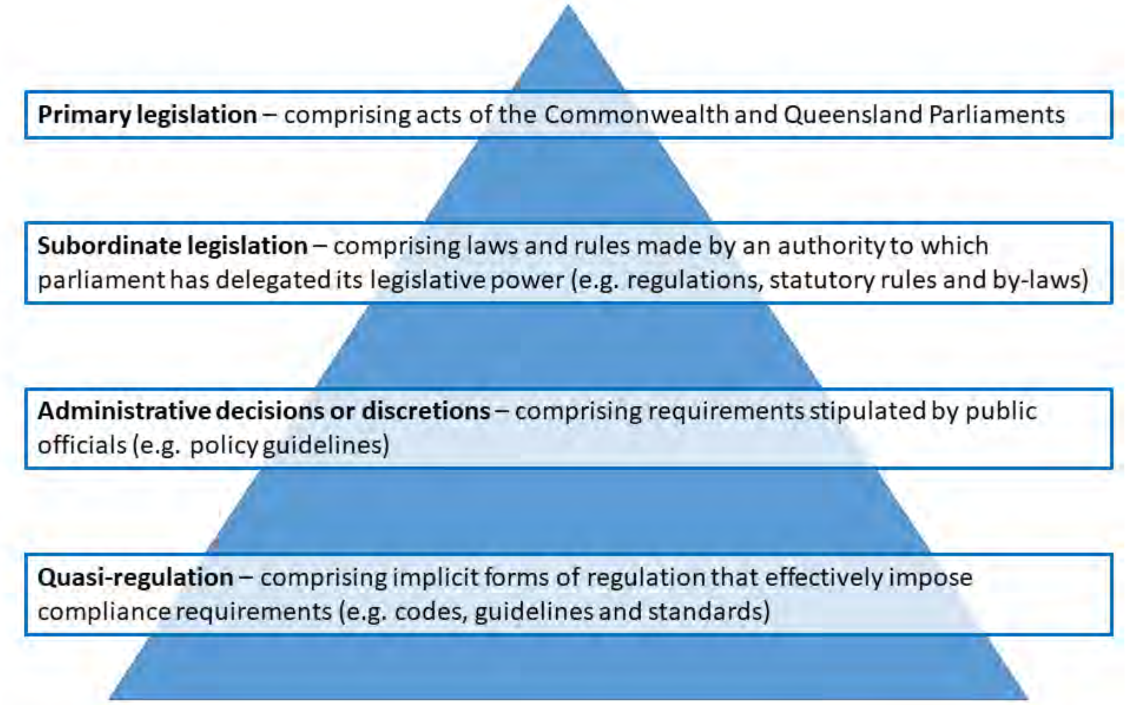

Figure 17 Regulation hierarchy in Queensland showing how subordinate legislation, policies and codes are nested below primary legislation

Source: Queensland Competition Authority (2014)
Element: GBA-ISA-2-198

There are six primary pieces of Queensland legislation applying to the petroleum resource industry. These are additional to the Commonwealth legislation that provides the overarching regulatory environment for the development of unconventional gas resources in Queensland, including shale gas (Table 2). There are additional regulations in Queensland that are also relevant to the development of these unconventional gas resources (Table 3).

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

Legislation	Description	Administering department
Petroleum Act 1923	Regulates certain petroleum and natural gas activities. The *Petroleum and Gas (Production and Safety) Act 2004* supersedes this Act, but an amended version of the *Petroleum Act 1923* was retained so that the rights of existing permit holders were not lost.	Department of Natural Resources, Mines and Energy
Queensland Heritage Act 1992	Provides for the protection of Queensland's cultural heritage.	Department of Environment and Science
Environmental Protection Act 1994	Regulates activities to avoid, minimise or mitigate impacts on the environment and to protect Queensland's heritage places.	Department of Environment and Science
Water Act 2000	Regulates the sustainable management of Queensland's water resources, water supply and the impacts on groundwater caused by the extraction of groundwater by the resources sector.	Department of Natural Resources, Mines and Energy; Department of Environment and Science

Legislation	Description	Administering department
Petroleum and Gas (Production and Safety) Act 2004	Regulates petroleum and gas exploration tenure, safety, production and pipelines.	Department of Natural Resources, Mines and Energy
Water Supply (Safety and Reliability) Act 2008	Regulates interactions and direct impacts associated with drinking water supply.	Department of Natural Resources, Mines and Energy; Department of Health
Gasfields Commission Act 2013	Established the Gasfields Commission – an independent statutory body with powers to review legislation and regulation; obtain and disseminate information; advise on coexistence issues; convene parties to resolve issues; and make recommendations to government and industry.	The commission is independent, but administrative matters are handled by the Department of State Development, Manufacturing, Infrastructure and Planning.
Planning Act 2016	Establishes integrated land use planning and development to achieve ecological sustainability. Provides standards and requirements for bore construction, especially artesian bores.	Department of State Development, Manufacturing, Infrastructure and Planning

Data: Queensland Competition Authority (2014)

Table 3 Additional Queensland legislation relevant to the development of petroleum resources in Queensland

Legislation	Description	Administering department
Environmental Offsets Act 2014	Regulates the requirements and management of environmental offsets in response to activities that cause a significant residual impact on prescribed environmental matters.	Department of Environment and Science
Environmental Protection (Water) Policy 2009	Identifies environmental values and management goals for Queensland waters, including water quality guidelines and objectives and monitoring and reporting on Queensland waters.	Department of Environment and Science
Mineral and Energy Resources (Common Provisions) Act 2014	Regulates land access for mineral and energy resource authority holders. Commenced on 27 September 2016.	Department of Natural Resources, Mines and Energy
State Development and Public Works Organisation Act 1971	Provides ability for Queensland's Coordinator-General to declare a project a 'coordinated project'. Coordinated projects require an environmental impact statement and a higher level of public input.	Department of State Development, Manufacturing, Infrastructure and Planning
Waste Reduction and Recycling Act 2011	Promotes waste avoidance and reduction, reduces consumption of natural resources, minimises the impact of waste generation and ensures shared responsibility between government, business and the community.	Department of Environment and Science
Regional Planning Interests Act 2014	Identifies and protects areas of Queensland that are of regional interest and resolves potential land use conflicts. Protects living areas in regional communities, high-quality agricultural areas from dislocation, strategic cropping land, and strategic environmental areas.	Department of State Development, Manufacturing, Infrastructure and Planning

Legislation	Description	Administering department
Public Health Act 2005	Protects and promotes the health of the Queensland public. Allows for public health orders to be issued that require the removal or reduction of the risk to public health from a public health risk or to prevent that risk from recurring. Allows for investigation of health complaints.	Department of Health
Fisheries Act 1994	Regulates the use of waterway barriers that may impact on fish movement along a waterway.	Department of Agriculture and Fisheries
Forestry Act 1959	Regulates activities involving the clearing of forest products and access to quarry material on state land.	Department of Agriculture and Fisheries
Biosecurity Act 2014	Manages and contains weeds and pest animals.	Department of Agriculture and Fisheries (Biosecurity Queensland)
Nature Conservation Act 1992	Regulates the protection of flora and fauna and enables offset conditions to be imposed on certain authorities.	Department of Environment and Science
Aboriginal Cultural Heritage Act 2003	Regulates activities to protect Queensland's Indigenous cultural heritage values.	Department of Aboriginal and Torres Strait Islander Partnerships
Queensland Heritage Act 1992	Regulates activities to protect Queensland's heritage places.	Department of Environment and Science
Transport Operations (Road Use Management) Act 1995	Regulates the transportation of dangerous goods by road, manages road use impacts, and issues directions on road use, including payment of compensation.	Department of Transport and Main Roads
Sustainable Planning Act 2009	Regulates developments not conducted under a relevant petroleum tenement.	Department of Infrastructure, Local Government and Planning
Work Health and Safety Act 2011	Provides a framework to protect the health, safety and welfare of all workers at work. It also protects the health and safety of all other people who might be affected by the work.	Office of Industrial Relations, which resides in the Queensland Department of Education

Source: Huddlestone-Holmes et al. (2018)

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

- The project proponent applies for an authority to prospect (ATP). An ATP allows a proponent to explore for petroleum resources (such as shale gas), test for petroleum production, evaluate the feasibility of petroleum production and evaluate or test natural underground reservoirs for the storage of petroleum or a prescribed storage gas. The process is conducted through tender and regulated through the *Petroleum and Gas (Production and Safety) Act 2004.* The financial and technical capability of proponents (i.e. the authority holder) is assessed along with an initial work program. An ATP holder must also obtain an environmental authority (EA) from the Queensland Department of Environment and Science (DES), and this must be done concurrently with the ATP tenure process. The requirements of the EA are regulated by the *Environmental Protection Act 1994.* Queensland waters, including water in rivers, streams, wetlands, lakes, groundwater aquifers estuaries and coastal areas, are protected by the *Environmental Protection (Water) Policy 2009*. The policy sets values (cultural, spiritual and environmental) and water quality objectives for Queensland waters.

- The holder of an ATP must comply with all conditions and any other permits and authorities that may be needed – for example, avoiding disturbance of sites of cultural significance in accordance with the *Aboriginal Cultural Heritage Act 2003*. Importantly, there are also obligations for ATP holders to engage and negotiate with relevant Indigenous groups, regardless of whether native title determination has been made or applied for.
- The holder of an ATP can apply to have the ATP declared as a potential commercial area to continue evaluation of production and market potential. The holder will be bound by the EA or would need to have the EA amended to reflect any planned activities.
- Once the ATP holder confirms the potential of the commercial viability of the project, the applicant can apply for a petroleum lease, also regulated through the *Petroleum and Gas (Production and Safety) Act 2004.* The applicant must submit an initial development program as part of their application. Applicants for a petroleum lease must obtain an EA or amend an existing EA for the development program. At this point consideration should be given to potential impacts on MNES that may trigger a referral under the EPBC Act. The Queensland Government's DES may require an environmental impact statement (EIS) to be prepared, according to the requirements of the *Environmental Protection Act 1994*. If the lease is considered to be commercially viable it must be developed within 15 years.
- If the project is deemed a 'coordinated project' (i.e. one deemed by the Queensland Coordinator-General as requiring rigorous impact assessment involving whole-of-government coordination), an EIS would need to be prepared under the requirements of the *State Development and Public Works Organisation Act 1971*. Regardless, environmental assessments are still required for projects that are not deemed a 'coordinated project'.
- The operator must operate in accordance with the conditions of their petroleum lease (PL) and EA and meet all other legislative requirements relevant to their activities.
- In an area of regional interest, such as a Strategic Environmental Area (SEA), a proponent will also have to obtain a regional interests development approval under the *Regional Planning Interests Act 2014*. This is directly relevant to the Isa GBA region, as the Gulf Rivers SEA is an area of regional interest and covers much of the region (see Section 4.1.3.2 for further discussion of the Gulf Rivers SEA).
- If the operator seeks to access groundwater or surface water resources to support their project, they must apply for an entitlement to take or interfere with water, which is made under the *Water Act 2000*. In the Isa GBA region, access to available water resources must also comply with specific requirements under the Water Plan (Gulf) 2007 or the Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017.

2 Geology and shale gas resources

2.1 Regional geological architecture

The Paleoproterozoic to earliest Mesoproterozoic Isa Superbasin is a geological province primarily defined in north-west Queensland. Although the full area covered by the superbasin remains unknown, it is likely to extend under cover into the NT for several hundred kilometres. The Isa GBA region contains only that part of the Isa Superbasin in Queensland explored for shale gas resources (as of November 2019). Overlying sedimentary basins include the Mesoproterozoic South Nicholson Basin, the Mesozoic Carpentaria Basin and the Cenozoic Karumba Basin. Regional aquifers that supply groundwater for a variety of users occur within the Carpentaria Basin, including the artesian Gilbert River Formation.

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

This section summarises the architecture and evolution of the Isa Superbasin and overlying geological South Nicholson, Carpentaria and Karumba basins. A more detailed review of the region's geological architecture is in the geology technical appendix (Orr et al., 2020).

2.1.1 Geological setting

The Isa Superbasin is a Paleoproterozoic to earliest Mesoproterozoic geological province in the North Australian Craton. It has been primarily identified and described from the Lawn Hill Platform within the complex Mount Isa Orogen in north-western Queensland. However, it extends under cover for potentially several hundred kilometres and has been identified in McArthur Basin sequences in the NT (Figure 3).

The geological and bioregional assessment of the Isa GBA region focuses on the northern Lawn Hill Platform of the Isa Superbasin – an area where limited exploration for shale gas resources hosted within organic-rich shales of the River and Lawn supersequences is currently underway (Bailey et al., 2020; Orr et al., 2020). The extent of the Isa GBA region (Figure 18) is constrained herein as the maximum extent of preserved and relatively continuous hydrocarbon-prone Isa Superbasin sedimentary rocks of the northern Lawn Hill Platform (Figure 18). Data constraints in the broader Isa Superbasin region currently preclude shale (and other) gas prospectivity assessments beyond the northern Lawn Hill Platform (Bailey et al., 2020).

Methods snapshot: comparing Proterozoic and Phanerozoic Earth

The Isa Superbasin formed during the Paleoproterozoic to earliest Mesoproterozoic eras (approximately 1670 to 1575 Ma). Earth at this time was markedly different from the Phanerozoic Earth of the present day. The planet had cooled to the point where modern-day plate tectonic processes became dominant, allowing for stable continents to form and accrete through significant mountain-building events (Ogg et al., 2016). However, land plants had yet to evolve (Knauth and Kennedy, 2009) and organic matter deposited alongside sediments was derived from simple organisms living in a marine environment, which may have included planktonic algae (Glikson et al., 2006; Glikson et al., 1992) and bacteria (Brocks et al., 2017), or from the growth of microbial mats, such as stromatolites. The conditions under which the organic matter was preserved in the Isa Superbasin sediments differ substantially from later Phanerozoic marine conditions. Proterozoic organic rich sediments were deposited under conditions of widespread ocean anoxia in the 1800 to 1000 Ma period (Planavsky et al., 2011). Anoxic conditions in depositional environments are associated with organic matter preservation and can result in enrichment of total organic carbon in sediments.

The Isa Superbasin overlies the Paleoproterozoic Calvert Superbasin throughout the Isa GBA region (Figure 19) and contains the prospective River and Lawn supersequences – organic-rich marine shales that are the key shale gas source rocks in the Isa GBA region (Bailey et al., 2020). The Isa Superbasin is completely exposed at the surface over the southern flanks of the Murphy Inlier in the north-west of the Isa GBA region and is partially exposed over the south-west part of the region, where it forms the McNamara Group (Bradshaw et al., 2000). The Isa Superbasin occurs beneath younger sedimentary basins in most parts of the Isa GBA region. The Mesoproterozoic South Nicholson Basin unconformably overlies the Isa Superbasin and is mainly preserved in the Gregory River Trough over the eastern part of the Isa GBA region (Figure 18) (Bradshaw et al., 2018a; Jackson et al., 1999; Sweet, 2017).

Mesozoic sedimentary rocks from the Carpentaria Basin unconformably overlie both the Isa Superbasin and the South Nicholson Basin over much of the Isa GBA region (McConachie et al., 1997). Sedimentary rocks from the Carpentaria Basin form an east-north-east-thickening wedge which reaches a maximum thickness of about 900 m in the eastern Isa GBA region (Bradshaw et al., 2018a). The Carpentaria Basin is in turn overlain by a relatively thin veneer (less than 250 m thick) of Cenozoic sediments from the Karumba Basin (McConachie et al., 1997; Smerdon et al., 2012b). Both the Carpentaria and Karumba basins are absent over the western part of the region.

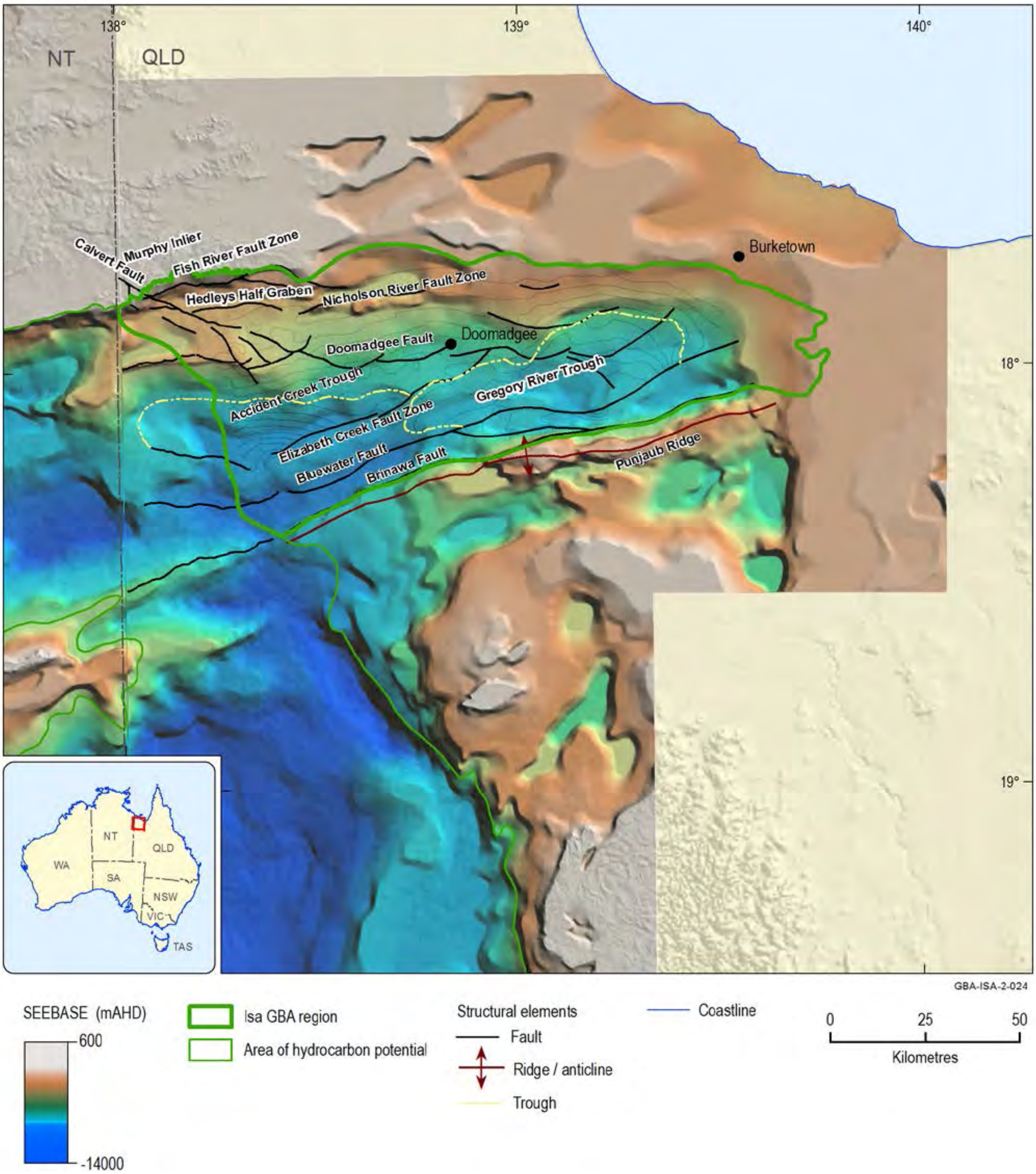

Figure 18 Structural elements map for the Isa GBA region superimposed over the Geological Survey of Queensland's depth to basement grid

AHD = Australian Height Datum

Source: Orr et al. (2020). Depth to basement grids are sourced from Frogtech Geoscience (2018b) for Queensland and Frogtech Geoscience (2018a) for the NT. Structural elements are derived from the base River Supersequence and the base Term Supersequence depth-structure maps of Bradshaw et al. (2018a)

Data: Bradshaw et al. (2018a); Frogtech Geoscience (2018b); Frogtech Geoscience (2018a)

Element: GBA-ISA-2-024

2.1.2 Structural elements

The Isa GBA region is located over a southward-thickening sequence of gently to moderately deformed sedimentary rocks from the Isa Superbasin (Figure 19 and Figure 20), which is generally referred to in geological literature as the northern Lawn Hill Platform (Day, 1983).

The structural architecture of the northern Lawn Hill Platform is dominated by a series of east-north-east-trending to east-trending fault systems, ridges and troughs, with some south-east-trending faults systems also present (Figure 18) (Bradshaw et al., 2018a; Scott and Tarlowski, 1999). These structural elements developed through a series of extensional and contractional tectonic events that occurred during and following deposition of the Isa Superbasin (Scott et al., 1998).

The southern boundary of the northern Lawn Hill Platform is formed by the east-north-east-trending Brinawa Fault System (Figure 18), which separates highly deformed and partially exhumed Isa Superbasin rocks over the Punjaub Ridge to the south from the wedge of preserved Isa Superbasin deposits to the north (Bradshaw et al., 2018a).

The northern boundary of the northern Lawn Hill Platform occurs over the Murphy Inlier basement rock complex (Figure 18), where a relatively thin (less than 1 km thick) package of sedimentary rocks from the Isa Superbasin is exposed at the surface (Bradshaw et al., 2000).

Strata from the Isa Superbasin deepen and thicken to the south (Figure 19) and are dissected by a series of north-dipping fault systems. These include the south-east-trending Calvert Fault, the east-trending Nicholson River Fault Zone and Doomadgee Fault System, and the east-north-east-trending Elizabeth Creek Fault Zone and Bluewater Fault System (Bradshaw et al., 2018a; Scott and Tarlowski, 1999) (Figure 19). These faults form the bounding structures for the major depocentres over the northern Lawn Hill Platform, including the Accident Creek and Gregory River troughs and the Hedleys Half Graben (Bradshaw et al., 2018a; Scott and Tarlowski, 1999) (Figure 18).

All of these faults were active during the 1640 Ma to 1630 Ma River extensional event. Most of these faults were subsequently reactivated during the 1595 Ma Wide transtensional tectonic event and during multiple compressional events following deposition of the Isa Superbasin (Scott and Tarlowski, 1999). Post-depositional compression inverted the northern, eastern and southern margins of the northern Lawn Hill Platform and also generated several ridges and a major east-north-east-trending synform over the Gregory River Trough (Bradshaw et al., 2018a; Scott and Tarlowski, 1999) (Figure 18).

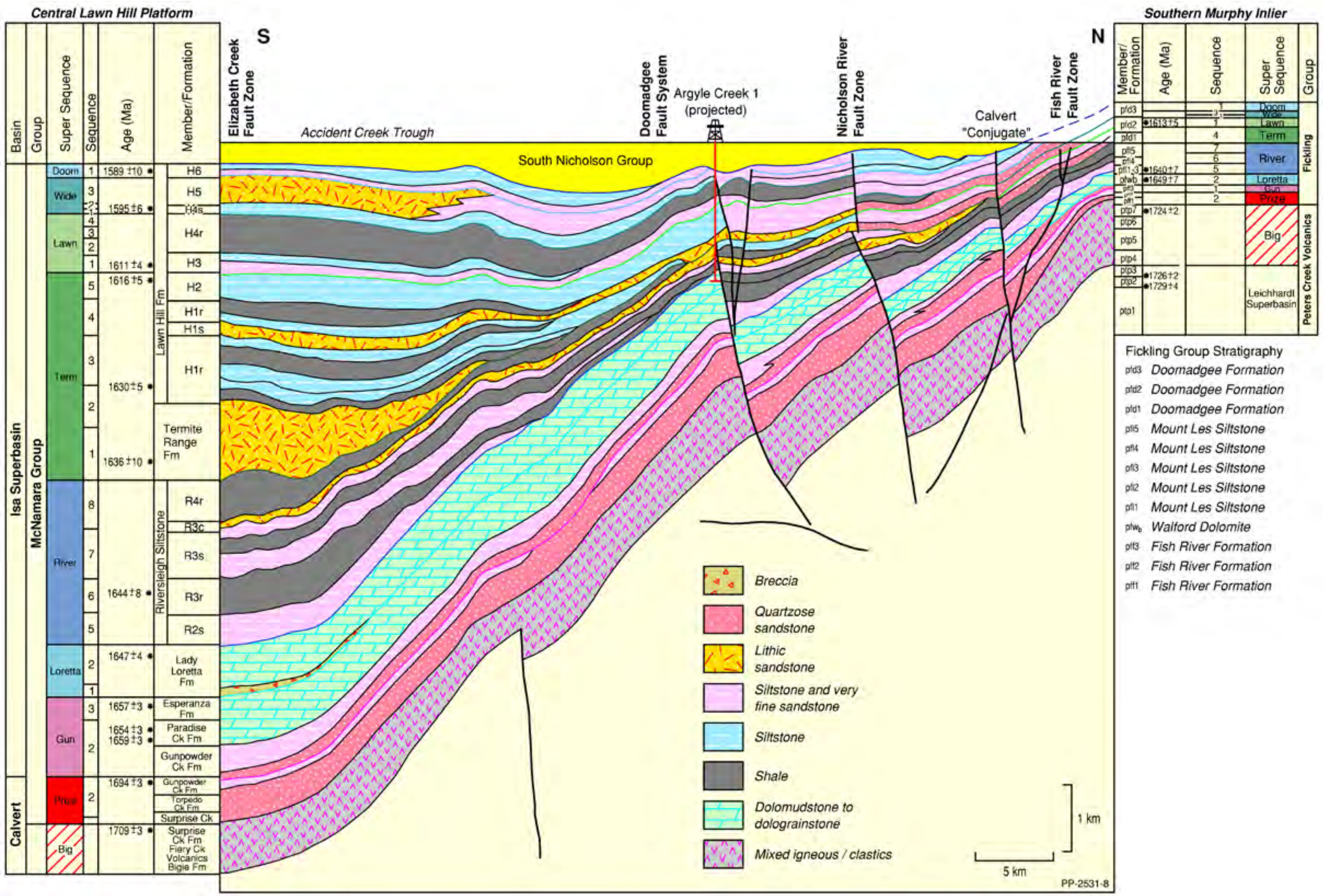

Figure 19 Schematic cross-section showing the stratigraphic architecture of supersequences and lithofacies units across the Isa GBA region

Presently, facies variations are poorly understood and those depicted in this figure are based on interpretation of limited well and seismic data, extrapolated through sequence stratigraphic relationships. The location of this south-to-north cross-section is shown in Figure 32.

Source: Orr et al. (2020), modified from Bradshaw et al. (2000)

Element: GBA-ISA-2-114

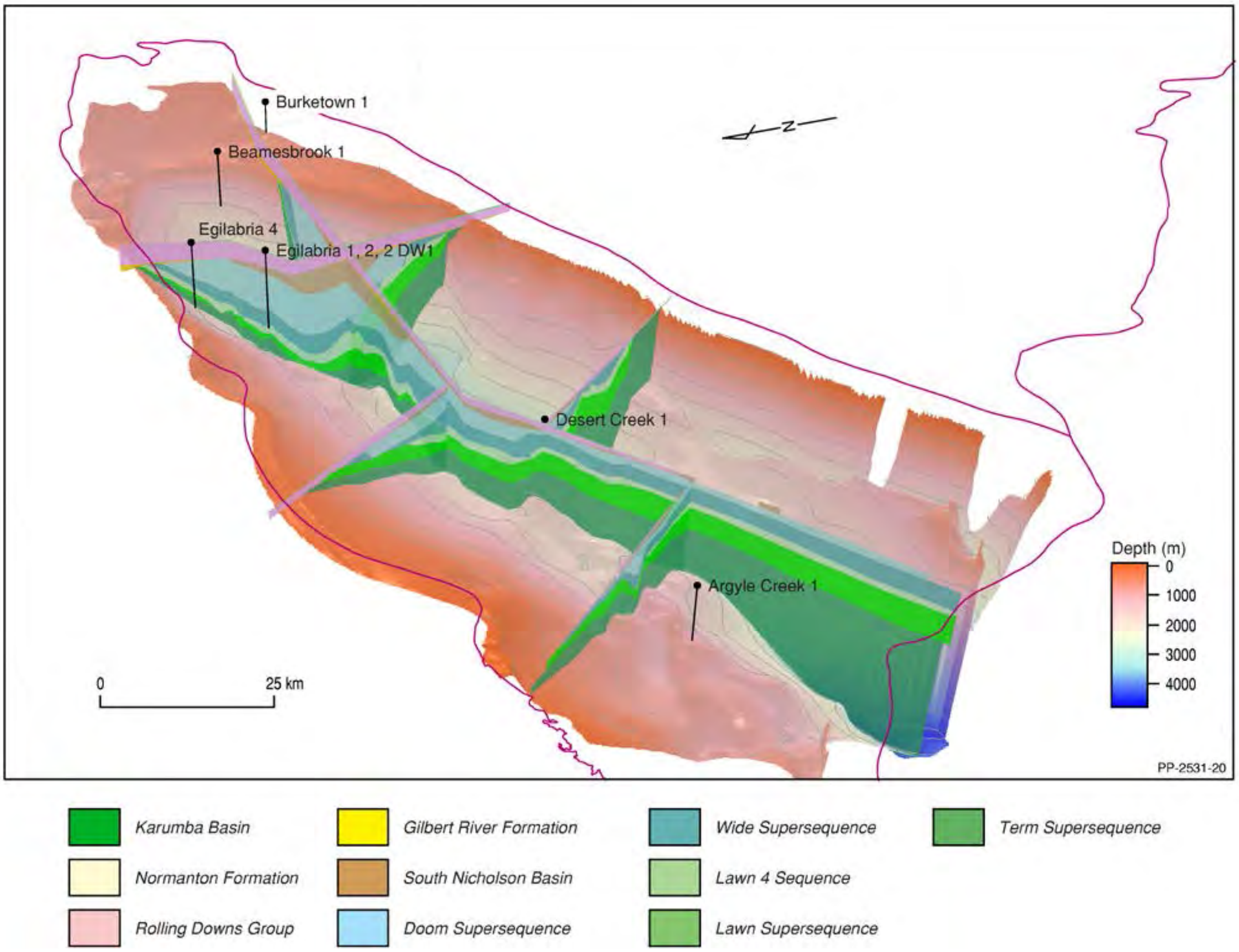

Figure 20 Oblique view of the regional three-dimensional geological model for the Isa Superbasin over the Isa GBA region (looking to the east)

The structural surface shown is the base of the Term Supersequence.
Source: Orr et al. (2020); based on the depth-converted grids published by Bradshaw et al. (2018a)
Data: Bradshaw et al. (2018a)
Element: GBA-ISA-2-121

2.1.3 Basin evolution

2.1.3.1 Isa Superbasin

The Isa Superbasin formed over a period of about 100 million years, from the late Paleoproterozoic to the early Mesoproterozoic. The sedimentary record associated with the Isa Superbasin is described using a sequence stratigraphic framework that subdivides the basin fill into seven supersequences (Table 4) (Figure 21) (Gorton and Troup, 2018; Southgate et al., 2000a). These supersequences define genetically related rock units deposited during major phases of basin subsidence, which often followed periods of erosion associated with major tectonic events.

Table 4 Stratigraphy of the Isa Superbasin

Supersequence	Lithostratigraphic equivalent	Lithological description	Maximum thickness (m)	Depositional environments
Doom	Lawn Hill Formation (upper Widdallion Sandstone Member (Pmh 5) and Pmh 6)	Sandstone, siltstone, shale, carbonate	1000	Fluvial, coastal, marine shelf, deep marine
Wide	Lawn Hill Formation (Widdallion Sandstone Member (Pmh 5) and upper Pmh 4)	Sandstone, siltstone, dolomitic siltstone, shale	1100	Coastal, marine shelf, deep marine
Lawn	Lawn Hill Formation (Bulmung Sandstone Member (Pmh 3) and lower Pmh 4)	Sandstone, siltstone, tuffaceous sandstone and siltstone, shale	900	Shoreface, marine shelf, deep marine
Term	Termite Range Formation, Lawn Hill Formation (units Pmh 1 and Pmh 2)	Sandstone, siltstone, tuffaceous sandstone and siltstone, shale	3500	Marine shelf to deep marine
River	Riversleigh Siltstone	Sandstone, siltstone, shale	3500	Coastal, marine shelf, deep marine
Loretta	Lady Loretta Formation	Breccia, carbonate	1400	Coastal to marine shelf
Gun	Upper Gunpowder Creek Formation, Paradise Creek Formation, Esperanza Formation	Sandstone, siltstone, carbonate	1700	Fluvial, coastal, marine shelf, deep marine

The geological units described here are presented in the stratigraphic diagram shown in Figure 21. The term 'Pmh' is a lithostratigraphic code used to identify the Lawn Hill Formation.
Source: geology technical appendix (Orr et al., 2020); based on data published in Krassay et al. (2000a) and Bradshaw et al. (2000)

Methods snapshot: sequence stratigraphy and lithostratigraphy in the Isa Superbasin

Published stratigraphic frameworks for basins in the Isa GBA region vary between the sub-disciplines of sequence stratigraphy and lithostratigraphy. The Isa Superbasin is described using sequence stratigraphy, whereas the Carpentaria and Karumba basins are described using lithostratigraphy. Both approaches are applied to the South Nicholson Basin.

The supersequences and sequences of sequence stratigraphy are composed of genetically linked strata related in time with boundaries defined by time-correlative erosional surfaces or depositional hiatus, whereas units in lithostratigraphy are defined on mappable units of comparable lithology with boundaries defined by mappable changes in primary lithology. A detailed methods snapshot further delineating the differences in each approach is available in the geology technical appendix (Orr et al., 2020).

There are seven identified supersequences within the Isa Superbasin. However, in the Isa GBA region, the River and Lawn supersequences are currently the focus of exploration for unconventional petroleum resources. The River Supersequence is composed of eight sequences on the central Lawn Hill Platform. However, in the Isa GBA region the River Supersequence consists of the sequences River 5 to 8 (Riversleigh Siltstone). River 1 (upper Lady Loretta Formation), River 2 to 3 (Shady Bore Quartzite) and River 3 to 4 (lower Riversleigh Siltstone) are interpreted as absent over the Isa GBA region. The Lawn

Supersequence is composed of four sequences, all of which are present on the central Lawn Hill Platform and through the Isa GBA region. Lawn 1 contains significant sand bodies (the Bulmung Sandstone Member, Pmh_3) as opposed to Lawns 2, 3 and 4 (the Lawn Hill Formation, lower Pmh_4), which contain very similar fine-grained facies. Lawn 4 is of interest for hydrocarbon prospectivity (Lawn Hill Formation, lower Pmh 4) as it is composed of organic-rich mudstones.

For further detail on both stratigraphic sequences, see the geology (Orr et al., 2020) and the shale gas prospectivity (Bailey et al., 2020) technical appendices.

Sedimentation began at about 1670 Ma during a period of extension associated with the opening of a small ocean basin between the Australian and Laurentian paleocontinents (Geological Survey of Queensland, 2011). The Gun Supersequence was initially deposited over the Isa GBA region, with fluvial and coastal sandstones deposited to the north and deeper water sandstones and siltstones deposited to the south (Bradshaw et al., 2000; Southgate et al., 2000b). A rise in relative sea level subsequently flooded the basin, resulting in a change from the deposition of shallow marine sandstones and siltstones to marine carbonates (Southgate et al., 2000b).

Uplift that was focused over the Murphy Inlier (a basement high) at about 1655 Ma is believed to have resulted in erosion of the Gun Supersequence and deposition of a breccia unit at the base of the Loretta Supersequence (Bradshaw et al., 2000). Deposition of a thick platform carbonate succession (Loretta Supersequence) was due to subsequent flooding by a shallow marine seaway (Southgate et al., 2000b). Loretta Supersequence deposition ended at about 1650 Ma during a major uplift and crustal shortening event associated with convergence of Australia and Laurentia (Gibson et al., 2017; Gibson et al., 2016). Much of the Loretta Supersequence was eroded over the northern parts of the Isa GBA region during this event.

The River Supersequence was deposited during the 1640 Ma to 1630 Ma River extension event (Frogtech Geoscience, 2018b; Gibson et al., 2016; Scott and Tarlowski, 1999). Regional north- to south-directed extension produced a series of major fault systems across the Isa GBA region. A pronounced change in sedimentation occurred with coastal and marine sandstones, siltstones and shales deposited in a series of fault-bounded depocentres. Marine sediments included organic-rich shales, which are key shale gas source rocks for the Isa Superbasin.

A change in sedimentation occurred at about 1630 Ma during the initial deposition of the Term Supersequence, with an influx of debris flow sandstones sourced from the Murphy Inlier and subsequently deposited in deep marine depocentres to the south (Frogtech Geoscience, 2018b; Krassay et al., 2000a). These debris flow deposits are known to occur in the Accident Creek Trough over the south-western part of the Isa GBA region but are absent to the north and north-east (Bradshaw et al., 2018a; Krassay et al., 1999). The upper part of the Term Supersequence consists of deep marine siltstones and carbonaceous shales grading up into marine shelf tuffaceous siltstones (Krassay et al., 2000a). These finer grained deposits from the upper part of the Term Supersequence were deposited during a period of regional thermal subsidence and extend across much of the region. There are no proven shale gas source rocks within any of the Term Supersequence deep marine shales within the Isa GBA region.

A regional uplift event occurred at about 1615 Ma that initiated deposition of high-energy, volcanic clast-rich shallow marine sandstones at the base of the Lawn Supersequence, extending across much of the Isa GBA region (Bradshaw et al., 2000; Krassay et al., 2000a). Subsequent thermal subsidence produced deeper marine environments, which produced progressively finer grained and more organic-rich sediments within the Lawn Supersequence (Krassay et al., 2000a). Highly organic-rich shale units at the top of the Lawn Supersequence form a major shale gas source rock within the Isa GBA region. Deposition of the Lawn Supersequence ended at about 1600 Ma during a period of uplift and erosion associated with the beginning of the Isan Orogeny, which eroded the shale gas source rock interval over the northern parts of the region (Bradshaw et al., 2018a).

The Wide Supersequence was deposited during a period of fault reactivation (the 'Wide Event') at the beginning of the Isan Orogeny from 1595 to 1585 Ma (Lindsay et al., 1999). Deposition occurred within fault-bounded depocentres across the Isa GBA region (Lindsay et al., 1999). Wide Supersequence deposits coarsen-up from marine shelf siltstones and dolomitic siltstones and shale into deep marine debris flow sandstones (Bradshaw et al., 2000).

The Doom Supersequence was deposited during a subsequent period of post-deformational subsidence prior to the end of Isa Superbasin deposition at about 1580 Ma (Bradshaw et al., 2018a). Deposition occurred in three distinct phases: (i) an initial high sediment flux phase of deep marine debris flow sandstones; (ii) a high accommodation phase of marine shelf siltstones, shales and carbonates; and (iii) a tectonically enhanced phase of shelf siltstones coarsening upwards to shallow marine to coastal and fluvial sandstones associated with the culmination of the Isan Orogeny (Krassay et al., 2000b).

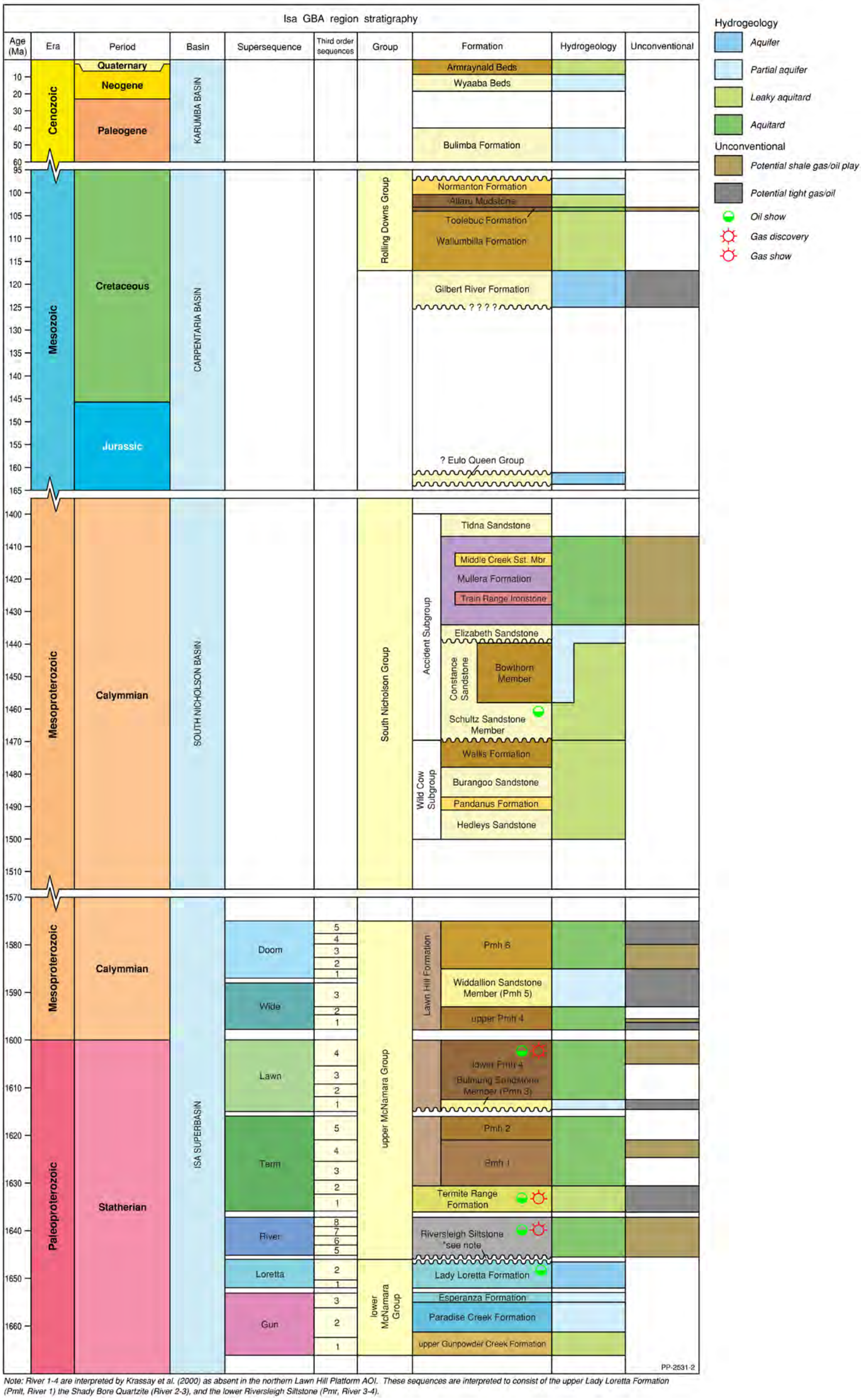

Figure 21 Sequence stratigraphy, lithostratigraphy, hydrostratigraphy and hydrocarbon occurences of the Isa Superbasin, South Nicholson Basin, Carpentaria Basin and Karumba Basin

The chart breaks at 1300 to 840 Ma and 480 to 120 Ma are for display purposes. Potential play types shown (shale gas/oil plays and tight gas/oil plays) are as indicated by Gorton and Troup (2018) and are, in most part, speculative based on present data. Only the shale gas plays of the River and Lawn supersequences have been confirmed as prospective. The figure has been optimised for printing on A3 paper (297 mm x 420 mm).

Source: Isa Superbasin and South Nicholson Basin after Gorton and Troup (2018); Carpentaria Basin after (Cook et al., 2013a) and McConachie et al. (1997); Karumba Basin after (Cook et al., 2013a); hydrostratigraphic units – see the hydrogeology technical appendix (Buchanan et al., 2020)

Element: GBA-ISA-2-113

2.1.3.2 South Nicholson Basin

The Mesoproterozoic South Nicholson Basin is interpreted to have formed between 1500 to 1400 Ma following a prolonged (about 70 My) period of deformation during the Isan Orogeny (Frogtech Geoscience, 2018b; Jackson et al., 1999; Rawlings et al., 2008; Sweet, 2017). Subsequent deformation of the South Nicholson Basin is likely to have occurred during amalgamation of the North and West Australian cratons with the South Australian Craton at about 1324 Ma (Frogtech Geoscience, 2018b; Sweet, 2017).

The stratigraphy of the South Nicholson Basin is divided into two subgroups – the Wild Cow Subgroup and the Accident Subgroup, which are separated by a major unconformity (Figure 21 and Table 5) (Gorton and Troup, 2018; Sweet, 2017). There are no proven hydrocarbon source rock intervals within the South Nicholson Basin.

The Wild Cow Subgroup is subdivided by Sweet (2017) into the Hedleys Sandstone, Pandanus Formation, Burangoo Sandstone and Wallis Formation. The Hedleys and Burangoo sandstones consist predominantly of sandstones deposited in fluvial to shallow marine environments, while the Pandanus and Wallis formations consist mainly of storm-dominated marine shelf shales, siltstones and thinly interbedded sandstones (Sweet, 2017; Withnall and Hutton, 2013).

Table 5 Stratigraphy of the South Nicholson Basin

Stratigraphic unit	Formation	Age	Lithological description	Maximum thickness (m)	Depositional environments
Accident Subgroup	Tidna Sandstone	Mesoproterozoic	Sandstone	350	Shallow marine
	Mullera Formation	Mesoproterozoic	Mainly shale and siltstone punctuated by sandstone, ferruginous sandstone, ironstone and minor conglomerate	2110	Shallow marine, storm-dominated marine shelf, deep marine
	Elizabeth Sandstone	Mesoproterozoic	Sandstone	200	Shallow marine
	Constance Sandstone	Mesoproterozoic	Conglomerate, sandstone (Schultz Sandstone Member) Shale, siltstone and sandstone (Bowthorn Member)	1170	Fluvial (Schultz Sandstone Member) Storm-dominated marine shelf (Bowthorn Member)
Wild Cow Subgroup	Wallis Formation	Mesoproterozoic	Shale, siltstone and minor sandstone	150	Storm-dominated marine shelf
	Burangoo Sandstone	Mesoproterozoic	Sandstone	320	Shallow marine to fluvial
	Pandanus Formation	Mesoproterozoic	Shale, siltstone and interbedded sandstone	130	Storm-dominated marine shelf
	Hedleys Sandstone	Mesoproterozoic	Conglomerate, sandstone	90	High-energy fluvial

Source: geology technical appendix (Orr et al., 2020); based on data published in Sweet (2017)

The Accident Subgroup includes the Constance Sandstone, Elizabeth Sandstone, Mullera Formation and Tidna Sandstone (Sweet, 2017). The Constance Sandstone consists of a lower unit of fluvial sandstones and conglomerates, which are overlain by alternating marine shelf mudstones and sandstones (Sweet, 2017). These are in turn unconformably overlain by the shallow marine sandstones from the Elizabeth Sandstone (Sweet, 2017). Deeper marine siltstones and shales make up the Mullera Formation, which is overlain by shallow marine sandstones from the Tidna Sandstone (Carr et al., 2016; Sweet, 2017; Withnall and Hutton, 2013).

2.1.3.3 Carpentaria Basin

The Carpentaria Basin is a Jurassic to Cretaceous geological basin that overlies the western part of the Isa GBA region. The basin deepens to the east and north, extending beneath most of the Gulf of Carpentaria (Figure 21 and Table 6) (Bradshaw et al., 2009; McConachie et al., 1997). The Carpentaria Basin formed during a period of regional subsidence in the Middle Jurassic and was subsequently locally faulted, uplifted and eroded around the basin margins during the Late Cretaceous (McConachie et al., 1997).

The oldest known Carpentaria Basin deposits in the Isa GBA region are the non-marine to shallow marine sandstones and siltstones from the lower Cretaceous Gilbert River Formation (McConachie et al., 1997). The Gilbert River Formation and Eulo Queen Group form part of the regionally important Cadna-owie–Hooray Aquifer of the Great Artesian Basin (Radke et al., 2012), which is further discussed in Section 3.1. The Gilbert River Formation progressively thins to the west and terminates stratigraphically against Proterozoic Isa Superbasin rocks within the Isa GBA region (Bradshaw et al., 2018a).

The Rolling Downs Group was deposited during a major rise in relative sea level and subsequent relative sea level retreat in the mid to Late Cretaceous. It consists of a basal marginal marine to deep marine sandstone, siltstone and silty limestone unit (Wallumbilla Formation), a middle organic-rich marine shale and carbonate unit (Toolebuc Formation), an upper shallow marine to nearshore sandstone, siltstone and claystone unit (Allaru Mudstone) and a marginal to shallow marine sandstone and siltstone unit known as the Normanton Formation (Audibert, 1976; McConachie et al., 1997). Although organic-rich source rock intervals are present within the Toolebuc Formation, these do not have the thermal maturity required to generate hydrocarbons across the Isa GBA region (Troup et al., 2015). The Rolling Downs Group forms a thick aquitard that overlies the Cadna-owie–Hooray Aquifer (Gilbert River Formation) and terminates over the western part of the Isa GBA region, where it has been uplifted and eroded near the basin margin (Ransley et al., 2012).

The Normanton Formation is the youngest stratigraphic unit from the Carpentaria Basin preserved in the Isa GBA region. It consists of near-shore to shallow marine sandstones and siltstones (McConachie et al., 1997). The Normanton Formation is also the youngest aquifer in the Carpentaria Basin, but it is only preserved over the eastern part of the region. Farther west, the Normanton Formation has been eroded (Ransley et al., 2012).

Table 6 Stratigraphy of the Carpentaria Basin

Stratigraphic unit	Age	Lithological description	Maximum thickness (m)	Depositional environments
Normanton Formation	Cenomanian	Glauconitic sandstone and siltstone	300	Marginal marine to shallow marine
Allaru Mudstone	Albian	Claystone, siltstone, calcareous siltstone, glauconitic sandstone	700	Shallow marine
Toolebuc Formation	Albian	Carbonaceous shale and carbonate	65	Restricted marine
Wallumbilla Formation	Aptian to Albian	Glauconitic sandstone fining-up to siltstone, claystone and silty limestone	600	Marginal marine to deep marine
Gilbert River Formation	Barremian to Aptian	Sandstone and siltstone	260	Fluvial to shallow marine
Eulo Queen Group	Oxfordian to Kimmeridgian	Sandstone interbedded with siltstone and claystone	150	Fluvial

Source: geology technical appendix (Orr et al., 2020); based on data published in Bradshaw et al. (2009)

2.1.3.4 Karumba Basin

The Karumba Basin forms only a thin veneer (less than 300 m thick across the entire basin and typically less than 50 m in the Isa GBA region) of Cenozoic fluvial, lacustrine and minor shallow marine sediments over the Carpentaria Basin (Figure 21 and Table 7) (Day, 1983). It was deposited unconformably over the Carpentaria Basin from the Paleogene to the Quaternary (Cook and Jell, 2013). Shallow aquifers are present in fluvial to coastal sandstones from the Bulimba Formation and Wyaaba beds (McConachie et al., 1997).

Table 7 Stratigraphy of the Karumba Basin

Stratigraphic unit	Age	Lithological descriptions	Maximum thickness (m)	Depositional environments
Armraynald beds	Pleistocene to Recent	Gravel, clayey sand, silt, clay	60	Fluvial to marginal marine
Wyaaba beds	Miocene to Pleistocene	Conglomerate, sandstone, calcareous siltstone	120	Fluvial to marginal marine
Bulimba Formation	Paleocene to Eocene	Conglomerate, sandstone, siltstone and claystone	65	Fluvial to marginal marine

Source: geology technical appendix (Orr et al., 2020); based on data published in Bradshaw et al. (2009)

2.2 Shale gas prospectivity

The Isa Superbasin is an underexplored petroleum province with demonstrated oil and gas shows from previous limited and sporadic exploration campaigns. Resource development companies are currently pursuing a range of shale gas plays hosted within the proven late Paleoproterozoic petroleum systems. In geology, a petroleum play, or simply a 'play', is a group of petroleum accumulations that occur in the same region and are controlled by the same set of geological circumstances. Play fairway analysis, adapted for use in unconventional exploration, was used to map the distribution of the Isa Superbasin's key shale gas plays. Play fairway mapping results show that, for those two key plays, the River Supersequence is potentially prospective for shale gas over most of the Isa GBA region, whereas the Lawn Supersequence is most likely prospective over the central and eastern parts of the region. Results inform where the plays are most likely to be present within the basin, which in turn aids assessment of potential connectivity to overlying surface water – groundwater systems and associated assets.

The basin is relatively remote with no existing gas processing facilities and little existing pipeline infrastructure. However, this situation is improving with the construction of the Northern Gas Pipeline, which links the NT gas market to the East Coast Gas Market. With Mount Isa becoming a regional gas hub, the area is potentially well suited to future development should further exploration and appraisal be successful and lead to commercialisation.

2.2.1 Conventional and unconventional petroleum resources

Conventional natural gas (and oil) occurs in discrete accumulations trapped by a geological structure and/or stratigraphic feature, typically bounded by a down-dip contact with water and capped by impermeable rocks (reservoir type 1 in Figure 22). Conventional petroleum was not formed in situ; it migrated from deeper source rocks into a trap containing porous and permeable reservoir rocks (Schmoker, 2002; Schmoker et al., 1995).

Unconventional gas is found in a range of geological settings (reservoir type 2 in Figure 22) and includes shale and tight gas (Cook et al., 2013b). Unlike conventional reservoirs, unconventional hydrocarbon reservoirs have low permeability and require innovative technological solutions to move the trapped hydrocarbons to the surface. The hydrocarbons that occur in many types of unconventional reservoirs (e.g. shale and deep coal gas reservoirs) have formed in situ and have not migrated away from their source rocks.

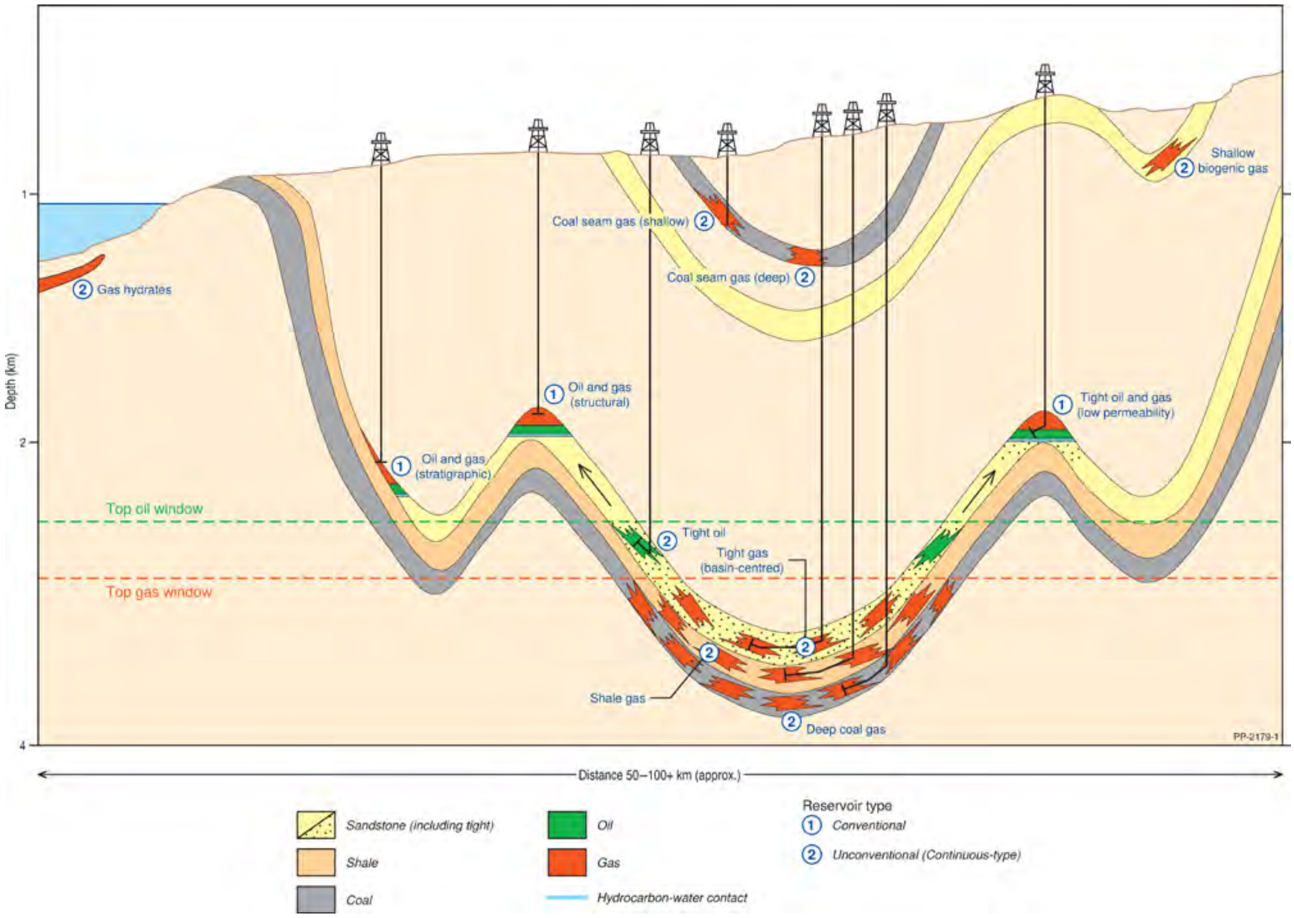

Figure 22 Schematic showing some conventional and unconventional types of oil and gas accumulations

The 'oil window' refers to the maturity range in which oil is generated from oil-prone organic matter. Below is the 'gas window', which refers to the maturity range in which gas is generated from organic matter.
CSG = coal seam gas
Source: after Schenk and Pollastro (2002); Cook et al. (2013b); Schmoker et al. (1995); Audibert (1976)
Element: GBA-ISA-2-205

The main type of unconventional gas resource under investigation in the Isa GBA region is shale gas (Figure 22). Shale gas is natural gas hosted in sedimentary rock with low to moderate porosity (with a pore size of 0.005 to 0.1 µm) and very low permeability. Shales are a common petroleum source rock and may retain more petroleum than they expel during the thermal maturation of organic matter. The gas remains trapped in the shale and is either adsorbed onto the organic matter or is held in a free state in the pores and fractures of the rock. Shale reservoirs suitable for hydrocarbon exploitation occur with significant (10 to 100 km) lateral continuity and can be of considerable thickness (>100 m). Where shales act as both the petroleum source and reservoir rock, they are sometimes referred to as 'self-sourcing reservoirs'. Shale gas resources usually occur at depths greater than 1000 to 1500 m.

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

A more detailed discussion of unconventional gas plays is in the petroleum prospectivity technical appendix (Bailey et al., 2020).

2.2.2 Petroleum prospectivity of the Isa Superbasin

The Isa Superbasin is an underexplored petroleum basin with limited hydrocarbon exploration and no hydrocarbon production to date. However, recent exploration by Armour Energy Limited (Armour Energy) indicates the potential for significant volumes of unconventional gas. Limited contingent shale gas resources and larger prospective resources have been discovered at the Egilabria Prospect within the Isa GBA region during Armour Energy's 2012 to 2014 exploration program, which focused on the shale gas potential of the Lawn and River supersequences of the Isa Superbasin (Figure 21) (Armour Energy, 2018). These sequences of the Isa Superbasin have the potential to host volumetrically significant gas resources. Due to the proximity to Mount Isa and related infrastructure, there is potential for these gas resources to supply the East Coast Gas Market at some stage in the future (Figure 3).

Gas has been recovered from within the source intervals of the Lawn and River supersequences, although gas and minor oil shows are identified within most geological units of the Isa Superbasin. The regional petroleum systems of the Isa Superbasin are summarised in Table 8, with further details in the petroleum prospectivity technical appendix (Bailey et al., 2020).

Table 8 Regional petroleum systems of the Isa Superbasin

Component of regional petroleum system	Description
Play types – conventional	Low potential for conventional oil and gas (structural and stratigraphic traps in clastic reservoirs, carbonate reservoirs).
Play types – unconventional	Shale gas plays confirmed through previous exploration. Basin-centred gas may be trapped in tight sandstones but is yet to be investigated.
Reservoirs	Potential conventional reservoirs exist through the Isa Superbasin. The Loretta Supersequence (Lady Loretta Formation) and sands of the Term (Termite Range Formation), Lawn (Bulmung Sandstone), Wide and Doom supersequences (Widdallion Sandstone Member) are all candidates. The Lawn and River supersequences are considered unconventional gas reservoirs.
Seals	Highstand mudstone units at the top of third-order sequences and supersequences may act as seals. Regional seals are likely to be provided by the latter.
Source rocks	Lawn Supersequence, River Supersequence, Term Supersequence (Termite Range Formation – potential), Gun Supersequence (Esperanza Formation – potential).
Hydrocarbon shows	Numerous hydrocarbon shows are observed through the Isa Superbasin and the overlying South Nicholson Basin: • significant gas shows in the Lawn and River supersequences, minor gas shows through most intersected units in Isa Superbasin • oil bleeds and bitumen in the Loretta Supersequence (Walford Creek Dolomite – a lateral equivalent to the Lady Loretta Formation) • bitumen in the Term Supersequence (Termite Range Formation), the Lawn Supersequence and River Supersequence. The best oil shows are in the Constance Sandstone of the South Nicholson Basin.

Source: petroleum prospectivity technical appendix (Bailey et al., 2020); after Gorton and Troup (2018).

There has been no on-the-ground exploration activity in the Isa Superbasin since August 2013, when Armour Energy drilled Egilabria 4 (Figure 23). However, Armour Energy maintains ownership of Authority to Prospect (ATP) 1087, which is the only exploration permit over the Isa GBA region and is actively seeking farm-in partners to further develop the permit (Armour Energy, 2018). To date, 14 vertical wells and one horizontal well have been drilled in the Isa GBA region and 1141 line kilometres of two-dimensional seismic reflection data have been acquired.

Figure 23 Eastward-facing aerial view of the Egilabria 4 well pad during drilling operations targeting shale gas plays in the Lawn Supersequence of the Isa Superbasin, August 2013

Source: Armour Energy Ltd
Element: GBA-ISA-2-203

2.2.3 Shale gas play characterisation

The amount of gas (and oil) present within a petroleum accumulation depends on the geological characteristics of both the petroleum source rock and the reservoir rock in which the petroleum is trapped. In the case of shale gas in the Isa GBA region the source and reservoir rocks are the same. To underpin further work in the region that could be used to inform potential shale gas development scenarios, key geological properties of shales within the Lawn and River supersequences were characterised based on available open-file data. The geological properties evaluated are:

- formation depth and extent (Figure 25, Figure 26)
- source rock properties, including net thickness, total organic carbon content, type of organic matter (kerogen type) and quality of the source rock (hydrogen index) (Table 9)
- source rock thermal maturity. This represents the degree to which a source rock has been heated under the Earth's surface and influences whether the generated petroleum is oil, liquids-rich gas or dry gas
- reservoir characteristics, including porosity, permeability, gas saturation, mineralogy and brittleness
- regional stress regime and overpressure.

Results are summarised in Table 9 and a full description of this characterisation is provided in the petroleum prospectivity technical appendix (Bailey et al., 2020). A petroleum systems event chart summarising the interpreted components of the unconventional petroleum systems analysed in this study is presented in Figure 24.

Table 9 Characteristics of formations hosting shale gas plays

Property	Description
Source rock characteristics	• Abundant source rocks are present in the Isa Superbasin succession. • Source rocks in the River and Lawn supersequences are interpreted as the thickest, most organically rich and most extensive (total organic carbon (TOC) content of 2–11 wt% and 2–7 wt%, respectively), with good to excellent source potential. • Distribution and variation of source rocks with depth is poorly constrained. Facies variations and TOC distributions are poorly understood due to low data density, and little information is available on source rock maturity.
Reservoir characteristics	• Based on an assessment of the brittleness of the shale sequences, both the Lawn and River supersequences appear to be brittle and, hence, favourable for fracture stimulation. • The average total porosity and permeability of the Lawn Supersequence shales is 3.79% and 1.01×10^{-5} mD, respectively. The values for the River Supersequence are 3.75% and 1.13×10^{-5} mD, respectively. • As-received total gas content from air-dried samples is favourable, with average values of 0.909 scc/g for the Lawn Supersequence and 1.143 scc/g for the River Supersequence.
Stress	• Approximately north-north-east-trending to south-south-west-trending maximum horizontal stress azimuth; Isa GBA region interpreted to host a predominately strike-slip faulting stress regime. • Stress magnitudes vary between lithologies, with stress variations a likely impediment to fracture propagation. • Relevant information is only available from two wells (Egilabria 2 and Egilabria 4) and provide data only on stresses in the upper ~1800 m of the sedimentary succession.
Pressure	• No indications of overpressure have been observed from previous exploration. However, data are sparse and overpressure might be present at greater depths.

TOC = total organic carbon; scc/g = standard cubic centimetres per gram; wt% = weight as a percentage; mD = millidarcy
Refer to the petroleum prospectivity technical appendix (Bailey et al., 2020) for full formation descriptions.

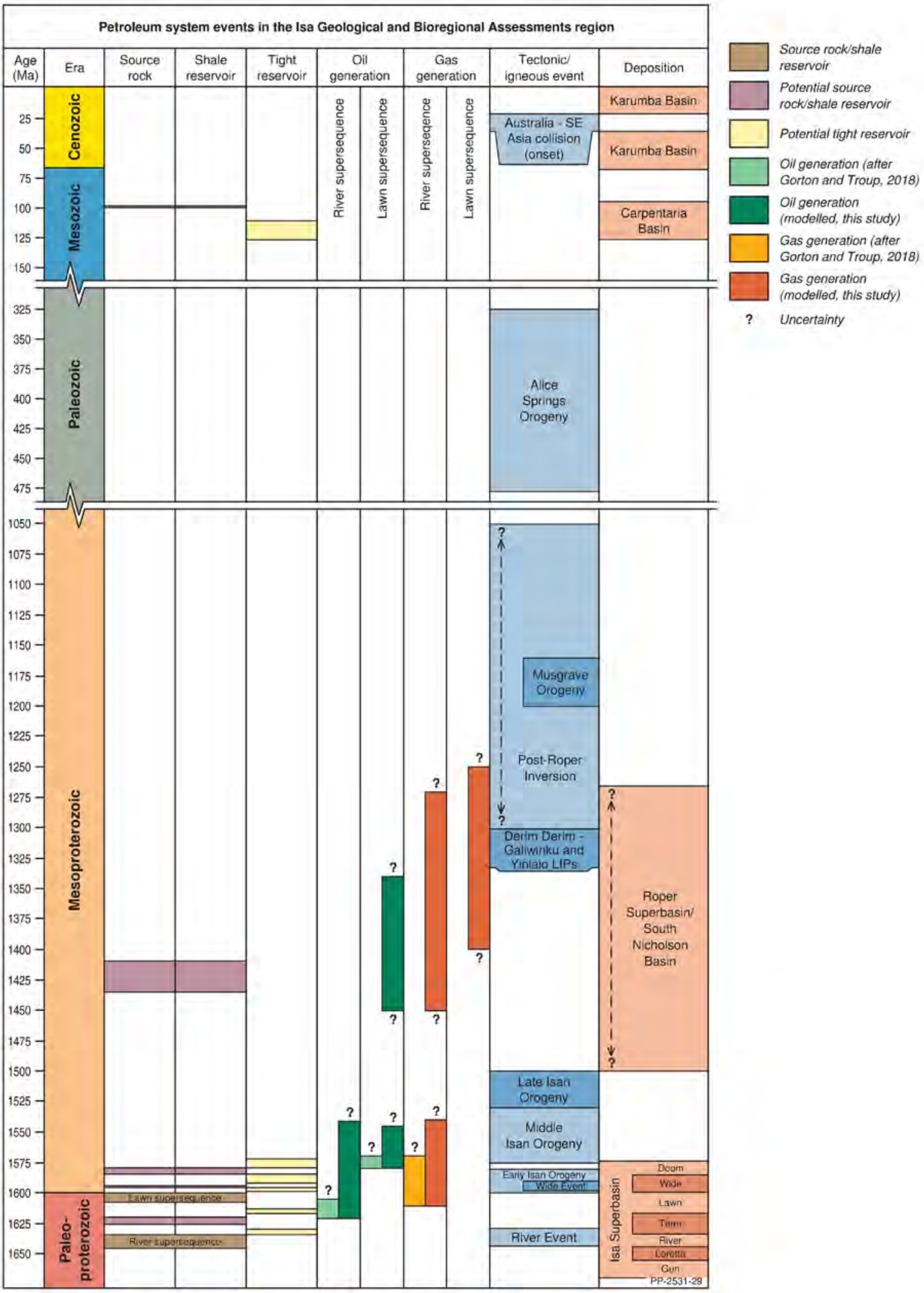

Figure 24 Unconventional petroleum systems events chart for prospective intervals of the Isa Superbasin, South Nicholson Basin and Carpentaria Basin within the Isa GBA region

Hydrocarbon generation timing is based on the work of Gorton and Troup (2018) and derived from the burial and thermal history modelling outlined in Section 3.4 of Bailey et al. (2020). See geology technical appendix (Orr et al., 2020) for more detail on tectonic events and basin evolution. Time breaks from 1040 to 485 Ma and from 310 to 160 Ma are illustrative only.
LIP = large igneous province
Source: petroleum prospectivity technical appendix (Bailey et al., 2020)
Data: after Palu et al. (2018)
Element: GBA-ISA-2-249

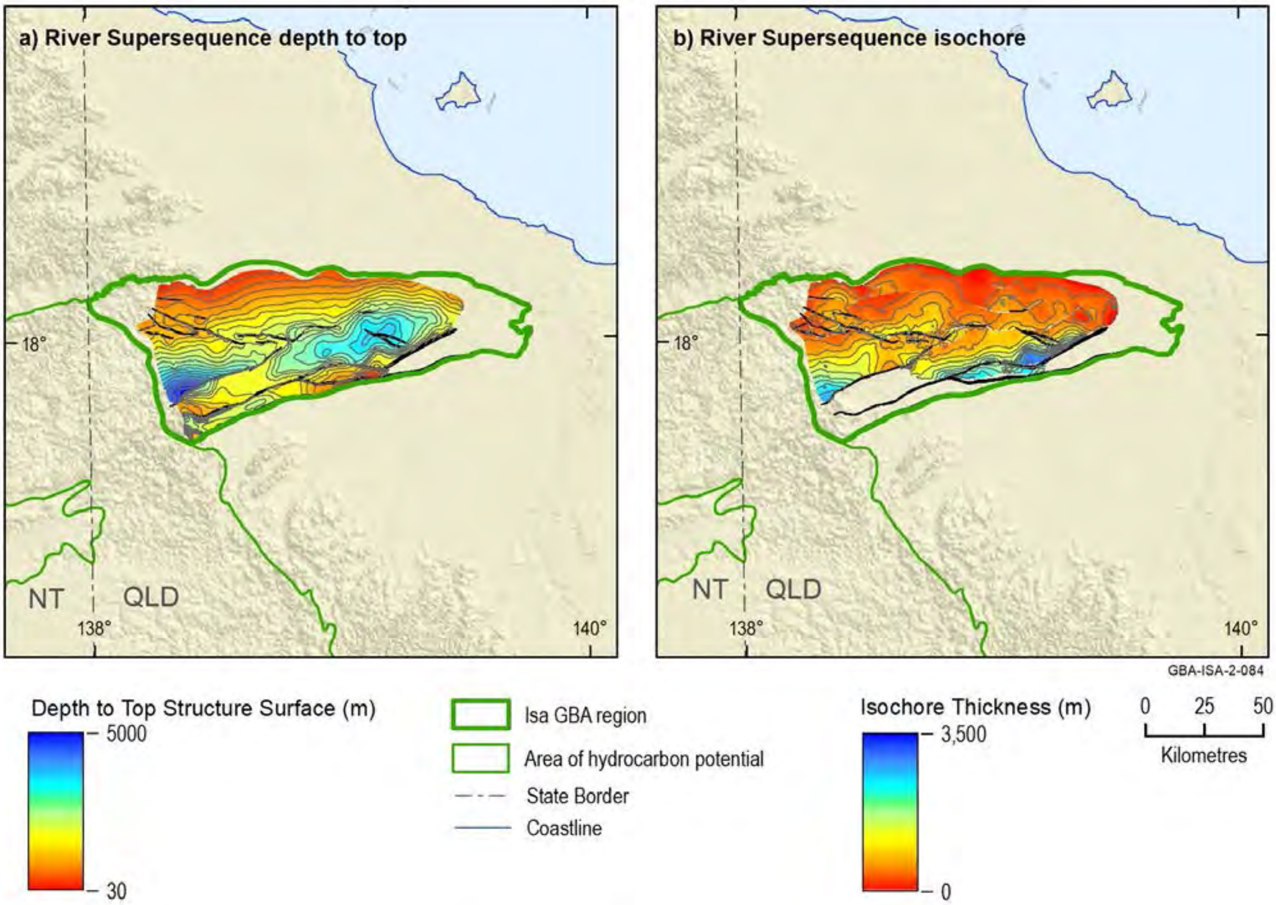

Figure 25 (a) Top River Supersequence depth structure map (metres below ground level); and (b) River Supersequence true vertical thickness (isochore) map

Contour interval = 250 m
Source: geology technical appendix (Orr et al., 2020); modified from Bradshaw et al. (2018a)
Data: Bradshaw et al. (2018a)
Element: GBA-ISA-2-084

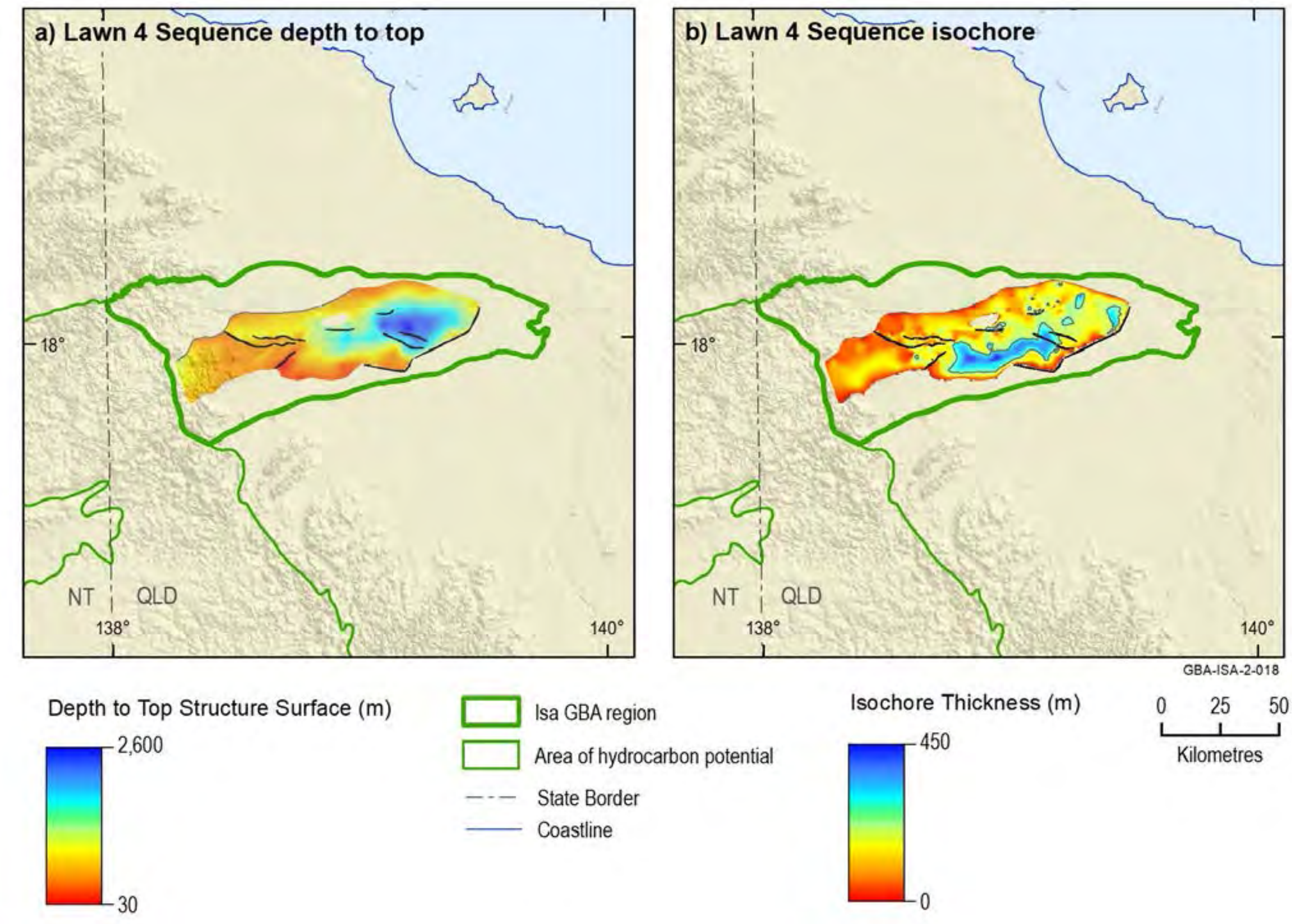

Figure 26 (a) Top Lawn 4 Sequence depth structure map (metres below ground level); and (b) Lawn 4 Sequence true vertical thickness (isochore) map

Contour interval = 250 m
Source: geology technical appendix (Orr et al., 2020); modified from Bradshaw et al. (2018a)
Data: Bradshaw et al. (2018a)
Element: GBA-ISA-2-018

2.2.4 Play fairway analysis workflow

The Isa Superbasin is an underexplored petroleum basin. Little data are available due to limited exploration (Bailey et al., 2020). As a result, it is not possible to undertake a process of relative prospectivity mapping within the Isa Superbasin (e.g. as done for the Cooper Basin in the GBA Program; see Lech et al. (2020)). Instead, play fairway analysis is used here to map the distribution of the Isa Superbasin's key unconventional shale gas plays. The resulting maps inform where shale gas resources are more likely to be present within the Isa GBA region, which in turn aids assessment of potential connectivity to overlying surface water – groundwater systems and associated assets.

Methods snapshot: play fairway analysis

Play fairway analysis, sometimes referred to as play fairway mapping, is used to identify areas where a specific play may potentially be successful and where additional work on a finer scale is warranted in order to further develop an understanding of a prospect. Firstly, the key geological properties required for a play to be present were mapped. For the Isa Superbasin (within the Isa GBA region), map data were only available for two geological properties: net source rock thickness and formation depth (which was used as a proxy for source rock thermal maturity). Each geological property map was then categorised into three classes (low/absent: 0; medium: 0.5; high: 1) based on the criteria shown in Table 10. The resulting classified maps were multiplied together to produce a play extent map, otherwise known as a 'play fairway map'. This play fairway maps highlight regions with the most favourable geological conditions for shale gas plays, based on the available data (Figure 27 and Figure 28).

Table 10 Shale gas play input parameters and classifying criteria used for the play fairway analysis

	Input type	Classified input parameter thresholds		
		None (0)	Medium (0.5)	High (1)
Net source rock thickness[a]	Gross sequence thickness, multiplied by the calculated net organically rich ratio	<15 m	≥15 to <30 m	≥30 m
Thermal maturity	A depth proxy was developed for maturity using one-dimensional burial modelling	Formation not present	≤500 m	>500 m

[a] Net source rock thickness is the cumulative thickness of organic-rich shale with a total organic carbon content >2 wt%. Refer to Bailey et al. (2020) for further details on input assumptions.
Source: petroleum prospectivity technical appendix (Bailey et al., 2020)

The potential extent of shale gas resources in the Isa GBA region was evaluated for both the Paleoproterozoic River and Lawn supersequences. Play fairway analysis results show that the River Supersequence is potentially prospective for shale gas exploration over most of the Isa GBA region (Figure 27), whereas the Lawn Supersequence is most likely prospective over the central and eastern parts of the Isa GBA region (Figure 28). Exploration for shale gas resources is less likely to occur over the southern flanks of the Murphy Inlier due to the inferred decreased thermal maturity of the River Supersequence and the absence of the Lawn Supersequence.

Results represent the maximum possible area within which each play may be present based on regional geological criteria alone. These maps do not capture any local-scale (<10 km) variations in geology within formations that may influence the prospectivity at a prospect scale. In addition, no factors relating to economics, politics or social issues are incorporated into this analysis. Inputs do not take into account uncertainty around petroleum systems (outlined in the petroleum prospectivity technical appendix of Bailey et al. (2020)) and assume source interval characteristics for the Isa GBA region based on limited well intersections.

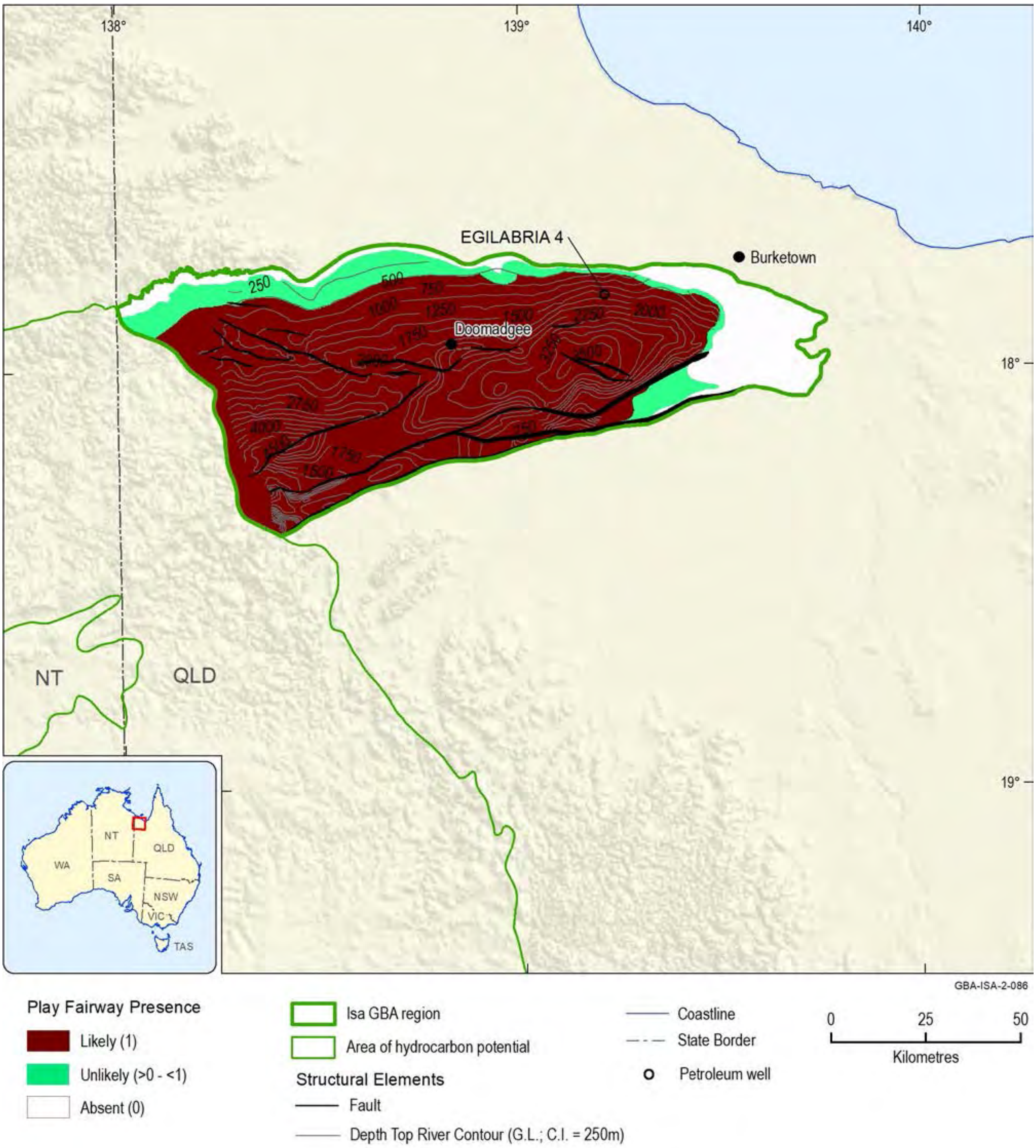

Figure 27 River Supersequence shale gas play fairway presence map

GL = relative to ground level; CI = contour interval
Source: petroleum prospectivity technical appendix (Bailey et al., 2020)
Data: Bradshaw et al. (2018b)
Element: GBA-ISA-2-086

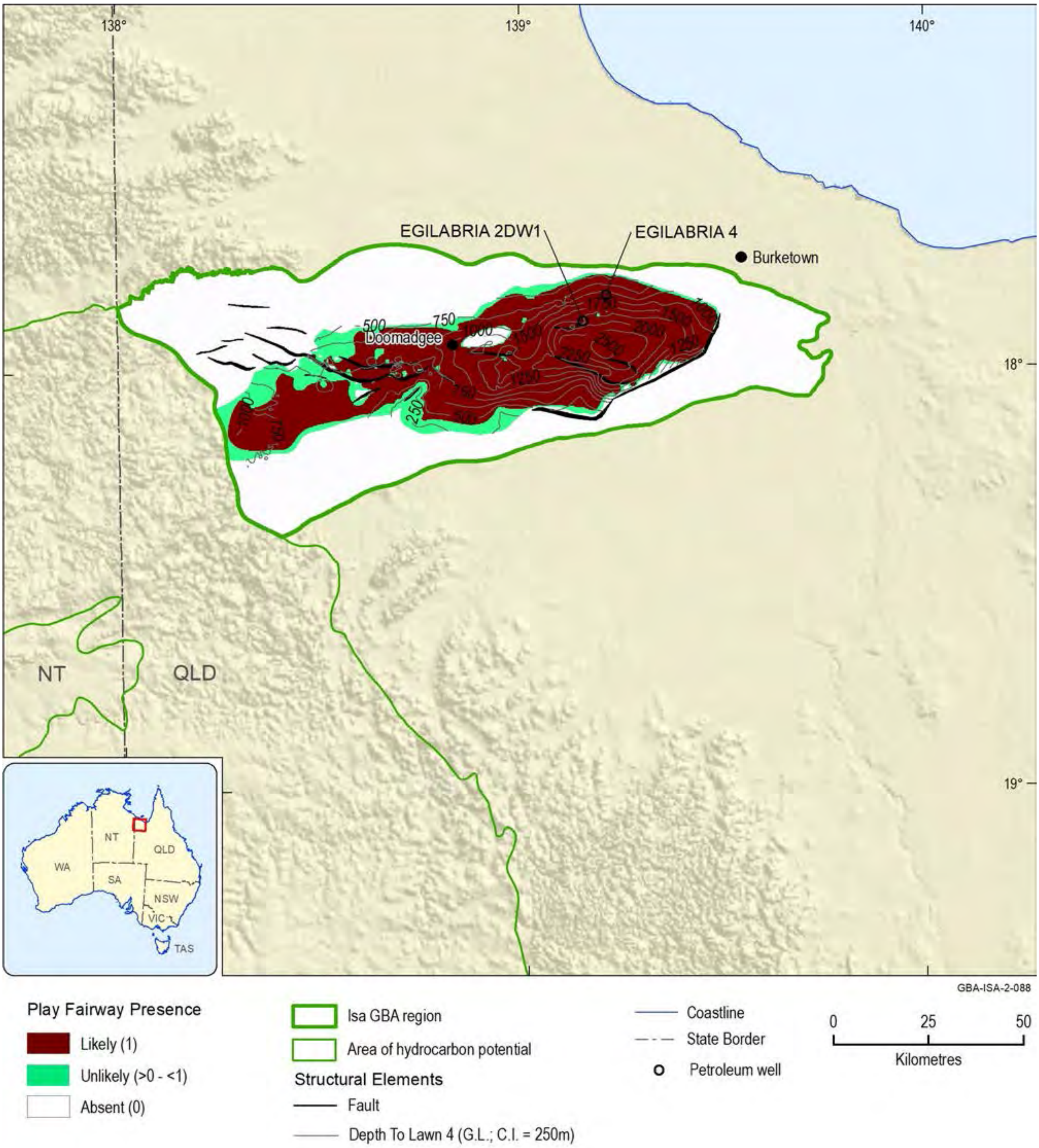

Figure 28 Lawn 4 Sequence shale gas play fairway presence map

GL = relative to ground level; CI = contour interval
Source: petroleum prospectivity technical appendix (Bailey et al., 2020)
Data: Bradshaw et al. (2018b)
Element: GBA-ISA-2-088

2.3 Knowledge gaps

As an underexplored energy province, the Isa Superbasin within the Isa GBA region is relatively data poor and this constitutes a significant limitation on this assessment. Limited well data are available and are generally not of a quality or type suitable for regional applications. Seismic coverage is sporadic and relatively old (mostly late 1980s and early 1990s) and, although there are areas where the seismic data are sufficient to confidently map shale gas intervals, there are also significant data gaps, which limit mapping confidence (Figure 29). Petroleum systems are poorly understood and, unlike most recognised petroleum provinces in Australia, there are very few available regional-scale datasets that would typically be used in assessing shale gas prospectivity (e.g. total organic carbon (TOC), maturity, overpressure, stress, etc.). Further information regarding data limitations is described in the petroleum prospectivity technical appendix (Bailey et al., 2020).

Play fairway mapping is based on the regional-scale geological conceptualisation detailed in the geology technical appendix (Orr et al., 2020). Results identify areas where further data acquisition and geological modelling can be undertaken. However, this regional analysis is not suitable for individual play- or prospect-scale evaluations. Due to local geological variations, which may not be captured by the limited regional-scale input datasets used to develop the play fairway maps, the areas identified as having a high likelihood of play fairway presence will not necessarily result in gas discoveries (Bailey et al., 2020).

Large capital expenditure is required to extract unconventional resources. If and how an unconventional play is developed depends on its economic viability, along with cultural and environmental considerations. Therefore, to better understand possible industry development scenarios and help determine the associated hazards and impacts, it is important to consider development of each play in the context of likely economic outcomes.

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

- hydrocarbon resource assessments to estimate total volume of gas-in-place for priority plays, based on the geological understanding outlined in this report
- estimation of the proportion of gas-in-place that is technically recoverable
- economic analyses to understand what shale gas resources would be economic to produce, based on market conditions (and considering current and projected future trends) and likely project costs.

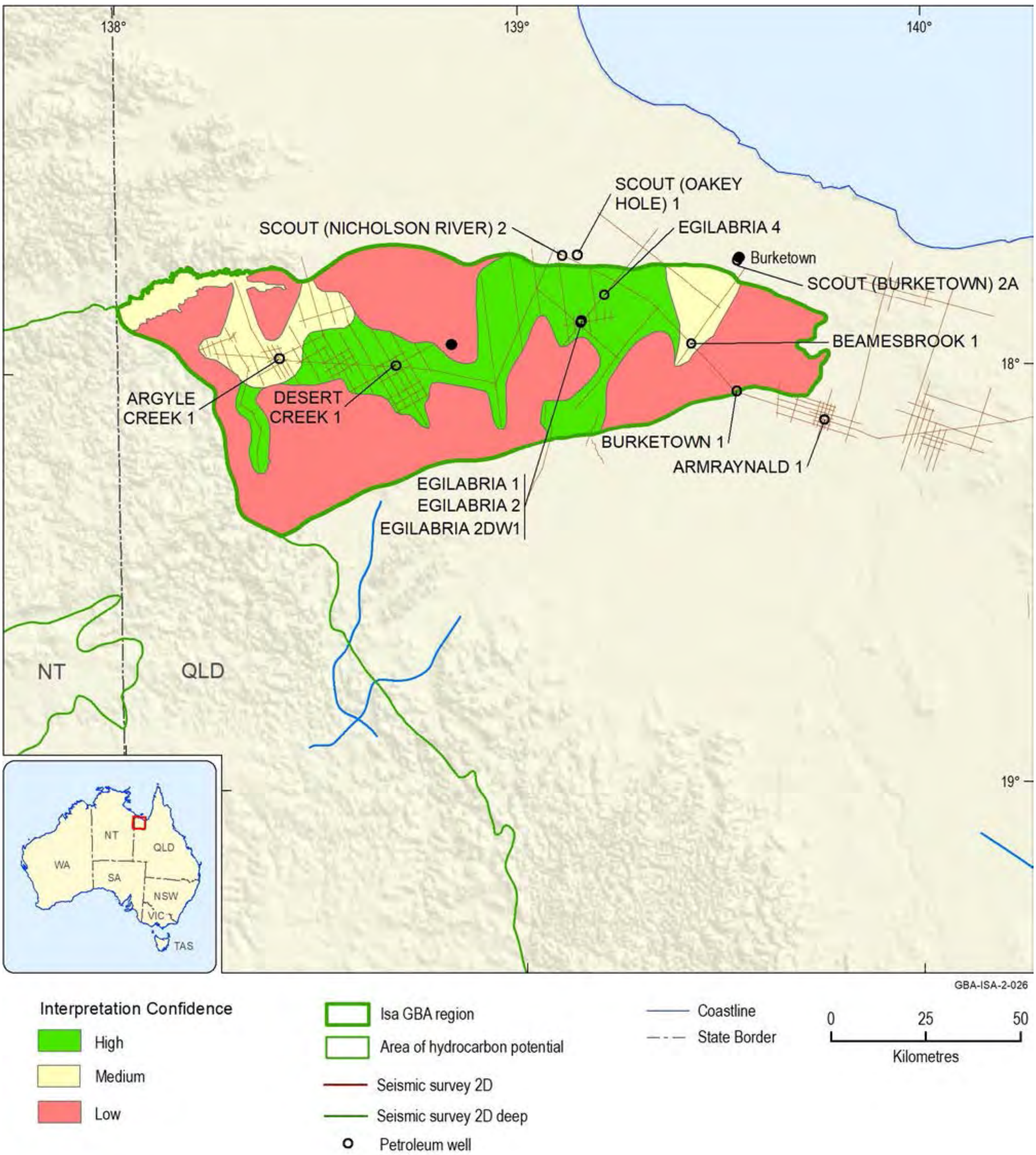

Figure 29 Interpretation confidence map for the Isa GBA region highlighting well locations and areas covered by two-dimensional seismic surveys

2D = two-dimensional

Source: petroleum prospectivity technical appendix (Bailey et al., 2020) and Bradshaw et al. (2018a)

Data: Bradshaw et al. (2018a)

Element: GBA-ISA-2-026

3 Water resources

The surface water and groundwater resources of the Isa GBA region are environmentally and economically important assets that provide vital water supplies to support the region's flora, fauna and people. The potential for future development of shale gas resources within this region (as discussed in Section 2.2) may affect the quantity, quality and availability of water for existing users, such as the region's many groundwater-dependent ecosystems and the local pastoral industry. In particular, shale gas operations typically require large volumes of water for drilling and hydraulic fracturing operations, as well as for associated construction activities. Such large-scale water extractions have the potential to impact the regional hydrology. Consequently, it is critical to understand the baseline (i.e. pre-development) condition of the surface water and groundwater systems of the region and the interactions that occur between them. This knowledge can help identify and understand potential hydrological connections (pathways) that may link shale gas development activities with water resources and water-dependent assets, as well as identify the most likely water sources that will support future shale gas development in the region.

3.1 Hydrogeological and groundwater conceptualisation

The Isa GBA region hosts two broad and potentially connected groundwater systems:

1. groundwater associated with the Proterozoic rock units of the Isa Superbasin and South Nicholson Basin. This is typically the deeper groundwater system in the region. The highest yielding aquifer in the Proterozoic units is the Lady Loretta Formation (Loretta Supersequence)

2. the overlying groundwater system of the Mesozoic Carpentaria Basin (part of the Great Artesian Basin (GAB)) and Cenozoic Karumba Basin. The GAB is a stacked series of aquifers and aquitards that, for most of the region, host the most readily accessible groundwater resources. The major aquifers include the basal Gilbert River Formation, the Normanton Formation and the shallow sediments of the Karumba Basin.

Groundwater interacts with surface waters in the region through a variety of mechanisms (Section 3.3), such as providing baseflow to streams and supplying a source of water for springs. Shallow groundwater is also recharged by streams and helps to support environmental assets, such as wetlands. The hydrological conceptualisation of the Isa GBA region is presented in Figure 30.

This section summarises the regional hydrogeology of the Isa GBA region and includes information on (i) the extent of aquifers and aquitards; (ii) recharge and discharge processes and rates; and (iii) groundwater flow dynamics and hydrochemistry. Information is presented on the hydrogeology of the deeper (Proterozoic) groundwater systems and is followed by the hydrogeology of the overlying GAB. Further information and analysis is provided in the hydrogeology technical appendix (Buchanan et al., 2020). Other regional groundwater investigations are outlined in the *Hydrogeological atlas of the Great Artesian Basin* (Ransley et al., 2015) and *Water resource assessment for the Carpentaria region* (Smerdon et al., 2012c).

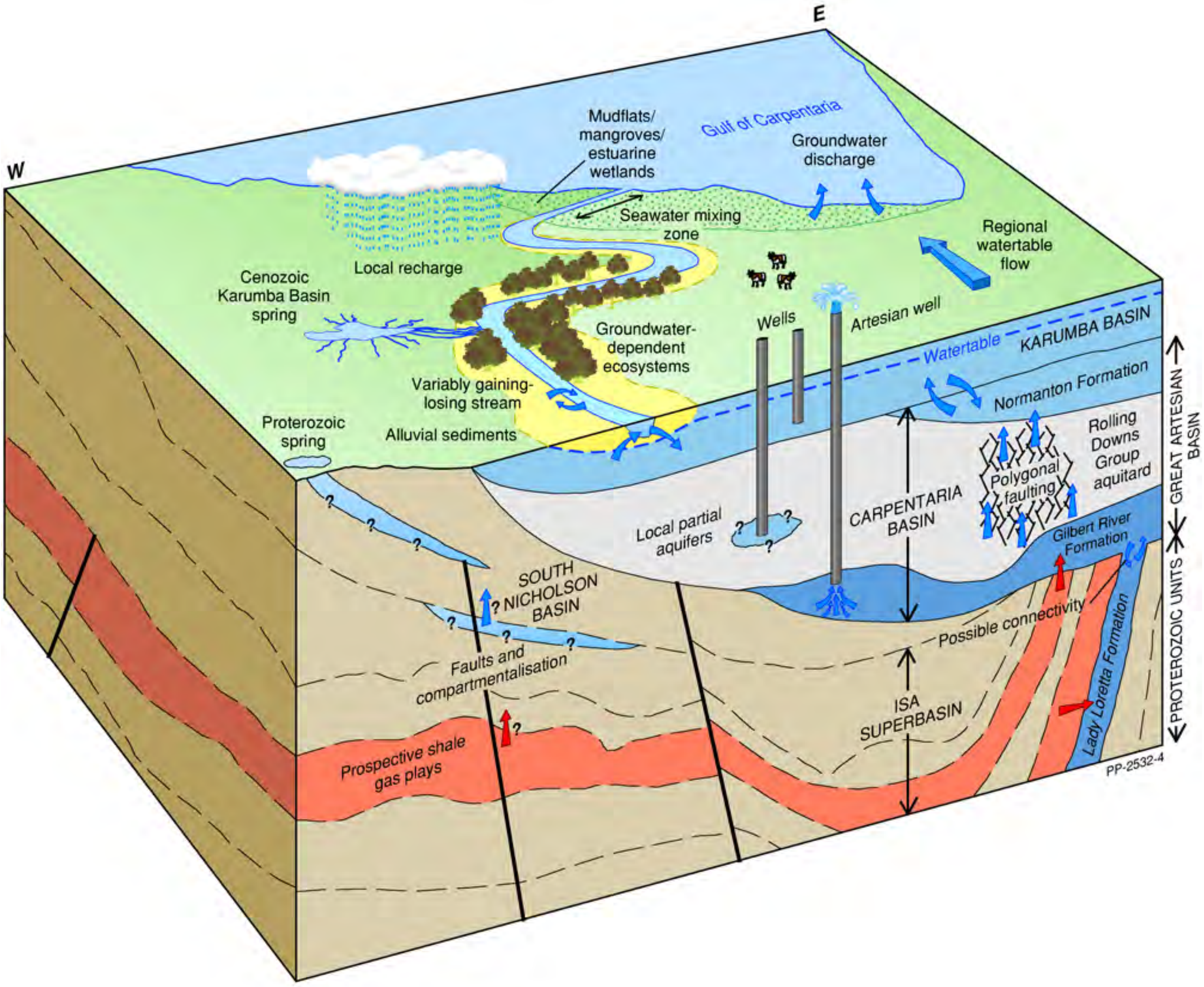

Figure 30 Key components of the groundwater systems of the Isa GBA region and potential connectivity pathways between aquifers and surface waters

The groundwater system includes the deeper Proterozoic units of the Isa Superbasin and South Nicholson Basin and the overlying Carpentaria Basin (part of the Great Artesian Basin) and Karumba Basin. The Isa Superbasin is host to the prospective shale gas plays and the Loretta Supersequence (Lady Loretta Formation) aquifer. Red arrows depict potential pathways for gas migration; blue arrows represent potential pathways for the movement of water. Refer to the 'alluvium' conceptual model (Figure 54) and potential hydrogeological connections (Figure 48 and Figure 49) for more detailed conceptual diagrams of mechanisms for connectivity.
This diagram is a schematic representation and is not drawn to scale. The diagram has been vertically exaggerated to emphasise key features and processes in the region.
Element: GBA-ISA-2-141

3.1.1 Hydrogeology of Proterozoic units

The supersequences of the Proterozoic Isa Superbasin and the overlying South Nicholson Basin extend from surface (outcrop) in the west of the Isa GBA region and dip southwards to depths of over 9 km under a gradual thickening of younger sedimentary cover of the GAB. The outcrop and subcrop extents of various Proterozoic units in the Isa GBA region and the extent of the overlying GAB are depicted in Figure 31. The Proterozoic units generally consist of highly lithified fine-grained sedimentary rocks and include the prospective shale gas plays of the Lawn and River supersequences (Section 2.2). The hydraulic properties of most Proterozoic rocks are characteristic of aquitards – for example, the rocks typically have very low porosity and hydraulic conductivity values. The inferred hydrogeological characteristics of the various Proterozoic units are shown on the hydrostratigraphic chart in Figure 21. A north-oriented cross-section in the west of the region illustrates the variable thickness and arrangement of these units, as well as their hydrogeological characteristics (Figure 32).

3.1.1.1 Gun and Loretta supersequences (lower McNamara Group)

Within the Gun Supersequence, the Paradise Creek and Esperanza formations are characterised by stromatolitic dolostone and are considered partial aquifers. The Gunpowder Creek Formation (Gun Supersequence) consists typically of laminated siltstone and is considered an aquitard.

The overlying Lady Loretta Formation (Loretta Supersequence) is also characterised by dolostone but contains cavernous sections with high transmissivities that may produce aquifer characteristics. For example, during drilling of exploration well Burketown 1 (Perryman, 1964), a 53-m section of cavernous dolostone was intersected in the Loretta Supersequence. This well flowed hot artesian groundwater at a rate of 63 L/minute when first drilled (see the hydrogeology technical appendix (Buchanan et al., 2020) for further details).

3.1.1.2 River, Term, Lawn, Wide and Doom supersequences (upper McNamara Group)

The upper McNamara Group – equivalent to the River, Term, Lawn, Wide and Doom supersequences – includes the hydrocarbon-prospective carbonaceous shales and siltstones of the upper Lawn Hill Formation (Lawn 4 Supersequence) and the Riversleigh Siltstone (River Supersequence). Similar to the lower McNamara Group, these rocks typically have aquitard properties. The main exceptions are the Bulmung Sandstone Member (Pmh 3) and the Widdallion Sandstone Member (Pmh 5) of the Lawn Hill Formation, which are considered partial aquifers (EHS Support, 2014). The lower part of the Term Supersequence (Termite Range Formation) is a turbiditic sandstone with low to moderate porosity and is classed as a leaky aquitard.

3.1.1.3 South Nicholson Basin

The rocks of the South Nicholson Basin in the Isa GBA region consist entirely of fluvial to shallow marine lithofacies and are typically highly lithified with aquitard to leaky aquitard properties. The exception is the Constance Sandstone, which in mid-sequence has an average porosity of between 0.5% and 5%, although much higher porosity values of up to 16% have been measured in some places (Gorton and Troup, 2018). During petroleum exploration, testing of the Constance Sandstone at well DDH83-3 produced water at a rate of about 750 L/minute (Dorrins et al., 1983).

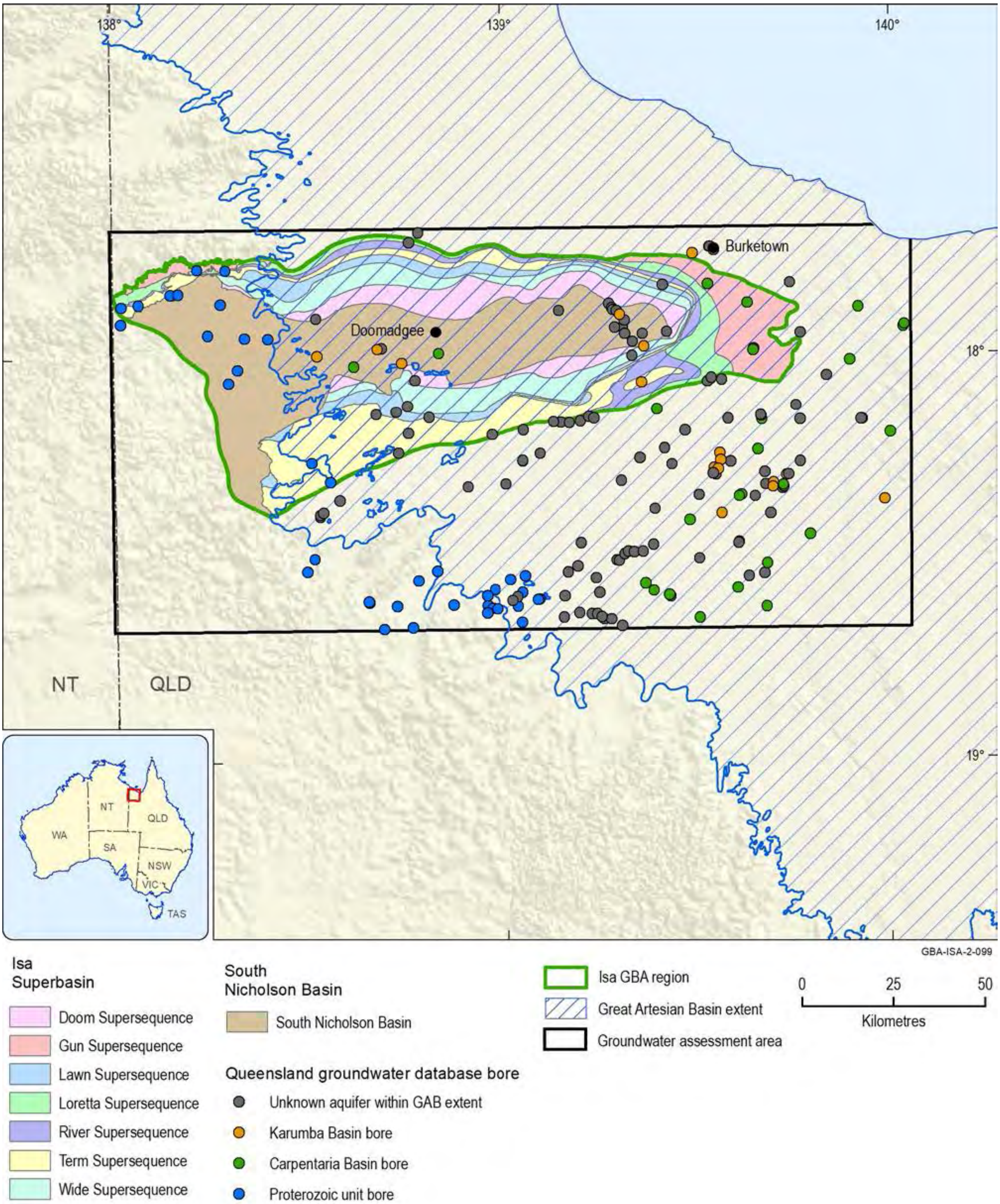

Figure 31 Spatial extents of Proterozoic units in the Isa GBA region and the Great Artesian Basin

Proterozoic units to the west of the Great Artesian Basin (GAB) boundary outcrop at surface. To the east of the boundary they subcrop beneath the overlying sedimentary rocks of the GAB. An oblique view of the regional three-dimensional geological model for the Isa Superbasin over the Isa GBA region is in Figure 20.
Data: geology (Bradshaw et al., 2018a); groundwater bores (Geoscience Australia, 2018c)
Element: GBA-ISA-2-099

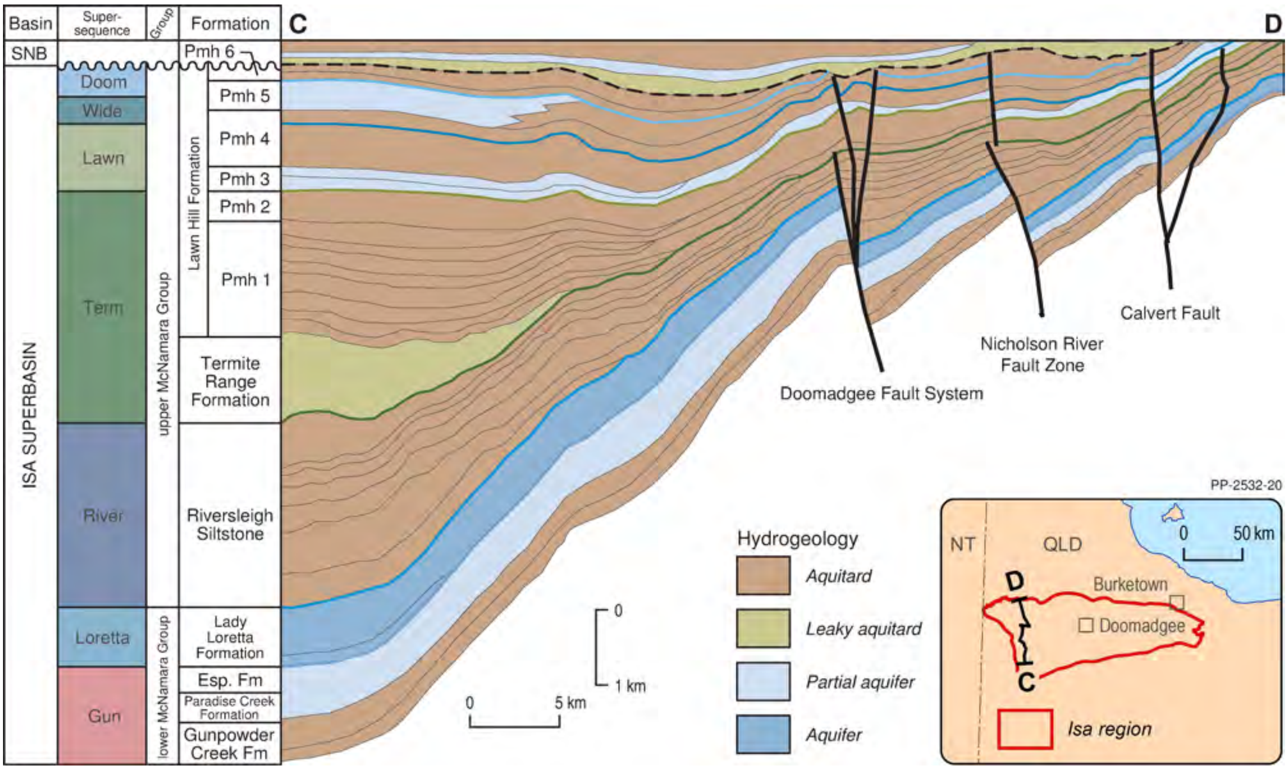

Figure 32 Inferred architecture and hydrostratigraphy of Proterozoic units in the Isa GBA region

In the Isa GBA region, the Loretta Supersequence (Lady Loretta Formation) has the greatest aquifer potential.
Esp. Fm = Esperanza Formation; Fm = Formation
Source: after Lindsay et al. (1999)
Element: GBA-ISA-2-154

3.1.1.4 Groundwater levels in Proterozoic units

Groundwater levels in the aquifers of the South Nicholson Basin and Isa Superbasin are not well understood due to the sparse number of groundwater bores that tap these units within and proximal to the Isa GBA region. According to the Queensland groundwater database (Department of Natural Resources, Mines and Energy (Qld), 2018b) there are 190 registered bores over an area of 24,000 km^2 (which includes areas beyond the Isa GBA region), equating to one bore every 126 km^2. Of the 190 groundwater bores registered in the Isa GBA region (Figure 33), 20% (38 bores) access groundwater from the Proterozoic units of the Isa Superbasin and South Nicholson Basin (Geoscience Australia, 2018c).

From the available data, groundwater levels (above mean sea level) in the aquifers of the South Nicholson Basin and Isa Superbasin range from 68.6 to 134.6 metres above sea level (mAHD). As there are too few data points, a groundwater level surface has not been generated from groundwater level measurements (Figure 33). Further, the extensive structural disruption of the Proterozoic units in the region (i.e. presence of many major faults) may compartmentalise groundwater flow systems. For example, the Doomadgee Fault System (shown in cross-section in Figure 32) has sufficient vertical offset to impede the flow of groundwater in the Lady Loretta Formation (Loretta Supersequence). Additional groundwater level data from Proterozoic aquifers are required to better characterise their flow characteristics.

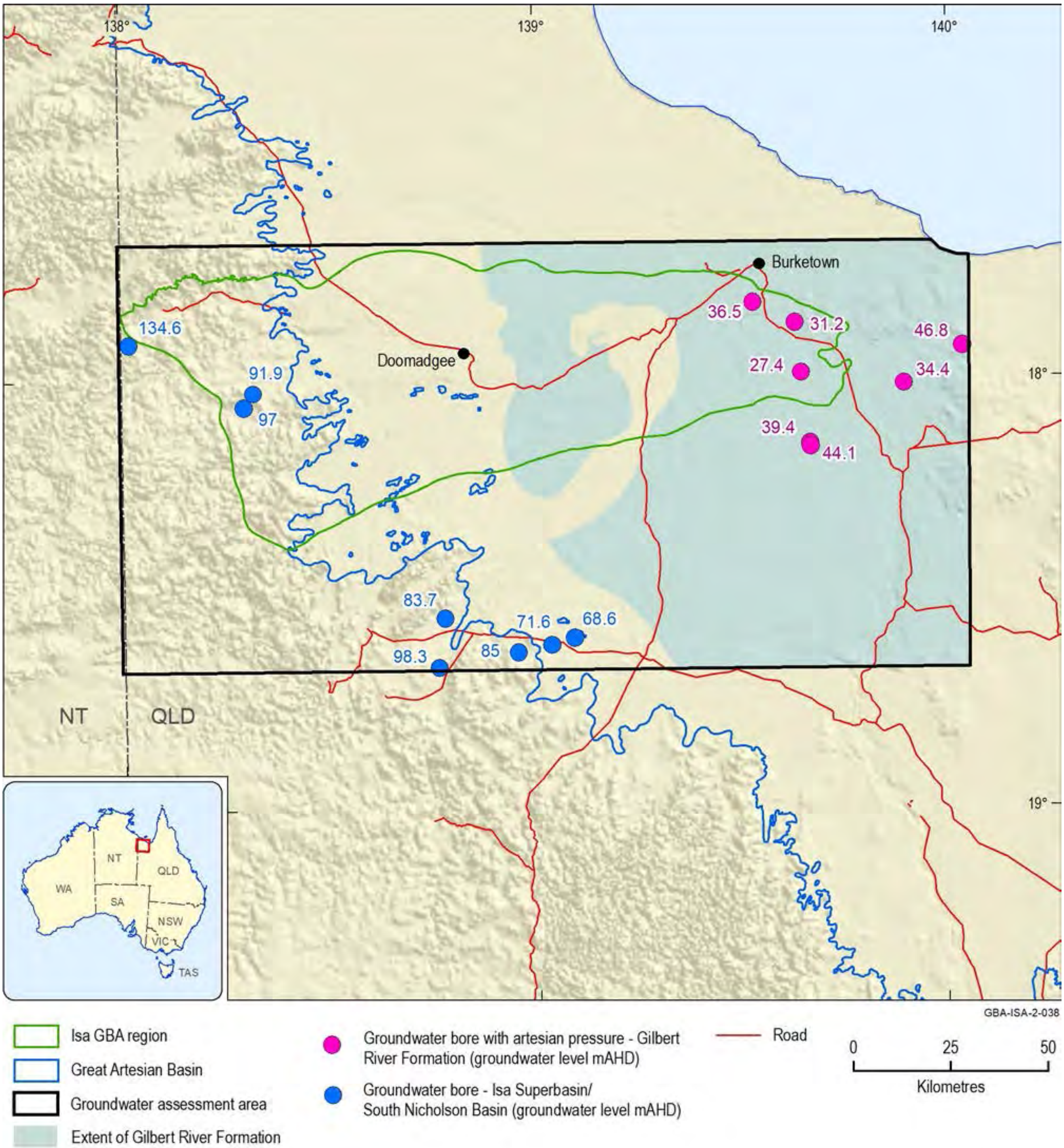

Figure 33 Groundwater levels in the Isa Superbasin and South Nicholson Basin and Gilbert River Formation aquifer of the Great Artesian Basin

Groundwater levels are shown in metres above sea level (mAHD).
Data: formation extent (Bradshaw et al., 2018a); groundwater levels (Geoscience Australia, 2018c)
Element: GBA-ISA-2-038

Within the region of investigation, artesian conditions (i.e. groundwater wells that naturally flow water to surface without the need for pumping) are reported during drilling at several bores (Department of Natural Resources, Mines and Energy (Qld), 2018b), including drilling into the Lady Loretta Formation (Loretta Supersequence) (Perryman, 1964). The cause of the artesian pressures evidenced during construction remains speculative, although one possibility is gas overpressure resulting from the adjacent River Supersequence (a known shale gas reservoir). The majority of

Proterozoic bores listed in the Queensland groundwater database (Department of Natural Resources, Mines and Energy (Qld), 2018b) are subartesian (refer to Figure 33 for bores with groundwater levels recorded).

3.1.1.5 Groundwater quality and recharge processes in Proterozoic units

The salinity of groundwater from the Proterozoic units of the Isa Superbasin and South Nicholson Basin is typically low to moderate. From the available sparse data, total dissolved solids (TDS) of groundwater from these aquifers range from 90 to 4614 mg/L, with a median of 663 mg/L. There are very little other water quality data available for these units, although some fluoride and sulfate analyses are reported in the hydrogeology technical appendix (Buchanan et al., 2020). However, despite the paucity of hydrochemical data in the region, the available information has been used in Section 3.4.2 to provide an additional line of evidence to investigate potential hydrogeological connections that may exist in the subsurface and provide fluid pathways from the Proterozoic units (including the aquifers and the shale gas plays) upwards to the overlying aquifers of the GAB.

Recharge to aquifers of the Isa Superbasin and South Nicholson Basin is expected to be primarily limited to diffuse recharge in formation outcrop areas in the west of the region. Due to the highly lithified nature of the Proterozoic rock units, potential recharge volumes are expected to be less than for the GAB (although no actual estimates are reported). Further, recharge is likely to be restricted to areas where meteoric weathering or fracture zones in outcrop areas provide a preferential pathway for infiltration to occur.

3.1.2 Hydrogeology of the Great Artesian Basin and overlying units

In the Isa GBA region the GAB comprises the Mesozoic (Jurassic to Cretaceous) Carpentaria Basin, which is overlain by the Cenozoic Karumba Basin (see hydrostratigraphy, Figure 21, and also Table 6 for a summary of lithological properties). The aquifers of the Carpentaria and Karumba basins are more commonly used than the Proterozoic groundwater systems in the region. Of the 190 registered groundwater bores within the area assessed (Figure 31), 152 bores tap aquifers of the Carpentaria and Karumba basins, which provide the shallowest and most accessible groundwater resources.

The Carpentaria Basin consists of a variably confined groundwater system comprising a multi-layered complex of aquifers and aquitards. The main aquifers occur within continental-derived sandstones. The hydrostratigraphy is presented in Figure 21, with a cross-section in Figure 34.

3.1.2.1 Gilbert River Formation

The Gilbert River Formation is a confined aquifer in the eastern part of the Isa GBA region (Figure 33). This unit is the deepest aquifer commonly accessed for groundwater in the region, with 23 registered bores (Geoscience Australia, 2018c). Bores in this aquifer are typically screened at depths greater than 150 m, and some are over 500 m below ground level.

3.1.2.2 Rolling Downs Group

The Rolling Downs Group consists of a series of aquitards (comprising the Wallumbilla and Toolebuc formations and the Allaru Mudstone), known as the Rolling Downs Group aquitard; and an overlying partial aquifer, the Normanton Formation.

The Rolling Downs Group aquitard is widespread across the Isa GBA region. It extends from the western boundary of the Carpentaria Basin (shown in Figure 35) and increases in thickness eastwards, where it is over 500 m thick around Burketown. This aquitard mainly consists of mudstones and other fine-grained sedimentary rocks and is considered the most effective aquitard in the Carpentaria Basin because of its wide extent, significant thickness and very low permeability (Ransley et al., 2015). Despite being a regionally important aquitard, limited supplies of saline groundwater have been obtained from thin sandstone interbeds within the lower part of the Wallumbilla Formation (Smart et al., 1980). Within the area assessed for this study there are six bores that access groundwater from the Rolling Downs Group aquitard (Geoscience Australia, 2018c).

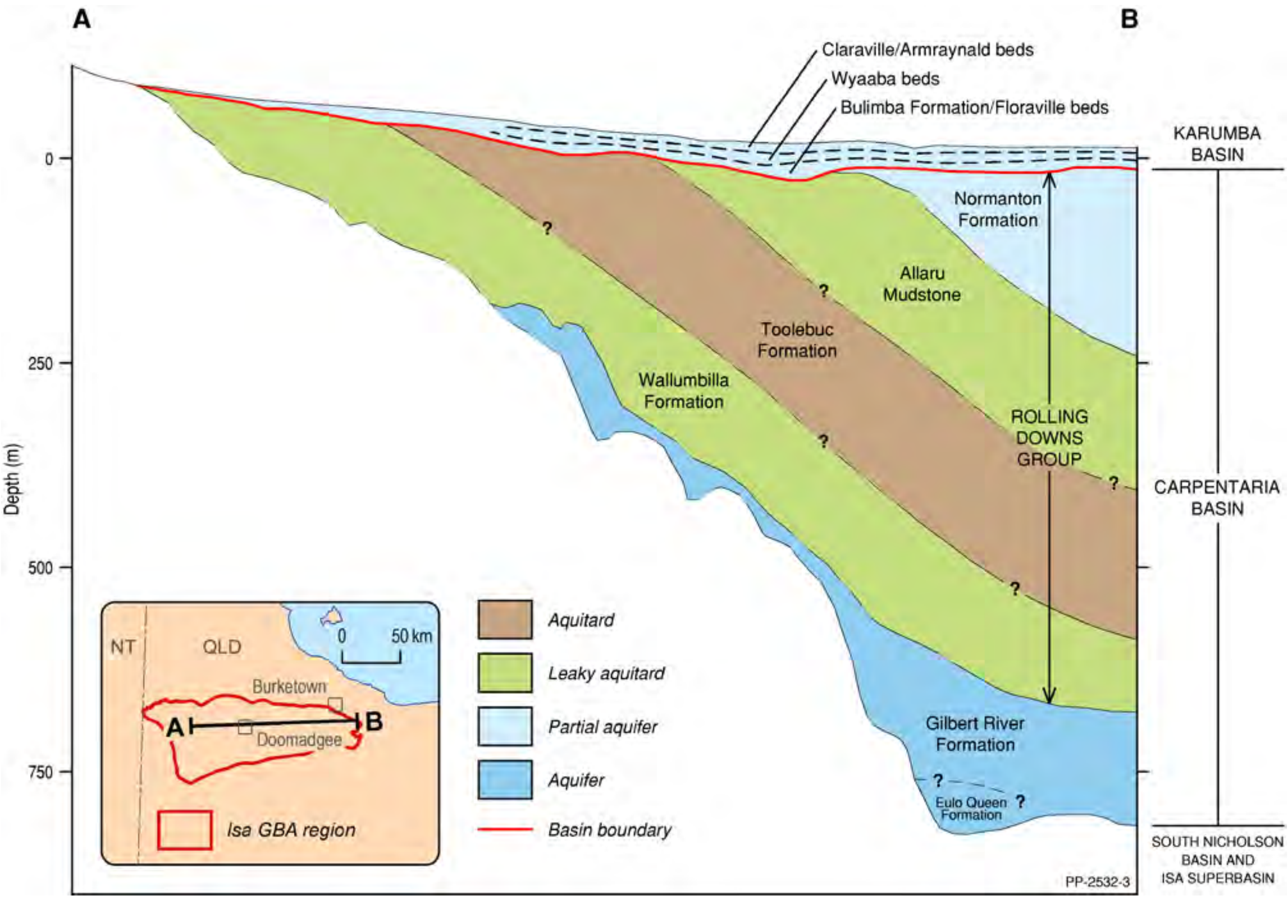

Figure 34 Conceptual hydrogeological stratigraphy of the Carpentaria and Karumba basins in the Isa GBA region

The thickness of the Toolebuc unit is indicative only and shown to illustrate hydrostratigraphic relationships.
Data: Geoscience Australia (2018d)
Element: GBA-ISA-2-140

The Normanton Formation occurs only in the eastern part of the Isa GBA region, south of Burketown. The formation thickness increases further eastwards to a maximum thickness of around 300 m near the Gulf of Carpentaria. Although the Normanton Formation is classed as a partial aquifer (Smerdon et al., 2012c), only one bore near the Isa GBA region is known to extract groundwater from the Normanton Formation, at a depth of 39.5 m below ground level (Geoscience Australia, 2018c).

3.1.2.3 Karumba Basin

The sediments of the Cenozoic Karumba Basin are relatively thin (typically less than 50 m thick) but occur widely across the Isa GBA region, pinching out approximately 45 km to the west of Doomadgee, corresponding to the edge of the GAB (extent of GAB in Figure 35). The three major units of the Karumba Basin are the Armraynald beds, Wyaaba beds and Bulimba Formation (see Figure 21 and also Table 7 for a summary of lithological properties). The Armraynald beds are generally considered a leaky aquitard, whereas the other units have partial aquifer characteristics (Smerdon et al., 2012b). The Bulimba Formation is the most commonly accessed unit of the Karumba Basin, with nine bores tapping this unit. Bore inlet screen depths range from 29 to 45 m below ground level.

3.1.2.4 Unconsolidated sediment deposits

Colluvium and sheetwash deposits are widespread over much of the region and form a thin cover over the Bulimba Formation and other units of the Karumba Basin. They are commonly underlain by ferricrete at a shallow depth. Seven bores access groundwater within alluvial deposits (Geoscience Australia, 2018c). Bore screen depths are generally shallow and typically only 5 m below surface, although some screens are up to 21 m deep.

3.1.2.5 Groundwater levels in Mesozoic and Cenozoic units

Based on available data, groundwater levels (above mean sea level) in the confined Gilbert River Formation range from 27.4 to 49.1 mAHD (Figure 33). There are insufficient data points to generate water level contours for this aquifer. Eight artesian bores (Geoscience Australia, 2018c) are in the north-east of the region, with recorded artesian pressures ranging from 137 to 290 kPa (groundwater level approximately 15 to 30 m above mean sea level).

The regional watertable is the uppermost groundwater system and is typically present in the sediments of the Karumba Basin. It is generally an unconfined aquifer, and the groundwater level (above mean sea level) ranges from about 60 mAHD on the western margin of the GAB to 0 mAHD near the coast (Ransley et al., 2015). The groundwater flow direction follows this north-easterly gradient, although it may be locally influenced by topography. The elevation of the regional watertable is presented in Figure 35. The zero watertable contour (0 mAHD) occurs up to 30 km inland from the coast, indicating a potentially large zone where tidal (and saltwater) influences may affect groundwater.

3.1.2.6 Groundwater quality and recharge in Mesozoic and Cenozoic units

Groundwater quality, as indicated by TDS, is typically considered low to moderately saline. The salinity of groundwater in the Gilbert River Formation aquifer ranges from 367 to 1638 mg/L, with a median of 1324 mg/L. The salinity of groundwater in the regional watertable covers a broader range, from 191 to 6912 mg/L, with a median of 790 mg/L.

Hydrochemical data indicate that the Gilbert River Formation in the Isa GBA region varies from sodium-bicarbonate-chloride (Na-HCO_3-Cl) to sodium-chloride-bicarbonate (Na-Cl-HCO_3) type. This is typical of groundwater in the GAB that has migrated from the original point of recharge and has undergone hydrochemical evolution along the flow path. Significantly different hydrogeochemical signatures exist for groundwater in the other aquifers of the region (i.e. the regional watertable in the Karumba Basin and the aquifers of the Isa Superbasin and South Nicholson Basin), possibly indicating that mixing of groundwater between different aquifers is of limited extent. Other hydrogeochemical data (such as fluoride and sulfate) for the Carpentaria and Karumba basin aquifers are presented and analysed in the hydrogeology technical appendix (Buchanan et al., 2020).

Most of the available groundwater chemistry data indicate that the main aquifers of the region have distinct groundwater signatures. Despite this, limited groundwater sampling data show some slightly elevated concentrations of gas (mostly methane) within the Gilbert River Formation and the Normanton Formation within the Isa GBA region (EHS Support, 2014). Although the source of gas in the aquifers is currently unknown, it may indicate that some degree of connectivity exists between these GAB aquifers and the deeper hydrocarbon-bearing units of the Isa Superbasin. This potential connectivity pathway is further assessed in Section 3.4.2.

Recharge to the Karumba Basin and Normanton Formation in the Carpentaria Basin is typically through diffuse recharge (where rainfall directly recharges down into an aquifer system) and streambed recharge (to a lesser extent). A large proportion of total recharge in the Karumba Basin is expected to enter the surface water system as baseflow to rivers (DSITIA, 2014) as well as spring discharge, overland flow or evapotranspiration losses. According to a recent hydrogeological assessment of the GAB (Klohn Crippen Berger, 2016), recharge to the Karumba Basin (within the Southern Carpentaria sub-basin, incorporating the Isa GBA region) is 160 GL/year on average, ranging from 80 to 400 GL/year. Recharge is estimated to be much lower for the Normanton Formation (within the Southern Carpentaria sub-basin), averaging 38 GL/year (ranging from 19 to 96 GL/year).

The primary source of recharge to the Gilbert River Formation, the deeper aquifer system of the Carpentaria Basin, is through intake beds where the formation outcrops and receives infiltration from rainfall (as explained in the hydrogeology technical appendix (Buchanan et al. (2020) the Gilbert River Formation does not outcrop within the Isa GBA region, and the main recharge intake beds for this aquifer occur several hundred kilometres away to the east of the region). Within the Southern Carpentaria sub-basin, recharge to the Gilbert River Formation is estimated as 22 GL/year on average, ranging from around 8 GL/year to 31 GL/year (Klohn Crippen Berger, 2016). The combined recharge rate to the Carpentaria Basin is 60 GL/year on average, ranging from 27 to 127 GL/year.

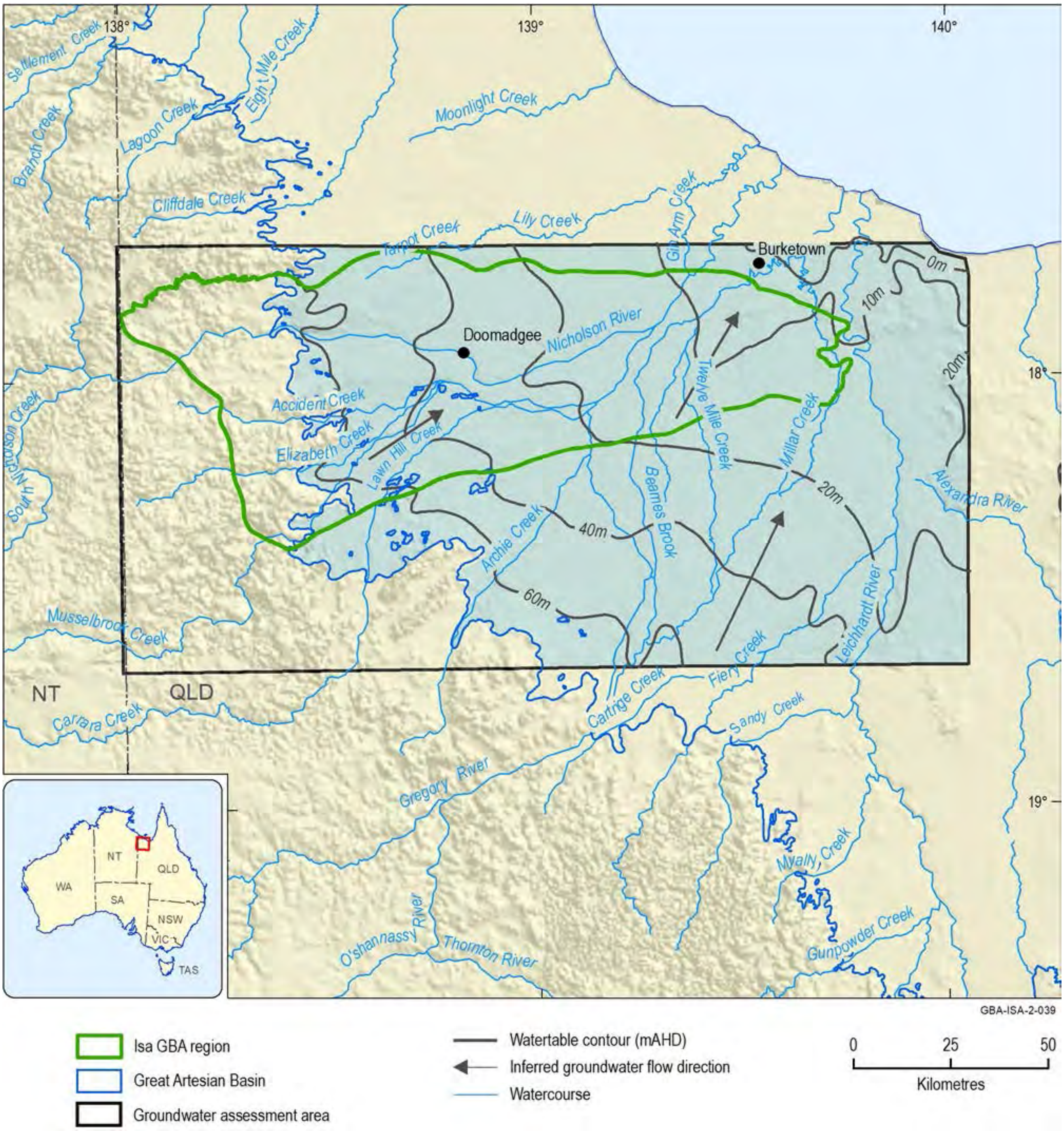

Figure 35 Regional watertable potentiometric contours and flow directions

mAHD = metres above sea level

Data: groundwater contours (Ransley et al., 2015)

Element: GBA-ISA-2-039

3.2 *Surface water conceptualisation*

Most of the Isa GBA region is in the catchment of the Nicholson River (8020 km²), with smaller areas within the Settlement Creek (190 km²) and Leichhardt River (8 km²) catchments. For the purposes of this assessment, the Nicholson River is the major stream of interest, with its catchment covering most of the region. There is a strong gradient in the runoff generated from south to north (Figure 37) that follows the rainfall gradient (Figure 11). The Nicholson

River discharges into the Gulf of Carpentaria after flowing through the extensive wetlands of the Nicholson Delta Aggregation – a complex, disjointed aggregation of wetlands merging with an extensive estuarine system of saline clay pans and tidal channels. A small weir at Doomadgee provides the main artificial impediment to streamflow along the Nicholson River.

Most of the Isa GBA region is in the Nicholson River catchment (8020 km^2), with smaller areas within the adjacent Settlement Creek (190 km^2) and Leichhardt River (8 km^2) catchments (Figure 36). The Nicholson River flows through the Isa GBA region and is the major river of interest for this assessment. Its entire catchment area covers 51,600 km^2. There is a strong gradient in the runoff generated from south to north (Figure 37) following the rainfall gradient (Figure 12), with the highest runoff generated near the coast. A small concrete weir at Doomadgee partly restricts streamflow along the river (Figure 38), especially during the dry-season months. This weir acts as a local barrier to impound water from the Nicholson River to supply local use at Doomadgee. However, there are no major dam storages in the Nicholson River catchment, so river flow is mostly unimpeded by regulation.

Gregory River and Lawn Hill Creek are perennial tributaries of Nicholson River fed from groundwater that discharges from the geological Georgina Basin upstream of the Isa GBA region (Figure 9). The Nicholson River becomes perennial downstream of the confluence of Gregory River, with dry-season flows decreasing toward the coast due to riparian zone evapotranspiration (CSIRO, 2009).

The Nicholson River discharges into the Gulf of Carpentaria after flowing through the extensive wetlands of the Nicholson Delta Aggregation, which is listed as a nationally important wetland (Environment Australia, 2001). The aggregation comprises a complex disjunct wetland aggregation of closed depressions in impeded drainage lines, flood-outs, back-plains and riverine channels merging with an extensive estuarine system of saline clay pans and tidal channels (Blackman et al., 1992).

The Leichhardt River catchment covers 33,300 km^2 and has several small headwater storages to supply water for the regional city of Mount Isa. Runoff (Figure 37) follows the rainfall gradient (Figure 12), with increasing runoff generated in a downstream direction. Settlement Creek catchment covers 17,300 km^2, with the highest runoff generated near the coast (Figure 37) in the area of relatively higher rainfall (Figure 12). However, as the Isa GBA region only intersects small parts of both the Leichhardt River and Settlement Creek catchments, these catchments are not further considered in this section.

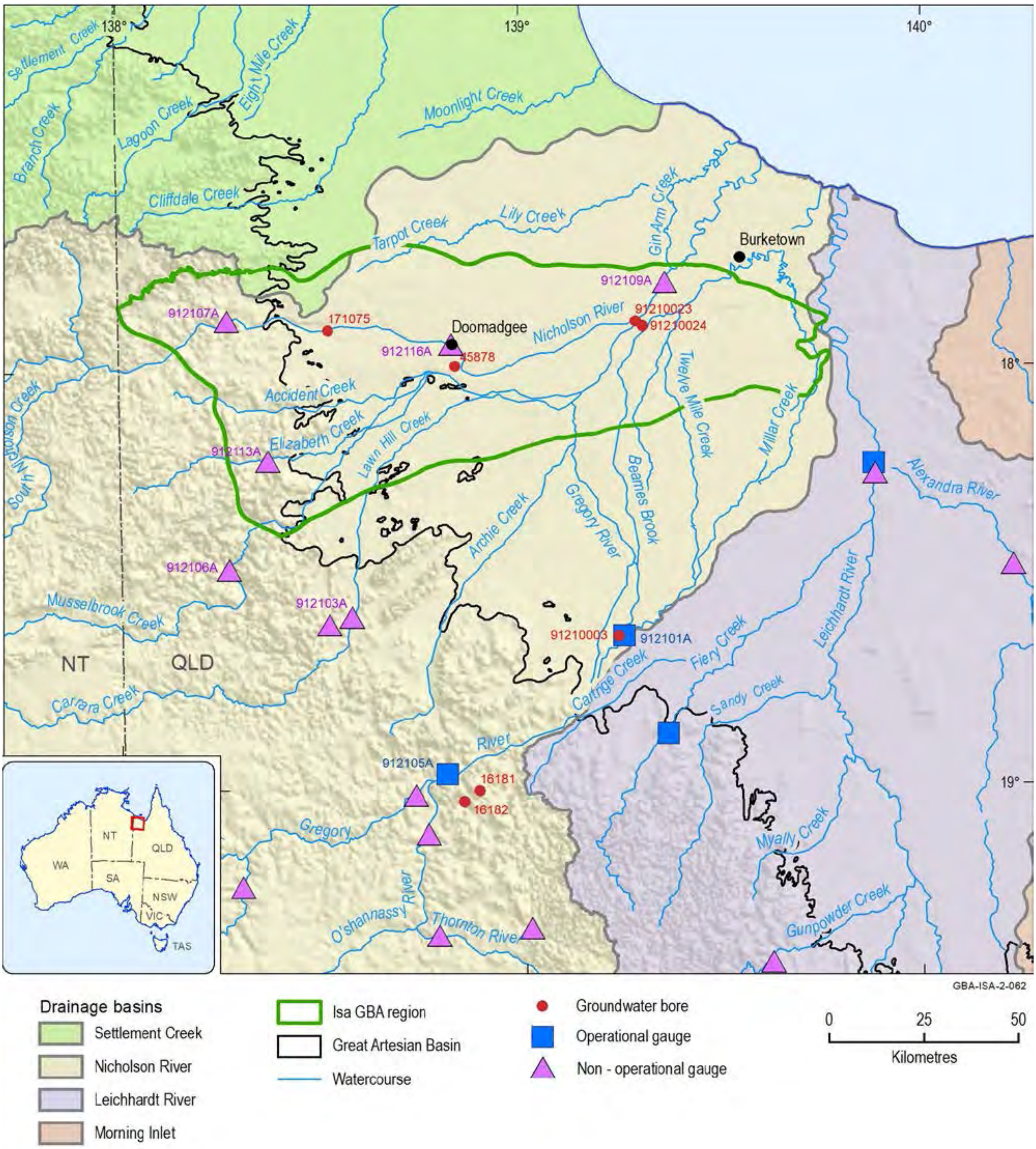

Figure 36 Major streams, stream gauges and selected groundwater monitoring bores

Selected stream gauges and bores that were assessed are labelled.
Data: stream gauging network (Department of Natural Resources, Mines and Energy (Qld), 2016); groundwater bores (Geoscience Australia, 2018c)
Element: GBA-ISA-2-062

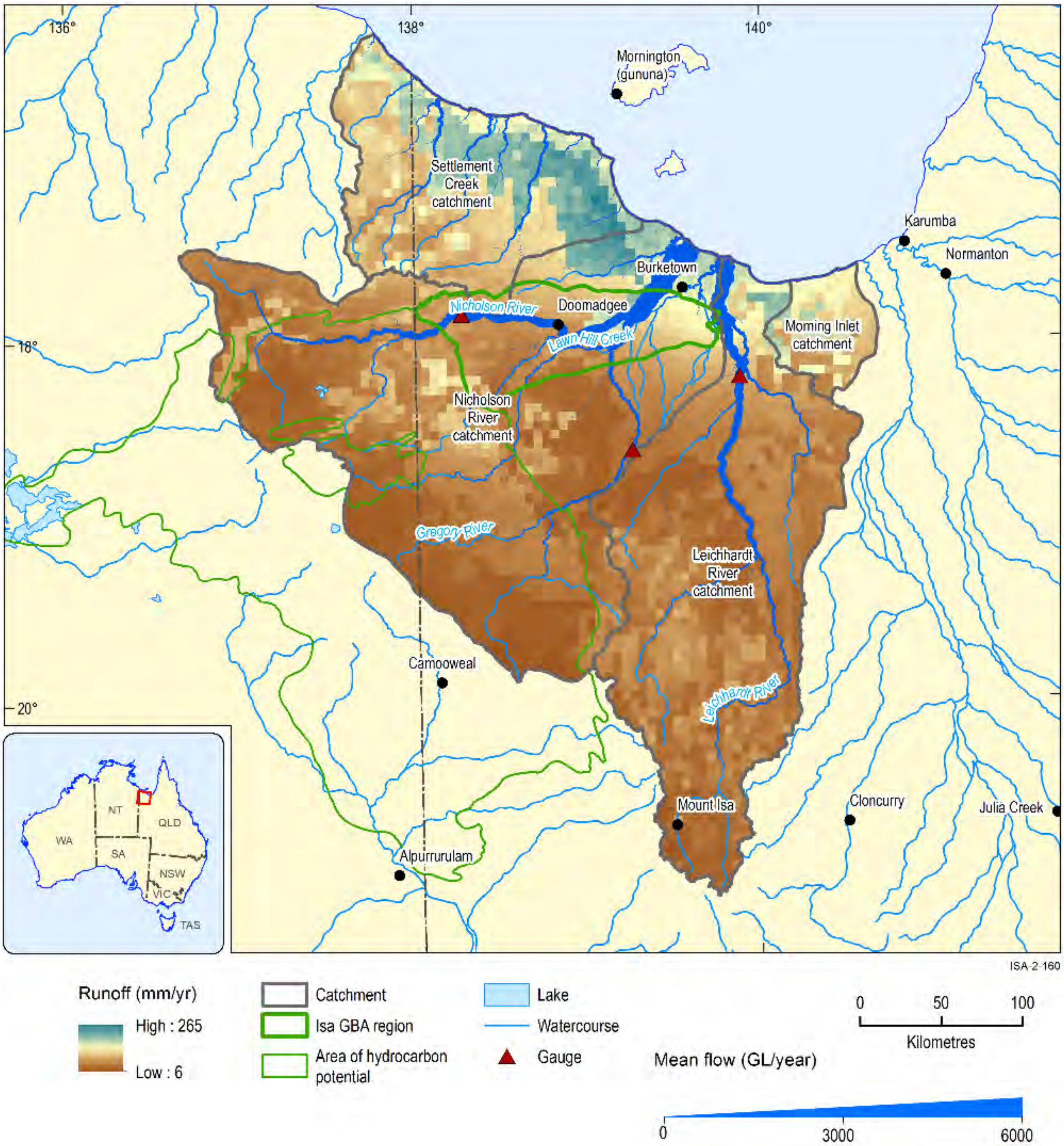

Figure 37 Runoff across the Nicholson River, Leichhardt River, Morning Inlet and Settlement Creek catchments

Data: CSIRO (2015)
Element: GBA-ISA-2-160

Monthly streamflow (see the upper three panels of Figure 39) at the three selected example gauges in the Isa GBA region are unevenly distributed throughout the year. Maximum flows occur in March for Nicholson River at Connollys Hole (gauge 912107A) and in January for Gregory River at Gregory Downs (gauge 912101A) and Leichhardt River at Floraville Homestead (gauge 913007B). The lowest flows occur in September for all three gauges.

Figure 38 View looking north along the concrete weir across the Nicholson River near Doomadgee, July 2018

The weir at Doomadgee impedes streamflow in the Nicholson River to form a large waterhole used by the local community. Downstream of the weir the river is mostly dry during the mid- to latter part of the dry season, with continuous flow in the river only resuming following significant wet-season rainfall across the catchment.
Source: Geological and Bioregional Assessment Program, Steven Lewis (Geoscience Australia), July 2018
Element: GBA-ISA-2-253

The catchments of the Isa GBA region have variable interannual flows. These range from less than 10 GL/year to over 4000 GL/year for the Nicholson River (gauge 912107A), from less than 100 GL/year to over 3000 GL/year for the Gregory River (gauge 912101A) and from less than 10 GL/year to over 13,000 GL/year for the Leichhardt River (gauge 913007B) (see middle three panels of Figure 39). Annual flow data are missing for some years because of missing daily flow data. However, there are no years with zero flow, so all gaps in the figures represent years with missing data (Figure 39). Furthermore, there are no missing data in any of the remaining annual totals. The mean annual flow for the Nicholson River (gauge 912107A) is about 1086 GL/year, about 619 GL/year for the Gregory River (gauge 912101A) and 2583 GL/year for the Leichhardt River (gauge 913007B) (Figure 39).

Flow in the Nicholson River is ephemeral upstream of the confluence of the Nicholson and Gregory rivers. At Connollys Hole (gauge 912107A) the Nicholson River flows less than 50% of the time (see Figure 39). Gregory River is a perennial river fed by groundwater discharge from the Georgina Basin upstream of the Isa GBA region. Dry-season flow in the Nicholson River decreases downstream of the confluence of the Gregory River due to evapotranspiration by riparian vegetation and potentially due to loss into the stream bed and shallow aquifer. The Leichhardt River is ephemeral at Floraville Homestead (gauge 913007B), with the river flowing less than 60% of the time.

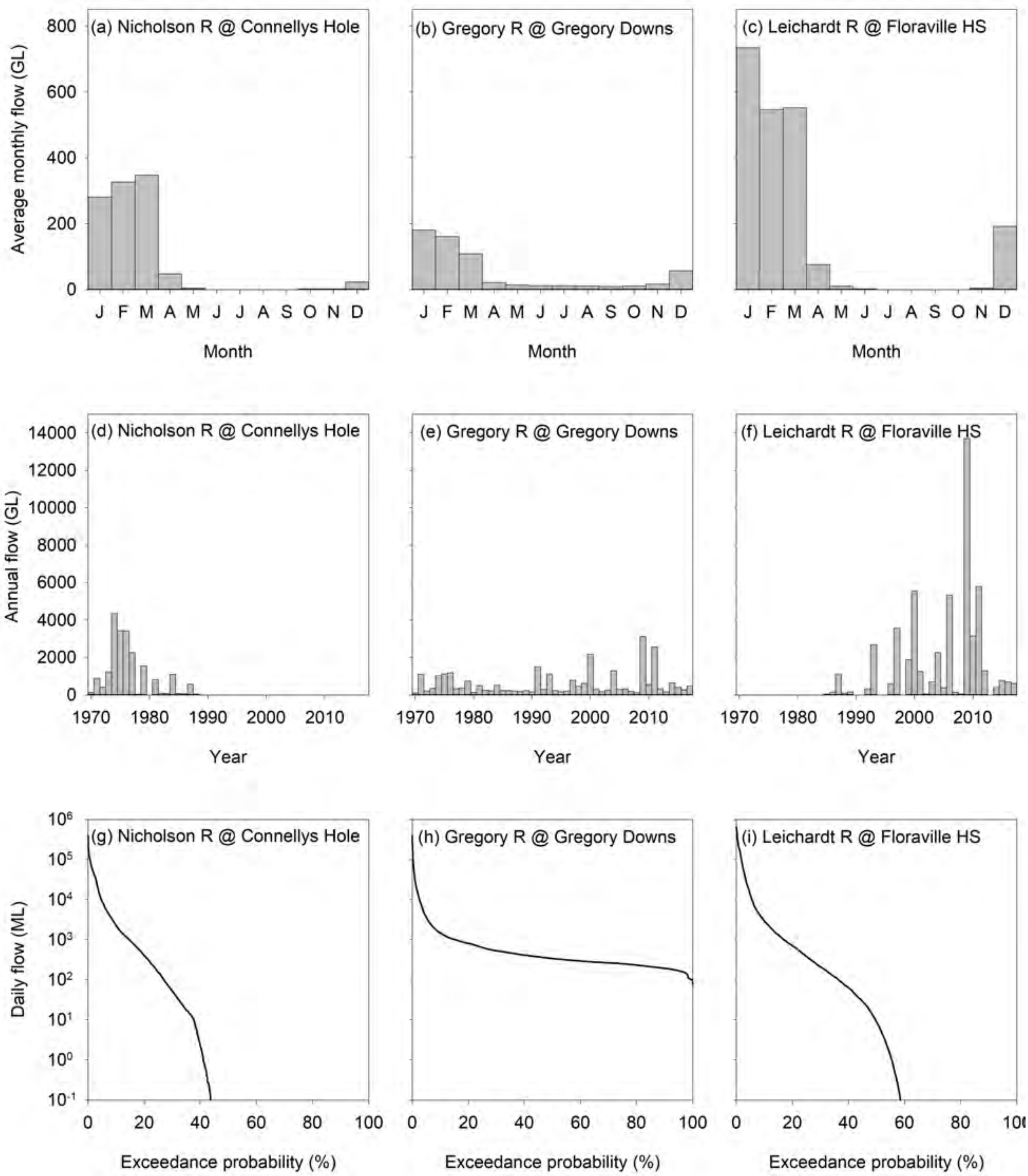

Figure 39 Monthly distribution of streamflow (top three panels), annual variability of streamflow (middle three panels) and flow duration curves (bottom three panels) for three gauges in or near the Isa GBA region

For the flow duration curve, streamflow data were log10 transformed with daily streamflow plus 1 ML/day to make sure the denominator does not equal zero. When flow is zero, the log10-transformed flow equals zero as well.
Data: Department of Natural Resources, Mines and Energy (Qld) (2016)
Element: GBA-ISA-2-261

Surface water quality in the Isa GBA region is variable in space and time. Over past decades, there has been systematic sampling of the water quality of the surface water system at the gauge network through the Surface Water Ambient Water Quality Network (SWAN) program in Queensland. For the three gauge sites shown in Figure 37 the median recorded TDS was 36 mg/L for Nicholson River at Connollys Hole, 281 mg/L for Gregory River at Gregory Downs and 105 mg/L for Leichhardt River at Floraville Homestead (Figure 40a). At all three sites TDS would be considered good quality for drinking water (NHMRC/ARMCANZ, 1996) and suitable for stock watering (ANZECC/ARMCANZ, 2000). In the absence of any specific guideline values in the Environmental Protection Policy (Water) for the rivers of the Isa GBA region, the nutrient levels have been compared against the national guidelines for aquatic ecology in tropical lowland rivers (ANZECC/ARMCANZ, 2000). Only the site on Leichhardt River has data: all samples are above the national guideline values for total phosphorous and 30% of samples are above the national guideline values for total nitrogen (Figure 40(b) and (c)). This does not necessarily mean poor quality water, as both Queensland's Environmental Protection Policy (Water) and the national guidelines highlight the importance of using guideline values tailored to the local environment.

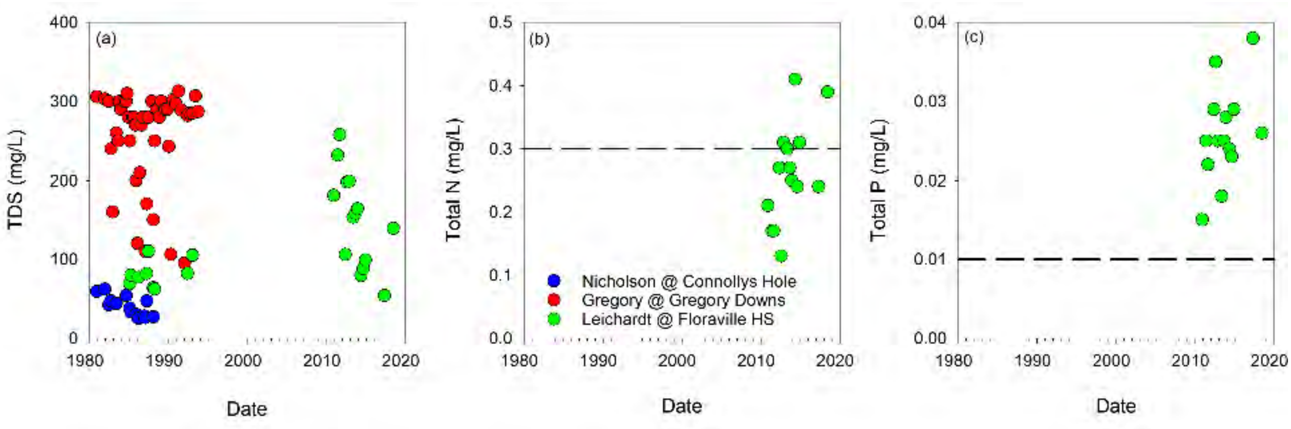

Figure 40 Indicators of surface water quality for three gauging stations in the Isa GBA region showing (a) total dissolved solids (TDS); (b) total nitrogen (Total N); and (c) total phosphorous (Total P)

The dashed lines represent the national guideline value for aquatic ecology in tropical lowland rivers (ANZG, 2018).
Data: Department of Natural Resources, Mines and Energy (Qld) (2018c)
Element: GBA-ISA-2-213

3.3 Surface water – groundwater conceptualisation

The interactions between surface water and groundwater are an important component of the hydrological system in the Isa GBA region. The conceptualisation of surface water – groundwater interactions depends on understanding groundwater flow systems (Section 3.1) and surface water flow characteristics (Section 3.2). A range of datasets, including streamflow, groundwater, geology and remote sensing products, have been analysed for this assessment. Only a summary of the main surface water – groundwater interactions are presented here, with more detail provided in the hydrogeology technical appendix (Buchanan et al., 2020). The key mechanisms of interaction are depicted in Figure 30.

The alluvial floodplains of the Isa GBA region have the greatest potential for surface water – groundwater interactions, arising from connectivity between groundwater hosted in the Karumba Basin sediments and surface waters. Spring ecosystems in the south-west are also supported by groundwater, potentially sourced from Proterozoic sandstone aquifers. The mechanisms of interaction vary spatially and are dynamic in nature due to the seasonal rainfall pattern. Groundwater provides baseflow to streams that intersect aquifers, emerges at spring vents and discharges offshore. Surface waters also recharge the groundwater system at certain times of the year – for example, during large flooding events. Groundwater supports aquatic and terrestrial groundwater-dependent ecosystems (GDEs) in the region, including springs, wetlands, instream waterholes and vegetation communities.

3.3.1 Stream–groundwater relationships and potential water sources

The Nicholson River catchment contains several operational and non-operational stream gauges. No operational gauges are in the Isa GBA region (Figure 36).

Major streams flow into the region from the west and south, meeting to the east of Doomadgee. Based on available historical stream, groundwater, geology and remote sensing data, stream–groundwater relationships can be summarised into three categories for streams that intersect the Isa GBA region: (i) streams flowing from the west; (ii) streams flowing from the south; and (iii) streams flowing through the alluvial floodplains.

3.3.1.1 Streams flowing from the west

The upper Nicholson River (west of Doomadgee), Elizabeth Creek and Musselbrook Creek flow through outcrop areas of the Constance Sandstone (South Nicholson Group) (Figure 41) and have intermittent or very low flows during the dry season. Evidence from remote sensing analysis (Water Observations from Space (WOfS) summary statistics) (Geoscience Australia, 2018e; Mueller et al., 2016) indicates that permanent pools may occur along these streams (Figure 42). The streams have a hydrochemical signature consistent with groundwater from Proterozoic sandstone units (upper McNamara Group). Shallow groundwater below the ferricrete zone (Grimes and Sweet, 1979) may also contribute baseflow to the Nicholson River or instream waterholes west of Doomadgee, where the ferricrete has been incised by the stream (Figure 41). Due to the paucity of data, the source waters for these streams are inconclusive. However, there is potentially some contribution, although not sustained, from groundwater.

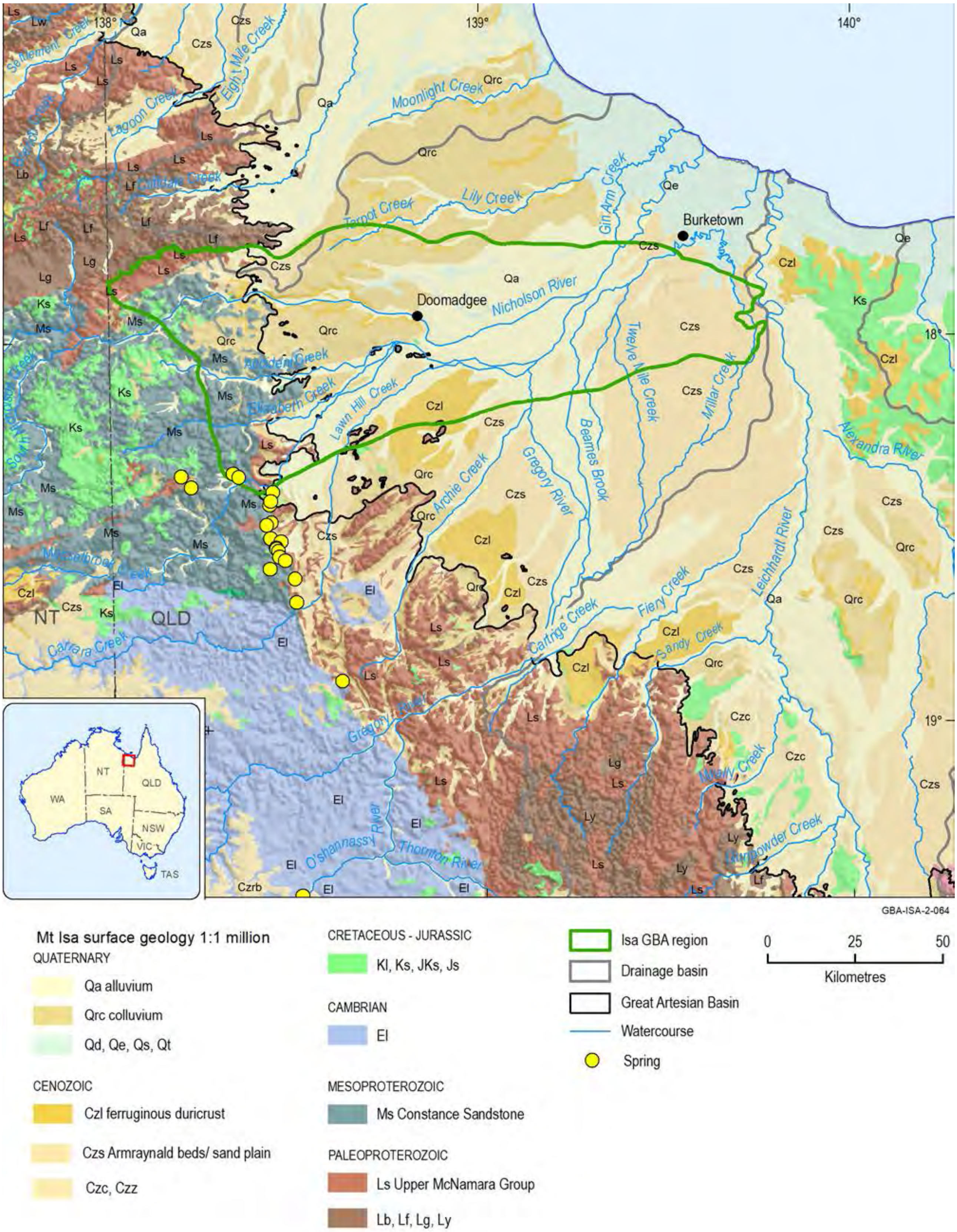

Figure 41 Simplified surface geology

Only the main geological units within and near the Isa GBA region are labelled on this map. The other geological units shown on the map are defined in the table of abbreviations and acronyms in the preamble of this report.
Data: surface geology (Geoscience Australia, 2012); springs (Department of Environment and Science (Qld), 2018c)
Element: GBA-ISA-2-064

3.3.1.2 Streams flowing from the south

The perennial streams of Lawn Hill Creek and Gregory River (Section 3.2) are sustained by baseflow from limestone aquifers (unit El in Figure 41) to the south of the region. These streams provide an indirect source of groundwater to the lower Nicholson River, which is perennial downstream of the confluence with the Gregory River (Figure 42). Consistent with the variation in regional surface geology and the presence of faults (Figure 41 and Figure 43), surface waters from Lawn Hill Creek, Gregory River and the lower Nicholson River overlap hydrochemically with groundwaters associated with various geological units (refer to Section 4.5.4 of the hydrogeology technical appendix (Buchanan et al., 2020)). Further hydrochemical data are needed to confirm water sources and relative contributions from groundwater to the streams.

3.3.1.3 Streams flowing through alluvial floodplains

Stream reaches within the alluvial floodplains of the region (landscape class ‘floodplain and alluvium’, Figure 52) are incised into sediments of the Karumba Basin, which are considered to be partial aquifers (Section 3.1.2). The overlying unconsolidated alluvial deposits also form widespread shallow aquifers and are associated with aquatic and terrestrial GDEs east of Doomadgee and in the south-west of the region (Elizabeth and Musselbrook creeks) (Figure 42). According to Smerdon et al. (2012a), groundwater discharge to streams originates from the Cenozoic aquifers of the Karumba Basin (Section 3.1.2.3). In addition, based on limited available groundwater and surface water level data, downwards leakage from the lower Nicholson River to alluvium and recharge to groundwater from the Gregory River are both plausible (see Section 4.5.2 in Buchanan et al. (2020)). Queensland’s Department of Science, Information Technology, Innovation and the Arts (DSITIA (2014)) suggested that a large proportion of total recharge in the Karumba Basin is expected to enter the surface water system, including baseflow to rivers. On balance, it is considered that the alluvial floodplains associated with the Karumba Basin sediments and alluvial deposits have a direct hydraulic connection to streams, with the potential for both gaining and losing stream reaches in different parts of the region and during different time periods.

3.3.2 Remote sensing analysis to identify groundwater-dependent ecosystems

Methods snapshot: mapping groundwater-dependent ecosystems using remote sensing

The *National atlas of groundwater dependent ecosystems* (GDE Atlas) (Bureau of Meteorology, 2017) provides a national dataset for the occurrence of groundwater-dependent ecosystems (GDEs) based on the compilation of a range of data sources. The GDE Atlas contains information about the potential occurrence of aquatic, terrestrial and subterranean GDEs. The degree of confidence in GDE mapping in the GDE Atlas (Bureau of Meteorology, 2017) varies from low to high and is based on national and regional studies. While detailed mapping has occurred in some areas of Australia, in most places the GDEs are identified using remote (desktop) methods and are unlikely to have been validated from field studies.

Combining existing GDE mapping with remote sensing products provides greater confidence in identifying, based on a consistent approach, parts of the landscape where there is greatest potential for surface water – groundwater interactions to occur. Based on available Landsat imagery (1987 to 2018), two remote sensing products from Digital Earth Australia (Geoscience Australia, 2018e) – Water Observations from Space (WOfS) summary statistics and Tasselled Cap Wetness (TCW) exceedance composite – were used to investigate the persistence of surface water or wetness in the landscape and identify perennial streams and other areas that may rely on groundwater. Remote sensing imagery associated with declining phases in residual rainfall, particularly within the dry-season months (May to October), provides an ideal opportunity for investigating surface water – groundwater interactions because it is assumed that groundwater will be the primary water source during these times.

The WOfS summary statistic represents, for each pixel, the percentage of time that water is detected at the surface relative to the total number of clear observations. Due to the 25 x 25 m pixel size of Landsat data, only features at least 25 m wide are detected. In contrast to WOfS, the TCW exceedance composite includes both open water and other wet/moist parts of the landscape such as soil, wet vegetation and leaf moisture. The TCW exceedance composite is particularly useful where open water features are too small to be detected by the satellite (less than 25 m) but the wetness footprint may be larger.

GDEs rely on groundwater for some or all of their water requirements. This makes them vulnerable to changes in the hydrological cycle, such as changes due to excessive groundwater extraction. Based on the GDE Atlas (Bureau of Meteorology, 2017), about one-third of the Isa GBA region has identified GDEs. Terrestrial GDEs are widespread on the alluvial floodplains to the east of Doomadgee and around Musselbrook Creek in the south-west (Figure 42; also Figure 41 in the hydrogeology technical appendix (Buchanan et al., 2020)). Aquatic GDEs are associated with streams, springs and other waterbodies – a subset associated with permanently flowing streams occur along Lawn Hill Creek and Gregory River. Conceptual diagrams for the occurrence of GDEs in floodplain and alluvial environments are shown in Figure 54. Parts of the mapped GDE areas correspond with environmental assets identified within the region, such as nationally important wetlands, protected areas and strategic environmental areas (Figure 51).

As a first-pass assessment, parts of the landscape that retain surface water or wetness for more than 80% of time are most likely to support GDEs. Given the highly seasonal rainfall pattern (Section 1.4), these areas are likely to have a reliable groundwater source or access to groundwater that maintains surface water features during periods of limited rainfall (i.e. in the dry season). Combining GDE Atlas mapping (Bureau of Meteorology, 2017) with remote sensing products (Figure 42) confirms that the identified aquatic GDEs correspond with surface water features, which retain open water as continuous flow or instream waterholes (water observed >80% of the time) or remain moist (wetness observed >80% of the time). Similarly, off-channel locations that maintain surface water or moisture in the landscape during the dry season are within the mapped extent of terrestrial GDEs, particularly in the south-west where springs occur. Further analysis of Earth observation data, including assessment of different spectral bands during a range of time periods, would enable a more comprehensive assessment of GDEs in the landscape of the Isa GBA region.

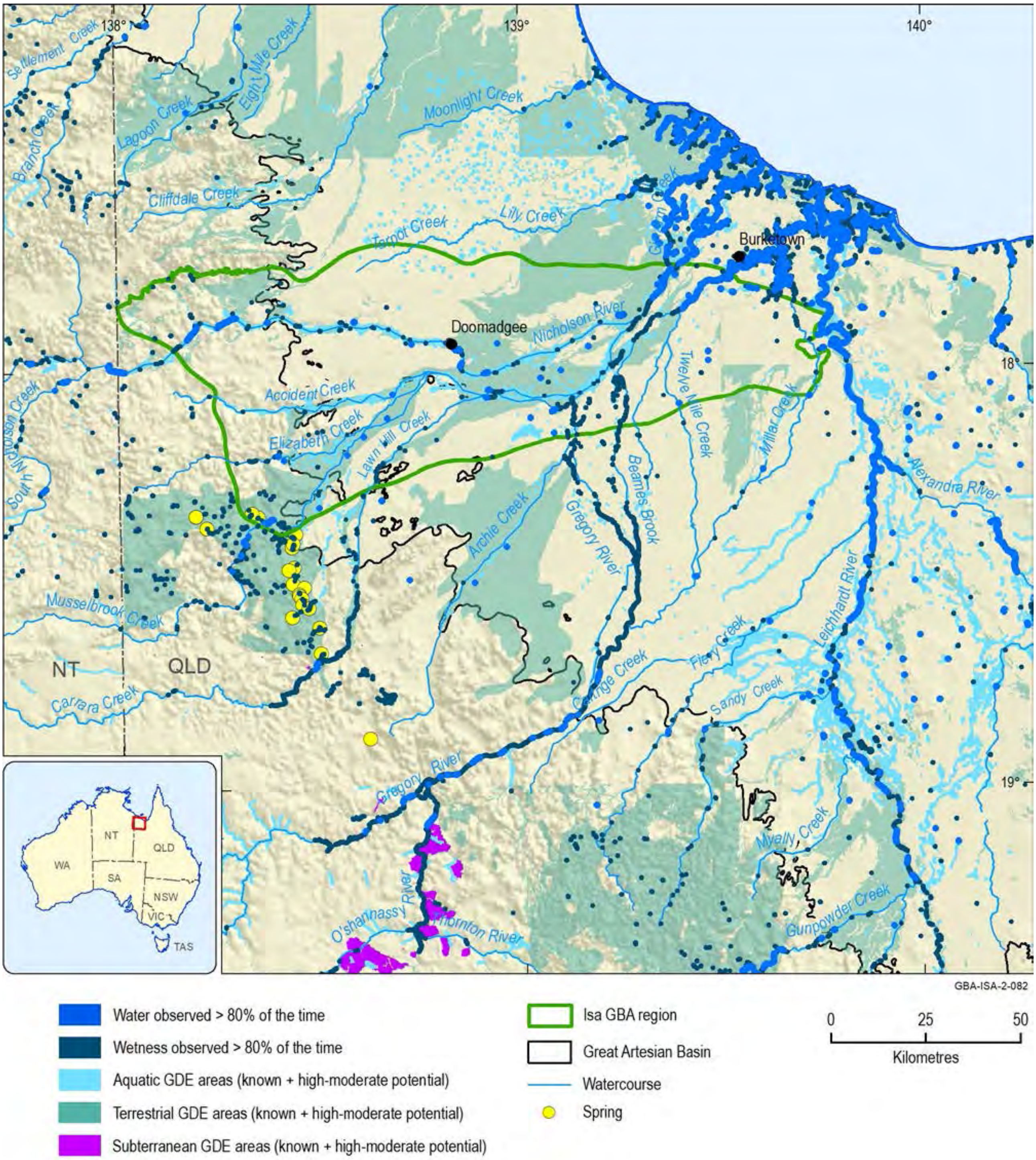

Figure 42 Composite of remote sensing analyses and mapped groundwater-dependent ecosystems (GDEs)

Remote sensing products include Water Observations from Space (WOfS) summary statistic (medium blue) (1987–2018) and Tasselled Cap Wetness (TCW) exceedance composite (dark blue) (May–October 2015). Pixels have been polygonised and classified to visually enhance key data in the remote sensing products. Groundwater-dependent ecosystems (GDEs) include aquatic, terrestrial and subterranean types.
Data: WOfS classified (Geoscience Australia, 2018f); TCW classified (Geoscience Australia, 2018a); *National atlas of groundwater dependent ecosystems* (Bureau of Meteorology, 2017); springs (Department of Environment and Science (Qld), 2018c)
Element: GBA-ISA-2-082

Despite the limitations of remote sensing products (see Section 4.5.8 in the hydrogeology technical appendix (Buchanan et al., 2020)), the analyses provide a consistent first-pass approach to mapping, at regional scale, parts of the landscape that rely on groundwater and enable assessment of where there is greatest potential for surface water – groundwater interactions. The remote sensing products assessed as part of this study are only a small part of the data and products currently available through Digital Earth Australia (Geoscience Australia, 2018e) and the interpretation provided here is preliminary. Further investigations of the Isa GBA region would benefit from comprehensive statistical and time-series trend analyses of a range of remote sensing datasets and improved integration with hydrological, hydrogeological and ecological data (particularly within or near areas of likely shale gas development).

In addition to assessing the current extent of GDEs and identifying potential areas of surface water – groundwater interactions, remote sensing techniques could be used to monitor potential impacts of future changes in land and water use in and around the Isa GBA region.

3.3.2.1 Springs

Methods snapshot: classifying springs in the Great Artesian Basin

Many ecosystems depend on groundwater from springs in the GAB (Smerdon et al., 2012a). Springs in the GAB have been divided into two broad categories: recharge springs and discharge springs (Fensham et al., 2016). Recharge springs occur in clusters throughout semi-arid Queensland (Fensham et al., 2016), commonly at the base of cliffs or escarpments, where they are fed by shallow groundwater discharging from higher terrain under gravitational pressure. After a succession of wet summers, water can seep out from recharge springs for some months but then, unlike discharge springs, they may be dry for years.

Springs are important aquatic ecosystems that depend on groundwater. Although no GAB springs have been identified in the Isa GBA region, there are 22 non-GAB recharge springs mapped in the south and south-west, both within and outside the region. All of these springs are permanently saturated and active, and the source aquifer of most springs is interpreted to be sandstones of the Lawn Hill Formation (upper McNamara Group) (Department of Environment and Science (Qld), 2018c). However, based on the surface geology (Geoscience Australia, 2012), the springs within the Isa GBA region are located within the Constance Sandstone (South Nicholson Group), which is interpreted to be a partial aquifer (Figure 41). Other springs to the south of the region have a linear alignment along a geological contact between the South Nicholson and upper McNamara groups (see Figure 41). The location of these springs corresponds with a marked change in elevation, consistent with groundwater discharge at a break in slope (Figure 43). Surface faults and regional structural features also occur near the springs and may influence their occurrence and their potential source aquifers.

In addition to the mapped springs (Department of Environment and Science (Qld), 2018c), other wet areas in the landscape have been identified by remote sensing methods, and these features may also represent springs (wetness observed >80% of the time in Figure 42). These wet areas are within the mapped extent of terrestrial GDEs centred on the Musselbrook Creek floodplain. Field observations and sampling would enable the presence and characteristics of these additional springs to be determined.

As springs are sensitive environmental assets, it is important to validate their potential source aquifers. However, there are currently no available hydrochemical or isotopic studies that have characterised the springs in and around the Isa GBA region. Collecting hydrochemical data such as environmental tracers would assist in determining their source aquifers. Although the source of the springs is inconclusive (based on available data), geological structures may provide connectivity pathways between surface water features and underlying Proterozoic aquifers of the Isa Superbasin. Therefore, activities associated with shale gas development have the potential to impact on surrounding environmental assets.

3.3.2.2 Coastal and marine ecosystems

In addition to rivers, wetlands and springs, groundwater may also support coastal and marine ecosystems. Given the north-easterly direction of groundwater flow towards the coast (Figure 35), and the mapped position of the 0 mAHD contour for the regional watertable (up to 30 km inland from the coast; Section 3.1.2.5), there is a potential source of groundwater to support coastal wetland, mangrove and estuarine environments. Groundwater discharge from the regional watertable aquifer into the Gulf of Carpentaria may also provide a source of freshwater for marine ecosystems, although little research has been undertaken in this part of the gulf to understand the processes and fluxes that may exist.

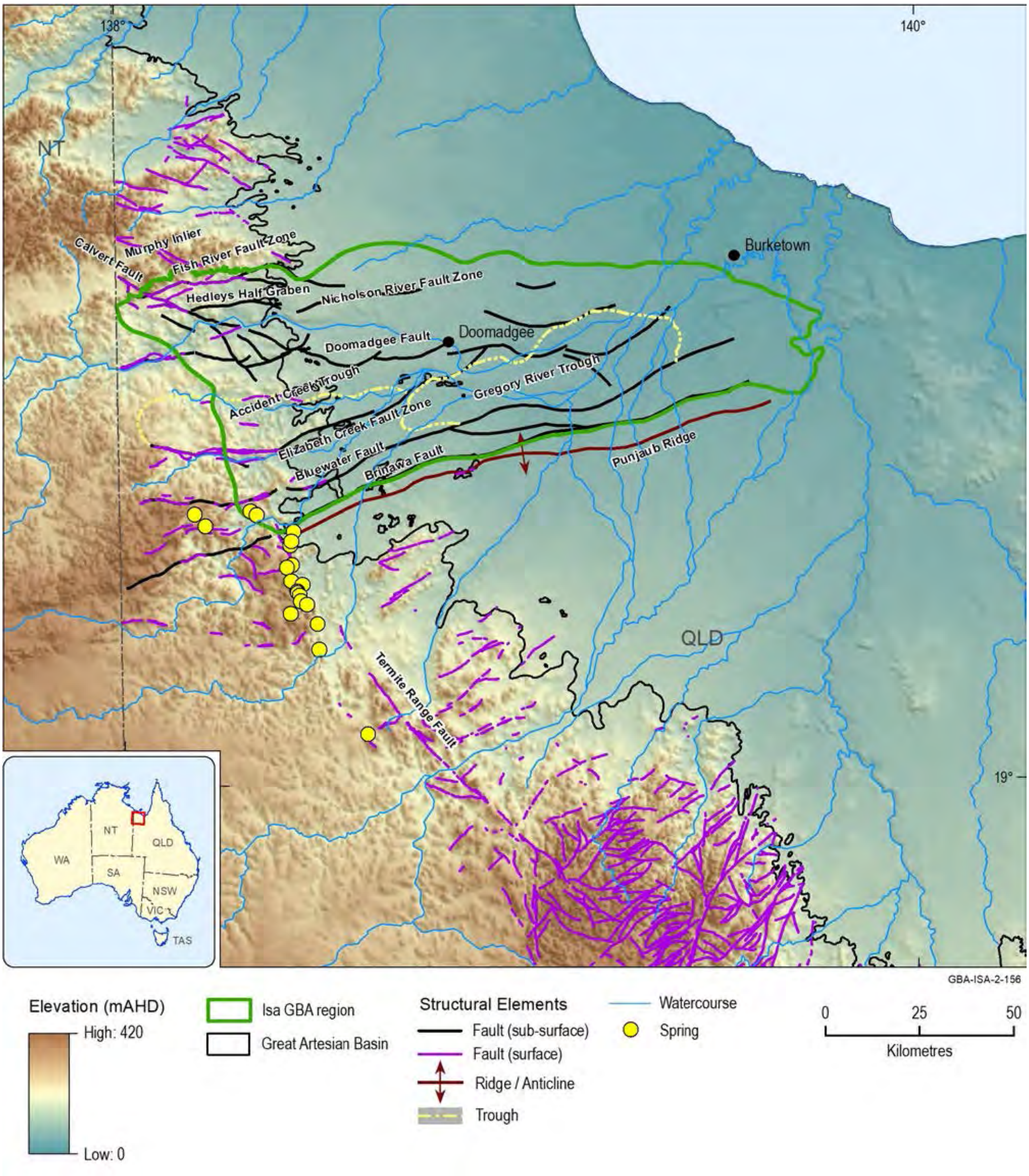

Figure 43 Relationship between mapped springs, elevation and structural features

mAHD = metres above sea level

Data: faults: structural elements (Geoscience Australia, 2013); surface faults (Geological Survey of Queensland, 2011); springs (Department of Environment and Science (Qld), 2018c)

Element: GBA-ISA-2-156

3.4 Potential hydrological connections

Five potential hydrological connections from shale gas reservoirs to aquifers, surface water systems and environmental assets may occur in the Isa GBA region. Plausible (though currently unconfirmed) hydrological pathways are assessed by conceptualising key subsurface features of the region, including aquifer and aquitard architecture, proximity of assets to faults and shale gas reservoirs, vertical continuity of faults, and geological heterogeneities near basin margins. The five potential connectivity pathways are:

1. via direct stratigraphic contact
2. via deep-seated faults
3. through porous aquifers
4. through partial aquifers/aquitards
5. at catchment constrictions and river diversions.

Dissolved gas concentrations within the Gilbert River Formation aquifer and Normanton Formation partial aquifer provide some evidence of potential connectivity between the deep and shallow hydrogeological systems. However, the assessment highlights that considerable data and knowledge gaps exist, and it describes conceptual models that can be tested in the future to improve confidence in understanding the extent and influence of these connectivity pathways.

3.4.1 Introduction

The potential development of shale gas plays in the Proterozoic Isa Superbasin of the Isa GBA region as well as groundwater extraction from aquifers to support development may affect fluid migration (e.g. groundwater or gas) between deeper rock units and various environmental and economic assets at or near the land surface. These assets include:

- **springs**, represented by a group of springs within and near the south-west of the Isa GBA region (Section 3.3.2.1)
- **streams** and **wetlands**, especially those in the Nicholson River catchment
- **GDEs**, including aquatic and terrestrial ecosystems that potentially depend on groundwater (Figure 42 and Section 4.1.5)
- **groundwater bores**, used mainly for pastoral water supplies, including bores sourcing water from both the deeper Proterozoic groundwater system and the shallower GAB (based on bores registered in the Queensland groundwater database (Department of Natural Resources, Mines and Energy (Qld), 2018b)).

Methods snapshot: conceptualising potential hydrological connections

Multiple datasets are integrated to develop conceptual models that describe the potential for hydrogeological connections between shale gas reservoirs or prospective aquifers that support development in the Isa GBA region and overlying environmental and economic assets. The geological framework for these conceptualisations uses the main geological unit boundaries and structural features in the three-dimensional geological model (summarised in Section 2.1 and described in the geology technical appendix (Orr et al., 2020)).

The conceptual models are based on the interpretation of several two-dimensional geological cross-sections that include the deeper Proterozoic units of the Isa Superbasin, the stacked aquifers and aquitards of the GAB, and the shallow Cenozoic sediment deposits of the Karumba Basin (Figure 48 and Figure 49). The cross-sections integrate available information about fault architecture and the regional stratigraphic framework, as well as the spatial distribution of near-surface assets.

The conceptual models identify where hydrological connections are more likely based on factors such as the:

- footprint and thickness of the shale gas plays (River and Lawn supersequences) and their linear distance (predominantly vertical) to the intra-basin Lady Loretta Formation aquifer (Loretta Supersequence) and Widdallion Sandstone partial aquifer (Wide Supersequence), as well as the overlying GAB and Cenozoic aquifers and near-surface assets
- upwards formation pore pressure (or hydraulic) gradient between the shale gas plays and underlying and overlying hydrostratigraphic units, which may be susceptible to pressure changes in the shale gas reservoirs
- regional stress regime associated with the geological structures that may be conducive to fault reactivation or structural enhancement
- spatial distribution of thickness and hydraulic properties of aquitards between the shale gas plays and the identified assets, including shallow aquifers
- anomalies identified in hydrochemical measurements in surface water and groundwater samples (Figure 46) and a limited number of gas measurements from groundwater bores
- spatial location and extent of environmental assets, including GDEs, springs and stream reaches where baseflow is likely to occur and groundwater bores are used for water supply.

3.4.2 Potential connectivity pathways

Analysis of the conceptual models developed (e.g. Figure 48) to assess potential hydrological connections in the Isa GBA region indicates that there may be five main connectivity pathways. These pathways may already be active zones of subsurface fluid movement (or could have been in the past). However, future shale gas development or groundwater extraction to support gas development could further affect or modify the migration of groundwater from deeper aquifers, as well as gas from shale gas plays in the Isa Superbasin, to environmental or cultural assets near or at the surface. Importantly, though, the subsurface fluid pathways described here are, while plausible, yet to be confirmed due to existing data and knowledge constraints. Many of the main hydrogeological features of the region, such as groundwater flow rates and the potential interactions along flow paths, are speculative due to the limited amount of data and lack of routine monitoring programs in this region.

The main factors that support the potential for subsurface hydrological connections in the Isa GBA region include understanding of aquifer and aquitard geometry and architecture (both in the Proterozoic units and the GAB), proximity of assets to faults, vertical continuity of faults, and existence of direct stratigraphic contacts between shale gas plays and aquifers. The five plausible hydrological connections recognised for this study are:

1. via direct stratigraphic contact
2. via deep-seated faults
3. through porous aquifers
4. through partial aquifers/aquitards
5. at catchment constrictions and river diversions.

Pathway ①: Potential connection via direct stratigraphic contact

There are at least two plausible scenarios for potential hydrological connection where direct stratigraphic contact exists between the shale gas plays of the River and Lawn supersequences and the overlying (e.g. Gilbert River Formation) and underlying (Loretta Supersequence) aquifers. These geological relationships are illustrated in a cross-section generated from the three-dimensional geological model (Figure 44).

Hydrochemistry data provide limited local-scale evidence for the potential existence of this hydrological pathway, although the interpretation of these data remains equivocal (at least until further groundwater sampling and analyses can be undertaken). For example, measurements of up to 4880 µg/L of methane were detected in groundwater bores screened within the Gilbert River Formation (basal GAB aquifer), which unconformably overlies and is in direct contact with various Proterozoic rock units (including, in places, the potential shale gas plays, as shown in Figure 44). In addition, dissolved methane occurs in groundwater within the Normanton Formation, with concentrations of up to 7320 µg/L (EHS Support, 2014). The relatively elevated methane concentrations in groundwater from different GAB aquifers could mean that gas migration from shale reservoirs has occurred in the past via this type of pathway. For example, shale gas originating from the Lawn Supersequence may have migrated into the Gilbert River Formation aquifer via pathway 1 and into the Normanton Formation aquifer via pathway 4.

However, there are also other possible origins for the elevated methane levels in these aquifers, such as biogenic methane production from lignite (or low-grade black coal) that may occur in some units of the Carpentaria Basin and then enter the local groundwater systems. The presence of dissolved methane in sedimentary basins is not unusual – for example, methane concentrations measured in the Eromanga Basin within the Cooper GBA region range from 150 to 216,500 µg/L (Holland et al., 2020). Likewise, concentrations of up to approximately 20,000 µg/L are common in aquifers of the Surat Basin (Mallants et al., 2016). Concentrations of dissolved methane in the Isa

GBA region (based on eight measurements, as depicted in Figure 47) range from less than 10 to 7320 µg/L (EHS Support, 2014). Compared with many other sedimentary basins, these methane concentrations in groundwater are relatively low. Additional methane and hydrochemistry data (ideally collected from multi-level groundwater bores) are required to help confirm or reject the existence of this connectivity pathway in the region. Furthermore, sampling of additional bores will help to further improve our understanding of the spatial extent and variability of methane levels in the GAB aquifers.

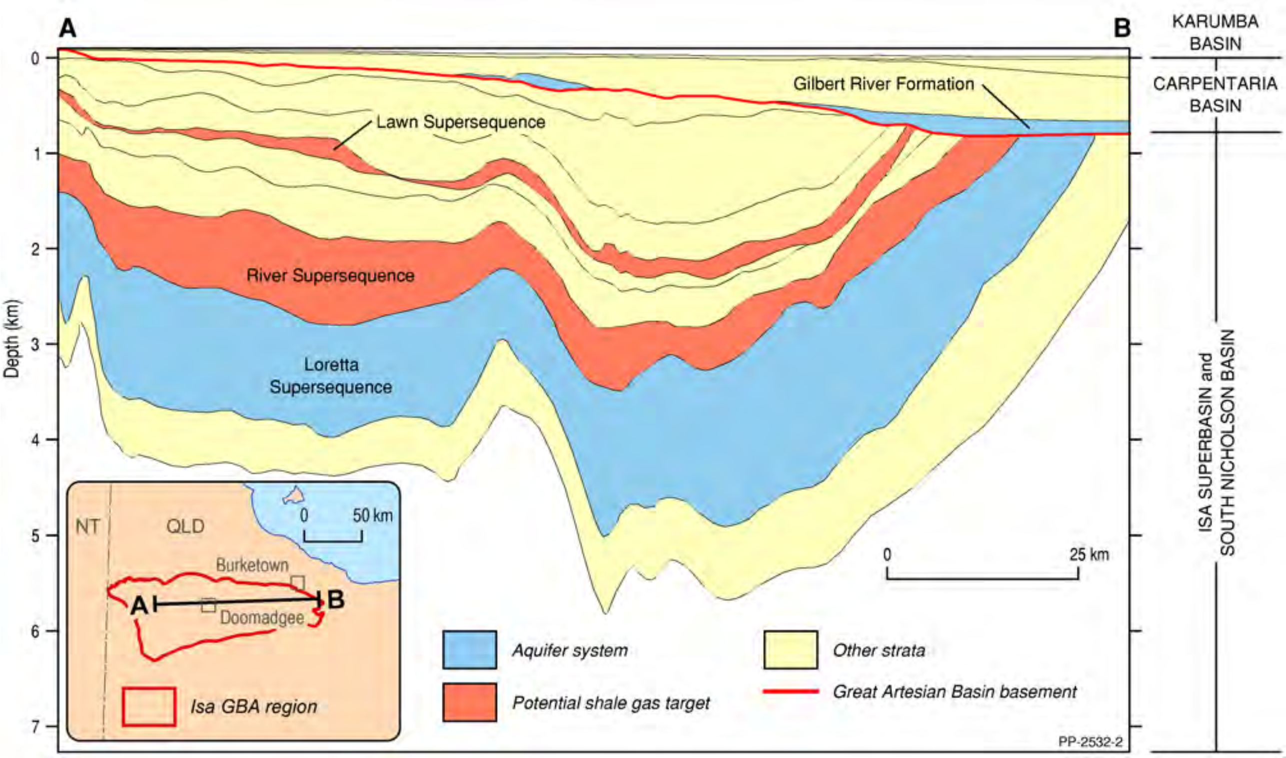

Figure 44 Cross-section through the Isa GBA region showing the relationship between the main aquifer systems and potential shale gas target sequences

The insert shows the location of the cross-section. The Normanton Formation is shown by the thin wedge-shaped aquifer at the top of the Carpentaria Basin sequence, extending about 20 km westwards from the far eastern edge of the cross-section.
Source: Bradshaw et al. (2018b)
Element: GBA-ISA-2-139

Hydrochemistry data combined with dissolved methane concentrations can provide additional insights into potential migration pathways. The multivariate statistical analyses of groundwater and surface water chemistry data (Table 11, Figure 45; see the hydrogeology technical appendix (Buchanan et al., 2020) for details of this statistical approach) show that there are five groups (termed 'clusters') with different hydrochemistry signatures in the region, each with distinct median values for different parameters. For example, the ratios of most major ions relative to chloride differ between clusters (Figure 45). Further, the median electrical conductivity (EC) of groundwater for Cluster 3 is 2050 µS/cm (which includes all samples from the Gilbert River Formation). Cluster 1 (which has a median EC of 2550 µS/cm) likely represents groundwater from a different, potentially deeper, aquifer relative to Cluster 3, although this hypothesis remains speculative due to the relatively low number of samples available.

The second potential hydrological pathway relates to connectivity of the shale gas plays of the River Supersequence and the underlying Lady Loretta Formation aquifer. The Lady Loretta Formation aquifer hosts an approximately 50 m thick cavernous dolostone zone with relatively high transmissivity. This zone is currently under artesian conditions and corresponds to the most widely accessed source of groundwater in the Isa Superbasin. Changes in reservoir pressures of overlying gas plays of River (in direct contact) or Lawn (further up in the stratigraphic column) supersequences may enhance connectivity with this underlying aquifer and change present-day hydraulic gradient conditions (see further discussion about this process in Section 5.3.2).

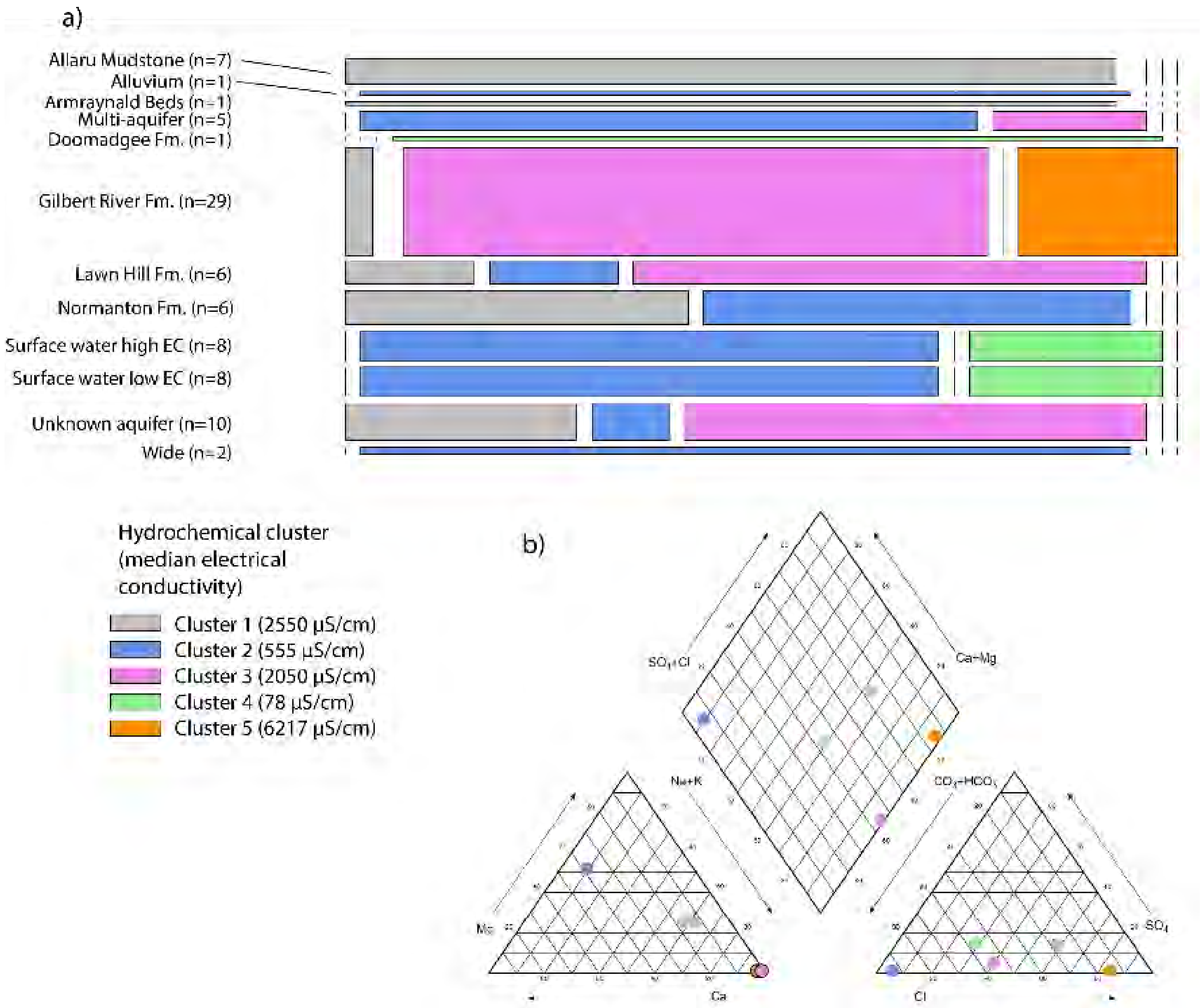

Figure 45 Aquifer cluster membership of aquifers in the Isa GBA region

(a) The width of the bars represents the relative percentage of groundwater records assigned to each cluster. The numbers in brackets behind the hydrostratigraphic unit correspond to the number of hydrochemical records for each formation.
(b) The Piper plot shows the median concentrations of the different clusters.
EC = electrical conductivity; Fm. = formation
Data: Geological and Bioregional Assessment Program (2019a)
Element: GBA-ISA-2-214

Table 11 Median values of the variables considered in the cluster analysis for each sample group

Cluster	EC (µS/cm)	pH	Na (mg/L)	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)	F (mg/L)	HCO_3 (mg/L)
1	2550	7.6	330	61	70.0	7.0	509.0	170	0.3	405.0
2	555	8.0	8.0	34.5	28.9	2.5	8.5	5	0.2	304.5
3	2050	8.3	484	4.8	0.9	6.4	290.0	50	5.3	690.0
4	78	6.9	5.2	1.6	1.5	2.1	7.0	5	0.1	24.5
5	6217.5	8.1	1320	30.2	6.3	22.5	1751.0	19	6.1	530.0

EC = electrical conductivity, Na = sodium, Ca = calcium, Mg = magnesium, K = potassium, Cl = chloride, SO_4 = sulfate, F = fluoride, HCO_3 = bicarbonate

Data: Geological and Bioregional Assessment Program (2019a)

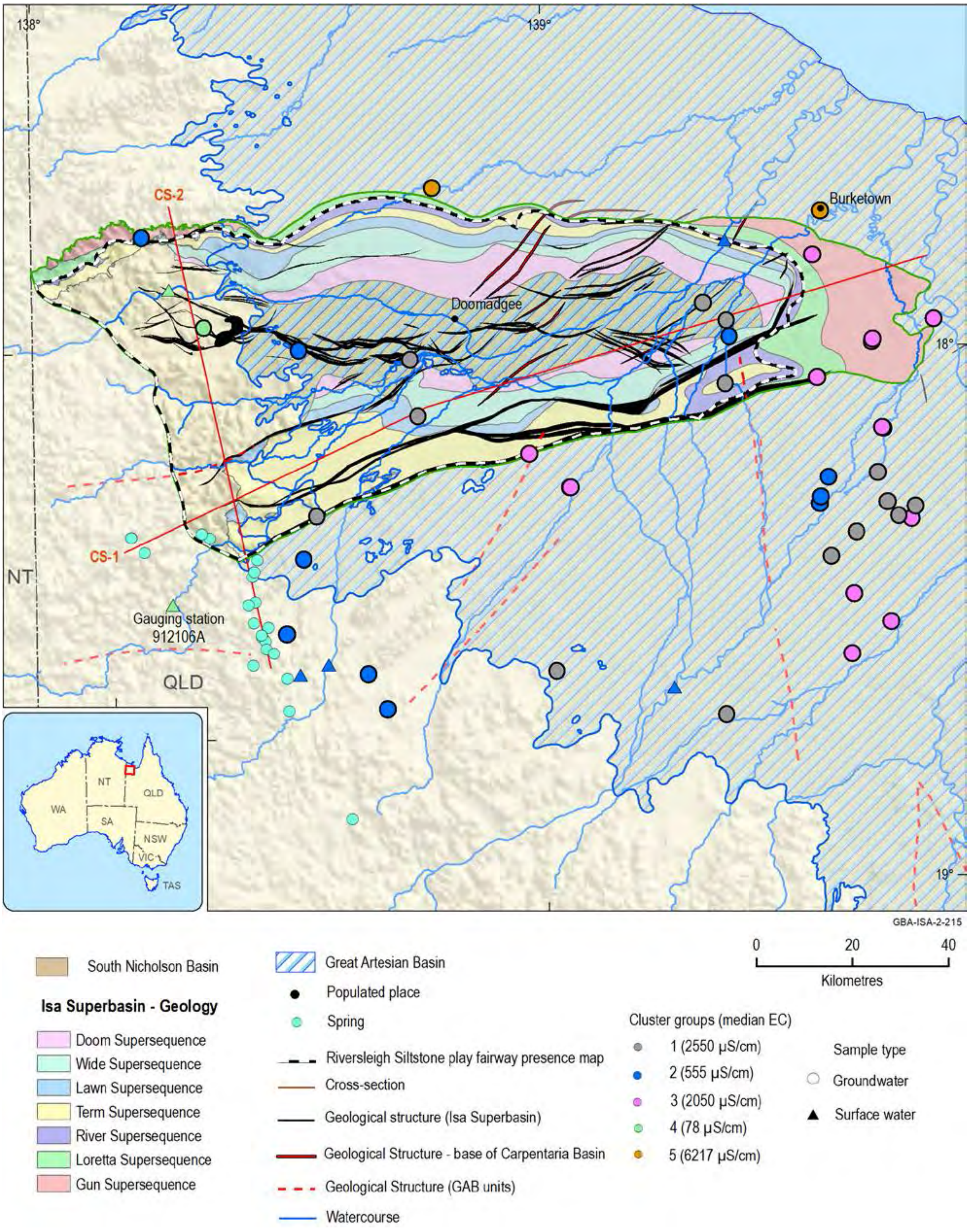

Figure 46 Map of Isa GBA region including Proterozoic geological units and geological structures, spatial distribution of hydrochemical data (surface water and groundwater) and orientation of cross-sections

The cross-sections are presented in Figure 48 and Figure 49.
EC = electrical conductivity; GAB = Great Artesian Basin
Data: Isa Superbasin and South Nicholson Basin geology (Bradshaw et al., 2018b); GAB extent (Ransley et al., 2015); hydrochemistry cluster group (Geological and Bioregional Assessment Program, 2019a). Faults associated with Isa Superbasin and to reach the base of Carpentaria Basin were sourced from Bradshaw et al. (2018b) and fault structural features obtained from Ransley et al. (2015), Bradshaw et al. (2018a) and Geoscience Australia (2013).
Element: GBA-ISA-2-215

Pathway ②: Potential connection through deep-seated faults

Faults can cause zones of direct vertical (or sub-vertical) hydraulic connection between hydrostratigraphic layers that would not otherwise be connected. In addition, faults may also laterally compartmentalise hydrogeological units and groundwater flow systems. Major faults that intersect the Proterozoic units have been interpreted from seismic data and are mapped across many parts of the Isa GBA region (see Figure 43; also discussion of geological structures in the geology technical appendix (Orr et al., 2020)).

Faults could potentially connect shale gas plays in the Lawn and River supersequences with overlying Proterozoic partial aquifers (e.g. Widdallion Sandstone Member of the upper Lawn Hill Formation, Pmh 5) as well as some GAB aquifers (such as the Gilbert River Formation). Such structures may extend upwards toward the surface, potentially reaching the Cenozoic and alluvial aquifers or near-surface assets such as perched watertables, springs and other GDEs. However, there are currently no data available on the nature and hydraulic characteristics of rock materials within these fault zones and whether they are likely to enhance or impede fluid flow. Consequently, a more comprehensive fault zone analysis that involves multiple complementary analysis methods (e.g. geophysics, structural geology, hydrochemistry and environmental tracers) is needed to assess whether actual hydrological connections exist and whether groundwater flow systems are preferentially directed along such structural conduits (Underschultz et al., 2018).

According to the Queensland Department of Environment and Science (Qld) (2018c) the aquifer source of approximately 20 springs located in the south-west of the Isa GBA region corresponds to sandstone of the Lawn Hill Formation. This gas play outcrops about 6 km north-east of two springs located within the south-western limits of the Isa GBA region (refer to Figure 47 for spring locations and Figure 46 for the Lawn Hill outcrop). The surfaces representing top and bottom of the Lawn Supersequence in the GBA geological model do not extend to these springs. However, as shown in cross-section 1 (Figure 48), sharp changes in the horizontal continuity of upper and lower unit surfaces immediately overlying the River Supersequence suggest the presence of faults, although their influence on groundwater flow and the relationship to mapped springs is currently uncertain.

Overall, there is considerable uncertainty about the potential source aquifers of the springs within or near the boundary of the Isa GBA region and lack of evidence on whether vertical migration of groundwater from deeper units is likely to occur along major geological structures. These factors represent a significant data and knowledge gap that would benefit from further investigation. A more detailed discussion of the potential influence of faults on groundwater flow within the Isa GBA region is in the hydrogeology technical appendix (Buchanan et al., 2020).

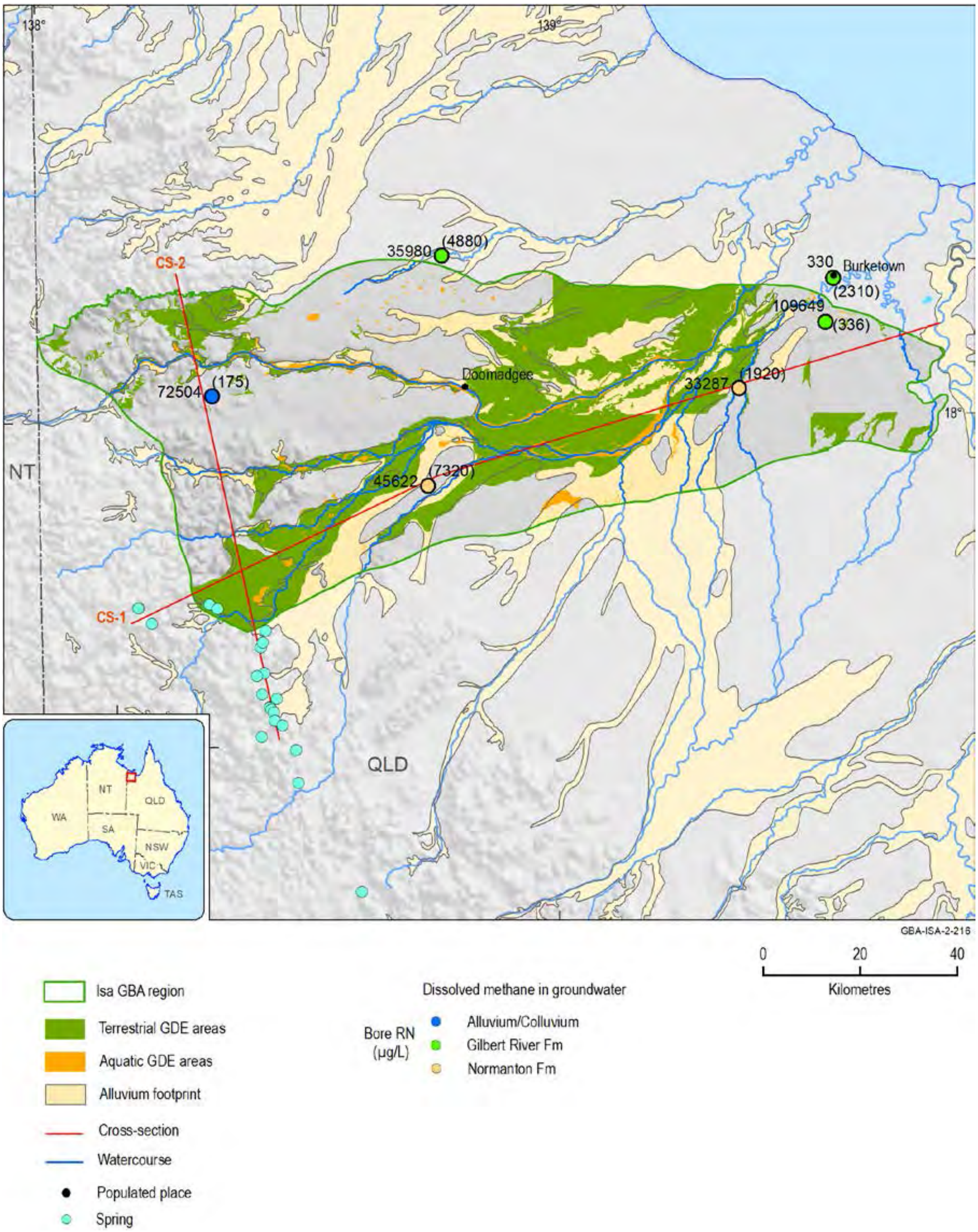

Figure 47 Distribution of alluvial sediments and key environmental assets in the Isa GBA region including springs, streams and groundwater-dependent ecosystems. The locations of groundwater bores analysed for dissolved methane in groundwater are also shown

Cross-section CS-1 is shown in Figure 48 and CS-2 is in Figure 49. The terrestrial and aquatic GDE areas shown here are based on data from the Bureau of Meteorology's GDE Atlas (Bureau of Meteorology, 2017). The terrestrial GDE areas are those interpreted as having a high to moderate potential of occurrence. The aquatic GDE areas include those that are known to occur as well as those interpreted as having a high to moderate potential of occurrence. The groundwater bores are colour-coded by hydrogeological unit and show the bore registered number (RN) as well as concentrations of dissolved methane in groundwater collected from each bore (methane concentrations given in brackets).

GDE= groundwater-dependent ecosystem; Fm = Formation

Data: methane measurements (EHS Support, 2014), *National atlas of groundwater dependent ecosystems* (Bureau of Meteorology, 2017); springs (Department of Environment and Science (Qld), 2018c); alluvium (Geoscience Australia, 2012)

Element: GBA-ISA-2-216

Pathway ③: Potential connection through porous aquifers

Some degree of groundwater flow (presently unquantified) is likely to occur in the main Proterozoic aquifers adjacent to the shale gas plays in the Isa GBA region, particularly the partial aquifer of the Widdallion Sandstone Member (part of the Wide Supersequence) and karstic zones of the Lady Loretta Formation (Loretta Supersequence). In addition, the Gilbert River Formation aquifer directly overlies the upper shale gas play in the eastern part of the Isa GBA region.

Connectivity in the Lady Loretta Formation aquifer may be impacted by structural displacement associated with major faults such as the Doomadgee Fault System, Nicholson River Fault Zone and the Calvert Fault, as illustrated in Figure 48 and Figure 49. Nevertheless, the potential compartmentalisation of the Lady Loretta Formation by structural zones does not rule out lateral and vertical fluid migration in this highly heterogeneous aquifer.

Direct evidence for groundwater movement in the confined Gilbert River Formation aquifer is limited. Ransley et al. (2015) produced a map indicating that regional groundwater flow in this aquifer is north-east from the Isa GBA region, towards the Gulf of Carpentaria. Groundwater levels vary from 40 m to 80 m above mAHD with an approximate gradient of 0.03%. Importantly, though, the Gilbert River Formation does not outcrop in or near the Isa GBA region, and throughout much of the area this aquifer is buried at depths of around 500 m below surface (Figure 34). Consequently, there is a high level of uncertainty associated with the location, extent, flow direction and rate of recharge of the Gilbert River Formation aquifer in the vicinity of the Isa GBA region, particularly as the main recharge area occurs several hundred kilometres away to the east. Nevertheless, the Gilbert River Formation aquifer is likely to have sufficient hydraulic gradient to promote fluid migration within the region, both laterally and vertically.

Pathway ④: Potential connection through partial aquifers/aquitards

In the east of the Isa GBA region, the potential may exist for the Gilbert River Formation aquifer to be hydrologically connected to the near-surface Normanton Formation aquifer. This could occur in places where the intervening Rolling Downs Group aquitard is extensively disrupted by internal polygonal fault systems (PFS) (discussed in Section 4.1.2 in the hydrogeology technical appendix (Buchanan et al., 2020)). However, as described in Section 3.1.2.2, the Rolling Downs Group aquitard is about 500 m thick where it underlies the Normanton Formation in the Isa GBA region, which indicates that polygonal faulting would need to be very pervasively and extensively developed throughout the aquitard to create a sufficiently connected hydraulic pathway across its entire vertical thickness. There were limited data available to evaluate the extent and nature of polygonal faulting within the Rolling Downs Group aquitard for this study, although further research on this subject may be possible – for example, using detailed analysis of recently published AusAEM electromagnetic data from Geoscience Australia's Exploring for the Future program (Geoscience Australia, 2018b).

The Normanton Formation partial aquifer is considered part of the Rolling Downs Group and is in direct stratigraphic contact with the underlying highly fractured aquitard. There are limited hydraulic data available for the Normanton Formation, with only one bore registered in the groundwater database (Geoscience Australia, 2018c). However, artesian pressure in the confined Gilbert River Formation aquifer suggests an upward pressure gradient exists. Thus, if a sufficiently connected PFS exists in the Rolling Downs Group to have formed a coherent pathway for fluids to flow along, there may be a hydraulic driver for groundwater to flow upwards to shallower aquifers from the lower GAB aquifer.

Additional evidence for this pathway may also be the presence of elevated methane concentrations in the Normanton Formation, as noted above for pathway 1. However, as previously discussed, the origin of the methane in this aquifer remains unknown, and additional methane and hydrochemistry data (ideally collected from multi-level groundwater bores) would help to better constrain the occurrence of this pathway.

Pathway ⑤: Potential connection at catchment constrictions and river diversions

Water or gas migration pathways may exist where partial aquifers of the Normanton Formation and/or Cenozoic sediments are connected to alluvial aquifers (effectively forming the bedrock below the alluvium). This may be particularly the case near catchment constrictions or stream/river diversions controlled (at least in part) by geological structures, where the alluvium pinches out against the hydraulically connected bedrock and where upward pressure gradients may exist (Figure 49 inset). Due to the limited thickness and width of the alluvial aquifers (and associated GDEs) in the vicinity of the catchment constrictions, these areas may be more sensitive to hydrological changes than the wider alluvial floodplains and their associated streams. Hydraulic pressure reduction in the sub-alluvial bedrock – or, conversely, a water level drop in the alluvial aquifer – can result in a rapid response (at timescales of years to decades) of water levels and water quality within shallow aquifers or streams.

In contrast to the Cooper GBA region (Holland et al., 2020), where many catchment constrictions exist, catchment constrictions associated with creeks and rivers in the Isa GBA region are less common. However, the course of the Nicholson River appears to be structurally controlled south-east of Doomadgee, evidenced by north-east-directed faults at the southern margins of the alluvial aquifer and a very distinct diversion of the river course from easterly to southerly flow (reversing back to an eastern flow direction further downstream) (Figure 46). Such stream diversions are often controlled by geological structures or basement highs (or both) (Twidale, 2004). The alluvium broadens at the northern margin of the Nicholson River near Doomadgee and is constricted at the southern margin where it appears bounded by faults. In this area, sub-alluvial bedrock (possibly equivalent to Cenozoic Bulimba Formation), alluvium and streams are proximal (Figure 49 inset), and the alluvial system becomes considerably thinner and narrower. This suggests an increased likelihood of connectivity and potential for groundwater and/or gas migration pathways between sub-alluvial bedrock, alluvium and streams, as observed in catchment constrictions elsewhere (e.g. Condamine River alluvium constriction near Chinchilla in Queensland).

Analysis of the available hydrochemical data indicates that surface waters are distinct from groundwater in the Gilbert River Formation. All surface water samples are assigned to Cluster 2 and Cluster 4, with median EC from 93 to 516 µS/cm (compared with 2047 µS/cm for Cluster 3). The clusters to which the surface water samples are assigned are also characterised by very high HCO_3/Cl ratios, as shown in Figure 45. Hydrochemistry data can be used to help assess the likelihood of connectivity between bedrock, alluvia and streams (Martinez et al., 2015; Raiber et al., 2019; King et al., 2014). It can also provide insights into possible connections between deeper groundwater systems and alluvia and streams in areas where catchment constrictions or stream diversions occur. However, due to sparse surface water and groundwater chemistry data, this level of assessment is not currently possible for the Isa GBA region. Additional surface water and groundwater chemistry observation data are required – for example, synoptic stream water chemistry surveying from many sampling points along the course of the rivers would help identify areas where connection between aquifers and streams may occur.

3.4.2.1 Concluding remarks on potential hydrological connectivity

These five hydrological pathways were developed based on the assessment team's expertise and interpretation of available geoscience datasets in the Isa GBA region. Importantly, these pathways should be considered as hypothetical pathways for subsurface fluid movement given the current data constraints. Key hydrogeological parameters – such as the volumes of fluids involved, their compositions and rates of movement, and the potential for chemical or physical interaction along the flow path – are speculative due to the limited availability of data and the lack of a monitoring network.

Some potential connectivity pathways are unlikely to occur simultaneously or create the necessary conditions to directly link development of shale gas plays to environmental assets (at least at timescales that can be directly monitored (i.e. years to tens of years)). Nevertheless, considering the many knowledge gaps that exist for this region, it is important to take a precautionary approach when assessing the possibility that subsurface hydrological pathways may naturally exist in the Isa GBA region. These could provide conduits for fluid and/or gas migration from one subsurface compartment of the region to another over a range of different timescales (e.g. tens to thousands of years) and eventually reach assets at the surface.

Analysis of existing datasets and an integrated assessment of the structural geology and hydrogeology of the Isa GBA region have helped to identify important knowledge and data gaps relevant to better understanding hydrological connectivity. Further investigations are required to evaluate the identified potential connectivity pathways. A summary of key research questions and possible investigative methods are outlined in Section 3.6 and Table 13.

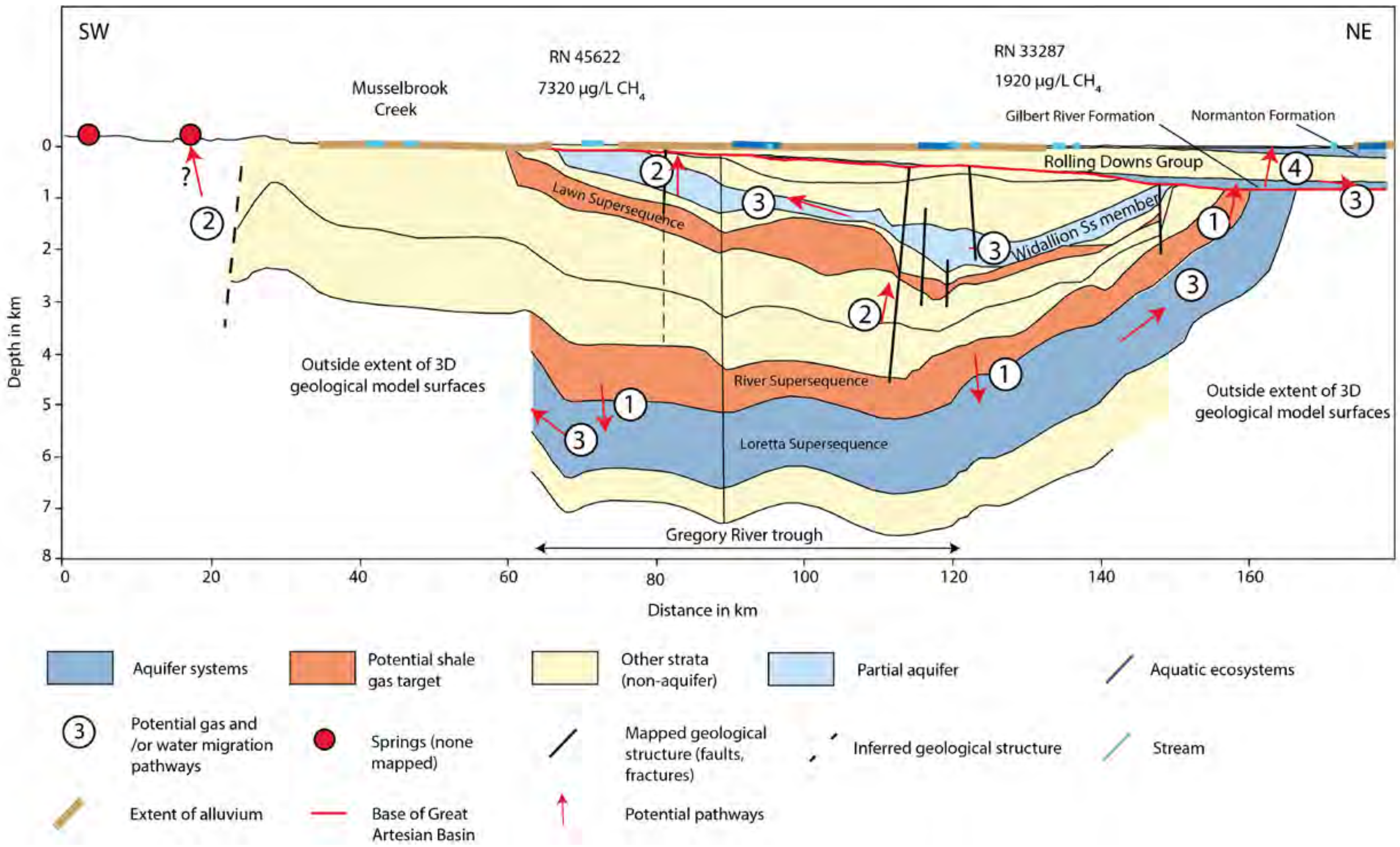

Figure 48 Cross-section 1 of the Isa GBA region, with south-west to north-east orientation through Isa Superbasin and South Nicholson, Carpentaria and Karumba basins, representing inferred Isa Superbasin margins and major geological structures and potential pathways for water or gas migration

The four potential connectivity pathways shown here are: Pathway 1 – potential connection via direct stratigraphic contact, Pathway 2 – potential connection through deep-seated faults, Pathway 3 – potential connection through porous aquifers, and Pathway 4 – Potential connection through partial aquifers/aquitards. See Table 13 for further details and knowledge gaps.
CH_4 = methane; 3D = three dimensional; GAB = Great Artesian Basin; RN = bore registered number; Ss = sandstone
Data: geology technical appendix (Orr et al., 2020); based on the depth-converted grids published by Bradshaw et al. (2018a), structural features obtained from Ransley et al. (2015); Bradshaw et al. (2018a) and Geoscience Australia (2013)
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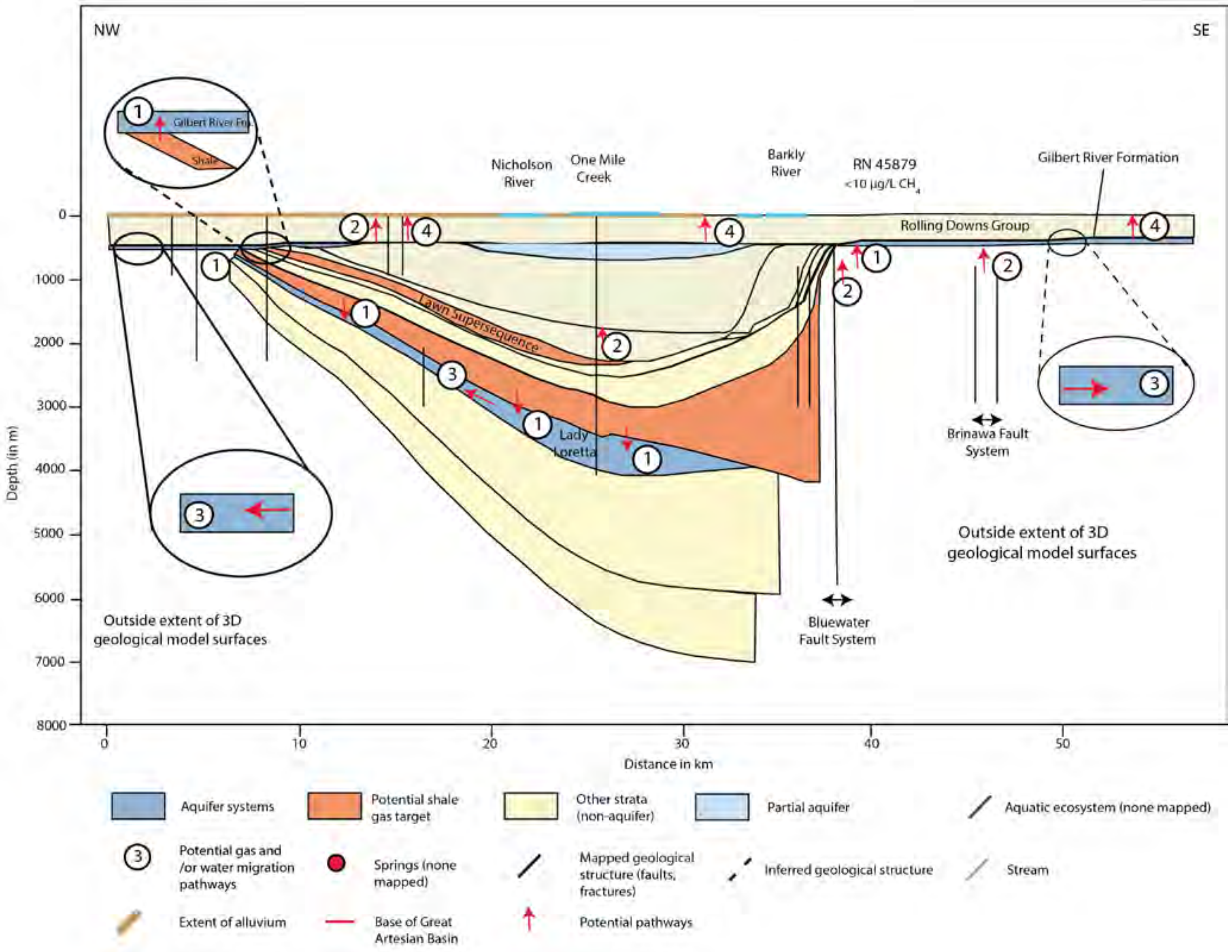

Figure 49 Cross-section 2, with north-west to south-east orientation, representing likely geological structural control of springs located to the south, near the Punjaub Ridge

The four potential connectivity pathways shown here are: Pathway 1 – potential connection via direct stratigraphic contact, Pathway 2 – potential connection through deep-seated faults, Pathway 3 – potential connection through porous aquifers, and Pathway 4 – Potential connection through partial aquifers/aquitards. See Table 13 for further details and knowledge gaps.
CH_4 = methane; 3D = three-dimensional; Fm. = Formation; GAB = Great Artesian Basin; GDE = groundwater-dependent ecosystem; RN = bore registered number
Data: geology technical appendix (Orr et al., 2020); based on the depth-converted grids published by Bradshaw et al. (2018a), structural features from Ransley et al. (2015); Bradshaw et al. (2018a) and Geoscience Australia (2013)
Element: GBA-ISA-2-217

3.5 Water accounts and potential water sources to support shale gas development

There are no existing water licences for the petroleum and gas industry in the Isa GBA region. Several groundwater and surface water sources are potentially available to supply water requirements for future shale gas development. These include water reserves from the GAB and surface water resources from the Nicholson River catchment. Recycling or reusing flowback or produced water associated with gas production may also be an option, although there is considerable uncertainty about the volumes of produced water likely to be recovered from shale gas wells in the Isa GBA region and the economic feasibility of its reuse.

3.5.1 Water plans

Water resources within the Isa GBA region are managed by the Queensland Government under two different water plans – the *Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017* (GABORA Plan) (Queensland Government, 2017c) and the *Water Plan (Gulf) 2007* (Gulf Water Plan) (Queensland Government, 2007). The GABORA Plan manages groundwater in identified regional aquifers, and also applies to GAB springs. The GABORA Plan has 16 constituent groundwater units, and three of these intersect with the Isa GBA region: the Hooray, Normanton and Rolling Downs groundwater units (Figure 50). In the Isa GBA region, the Hooray unit is represented by the Carpentaria South Gilbert River Aquifer groundwater sub-area, and the Rolling Downs unit is represented by the Carpentaria South Wallumbilla groundwater sub-area (sub-areas occur over much larger parts of Queensland than the Isa GBA region extent).

In the 2017 GABORA Plan, the Queensland Government reserved a total of 39,505 ML across the 16 groundwater units to meet potential future water demands (Queensland Government, 2017c). This comprised 10,015 ML for general reserve, 880 ML for Aboriginal and Torres Strait Islander economic reserve and 28,610 ML for state reserve. Any new take of water under the GABORA Plan will require an appropriate water licence and will also be subject to satisfying current bore separation and groundwater-dependent ecosystem protection criteria. The available water reserves (as of September 2019) relevant to the Isa GBA region are as follows:

- There is 1440 ML of general reserve available in the Carpentaria South Gilbert River Aquifer groundwater sub-area (although this reserve is shared with the Bulimba Formation, Cape Rolling Downs and Gulf Gilbert River Aquifer groundwater sub-areas). There is no general reserve available in the Carpentaria South Wallumbilla groundwater sub-area.
- There is 500 ML of state reserve available in the Carpentaria South Gilbert River Aquifer and the Carpentaria South Wallumbilla groundwater sub-areas. This state reserve is shared with other groundwater sub-areas, including the Cape Rolling Downs, Gulf Rolling Downs, Normanton and Gulf Gilbert River Aquifer.
- There is 115 ML of Aboriginal and Torres Strait Islander economic reserve in the Carpentaria South Gilbert River Aquifer and the Carpentaria South Wallumbilla groundwater sub-areas. This reserve is shared with the Cape Rolling Downs, Gulf Rolling Downs, Normanton, Cape Gilbert River Aquifer and Gulf Gilbert River Aquifer groundwater sub-areas.

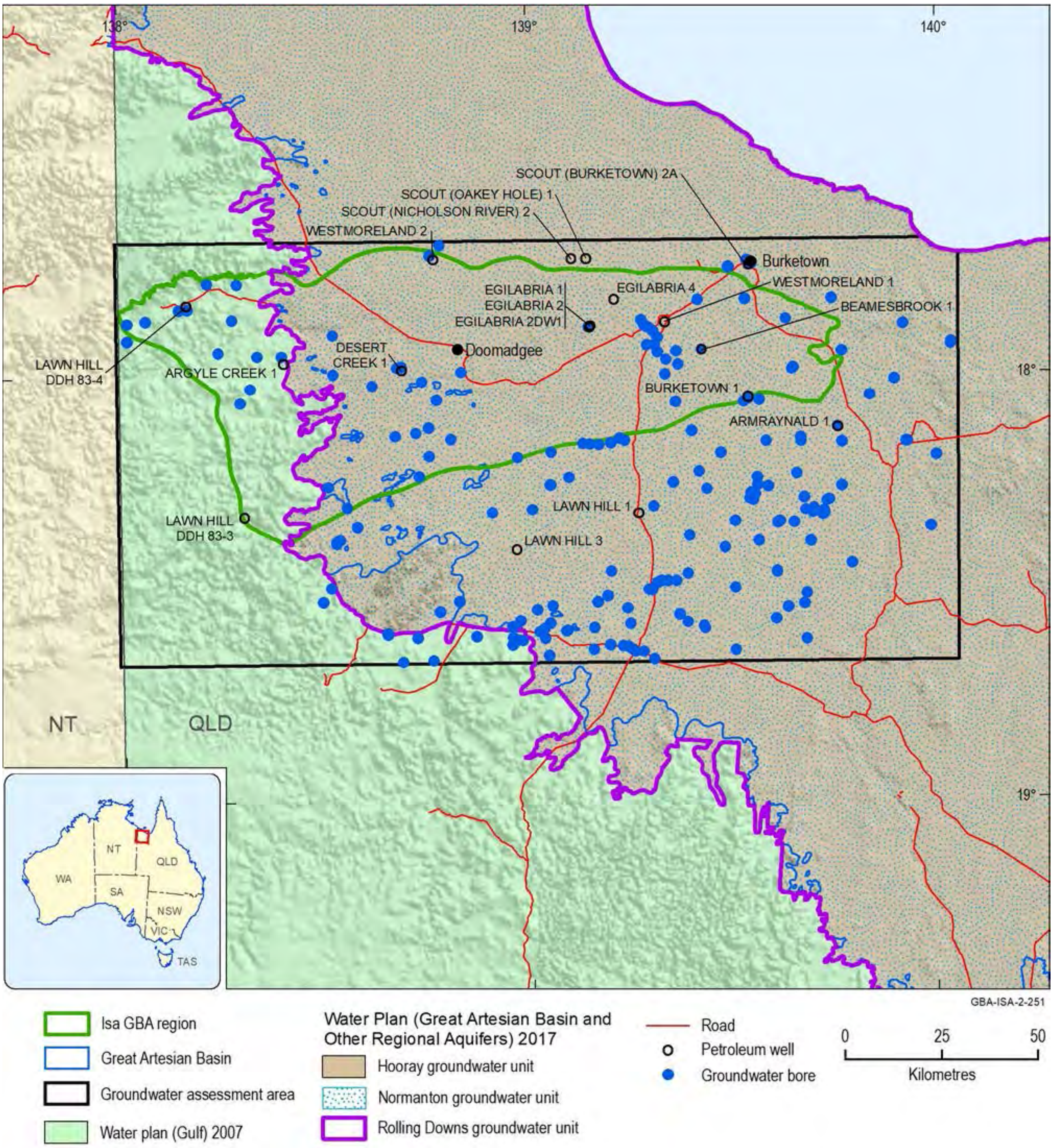

Figure 50 Queensland water plan areas and groundwater bores in the Isa GBA region

Data: water plan areas (Department of Natural Resources, Mines and Energy (Qld), 2018d); groundwater bores (Department of Natural Resources, Mines and Energy (Qld), 2018b); petroleum well locations – Queensland (Department of Natural Resources, Mines and Energy (Qld), 2018a)
Element: GBA-ISA-2-251

Current Queensland Government policy suggests that capping and piping of existing (non-watertight) bores and drains in the GAB would be encouraged in the first instance as the preferred way to access groundwater, prior to granting further release under the available general or state reserves. Notably, most of the opportunities available to cap and pipe existing GAB bores do not actually exist within or near the Isa GBA region – they exist in areas that may be up to hundreds of kilometres distant.

In addition to the GABORA Plan, the *Water Plan (Gulf) 2007* (Gulf Water Plan) (Queensland Government, 2007) is also relevant for managing water resources in and around the Isa GBA region. This plan applies to the Nicholson and Gregory river catchments, the main surface water catchments that intersect the region. The Gulf Water Plan also covers the Nicholson groundwater management area (GMA), which applies to non-GAB groundwater resources in either the Cenozoic Karumba Basin or the Proterozoic fractured rock aquifers that may lie beneath the GAB or west of the GAB boundary. The surface water reserves applicable to the Isa GBA region are the:

- Nicholson River subcatchment area, which has 4166 ML of strategic reserve and 4400 ML of general reserve available
- Gregory River subcatchment area, which has 5000 ML of strategic reserve and 1000 ML of Indigenous reserve available.

In addition to surface water resources, licences for groundwater extraction can potentially be granted under the Gulf Water Plan in the Nicholson GMA, or within 1 km of a prescribed watercourse in the region. Outside of the Nicholson GMA groundwater resources administered under the Gulf Water Plan can be accessed without needing a water licence.

3.5.2 Water use

Groundwater use in the Southern Carpentaria Basin (part of the GAB) was estimated as part of a detailed hydrogeological assessment for the Queensland Government (Klohn Crippen Berger, 2016). The Isa GBA region occurs in the far north-west of this area and covers about 10% of the Southern Carpentaria Basin. Groundwater development in most of the Southern Carpentaria Basin (particularly the Isa GBA region) has primarily been for stock and domestic use accessed through private water bores (Klohn Crippen Berger, 2016). Approximately 1300 bores are recorded in the Queensland groundwater database across the Southern Carpentaria Basin, with about 27% of these being artesian bores that tap the Gilbert River Formation. The estimated water use (in 2016) in the Southern Carpentaria Basin highlights that most annual extraction from the Gilbert River Formation is as uncontrolled flow from artesian bores or as loss from bore drains (Table 12).

The Isa GBA region has 53 bores recorded in the Queensland groundwater database. Of these, about 30% (16 bores) are specified as ‘stock and domestic’. However, based on knowledge of the main land and water users in the region, most bores are assumed to have been installed for stock and domestic purposes – e.g. bores commonly provide watering points for cattle on pastoral leases. As the Queensland groundwater database does not record information on water use for stock bores, there is some uncertainty about the total volume of groundwater annually extracted by bores in the region. However, Klohn Crippen Berger (2016) estimated that the average volume of water extracted for stock and domestic use (across the whole Southern Carpentaria Basin) was about 3.6 ML/bore for the Normanton Formation and 4.4 ML/bore for the Gilbert River Formation. In the overlying aquifer of the Bulimba Formation (part of the Karumba Basin), stock and domestic water use was estimated at about 2.7 ML/bore. Using these estimated extraction volumes, the likely volume of groundwater extracted for stock and domestic use in the Isa GBA region is around 210 to 230 ML/year. This may be an upper estimate of groundwater extraction if some bores are no longer operational or do not extract at the assumed rate.

Table 12 Estimated water use for the Southern Carpentaria Basin, Queensland (2016)

Aquifer	Estimated stock and domestic use volume (ML/year)	Uncontrolled flow from artesian bores (ML/year)	Estimated loss from bore drains	Entitlement volumes (ML/year)	Total volume (ML/year)
Normanton Formation	809	43	596	0	1,448
Gilbert River Formation	2,126	3,913	3,914	386	10,339
Total	2,935	3,956	4,510	386	11,787

Source: Klohn Crippen Berger (2016)

Within the Nicholson River catchment there are currently 35 water licences, comprising 20 groundwater and 15 surface water licences. About half (45%) of the groundwater licences are administered under the GABORA Plan, with the remainder under the Gulf Water Plan.

3.5.3 Potential water sources for shale gas development

The future development of shale gas resources in the Isa GBA region will require substantial volumes of water (i.e. ranging from 100s to 1000s of ML) throughout major life-cycle stages, particularly during gasfield development, when most production wells are drilled and hydraulically fractured. Water is also needed for other activities such as construction and maintenance of access roads, pipelines and gas production facilities, as well as site decommissioning and rehabilitation works.

Data from US shale gas operations indicates substantial regional variability in the volume of water needed to hydraulically fracture shale gas wells. Factors such as local geological conditions, average vertical drilling depths and horizontal well lengths, and the number of hydraulic fracturing stages per well all influence the total volume of water required for different basins. Kondash and Vengosh (2015) demonstrated that the median volume of water needed for hydraulic fracturing of a US shale gas production well can be as low as 1.5 ML/well (e.g. in the Niobrara Shale in central US) but is more commonly around 13 to 15 ML/well (e.g. for wells in the Eagle Ford and Barnett shales in Texas) and, in some cases, more than 20 ML/well (Fayetteville (Arkansas) and Woodford (Oklahoma) shales).

Data on water usage for shale gas wells in Australia are relatively sparse, as the local industry is much less mature than in the US. Origin Energy indicated in their submission to the NT hydraulic fracturing inquiry that around 50 to 60 ML of water may be needed to drill and hydraulically fracture each production well in the Beetaloo Sub-basin (Pepper et al., 2018). In the Isa GBA region, the only hydraulic fracturing undertaken to date was for Armour Energy's Egilabria 2DW1 exploration well (Section 2.2). The investigative nature of this well meant that only a relatively small volume hydraulic fracturing operation was undertaken, involving the injection of about 2 ML of hydraulic fracturing fluid mixture (water, sand and various chemical additives). Further reservoir appraisal and engineering assessments of shale gas target reservoirs is needed to develop a clearer understanding of specific drilling and hydraulic fracturing water requirements in the Isa GBA region.

To provide a preliminary estimate of the potential scale of water resources required for shale gas operations in the Isa GBA region, a relatively simple development scenario can be assessed. Assuming the drilling and fracturing of a total of 400 shale gas production wells over a 20- to 30-year time frame, with each well requiring approximately 12 to 15 ML of water to enable installation, approximately 4800 to 6000 ML of water may be needed to support this scale of development. There would also be some additional water required for drilling and general operational requirements to support construction and ongoing operations over the life of the gasfield. However, it must be stressed that this scenario and the associated water use estimates are purely indicative and that considerable further work is required to better understand the future shale gas development profile (including water use requirements) of this region.

3.5.3.1 Groundwater and surface water resources

There are several groundwater and surface water sources potentially available to supply the water required for shale gas development in the Isa GBA region. These options include access to water resources of the GAB (i.e. the GABORA Plan) as well as surface water and groundwater resources administered under the Gulf Water Plan.

Future water requirements to support new gas industry development (including potential for shale gas and other unconventional gas resources) in parts of Queensland covered by the GAB was specifically considered as part of the planning process for the GABORA Plan. Consultation with water policy staff in the Queensland Department of Natural Resources, Mines and Energy indicates that the most likely GAB water supply options available to cater for shale gas development in the Isa GBA region include (but are not limited to):

- capping and piping of uncontrolled (flowing) artesian bores and drains in GAB aquifers (not necessarily within or proximal to the Isa GBA region) to save large volumes of groundwater that are currently lost from GAB aquifers (i.e. several thousand megalitres or more); a portion of the saved volume could then be granted as a water licence
- relocation of existing water licences (which is possible under the GABORA Plan)
- access to available water reserves from the three groundwater units that intersect the region (as noted in Section 3.5.1)
- water permits for activities of limited duration, which may be available for initial exploration and appraisal operations prior to full-scale development.

In addition to accessing GAB water resources, shale gas proponents could potentially access available water reserves through the Gulf Water Plan. For example, licences may be granted to extract surface water from the Nicholson River or the Gregory River. It is also possible that licences could be granted to access groundwater from non-GAB sources that occur within or near the Isa GBA region (available through the Nicholson GMA), such as the shallow aquifers of the Karumba Basin or the Proterozoic fractured rock aquifers that occur beneath the GAB aquifers, as well as to the west of the GAB boundary. In addition, it may be possible for shale gas proponents to access non-GAB groundwater resources outside of the Nicholson GMA (and greater than 1 km away from a prescribed watercourse), as no water licence is required in these circumstances.

3.5.3.2 Produced water

Conventional and unconventional oil and gas formations exist naturally under pressure within a geological reservoir. When these formations are drilled to extract oil and/or gas there is usually some volume of water from the reservoir that is also extracted. This water is known as produced water and is separated at the surface from the oil and/or gas that flows from the well in various onsite processing facilities. Management options for produced water associated with hydrocarbon production typically involve the use of an integrated system of storage ponds or dams (possibly with offsite discharge to nearby streams if water can be suitably treated to specified guidelines) or reuse of the water depending on its quality and the reuse activity. In addition to produced water, some of the water that was originally injected to hydraulically fracture the shale gas reservoir is also recovered at the surface, and this is typically known as flowback water.

Evidence from a number of different geological basins in the US indicates that the volumes of produced water from shale gas reservoirs can be quite variable and typically (though not always) substantially lower than for conventional gas or coal seam gas reservoirs. Kondash and Vengosh (2015) highlighted the variable volume of produced water from different US shale gas basins – for example, the average volume of produced and flowback water from a shale gas well in the Barnett Shale was about 12.4 ML/well compared to 25.8 ML of produced/flowback water for wells in the Eagle Ford Shale. In contrast, average wells drilled in the Marcellus and Niobrara shales have much lower volumes of produced/flowback water, typically 5 to 6 ML/well (Kondash and Vengosh, 2015).

Depending on the volume of produced water recovered during gas production operations, it may be possible for it to be treated and reused as a water source for hydraulic fracturing and drilling operations. However, in the Isa GBA region, there is considerable uncertainty about the volumes of produced water likely to be extracted from shale gas reservoirs of the Lawn and River supersequences and whether it would be possible to reuse some proportion of this water for further operations. This critical knowledge gap reflects the limited amount of exploration work undertaken to date and the need to improve understanding of shale gas reservoir characteristics, including produced water volumes, water quality parameters and temporal production trends.

Reusing any produced or flowback water that may be captured as part of shale gas extraction in the Isa GBA region would be subject to a range of water management rules and obligations under existing Queensland legislation. Any proponent that seeks to reuse water to support their operations must accord with these existing legislative requirements and specific conditions in environmental authorities granted under Queensland's *Environmental Protection Act 1994*.

3.6 Knowledge gaps and future work

Due to the available data and information on the surface water and groundwater systems of the Isa GBA region, only a preliminary hydrological assessment has been conducted. Although the major hydrological components of the region are broadly understood (i.e. the key aquifers, major streams and dominant water users), there are currently insufficient data to inform many finer scale aspects of regional hydrological processes and parameters. In particular, a relatively high degree of uncertainty exists about important features such as groundwater flow dynamics (especially of the deeper GAB and Proterozoic rock aquifers), surface water – groundwater interactions and the nature of potential subsurface hydrological connections. Further research on these three critical aspects of the regional hydrology is needed to enhance baseline knowledge and develop an improved understanding of potential impacts that may be associated with any future shale gas development.

3.6.1 Groundwater dynamics and baseline data

There is currently a high degree of uncertainty about groundwater dynamics in most aquifers of the region, including the seasonal variation in groundwater elevation, groundwater flow rates and flow directions in deeper aquifers, and lag time in response to rainfall and streamflow events. Collecting further baseline data (i.e. prior to any shale gas development that may occur) with significant temporal and spatial reach is required to improve this understanding – for example, through collecting additional groundwater level data from the main aquifers of the region. Collecting data at both the end of the dry season and the end of the wet season across multiple years would further improve understanding of seasonal trends in water levels.

Faulting within the Isa Superbasin and South Nicholson Basin (such as the Doomadgee Fault System, Nicholson River Fault Zone and the Calvert Fault) may contribute to groundwater flow compartmentalisation. This could have implications for groundwater recharge rates, potential accessibility of the aquifer resource and the potential for subsurface impacts associated with shale gas development to propagate away from the gas reservoirs and affect aquifers. Targeted hydrochemical groundwater sampling across suspected fault boundaries would enable potential structural controls on groundwater flow and aquifer interaction to be determined.

3.6.2 Surface water – groundwater interactions

There is considerable uncertainty in understanding surface water – groundwater interactions in the region due to the paucity of baseline groundwater and streamflow data. Availability of continuous long-term streamflow and groundwater time-series data, accurate stream gauge and bore elevations, and detailed lithological information would enable a more thorough assessment of the magnitude and dynamics of surface water – groundwater connectivity. There are also limited mapping of springs and insufficient data to confidently assign source aquifers for the spring cluster in the south-west of the region. Collecting targeted hydrochemistry data from bores, along streams and from springs would greatly improve understanding of water sources that support GDEs in the region. In particular, targeted hydrochemical sampling of springs and along stream transects during the dry season (e.g. sampling at several sites along the length of the Nicholson River) would enable identification of source aquifers contributing to surface waters in different locations. In addition, surveying of bore and stream gauge elevations and data logging of selected groundwater wells near monitored streams would enhance understanding of surface water – groundwater dynamics.

Analysis of remote sensing data has enabled a rapid, consistent approach to mapping parts of the landscape that have potential dependence on groundwater. However, field validation in targeted areas is required to confirm the preliminary interpretations made in this assessment. Additional remote sensing data products and assessment methods could be integrated with other datasets to enhance understanding of surface water – groundwater interactions at both local and regional scales.

3.6.3 Potential hydrological connections

The assessment of potential hydrological connections has identified important data and knowledge gaps that will require further research to improve the assessment of potential impacts associated with any future shale gas development. The key knowledge gaps highlighted by the analysis of potential hydrological connections include:

- limited understanding of vertical variation of in-situ stress orientation, fault reactivation and fault dilation tendencies, particularly in the deeper Proterozoic units and in places where faults occur near assets at the surface
- improvements to the three-dimensional geological model to better represent fault displacements and geological architecture and structural features, especially structures that may extend from the Isa Superbasin into the overlying Carpentaria Basin
- sparse aquifer and aquitard characterisation datasets, including groundwater pressure, hydrochemistry, dissolved methane and isotope data
- limited knowledge of the role that polygonal faulting in the Rolling Downs Group aquitard may play in connecting the artesian Gilbert River Formation with the near-surface aquifer of the Normanton Formation and sediments of the Karumba Basin
- lack of evidence supporting assigned aquifer sources for non-GAB springs in and near the region.

Table 13 provides a summary of the five potential hydrological connections that may occur in the Isa GBA region, including the existing evidence base that may test and enhance confidence in the current conceptual understanding. This table also outlines the priority research questions identified during this assessment for each pathway, as well as recommendations for further work that could be carried out to provide additional evidence to validate (or invalidate) these hypotheses.

Table 13 Summary table linking identified connectivity pathways, evidence based on current data/knowledge, gaps and recommended future activities

Potential hydrological connections		Potential impacts on water and the environment	Evidence base	Research questions	Possible focus for future research and investigation
Pathway ①	**Potential connection via direct stratigraphic contact** between shale gas plays of the Paleoproterozoic River and Lawn supersequences and the: • overlying Widdallion partial aquifer • overlying GAB Gilbert River aquifer • underlying Lady Loretta Formation aquifer. The occurrence of mapped faults intersecting the Proterozoic units near their contact with the main Great Artesian Basin (GAB) aquifer (eastern section of Isa GBA region) increases the likelihood for this connectivity pathway to occur (by the potential for increased hydraulic connectivity promoted by secondary permeability).	Water bores that access the GAB and shallower aquifers as well as the cavernous zone of Lady Loretta Formation aquifer and Widdallion partial aquifer as well as surface water bodies and groundwater-dependent ecosystems (GDEs).	• Zones of direct stratigraphic contact between shale gas plays and groundwater assets (Widdallion partial aquifer, GAB and Lady Loretta Formation aquifers) are represented in cross-sections (Figure 48 and Figure 49). • North-west-oriented faults that bound the north-eastern Gregory River Trough may increase permeability in this region and enhance this pathway. • Up to 4880 μg/L of methane (CH_4) detected in groundwater bores in the Gilbert River Formation and up to 7320 μg/L of methane in the Normanton Formation (EHS Support, 2014). • The cavernous zone of Loretta aquifer is under artesian pressure and corresponds to the most widely accessed formation of the Isa Superbasin for groundwater use.	• What is the travel distance and travel time in which water and/or gas can migrate from the Proterozoic shale gas reservoirs into the overlying GAB and underlying Lady Loretta Formation aquifers? • Is there evidence of upward hydraulic gradients that would facilitate such groundwater flow processes? • How do faults that potentially intersect the shale gas plays enhance connectivity with overlying aquifers in direct contact with the shale gas reservoir? • How likely is it that the shale gas reservoirs are directly connected to the near-surface environmental assets via major faults, considering the proximity between stressors and assets along the zone of greatest potential connectivity? • What is the likelihood that the hydraulic pressures in the cavernous zone of the Lady Loretta Formation aquifer will be reduced by depressurisation of the overlying gas plays, particularly the River Supersequence? What is the extent of potential impacts to the quality and quantity of this groundwater source?	• Collect a greater number of hydraulic data from both the shale gas plays and the overlying GAB aquifers along the zone of greater connectivity potential to investigate the upward hydraulic gradient hypothesis. • Conduct hydrochemical and isotopic fingerprinting of groundwater and dissolved gases at representative bores in different hydrostratigraphic units for inter-aquifer/ reservoir–aquifer connectivity assessment, including helium, methane and tracers such as $^{87}Sr/^{86}Sr$. • Use existing proximal water bores to target different formations of interest (a proxy for nested wells) as a first pass for improved hydrochemical and isotopic characterisation of aquifers. • Conceptually evaluate potential groundwater-related hazards in the cavernous zone of the Lady Loretta Formation aquifer due to shale gas development via depressurisation and hydraulic fracturing.
Pathway ②	**Potential connection through deep-seated faults** potentially intersecting shale gas reservoirs in the River Supersequence and overlying Proterozoic partial aquifer (Widdallion Sandstone Member of Lawn Hill Formation – Pmh 5) and GAB (mainly Gilbert River Formation) aquifers. It may also be plausible that there are hydrological connections between the shale gas reservoirs and springs located in the south-western parts of the region.	Water bores that access the Proterozoic partial aquifers and Gilbert River Formation aquifer (absent in the western half of the Isa GBA region) and spring complexes in the south-west of the region.	• Spring complexes about 12 km from the south-west border of the Isa GBA region have been interpreted to source water from Proterozoic sandstones. • The shape of top and bottom surfaces of River Supersequence in the three-dimensional geological model built for this study infer that faults may be present in the vicinity of these springs.	• What is the likelihood for vertical fluid or gas migration to occur through deep-seated faults from unconventional gas plays to overlying aquifers and near-surface assets (particularly springs in the south-west corner of the Isa GBA region)?	• Carry out targeted groundwater sampling campaign to constrain the source of springs near mapped faults, with particular focus on groundwater tracers to evaluate potential source contribution from deeper geological units (may include sampling for helium content). • Obtain any production well chemistry data and update the multivariate statistical analyses undertaken for this study with new data to identify potential connections between deep reservoirs and shallower aquifers. • Conduct hydrochemical and isotopic fingerprinting of groundwater and dissolved gases at representative bores in different hydrostratigraphic units to assess inter-aquifer and/or reservoir–aquifer connectivity, including sampling for helium, methane and tracers such as $^{87}Sr/^{86}Sr$. • Perform shallow geophysical surveying (e.g. transient electromagnetic (TEM) surveys) to locate and
Pathway ③	**Potential connection through porous aquifers**, such as the porous Proterozoic partial aquifer of the Widdallion Sandstone Member (Pmh 5) and overlying GAB aquifers and through the karstic interval of the Lady Loretta Formation aquifer.	Water bores that access these aquifers, partial aquifers and overlying potential receptors. There may also be an intermediate conduit through other pathways (e.g. pathway 2).	Groundwater flow is known to occur in the Gilbert River Formation aquifer (Ransley et al., 2015). It is most likely to occur considering the high yields reported in the cavernous zone of the Lady Loretta Formation aquifer, and the high degree of dip of this unit, potentially causing artesian conditions in the east of the region.	• Is there evidence that gas within the main shale gas reservoirs can migrate through adjacent aquifers? • What is the extent of lateral and vertical fluid migration (water and/or gas) through the most porous subsurface aquifers of the region?	

Potential hydrological connections		Potential impacts on water and the environment	Evidence base	Research questions	Possible focus for future research and investigation
Pathway ④	**Potential connection through partial aquifers/aquitards**, such as Rolling Downs Group partial aquitard via polygonal fault systems (PFS).	Bores that access the overlying Normanton Formation partial aquifer.	Artesian pressure from underlying Gilbert River Formation aquifer may promote upward flow through zones of the highly fractured aquitard.	• Is there evidence to confirm that fluids or gases migrate vertically and horizontally through the Rolling Downs Group aquitard due to the influence of PFSs?	characterise structural elements in the top 100 m of the subsurface near sensitive environmental assets. • Undertake synoptic surface water chemistry and tracer surveying along the Nicholson River to assess potential for surface water – groundwater interaction, and alluvium and bedrock connectivity.
Pathway ⑤	**Potential connection at catchment constrictions and river diversions** (likely controlled by geological structures), where steep hydraulic gradients exist between alluvial aquifers/surface water and underlying bedrock formations.	Water bores, springs, GDEs and perched watertables associated with the alluvial aquifer.	The geomorphology of the Nicholson River south-east of Doomadgee suggests possible geological structural control of the river, potentially due to the extent of nearby deep-seated faults that occur close to the surface.	• Do the faults mapped in the GAB and underlying hydrostratigraphic units potentially extend upwards to permeable units near the surface, including the Normanton Formation and Cenozoic units of the Karumba Basin, alluvial aquifers and streams?	• Perform shallow geophysical surveying (e.g. TEM surveys) to locate and characterise structural elements in the top 100 m of the subsurface near sensitive environmental assets. • Undertake synoptic surface water chemistry and tracer surveying along the Nicholson River to assess potential for surface water – groundwater interaction, and alluvium and bedrock connectivity.

The possible future research investigations for pathways 2, 3 and 4 (as shown in the last column) have been merged into a single list (cell) in this table as all of these recommended investigations are relevant to these three pathways.
GAB = Great Artesian Basin; GDE = groundwater-dependent ecosystem; PFS = polygonal fault system

4 Protected matters

Matters of National Environmental Significance (MNES) in the Isa GBA region include two subspecies of bar-tailed godwit and 24 other vertebrate species listed nationally as threatened (critically endangered, endangered or vulnerable). There are also 32 species that are listed as migratory and 11 species that are both threatened and migratory. Threatened species include the curlew sandpiper (*Calidris ferruginea*), Gouldian finch (*Erythrura gouldiae*) and ghost bat (*Macroderma gigas*).

Other protected matters in the Isa GBA region include seven listed marine species (six birds and one reptile) that are not listed as threatened and/or migratory. Matters of State Environmental Significance (MSES) include four nationally important wetlands, three state and territory reserves, the Gulf Rivers strategic environmental area and three state-listed threatened species.

4.1 Environmental baseline synthesis

4.1.1 Matters of National Environmental Significance

MNES are Australia's national environmental assets as defined in the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). MNES, other protected matters and MSES that occur or potentially occur in the Isa GBA region are identified in this section. These matters may potentially be impacted by shale gas development.

Methods snapshot: identifying protected matters

The matters considered in this report were identified in the Isa GBA region based on the EPBC Act protected matters reports run by the Department of the Environment and Energy on 24 August 2018. This search was re-run on 15 March 2019 to validate the original report and assess if any matters had been either added or removed from the list.

The protected matters reports run for the Isa GBA region searched for the following MNES: world heritage properties, national heritage places, wetlands of international importance, threatened species, threatened ecological communities, migratory species, Commonwealth marine areas and the Great Barrier Reef Marine Park. The report also searched for other matters protected under the EPBC Act that are not listed as MNES. These are Commonwealth lands, Commonwealth heritage places, listed marine species, whales and other cetaceans, critical habitats, Commonwealth reserves and Australian marine parks.

The search also provided information on extra matters of environmental significance that are not protected matters under the EPBC Act. These include MSES, nationally important wetlands and groundwater-dependent ecosystems (GDEs).

4.1.1.1 World heritage properties and national heritage places

There are no world heritage properties or national heritage places within the Isa GBA region. However, about 50 km south of the Isa GBA region (within the broader area of hydrocarbon potential), the Australian Fossil Mammal Sites (Riversleigh) is both a world heritage property and a national heritage place (Figure 4).

4.1.1.2 Nationally listed threatened species

Two subspecies of bar-tailed godwit and 24 other vertebrate species listed nationally as threatened (critically endangered, endangered or vulnerable) were identified as occurring or potentially occurring within the Isa GBA region (Table 14). These species/subspecies comprise fish (four), reptiles (eight), birds (ten) and mammals (four). No plants, invertebrates or frogs listed as threatened under the EPBC Act occur or potentially occur within the Isa GBA region. About 70% of the taxa (17) that are threatened and occur or potentially occur in the Isa GBA region are aquatic or semi-aquatic.

The list of protected matters under the EPBC Act is dynamic and the status of individual matters can change. As an example, the Carpentaria antechinus (*Pseudantechinus mimulus*) was listed as a threatened species during the protected matters search run on the 24 August 2018 but was no longer listed as a threatened species when the search was re-run on the 15 March 2019.

A detailed account of each nationally threatened species is in the protected matters technical appendix (MacFarlane et al., 2020). These accounts provide an overview of the ecology, distribution and status of the taxon, followed by an assessment of water dependency and a comment on the potential hazards associated with shale gas development that may impact their conservation status. A summary of relevant information for these threatened species is in Table 14.

4.1.1.3 Nationally listed migratory species

Twenty-one species that occur or potentially occur within the Isa GBA region are listed as migratory under the EPBC Act but are not listed nationally as threatened (Table 14). This includes the bar-tailed godwit (*Limosa lapponica*), which is listed as migratory at the species level, although two subspecies of bar-tailed godwit are listed separately as threatened under the EPBC Act: one is critically endangered (*L. l. menzbieri*) and the other is vulnerable (*L. l. baueri*) (Table 14).

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

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

The International Union for Conservation of Nature’s (IUCN) classification of the global conservation status of the 21 migratory species that are not classified as threatened in Australia under the EPBC Act is given in Table 14. Many of these species have both a large global population size and a large population size in Australia. All except six of the 21 species have a global conservation status of least concern, which is the status with the lowest level of concern in the IUCN classification system. The six species that are exceptions in having a status other than least concern are the narrow sawfish (*Anoxypristis cuspidata*), streaked shearwater (*Calonectris leucomelas*), reef manta ray (*Mobula alfredo*), giant manta ray (*Mobula birostris*), Irrawaddy dolphin (*Orcaella brevirostris*) and Indo-Pacific humpback dolphin (*Sousa chinensis*). Each of these species is marine and does not use terrestrial or freshwater environments on the Australian mainland and, hence, is unlikely to occur in the Isa GBA region.

Table 14 Species classified as Matters of National Environmental Significance under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* that occur, or potentially occur, in the Isa GBA region

For those species that are migratory but not threatened, information is also provided on IUCN global conservation status and global population trend (IUCN, 2019).

EPBC Act status	Scientific name	Common name	Summary of biology, distribution and habitat
Critically endangered	*Calidris ferruginea*[a]	Curlew sandpiper	Migratory shorebird. Breeds mainly in the Arctic region of northern Siberia. Non-breeding migrant during Austral summer across Africa, Asia and Australasia. Large numbers visit Australia where they mostly occupy intertidal mudflats in sheltered coastal areas (estuaries, bays, inlets, lagoons). Occurs less commonly inland occupying lakes, dams and bore drains. Global population estimated at between 1.085 and 1.285 million birds. Numbers declining globally.
	Limosa lapponica menzbieri[b]	Bar-tailed godwit (*menzbieri*)	Migratory shorebird. Breeds in northern Siberia. Non-breeding migrant during Austral summer in Australia and south-east Asia. Most birds visiting Australia are in north and north-west Western Australia. Occurs mainly in coastal areas including intertidal sandflats, mudflats and estuaries. Numbers declining globally.
	Numenius madagascariensis[a]	Eastern curlew	Migratory shorebird. Breeds in Siberia, Kamchatka and Mongolia. Non-breeding migrant during Austral summer in coastal East Asia, mostly in Australia (where up to 28,000 of the global population of 36,000 occur). Occurs on sheltered intertidal mudflats and sandflats and other coastal habitats. Numbers declining globally.
	Glyphis glyphis	Speartooth shark	Moderate-sized fish (grows to 2 m). Occurs in northern Australia in three discrete populations in Queensland and the NT. Also in Papua New Guinea. Lives in large tropical river systems when neonate, juvenile and sub-adult, migrating to coastal, marine environments for the entire adult life stage. Population trend is unclear.
Endangered	*Amytornis dorotheae*	Carpentarian grasswren	Passerine bird. Endemic to the Gulf of Carpentaria region from Tawallah Range / Limmen Bight River in the NT to the Mount Isa district in Queensland. Occurs in rocky environments with long-unburnt spinifex hummock grassland. Numbers have declined in the past ten years.
	Erythrura gouldiae	Gouldian finch	Passerine bird. Endemic to northern Australia from inland north Queensland across the Top End of the NT to the Kimberley region of WA. Occupies open

EPBC Act status	Scientific name	Common name	Summary of biology, distribution and habitat
			woodland that is relatively close to water; it feeds on seeding grasses and nests in hollows in eucalypts. Mounting evidence that numbers are recovering and that status should be downgraded (Garnett et al., 2011).
	Rostratula australis	Australian painted snipe	Resident shorebird. Endemic to Australia, where it occupies shallow freshwater wetlands. Although recorded across the mainland, its area of occupancy is comparatively small, being estimated at about 2000 km^2 by (Garnett et al., 2011). Numbers appear to be stable.
	Dasyurus hallucatus	Northern quoll	Medium-sized carnivorous marsupial. Nocturnal. Endemic to northern Australia from eastern Queensland across Top End of the NT to Kimberley and Pilbara regions in WA. Occupies savannah woodland and patches of rainforest and favours rocky escarpments. Numbers declining.
	Caretta caretta[a]	Loggerhead turtle	Marine turtle. Occurs in the Indian, Atlantic and Pacific oceans. Pelagic most of their lives. Only contact with land is when females come ashore to nest in the sand of beaches above the high tide mark. Forages in all coastal states and the NT; nests in Queensland and WA. Numbers declining globally.
	Dermochelys coriacea[a]	Leatherback turtle	Marine turtle. Occurs in the Indian, Atlantic and Pacific oceans. Pelagic most of their lives. Only contact with land is when females come ashore to nest in the sand of beaches above the high tide mark. Forages most commonly along the east coast of Australia and Bass Strait. Nests on the Cobourg Peninsula (NT) and possibly along the WA coast. Numbers declining globally.
	Elseya lavarackorum	Gulf snapping turtle	Freshwater turtle. Endemic to northern Australia with limited range covering upper and middle reaches of the Nicholson and Gregory rivers in north-west Queensland / north-east NT and the upper reaches of the Calvert River in the NT. Occurs in deep water pools of permanent spring-fed rivers.
	Lepidochelys olivacea[a]	Olive ridley turtle	Marine turtle. Occurs in parts of the Indian, Atlantic and Pacific oceans. Pelagic most of their lives. Only contact with land is when females come ashore to nest in the sand of beaches above the high tide mark. Forages in waters off northern Australia remaining on Australian continental shelf and off Indonesia. Nests on beaches in the NT, western Cape York (Queensland) and the Kimberley (WA). Numbers declining globally.
Vulnerable	*Erythrotriorchis radiatus*	Red goshawk	Bird of prey. Endemic to Australia with wide but patchy range across coastal and interior regions of Queensland, NT and north-east of WA. Also in north-east NSW. Occurs in open forest and woodland and along rainforest edges. Numbers appear to be stable.
	Grantiella picta	Painted honeyeater	Passerine bird. Specialised on fruit of mistletoes. Wide distribution across eastern Australia extending to the

EPBC Act status	Scientific name	Common name	Summary of biology, distribution and habitat
			tropics in north-west Queensland and north-east NT. Exhibits seasonal movement in response to food availability. Occupies acacia-dominated woodlands, preferring those with mature trees. Numbers appear to be stable.
	Limosa lapponica baueri[b]	Bar-tailed godwit (*baueri*)	Migratory shorebird. Breeds in north-east Siberia and in west Alaska. Non-breeding migrant during Austral summer to New Zealand and Australia. Most birds visiting Australia are in northern and eastern Australia. Occurs mainly in coastal areas, including intertidal sandflats, mudflats and estuaries. Numbers declining globally.
	Tyto novaehollandiae kimberli	Masked owl (northern)	Large owl. The subspecies occurs across northern Australia from the coast of north Queensland across the Top End to the Kimberley region in WA. Forages in tall open eucalypt forest and along margins of agricultural fields. Nests and roosts in hollows in large trees within forest patches. Numbers appear to be stable.
	Macroderma gigas	Ghost bat	Insectivorous bat (largest insectivorous bat in Australia with body mass of up to 165 g). Endemic to tropical northern Australia from Rockhampton, central Queensland across the Top End of the NT to Kimberley and Pilbara regions in WA. Spends the day in caves and disused mines and forages in woodland. Recent declines in numbers. Listed as threatened in 2016.
	Saccolaimus saccolaimus nudicluniatus	Bare-rumped sheath-tailed bat	Insectivorous bat. Occurs in northern Australia (Townsville to Iron Range in Queensland and Top End of the NT) and in New Guinea, Timor, Indonesia and elsewhere in South-East Asia. Forages in open space above woodland and roosts during the day in colonies of up to 100 bats in tree hollows. Recent status change from critically endangered because of new information on distribution.
	Xeromys myoides	Water mouse	Small rodent. Semi-aquatic. Endemic to northern Australia occurring in coastal areas of south-east and central Queensland and in the Top End of the NT. Occupies mangrove forest, saltmarsh flats, sedgeland in lakes near foredunes and freshwater swamps. Feeds on aquatic invertebrates. Population trend is unclear.
	Acanthophis hawkei	Plains death adder	Elapid snake. Small (length of about 60 cm) and stout-bodied. Endemic to northern Australia from the extreme north-east of WA, across the Top End and Barkly Tableland of the NT/Queensland border and the Mitchell Grass Downs in south-west Queensland. Occurs on floodplains with cracking clay soils. Numbers may be declining because of consumption of cane toads.
	Chelonia mydas[a]	Green turtle	Marine turtle. Occurs in the Indian, Atlantic and Pacific Oceans. Pelagic most of their lives. Only contact with land is when females come ashore to nest in the sand of beaches above the high tide mark. Forages mostly in

EPBC Act status	Scientific name	Common name	Summary of biology, distribution and habitat
			waters off WA, Queensland and the NT. Nests on beaches in these regions. Numbers declining globally.
	Eretmochelys imbricata[b]	Hawksbill turtle	Marine turtle. Occurs in Indian, Atlantic and Pacific Oceans. Pelagic most of their lives. Only contact with land is when females come ashore to nest in the sand of beaches above the high tide mark. Forages mostly in waters off WA, Queensland and the NT. Nests on beaches in these regions. Numbers declining globally.
	Natator depressus[a]	Flatback turtle	Marine turtle. Pelagic most of their lives. Only contact with land is when females come ashore to nest in the sand of beaches above the high tide mark. Forages across continental shelf of Australia and continental waters of Indonesia and Papua New Guinea. Nests only in Australia; Queensland, the NT and WA. Population trend unknown.
	Pristis clavata[M]	Dwarf sawfish	Marine fish. Although formerly more widespread, it is now confined to Australian waters from Cairns in Queensland north across the NT to the Pilbara coast. Occurs in shallow coastal and estuarine environments with high turbidity and low dissolved oxygen (does not occupy purely freshwater habitat). Numbers appear to be declining.
	Pristis pristis[a]	Freshwater sawfish	Freshwater fish (largest freshwater fish in Australia reaching maximum body length of 5.82 m). Occupies river (up to 400 km inland) and estuarine environments and up to 100 km offshore in northern and western Australia as well as in North and South America, Africa, Asia and New Guinea. In Australian rivers during dry season, habitat is a series of isolated waterholes. Numbers appear to be declining.
	Pristis zijsron[a]	Green sawfish	Large fish (maximum length of 7.3 m). Widespread from Australia through New Guinea, Indonesia, Malaysia, Kenya and Persian Gulf. In Australia, occurs from central Queensland across the NT to Shark Bay in WA. Occupies coastal environments, including estuaries, river mouths and beaches. Numbers appear to be declining.
Migratory	*Actitis hypoleucos*	Common sandpiper	Migratory shorebird. Global population estimated at 2.6 to 3.2 million birds. Breeds in Europe and Asia. Non-breeding migrant in Austral summer in large numbers along all coastlines and in many inland areas of Australia. Mapped extent of potential habitat covers entire Australian continent. IUCN global status is least concern. However, numbers may be decreasing.
	Anoxypristis cuspidata	Narrow sawfish	Marine fish. Widespread global range, including Australia, Papua New Guinea and Indonesia through Asia to Iran. In Australia restricted to the north coast from western Cape York (Queensland) across the NT to the Kimberley coast (WA). IUCN status is endangered, with numbers declining.
	Apus pacificus	Fork-tailed swift	Migratory swift. Breeds in south-east China and adjacent countries. Non-breeding migrant in Austral

EPBC Act status	Scientific name	Common name	Summary of biology, distribution and habitat
			summer across Australia. Exclusively aerial. Mapped extent of potential habitat covers most of Australia. IUCN global status is least concern and numbers are stable.
	Calonectris leucomelas	Streaked shearwater	Seabird. A transequatorial migrant that breeds on offshore islands in the western Pacific Ocean. Occurs off the coast of northern and eastern Australia in the Austral summer. Does not occur inland. Global population estimate of 3 million birds. IUCN global status is near threatened, with numbers declining.
	Calidris acuminata	Sharp-tailed sandpiper	Migratory shorebird. Breeds in northern Siberia. Non-breeding migrant in Austral summer in large numbers along all coastlines and in many inland areas of Australia, where population is estimated at up to 140,000 birds (global population estimate is >160,000 birds). Mapped extent of potential habitat covers entire continent. IUCN global status is least concern and numbers are stable.
	Calidris melanotos	Pectoral sandpiper	Migratory shorebird. Breeds in northern Russia and North America. Non-breeding migrant in Austral summer in low numbers along coastlines and inland areas of Australia. Global population estimate is 25,000 to 100,000 birds. Mapped extent of potential habitat covers entire continent. IUCN global status is least concern and numbers are stable.
	Charadrius veredus	Oriental plover	Migratory shorebird. Breeds in Mongolia and adjacent Russia. Approximately 90% of global population migrates to Australia in Austral summer, occupying coastal and inland areas. Non-breeding in Australia. 144,000 birds at Eighty Mile Beach, WA, in February 2010. Occupies a wide range of marine, freshwater and terrestrial habitats. IUCN global status is least concern. The population trend is unclear.
	Crocodylus porosus	Saltwater crocodile	Large aquatic reptile. Occurs in Bangladesh, Brunei, Cambodia, India, Sri Lanka, Malaysia, Myanmar, Papua New Guinea, Philippines, Solomon Islands, Vanuatu, Vietnam, Timor and Indonesia. Occupies inland lakes, swamps and marshes, coastal brackish waters and tidal sections of rivers. In Australia, occupies rivers and estuarine areas from the Kimberley region across northern Australia to southern coastal Queensland. IUCN global status of least concern with numbers increasing.
	Cuculus optatus	Oriental cuckoo	Migratory cuckoo. Large global distribution, including breeding range across the Palearctic region. Non-breeding migrant to the Top End of the NT and eastern Australia in the Austral summer. Global population is estimated at between 5 and 15 million birds. IUCN global status is least concern and numbers are stable.
	Glareola maldivarum	Oriental pratincole	Migratory shorebird. Breeds in eastern China and Russia and parts of south-east Asia. Non-breeding migrant in Austral summer, mainly in the north of WA and across the Top End of the NT to north-west

EPBC Act status	Scientific name	Common name	Summary of biology, distribution and habitat
			Queensland. Occupies a wide range of marine, freshwater and grassland habitats. IUCN global status is least concern. However, numbers may be decreasing.
	Hirundo rustica	Barn swallow	Passerine bird. One of the world's most widespread birds (global population estimate between 290 and 500 million), occurring across all continents except for Antarctica. Rare summer visitor across north of Australia. IUCN global status is least concern.
	Limosa lapponica[b]	Bar-tailed godwit	Refer to accounts for subspecies (above).
	Mobula alfredo	Reef manta ray	Marine fish. Inhabits warm tropical or subtropical waters in the Indian and eastern Pacific Ocean. In Australia, occurs north from the Queensland/NSW border to the central coast of WA. Resident in or along productive nearshore waters. IUCN global status is vulnerable, and numbers are decreasing.
	Mobula birostris	Giant manta ray	Marine fish. Widespread in tropical, subtropical and temperate waters of the Atlantic, Pacific and Indian oceans. Occupies wide range of habitats and appears to undergo seasonal migrations. Occurs across northern Australia waters. IUCN global status is vulnerable, and numbers are decreasing.
	Motacilla cinerea	Grey wagtail	Passerine bird. Widespread in the Northern Hemisphere and tropics, with some populations breeding in Europe and Asia then migrating to tropical Africa and Asia. Global population estimate of 6.9 million to 19.8 million birds. A non-breeding vagrant in Australia. Occupies riverine areas. IUCN global status is least concern and numbers are stable.
	Motacilla flava	Yellow wagtail	Passerine bird. Extremely large range from Europe to Siberia to west Asia and China south to Egypt. Global population estimate of 64 to 107 million birds. A non-breeding vagrant in Australia. Occupies terrestrial and freshwater habitat. IUCN global status is least concern.
	Orcaella brevirostris	Irrawaddy dolphin	Marine mammal. Now classified as the Australian snubfin dolphin (*Orcaella heinsohni*). Inshore species; inhabits a narrow strip of shallow coastal water in tropical and subtropical Australia and along the south coast of the island of New Guinea. In Australia, extends from the Brisbane River, Queensland, to Roebuck Bay, WA. Occurs within 20 km of the coast and within 20 km of river estuaries. IUCN global status is vulnerable, with numbers decreasing.
	Pandion haliaetus	Osprey	Bird of prey. Occurs in all continents except Antarctica. Breeding resident along the entire coast of mainland Australia (but not Tasmania). The global population is between 100,000 and 500,000 birds and is increasing. IUCN global status is least concern, and numbers are increasing.
	Rhipidura rufifrons	Rufous fantail	Passerine bird. Occurs in eastern Australia, the island of New Guinea, Timor-Leste and the Solomon Islands. Occurs in forest and shrubland, where it forages on

EPBC Act status	Scientific name	Common name	Summary of biology, distribution and habitat
			invertebrates. IUCN global status is least concern. However, numbers may be decreasing.
	Sousa chinensis	Indo-Pacific humpback dolphin	Marine mammal. Now classified as the Australian humpback dolphin (*Sousa sahulensis*). Inshore species in tropical and subtropical waters of the Sahul Shelf from northern Australia to the southern waters of the island of New Guinea. In Australia, extends from approximately the Queensland–NSW border to western Shark Bay, WA. Occurs within 20 km of the coast. IUCN status of vulnerable, with numbers decreasing.
	Tringa nebularia	Common greenshank	Migratory shorebird. Breeds in Scandinavia and across Russia. Non-breeding migrant in Austral summer in small numbers along most coastlines and in many inland areas of Australia. Australian population estimated at 18,000 to 19,000 birds (global population estimate of 440,000 to 1.5 million). Occupies a range of wetland types. IUCN global status is least concern, with numbers stable.

[a] Also listed as migratory.

[b] Bar-tailed godwit is listed at the species level as migratory, whereas two subspecies are recognised separately as threatened.

IUCN = International Union for Conservation of Nature

Source: IUCN (2019)

Data: assets Geological and Bioregional Assessment Program (2019c)

4.1.2 Other matters protected by the EPBC Act

The EPBC Act protected matters search for the Isa GBA region identified the occurrence, or potential occurrence, of two categories of other matters that are protected under the EPBC Act. Firstly, there are 31 species of birds and reptiles that are 'listed marine species'. Of these 31 species, eight species are also listed as both threatened and migratory, one species is also listed as threatened and 15 species are also listed as migratory. These species are covered in Section 4.1.1. Secondly, there are two species listed in the category 'whales and other cetaceans'.

4.1.2.1 Listed marine species

Listed marine species are those that occur in Commonwealth marine areas. Among the other matters protected under the EPBC Act, seven species are listed as marine but are not migratory or threatened or both (i.e. they are not MNES). The seven species comprise six birds and one reptile, and all have a global conservation status of 'least concern'. The global population size for five of the species is stable or increasing. A brief profile of each of these seven listed marine species is given in Table 15, together with information on each species' biology, distribution, habitat, IUCN global conservation status and global population trend.

Table 15 Listed marine species classified as other matters protected under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* that occur, or potentially occur, in the Isa GBA region

Information is sourced from IUCN (2019). Species that are also Matters of National Environmental Significance are not covered in this list. Refer to Table 14 for a listing of threatened and migratory species.

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

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

IUCN = International Union for Conservation of Nature
Source: IUCN (2019)
Data: assets Geological and Bioregional Assessment Program (2019c)

4.1.2.2 Whales and other cetaceans

Two species of inshore dolphin potentially occur in marine waters near the Isa GBA region. These are the Irrawaddy dolphin (*Orcaella brevirostris*) and Indo-Pacific humpback dolphin (*Sousa chinensis*). Both species are MNES and listed as migratory (Table 14). As noted in Section 4.1.1.3, both of these dolphins are marine species that are unlikely to occur within freshwater streams of the Isa GBA region.

4.1.3 Matters of State Environmental Significance

Multiple categories of important environmental assets listed under Queensland legislation occur in the Isa GBA region. These include two state reserves, the Gulf Rivers Strategic Environmental Area, and one endangered regional ecosystem (along with 27 regional ecosystems 'of concern'). Several species listed under the Queensland legislation but not in the EPBC Act also occur or potentially occur in the region. The Isa GBA region contains sections of four nationally important wetlands (recognised as such in *A directory of important wetlands* (Department of the Environment and Energy, 2010) (Figure 51)). In addition, both aquatic and terrestrial GDEs (Bureau of Meteorology, 2017) have been identified in the region (2892 km^2) (Section 3.3.1.2).

4.1.3.1 Protected area estates

Two state reserves in Queensland partially occur in the south-west of the Isa GBA region. These reserves are the Lawn Hill (Widdallion) and Lawn Hill (Arthur Creek) protected areas (Department of the Environment and Energy, 2016). Of these reserves, 56 km^2 is within the Isa GBA region (Figure 51).

An additional reserve is adjacent to the far north-west of the Isa GBA region, but, as it occurs only in the NT, it does not intersect with the region. This reserve is the Ganalanga-Mindibirrina Indigenous Protected Area (IPA), which is a Category VI Managed Resource Protected Area under IUCN criteria.

4.1.3.2 Designated precinct in a strategic environmental area

The designated precinct of the Gulf Rivers Strategic Environmental Area (SEA) (Figure 51) intersects the Isa GBA region and covers an area of 1480 km^2. Under Queensland legislation, an SEA is prescribed within the *Regional Planning Interests Regulation 2014* or within a regional plan. Prescribed activities within an SEA can only occur where they will not result in widespread or irreversible impact on an environmental attribute of the SEA. The environmental attributes include natural hydrological processes and geomorphological processes, riparian processes, wildlife corridors, and water quality in watercourses and aquifers.

4.1.3.3 Important regional ecosystems

There are 65 regional ecosystems in the Isa GBA region, of which one is 'endangered' (this is regional ecosystem 1.3.7, '*Eucalyptus camaldulensis* woodland on channels and levees'), 27 are 'of concern' and the remainder are listed as 'no concern at present'. The 'endangered' and 'of concern' regional ecosystems that intersect the region are described in Table 16.

Table 16 Regional ecosystems that are 'endangered' or 'of concern' in the Isa GBA region

Regional ecosystem	Description
1.3.7[a]	*Eucalyptus camaldulensis* woodland on channels and levees
1.10.2	*Eucalyptus miniata* woodland on sandstone plateaus
1.10.6	Springs mostly associated with quartzose sandstone
1.10.9	*Acacia* spp. and/or *Calytrix exstipulata* open shrubland on rock pavement
1.3.12	*Terminalia bursarina* open woodland on recent levees
1.3.9	Forest or woodland fringing perennial watercourses and on associated alluvium
1.5.10	Mixed shrubland on older sandy alluvium
2.3.12	*Eucalyptus microtheca* and/or *Excoecaria parvifolia* open woodland on seasonally flooded plains/depressions with numerous distributary channels
2.3.13	*Acacia stenophylla* low open forest in seasonal swamps on active Quaternary alluvial plains
2.3.15	*Eucalyptus microtheca* woodland to low open woodland with *Sarga* spp. in seasonally flooded depressions on gleyed podsolics
2.3.16	Billabongs (abandoned channels) on active Quaternary alluvial plains, fringed with *Eucalyptus* spp., *Corymbia* spp. and *Melaleuca* spp.
2.3.17	*Eucalyptus microtheca* +/- *Excoecaria parvifolia*, *Lysiphyllum cunninghamii*, *Atalaya hemiglauca* woodland fringing channels in fine-textured alluvial systems
2.3.18	*Atalaya hemiglauca*, *Grevillea striata*, *Vachellia sutherlandii* and *Eucalyptus microtheca* in mixed low woodlands on active Quaternary alluvial plains
2.3.19	*Eucalyptus tectifica* +/- *Corymbia confertiflora* woodland on old alluvial plains (recent Pleistocene surface)
2.3.20	*Corymbia bella*, *Eucalyptus pruinosa*, *C. terminalis, Lysiphyllum cunninghamii* in mixed woodlands on active levees and alluvial plains in the west
2.3.26	*Eucalyptus camaldulensis* +/- *Melaleuca* spp. woodland fringing sandy, seasonal channels
2.3.42	*Eucalyptus microtheca* +/- *Excoecaria parvifolia*, *Lysiphyllum cunninghamii*, *Melaleuca* spp. open woodland on Quaternary alluvial plains with coarse-grained parent material
2.3.5	*Lysiphyllum cunninghamii* woodland on plains of calcareous clays
2.3.50	Waterholes, bare sand and rock in the channels of major watercourses
2.3.52	*Melaleuca* spp., *Eucalyptus camaldulensis*, *Lophostemon grandiflorus* and *Livistona rigida* in mixed woodlands fringing major spring-fed watercourses

Regional ecosystem	Description
2.3.58	*Eriachne glauca* var. glauca, *Oryza australiensis* and *Eulalia aurea* tussock grassland in shallow alluvial depressions in the Doomadgee Plains subregion
2.3.59	*Excoecaria parvifolia*, *Melaleuca* spp., *Grevillea striata* and *Hakea pedunculata* in mixed tall open shrublands on coastal alluvial surfaces
2.3.62	*Eucalyptus camaldulensis* +/- *Corymbia polycarpa*, *Melaleuca viridiflora* woodland on abandoned stream channels and upper drainage areas in lateritic landscapes
2.3.63	*Eucalyptus microtheca* +/- *Excoecaria parvifolia*, *Atalaya hemiglauca* woodland on scroll plains associated with meanders of major watercourses
2.3.69	*Dichanthium* spp., *Iseilema* spp., *Aristida* spp. and *Brachyachne convergens* in mixed tussock grasslands on active Quaternary alluvial deposits derived from coarse-grained parent material in the west
2.3.70	*Eucalyptus pruinosa* low woodland on old alluvial plains (recent Pleistocene surface)
2.4.5	*Atalaya hemiglauca*, *Grevillea striata*, *Acacia victoriae* and *Vachellia sutherlandii* in mixed low open woodlands on Tertiary clay plains
2.5.27	*Acacia torulosa*, *Corymbia setosa* and *A. platycarpa* in mixed tall shrublands on degraded residuals of inland sand dunes

[a] Endangered. All other ecosystems are 'of concern'.
Data: Queensland Herbarium (2018)

4.1.3.4 State-listed threatened species

Two species that are listed as threatened in Queensland under the *Nature Conservation Act 1992* but are not listed nationally under the EPBC Act occur, or potentially occur, in the Isa GBA region. These are the purple-crowned fairy wren (*Malurus coronatus)* and the clonal herb or sub-shrub *Solanum carduiforme* (Table 17). Both species are listed as vulnerable in Queensland. *Solanum carduiforme* was formerly listed as vulnerable nationally under the EPBC Act but was delisted in 2013. The oriental pratincole (*Glareola maldivarum*) is listed as a threatened species (special of least concern) under Queensland legislation but is also a nationally listed migratory species under the EPBC Act (Table 14).

Table 17 Queensland threatened species identified in the Isa GBA region from WildNet data

Taxon	Scientific name	Common name	Conservation status	EPBC Act status
Birds	*Glareola maldivarum*	Oriental pratincole	Special least concern	Not listed
Birds	*Malurus coronatus*	Purple-crowned fairy wren	Vulnerable	Not listed
Plants	*Solanum carduiforme*	na	Vulnerable	Not listed

na = not applicable; EPBC Act = *Environment Protection and Biodiversity Conservation Act 1999*
Data: Department of Environment and Science (Qld) (2018d)

4.1.3.5 High ecological significance wetlands and high ecological value waters

There are no high ecological value waters in the Isa GBA region. The 77 km^2 of high ecological value wetlands (Department of Environment and Science (Qld), 2019) correspond closely to the distribution of nationally important wetlands, as outlined in Section 4.1.4 and Figure 51.

4.1.3.6 Cultural heritage areas

There are no state-listed cultural heritage areas in the Isa GBA region.

4.1.4 Nationally important wetlands

Four wetlands that occur in the Isa GBA region are listed as nationally important in the Directory of Important Wetlands in Australia (DIWA) (Department of the Environment and Energy, 2010). They are Bluebush Swamp and the three individual aggregations of Musselbrook Creek, Nicholson Delta and the Southern Gulf (612 km²). The locations of these sites are shown in Figure 51.

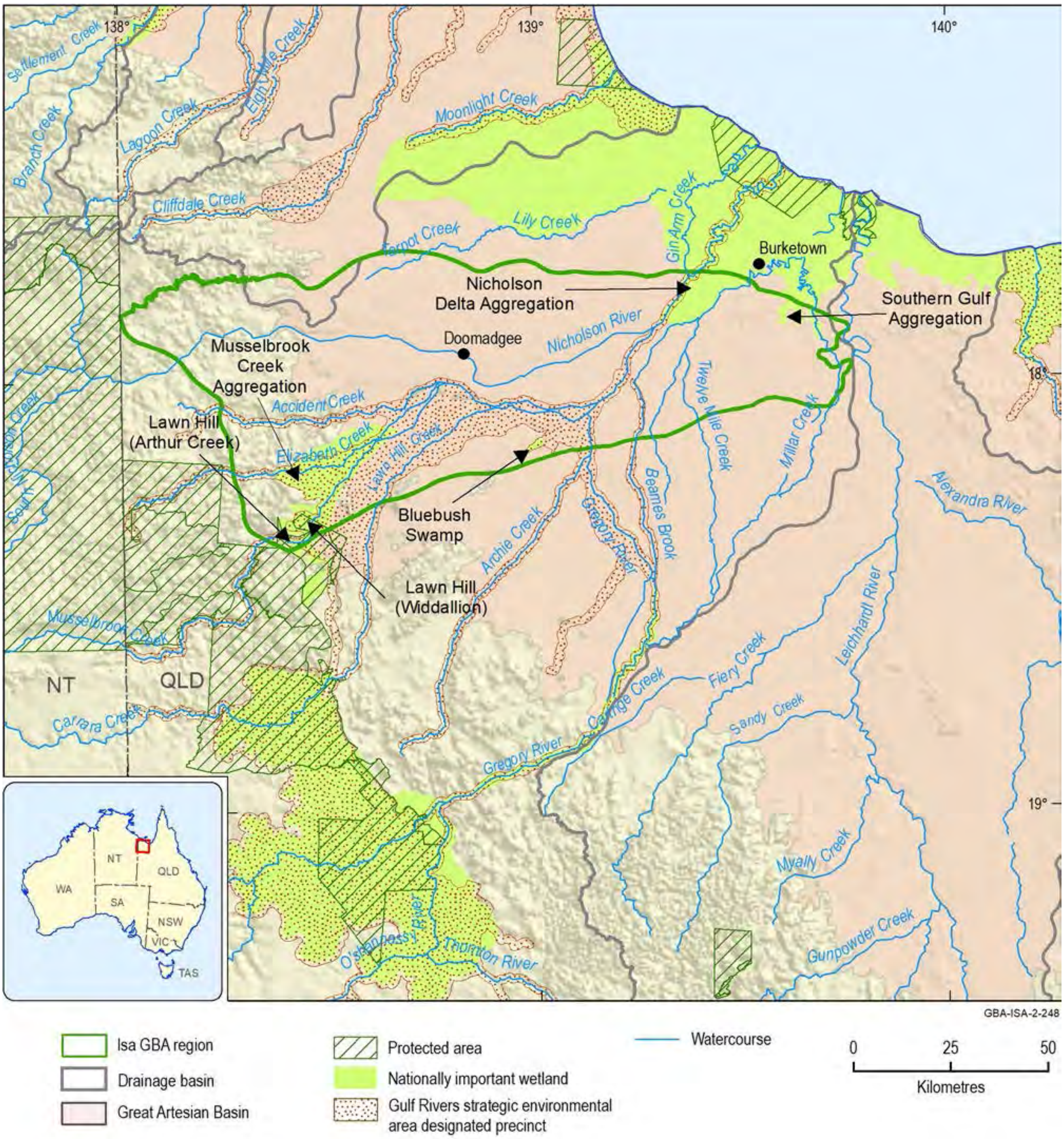

Figure 51 Nationally important wetlands, protected areas and strategic environmental areas in the Isa GBA region

Data: wetlands (Department of the Environment and Energy, 2010); protected areas (Department of the Environment and Energy, 2016); strategic environmental areas (Department of Environment and Science (Qld), 2017b)
Element: GBA-ISA-2-248

4.1.5 Groundwater-dependent ecosystems

In addition to matters of national and state environmental significance, the GBA Program also considers GDEs. The Isa GBA region contains many GDEs that shale gas resource development may impact and that may fall outside the matters of environmental significance outlined above. The Queensland GDE mapping, for example, identifies surface expression GDEs located near Lawn Hill National Park in the south-west of the region. These are part of the Boodjamulla complex, which is located outside of the region but is potentially hydrologically connected. Further, Figure 43 in the hydrogeology technical appendix shows the location of known and potential GDEs, including springs that shale gas resource development may impact (Buchanan et al., 2020).

4.1.6 Threatening processes with potential to impact species

There are nine key threatening processes identified under the EPBC Act that are relevant to the Isa GBA region. These existing processes are not specifically related to shale gas development (or, indeed, any type of petroleum resource) in the region, but they potentially affect some of the species listed under the EPBC Act. Furthermore, future shale gas development activities within the region may interact with these existing threatening processes, potentially modifying their impacts. A number of threatening processes that are important in southern Australia are not relevant for the Isa GBA region, including the threats posed by European red foxes and feral goats. The key threatening processes relevant to the Isa GBA region are:

1. loss of climatic habitat caused by anthropogenic emissions of greenhouse gases
2. injury and fatality to vertebrate marine life caused by ingestion of, or entanglement in, harmful marine debris
3. incidental catch (bycatch) of sea turtle during coastal otter-trawling operations within Australian waters north of 28 degrees south
4. land clearance
5. invasion of northern Australia by gamba grass and other introduced grasses
6. novel biota and their impact on biodiversity (e.g. feral horses, donkeys, camels)
7. predation by feral cats
8. predation, habitat degradation, competition and disease transmission by feral pigs
9. biological effects, including lethal toxic ingestion, caused by cane toads (*Rhinella marina*).

4.2 Cultural baseline synthesis

Methods snapshot: identifying cultural assets

Cultural assets within the Isa GBA region were identified through a search of the EPBC Act protected matters database (which searched both the Isa GBA region and the broader area of hydrocarbon potential) and the Queensland Heritage Register, undertaken on the 24 August 2018 and again on the 3 July 2019.

The Australian Fossil Mammal Sites (Riversleigh) is in north-western Queensland close to the NT border, about 250 km north-west of Mount Isa and 200 km south of the Gulf of Carpentaria. The Riversleigh site is both a world heritage-listed property (listed in 1994) and a national heritage-listed place (listed in 2007). Although it is not within the Isa GBA region, it does occur within the broader area of hydrocarbon potential (as previously defined in Section 1.2) (Figure 4).

The Australian Fossil Mammal Sites (Riversleigh) is among the world's ten most important fossil sites (UNESCO, 2019). It possesses an outstanding collection of Australia's mammal fauna from the Oligocene to the Miocene (approximately 10 to 30 million years ago). The site records a changing fauna as the environment transitioned from moist lowland rainforest to dry eucalypt forest and woodland.

The Riversleigh site is also important for its human history. The Traditional Owners, the Waanyi people, continue to live in the region. Significant sites for rock art, middens and artefacts and other important areas occur in the region.

The Australian Fossil Mammal Sites (Riversleigh) is managed with the assistance of the Riversleigh Management Strategy (Queensland Environmental Protection Agency et al., 2002). A Riversleigh Community and Scientific Advisory Committee has been established, with representation from the scientific community, including the Queensland Museum, the tourism sector and Waanyi Traditional Owners as well as local, Queensland and Australian governments. In addition, a Waanyi Advisory Committee provides advice on Indigenous issues.

The entire Isa GBA region has supported Indigenous cultures for many thousands of years. Indigenous people continue to maintain a strong and ongoing connection to the region.

No places were identified within the Isa GBA region from the Queensland Heritage Register.

4.3 Landscape classification and ecohydrological conceptualisation

Ten landscape classes, based on the Land Zones of Queensland, are defined for the Isa GBA region (Figure 52). Landscape classifications are used in this GBA to ensure that the main ecological systems of the region are accounted for and to provide a framework for determining how changes due to shale gas development may affect ecosystems at the landscape scale.

The Isa GBA region is dominated by the landscape classes 'floodplain and alluvium' and 'loamy and sandy plains'. It also contains substantial areas of 'clay plains' and of 'tablelands and duricrusts'. There are lesser areas of 'undulating country on fine-grained sedimentary rocks', 'hills and lowlands on metamorphic rocks' and 'sandstone ranges'. Only traces of 'tidal flats and beaches' and of 'hills and lowlands on granitic rocks' occur in the region.

4.3.1 Introduction to landscape classes

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

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

The landscape classification developed for the Isa GBA region is based on the Land Zones of Queensland (Wilson and Taylor, 2012). Consistent with the principles outlined above, it sought to use existing data sources and classifications and to leverage the extensive effort already expended to develop highly relevant conceptual models at both landscape and wetland scales by the Queensland Government as part of its Wetlands Program (Department of Environment and Science (Qld), 2017a). These conceptual models are presented for each landscape class in the protected matter technical appendix (MacFarlane et al., 2020), with an example given in Figure 54 for the ‘floodplain and alluvium’ landscape class.

Methods snapshot: developing the landscape classification

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

Detailed land zones (Table 18) within the Isa GBA region were supplied by the Queensland Government (Department of Environment and Science (Qld), 2018a) and assigned to corresponding landscape classes (Figure 52). The main land zones in the Isa GBA region are described in Table 18, with the relationship between land zones and the GBA landscape classification shown in Table 19. Landscapes in the Isa GBA region can also be classified using the Interim Biogeographic Regionalisation of Australia (IBRA) (see Table 20 and Figure 53).

Table 18 Land zones (Queensland) in the Isa GBA region

Name	Detailed description
Cainozoic duricrusts[a]	Cainozoic duricrusts formed on a variety of rock types, usually forming mesas or scarps. Includes exposed ferruginous, siliceous or mottled horizons and associated talus and colluvium, and remnants of these features. Soils are usually shallow Rudosols and Tenosols, with minor Sodosols and Chromosols on associated pediments, and shallow Kandosols on plateau margins and larger mesas.
Coarse-grained sedimentary rocks	Medium- to coarse-grained sedimentary rocks, with little or no deformation, forming plateaus, benches and scarps. Includes siliceous (quartzose) sandstones, conglomerates and minor interbedded volcanics, and springs associated with these rocks. Excludes overlying Cainozoic sand deposits. Soils are predominantly shallow Rudosols and Tenosols of low fertility but include sandy-surfaced Kandosols, Kurosols, Sodosols and Chromosols.
Deposits subject to periodic tidal inundation	Quaternary estuarine and marine deposits subject to periodic inundation by marine waters. Includes mangroves, saltpans, off-shore tidal flats and tidal beaches. Soils are predominantly Hydrosols (saline muds, clays and sands) or beach sand.
Fine-grained sedimentary rocks	Fine-grained sedimentary rocks, generally with little or no deformation and usually forming undulating landscapes. Siltstones, mudstones, shales, calcareous sediments and labile sandstones are typical rock types, although minor interbedded volcanics may occur. Includes a diverse range of fine-textured soils of moderate to high fertility, predominantly Vertosols, Sodosols, and Chromosols.
Mesozoic to Proterozoic igneous rocks	Mesozoic to Proterozoic igneous rocks, forming ranges, hills and lowlands. Acid, intermediate and basic intrusive and volcanic rocks such as granites, granodiorites, gabbros, dolerites, andesites and rhyolites, as well as minor areas of associated interbedded sediments. Excludes serpentinites and younger igneous rocks. Soils are mainly Tenosols on steeper slopes with Chromosols and Sodosols on lower slopes and gently undulating areas. Soils are typically of low to moderate fertility.
Metamorphic rocks	Metamorphosed rocks, forming ranges, hills and lowlands. Primarily lower Permian and older sedimentary formations which are generally moderately to strongly deformed. Includes low- to high-grade and contact metamorphics such as phyllites, slates, gneisses of indeterminate origin and serpentinite, and interbedded volcanics. Soils are mainly shallow, gravelly Rudosols and Tenosols, with Sodosols and Chromosols on lower slopes and gently undulating areas. Soils are typically of low to moderate fertility.
Recent Quaternary alluvial systems	Recent Quaternary alluvial systems, including closed depressions, paleo-estuarine deposits currently under freshwater influence, inland lakes and associated wave-built lunettes. Excludes colluvial deposits such as talus slopes and pediments. Includes a diverse range of soils, predominantly Vertosols and Sodosols; also with Dermosols, Kurosols, Chromosols, Kandosols, Tenosols, Rudosols and Hydrosols; and Organosols in high rainfall areas.
Tertiary-early Quaternary clay deposits	Tertiary-early Quaternary clay deposits, usually forming level to gently undulating plains not related to recent Quaternary alluvial systems. Excludes clay plains formed in-situ on bedrock. Mainly Vertosols with gilgai microrelief but includes thin sandy or loamy surfaced Sodosols and Chromosols with the same paleo-clay subsoil deposits.
Tertiary-early Quaternary loamy and sandy plains and plateaus	Tertiary-early Quaternary extensive, uniform near level or gently undulating plains with sandy or loamy soils. Includes dissected remnants of these surfaces. Also includes plains with sandy or loamy soils of uncertain origin; and plateau remnants with moderate to deep soils usually overlying duricrust. Excludes recent Quaternary alluvial systems, exposed duricrust, and soils derived from underlying bedrock. Soils are usually Tenosols and Kandosols, also minor deep sandy-surfaced Sodosols and Chromosols. There may be a duricrust at depth.

[a] Typology and punctuation are consistent with Queensland Land Zones (Wilson and Taylor, 2012), which uses the now superseded geological terminology to refer to the time periods of the Cainozoic and the Tertiary.
Source: adapted from Wilson and Taylor (2012)

Table 19 Landscape classes within the Isa GBA region and corresponding Queensland land zones

Landscape class (GBA)	Land zone (Queensland)[a]	Area (km^2)	Percentage of total GBA region (%)
Floodplain and alluvium	Recent Quaternary alluvial systems	2925	36%
Loamy and sandy plains	Tertiary – early Quaternary loamy and sandy plains and plateaus	2689	33%
Clay plains	Tertiary – early Quaternary clay deposits	1218	15%
Tablelands and duricrusts	Cainozoic duricrusts	1000	12%
Hills and lowlands on metamorphic rocks	Metamorphic rocks	190	2.3%
Undulating country on fine-grained sedimentary rocks	Fine-grained sedimentary rocks	117	1.4%
Sandstone ranges	Coarse-grained sedimentary rocks	58	0.7%
Tidal flats and beaches	Deposits subject to periodic tidal inundation	23	0.3%
Hills and lowlands on granitic rocks	Mesozoic to Proterozoic igneous rocks	3	0.04%
Total		**8223**	**100%**

The 'springs' landscape class is not listed in this table, as springs are represented as point locations for purposes of this assessment.
[a] Typology and punctuation are consistent with the Land Zones of Queensland (Wilson and Taylor, 2012), which uses the now superseded geological terminology to refer to the time periods of the Cainozoic and the Tertiary.
Source: Geological and Bioregional Assessment Program (2018b)

The total area of landscape classes in the Isa GBA region is 8223 km^2 (Table 19). The floodplain and alluvium landscape class dominates in area (2925 km^2) and is associated with the Albert and Nicholson rivers on the Doomadgee Plains and Armraynald Plains (Figure 53), as well as loamy and sandy plains (2689 km^2) on the Doomadgee Plains. There are substantial areas of clay plains (1218 km^2) in the east of the Isa GBA region on the Armraynald Plains. The tablelands and duricrusts (1000 km^2) in the west of the Isa GBA region intersect the McArthur IBRA subregion (Figure 53) of the North-West Highlands. There are also smaller areas of undulating country on sedimentary rocks (175 km^2), hills and lowlands on metamorphic rocks (190 km^2) and hills and lowlands on granitic rocks (3 km^2) associated with the McArthur IBRA subregion. There are 23 km^2 of tidal flats and beaches in the extreme north-east of the Isa GBA region associated with the upper reaches of Saltwater Arm River overlying the Karumba Plains IBRA subregion (Figure 53).

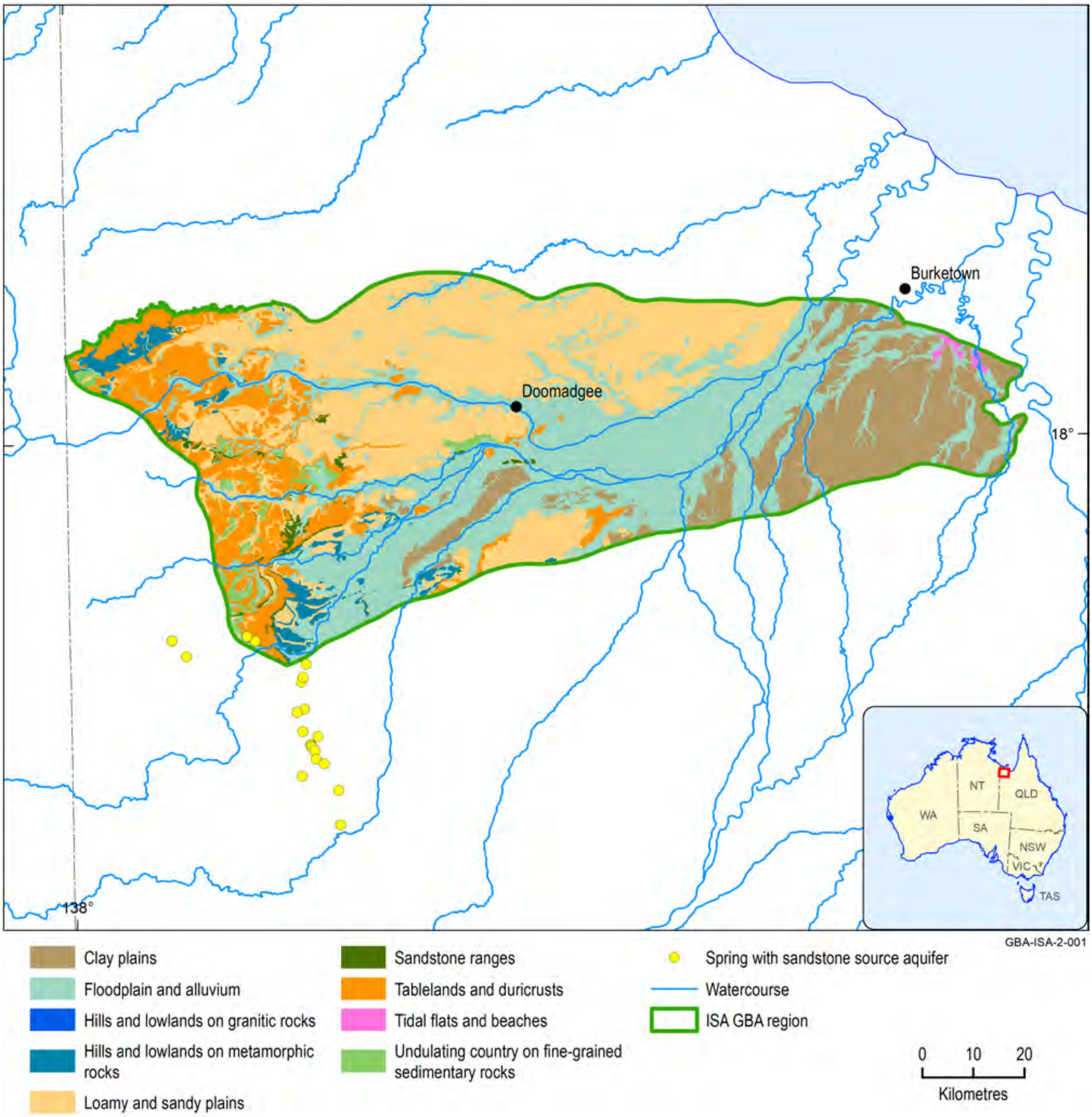

Figure 52 Landscape classes within the Isa GBA region

Source: Geological and Bioregional Assessment Program (2018b)
Element: GBA-ISA-2-001

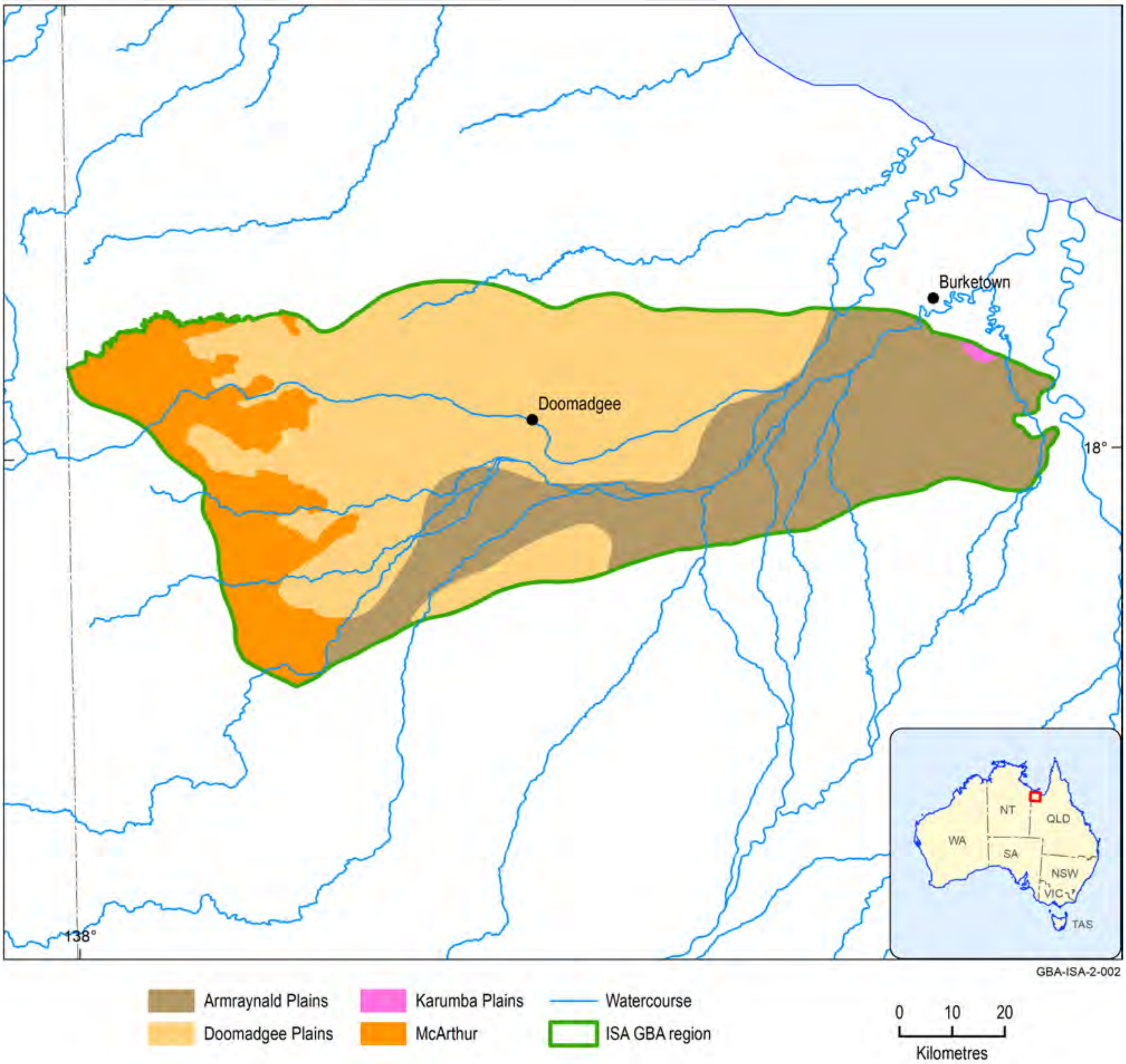

Figure 53 Interim Biogeographic Regionalisation of Australia (IBRA) subregions within the Isa GBA region

Source: Department of the Environment and Energy (2018)
Element: GBA-ISA-2-002

Table 20 Interim Biogeographic Regionalisation for Australia (IBRA) subregions in the Isa GBA region

IBRA subregion	Description	Area in Isa GBA region (km^2)
Doomadgee Plains	Doomadgee Plains subregion, in the Gulf Plains IBRA region, lies in the far north-western corner of the Gulf Plains bioregion, and extends into the NT. These lowlands extend between the Northwest Highlands and the Karumba Plains north of the Nicholson River, but remnants of the surface continue around the north-eastern margin of the highlands as far as the Leichhardt River. The subregion is characterised by laterised Tertiary surfaces that have been partly overlain by sandy outwash from the adjacent ranges.	4014
Armraynald Plains	Armraynald Plains subregion, in the Gulf Plains IBRA region, contains the extensive grasslands and low open grassy woodlands on the clay plains associated with the major rivers entering the southern gulf. The subregion is dominated by clay plains, with extensive, older and higher plains channelled by younger braided watercourses. Seasonal and permanent wetlands are associated with the watercourses and back-plains, and near the coast where the alluvia meet the marine plains. There are also areas of sandier alluvium, especially where major watercourses enter the Gulf Plains from the Northwest Highlands. Small areas of sand sheet overlie the clays, usually as outliers of adjacent provinces. In the far west there are low hills that are outliers of the Mount Isa Inlier province of the Northwest Highlands.	2839
McArthur	McArthur subregion, in the Gulf Fall and Uplands IBRA region, is composed almost entirely of low hills and plateaus on gently deformed pre-Cambrian sediments, overlain in places by Mesozoic sediments of the Carpentaria Basin forming residual plateaus and scarps. Folded pre-Cambrian sediments underlie most of the subregion and outcrop mainly along its eastern margin. These low hills are essentially outliers of the Mount Isa Inlier subregion. Sandy alluvia are common along the larger watercourses. Sandstone areas sometimes contain springs and other areas of permanent or near-permanent water. This is a remote subregion and its biology is poorly known. It drains largely into the Nicholson River and the lower reaches of Lawn Hill Creek, and then into the Gulf of Carpentaria.	1354
Karumba Plains	Karumba Plains subregion, in the Gulf Plains IBRA region, contains all areas subject to coastal influences including dunes, saline mudflats and mangrove-lined estuaries. It extends around the entire seaward margin of the Gulf Plains bioregion. The major watercourses of the Gulf Plains bioregion have their headwaters in four other bioregions. The estuaries of these large and diverse river systems are contained within the Karumba Plains subregion. Between these estuaries are the most extensive marine plains in Australia. Sand dunes are prominent throughout, but particularly in the west, and north of Karumba. The marine plains receive runoff from adjacent subregions.	16
Total area		**8223**

Source: Department of the Environment and Energy (2018); Sattler and Williams (1999)

4.3.2 Description of landscape classes

4.3.2.1 Floodplain and alluvium

The ‘floodplain and alluvium’ landscape class, associated with the Albert and Nicholson rivers on the Doomadgee Plains and the Armraynald Plains IBRA subregions, is prevalent in the Isa GBA region (2925 km^2). Young, braided watercourses pass through the old clay, loamy and sandy plains. These plains, along with the back-plains, are associated with many seasonal and permanent wetlands (Morgan, 1999).

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

Floodplain and alluvium landforms are mostly flat to gently undulating with levees, bars, streambed and banks creating minor local relief (Wilson and Taylor, 2012). Soils are very diverse and are dominated by Vertosols and Sodosols but include a range of other soils. They are usually fertile and may be cleared or developed for agriculture or pastoralism (although clearing of native vegetation has not occurred widely in the Isa GBA region). Riparian vegetation adjacent to watercourses is generally more biodiverse than that of the surrounding landscape and is commonly denser due to greater water availability.

The ‘floodplain and alluvium’ landscape class is associated with many wetlands classified within Queensland’s Regional Ecosystem Framework (Nelder et al., 2017) as either ‘floodplain (other than floodplain wetlands)’, ‘frequently inundated areas (not wetlands or floodplains)’, ‘palustrine wetland (e.g. vegetated swamp)’ or ‘riverine wetland or fringing riverine wetland’.

Dominant regional ecosystems that contain wetlands include:

- *Eucalyptus microtheca* +/- *Excoecaria parvifolia*, *Atalaya hemiglauca*, *Grevillea striata* low woodland on active Quaternary alluvial plains with cracking clay soils
- *Eulalia aurea*, *Panicum decompositum*, *Astrebla pectinata* and *Dichanthium* spp. in mixed tussock grasslands on active Quaternary alluvial plains within Tertiary clay deposits
- *Corymbia bella*, *Eucalyptus pruinosa*, *C. terminalis*, *Lysiphyllum cunninghamii* in mixed woodlands on active levees and alluvial plains in the west
- *Eucalyptus microtheca* +/- *Excoecaria parvifolia*, *Lysiphyllum cunninghamii*, *Melaleuca* spp. open woodland on Quaternary alluvial plains with coarse-grained parent material.

This landscape class is represented by the ‘alluvia’ conceptual model, as illustrated in Figure 54 (Queensland Government, 2017d) (see the protected matters technical appendix for further information about this conceptual model (MacFarlane et al., 2020)).

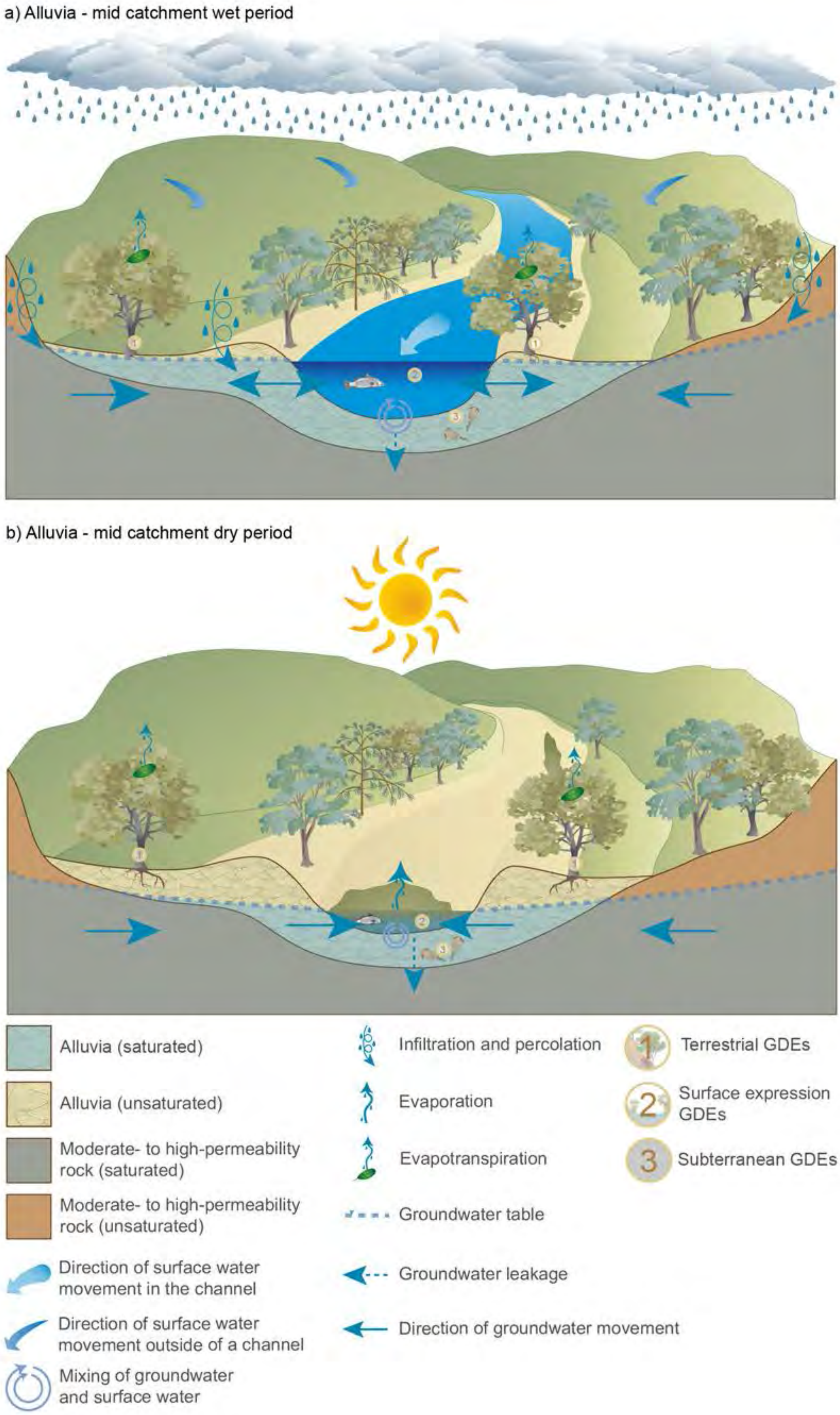

Figure 54 'Floodplain and alluvium' landscape class conceptual models showing wet-season and dry-season phases

GDE = groundwater-dependent ecosystem
Source: adapted from the 'alluvia–mid-catchment' conceptual model (Queensland Government, 2017d, 2013)
Element: GBA-ISA-2-260

4.3.2.2 Loamy and sandy plains

There are extensive areas (2689 km^2) of loamy and sandy plains within the Isa GBA region, mainly associated with the Doomadgee Plains IBRA subregion, which is characterised by laterised Tertiary surfaces that have been partly overlain by sandy outwash from the adjacent ranges (Table 20).

Loamy and sandy plains may be formed by redeposition of colluvium or be formed in situ from 'old' alluvial processes (Wilson and Taylor, 2012). They may also result from prolonged, intense, deep weathering of parent rock material high in iron and/or aluminium oxides and kaolin clays. Landforms are flat to gently undulating plains, plateaus and dissected tablelands. A variety of regional ecosystems exist within this landscape class, depending on local climate and soil factors, but the major regional ecosystems (Queensland Government, 2017e) are *Eucalyptus pruinosa, Lysiphyllum cunninghamii, E. chlorophylla* and *Corymbia setosa* in mixed low open woodlands; and *Melaleuca* spp. +/- *Eucalyptus pruinosa, Asteromyrtus symphyocarpa, Terminalia canescens* low open woodland.

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

4.3.2.3 Clay plains

In the east of the Isa GBA region, 1218 km^2 of the landscape is classified as clay plains. These are typically gently undulating plains, with clay soils and texture-contrast soils derived from fine-grained sediments. Clay plains include paleo-clay unconsolidated sediments originating from 'old' alluvial processes and aeolian clays forming predominantly level to gently undulating plains. The paleo-clay deposits are now elevated above and usually isolated from the alluvial valleys and floodplains (Wilson and Taylor, 2012). As a result, this is now an erosional landscape with poorly defined drainage. These clay soils have been extensively cleared for introduced pastures and cropping in some higher rainfall areas due to their relatively high soil moisture availability and high fertility. Soils are dominated by Vertosols with gilgai microrelief. Larger gilgai may provide ephemeral wetland habitat due to ponding of rainfall. Soils usually have restricted rooting depth caused by the adverse effects of high sodium levels.

Dominant regional ecosystems (Queensland Government, 2017e) within the Gulf Plains IBRA region include *Dichanthium* spp., *Eulalia aurea, Chrysopogon fallax* and *Themeda avenacea* in mixed tussock grasslands; and *Eucalyptus microtheca* +/- *Excoecaria parvifolia* low open woodland.

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

4.3.2.4 Tablelands and duricrusts

Tablelands and duricrusts are common in the west of the Isa GBA region (1000 km^2). This landscape occurs mainly in the McArthur IBRA subregion (Figure 53), which is composed almost entirely of low hills and plateaus on gently deformed pre-Cambrian sedimentary rocks, overlain in places by Mesozoic rocks of the Carpentaria Basin forming residual plateaus and scarps.

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

Vegetation is extremely variable depending on climatic conditions, depth of soil and position in the landscape (Wilson and Taylor, 2012). The absence of vegetation on the bare rock and scarp areas is typical. The dominant regional ecosystem (Queensland Government, 2017e) is *Corymbia capricornia* +/- *Eucalyptus leucophloia* or *E. miniata* low open woodland.

This landscape class is represented by the ‘exclusion zones’ conceptual model (Queensland Government, 2017b) (see the protected matters technical appendix (MacFarlane et al., 2020)).

4.3.2.5 Hills and lowlands on metamorphic rocks

Hills and lowlands on metamorphic rocks consist of undulating to steep hills, ranges and mountains and associated gently undulating colluvial slopes and pediments (Wilson and Taylor, 2012). This landscape class (190 km^2) (Table 19) is associated with both the McArthur and Doomadgee Plains IBRA subregions, where it is considered an outlier of the Mount Isa IBRA subregion (Wilson and Taylor, 2012). Dominant regional ecosystems include *Eucalyptus leucophloia* and *E. pruinosa* low open woodlands.

This landscape class is represented by the ‘exclusion zones’ conceptual model (Queensland Government, 2017b) (see the protected matters technical appendix (MacFarlane et al., 2020)).

4.3.2.6 Undulating country on fine-grained sedimentary rocks

Undulating country on fine-grained sedimentary rocks in the Isa GBA region is associated with the McArthur IBRA subregion, which is composed almost entirely of low hills and plateaus on gently deformed pre-Cambrian sedimentary rocks, overlain in places by Mesozoic rocks of the Carpentaria Basin forming residual plateaus and scarps. This landscape class has an area of 117 km^2 (Table 19). Fine-grained sedimentary rocks include siltstones, mudstones and shales. Depending on the lithology (mineral composition) of the lithic fragments, these fine-grained sedimentary rocks form clayey soils or soils with clay subsoils (Wilson and Taylor, 2012). Due to the general ‘soft’ nature of the sedimentary rocks and the readily weathered nature of the lithology, the landforms are dominated by gently undulating plains and rises, many of which have been extensively developed or cleared for pasture. The dominant regional ecosystem within the Isa GBA region is *Eucalyptus leucophloia* low open woodland on limestone.

This landscape class is represented by the ‘exclusion zones’ conceptual model (Queensland Government, 2017b) (see the protected matters technical appendix (MacFarlane et al., 2020)).

4.3.2.7 Sandstone ranges

Areas of sandstone ranges are scattered throughout the McArthur IBRA subregion in the Isa GBA region (58 km^2). Medium- to coarse-grained sedimentary rocks composed predominantly of resistant quartz form undulating to steep rises and hills, plateaus, precipitous cliffs and scarps, and talus. Rock outcrops are typical of the cliffs and immediate edges (Wilson and Taylor, 2012).

Vegetation communities on sandstone ranges are driven by climate and the low fertility sandy soils and, less commonly, the micro-climates within gorges. Dominant regional ecosystems include *Eucalyptus miniata* woodland and *Corymbia aspera* low open woodland on rocky soils. Springs (which are a separate landscape class) associated with quartzose sandstone are also present.

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

4.3.2.8 Tidal flats and beaches

The 'tidal flats and beaches' landscape class includes the sands and/or muds deposited by wind and waves in the intertidal zone and higher supratidal areas under the periodic influence of sea water (Wilson and Taylor, 2012). The 23 km^2 of tidal flats and beaches in the Isa GBA region are dominated by periodically inundated, saline clay plains (Morgan, 1999). These are largely unvegetated but include some areas of *Tecticornia* spp., *Salicornia* spp. and *Suaeda* spp. There are lesser areas of margins and levees of channels that are subjected to tidal inundation and covered by saline muds and mangroves. These areas are classified by Nelder et al. (2017) as estuarine wetlands (e.g. mangroves) and are seasonally important for waterbird breeding, feeding and roosting.

This landscape class is represented by the OzCoasts conceptual model for tidal creeks (see the protected matters technical appendix (MacFarlane et al., 2020) for further information).

4.3.2.9 Hills and lowlands on granitic rocks

Hills and lowlands on granitic rocks form extensive gently undulating rises to steep mountains (Wilson and Taylor, 2012). There are only small areas (Table 19) of this landscape class along the north-west margin of the Isa GBA region (3 km^2) associated with the McArthur IBRA subregion. The dominant regional ecosystem is *Eucalyptus leucophloia* low open woodland.

This landscape class is represented by the 'exclusion zones' conceptual model (Queensland Government, 2017b) (see the protected matters technical appendix (MacFarlane et al., 2020) for further information).

4.3.2.10 Springs

Springs in the Isa GBA region are described in detail in Section 3.3.1.2. There are two springs associated with sandstone in the south-west of the Isa GBA region. They are located near other springs associated with sandstone outside the margins of the region. Regional ecosystem 1.10.6 ('springs mostly associated with quartzose sandstone') is classified by Nelder et al. (2017) as palustrine wetland (e.g. vegetated swamp).

The 'springs' landscape class is represented by the 'permeable rocks (rocks with predominantly primary porosity)' conceptual model (Queensland Government, 2017a) (see the protected matters technical appendix (MacFarlane et al., 2020) for further information).

4.4 Protected matters prioritisation and screening

Eleven species of national environmental significance were identified as being potentially at risk from shale gas development. These species, which are recommended for more detailed assessment as part of any future impact and risk analysis, include:

- the endangered species
  - *Amytornis dorotheae* (Carpentaria grasswren)
  - *Erythrura gouldiae* (Gouldian finch)
  - *Rostratula australis* (Australian painted-snipe)
  - *Dasyurus hallucatus* (northern quoll)
  - *Elseya lavarackorum* (gulf snapping turtle)
- the vulnerable species
  - *Erythrotriorchis radiatus* (red goshawk)
  - *Tyto novaehollandiae kimberli* (masked owl (northern))
  - *Macroderma gigas* (ghost bat)
  - *Saccolaimus saccolaimus nudicluniatus* (bare-rumped sheath-tailed bat)
  - *Acanthophis hawkei* (plains death adder)
  - *Pristis pristis* (freshwater sawfish, also known as the largetooth sawfish, river sawfish, Leichhardt's sawfish or northern sawfish).

In addition, two species identified as MSES, the purple-crowned fairy wren (*Malurus coronatus*) and the plant *Solanum carduiforme,* would also benefit from further assessment. Both species are listed as vulnerable under state legislation.

Of the ten landscape classes in the Isa GBA region, only eight intersect the area where the play fairway mapping undertaken for this assessment (Section 2.2.4) indicates shale gas plays are likely to occur. The 'hills and lowlands on granitic rocks' landscape class (and its associated regional ecosystems) does not intersect the area where shale gas play fairways are likely (see Figure 27 and Figure 28), and there is little evidence to suggest that this landscape class would be hydrologically connected to this area. Thus, the 'hills and lowlands on granitic rocks' landscape class is regarded as low priority (priority 3) within the region. Conversely, the 'tidal flats and beaches' landscape class has potential groundwater connections to the broader region and is recommended for further consideration, even though there is no areal overlap with the likely play fairway areas.

All other protected matters identified as priority 1 and priority 2 (see methods snapshot box below), including wetlands of national significance, are recommended for further assessment as part of any future impact and risk analysis.

Methods snapshot: prioritisation criteria

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

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

- species listed as endangered or critically endangered and known or expected to occur in the region
- important populations of migratory or vulnerable species that are known or expected to occur in the region
- expert opinion suggests the threatened species is likely to occur in the region
- any threatened ecological community or endangered regional ecosystem
- all listed wetlands in or downstream of the region – Ramsar-listed wetlands, nationally important wetlands, high ecological significance wetlands and high ecological value waters (wetland and watercourse) any strategic environmental areas in or downstream of the region.
- any strategic environmental areas in or downstream of the region.

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

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

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

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

4.5 Knowledge gaps

A lack of accurate records of the distribution of MNES (and MSES), particularly for threatened species and migratory species, is an important knowledge gap for the Isa GBA region. This lack of information on distribution of protected matters will be an impediment to assessing environmental impacts. Currently, several of these species are identified as ‘likely to occur’ or ‘may occur’, rather than ‘known to occur’, within the region. Resolving whether individual species occur (or did occur) within the Isa GBA region – and, if so, when and where – is necessary to identify those species that may be impacted by future shale gas development.

Another serious knowledge gap is the lack of detailed information of the ecology for many of the species identified. Information that is lacking includes habitat preferences, movement patterns and diet. This lack of knowledge may act to constrain an analysis of potential impacts of shale gas resources.

Most species not listed nationally but listed under Queensland legislation have not had known or potential threatening processes identified. This type of information is important to help understand potential environmental change to species due to shale gas development, particularly where these changes may act cumulatively with other threats. Similarly, knowledge relating to the interactions of the additional causal pathways associated with development and existing threatening processes is limited and will complicate assessment of cumulative impacts on protected matters and landscape classes.

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

5 Potential impacts of shale gas development

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

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

Potential impacts to water and the environment due to shale gas development are systematically identified to determine which impact modes should be considered in any future impact assessment and which impact modes, given the evidence base presented in this report and the technical appendices, may be ruled out or considered a minimal risk. Risks are evaluated using causal pathways – the logical chain of events that link shale gas resource development with potential impacts on water and the environment. Analysis of the three causal pathway groups – (i) landscape management; (ii) subsurface flow paths; and (iii) water and infrastructure management – is used to integrate understanding of risks to water and the environment from the potential development of shale gas resources in the Isa GBA region.

The focus for Stage 2 is on identifying potential hazards and causal pathways that may affect ecological, economic and/or social values in the Isa GBA region. This has involved a preliminary consideration of standard management and mitigation measures to control these risks. Those hazards ranked the lowest (priority 3) are not recommended for further assessment. In contrast, all other hazards would benefit from further evaluation (in some way) as part of any future impact and risk analysis undertaken in the region. Overall, this approach is precautionary, as it is expected that many of the hazards identified for further analysis will present lower risks when the available management and mitigation measures are considered more extensively in the risk assessment process.

5.1 Impact and risk assessment approach

The risk assessment approach follows the guiding principles for ecological risk assessment, with a view to meeting regulatory processes for the Isa GBA region. Stage 2 establishes the context for the impact and risk assessment, including summarising the important components and processes in the Isa GBA region and conceptualising how they work and interact. It also identifies hazards that are aggregated into a smaller set of causal pathways to represent how potential impacts may occur.

The risk assessment approach follows the principles for ecological risk assessment outlined by the US EPA (1998) and Hayes (2004) and the needs of a potential future strategic assessment for the Isa GBA region. The latter places additional emphasis on impacts that may trigger the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) approval process. At the highest level it seeks to evaluate the likelihood of adverse environmental impacts that may be attributed to development of shale gas resources in the region.

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

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

Components of the overall risk assessment process proposed for the GBA program are summarised in Figure 55. The approach for the Stage 3 impact analysis can be used to guide any future assessments of potential shale gas development in the Isa GBA region.

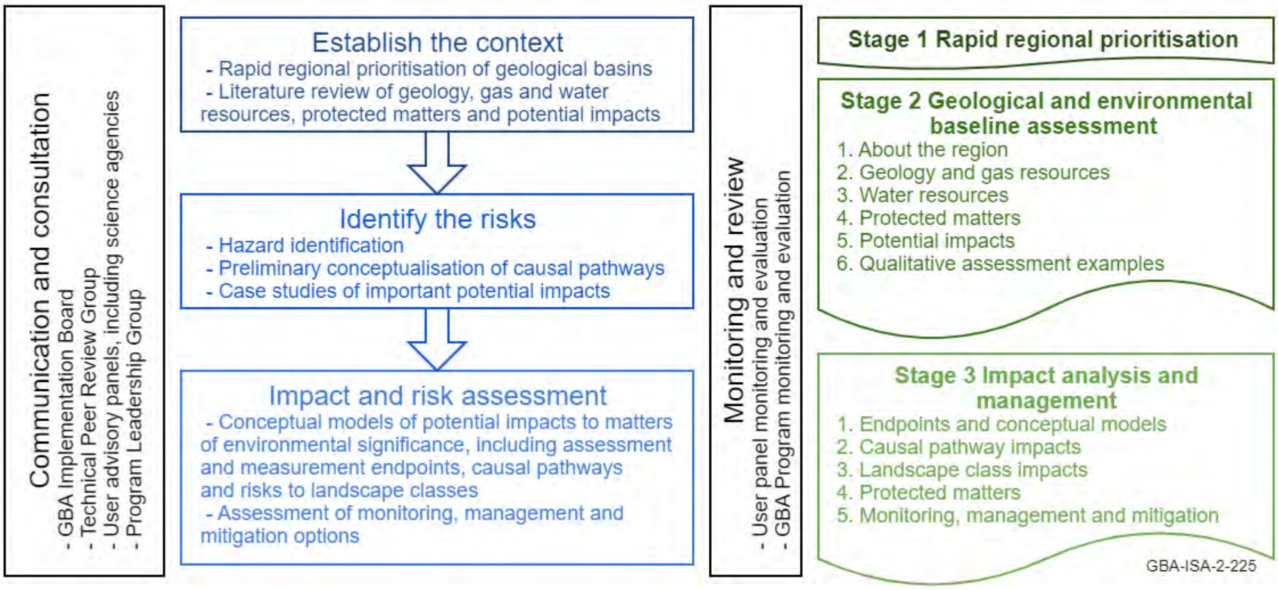

Figure 55 Impact and risk assessment approach and staged reporting structure for the Geological and Bioregional Assessment Program

Element: GBA-ISA-2-225

Section 5.2 describes a systematic hazard analysis that (i) identifies potential changes that may stem from the development of shale gas resources; (ii) aggregates individual hazards to a smaller set of causal pathways; and (iii) uses hazard scores to prioritise the causal pathways for further consideration. Section 5.3 then presents preliminary conceptual models for each causal pathway from hazards to potential impacts on landscape classes and values assessed as endpoints. *Endpoints* include *assessment endpoints* – an explicit expression of the ecological, economic and/or social values to be protected; and *measurement endpoints* – measurable characteristics related to the assessment endpoint. *Potential impacts* include changes to endpoints caused by *potential effects*, which are specific types of impacts or changes to water or the environment.

The hazard identification and preliminary conceptualisation are complemented by qualitative assessments of three risks associated with drilling and hydraulic fracturing activities (see Section 6). The evaluation of these risks in Stage 2 was prompted by their importance to government, industry and the community (e.g. as recognised by community representatives at the first meeting of the user panel in May 2018 (Geological and Bioregional Assessment Program, 2018d)). Two of the qualitative assessments focus on the causal pathways of hydraulic fracturing and compromised well integrity, whereas the third assessment is a preliminary screening of industrial chemicals used in drilling and hydraulic fracturing operations in Australia.

The causal pathways and endpoints identified in Stage 2 are key building blocks for any future impact and risk assessment in the Isa GBA region. Figure 56 emphasises the central role of causal pathways in the assessment process. These pathways connect hazards and potential effects arising from shale gas development activities, as well as considering the existing activities and key threatening processes within the region (see Section 4.1.6), to the potential impacts on the values to be protected (which are represented in the assessment by endpoints). The assessment of potential impacts on ecological, economic and/or social values represented by endpoints will be strongly influenced by the ecohydrological conceptual models and associated narrative tables that guide the expectation about causal pathways and likely impacts for each landscape class.

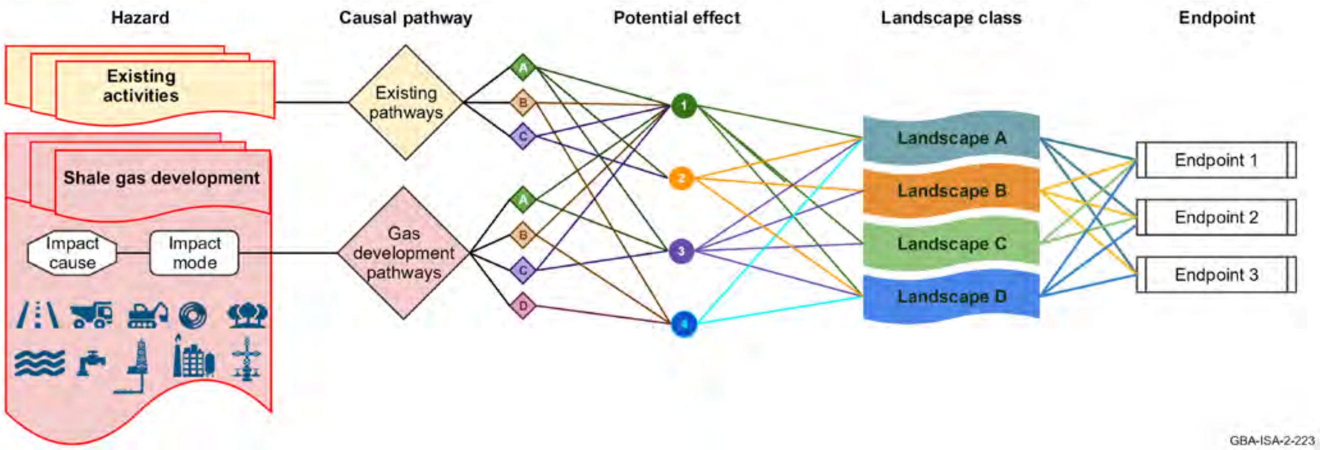

Figure 56 Overview of the impact and risk assessment approach used in the Isa GBA region, connecting hazards and potential effects from existing activities and future shale gas development through causal pathways to potential impacts on landscape classes and values assessed as endpoints

See Table 21 for explanation of terms used in this diagram.
Element: GBA-ISA-2-223

Table 21 Definition of terms commonly used in Impacts Mode and Effects Analysis

Impact Modes and Effects Analysis term	Definition
Hazard	An event, or chain of events, that might result in an effect
Impact cause	An activity (or aspect of an activity) that initiates a hazardous chain of events
Impact mode	The manner in which a hazardous chain of events (initiated by an impact cause) could result in an effect (e.g. a change in the quality or quantity of surface water or groundwater)
Causal pathway	The logical chain of events, either planned or unplanned, that link unconventional gas resource development and potential impacts on water and the environment
Potential effect	Specific types of impacts or changes to water or the environment, such as changes to the quantity and/or quality of surface water or groundwater, or to the availability of suitable habitat
Landscape class	A collection of ecosystems with characteristics that are expected to respond similarly to changes in groundwater and/or surface water due to unconventional gas resource development
Endpoint	Includes 'assessment endpoints', which are an explicit expression of the ecological, economic and/or social values to be protected; and 'measurement endpoints', which are measurable characteristics related to the assessment endpoint

Two types of endpoints are described by Suter (1990) and US EPA (2016a). 'Assessment endpoints' are defined as an explicit expression of the ecological, economic and/or social values to be protected, whereas 'measurement endpoints' are measurable characteristics related to the valued characteristic chosen as the assessment endpoint. For example, where an assessment endpoint might be the condition of the natural environment, the associated measurement endpoints could be drawn from the national fresh and marine water quality guidelines (ANZG, 2018) or established lethal concentrations of specific chemicals for individual species because of the interest in potential water quality pathways. Or, where the assessment endpoint might be the size of a population of an endemic native species, the measurement endpoint could be measures of population abundance or occurrence of that species from targeted ecological surveys.

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

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

The GBA Program also considers endpoints beyond MNES, such as those related to agriculture and water resources, in order to consider the potential impacts due to unconventional gas resources more broadly. However, potential socio-economic impacts, such as to tourism or urban environments, are beyond the scope of the Program.

Table 22 presents examples of assessment endpoints for different categories of MNES, water resources and agriculture. The approach taken here is consistent with Beckett (2019) and reduces the criteria used in the significant impact guidelines (Commonwealth of Australia, 2013a) for each category of threatened species into a single set of assessment endpoints. It then applies these endpoints to all sets of native species regardless of their listed status. These examples are intended to provide context for future impact and risk assessments of potential shale gas developments in the region.

Table 22 Examples of assessment endpoints

Ecological endpoints are derived from the significant impact guidelines (Commonwealth of Australia, 2013a) and representation by Beckett (2019). The suite of specific assessment and measurement endpoints applicable to the Isa GBA region require further consideration as part of future impact and risk assessment.

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

As part of any future impact and risk assessment it is recommended that measurement endpoints be identified as specific indicators of potential changes for all assessment endpoints. These could draw on existing literature or expert opinion and be complemented by jurisdictional input. For instance, the ecological character of the nationally important wetland Bluebush Swamp (Spain and Blackman, 1992) may be assessed through specific measurement endpoints such as the frequency of annual inflows, vegetation extent and condition, and the abundance of waterbirds during inundation events. More generally, the choice of measurement endpoints may include metrics such as the extent of habitat for an ecological community, the frequency of inundation events for a wetland, age structure of a threatened species population, measures of breeding success or the ANZG (2018) water quality guidelines for key water quality parameters or contaminants. The choice of measurement endpoints will follow the approach outlined by Suter (1990), Hayes (2004) and US EPA (2016c).

The potential for 'significant impacts' for each measurement endpoint (Table 22) will be described using thresholds to more precisely describe the aspects of tolerance, resilience and persistence of the asset to be protected, how cumulative impacts interact and the spatial and temporal scales of the response. A relevant example of this approach is available for the Cooper GBA region, one of the other areas assessed in the GBA Program (Holland et al., 2020). For the Ramsar-listed wetlands of the Coongie Lakes in SA, Butcher and Hale (2011) used limits of acceptable change to specify thresholds for indicators beyond which there may be material change to aspects of the wetlands' ecological character.

Landscape class case studies could be used to assess the relevance and importance of different causal pathways for different ecosystems identified in Section 4.3. Developing control and stressor conceptual models (e.g., Gross (2003)) for each landscape class will help to understand how causal pathways from shale gas resource development may interact with causal pathways from existing threatening processes within the region.

Protected matters (e.g. nationally listed threatened species) could be investigated further through individual asset-level assessments that consider the potential exposure of that asset to causal pathways and the impacts to the asset that may arise from that exposure.

Other components of future impact and risk analysis in the region may include:

- Identifying mitigation and management options that could be considered in an abatement plan for individual assets and that are relevant for specific causal pathways
- Developing monitoring recommendations, including design principles and possible indicators, that could validate (or invalidate) risk predictions.

5.2 Hazard identification

Hazards were systematically identified by considering all the possible ways an activity in the life cycle (Figure 58) of shale gas development may have an impact on ecological, economic and/or social values. Hazards were prioritised using the highest hazard score (severity + likelihood), which means that low-priority hazards can be 'ruled out' from further assessment. Most of the priority hazards are in the landscape management (38 out of 108) and water and infrastructure management (28 out of 92) causal pathway groups, with fewer (two out of 22) in the subsurface flow paths causal pathway group.

5.2.1 Impact Mode and Effects Analysis

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

IMEA is a 'bottom-up' hazard analysis tool. It begins with a thorough description of the overall system and its subsystems, individual components and activities. It then identifies all the possible ways in which each activity can have an impact (the *impact modes*) and assesses the severity of the impact on the ecological, economic and social values (the *endpoints*). It considers the *impact modes*, which are the manner in which a hazardous chain of events (initiated by an *impact cause*) could result in a *potential effect* (Figure 56). An *impact cause* is an activity (or aspect of an activity) that initiates a hazardous chain of events. *Potential effects* are specific types of impacts or changes to water or the environment, such as changes to the quantity and/or quality of surface water or groundwater; or to the availability of suitable habitat for a particular species. Multiple impact modes and potential effects may be associated with each activity. The range of severity and likelihood of the potential effect is scored on an interval (minimum to maximum) for each hazard. Current controls that are in place to mitigate each hazard are identified and considered in the scoring and are thus part of the hazard prioritisation. These controls, and additional mitigation or management options that may reduce the severity and/or likelihood of potential impact, need to be considered in greater detail when assessing the causal pathways. The implementation of IMEA used in the Geological and Bioregional Assessments differs from the Bioregional Assessment Program (Ford et al., 2016) in that it does not score the detectability of the impact. Detectability can be useful for weighting more highly those hazards that are harder to detect. In this context these are often subsurface hazards, which may take years to present. This was assessed as more important for the Bioregional Assessment Program given the subsurface causal pathways are typically nearer to assets at the surface for CSG and coal mining compared with deeper shale gas resources.

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

5.2.2 Typical shale gas development activities

Activities that typically occur during shale gas development have been grouped into ten major activities (Figure 57) that span five life-cycle stages (Figure 58). The ten major activities are:

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

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

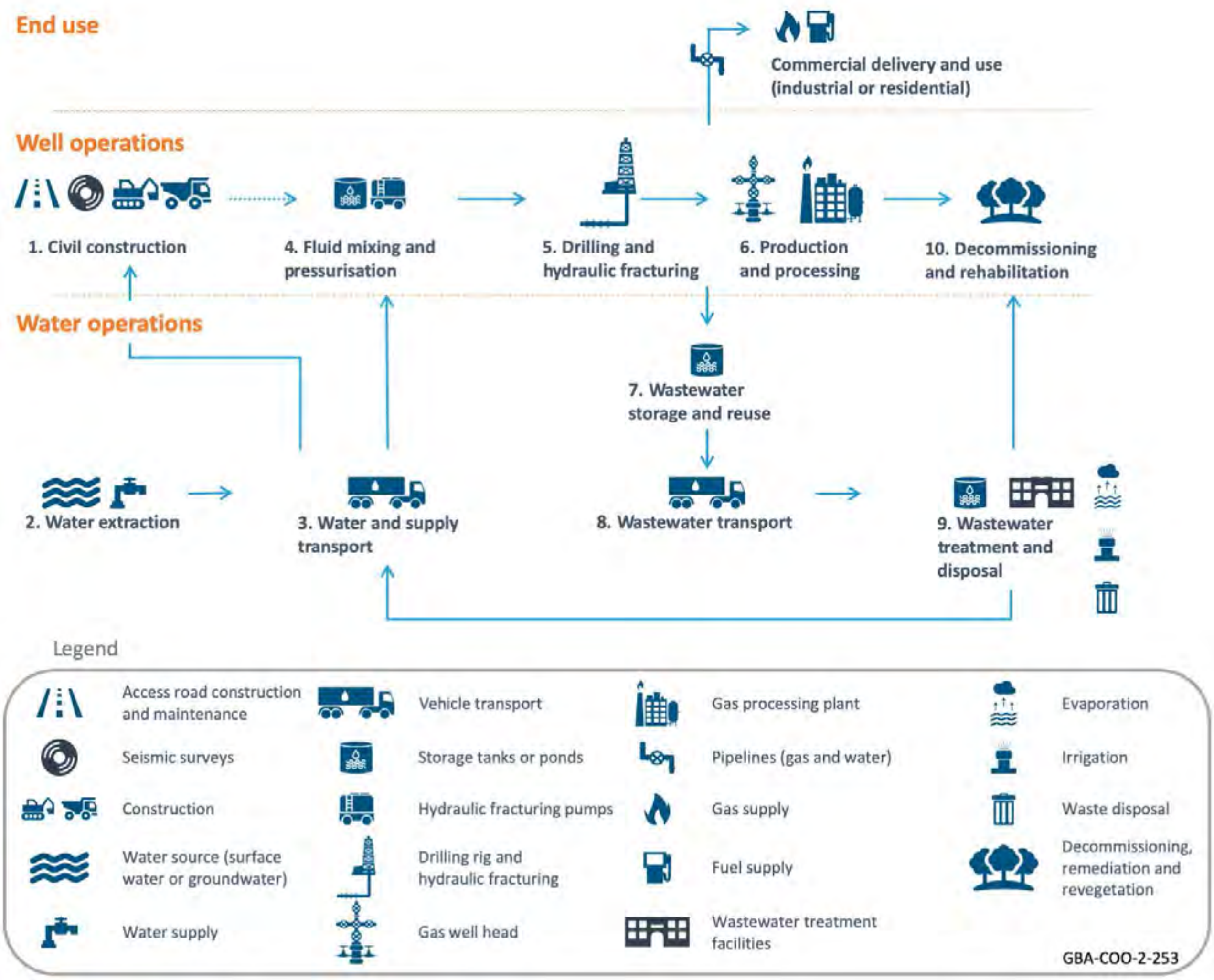

Figure 57 Ten major activities involved in typical shale gas resource development

Source: adapted from Litovitz et al. (2013)
Element: GBA-COO-2-253

Importantly, the frontier status of the Isa GBA region and the low level of previous exploration work undertaken for shale gas resources mean that many of the development activities outlined here have not yet actually been undertaken in the region. This means that the major activities described here are based on general understanding of the typical stages involved over the course of developing a shale gas resource, rather than on specific activities that may have occurred in the region. Indeed, the only life-cycle stage that has thus far occurred in the Isa GBA region is the initial exploration stage. This may mean that some of the specific hazards that have been identified here may not eventuate in future, depending upon specific design and development approaches. For example, this hazard assessment has included activities such as reinjection of wastewater into subsurface reservoirs. However, without targeted site-specific investigations to provide additional data on relevant subsurface parameters, it is unknown if this particular method of wastewater disposal is possible in the Isa GBA region.

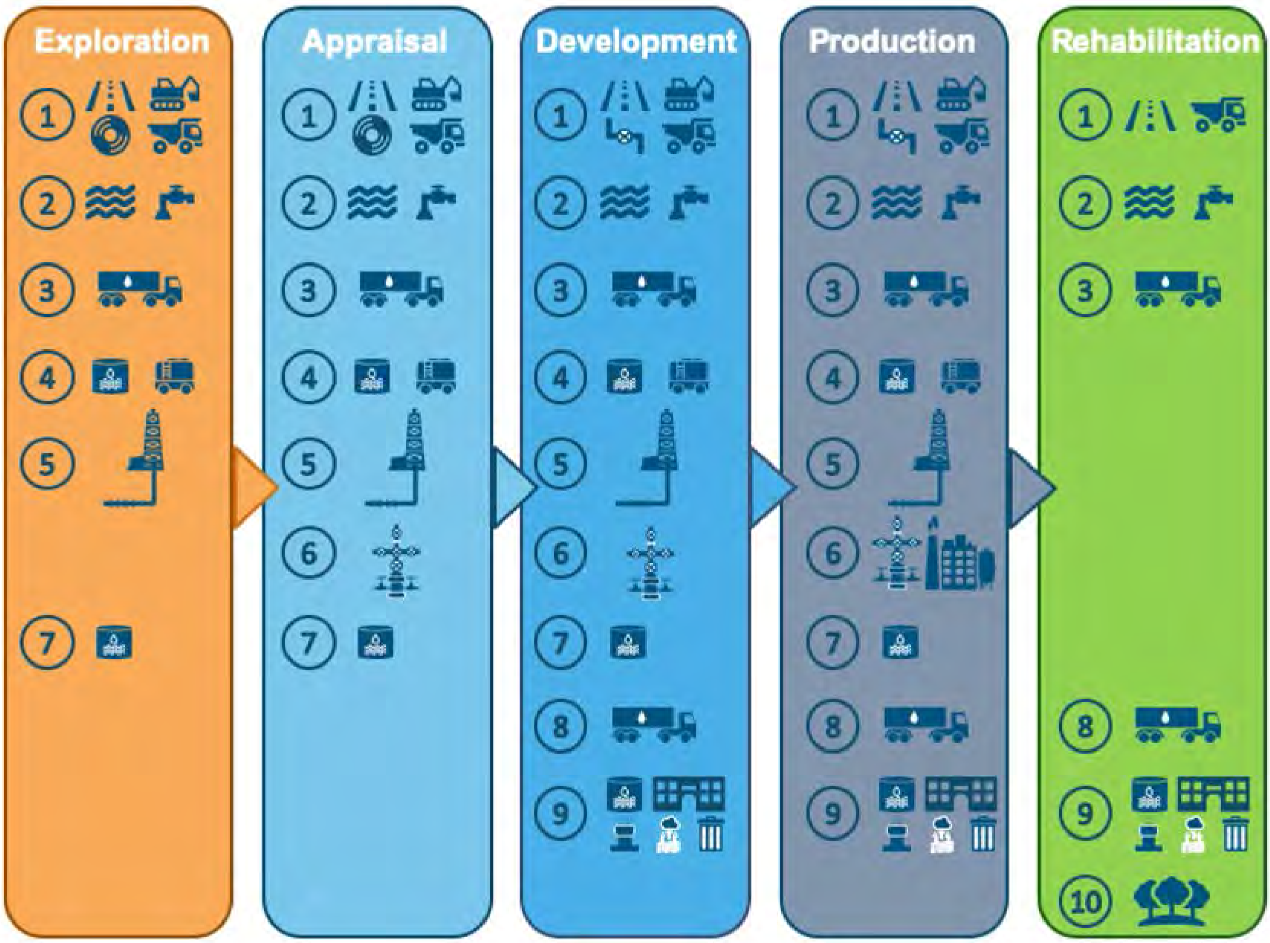

Figure 58 Life-cycle stages and major activities expected for future shale gas development in the Isa GBA region

Symbols for the ten major activities (1. Civil construction; 2. Water extraction; 3. Water and supply transport; 4. Fluid mixing and pressurisation; 5. Drilling and hydraulic fracturing; 6. Production and processing; 7. Wastewater storage and reuse; 8. Wastewater transport; 9. Wastewater treatment and disposal; and 10. Decommissioning and rehabilitation) are defined in Figure 57.
Element: GBA-ISA-2-262

1. Civil construction

Vegetation clearing and preliminary earthworks are usually early steps in the development of a shale gas resource. Construction activities focus on the development of supporting infrastructure and may include building new access roads, fire breaks, pipelines (gas and water), power lines, storage dams, surface infrastructure and well pads. Civil construction increases in intensity during the development stage and is likely to take at least several years for complete gasfield development.

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

A variety of potential hazards associated with civil construction activities are considered during the IMEA. For example, contamination of soils, surface water and/or groundwater systems may arise from disposal and storage of site materials, from reuse of extracted water onsite or due to failure of surface infrastructure when leading-practice management protocols are ineffective. Construction activities may also damage cultural heritage, increase soil erosion and reduce soil productivity when management protocols are not used effectively. Natural habitat and species distribution may be threatened due to changed air quality; bank instability and erosion near watercourses; habitat fragmentation and loss; increased mortality of native species; and contamination of soils, surface water and/or groundwater during construction and clearing activities. Access roads and vegetation clearance may make it easier to transport seeds and pest species that increase the threat of competition and predation by invasive species on native species.

2. Water extraction

Water is extracted for a variety of site operations over the course of all shale gas development life cycles, including for access road construction, well pad development, construction of enabling infrastructure (such as gas pipelines and compression stations) and site rehabilitation activities. Water is also needed to develop shale gas resources during the drilling and hydraulic fracturing of exploration, appraisal and production wells. Greater volumes of water are required for hydraulic fracturing than for drilling (e.g. 10s of ML versus 1s of ML; Huddlestone-Holmes et al. (2018)). Due to the low level of understanding that currently exists about actual water requirements needed for shale gas wells in the Isa GBA region, the hazard identification workshops assumed that approximately 15 to 20 ML of water per well (in total) may be needed for drilling and hydraulic fracturing during the exploration, appraisal and development stages. Water use will be highest in the development stage, when well drilling intensity is greatest relative to the exploration and appraisal stages. During the production stage, additional water requirements may be needed (approximately 10 ML/well) for well workovers, intervention and re-fracturing to extend gas production. Huddlestone-Holmes et al. (2018) noted that low-salinity water is preferred for drilling and hydraulic fracturing because high-salinity water may damage equipment and target formations.

As discussed in Section 3.5.3, the water required to support any future shale gas development in the Isa GBA region could potentially be sourced from surface water or groundwater. Access to either of these water resources is regulated under existing Queensland water sharing plans, although there may be potential to access available reserves to support shale gas development. Groundwater extraction for shale gas operations can affect groundwater levels or pressures and/or groundwater quality in the target aquifers. In contrast, sourcing water from surface water systems in the catchment area of the Nicholson River has the potential to affect flows and water quality and/or cause bank instability and erosion in watercourses.

3. Water and supply transport

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

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

4. Fluid mixing and pressurisation

Water and chemicals for use in drilling fluids and hydraulic fracturing are typically stored in bunded areas at the well pad before being mixed and ready for use. Hydraulic fracturing fluid comprises water, sand and other chemical additives. Risks from the likely chemical constituents of hydraulic fracturing fluids are assessed qualitatively in Section 6.3. Fluids are mixed and stored in tanks and/or ponds prior to injection into the well through an integrated system of pumps, pipes and valves. Use of drilling and hydraulic fracturing fluids is greatest during the development stage when most of the wells are drilled and hydraulic fracturing performed. Smaller volumes are needed during exploration and appraisal and during production for workover of wells or refracturing, as fewer wells are drilled and fractured at these times.

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

5. Drilling and hydraulic fracturing

As mentioned in Section 2.2, the Isa GBA region is recognised as a frontier basin for shale gas resources (as well as possible other types of petroleum systems), given the relatively low level of previous exploration and the many uncertainties around the region's shale gas development potential. Consequently, the region-specific characteristics of any future wellfield drilling and hydraulic fracturing operations remain speculative. While the total number of production wells that the Isa GBA region is capable of supporting is currently unknown, for the purposes of the hazard identification workshops it was assumed that between 300 and 400 wells could be drilled to extract shale gas resources over the next 20 to 30 years. Based on proposed shale gas wellfield designs from other places in Australia (e.g. Beetaloo Sub-basin), it is likely that multiple wells (four to eight wells) with horizontal (lateral) extensions of 500 to 3000 m into the target formation may be drilled from each 2- to 4-ha well pad. This type of layout typically maximises gas production (Huddlestone-Holmes et al., 2018), although, as previously noted, the design and development of any shale gas wellfield in the region would require substantial further exploration and appraisal work.

In the exploration and appraisal life cycles, drilling and hydraulic fracturing are focused on assessing the potential of the shale gas resources for commercialisation. Well appraisal involves drill stem tests, diagnostic fracture injection tests and reservoir parameter testing. Multiple horizontal or lateral extensions from a well are less likely during these life-cycle stages. During the production stage, new wells are sequentially drilled and hydraulically fractured to maintain gas production and maximise use of drilling and hydraulic fracturing equipment. Hydraulic fracturing is required to stimulate gas flow from the target shale formations (as the very low permeability of shales means that gas cannot otherwise be commercially extracted). Existing wells may also be worked over to improve productivity by cleaning out the well and refracturing the target formation, typically after a well has been operational for several years.

Risks associated with hydraulic fracturing (refer to Section 6.1) and compromised well integrity (refer to Section 6.2) are reviewed in more detail later in this report, in response to strong levels of community concern about these particular hazards raised at the first meeting of the Isa GBA user panel. However, it is worthwhile to note here that government and industry have a strong awareness of these risks and associated concerns; and existing regulations, management options and mitigation measures are routinely used to address them.

Dust and emissions from operation of machinery may affect natural habitat and species distribution through habitat fragmentation and loss, including through changes to air quality or noise and light pollution. Disposal and storage of site materials may contaminate soil, surface water and/or groundwater through accidental spillage or leaks and leaching from drill cuttings. Unplanned intersection or hydraulic fracture growth into faults, non-target geological layers or offset abandoned wells during drilling and hydraulic fracturing may change subsurface physical flow paths. Loss of well control and failure of well integrity (gas and fluids) may lead to soil, surface water and/or groundwater contamination and changes to air quality, groundwater composition and pressures. Changes to groundwater pressures could potentially lead to fault reactivation and induced seismicity.

6. Production and processing

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

Gas production is intensive during the production stage and tails off at an individual well as it ages. The average lifespan of a typical shale gas well in the Isa GBA region is unknown, although wells in other places commonly produce gas for ten to 15 years. Wells will typically be sequentially added during the production stage to maintain overall production rates and maximise the use and capacity of the associated infrastructure (e.g. pipelines and processing facilities). Gas produced from the small number of wells drilled during the exploration and appraisal stages is often 'flared off' during well testing for safety and operational reasons. Gas may also be vented and flared from gas processing facilities if required.

Processing and compression of gas, including flaring or venting of gas (Figure 59), can affect air quality or light and noise levels, which may alter natural habitat and species distributions. Failure of construction and operational surface infrastructure – for example, leaks from equipment or pipelines – may affect air quality. Natural hazards, such as bushfires or cyclones, may increase soil erosion if control measures are inadequate during this stage of development (as this is typically the longest life-cycle stage, there is greater potential that it will be affected by natural hazards). Unconventional gas extraction may alter deep groundwater quality and pressures, which can lead to subsidence of land surface, fault reactivation and induced seismicity (although such effects are typically minor and spatially restricted due to the depths that shale gas is typically extracted from, i.e. commonly greater than 2 to 3 km below surface).

7. Wastewater storage and reuse

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

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

Storage of water in dams may unintentionally affect water availability and water quality of habitat for waterbirds and other species (both natives and invasives). Soil, surface water and/or groundwater contamination may arise from leaks, spills or overflows due to integrity failure or uncontrolled releases during high rainfall events associated with cyclones.

Figure 59 Flaring gas from exploration well Egilabria 2DW1 in the Isa GBA region, October 2014

Source: Armour Energy Ltd
Element: GBA-ISA-2-254

8. Wastewater transport

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

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

9. Wastewater treatment and disposal

Disposal of treated wastewater from drilling and hydraulic fracturing operations is carefully managed and governed by state regulations (see Section 1.6.2). Water may need to be treated to remove certain contaminants or reduce their concentrations to acceptable levels before it can be disposed of from an onsite treatment facility. Disposal options are varied and may include discharge to surface waters under suitable hydrological conditions, reinjection into groundwaters in ways that do not affect the beneficial uses of that groundwater, and evaporation from storage ponds.

Treatment of shale gas wastewater may result in the formation of residual salt-rich brines. The actual concentration and composition of salts in these brines will depend on the characteristics of the flowback water and whatever treatment processes are applied. Current Queensland Government policy requires that saline brines (e.g. produced from CSG operations) are managed so that the brine is treated to create useable products or, if this is not feasible, to dispose of the brine according to strict standards that protect the environment (Department of Environment and Heritage Protection (Qld), 2012).

The disposal of treated water typically peaks during drilling and hydraulic fracturing in the development stage given the large increase in the number of wells coming into operation at that time. Treated water disposal also occurs during other operational stages (e.g. during the production stage as new wells are drilled to maintain production rates), although the volumes involved are substantially less during the exploration and appraisal stages.

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

10. Decommissioning and rehabilitation

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

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

5.2.3 Hazard workshops and consultation

Systematically identifying and scoring the hazards associated with possible future development of a shale gas industry in the Isa GBA region involved a combination of technical workshops and consultation with government, industry and the community. The hazard identification process also leveraged the results of the earlier hazard analysis work done for the Cooper GBA region, which provided a consistent Program-wide framework for hazard evaluation (Holland et al., 2020). A total of 222 individual hazards were identified and scored for the Isa GBA region, resulting in a relative ranking of all plausible hazards considered across future shale gas life-cycle stages. The IMEA assumes that relevant control measures, such as standard Australian gas industry operating procedures and regulatory requirements, are met for all activities and life-cycle stages.

The hazard process for the Isa GBA region commenced with an internal workshop comprising staff from CSIRO, Geoscience Australia and the Department of the Environment and Energy. Based on the results from the hazard analysis for the Cooper GBA region, the workshop participants systematically considered individual activities associated with each life-cycle stage and all plausible pathways to impact and the associated effects. Any region-specific differences between the Cooper and Isa GBA regions were also evaluated as part of this process. Following the initial workshop, further consultation was undertaken with experts from industry and the Queensland Government to gain further insight into the potential hazards and to identify and score any hazards that were not initially considered.

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

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

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

The key output from the hazard analysis process is the hazard identification dataset for the Isa GBA region (Geological and Bioregional Assessment Program, 2019b). This dataset describes each individual hazard through the combination of the activity (and the major life-cycle stage of the activity), impact cause, impact mode, potential effect and current controls; and also provides the lower and upper estimates for severity, likelihood and hazard score.

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

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

Source: Geological and Bioregional Assessment Program (2019b)

5.2.4 Prioritising hazards and developing causal pathways

Methods snapshot: developing and prioritising causal pathways

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

> Causal pathways were prioritised for any further analyses in the Isa GBA region where the upper estimate (i.e. highest hazard score (severity + likelihood)) was at least medium or high. This means that future analysis can focus on higher priority hazards and that low priority hazards can be 'ruled out' from further assessment.

Identifying and ranking the potential hazards associated with shale gas development provides the basis for further assessing *causal pathways* (Section 5.3) – that is, the chain of events that may link future gas development activities in the Isa GBA region with potential impacts on water and the environment, such as protected environmental matters. More detailed assessment of the priority hazards and their associated causal pathways is recommended as part of any future impact and risk analysis in the Isa GBA region. However, Section 6 provides a preliminary qualitative assessment of two pathways of particular community concern (hydraulic fracturing and compromised well integrity), as well as an initial screening of chemicals that may be used during drilling and hydraulic fracturing operations. The distribution of the 222 hazards (Figure 60) scored for the Isa GBA region (Geological and Bioregional Assessment Program, 2019b) shows that there are three priority classes of hazards:

- Priority 1 – the upper 30% (approximate) of ranked hazards have scores of 4.5 or greater. Due to their relatively high scores these 68 hazards are recommended as the main focus for further impact assessment of any future shale gas developments that may occur in the Isa GBA region.
- Priority 3 – the lower 30% (approximate) of all hazards have scores of 3 or less. Given their relatively low ranking (which reflects indicative environmental impacts ranging from 'none' to 'tiny', and recurrence likelihoods of 'extremely rare' to 'very unlikely'; see Table 23 for details), these 61 hazards are effectively 'ruled out' from further assessment.
- Priority 2 – the mid-tier comprises the remaining 40% (approximate) of hazards, with scores of either 3.5 or 4. Depending on the operational constraints of any future impact and risk analysis for the Isa GBA region, it is recommended that at least some of these 93 hazards are further assessed, particularly if other lines of evidence (e.g. heightened community concerns or available national or international scientific literature) indicate that they cannot be 'ruled out' solely on the basis of the IMEA.

The priority 1 hazards include activities where *severity* of the potential effect is 'moderate' or 'major' indicating significant, widespread impacts that are reversible in ten or more years and *likelihood* is rare or extremely rare (less than one event per 100 years) or where likelihood of 'tiny' or 'minimal' impacts is 'likely' to 'most certain' (more than one event per year). Examples of some priority 1 hazards and their associated causal pathways (and causal pathway groups) are listed in Table 24, using the combination of activity, impact mode and potential effect to define the hazard.

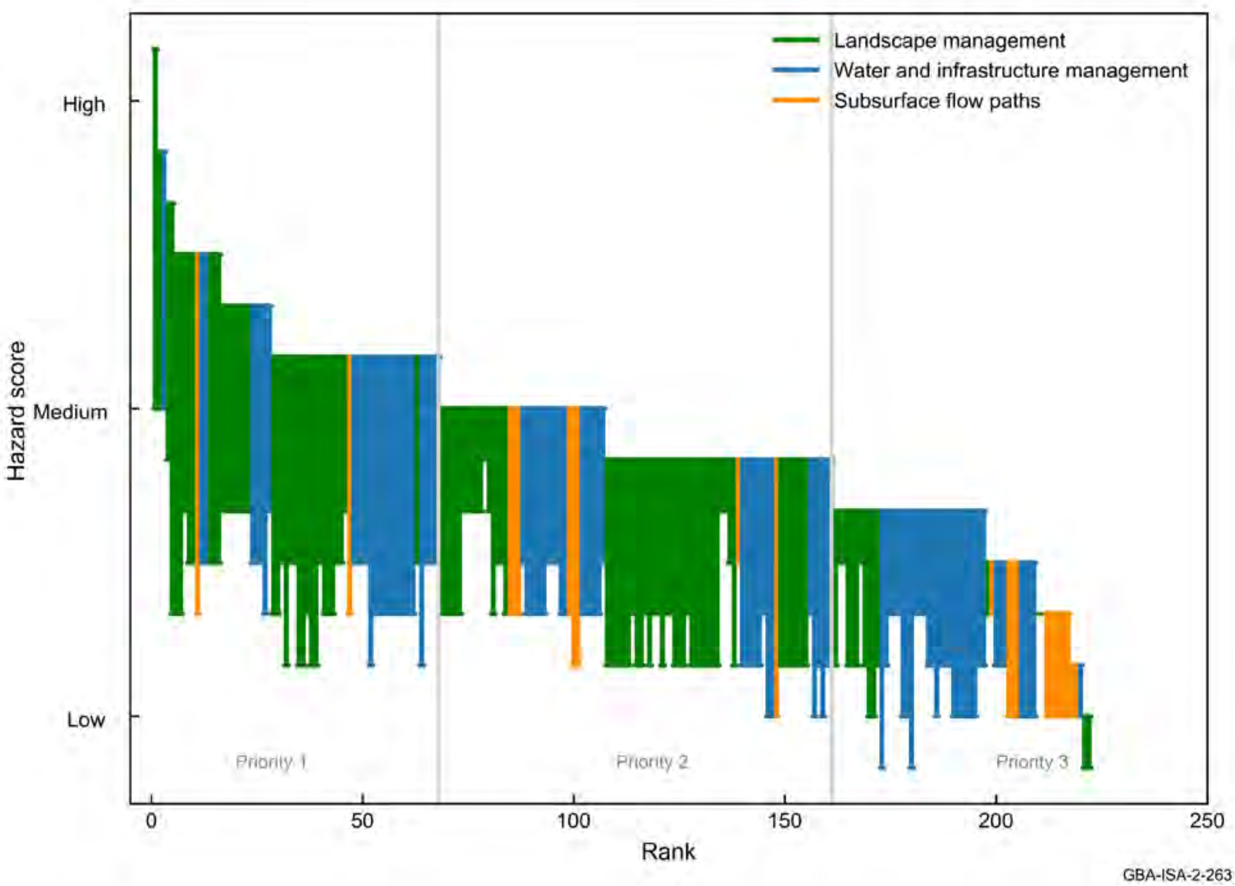

Figure 60 Upper and lower hazard scores for all hazards associated with potential shale gas development in the Isa GBA region, categorised by causal pathway groups

Further information about the three causal pathway groups (landscape management, water and infrastructure management and subsurface flow paths) is in Section 5.3.
Hazard score = severity score + likelihood score
Source: IMEA dataset (Geological and Bioregional Assessment Program, 2019b)
Element: GBA-ISA-2-263

Table 24 Examples of priority 1 hazards for the Isa GBA region

The individual priority 1 hazards shown here are defined by the combination of activity, impact mode and potential effect. Other information, such as impact cause and current controls, is listed in the impact modes and effects analysis dataset.

Activity	Impact mode	Potential effect	Causal pathway	Causal pathway group
Pipeline construction	Site vegetation removal	Habitat fragmentation and loss	Altering natural habitat and species distributions	Landscape management
Access road construction and maintenance	Transport of seeds and pest species	Increased competition and predation	Introduction of invasive species	Landscape management
Surface infrastructure construction	Site vegetation removal	Cultural heritage damage or loss	Altering cultural heritage	Landscape management
Subsurface fluid production	Migration of fluids between different geological layers	Changed groundwater quality	Compromised well integrity	Subsurface flow paths
Plug and abandon wells	Failure of well integrity after well decommissioning	Changed groundwater quality	Compromised well integrity	Subsurface flow paths
Well pad construction	Spill or leak from machinery	Soil, groundwater and/or surface water contamination	Failure of surface infrastructure	Water and infrastructure management
Drilling and well construction	Disposal and storage of drilling muds and well construction materials	Soil, groundwater and/or surface water contamination	Disposal and storage of site materials	Water and infrastructure management
Flowback water treatment and disposal	Discharge of treated water to surface waters	Changed surface water flows	Altering surface hydrology	Water and infrastructure management

Source: Geological and Bioregional Assessment Program (2019b)

5.3 Causal pathways

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

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

The priority 1 hazards in the water and infrastructure management causal pathway group occur when management protocols, techniques and practices are not effective; or as a consequence of natural hazards. Potential effects include contamination of soil, groundwater and/or surface water; changes to groundwater levels, pressures or quality; and changes to surface water flows or quality.

The information compiled during the hazard analysis process has been used to develop and define a set of *causal pathways*, which represent the logical chain of events – either planned or unplanned – that may link shale gas development activities with potential impacts on water and the environment (Figure 56). There are 14 individual causal pathways, which have been aggregated into three main causal pathway groups (as shown in Figure 61 and described in Table 25):

- landscape management
- subsurface flow paths
- water and infrastructure management.

Each of the 222 hazards identified for the Isa GBA region has been assigned to one of the 14 causal pathways. The remainder of this section provides a description of these causal pathways and outlines their main potential effects and impact modes. A preliminary conceptual model for each pathway illustrates the current knowledge base, showing how potential impacts may link to landscape classes and assessment endpoints. These conceptualisations provide a framework for subsequent and more detailed assessments that may occur in the future.

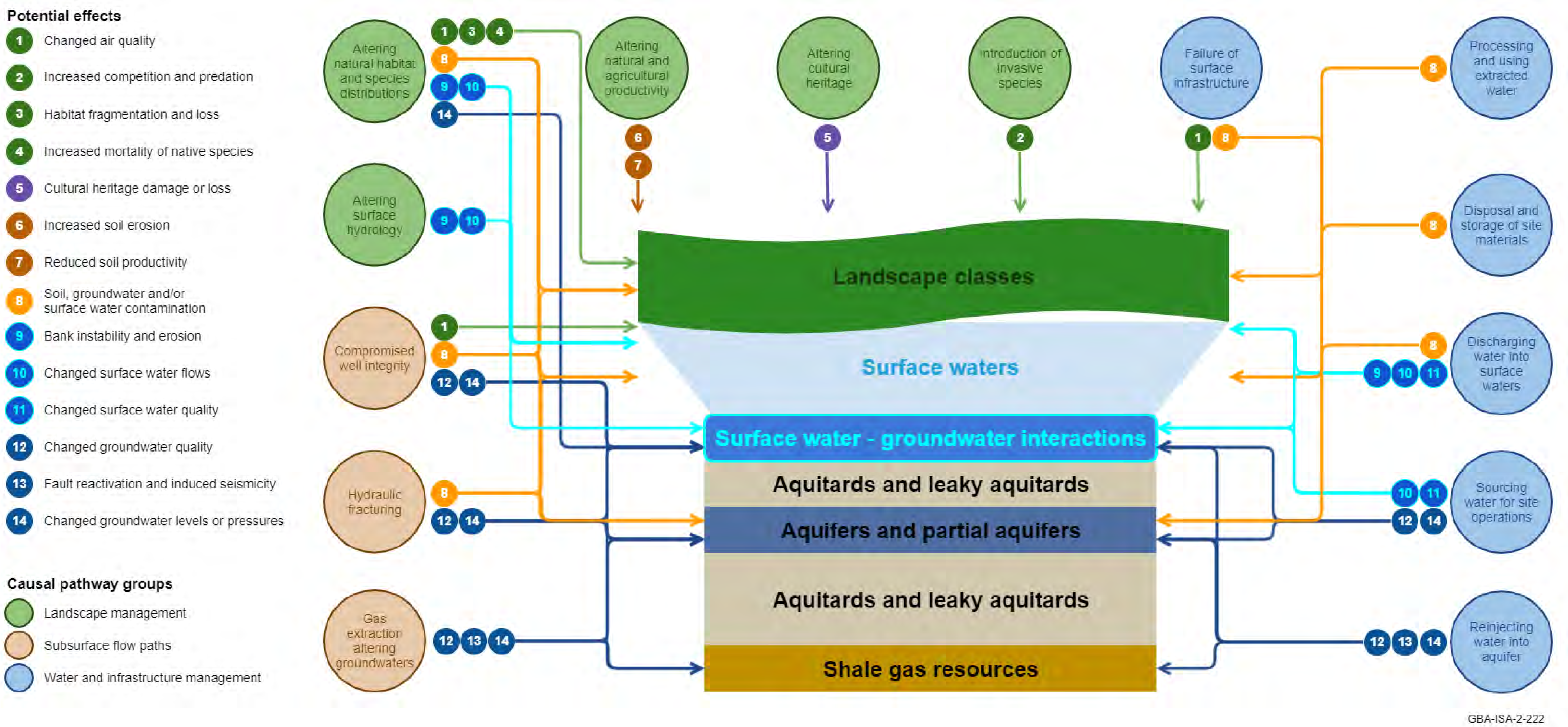

Figure 61 Causal pathways, causal pathway groups and potential effects associated with potential future shale gas development in the Isa GBA region

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

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

Element: GBA-ISA-2-222

Table 25 Description of potential effects and related site management procedures for hazards grouped by causal pathway and causal pathway group

Causal pathway group	Causal pathway	Examples of potential effects and site management procedures for causal pathways
Landscape management • 38 priority 1 hazards • 54 priority 2 hazards • 16 priority 3 hazards • (n=108 hazards)	**Altering cultural heritage** • 5 priority 1 hazards • 2 priority 2 hazards • (n=7 hazards)	Construction of access roads and surface infrastructure may diminish cultural values through alteration, damage, disturbance, removal or restriction of use of cultural artefacts, ceremonial objects, rock art and cultural values. Cultural heritage clearances, training and site-based protocols manage potential impacts to cultural heritage.
	Altering natural and agricultural productivity • 1 priority 1 hazard • 14 priority 2 hazards • 5 priority 3 hazards • (n=20 hazards)	Construction and rehabilitation of access roads, seismic surveys, surface infrastructure and well pads can cause increased soil erosion, reduced soil productivity and changed vegetation composition. Site management protocols aim to avoid sensitive areas (such as slopes, sensitive vegetation and fragile landscapes), minimise extent and timing of vegetation disturbance and earthworks and use progressive clearing and reinstatement practices to restore natural topsoil, contours and seedstock during rehabilitation.
	Altering natural habitat and species distributions • 22 priority 1 hazards • 27 priority 2 hazards • 8 priority 3 hazards (n=57 hazards)	Changed air quality, groundwater levels or pressures; surface water flows; soil erosion; habitat fragmentation and loss; increased mortality of native species (and/or possible chronic effects on their growth and reproduction); and exposure to soil, groundwater and/or surface water contamination can affect natural habitat and species distributions. Habitat fragmentation and loss can arise through direct impacts, such as alteration of natural fire regimes, excavation and site vegetation removal; and by indirect impacts, such as light and noise impacts on fauna. Invasive plants may displace or reduce native vegetation and consequently alter natural habitat. Mortality of native species can arise by entrapment, increased road mortality and changes to vegetation, groundwaters and surface waterbodies. Site management protocols aim to avoid, minimise or mitigate potential impacts on natural habitat and species distributions.
	Altering surface hydrology • 5 priority 1 hazards • 4 priority 2 hazards • 3 priority 3 hazards (n=12 hazards)	Civil construction, rehabilitation and surface water extraction can alter the topography of the landscape, as well as the distribution of vegetation, which can change surface water flows and potentially cause bank instability and erosion. Surface water extraction can alter the magnitude, timing and duration of surface water flows. Water sharing plans regulate access and provide an upper limit for surface water use. Subsurface fluid production and groundwater extraction can cause subsidence of land surface, creating artificial topographic lows where surface water may pool, altering surface water flows.
	Introduction of invasive species • 5 priority 1 hazards • 7 priority 2 hazards (n=12 hazards)	Construction of access roads and surface infrastructure can increase competition and predation on native species by invasive species. Invasive plants may displace or reduce cover of native vegetation, thereby reducing available habitat and food sources (e.g. seeds) for native species such as some threatened birds. Dispersal associated with vehicle transport, landscape modification and ecosystem disturbance are managed by site-based conditions and rules. Other dispersal mechanisms associated with agricultural activities, stock movements and natural methods (via wind, water and dispersal activities by fauna) are managed by Commonwealth, state and local government regulations.

Causal pathway group	Causal pathway	Examples of potential effects and site management procedures for causal pathways
Subsurface flow paths • 2 priority 1 hazards • 8 priority 2 hazards • 12 priority 3 hazards • (n=22 hazards)	**Compromised well integrity** • 2 priority 1 hazards • 4 priority 2 hazards • 5 priority 3 hazards • (n=11 hazards)	Failure of well barriers may create a direct fluid pathway between the target formation and overlying aquifers, the surface, or between non-target formations. Well barriers may be compromised by exposure to high fluid pressure, mechanical stresses, poor well construction, degradation of the cement or steel casing or thermal cycling. Changes to air quality and groundwater composition, levels or pressures; and soil, groundwater and/or surface water contamination may arise from compromised well integrity. After well decommissioning, abandoned wells may act as preferential pathways for fluid movement between geological layers. Multiple well barriers ensure that control of the well is maintained during all life-cycle stages.
	Gas extraction altering groundwaters • 1 priority 2 hazard • 2 priority 3 hazards • (n=3 hazards)	Subsurface fluid production and migration may change groundwater composition, levels or pressures and may cause fault reactivation and induced seismicity due to pressure changes in the target formation. Unlike conventional oil and gas production, the shale formations in the Isa GBA region are unlikely to yield large volumes of produced water. These target formations are 'gas-charged' units, as the high pressure of the gas in the target formations has expelled much of the groundwater. In addition, water sharing plans regulate access and provide an upper limit for water use.
	Hydraulic fracturing • 3 Priority 2 hazards • 5 Priority 3 hazards • (n=8 hazards)	Hydraulic fracturing increases the productivity of shale gas wells by propagating hydraulic fractures that increase the effective permeability of the reservoir. Potential impacts that may arise following hydraulic fracturing include changed groundwater levels or pressures and groundwater composition, as well as fault reactivation and induced seismicity due to pressure changes. Potential impacts may arise from unplanned fracture growth into non-target geological layers, faults or wells that have higher permeability than the natural geological layers. Potential impacts are managed to a suitably low level by regulatory controls, sufficient understanding of the baseline geological and environmental systems, and acceptable industry practices.
Water and infrastructure management • 28 priority 1 hazards • 31 priority 2 hazards • 33 priority 3 hazards • (n=92 hazards)	**Discharging water into surface waters** • 7 priority 1 hazards • 2 priority 2 hazards • 1 priority 3 hazard • (n=10 hazards)	Storage of flowback and produced water in ponds before discharge to surface waters may change water quality and flows, leading to bank instability, erosion and contamination of soil, groundwater and/or surface waters. Discharge into surface water is a regulated activity governed by specific conditions and rules. The Queensland wastewater management hierarchy means that, after treatment, beneficial reuse of wastewater is preferred, then discharge to a watercourse or evaporation. Discharge of treated water into surface waters can be used to water stock or manage surface water flows. However, discharge to a watercourse can interfere with aquatic ecosystems by altering natural flow regimes (e.g. change ephemeral streams into perennial streams) or changing nutrient dynamics.
	Disposal and storage of site materials • 2 priority 1 hazards • 10 priority 2 hazards • 9 priority 3 hazards • (n=21 hazards)	Soil, groundwater and/or surface water contamination may arise from disposal and storage of materials during construction, drilling and hydraulic fracturing, decommissioning, rehabilitation, vehicle transport, waste disposal and wastewater treatment. Potential spills from storage areas are contained by bunding and hardstand within designated facilities. Typical wastes include cement, contaminated soils, drill cuttings, drilling and hydraulic fracturing chemicals, fluids, fertilisers and herbicides used for rehabilitation, sand, and evaporated waste from water treatment facilities, including biosolids, brines and sludge. Disposal and storage of site materials is a regulated activity governed by specific conditions and rules, particularly for waste that is stored onsite or taken offsite for disposal in an approved facility.

Causal pathway group	Causal pathway	Examples of potential effects and site management procedures for causal pathways
	Failure of surface infrastructure • 13 priority 1 hazards • 7 priority 2 hazards • 10 priority 3 hazards • (n=30 hazards)	Leaks, spills or overflow from surface infrastructure during construction, drilling and hydraulic fracturing, natural hazards such as cyclones or bushfires, water management and rehabilitation can affect air quality and lead to soil, groundwater and/or surface water contamination. Ponds, tanks and pipelines are designed and managed to maintain integrity and operability. Management protocols include leak detection, corrosion mitigation, overpressure protection and fencing to exclude native fauna and livestock. Leaks, spills or overflow from surface infrastructure are regulated activities governed by specific conditions and rules. However, unregulated releases can occur – for example, due to extreme flood inundation, natural hazards or failure of storage dams.
	Processing and using extracted water • 1 priority 1 hazard • 7 priority 2 hazards • (n=8 hazards)	Reuse of extracted water can lead to soil, groundwater and/or surface water contamination. Beneficial or productive reuse of water is a regulated activity that aims to protect the environment and maximise the productive use of water. Reused water must meet relevant water quality guidelines for the end use and receiving environment. Potential beneficial reuse options include aquaculture, construction, dust suppression, industrial and manufacturing operations, landscaping and revegetation, and stock and domestic water supplies.
	Reinjecting water into aquifer • 1 priority 1 hazard • 3 priority 2 hazards • 6 priority 3 hazards • (n=10 hazards)	Reinjection of water into aquifers or deep reservoirs can be used to dispose of treated waste water (along with beneficial reuse, discharge to surface water and evaporation). Reinjection may change groundwater composition, groundwater levels or pressures and can potentially reactivate faults, leading to induced seismicity. Reinjected water is initially treated to remove solids. Biocide dosing and other chemical treatments then ensure the water is of similar quality to that of the target formation to minimise the potential for degradation of reservoir conditions.
	Sourcing water for site operations • 4 priority 1 hazards • 2 priority 2 hazards • 7 priority 3 hazards • (n=13 hazards)	Water is extracted from surface water and groundwaters for onsite operations, which may change groundwater composition, groundwater levels or pressures, surface water flows and surface water quality. Existing water sharing plans regulate access and provide an upper limit on water use. 'Make good' provisions apply for interference with existing users and the environment.

Source: hazard identification dataset (Geological and Bioregional Assessment Program, 2019c)

5.3.1 Landscape management causal pathways

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

- altering natural habitat and species distributions (57 hazards)
- altering natural and agricultural productivity (20 hazards)
- altering surface hydrology (12 hazards)
- introduction of invasive species (12 hazards)
- altering cultural heritage (seven hazards).

The individual hazards and potential effects associated with these causal pathways in the Isa GBA region are illustrated conceptually in Figure 62. Each causal pathway includes a range of different impact modes and potential effects identified through the IMEA process, most of which are focused on impacts at the land surface, such as habitat fragmentation and loss, increased competition and predation from invasive species, changed surface water flows and increased mortality (and/or possible chronic effects on growth and reproduction) of native species.

Priority 1 hazards are identified in all five causal pathways, although most are in the 'altering natural habitat and species distributions' causal pathway:

- altering natural habitat and species distributions (22 priority 1 hazards out of 57 hazards)
- altering cultural heritage (five priority 1 hazards out of seven hazards)
- altering surface hydrology (five priority 1 hazards out of 12 hazards)
- introduction of invasive species (five priority 1 hazards out of 12 hazards)
- altering natural and agricultural productivity (five priority 1 hazard out of 20 hazards).

Potential effects associated with priority 1 hazards are:

- habitat fragmentation and loss (12 out of 25 hazards)
- changed surface water flows (eight out of 13 hazards)
- cultural heritage damage or loss (five out of seven hazards)
- increased competition and predation (five out of 12 hazards)
- increased mortality (and/or possible chronic effects on growth and reproduction) of native species (five out of 14 hazards)
- soil, groundwater and/or surface water contamination (one out of two hazards)
- increased soil erosion (one out of ten hazards).

These hazards arise when current leading-practice design, construction and management protocols, techniques and practices are not effective or properly implemented. Potential effects that are not associated with priority 1 hazards in the 'landscape management' causal pathway group include bank instability and erosion, changed air quality, changed groundwater levels or pressures, and reduced soil productivity.

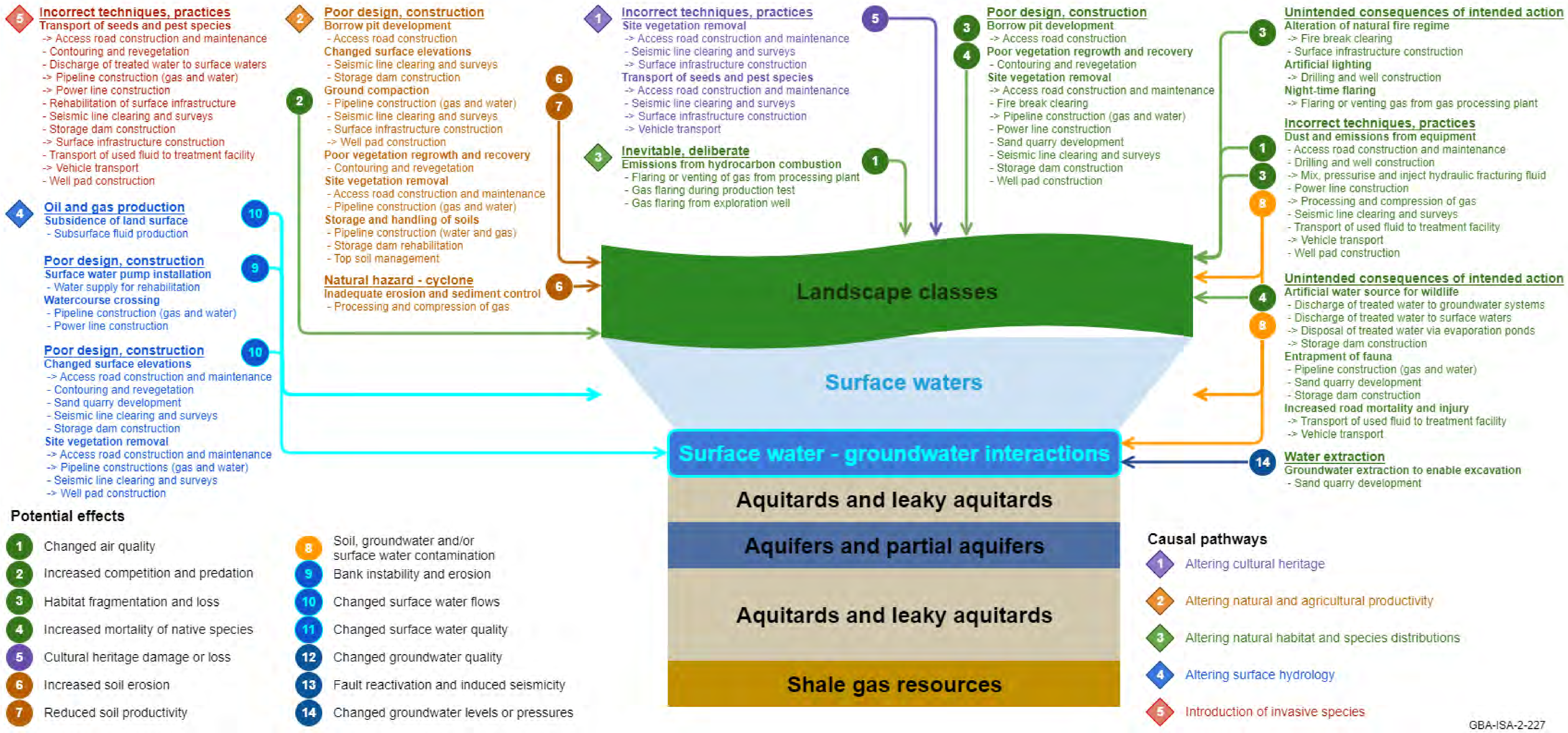

Figure 62 Hazards (impact causes, impact modes and activities) and associated effects in the 'landscape management' causal pathway group identified for potential future shale gas development in the Isa GBA region

Impact causes are underlined, impact modes are bold, and activities are bullet points (low-priority hazards = '-'; and priority hazards = '->'). An individual activity may lead to more than one hazard if there are multiple potential effects associated with it. Arrows show how the individual hazards interact with key components: aquifers and partial aquifers, aquitards and partial aquitards, landscapes, shale gas resources, surface water – groundwater interactions and surface waters. Causal pathways are identified by number and text colour. This figure has been optimised for printing on A3 paper (297 mm x 420 mm).
Typology and punctuation are consistent with the hazard identification dataset (Geological and Bioregional Assessment Program, 2019c).
Element: GBA-ISA-2-227

5.3.1.1 Altering cultural heritage

Cultural heritage sites can be physically, socially and spiritually linked to ecologically significant areas and archaeological or historic sites. Risks to cultural heritage in the Isa GBA region are related to changes to water resources, vegetation and wildlife values that have strong connections with cultural traditions. Traditional Owners value their country and have good knowledge of ecosystem function, particularly the links between landscapes, water, vegetation and wildlife. Damage or loss of cultural heritage may permanently diminish cultural values for a community or group. Many waterholes, springs and streams have spiritual values, with some sites attached to creation stories. Traditional Owners are concerned about damage to sacred sites that may restrict or inhibit use as a cultural or ceremonial site. This includes waterholes associated with customary rituals, such as women's business and historic burial sites (Constable et al., 2015).

Risks to cultural heritage values in the Isa GBA region include potential changes to water resources, such as erosion of waterholes from release of treated water, or shrinkage of waterholes from water extraction (surface water and groundwater). Depending on the source aquifer for the springs within the region (which is currently uncertain), there may be potential effects to springs caused by future shale gas operations such as drilling, hydraulic fracturing and gas production. Development of roads and surface infrastructure can potentially affect vegetation (Figure 63), including food and medicinal plants, as well as natural habitat and species distributions. Site vegetation removal that causes minor to moderate damage or loss to cultural heritage (reversible in ten years or less) was recognised as a priority concern in the Isa GBA region from the IMEA. Changes to cultural heritage can affect food supply and cultural connectedness of Traditional Owners. Introduction of invasive weeds and pests, as well as activities that may enhance or promote invasive species that already occur in an area, could also upset the natural balance, potentially affecting cultural values. Incorrect techniques or practices used during construction activities may remove, damage or substantially disturb cultural artefacts, archaeological deposits, Indigenous built structures or ceremonial objects. This may include resource areas, paintings, engravings, scar trees, quarries, shell middens, dwellings, burial sites, artefact scatters, stone arrangements, pathways and important story places (Constable et al., 2015).

Mitigation measures include awareness and avoidance of culturally significant areas. Cultural heritage consultation and clearances, along with training to recognise culturally sensitive areas, are part of existing site-based management protocols.

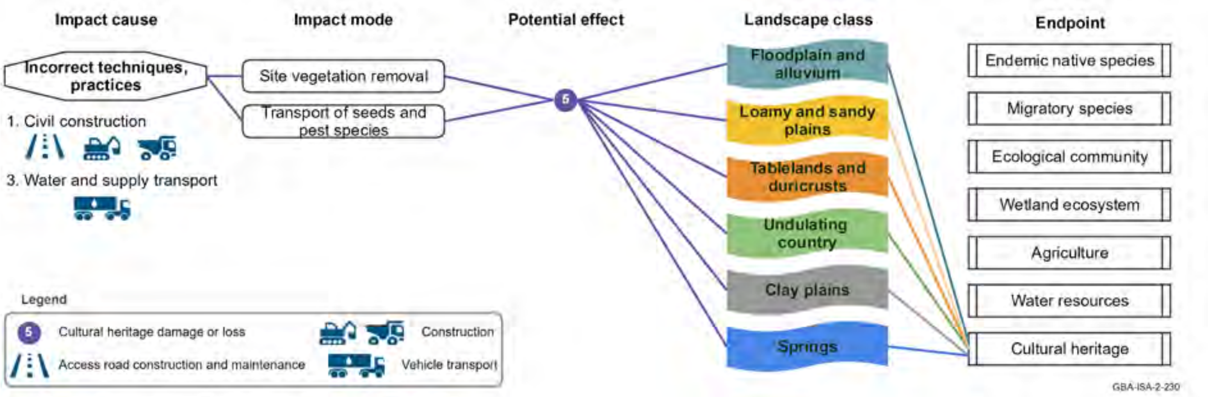

Figure 63 Preliminary conceptualisation of hazards associated with potential future shale gas development in the Isa GBA region for the 'altering cultural heritage' causal pathway

To simplify this diagram, the landscape class 'undulating country' is a combination of three similar classes in the Isa GBA region that collectively comprise less than 5% of the area and occur only in the far west of the region. These are 'hills and lowlands on metamorphic rocks', 'undulating country on fine-grained sedimentary rocks' and 'sandstone ranges'. Similarly, the landscape classes 'tidal flats and beaches' and 'hills and lowlands on granitic rocks' are not shown, as they each comprise less than 0.5% of the region.
The numbered item under 'impact cause' refers to the major activities identified in Figure 56.
Element: GBA-ISA-2-230

5.3.1.2 Altering natural and agricultural productivity

Risks to natural and agricultural productivity in the Isa GBA region include increased soil erosion and reduced soil productivity (Figure 64). Increased soil erosion is most likely to occur during heavy rainfall events (e.g. associated with severe low pressure or cyclonic weather systems during the wet season). Soil erosion is caused by disturbance to the soil structure by natural or mechanical means (e.g. during civil construction activities), which enhances the removal of rocks and soil particles during heavy rainfall and may affect natural landforms. Poor design and construction of access roads, gravel pits, pipelines (gas and water), seismic surveys, surface infrastructure and well pads can alter drainage pathways, increase soil erosion and reduce soil productivity. Increased soil erosion due to ground compaction during well pad construction is a priority 2 hazard.

Changes to surface elevations, site vegetation removal, poor top soil management and ground compaction from earthmoving equipment can reduce soil productivity in nutrient-poor environments. These impacts can reduce regrowth and recovery during the re-establishment of native flora in the rehabilitation life-cycle stage. Changes to surface water flows, waterhole depths and extents, and water quality from various development activities can also affect natural and agricultural productivity through change in soil moisture (too much or too little) and loss of surface water connectivity. Removing nutrients and/or enhancing soil salinity due to soil erosion, introduction and facilitation of invasive species impacting natural ecosystem productivity and changes to soil structure can also alter agricultural productivity.

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

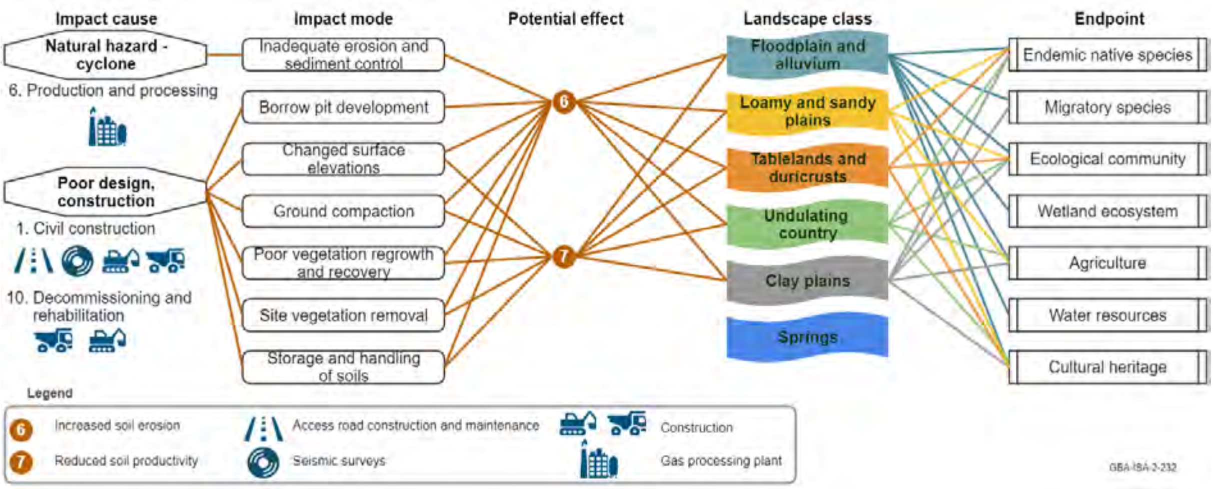

Figure 64 Preliminary conceptualisation of hazards associated with potential future shale gas development in the Isa GBA region in the 'altering natural and agricultural productivity' causal pathway

To simplify this diagram, the landscape class 'undulating country' is a combination of three similar classes in the Isa GBA region that collectively comprise less than 5% of the area and occur only in the far west of the region. These are 'hills and lowlands on metamorphic rocks', 'undulating country on fine-grained sedimentary rocks' and 'sandstone ranges'. Similarly, the landscape classes 'tidal flats and beaches' and 'hills and lowlands on granitic rocks' are not shown, as they each comprise less than 0.5% of the region.
The numbered items under 'impact cause' refer to the major activities identified in Figure 56.
Element: GBA-ISA-2-232

5.3.1.3 Altering natural habitat and species distributions

Natural habitat and species distribution may be affected by habitat fragmentation and loss; increased mortality (and/or potential chronic effects on growth and reproduction) of native species; changed air quality; contamination of soil, groundwater and/or surface water; and changes to groundwater levels or pressures (Figure 65). In particular, land clearance is a key threatening process identified under the EPBC Act, with vegetation clearing potentially affecting both terrestrial and aquatic environments, including leading to the potential introduction of invasive species through machinery bringing in weeds, removing ground cover and altering natural habitat. Invasive species can out-compete native vegetation and have impacts such as creating monocultures that reduce suitable habitat for threatened species (e.g. the endangered Carpentaria grasswren (*Amytornis dorotheae*)). Introduced plant species can also affect fire regimes – for example, invasive grasses can increase the occurrence and severity of bushfires, which can severely affect fire-sensitive plant communities and less mobile native wildlife.

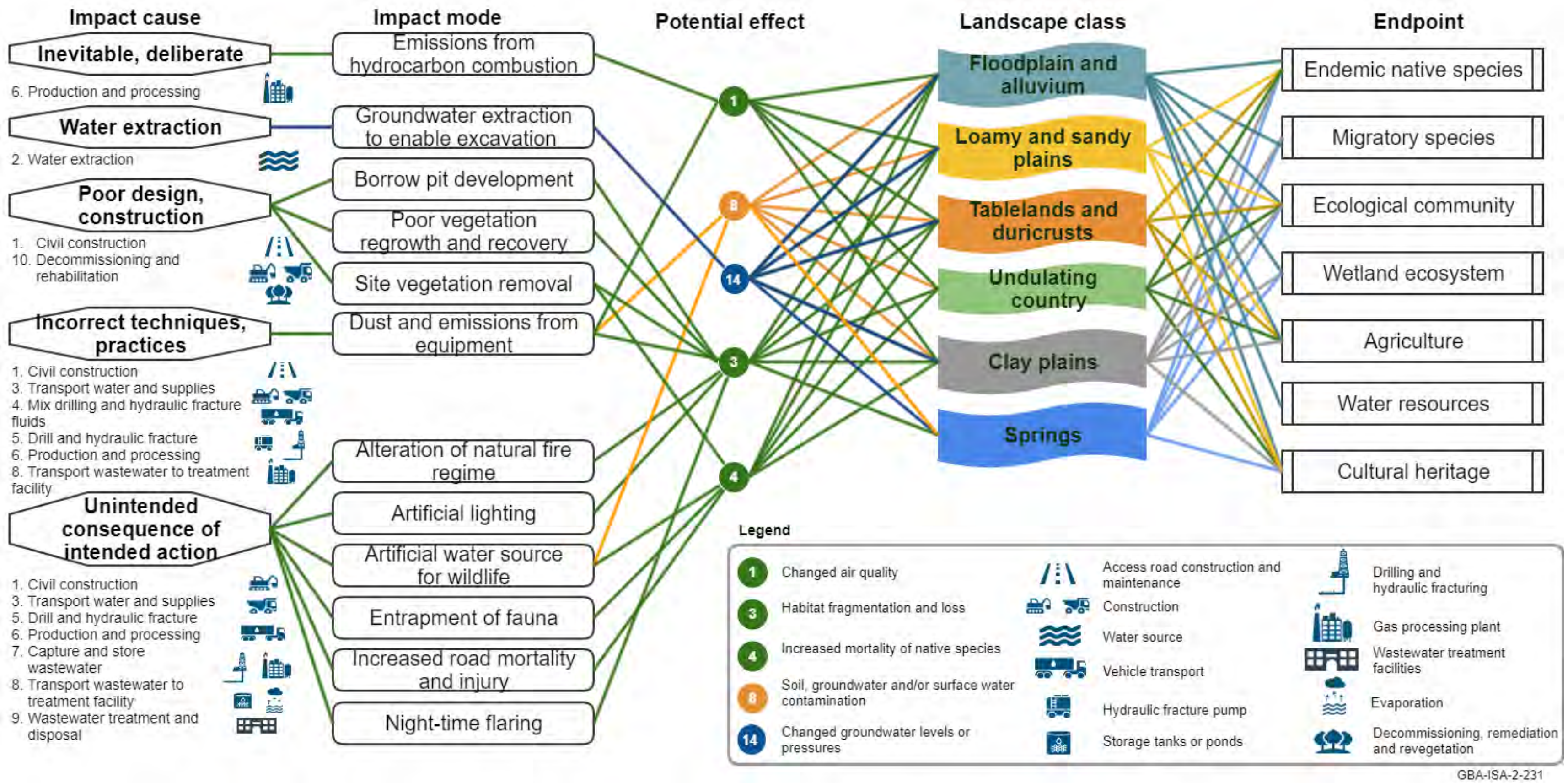

Figure 65 Preliminary conceptualisation of hazards associated with potential future shale gas development in the Isa GBA region in the 'altering natural habitat and species distribution' causal pathway

To simplify this diagram, the landscape class 'undulating country' is a combination of three similar classes in the Isa GBA region that collectively comprise less than 5% of the area and occur only in the far west of the region. These are 'hills and lowlands on metamorphic rocks', 'undulating country on fine-grained sedimentary rocks' and 'sandstone ranges'. Similarly, the landscape classes 'tidal flats and beaches' and 'hills and lowlands on granitic rocks' are not shown, as they each comprise less than 0.5% of the region.
The numbered items under 'impact cause' refer to the major activities identified in Figure 56.
Element: GBA-ISA-2-231

Creating artificial watering points (e.g. through building water storages) may alter natural habitat and species distributions by allowing some native species populations to increase or by allowing some introduced species to establish. This can create a trophic imbalance within the ecosystem and potentially impact threatened species – for example, by increasing predation levels of native species by feral cats. Increased populations of some introduced species, such as wild horses, can also exacerbate erosion and affect habitat structure and density (although this may be less of an issue in the Isa GBA region due to widespread grazing by cattle that has occurred across the region for many decades).

Changing surface water flows can affect flooding regimes, which may impact species distributions and natural habitat, especially in areas where native species are not adapted to the changed flow regime. This may result in reduced productivity of water-sensitive species (or, potentially, mortality in some cases).

Airborne dust and emissions from construction equipment occurs throughout development but is likely to be of greatest concern at times when major infrastructure is built or when wells are drilled and hydraulically fractured. Various noxious compounds and particulate matter emitted during drilling and operation of wells may create air pollution, due to the presence of nitrogen oxides, sulphur dioxide, carbon monoxide and volatile organic compounds (Huddlestone-Holmes et al., 2018). Noise and light pollution can affect habitat quality and species distribution. Wildlife such as terrestrial mammals, birds and reptiles are at risk due to collisions with increased vehicle traffic, particularly during gasfield development. Entrapment of native fauna in pitfall traps created through construction of quarries, dams and trenches may also increase mortality rates.

Other priority hazards that may cause habitat fragmentation and loss include alteration of natural fire regimes during construction of fire breaks, artificial lighting during drilling and well construction, artificial water sources for wildlife such as water storage or evaporation ponds, increased road mortality and injury from vehicle transport and night-time flaring from the gas processing plant. Poor design or construction of access roads and pipelines, as well as site vegetation removal, are priority 1 hazards that may have a moderate impact on ecosystems (potentially reversible in less than ten years).

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

5.3.1.4 Altering surface hydrology

Surface water hydrology may be affected by bank instability and erosion, as well as changed surface water flows (Figure 66). This is most likely to occur in streams and on floodplains but can also occur anywhere in the landscape that surface water flows occur. Activities related to reducing surface water availability due to extraction of water for hydraulic fracturing and disposal of treated flowback water are included in the ‘water and infrastructure management’ causal pathway group. Five of the 12 activities that can alter the hydrology of surface waters are identified as high-priority hazards. These include construction of access roads and well pads, which could impact the magnitude, duration, timing and frequency of surface water flows.

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

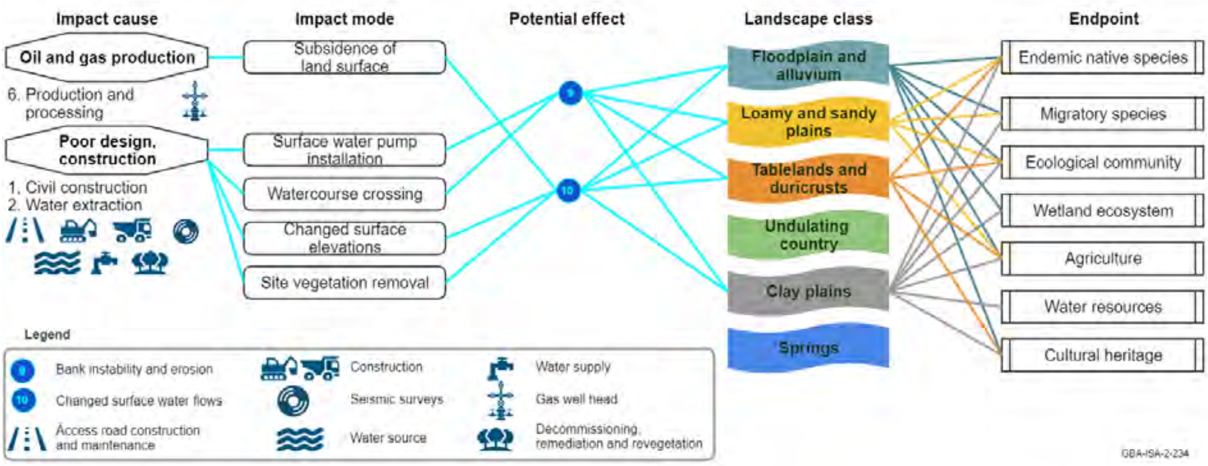

Figure 66 Preliminary conceptualisation of hazards associated with potential future shale gas development in the Isa GBA region in the ‘altering surface hydrology’ causal pathway

To simplify this diagram, the landscape class ‘undulating country’ is a combination of three similar classes in the Isa GBA region that collectively comprise less than 5% of the area and occur only in the far west of the region. These are ‘hills and lowlands on metamorphic rocks’, ‘undulating country on fine-grained sedimentary rocks’ and ‘sandstone ranges’. Similarly, the landscape classes ‘tidal flats and beaches’ and ‘hills and lowlands on granitic rocks’ are not shown, as they each comprise less than 0.5% of the region.
The numbered items under ‘impact cause’ refer to the major activities identified in Figure 56.
Element number: GBA-ISA-2-234

There are several management protocols in place to minimise the impact of road construction on surface waters. Prior to development, roads and access tracks should be sufficiently well planned and sited so as to minimise environmental impacts – for example, by not crossing ecologically sensitive habitat. In addition, planning should also avoid exposing roadways to areas with increased likelihood of being affected by natural hazards (e.g. excessive inundation on floodplains). During construction, roads and tracks are developed in accordance with applicable Australian standards and state legislation. Erosion control measures are installed where required and, where relevant, detailed hydrological assessments may be needed to ensure there are no significant impacts on surface water flows (Santos, 2015).

5.3.1.5 Introduction of invasive species

Invasive species can be introduced through incorrect techniques or practices throughout most life-cycle stages during shale gas development (Figure 67). In addition, some activities associated with shale gas development can further enhance or facilitate the spread of invasives that may already be established in an area. Many high-priority hazards are associated with the invasive species causal pathway, including transport of seeds and pest species during construction of access roads, pipelines, powerlines and surface infrastructure, and transport of water and supplies. Five of the 12 hazards in this casual pathway, including those related to construction and maintenance of access road and pipeline corridors, are identified as priority 1 hazards.

The introduction of invasive species may have a moderate to major impact on ecosystems. This is because, once weeds and pests become established, eradication becomes very difficult. Ground-cover disturbance brings opportunity for weeds to establish. Weeds are typically fast-growing and reach reproductive capability before native species, therefore out-competing native species in disturbed soils. Pest plant seeds can be introduced by vehicles and machinery during construction and maintenance activities. Soil disturbance and vegetation removal increase the risk of establishment of introduced plants.

Pest species can also become established when natural surface cover and habitat areas are disturbed by development activities. Predators, such as wild dogs, will commonly use access roads, increasing predation rates on native species in these areas. However, this effect is less prominent in rangeland environments, where predator movement is typically not as restricted as it is in forested environments. Predators also congregate where food resources are more plentiful. Newsome et al. (2013) noted larger group size and smaller home ranges of dingoes in arid areas near supplementary food resources from mine sites than those of dingoes where no supplementary food resources occurred. If the supplementary food resource stops in the area – for example, at the end of mining activity – these larger packs could turn to more natural food sources, affecting local wildlife populations.

Invasive species can also alter habitat structure and food sources that may be crucial for threatened species – for example, the invasive gamba grass (*Andropogon gayanus*) can out-compete native grasses and potentially affect habitat for some invertebrates and native bird species, as well as affecting native seed sources for granivorous birds. Invasive plants can also change the fire regime for an area, increasing risk of fire that may be detrimental to fire-sensitive native plants.

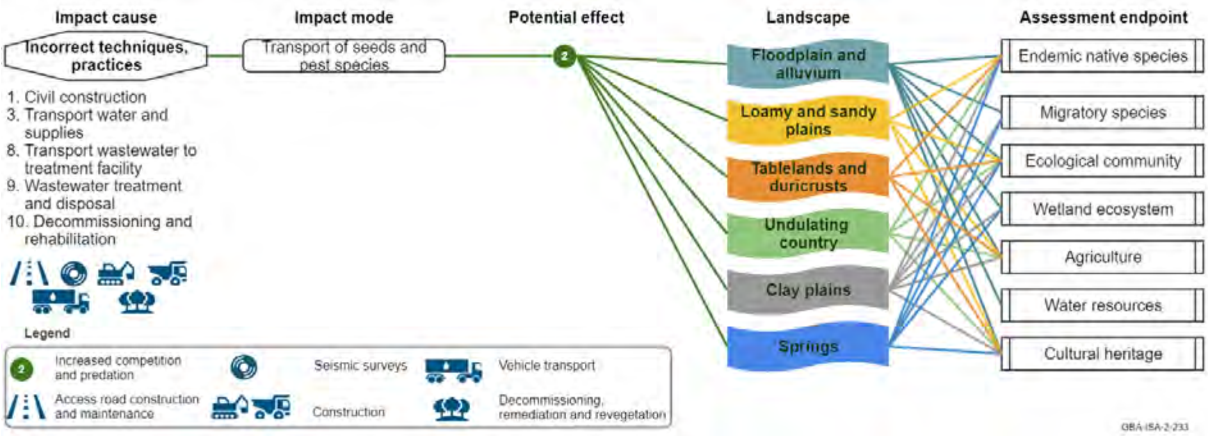

Figure 67 Preliminary conceptualisation of hazards associated with potential future shale gas development in the Isa GBA region in the 'introduction of invasive species' causal pathway

To simplify this diagram, the landscape class 'undulating country' is a combination of three similar classes in the Isa GBA region that collectively comprise less than 5% of the area and occur only in the far west of the region. These are 'hills and lowlands on metamorphic rocks', 'undulating country on fine-grained sedimentary rocks' and 'sandstone ranges'. Similarly, the landscape classes 'tidal flats and beaches' and 'hills and lowlands on granitic rocks' are not shown, as they each comprise less than 0.5% of the region.
The numbered items under 'impact cause' refer to the major activities identified in Figure 56.
Element: GBA-ISA-2-233

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

Site-based protocols to avoid introduction of pest species include vehicle and machinery cleaning when arriving and leaving sites to remove all seeds or plant material, particularly washdown of drill rigs for interstate movement. Introduced plants of particular concern in the Isa GBA region are invasive species, such as rubber vine (*Cryptostegia grandiflora*), prickly acacia (*Vachellia nilotica*), calotrope (*Calotropis procera*) and parkinsonia (*Parkinsonia aculeata*). Management protocols target the detection and assessment of spread of pest plants and animals.

5.3.2 Subsurface flow paths causal pathways

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

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

The individual hazards and potential effects associated with these causal pathways in the Isa GBA region are illustrated conceptually in Figure 68. The subsurface flow paths causal pathways are focused on water-related impacts that may occur at various depths below the surface, such as changes to groundwater quality or groundwater pressures in an aquifer. There are two priority 1 hazards in the 'compromised well integrity' causal pathway, where failure of well integrity may permit the unintentional migration of fluids between different geological units and potentially affect groundwater quality. There are also four Priority 2 hazards in the 'compromised well integrity' causal pathway, and three Priority 2 hazards in the 'hydraulic fracturing' causal pathway. The hazards associated with compromised well integrity and hydraulic fracturing are discussed further in Section 6.

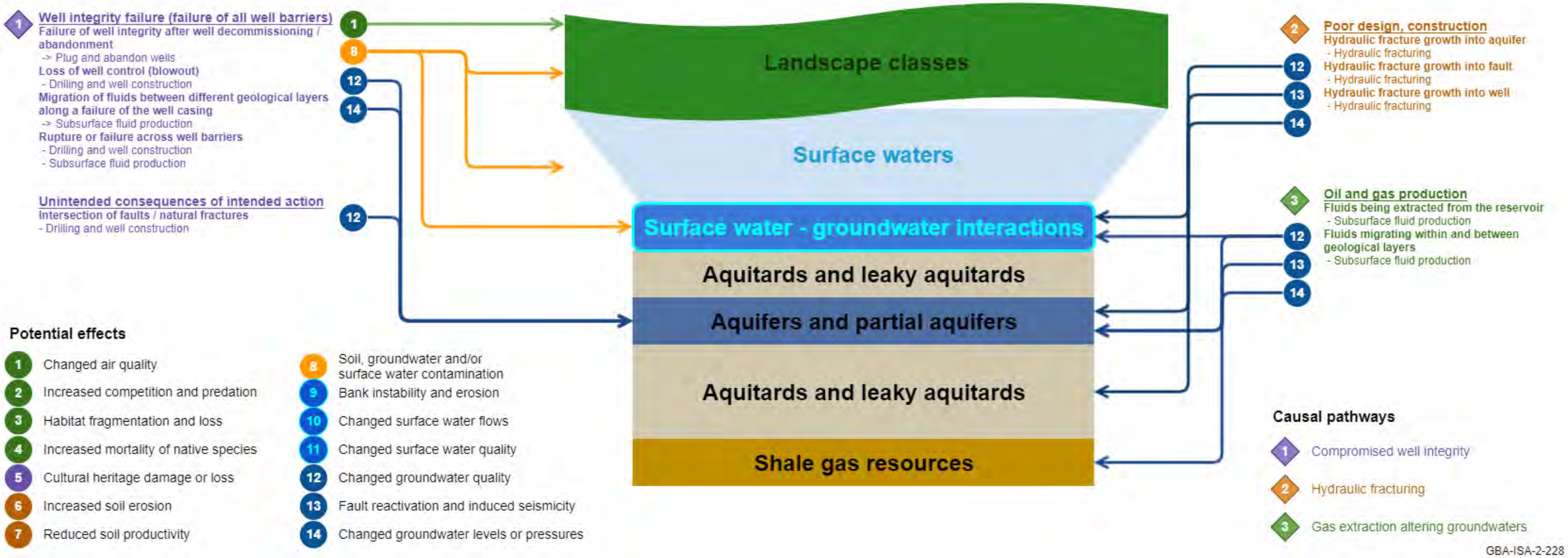

Figure 68 Hazards (impact causes, impact modes and activities) and associated effects in the 'subsurface flow paths' causal pathway group identified for potential future shale gas development in the Isa GBA region

Impact causes are underlined, impact modes are bold, and activities are bullet points (low-priority hazards = '-'; and priority hazards = '->'). Arrows show how the individual hazards interact with key components: aquifers and partial aquifers, aquitards and partial aquitards, landscapes, shale gas resources, surface water – groundwater interactions and surface waters. Causal pathways are identified by number and text colour. This figure has been optimised for printing on A3 paper (297 mm x 420 mm).
Typology and punctuation are consistent with the hazard identification dataset (Geological and Bioregional Assessment Program, 2019c).
Element: GBA-ISA-2-228

5.3.2.1 Compromised well integrity

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

The IMEA hazard analysis undertaken for the Isa GBA region identified 11 hazards that relate to issues of compromised well integrity. These issues can occur at various stages in the life cycle of a well, including during construction, while the well is in operation (i.e. producing gas), and after the well has been decommissioned (e.g. plugged and abandoned) at the end of its operational lifespan. Huddlestone-Holmes et al. (2018) summarised the four main well barrier failure mechanisms as:

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

Hazards associated with compromised well integrity are most likely to have a localised effect on groundwater systems, including groundwater quality (five hazards) and groundwater levels or pressures (one hazard). However, if well integrity failure resulted in the uncontrolled release of gas or other fluids to the surface, there is also potential for changes to air quality (e.g. the escape of methane to the atmosphere – three hazards), as well as contamination of soils, surface water or shallow groundwater systems (two hazards). If gas or other fluids were accidentally released at surface due to compromised well integrity, the greatest impacts would most likely be localised to the landscape class where the well occurs. Neighbouring landscape classes may be affected to a lesser degree – for example, due to airborne dispersal of gas (Figure 69).

The highest priority hazards in the compromised well integrity causal pathway involve potential impacts on groundwater quality (two priority 1 hazards and three priority 2 hazards). The uncontrolled migration of fluids between different geological formations due to well casing failure is ranked as the highest priority hazard in the subsurface flow paths causal pathway group. This hazard is of greatest concern in situations where fluids may migrate into an aquifer that is used as a water source to support ecological, economic or cultural values – for example, where changes to groundwater quality affect the source aquifer for a culturally and/or ecologically important spring; or where the groundwater quality of an aquifer used as a pastoral supply bore is adversely affected (Figure 69).

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

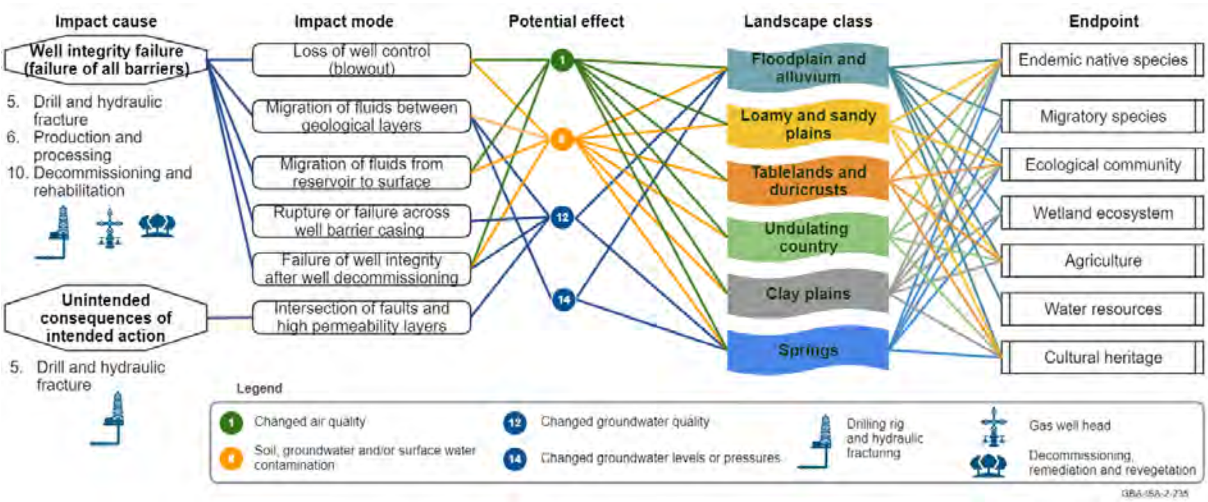

Figure 69 Preliminary conceptualisation of hazards associated with potential future shale gas development in the Isa GBA region in the 'compromised well integrity' causal pathway

To simplify this diagram, the landscape class 'undulating country' is a combination of three similar classes in the Isa GBA region that collectively comprise less than 5% of the area and occur only in the far west of the region. These are 'hills and lowlands on metamorphic rocks', 'undulating country on fine-grained sedimentary rocks' and 'sandstone ranges'. Similarly, the landscape classes 'tidal flats and beaches' and 'hills and lowlands on granitic rocks' are not shown, as they each comprise less than 0.5% of the region.
The numbered items under 'impact cause' refer to the major activities identified in Figure 56.
Element: GBA-ISA-2-235

In addition to the IMEA hazard identification, a more detailed qualitative analysis of well integrity and hydraulic fracturing was undertaken as a key component of Stage 2 of the geological and bioregional assessment for the Isa GBA region, leading to a supporting technical appendix for the three GBA regions (Kear and Kasperczyk, 2020). A summary of the appendix is provided in Section 6.2. The specific focus on these subsurface aspects of shale gas development was considered appropriate given the high level of community concern raised about these issues at the first user panel meeting for the Isa GBA region. This review focused in detail on summarising the findings from several domestic and international inquiries, as well as analysing relevant well and geological data for the Isa Superbasin.

5.3.2.2 Hydraulic fracturing

Hydraulic fracturing is a subsurface engineering technique routinely applied following drilling of a well to increase the production rate of shale gas reservoirs. The hydraulic fracture fluid mixture consisting of water, proppant (such as sand or small ceramic balls) and relatively small amounts of various chemical additives (see the chemical screening technical appendix for further details (Kirby et al., 2020)) is injected into the target reservoir via the well at high pressures to fracture (stimulate) these otherwise low-permeability rocks. Hydraulic fracturing creates a network of fractures within the shale gas reservoir, directly connecting fractures to the well. The created fractures are held open by proppant once the hydraulic fracture fluid pressure is released and the propped fractures increase the permeability of the reservoir. The newly enhanced permeability allows for gas to flow from the reservoir to surface via the well.

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

Potential effects that may arise during hydraulic fracturing of shale gas reservoirs in the Isa GBA region include changes to groundwater quality within an aquifer (three hazards) and changes to groundwater pressures in confined aquifers (three hazards). These effects may arise due to the unintentional release of hydraulic fracturing fluids into geological formations (other than the target gas reservoir). As these potential effects are groundwater related, they are most likely to directly affect the ‘floodplain and alluvium’ or the ‘springs’ landscape classes. A range of assessment endpoints that occur within these landscape classes could then be affected by groundwater changes caused by hydraulic fracturing, including ecological communities, agricultural water resources and cultural heritage values (Figure 70).

There is also potential for hydraulic fractures to intersect other petroleum or water supply wells, possibly leading to contamination of soils, groundwaters or surface waters (in the event of unintentional fluid migration along these existing wells). This may affect landscape classes and endpoints within the local vicinity of the older well. Growth of a fracture into a fault could also lead to fault reactivation and induced seismicity (one hazard). Elevated cyclical pressures applied to wells during hydraulic fracturing could also affect the integrity of the well (Huddlestone-Holmes et al., 2018). This is addressed by the 'compromised well integrity' causal pathway (Figure 69).

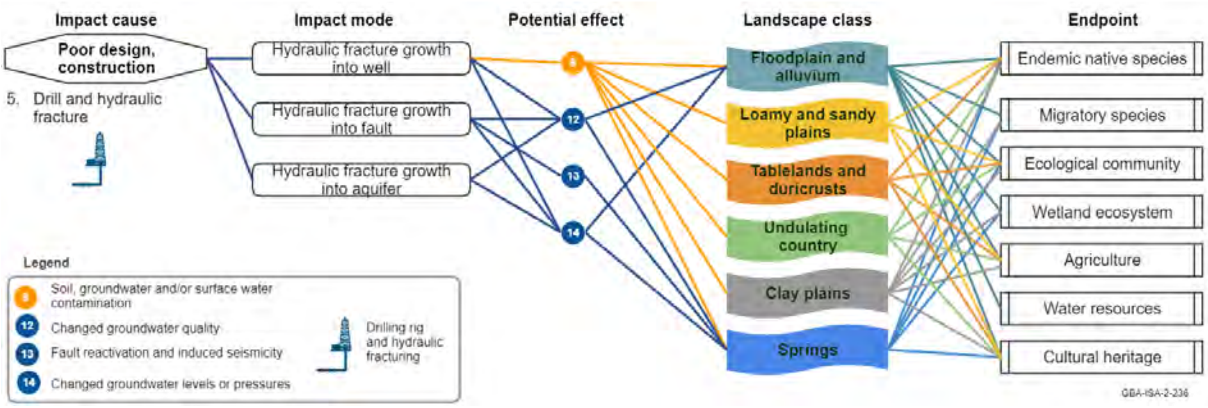

Figure 70 Preliminary conceptualisation of hazards associated with potential future shale gas development in the Isa GBA region in the 'hydraulic fracturing' causal pathway

To simplify this diagram, the landscape class 'undulating country' is a combination of three similar classes in the Isa GBA region that collectively comprise less than 5% of the area and occur only in the far west of the region. These are 'hills and lowlands on metamorphic rocks', 'undulating country on fine-grained sedimentary rocks' and 'sandstone ranges'. Similarly, the landscape classes 'tidal flats and beaches' and 'hills and lowlands on granitic rocks' are not shown, as they each comprise less than 0.5% of the region.
The numbered items under 'impact cause' refer to the major activities identified in Figure 56.
Element: GBA-ISA-2-236

The main impact modes associated with hydraulic fracturing relate to the unplanned or unexpected growth of a fracture beyond the extent of the shale gas target reservoir. This could result in part of a hydraulic fracture network intersecting a non-target geological layer (such as an aquifer), a permeable fault zone, or even another existing water bore or petroleum well (including an abandoned well). In these cases, the hydraulic fracture network grows larger than originally planned, potentially leading to the unintentional migration of hydraulic fracturing fluids into subsurface formations other than the gas reservoir. Given the nature of hydraulic fracturing fluids (see Section 6.3), which may contain diverse chemical additives, there are risks (and significant community concerns) associated with the unintended release of such fluids into non-target formations. However, many domestic and international inquiries (US EPA, 2016a; Hawke, 2014; Cook et al., 2013b; The Royal Society and The Royal Academy of Engineering, 2012; Wright, 2014; Council of Canadian Academies, 2014; Atherton et al., 2014; Pepper et al., 2018; Hatton et al., 2018) find that likelihoods of these impact modes range between unlikely and rare and that risks associated with hydraulic fracturing are manageable to suitably low levels. Recent research from (Shanafield et al., 2018) fits data (Davies et al., 2012) to a log-normal distribution to quantify the likelihood of contamination due to inter-aquifer leakage from wells that are hydraulically fractured as 1 in 1,000,000 or less for a vertical separation of 2000 m. This likelihood is highly dependent on the separation distance between the gas-producing reservoir and the overlying aquifer. The separation distance between unconventional gas reservoirs and aquifers in the Isa GBA region is further discussed in Section 6.1 (and the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020)).

Effective planning, design and implementation of each hydraulic fracturing stage is critical to ensuring that the risks to groundwater associated with hydraulic fracturing are adequately managed. Given adherence to existing controls and guidelines designed to safeguard the process, the risks posed by hydraulic fracturing are generally regarded as acceptable to both the gas industry and government regulators. However, due to heightened community concern related to hydraulic fracturing impact modes, the qualitative assessment outlined in Section 6.1 recommends further analysis to evaluate the potential for hydraulic fracture growth into overlying aquifers from the shale gas target reservoirs, specific to the Isa GBA region.

5.3.2.3 Gas extraction altering groundwaters

The IMEA hazard analysis identified several potential hazards associated with the production of gas from shale gas reservoirs (Figure 71). These are subsurface hazards that may arise due to changes in reservoir pressures as gas is extracted during the life of the well (typically ten to 20 years), with potential effects on the quality and/or pressure of groundwaters (two hazards). Another potential effect identified by the hazard analysis relates to changes in reservoir pressures, which may lead to fault reactivation and potentially induced seismic activity. Collectively, these hazards are assigned to the ‘gas extraction altering groundwaters’ causal pathway.

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

Although three gas extraction hazards were identified through the IMEA process, they were recognised as having a relatively low likelihood of occurring (typically considered rare to very unlikely events using the IMEA nomenclature). This reflects the much greater depths below surface at which shale gas reservoirs occur and the significant vertical separation that exists between these reservoirs and most groundwaters – especially the shallower (<100 m deep) groundwaters that are most commonly used in the Isa GBA region.

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

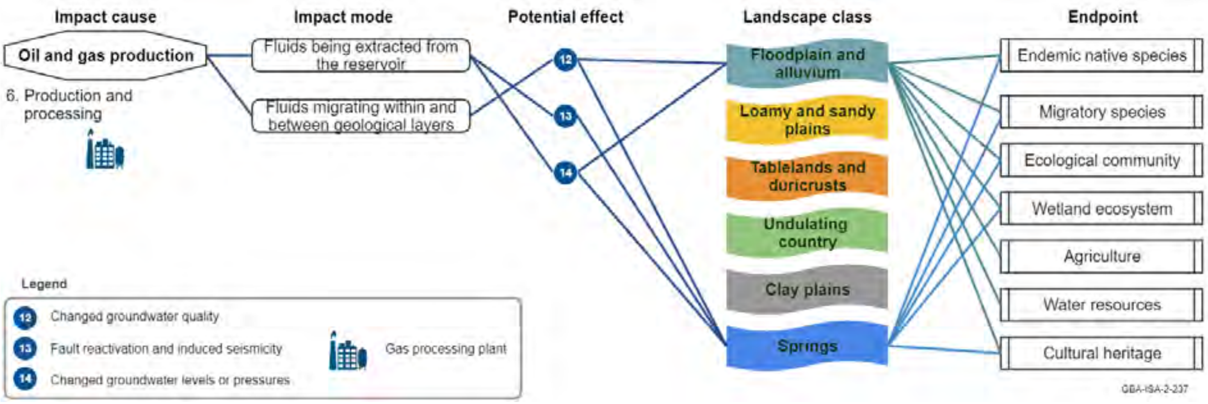

Figure 71 Preliminary conceptualisation of hazards associated with potential future shale gas development in the Isa GBA region in the 'gas extraction altering groundwaters' causal pathway

To simplify this diagram, the landscape class 'undulating country' is a combination of three similar classes in the Isa GBA region that collectively comprise less than 5% of the area and occur only in the far west of the region. These are 'hills and lowlands on metamorphic rocks', 'undulating country on fine-grained sedimentary rocks' and 'sandstone ranges'. Similarly, the landscape classes 'tidal flats and beaches' and 'hills and lowlands on granitic rocks' are not shown, as they each comprise less than 0.5% of the region.
The numbered items under 'impact cause' refer to the major activities identified in Figure 56.
Element: GBA-ISA-2-237

Although the reduction in reservoir pressures due to gas production will invariably occur to some degree in shale gas systems, the typical depth of gas production and lack of active dewatering mean that such pressure reductions are unlikely to propagate far beyond the boundaries of the target reservoir. Additionally, the low permeability of these reservoir rocks (and potentially other fine-grained geological layers above and below the reservoir) is likely to further impede the propagation of subsurface pressure changes from the reservoir. Consequently, these are not considered priority 1 hazards in the Isa GBA region. The most likely landscape classes that would be affected by the 'gas extraction altering groundwaters' causal pathway are those most closely linked with groundwater systems – namely, the 'floodplain and alluvium' and 'springs' landscape classes (Figure 71).

5.3.3 Water and infrastructure management causal pathways

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

- discharging water into surface waters (ten hazards)
- disposal and storage of site materials (21 hazards)
- failure of surface infrastructure (ponds, tanks, pipelines, etc.) (30 hazards)

- processing and using extracted water (eight hazards)
- reinjecting water into aquifer (ten hazards)
- sourcing water for site operations (13 hazards).

The individual hazards and potential effects associated with these causal pathways are illustrated conceptually in Figure 72. Each causal pathway includes a range of different impact modes and potential effects identified through the IMEA process, most of which are focused on impacts to surface waters or groundwaters, including changes to levels, pressures or flows and water quality.

High-priority hazards were identified for all six causal pathways:

- discharging water into surface waters (seven priority 1 hazards out of ten hazards)
- disposal and storage of site materials (two priority 1 hazards out of 21 hazards)
- failure of surface infrastructure (ponds, tanks, pipelines, etc.) (13 priority 1 hazards out of 30 hazards)
- processing and using extracted water (one priority 1 hazard out of eight hazards)
- reinjecting water into aquifer (one priority 1 hazard out of ten hazards)
- sourcing water for site operations (four priority 1 hazards out of 13 hazards).

The main potential effects that are associated with the priority hazards are:

- soil, groundwater and/or surface water contamination (16 out of 58 hazards)
- changed surface water flows (four out of eight hazards)
- changed surface water quality (three out of four hazards)
- changed groundwater levels or pressures (two out of nine hazards)
- increased mortality of native species (two out of two hazards)
- changed groundwater quality (one out of six hazards).

The hazards identified during the IMEA process can arise when current leading-practice design, construction and management protocols are not implemented properly or as a consequence of external factors such as natural hazards (e.g. cyclones or bushfires).

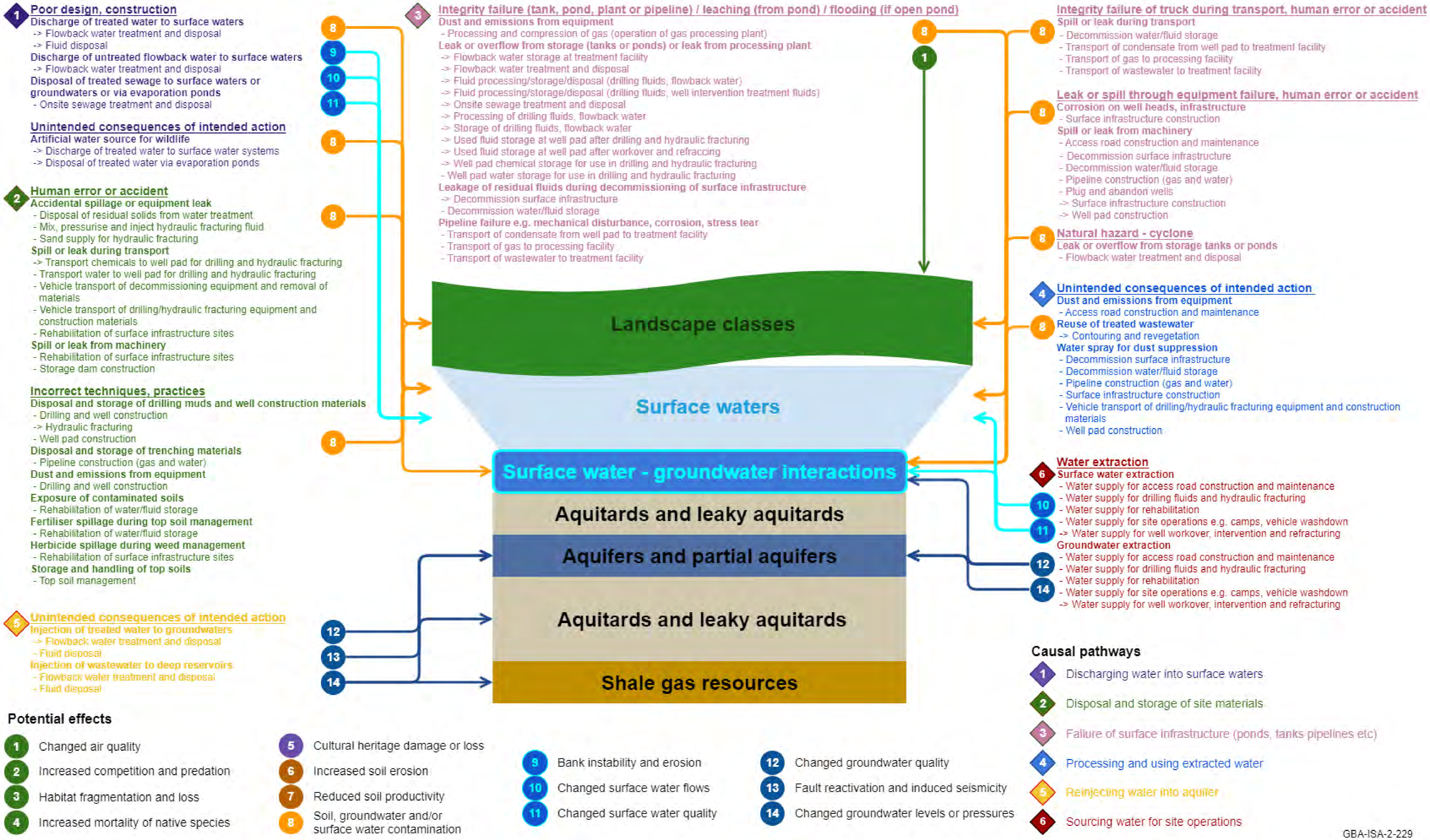

Figure 72 Hazards (impact causes, impact modes and activities) and associated effects in the 'water and infrastructure management' causal pathway group identified for potential future shale gas development in the Isa GBA region

Impact causes are underlined, impact modes are bold, and activities are bullet points (low priority hazards = '-'; and priority hazards = '->'). Arrows show how the individual hazards interact with key components: aquifers and partial aquifers, aquitards and partial aquitards, landscapes, shale gas resources, surface water – groundwater interactions and surface waters. Causal pathways are identified by number and text colour. This figure has been optimised for printing on A3 paper (297 mm x 420 mm).

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

Element: GBA-ISA-2-229

5.3.3.1 Discharging into surface waters

Surface waters can be impacted by discharge of treated or untreated flowback water into streams, as well as disposal of treated water into streams and rivers or via evaporation ponds (Figure 73). Potential effects are changes to surface water flows (three hazards) or quality (three hazards); contamination of soil, groundwater or surface water (three hazards); and bank instability and erosion (one hazard). The potential impacts from discharge and storage of water are typically restricted to changes in the 'floodplain and alluvium' landscape class in the Isa GBA region, as water discharge and storage operations are most likely to occur in areas where this landscape class exists. However, other landscape classes that are hydrologically connected to floodplains and alluvium, such as 'loamy and sandy plains' or 'clay plains', may also be affected (Figure 52) as water discharged from storage ponds makes its way downstream towards the coast.

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

In addition to providing a greater volume of water, discharge of both treated and untreated water may change the quality of receiving waters. This may have unintended consequences for natural habitat, depending on the water quality requirements of species within these aquatic ecosystems. For example, remnant waterholes downstream of discharge sites may be affected during the dry season if dissolved contaminants in the discharge water were concentrated within these pools due to evaporation.

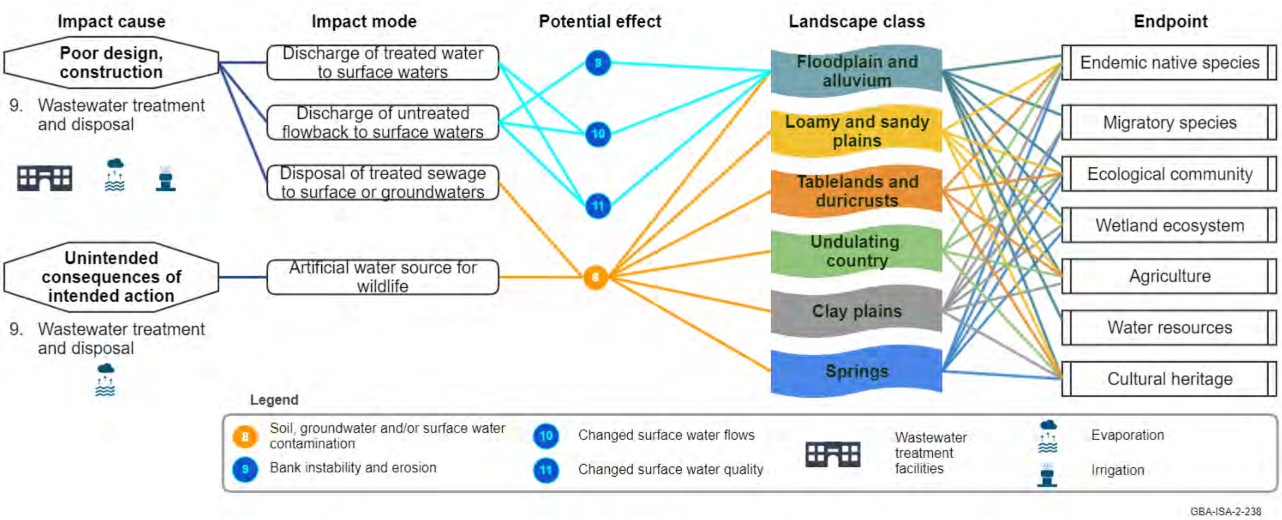

Figure 73 Preliminary conceptualisation of hazards associated with potential future shale gas development in the Isa GBA region in the 'discharging water into surface waters' causal pathway

To simplify this diagram, the landscape class 'undulating country' is a combination of three similar classes in the Isa GBA region that collectively comprise less than 5% of the area and occur only in the far west of the region. These are 'hills and lowlands on metamorphic rocks', 'undulating country on fine-grained sedimentary rocks' and 'sandstone ranges'. Similarly, the landscape classes 'tidal flats and beaches' and 'hills and lowlands on granitic rocks' are not shown, as they each comprise less than 0.5% of the region.
The numbered items under 'impact cause' refer to the major activities identified in Figure 57.
Element: GBA-ISA-2-238

Management protocols can be used to reduce the impacts of treated and untreated water discharge into natural waterways (Santos, 2015). These protocols can include the requirement to treat water to an acceptable level before discharge, as well as only discharging during high flow events when the relative impact of additional water of a lower (or higher) quality will be diminished. Other approaches include well-designed water quality testing and monitoring procedures and, in some cases, fencing of water storage ponds to minimise access to water for native and introduced species as well as livestock.

5.3.3.2 Disposal and storage of site materials

Soil, groundwater and/or surface water contamination may arise due to human error or accident (ten hazards) or when incorrect techniques and practices (nine hazards) are used for the disposal and storage of site materials (Figure 74). Spills in chemical storage areas are contained by bunding and hardstand surrounds within designated facilities. Typical wastes include cement, contaminated soils, drill cuttings, drilling and hydraulic fracturing chemicals, fluids, fertilisers and herbicides used for rehabilitation, sand, and evaporated waste from water treatment facilities (such as brines and sludge). Disposal and storage of site materials is a regulated activity governed by specific conditions and rules, particularly for waste that is stored onsite or taken offsite for disposal in an approved facility. Spills and accidents involving chemicals may occur during all phases of operation (e.g. well blowouts, well casing failures, spills during fluid transport) and could potentially lead to contamination of soils, surface water and/or shallow groundwater. Changes to water quality may increase stress and/or mortality of aquatic species and potentially also affect non-aquatic wildlife that drinks from affected surface waters.

Potential impacts associated with this causal pathway are typically localised to the landscape class where disposal and storage operations occur. In the Isa GBA region this is most likely to be in the 'floodplain and alluvium' landscape class, although the other landscapes could also be affected to a lesser degree (Figure 74). A variety of endpoints linked to the potentially affected landscapes may be affected by hazards associated with disposal and storage of materials.

It is unlikely that accidental spills or leaks during transport of drilling and hydraulic fracturing equipment that contaminate soil, groundwater and/or surface waters due to human error or accident will occur, but they are considered a priority 1 hazard because of the potential severity – that is, they may have a moderate impact on ecosystems that is reversible in five to ten years. Similarly, it is possible that incorrect techniques and practices used in the disposal and storage of drilling muds and well construction materials during drilling operations may have a similar impact.

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

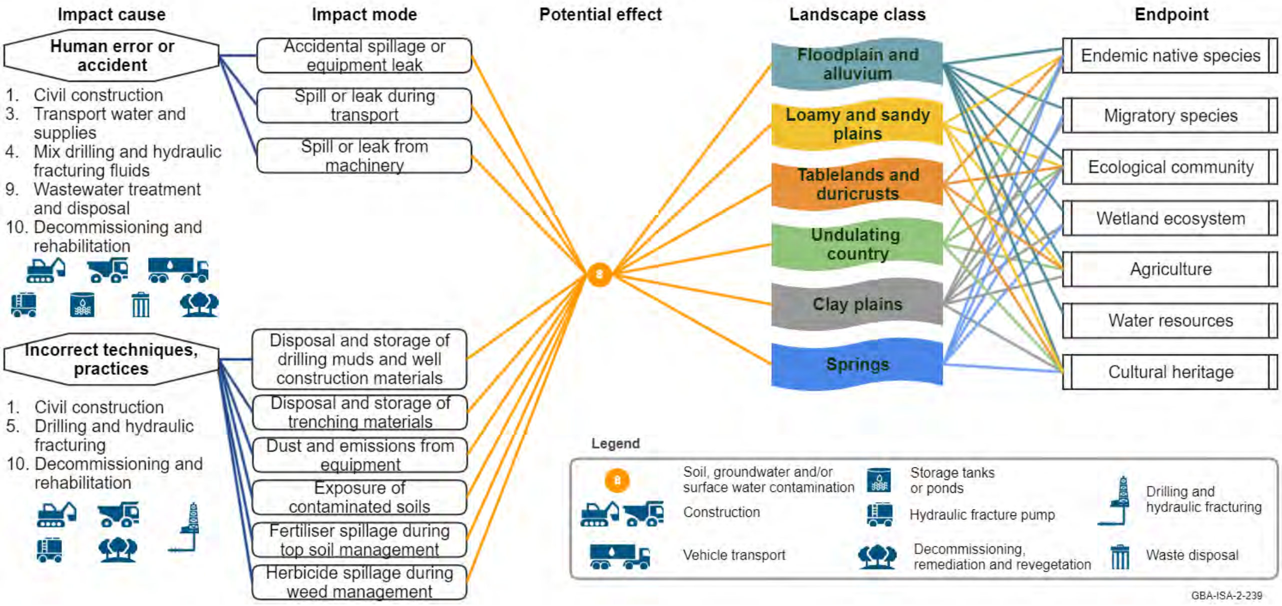

Figure 74 Preliminary conceptualisation of hazards associated with potential future shale gas development in the Isa GBA region in the 'disposal and storage of site materials' causal pathway

To simplify this diagram, the landscape class 'undulating country' is a combination of three similar classes in the Isa GBA region that collectively comprise less than 5% of the area and occur only in the far west of the region. These are 'hills and lowlands on metamorphic rocks', 'undulating country on fine-grained sedimentary rocks' and 'sandstone ranges'. Similarly, the landscape classes 'tidal flats and beaches' and 'hills and lowlands on granitic rocks' are not shown, as they each comprise less than 0.5% of the region.
The numbered items under 'impact cause' refer to the major activities identified in Figure 57.
Element: GBA-ISA-2-239

5.3.3.3 Failure of surface infrastructure

Failure of surface infrastructure may result in changes to air quality (two hazards) or contamination of soil, groundwater and/or surface water (28 hazards). As shown in Figure 75, the impact causes for this causal pathway range from relatively minor failures (e.g. small to moderate leaks from pipes, machinery or equipment) to catastrophic infrastructure failures caused, for example, by natural hazard events. Surface infrastructure includes pipelines, storage tanks, transport vehicles, machinery (civil construction equipment, drilling and hydraulic fracturing equipment) and operating plant. Fluids that may be released from infrastructure include produced hydrocarbon gas and liquids, produced water, flowback water, hydraulic fracturing fluids, fuels and lubricants in machinery and plant, and process chemicals that are used in some infrastructure.

The impacts of hazards associated with failure of surface infrastructure can range from localised (e.g. minor leak of fuel or lubricant) to more widespread (e.g. overflow of wastewater storage dams). Consequently, there is potential in the Isa GBA region for all of the landscape classes and many of their associated endpoints to be affected by these hazards, particularly where soil, shallow groundwater or surface water systems may be contaminated (Figure 75).

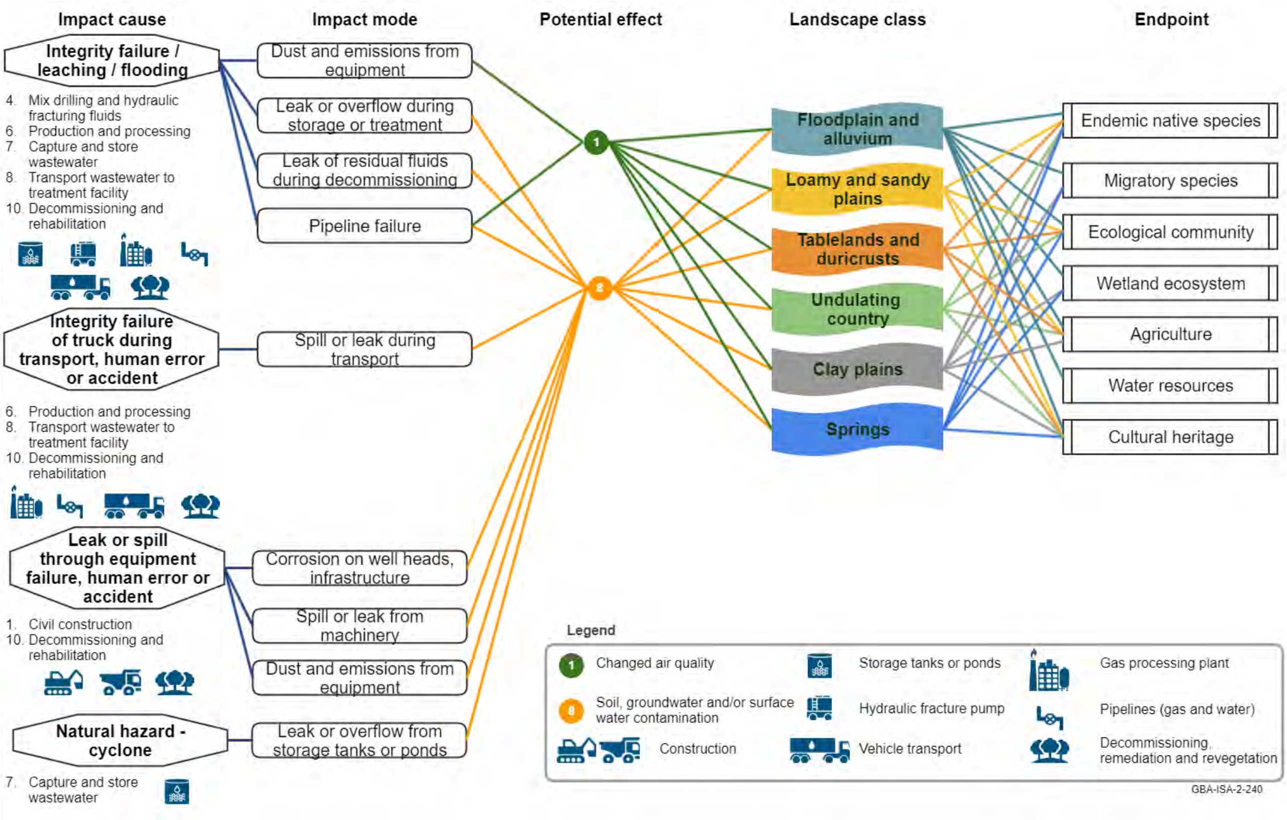

Figure 75 Preliminary conceptualisation of hazards associated with potential future shale gas development in the Isa GBA region in the 'failure of surface infrastructure' causal pathway

To simplify this diagram, the landscape class 'undulating country' is a combination of three similar classes in the Isa GBA region that collectively comprise less than 5% of the area and occur only in the far west of the region. These are 'hills and lowlands on metamorphic rocks', 'undulating country on fine-grained sedimentary rocks' and 'sandstone ranges'. Similarly, the landscape classes 'tidal flats and beaches' and 'hills and lowlands on granitic rocks' are not shown, as they each comprise less than 0.5% of the region.
The numbered items under 'impact cause' refer to the major activities identified in Figure 56.
Element: GBA-ISA-2-240

Release of fluids may result from a failure in the integrity of the fluid storage/delivery system (storage vessels and tanks, tankers and pipelines) or operating equipment (pumps and other plant); human error or accidents during transport or operation of equipment; or overflow of open storage tanks or ponds due to heavy rainfall and/or flooding associated with cyclonic weather systems.

Ponds, tanks and pipelines are designed, built and managed to maintain integrity and operability throughout their intended lifespan. Management protocols to address infrastructure failures include leak detection, maintenance, corrosion mitigation, overpressure protection and fencing to exclude native fauna and livestock. Managing leaks, spills or overflows from surface infrastructure is a regulated activity governed by specific conditions and rules. There may be situations where an unregulated activity occurs – for example, due to extreme flood inundation, natural hazards or sudden failure of storage dams – but even in these circumstances there are typically overarching policies or guidelines in place to address the issue.

5.3.3.4 Processing and using extracted water

Reuse of extracted water – that is, produced or flowback water – reduces the volume of water extracted for operational use (e.g. for drilling and hydraulic fracturing of production wells), as well as the volume of wastewater to be disposed of and managed during shale gas development. Extracted water may be reused for activities, including drilling and well completions, hydraulic fracturing, earthworks, dust suppression on well pads and access tracks, and in rehabilitation and revegetation activities. Beneficial reuse of extracted water outside of petroleum activities is also possible, including for agricultural purposes such as irrigation or stock watering, or as process water for other industries. Extracted water may undergo varying levels of treatment (e.g. reverse osmosis) depending on its original quality and the intended end use.

Potential effects of processing and use of extracted water (Figure 76) relate primarily to the use of water for dust suppression and during remediation and revegetation activities (eight hazards). Reuse of extracted water for dust suppression can lead to soil, groundwater and/or surface water contamination. As these activities can occur throughout the region, it is possible that all of the landscape classes and many of their associated endpoints could be affected by this causal pathway. Contamination from dust suppression was considered of minimal severity and was not a priority hazard. However, a possible unintended consequence of reuse of treated wastewater for contouring and revegetation during rehabilitation that could cause soil, groundwater and/or surface water contamination with minimal severity that is reversible in one to five years is considered to be a priority 1 hazard. No other priority hazards were identified in the 'processing and using extracted water' causal pathway.

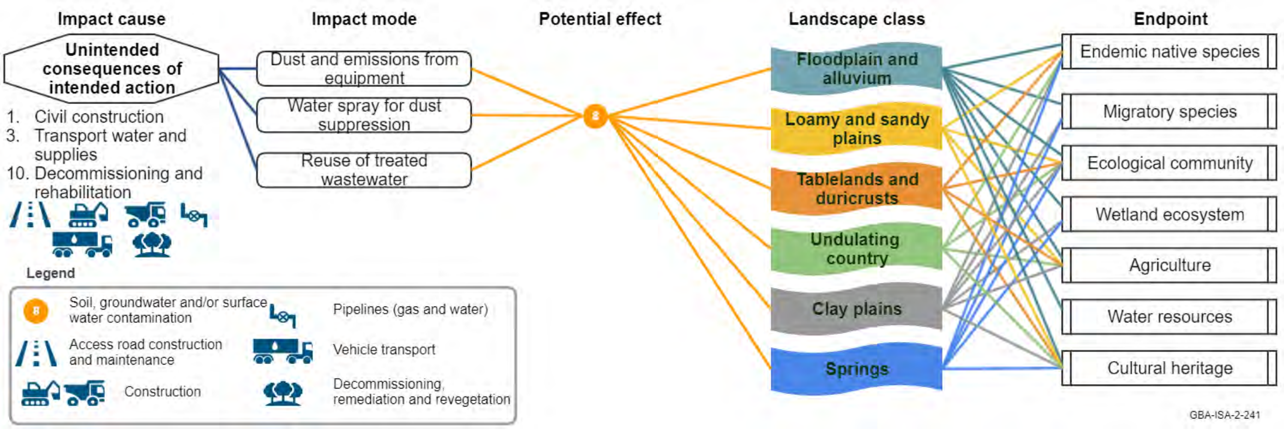

Figure 76 Preliminary conceptualisation of hazards associated with potential future shale gas development in the Isa GBA region in the 'processing and using extracted water' causal pathway

To simplify this diagram, the landscape class 'undulating country' is a combination of three similar classes in the Isa GBA region that collectively comprise less than 5% of the area and occur only in the far west of the region. These are 'hills and lowlands on metamorphic rocks', 'undulating country on fine-grained sedimentary rocks' and 'sandstone ranges'. Similarly, the landscape classes 'tidal flats and beaches' and 'hills and lowlands on granitic rocks' are not shown, as they each comprise less than 0.5% of the region.
The numbered items under 'impact cause' refer to the major activities identified in Figure 56.
Element: GBA-ISA-2-241

Beneficial or productive reuse of water is a regulated activity that aims to protect the environment and maximise the productive use of water. Reused water is treated to meet relevant water quality guidelines (such as those in the recently released 2018 edition of the *Australian and New Zealand* *guidelines for fresh and marine water quality* (ANZG, 2018)) for the intended end use and receiving environment.

5.3.3.5 Reinjecting water into aquifer

Effective management of wastewaters produced during shale gas production is critically important, especially as these types of fluids are potentially harmful to the environment if not properly managed. Most wastewaters produced from future shale gas developments in the Isa GBA region are likely to be primarily flowback waters that return to the surface following the injection of large volumes of hydraulic fracturing fluids (which are used to fracture the gas reservoir and enhance permeability). The proportion of hydraulic fracturing fluid that returns to the surface can vary from well to well and field to field (due to factors such as the physical properties of the reservoir and the types of fluids used in the fracturing process) but is typically 25% to 75% of the total injected volume (The Royal Society and The Royal Academy of Engineering, 2012). Consequently, in areas with many production wells, significant volumes of flowback water are likely to exist and thus require appropriate management over the lifespan of the gasfield.

Produced water from the formation is typically a minor component of overall wastewater recovered from shale gas reservoirs (particularly in comparison to volumes of co-produced water from CSG wells). This is due to the greater depths, lower reservoir permeability and lack of water saturation in available pore space within deep shale gas reservoirs. Flowback waters may potentially also contain other constituents that are initially absent from the hydraulic fracturing fluid. These components can occur due to mobilisation of geogenic chemicals within the reservoirs or due to chemical reactions between the injected fluid mixture and the in-situ mineral and/or organic components of the reservoir. A preliminary assessment of geogenic chemicals that may be mobilised in flowback waters from the Isa GBA region is provided in the chemical screening technical appendix (Kirby et al., 2020) and is summarised in Section 6.3.

Disposal of wastewater fluids (both treated and untreated) from unconventional gas wells by reinjection into deep underground formations (such as depleted oil/gas reservoirs or deep unutilised aquifers) is common practice in many parts of the US (US EPA, 2016b). Although it is uncertain to what extent reinjection may occur in the future in the Isa GBA region, this impact mode has been assessed as part of the IMEA (Figure 77). The IMEA for the Isa GBA region identified ten potential hazards associated with the injection of flowback water and/or other fluids into deep aquifers, which are aggregated in the 'reinjecting water into aquifer' causal pathway. Most of the hazards in this causal pathway are low priority. However, there is one high-priority hazard. The potential effects of aquifer reinjection include changes to groundwater quality (i.e. of the target aquifer), changes to groundwater pressures, and reactivation of existing geological faults, which may cause subsequent seismic events (known as 'induced seismicity'). The landscape classes that are most likely to be affected by aquifer reinjection are 'floodplain and alluvium' and/or the 'springs', due to their close association with groundwater systems. A variety of assessment endpoints related to these two landscape classes are potentially affected by aquifer reinjection, including ecological communities, wetland ecosystems and cultural heritage (Figure 77).

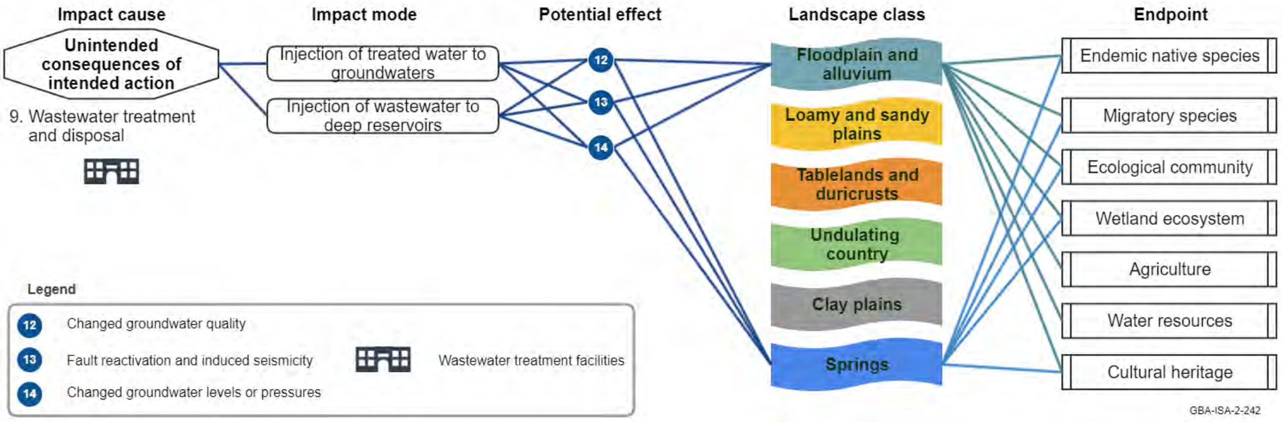

Figure 77 Preliminary conceptualisation of hazards associated with potential future shale gas development in the Isa GBA region in the 'reinjecting water into aquifer' causal pathway

To simplify this diagram, the landscape class 'undulating country' is a combination of three similar classes in the Isa GBA region that collectively comprise less than 5% of the area and occur only in the far west of the region. These are 'hills and lowlands on metamorphic rocks', 'undulating country on fine-grained sedimentary rocks' and 'sandstone ranges'. Similarly, the landscape classes 'tidal flats and beaches' and 'hills and lowlands on granitic rocks' are not shown, as they each comprise less than 0.5% of the region.
The numbered items under 'impact cause' refer to the major activities identified in Figure 56.
Element: GBA-ISA-2-242

Injecting substantial volumes of wastewater into deep aquifers will invariably alter the pre-injection groundwater pressures and quality of the target aquifer to some extent. Consequently, it is necessary to develop a comprehensive understanding of the local geology and groundwater systems in the area prior to reinjection, so that the likely changes can be evaluated and/or modelled. Effective planning is needed to ensure that the deep aquifer targeted for reinjection contains non-potable groundwater that is effectively isolated from other (i.e. shallower) aquifers that may be used for water supply purposes, such as for human, stock or environmental use. Installing an adequate monitoring network is also necessary so that changes in groundwater pressure and quality can be effectively tracked over time, and any unexpected hydrological changes can be detected early and managed appropriately to avoid future risks to productive aquifers.

Probably the highest profile hazard associated with reinjection of wastewaters is the potential for fault reactivation and associated induced seismic events to occur, with several notable examples from the US (e.g. Magnani et al. (2017)). This hazard can arise when increased aquifer pressures (that result from the large volumes of fluid pumped underground) cause pre-existing faults to be reactivated and for some degree of fault plane movement to occur. Indeed, the magnitude of seismic events caused by wastewater disposal injection is typically much greater than events caused by hydraulic fracturing (Zoback, 2012). The probability of seismic events occurring will depend on local geological conditions, such as the number and nature of faults that intersect the reinjection target and the nature of the subsurface stress field, as well as on the volume and rate of reinjected fluid.

Protocols exist in some countries (such as the US) for mitigating seismicity associated with wastewater disposal via aquifer reinjection. These protocols require comprehensive evaluation of reinjection plans against a range of criteria, including understanding historical seismic events, local geology, regional stress fields and the nature of the proposed reinjection process (The Royal

Society and The Royal Academy of Engineering, 2012). It is important to adhere to such protocols and any other relevant jurisdictional regulations, because these mechanisms minimise risks associated with wastewater reinjection. In addition to developing a good understanding of the seismic risk profile at the reinjection site, it is also necessary to design and install an effective seismic monitoring network to monitor baseline seismic activity and potential long-term seismic hazards posed by wastewater reinjection.

5.3.3.6 Sourcing water for site operations

The development and operation of shale gas resources requires large volumes of water (10s to 100s of MLs) throughout all major life-cycle stages, especially during the production stage when the greatest number of wells are drilled. Water is also required to support various other gasfield development activities, such as the construction and maintenance of access roads, pipelines and gas production facilities, as well as site decommissioning and rehabilitation activities. Although the actual volume of water needed for drilling and hydraulic fracturing of a well depends on a variety of factors (such as local geological conditions, vertical drilling depths and horizontal well lengths, and the number of hydraulic fracturing stages per well), typical estimates are that around 1 to 2 ML per well are needed for drilling operations and anywhere from 10 to 25 ML (or more) per well may be needed for fracturing operations. For example, Origin Energy indicated in their submission to the NT fracking inquiry that around 50 to 60 ML of water may be needed to drill and hydraulically fracture each production well in the Beetaloo Sub-basin (Pepper et al., 2018).

As discussed in Section 3.5.3, there are likely to be several options available to supply water for onsite operations in the Isa GBA region, including extraction from locally available (unallocated) groundwater or surface water resources. It may also be possible to reuse flowback water from previously drilled unconventional gas wells, although such water may require treatment to ensure it is suitable for reuse.

The IMEA hazard analysis for the Isa GBA region identified 13 hazards in the 'sourcing water for site operations' causal pathway, with seven related to extraction of groundwater from aquifers and six related to surface water extraction (Figure 78). Changes to groundwater levels or pressures within an aquifer are the main potential effect of extracting groundwater to support shale gas development. Given the volumes required, the spatial extent of aquifer drawdown associated with extractions will typically be localised around water production borefields and are thus most likely to directly affect the 'floodplain and alluvium' and/or the 'springs' landscape classes and their associated endpoints. The 'floodplain and alluvium' landscape class is most likely to be affected by surface water extractions. In addition, the preliminary conceptualisation for this causal pathway explicitly considers the potential for indirect effects to groundwater or surface water that may result from extraction – for example, the potential for changes to shallow groundwater levels or quality due to extraction of hydrologically connected surface waters (Figure 78).

Groundwater levels and pressures will begin to recover to pre-development levels once pumping ceases, although there may be an ongoing intermittent need to extract water at different life-cycle stages (e.g. during workover of a well). Changes to groundwater quality is another potential effect due to extracting groundwater for drilling and hydraulic fracturing operations. For example, extraction of groundwater from one aquifer may induce inter-aquifer flow from adjacent groundwater sources of lower quality, thereby affecting water quality in the target aquifer.

Water supply for shale gas development is governed by existing Queensland water management plans and regulatory conditions. Any new water withdrawals to support shale gas operations in the Isa GBA region must adhere to relevant Queensland Government regulations and water sharing objectives, without inadvertently affecting other water users (including groundwater-dependent ecosystems). Indeed, current controls recognised during the IMEA process to reduce potential impacts of sourcing water for site operations include adherence to existing regulations, good management and operational procedures during extraction, and establishment of effective monitoring systems. A summary of relevant water sharing plans and water accounts for groundwater and surface water systems in the Isa GBA region is in Section 3.5.

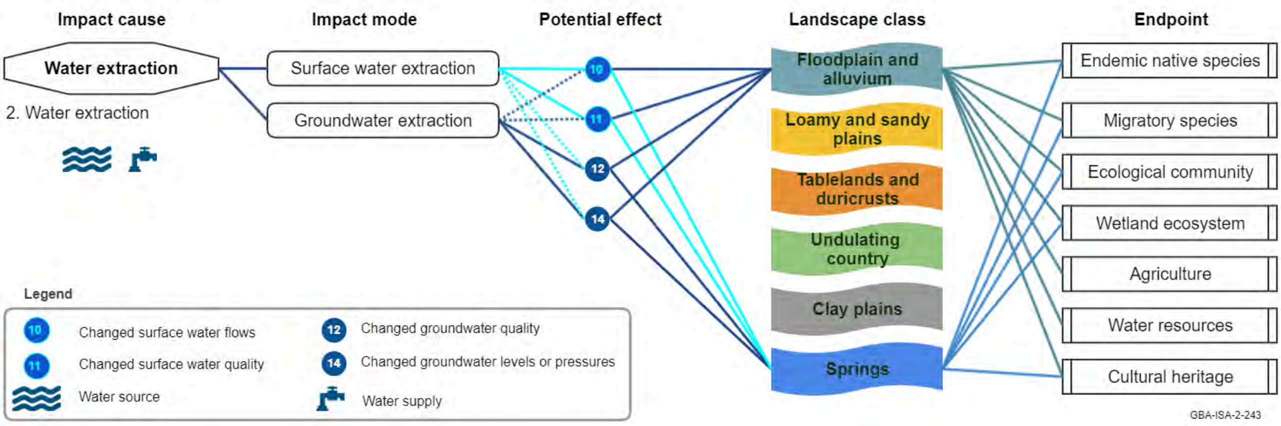

Figure 78 Preliminary conceptualisation of hazards associated with potential future shale gas development in the Isa GBA region in the 'sourcing water for site operations' causal pathway

To simplify this diagram, the landscape class 'undulating country' is a combination of three similar classes in the Isa GBA region that collectively comprise less than 5% of the area and occur only in the far west of the region. These are 'hills and lowlands on metamorphic rocks', 'undulating country on fine-grained sedimentary rocks' and 'sandstone ranges'. Similarly, the landscape classes 'tidal flats and beaches' and 'hills and lowlands on granitic rocks' are not shown, as they each comprise less than 0.5% of the region.
The numbered items under 'impact cause' refer to the major activities identified in Figure 56. The dotted lines indicate potential for indirect effects of groundwater extraction affecting surface waters and for surface water extraction affecting groundwater.
Element: GBA-ISA-2-243

5.4 Knowledge gaps

The assumptions about the timing, extent and operational processes involved with possible future shale gas development in the Isa GBA region are a major knowledge gap that affects estimates of severity and likelihood of potential impacts that were discussed at the hazard workshops and during consultation. A better understanding of these key aspects of shale gas development will reduce uncertainty in the nature and severity of risks expressed by experts at the hazard workshops – particularly the spatial and temporal scales of potential impacts and causal pathways, including changes over time (if relevant) and how they may be affected by the pulsed nature of flows and water inputs at and near the surface in the context of the local ecosystems of the Isa GBA region.

Future impact and risk analysis efforts in the Isa GBA region are recommended to build upon the preliminary conceptual models developed here that link development-related activities and hazards with landscape classes and endpoints specific to the Isa GBA region. Many of the links shown in the various causal pathway conceptual models presented are speculative at this stage of the assessment. In particular, there is considerable uncertainty about the nature of many proposed links between potential effects, different landscape classes and assessment endpoints. There is also a lack of understanding about how the various causal pathways presented here may interact with each other and what the potential cumulative effects of such interactions may be – for example, could the interaction of several causal pathways result in more severe and/or less reversible impacts to landscape classes and endpoints? Further work could seek to better identify how risks from shale gas development may affect protected matters within the environment (e.g. landscape classes), including how it may interact with existing threatening processes such as changing climate patterns, land clearing and biodiversity impacts due to introduced pests, such as weeds and feral animals.

Conceptualisation of the regional geology and hydrogeology, as well as the potential hydrological connections from shale gas reservoirs to near-surface assets such as the regional watertable aquifer, includes substantial uncertainties and alternative conceptual models. Future investigations could focus on capturing, representing and testing many of these uncertainties through the application of relatively simple screening models. For example, uncertainties can be propagated through models by basing predictions upon plausible distributions of model parameters rather than fixed values. The preliminary conceptualisations presented here for each causal pathway will ideally be updated as part of further impact and risk analysis investigations using a range of approaches, including expert elicitation.

6 Qualitative assessments

6.1 Hydraulic fracturing

Hydraulic fracture stimulation is used to create hydraulic fractures in the target petroleum reservoir to maximise the flow of gas to the well. Over the past 50 years, hydraulic fracturing has been used to stimulate conventional oil and gas and unconventional gas reservoirs in Australia. Potential environmental risks of hydraulic fracturing have been the focus of active discussion across industry, government and academic agencies for the past decade and have led to several significant domestic and international inquiries into onshore gas industry operations. A review of the findings of these inquiries, along with a review of the limited hydraulic fracturing activity in the Isa GBA region and hazard identification and scoring (see Section 5.2) for the region, provide an initial assessment of the relative likelihood of occurrence of three impact modes in the Isa GBA region (Table 26). While this initial assessment did not highlight any of the three hydraulic fracturing impact modes as a high priority, one impact mode, ‘F1: hydraulic fracture growth into aquifer’, is recommended for further analysis based on heightened community concern around hydraulic fracturing and the specific geological characteristics of the Isa GBA region.

Hydraulic fracture stimulation is used to increase the productivity of petroleum wells and is critical to the performance of wells in low-permeability ‘unconventional’ reservoirs. Fluid is injected at sufficient pressure and flow rate to propagate hydraulic fractures into the target formation. After the fluid pressure is released, proppant (sand or artificial ceramics) remains in the newly created fracture network to increase the effective permeability in the target formation and ultimately increase the flow of gas to the well. Wells are usually fractured in stages, where isolated sections are fractured individually. The number of hydraulic fracturing stages depends on the length of the well and can range from one to 50 stages per well.

Petroleum industry activity in the Isa GBA region has been minimal to date, resulting in limited data on hydraulic fracture growth in the region. While smaller diagnostic hydraulic fractures have been placed in several oil and gas wells, the first large-scale hydraulic fracture stimulation in the Isa GBA region was completed in the horizontal component of the Egilabria 2 exploration well over the Lawn Supersequence in 2013. The subsequent production tests represented the first successful gas flows from a multistage, fracture-stimulated, laterally drilled shale gas well in Australia (Johnson and Titus, 2014). Figure 79 shows the location of the Egilabria 2 exploration well where the hydraulic fracturing activity took place.

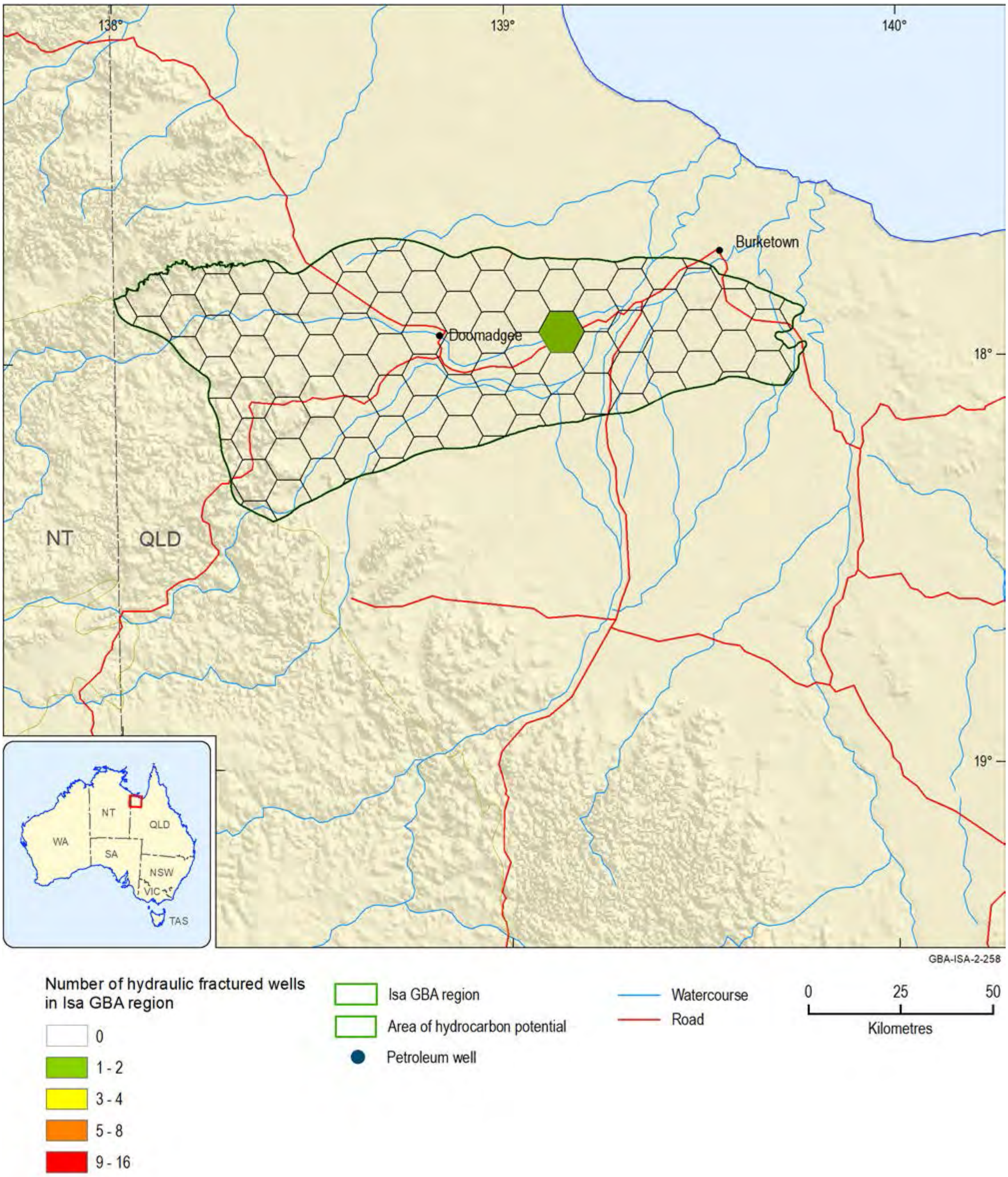

Figure 79 Location of the hydraulically fractured Egilabria 2 exploration well in the Isa GBA region

The Egilabria 2 petroleum exploration well occurs in the green hexagon.
Element: GBA-ISA-2-258

Over the last decade, the potential environmental risks of hydraulic fracturing have been the focus of active discussion and investigation across industry, government and academic agencies (Davies, 2011; Atherton et al., 2014; Vengosh et al., 2014; Wright, 2014; Dusseault and Jackson, 2014; Hawke, 2014; US EPA, 2016b; Pepper et al., 2018; Hatton et al., 2018).

In response to heightened public interest in the risks associated with hydraulic fracturing, international and domestic inquiries have reviewed hydraulic fracturing activities, including considering the potential likelihoods of many of the impact modes in their local contexts. Although local geological properties, in-situ stresses and applied hydraulic fracture techniques will impact local risk profiles, the qualitative findings of these domestic and international reviews provide an important line of evidence in assessing the relative likelihood of each impact mode in the Isa GBA region. The findings from nine of these international and domestic inquiries have been interpreted to distil, where possible, a relative likelihood of occurrence for each impact mode. These findings are summarised in Table 26, with further details available in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020).

While there are several impact modes by which hydraulic fracturing activities could potentially dilate or create a pathway for fluid migration between subsurface geological layers or to the surface, the likelihood of those impacts occurring is generally considered manageable to a suitably low level given appropriate regulatory controls, sufficient understanding of the baseline geological and environmental systems, and acceptable industry practices (US EPA, 2016b; Hawke, 2014; Cook et al., 2013b; The Royal Society and The Royal Academy of Engineering, 2012; Wright, 2014; Council of Canadian Academies, 2014; Atherton et al., 2014; Pepper et al., 2018; Hatton et al., 2018). However, several sources (Council of Canadian Academies, 2014; Jackson et al., 2013; US EPA, 2016b; Vidic et al., 2013) noted that, due to the difficulty in observing potential impacts, especially to groundwater resources, it is challenging to validate many of the estimates of rates of these occurrences. The uncertainty caused by the lack of validation data cannot be fully overcome within the scope of the GBA Program.

The qualitative review in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020) compares data from the Egilabria 2 exploration well in the Isa GBA region with findings from international and domestic hydraulic fracturing inquiries. This comparison presents an initial evaluation of the likelihood of three impact modes by which hydraulic fracturing could conceivably cause contaminants to impact ecosystems and values in the Isa GBA region.

The three impact modes relating to hydraulic fracture stimulation that were considered in the hazard analysis and qualitative review (Kear and Kasperczyk, 2020) are:

- F1 – hydraulic fracture growth into aquifer
- F2 – hydraulic fracture growth into well
- F3 – hydraulic fracture growth into fault.

Each impact mode was evaluated against the findings of the various domestic and international inquiries, as well as data from the Egilabria 2 exploration well and the hazard scoring results from the hazard screening workshop for the Isa GBA region. The evaluation results are shown in Table 26, with details of the review presented in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020).

The scoring from the hazard screening workshop (Section 5.2) did not highlight any of these three hydraulic fracturing impact modes in the highest priority tier (based on assessed severity and likelihood of the potential impacts). However, the growth of hydraulic fractures into a well was ranked as a mid-tier hazard. These findings are broadly consistent with the findings of the qualitative review of the domestic and international inquiries.

Analyses of the Isa GBA region geological data indicated that there is a slightly higher potential likelihood (unlikely vs rare) of 'F1: hydraulic fracture growth into aquifer' than encountered in other shale gas study areas. This is due to the relative proximity of the River Supersequence to the underlying Lady Loretta Formation aquifer (e.g. see schematic cross-section in Figure 19), as well as proximity of the Lawn 4 sequence to the overlying Gilbert River Formation (basal GAB aquifer). Although the likelihood of this occurrence is considered low and the hazard score alone is not sufficient to warrant prioritisation, the impact mode 'F1: hydraulic fracture growth into aquifer' is recommended for further analysis on the basis of heightened community concern around hydraulic fracturing and the local geological characteristics of the Isa GBA region.

Table 26 Summary of likelihoods for hydraulic fracturing impact modes

Likelihood terminology definitions and further details of the reviews are in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020).

Likelihood estimates	F1 – hydraulic fracture growth into aquifer	F2 – hydraulic fracture growth into well	F3 – hydraulic fracture growth into fault
Isa GBA region hazard identification (Isa IMEA dataset)	Rare – Very unlikely	Rare – Unlikely	Rare – Very unlikely
Likelihood estimated from historical Isa GBA region data (Kear and Kasperczyk, 2020)	Unlikely	Rare	Rare
Overall qualitative likelihood from the nine inquiries	Rare	Unlikely	Rare
Range of inquiry qualitative likelihood ratings	Rare – Unlikely	Rare – Unlikely	Rare – Unlikely
Hydraulic fracturing for oil and gas: impacts from the hydraulic fracturing water cycle on drinking water resources in the United States (US EPA, 2016b)	Unlikely	Unlikely	Rare
Report of the independent inquiry into hydraulic fracturing in the Northern Territory (Hawke, 2014)	Rare	Not assessed	Unlikely
Engineering energy: unconventional gas production. Report for the Australian Council of Learned Academics (Cook et al., 2013b)	Unlikely	Not assessed	Unlikely
Shale gas extraction in the UK: a review of hydraulic fracturing (The Royal Society and The Royal Academy of Engineering, 2012)	Rare	Not assessed	Unlikely
Drilling for oil and gas in New Zealand: environmental oversight and regulation (Wright, 2014)	Not assessed	Not assessed	Not assessed
Environmental impacts of shale gas extraction in Canada (Council of Canadian Academies, 2014)	Rare	Unlikely	Rare
Report of the Nova Scotia Independent Panel on Hydraulic Fracturing (Atherton et al., 2014)	Rare	Unlikely	Not assessed
Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory (Pepper et al., 2018)	Rare	Not assessed	Rare

Likelihood estimates	F1 – hydraulic fracture growth into aquifer	F2 – hydraulic fracture growth into well	F3 – hydraulic fracture growth into fault
Independent scientific panel inquiry into hydraulic fracture stimulation in Western Australia (Hatton et al., 2018)	Rare	Rare	Unlikely

6.2 Compromised well integrity

Compromised well integrity is a concern for government and the community. Regulations for construction of wells aim to ensure that fluid and gas are prevented from flowing unintentionally from the reservoir into another geological layer or to the surface. In this qualitative review, Isa GBA region historical data were compared with findings from international and domestic inquiries to present an initial evaluation of five conceptual impact modes (Table 27). These were compared with the prioritisations from the Isa GBA region hazard identification (Section 5.2) and are broadly consistent. Two priority impact modes are recommended for further investigation as part of any future impact and risk analysis: 'W3 – migration of fluids between different geological layers along a failure of the well casing' and 'W4 – failure of well integrity after well decommissioning/abandonment' (Section 6.4).

Petroleum wells are constructed to have integrity such that fluid and gas are prevented from flowing unintentionally from the reservoir into another stratigraphic layer or to the surface. The components that prevent this fluid movement are known as 'well barrier elements' and form 'well barriers'. The well barriers are pressure containment envelopes, and maintenance of their integrity is typically required under international standards for industry practice and regulations (e.g. Department of Natural Resources Mines and Energy, 2018; ISO 16530; NORSOK Standard D-010 and ANSI/API RP 100-1 and 100-2). By having multiple well barriers, a failure within one well barrier element does not result in the loss of integrity of a well (US EPA, 2016b).

If the integrity of a well were to be compromised, there could be a potential pathway for fluids to flow vertically between geological layers and/or to the surface. Although there are several impact modes by which loss of well integrity could potentially cause the well to act as a conduit for fluid migration, the likelihood of those impact modes occurring is generally considered manageable to a suitably low level. Management will depend on appropriate regulatory controls, sufficient understanding of the baseline geological and environmental systems, and acceptable industry practices (US EPA, 2016b; Hawke, 2014; Cook et al., 2013b; The Royal Society and The Royal Academy of Engineering, 2012; Wright, 2014; Council of Canadian Academies, 2014; Atherton et al., 2014; Pepper et al., 2018; Hatton et al., 2018). However, data limitations make it difficult to assess the rates at which well integrity failures have impacted groundwater resources (Council of Canadian Academies, 2014; Jackson et al., 2013; US EPA, 2016b; Vidic et al., 2013). The uncertainty caused by the lack of validation data cannot be fully overcome within the scope of this assessment.

The qualitative review in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020) compares the limited data available for the Isa GBA region (Figure 80) with findings from international and domestic inquiries to present an initial evaluation of the likelihood of five impact modes by which well integrity failures could conceivably cause contaminants to impact ecosystems in the Isa GBA region.

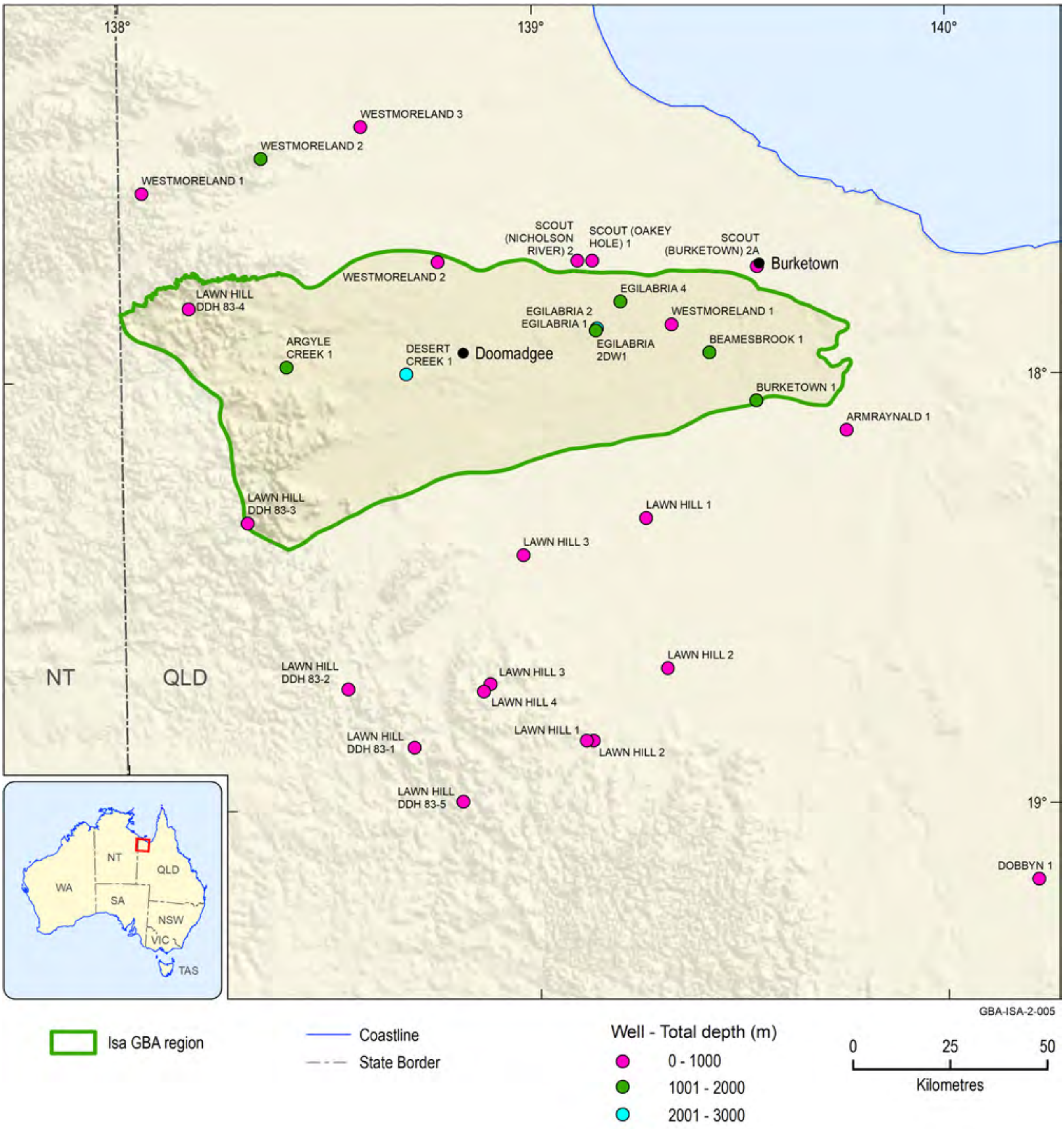

Figure 80 Distribution of stratigraphic and petroleum exploration wells across the Isa GBA region and surrounds, classified according to depth of penetration

Egilabria 2 DW1 is a lateral well. The Westmoreland 1 and Westmoreland 2 wells to the north of the Isa GBA region are stratigraphic wells drilled by the Geological Survey of Queensland in 1984; those of the same name within the Isa GBA region, and Westmoreland 3 to the north, are stratigraphic wells drilled by the Bureau of Mineral Resources in 1970 and 1972.
Source: State of Queensland (2018)
Element: GBA-ISA-2-005

Three of the reviewed well integrity failure impact modes relate to the production life-cycle stage of a well:

- W1 – rupture or failure across well barriers that allows fluids to move between the inside and the outside of the well
- W2 – migration of fluids from the reservoir to the surface along a failure of the well casing
- W3 – migration of fluids between different geological layers along a failure of the well casing.

Two of the reviewed impact modes relate to well integrity failure during construction, workover and decommissioning operations:

- W4 – failure of well integrity after well decommissioning / abandonment
- W5 – loss of well control (blowout).

Each of the five reviewed well integrity failure impact modes has been evaluated against the findings of significant domestic and international inquiries, historical data from the Isa GBA region (information available from the petroleum wells drilled in Figure 80) and the results from the Isa GBA region hazard screening process (Section 5.2). The evaluation results are shown in Table 27, with further details available in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020).

Two aspects of the Isa GBA region are relevant to the qualitative assessment of the compromised well integrity impact modes: the very low permeability of the Isa GBA region shale gas target intervals and the geological conditions in the Lawn Supersequence (see Section 2.2). Shale gas wells drilled in low-permeability reservoirs, such as those of the Isa GBA region, are intrinsically less prone to significant loss of well control incidents, as they cannot support significant flow to surface until after the well has been completed and hydraulically fractured (Huddlestone-Holmes et al., 2018). In addition, although some overpressured intervals were encountered during the drilling of the Egilabria 2 well (Johnson and Titus, 2014), the petroleum prospectivity technical appendix does not anticipate overpressured intervals to be common in the Isa GBA region (Bailey et al., 2020). Overpressured intervals are required to provide the driving pressure to enable the flow of fluids to the surface in the event of a well integrity failure.

Johnson et al. (2014) noted that horizontal drilling instabilities through the Lawn Supersequence in the Egilabria 2 well led to a two-stage cement job with areas of poor cement bonding. These apparently difficult geological conditions in the Lawn Supersequence could require future operators to develop appropriate engineering techniques to achieve competent cement jobs to reduce the likelihood of well annulus integrity problems. Additional details of well integrity qualitative considerations in the Isa GBA region are presented in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020).

Table 27 Summary of likelihoods for compromised well integrity impact modes

Likelihood terminology definitions and further details of the reviews are available in the hydraulic fracturing technical appendix (Kear and Kasperczyk, 2020).

Likelihood estimates	W1 – rupture or failure across well barriers that allows fluids to move between the inside and the outside of the well	W2 – migration of fluids from the reservoir to the surface along a failure of the well casing	W3 – migration of fluids between different geological layers along a failure of the well casing	W4 – failure of well integrity after well decommissioning / abandonment	W5 – loss of well control (blowout)
Isa GBA region hazard identification (Isa IMEA hazard dataset)	Rare – Unlikely	Rare – Unlikely	Rare – Possible	Unlikely – Possible	Rare – Unlikely
Likelihood estimated from historical Isa GBA region data (Kear and Kasperczyk, 2020)	Rare	Rare	Unlikely	Not assessed	Rare
Overall qualitative likelihood from the nine inquiries	Rare	Rare	Unlikely	Unlikely	Not assessed
Range of inquiry qualitative likelihood ratings	Very rare – Rare	Rare – Unlikely	Very rare – Unlikely	Unlikely – Likely	Not assessed
Hydraulic fracturing for oil and gas: impacts from the hydraulic fracturing water cycle on drinking water resources in the United States (US EPA, 2016b)	Rare	Unlikely	Unlikely	Unlikely	Not assessed
Report of the independent inquiry into hydraulic fracturing in the Northern Territory (Hawke, 2014)	Rare	Rare	Vary rare	Unlikely	Not assessed
Engineering energy: unconventional gas production. Report for the Australian Council of Learned Academics (Cook et al., 2013b)	Rare	Not Assessed	Unlikely	Unlikely	Not assessed
Shale gas extraction in the UK: a review of hydraulic fracturing (The Royal Society and The Royal Academy of Engineering, 2012)	Not Assessed	Rare	Not Assessed	Unlikely	Not Assessed
Drilling for oil and gas in New Zealand: environmental oversight and regulation (Wright, 2014)	Rare	Rare	Not assessed	Unlikely	Not assessed
Environmental impacts of shale gas extraction in Canada (Council of Canadian Academies, 2014)	Rare	Unlikely	Unlikely	Unlikely	Not assessed

Likelihood estimates	W1 – rupture or failure across well barriers that allows fluids to move between the inside and the outside of the well	W2 – migration of fluids from the reservoir to the surface along a failure of the well casing	W3 – migration of fluids between different geological layers along a failure of the well casing	W4 – failure of well integrity after well decommissioning / abandonment	W5 – loss of well control (blowout)
Report of the Nova Scotia Independent Panel on Hydraulic Fracturing (Atherton et al., 2014)	Vary rare	Rare	Rare	Likely	Rare
Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory (Pepper et al., 2018)	Rare	Rare	Unlikely	Unlikely	Not assessed
Independent scientific panel inquiry into hydraulic fracture stimulation in Western Australia (Hatton et al., 2018)	Vary rare	Not assessed	Rare	Unlikely	Not assessed

6.3 Screening of drilling and hydraulic fracturing chemicals

A total of 116 chemicals have been identified as being associated with drilling and hydraulic fracturing at shale, tight and deep coal gas operations in the three regions (Cooper, Isa and Beetaloo) of the GBA Program between 2011 and 2016. Of the 116 chemicals, nine were drilling chemicals, 99 were hydraulic fracturing chemicals and eight were chemicals used for both drilling and hydraulic fracturing. Fifty-eight percent of the chemicals identified in the current study were not assessed in the *Identification of chemicals associated with coal seam gas (CSG) extraction in Australia* (NICNAS, 2017).

A Tier 1 qualitative (screening) environmental risk assessment (ERA) of these chemicals found: (i) 42 chemicals were of ‘low concern’ and considered to pose minimal risk to aquatic ecosystems; (ii) 33 chemicals were of ‘potentially high concern’; and (iii) 41 were of ‘potential concern’. Further site-specific quantitative chemical assessments of the identified chemicals of potential concern and potentially high concern would need to be performed to determine risks from specific gas development to aquatic ecosystems.

Methods snapshot: laboratory analyses of shale gas source rocks in the Isa GBA region

Natural rock formations contain elements and compounds (geogenic chemicals) that could potentially be mobilised into flowback and produced waters during hydraulic fracturing. Laboratory-based leachate and extraction tests were undertaken to provide an upper-bound estimate of geogenic chemical mobilisation from target formations in the Isa GBA region. The test results are intended to guide future field-based monitoring, management and treatment options. The leachate tests on powdered rock samples collected from geological units in the Isa GBA region identified several elements that could be substantially mobilised into solutions by hydraulic fracturing fluids: aluminium, barium, cadmium, cerium, cobalt, copper, iron, lanthanum, manganese, neodymium, nickel, lead, yttrium and zinc. Targeted polycyclic aromatic hydrocarbons (PAHs) were detected in six of nine sample extracts. Phenols were not detected (below reporting limits) in powdered rock sample extracts. The highest concentration of total recoverable hydrocarbons (TRHs) was found to be associated with the >C16–C34 National Environmental Protection Measure (NEPM) TRHs (54 to 134 mg/kg; 41% to 46% TRHs) and TRHs C15–C28 (26 to 105 mg/kg; 19% to 34% TRHs) fractions in sample extracts. Targeted analysis of PAHs represented a small fraction of the total organic geogenic compounds present in the sample extracts. Hence, the majority of organic compounds in sample extracts (as TRHs) were unidentified and their risk (individual and mixtures) to aquatic environments is unknown.

The composition and concentration of geogenic chemicals in flowback and produced waters will depend on many factors, including: (i) geology and mineralogy of formations; (ii) surface area of the fracture network exposed to hydraulic fracturing fluids; (iii) composition and concentration of chemicals used in hydraulic fracturing; (iv) residence time of hydraulic fracturing fluids in formations; (v) operational and environmental conditions (e.g. volumes added and recovered, temperature, pressure); and (vi) chemical and physical reactions (e.g. adsorption, complexation, precipitation, aggregation, degradation and transformations).

The independent collection and open and transparent reporting of water quality data at future gas operations before, during and after hydraulic fracturing would improve community and government understanding of the ERA process, controls and monitoring of chemicals; and inform wastewater management and treatment options.

6.3.1 Identification of chemicals associated with shale, tight and deep gas operations

Industrial chemicals are required in shale, tight and deep coal gas operations[1] for activities such as drilling, cementing, well construction and completion, well clean-up, hydraulic fracturing and waste treatment. The composition and concentration of chemicals will depend on site-specific conditions such as geology and mineralogy of formations, environmental conditions such as temperature and pressure, and requirements to maintain well integrity and production. The managed use or accidental release of chemicals (industrial and geogenic) may have negative impacts on local and regional water quality (surface water and groundwater) and water-dependent ecosystems if not adequately controlled or managed.

Companies undertake an ERA of gas operations (in consultation with government agencies) that includes identifying potential hazards (e.g. chemical transport and storage, hydraulic fracturing fluid injection, flowback and produced water storage), determines the likelihood and consequence of a risk event occurring, identifies and evaluates control and mitigation measures (e.g. what controls are in place or need to be in place to address the identified risk and how effective are

[1] Although only shale gas resources have been assessed for the Isa GBA region in this study, the approach to identify drilling and hydraulic fracturing chemicals took a broader view and was done for all three regions assessed for the GBA Program.

these controls), and develops a monitoring program to ensure controls and management strategies are adequate/effective and for compliance.

6.3.1.1 Drilling chemicals

Shale, tight, and deep coal gas operations will require the construction of a well to access formations at depths to liberate the gas reserves. The wells are constructed to provide the necessary integrity and isolation (e.g. from groundwater) during the operational phase and post-decommissioning. As the well is being drilled, a series of metal casings are installed and cemented to provide well stability, integrity and isolation from aquifers and other non-target formations. The target formation(s) for gas production are accessed at specific well depths by perforating (creating small holes) the well casing and cement using small explosive charges or guns. Well pressure is tested at different stages during drilling and completion prior to hydraulic fracturing to monitor and confirm the well integrity.

6.3.1.2 Hydraulic fracturing fluid chemicals

Hydraulic fracturing (Section 6.1) involves the injection of fluids with chemical additives under high pressure to fracture the target rock formations and enable gas to flow into the well. Common chemical additives in hydraulic fracturing fluids for shale, tight and deep coal gas operations are listed in Table 28.

Table 28 Common hydraulic fracturing fluid chemical additives used in shale, tight, and deep coal gas operations

Chemical additive	Purpose
Acid/solvent	Removes mineral scales and deposits, and cleans the wellbore prior to hydraulic fracturing; dissolves minerals and initiates fractures in formations
Buffer/acid	Adjusts pH to maintain the effectiveness of fluid components and iron control
Biocide	Prevents or limits bacterial growth that can result in clogging, unwanted gas production, and corrosion
Clay stabiliser	Prevents swelling or shifting in formations
Crosslinking agent	Used to link polymers or gelling agent to improve cohesion, adhesion and thermal stability and maintain fluid viscosity
Inhibitor mineral scales and deposits	Prevents build-up of material on sides of well casing and surface equipment; iron control agent to prevent precipitation of metal oxides, such as iron oxides and hydroxides
Friction reducer	Minimises friction of the hydraulic fracturing fluid
Corrosion inhibitor	Prevents damage to the wellbore and corrosion of pipes
Surfactant	Allows for increased matrix penetration and aids in recovery of water/fluid
Proppant	Holds open fractures to allow gas flow
Gelling agent / viscosifier	Adjusts fluid viscosity and thickens fluid to suspend the proppant
Breaker/deviscosifier	Degrades or breaks down the gelling agent/viscosifier

In general, most of the hydraulic fracturing fluid consists of water (>97%), with smaller proportions of proppant (sand) and chemical additives (Figure 81).

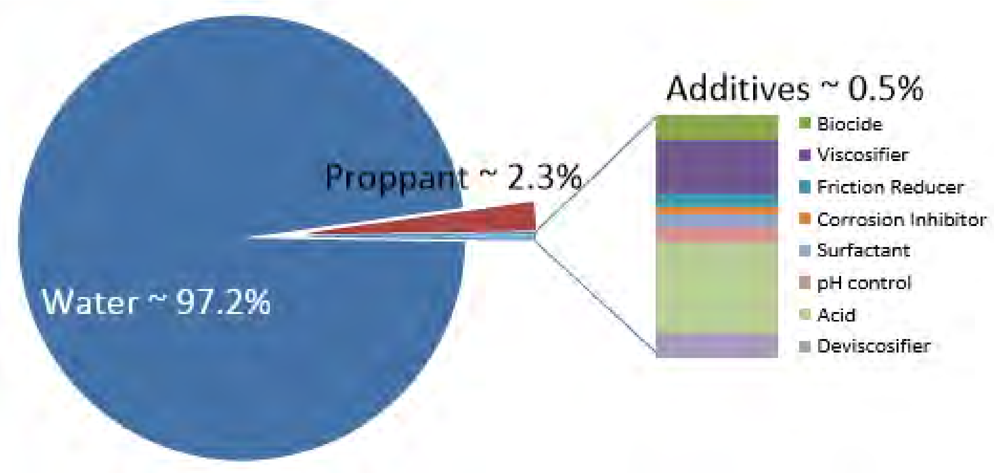

Figure 81 Example of overall percentages of water, proppant and chemical additives in hydraulic fracturing fluid in a deep shale gas well fracturing operation in the Cooper Basin

Source: figure reproduced from Beach Energy and RPS (Beach Energy and RPS, 2012)
Element: GBA-ISA-2-245

The well pressure and volumes of hydraulic fracturing fluids added and recovered are routinely monitored in wells during stimulation to assess well integrity and optimise gas production. Typically, flowback and produced water, and liquid from the gas separator, are directed to storage locations/ponds/tanks (above or below ground), which have specifications dependent on the environmental conditions and requirements at the well site. Depending on the water quality, environmental conditions and treatment/management costs, the stored wastewater can be: (i) treated onsite (e.g. reverse osmosis); (ii) reused, or recycled onsite (e.g. dust suppression); (iii) used for beneficial purposes by the company or a third party (e.g. irrigation pending the necessary approvals and it being fit for purpose); (iv) evaporated onsite in ponds to a solid waste or brine for storage in a controlled manner; (v) reinjected to deep aquifers (pending the necessary approvals); or (vi) transported and disposed offsite at an approved treatment/disposal facility.

6.3.1.3 Geogenic (natural) chemicals

Natural rock formations contain geogenic chemicals (compounds and elements) that could be mobilised into flowback and produced waters during hydraulic fracturing activities. These geogenic chemicals include nutrients, organics (e.g. PAHs and phenols), metals and metalloids (e.g. arsenic, manganese, barium, boron and zinc) and naturally occurring radioactive materials (NORMs) (e.g. isotopes of radium, thorium and uranium). The composition and concentration of geogenic chemicals in flowback waters will depend on many factors, including: (i) geology and mineralogy of formations; (ii) surface area of the fracture network exposed to hydraulic fracturing fluids; (iii) composition and concentration of chemicals used in hydraulic fracturing; (iv) residence time of hydraulic fracturing fluids in formations; (v) operational and environmental conditions (e.g. volumes added and recovered, temperature, pressure); and (vi) chemical reactions (e.g. adsorption, complexation, precipitation, aggregation, degradation and transformations).

Aim, objectives and methods snapshot: Tier 1 qualitative chemical screening ERA and laboratory-based leachate and extraction tests

The aim of the chemical screening study was to gain a better understanding of risks of chemicals to surface water and groundwater quality and aquatic ecosystems from shale, tight and deep coal gas operations in Australia. The objectives were to:

1. undertake a Tier 1 qualitative ERA for chemicals associated with shale, tight and deep coal operations in the three GBA regions in Australia

2. identify geogenic chemicals (compounds and elements) that could be mobilised into flowback and produced waters from powdered rock samples sourced from target formations in the Isa GBA region due to hydraulic fracturing.

An ERA provides for a systematic and transparent approach for evaluating the likelihood and consequences that adverse ecological effects may occur due to exposure to one or more stressors (e.g. chemicals) (Norton et al., 1992; US EPA, 1992). The Australian Government Department of the Environment and Energy has outlined a framework for performing an ERA of chemicals associated with CSG extraction in Australia (Department of the Environment and Energy, 2017b). This framework provides a sound basis for undertaking an ERA of chemicals associated with shale, tight and deep coal gas operations in Australia. A tiered approach to ERA is often used to provide a systematic way of evaluating risk that is proportional to resources, complexity, and cost (Department of the Environment and Energy, 2017b; US EPA, 2004). The tiers progress in complexity and refinement from Tier 1 to Tier 3. In this study, Tier 1 qualitative chemical screening was undertaken as an initial step in the ERA chemical assessment process (on chemical data sourced at the time of the study) to determine if the use of chemicals poses a potential risk to aquatic ecosystems. If a potential risk was identified from chemicals, a site-specific quantitative chemical assessment would need to be undertaken to determine risks from specific gas development to aquatic ecosystems.

A Tier 1 qualitative ERA was undertaken on identified drilling and hydraulic fracturing fluid chemicals used in shale, tight and deep coal gas activities across the three regions in the GBA program (Cooper, Isa and Beetaloo) during 2011 to 2016 (chemical screening technical appendix (Kirby et al., 2020)). The main exposure pathway for chemicals, if released during shale, tight and deep coal gas operations, will likely occur through water (surface water and groundwater); hence, this assessment focused on the potential effects to aquatic organisms. The Tier 1 assessment used a decision tree framework that evaluates sourced data for chemicals in relation to their persistence (P), bioaccumulation (B) and toxicity (T) to aquatic organisms (Figure 82). A conservative (precautionary) approach (e.g. P, B, T data sourced only from standard testing protocols and international recognised ERA organisations/agencies and models, and assessments did not make assumptions based on chemical classes or groups) was applied to the evaluation of chemical and ecotoxicity data and in the Tier 1 qualitative ERA.

Laboratory-based leachate and extraction tests on powdered rock samples from formations in the Isa GBA region were undertaken to examine potential mobilisation of geogenic chemicals (elements and compounds) into solution from exposure to a hydraulic fracturing fluid (refer to chemical screening technical appendix (Kirby et al., 2020)). The laboratory-based tests were designed to provide an upper-bound estimate of geogenic chemical mobilisation from target formations in the Isa GBA region and intended to guide future field-based monitoring, management and treatment options. Powdered rock samples (<70 μm) were sourced from formations based on their potential as targets for shale gas development in the Isa GBA region: Lawn Hill, Termite Range and Riversleigh Siltstone. For inorganic elements, the leachate test solutions comprised a synthetic groundwater, dilute hydrochloric acid and an in-house hydraulic fracturing fluid at 80°C. Leachate tests were also conducted at elevated pressure (18,400 KPa) to ascertain if pressure can have an effect on geogenic chemical (element) mobilisation. A wide range of inorganic elements (>60) were quantified in leachates using inductively coupled plasma-atomic emission spectrometry (ICP-AES) and inductively coupled plasma-mass spectrometry (ICP-MS). For organic compounds, powdered rock samples were extracted using an accelerated solvent extraction (ASE) system and a combination of hydrophilic and hydrophobic solvents. The solvent extracts were analysed for a range of targeted priority organics compounds: 14 substituted phenols, 15 PAHs, and TRH fractions (C10–C40).

Additional information on the experimental design, methodology, findings, and conclusions is in the chemical screening technical appendix (Kirby et al., 2020).

6.3.2 Chemical screening assessment

6.3.2.1 Chemicals associated with shale, tight and deep coal gas operations in the three GBA regions in Australia

A total of 116 chemicals were identified for use in drilling and hydraulic fracturing at shale, tight and deep coal gas operations between 2011 and 2016 (chemical screening technical appendix (Kirby et al., 2020)). Of the 116 chemicals identified, nine were drilling chemicals, 99 were hydraulic fracturing chemicals and eight were chemicals used for both activities. An additional 32 proprietary chemicals were identified as being used for drilling and hydraulic fracturing but are not assessed here due to limitations in public disclosure of information.

A similar number of chemicals (n=113) were identified as being used with CSG extraction in Australia (NICNAS, 2017). Fifty-eight percent of the chemicals (n=67) identified in the current study were not assessed in the *Identification of chemicals associated with coal seam gas extraction* (NICNAS, 2017). Of the 67 chemicals not previously assessed, a Tier 1 qualitative ERA found 16 chemicals were of ‘low concern’, 28 chemicals were of ‘potential concern’ and 23 chemicals were of ‘potentially high concern’. The additional chemicals identified in this study for shale, tight and deep coal gas operations may be due to site-specific requirements needed for higher temperatures and pressure, geology and mineralogy of the specific formations, scale and biofilm build-up, fluid stability and viscosity, proppant transport, improved gas extraction and efficiency, and a move by industry towards ‘greener, safer’ options.

The Tier 1 screening of 116 chemicals identified 42 of ‘low concern’ (Screen 1 (13) and Screen 4 (29)), 33 of ‘potentially high concern’ (Screen 2), and 41 of ‘potential concern’ (Screen 3 (18) and Screen 4 (23)) (Figure 83). Data on persistence, bioaccumulation and ecotoxicity for individual chemicals and screening categories are reported in the chemical properties and ecotoxicity database (Geological and Bioregional Assessment Program, 2018f) and chemical screening technical appendix (Kirby et al., 2020).

Of the 33 chemicals identified as being of ‘potentially high concern’, five chemicals (one biocide and four defoaming agents) are not likely to be easily degraded (persistent), are bioaccumulative (potentially can accumulate in aquatic organisms) and exhibit very high acute toxicity to aquatic organisms (P, B, T chemicals) (Table 29; Figure 83; chemical screening technical appendix (Kirby et al., 2020)). Such chemicals are considered a high concern/risk to the environment, as they can pose serious harm to aquatic ecosystems if released and require specific controls to prevent their release into the environment.

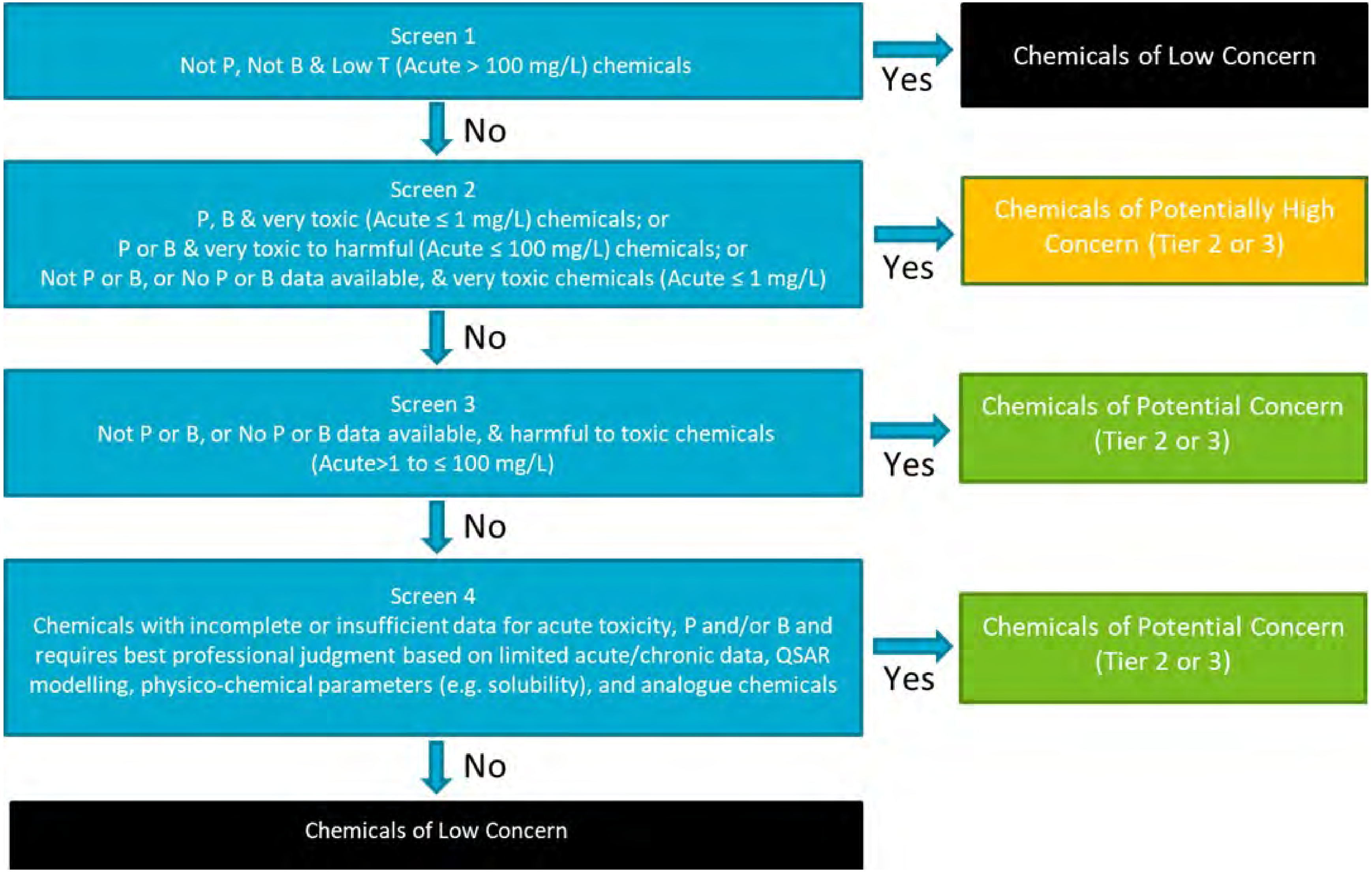

Figure 82 Decision tree framework for Tier 1 qualitative (screening) ERA of chemicals associated with shale, tight, and deep coal gas operations in Australia

P = persistent; B = bioaccumulative; T = toxic; QSAR = quantitative structure-activity relationships

Element: GBA-ISA-2-246

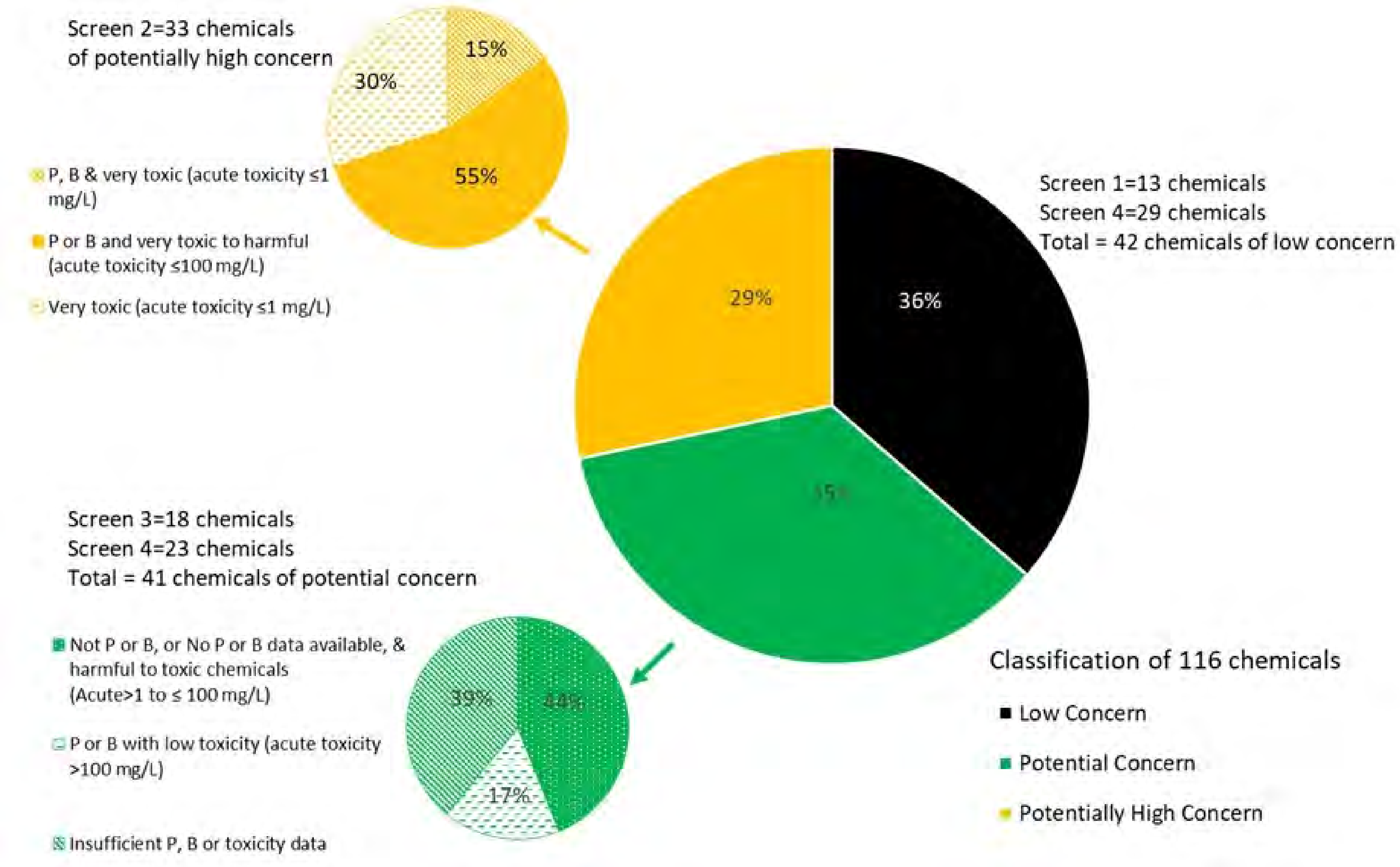

Figure 83 Tier 1 qualitative ERA of chemicals associated with shale, tight and deep coal gas operations in Australia

Refer to Figure 82 for Screen 1 to 4 details. Percentage of chemicals in each category are shown in each segment. Further breakdown of chemicals of 'potential concern' and 'potentially high concern' are shown in the smaller coloured circles.
P = persistent; B = bioaccumulative; T = toxic
Element: GBA-ISA-2-247

Table 29 Chemicals of 'potentially high concern' that are persistent (P) and bioaccumulative (B), and exhibit very high acute toxicity (T)

Chemical	CAS RN	Use	P1[a]	B2[b]	T3[c]
Dicoco dimethyl ammonium chloride	61789-77-3	Biocide/surfactant	##	‡‡	***
Decamethylcyclopentasiloxane (D5)	541-02-6	Defoaming agent / surfactant	##	‡‡	***
Silicone oil (poly(dimethyl siloxane)	63148-62-9	Defoaming agent / surfactant	##	‡‡	***
Dodecamethylcyclohexasiloxane (D6)	540-97-6	Defoaming agent / surfactant	##	‡‡	***
Octamethylcyclotetrasiloxane (D4)	556-67-2	Defoaming agent / surfactant	##	‡‡	***

[a]Persistence = half-life >60 days (##); [b]Bioconcentration factor = BCF >2000 or octanol/water partition coefficient = Log Kow ≥ 4.2 (‡‡); [c]Toxicity = ≤1 mg/L (***)
CAS RN = Chemical Abstracts Services Registry Number

The remaining 28 chemicals identified as being of 'potentially high concern' are persistent or bioaccumulative and harmful to very toxic chemicals (n=18) (Table 30; Figure 83) or not persistent or bioaccumulative (or no data available) and very toxic (n=10) chemicals (Table 31; Figure 83) to aquatic organisms. These chemicals can pose serious harm to aquatic ecosystems if released and require specific controls to prevent their release into the environment. Persistent and bioaccumulative chemicals are generally considered of high concern in the environment due to the potential for organisms to be exposed for longer time periods (chronic effects). There were limited aquatic chronic toxicity data available (using standard tests) for most of the 116 chemicals associated with shale, tight and deep coal gas operations in Australia.

The 41 chemicals identified as 'potential concern' are not persistent and not bioaccumulative (or no persistence and bioaccumulative data could be sourced) but are toxic or harmful chemicals (n=18) (Screen 3) and are chemicals with incomplete data that require professional judgment (n=23) (Screen 4) (Figure 83). These chemicals have the potential to harm aquatic ecosystems if released and may require specific control and management measures to prevent their release into the environment.

For Screen 4 (Figure 83), seven of the 52 chemicals identified were found to be persistent or bioaccumulative and have low toxicity. These seven chemicals are: (i) 1-benzyl quinolinium chloride; (ii) sodium acryloyldimethytaurate; (iii) amaranth (acid red 27); (iv) alcohols, C6-12 ethoxylated propoxylated; (v) ethylene glycol butyl ether; (vi) poly(ethylene glycol); and (vii) tall oil (fatty acids). Since the Tier 1 ERA used mainly acute toxicity data, these chemicals are considered to be of 'potential concern' due to their unknown effects on organisms that may occur due to long-term exposure (chronic toxicity).

Table 30 Chemicals of 'potentially high concern' that are persistent (P) or bioaccumulative (B), and harmful to very toxic (T)

Chemical	CAS RN	Use	P1[a]	B2[b]	T3[c]
1,2,4-Trimethylbenzene	95-63-6	Solvent	##	‡	**
1-Benzyl methyl pyridinium chloride	68909-18-2	Corrosion inhibitor	##	‡	***
5-Chloro-2-methyl-4-isothiazolol-3-one	26172-55-4	Biocide	##	‡	***
2-Mercaptoethyl alcohol	60-24-2	Surfactant	##	‡	***
2-Methyl-4-isothiazol-3-one	2682-20-4	Biocide	##	‡	***

Chemical	CAS RN	Use	P1[a]	B2[b]	T3[c]
Acrylamide	79-06-1	Friction reducer / gelling agent	##	‡	*
Alcohols, C10-16, ethoxylated propoxylated	69227-22-1	Surfactant	##	‡	***
Alcohols, C12-C16, ethoxylated	68551-12-2	Surfactant	##	‡	***
Amines, tallow alkyl, ethoxylated	61791-26-2	Surfactant	##	‡	***
C12-18-alkyldimethylbenzyl ammonium chlorides	68391-01-5	Biocide	##	‡	***
Coco alkyldimethyl oxide	61788-90-7	Surfactant	#	‡‡	***
Dipentene terpene hydrocarbon by-products	68956-56-9	Friction reducer / gelling agent	#	‡‡	**
Naphthalene	91-20-3	Friction reducer / gelling agent	##	‡	***
Naphthenic acids, ethoxylated	68410-62-8	Friction reducer / gelling agent	##	‡	*
Polyethylene glycol monohexyl ether	31726-34-8	Non-emulsifier	##	‡	*
Pontacyl carmine 2B (acid violet 12)	6625-46-3	Tracking dye	##	‡	*
Heavy aromatic solvent naphtha (petroleum)	64742-94-5	Friction reducer / gelling agent	##	‡	**
Hydrotreated light distillate (C13-C14 isoparaffin)	64742-47-8	Friction reducer / gelling agent	##	‡	***

[a]Persistence = half-life >60 days (##), half-life ≤60 days (#); [b]Bioconcentration factor = BCF >2000 or octanol/water partition coefficient = Log Kow ≥4.2 (‡‡); BCF ≤2000 or octanol/water partitioning coefficient = Log Kow < 4.2 (‡);
[c]Toxicity = ≤1 mg/L (***), >1 to ≤10 mg/L (**), >10 to ≤100 mg/L (*)
CAS RN = Chemical Abstracts Services Registry Number

Table 31 Chemicals of 'potentially high concern' that are not persistent (P) or bioaccumulative (B), and very toxic (T)

Chemical	CAS RN	Use	P1[a]	B2[b]	T3[c]
2-Bromo-2-nitro-1,3-propanediol	52-51-7	Biocide	#	‡	***
Chromium (VI)	18540-29-9	Breaker	na	na	***
Cupric sulfate	7758-98-7	Biocide / breaker	na	na	***
Glutaraldehyde	111-30-8	Biocide	#	‡	***
Hydrochloric acid	7647-01-0	Scale remover	na	na	***
Sodium chlorite ($NaClO_2$)	7758-19-2	Biocide / breaker	na	na	***
Sodium hypochlorite	7681-52-9	Biocide / breaker	na	na	***
Sodium iodide	7681-82-5	Biocide / breaker	na	na	***
Tetrakis(hydroxymethyl) phosphonium sulfate	55566-30-8	Biocide	#	‡	***
Tributyl-tetradecylphosphonium chloride	81741-28-8	Biocide	na	na	***

[a]Persistence = half-life ≤60 days (#), not applicable (na); [b]Bioconcentration = BCF ≤2000 or octanol/water partition coefficient = Log Kow <4.2 (‡), not applicable or no data (na); [c]Toxicity = ≤1 mg/L (***)

Biocides are used in drilling and hydraulic fracturing to prevent excess biofilm production in wells and formations, which may lead to clogging, unwanted gas production (e.g. hydrogen sulfide gas) and corrosion of underground casing/tubing and equipment (Kahrilas et al., 2016; Kahrilas et al., 2015). Biocide selection will depend on factors, including: (i) the mineralogy and biogeochemistry of the formation; (ii) compatibility with environmental conditions (e.g. temperature, pressure, salinity and organic matter contents); (iii) abiotic transformations; (iv) sorption reactions; (v) performance against specific microbial species (mode of action); and (vi) cost.

Biocides are inherently toxic and are, therefore, of 'potentially high concern' if released into the environment. Four biocides identified are water-soluble, persistent and highly toxic to aquatic organisms (Geological and Bioregional Assessment Program, 2018e): (i) dicoco dimethyl ammonium chloride (CAS RN 61789-77-3); (ii) 2-methyl-4-isothiazol-3-one (CAS RN 2682-20-4); (iii) 5-chloro-2-methyl-4-isothiazolol-3-one (CAS RN 26172-55-4); and (iv) C12-18-alkyldimethylbenzyl ammonium chlorides (CAS RN 68391-01-5). The effect on biota in the receiving aquatic environment is likely to be dependent on the release scenario (e.g. surface spills, pond overflow to soil and surface water or well leakage to groundwater), exposure concentrations, fate and behaviour in environments (e.g. rate of degradation and transformation, partitioning and complexation), bioavailability and sensitivity of aquatic organisms.

Biocides such as glutaraldehyde (CAS RN 111-30-8) and tetrakis (hydroxymethyl) phosphonium sulfate (CAS RN 55566-30-8), which are very toxic to aquatic organisms, may pose a lower risk to aquatic organisms due to their expected rapid (i.e. ≤60 days) degradation in aquatic environments (Geological and Bioregional Assessment Program, 2018f). However, degradation products of some biocides have been reported to be more toxic and/or persistent than their parent compounds (Kahrilas et al., 2016; Kahrilas et al., 2015), and this highlights the need for the development of sensitive and selective analytical methods to detect parent and transformation products in wastewaters and receiving waters to assess impacts on aquatic ecosystems.

Siloxanes are added to hydraulic fracturing fluids as defoaming agents and surfactants. These chemicals have low water solubility (soluble/miscible in solvents), are hydrophobic and, in the case of cyclic siloxanes, are volatile. The siloxanes are of 'potentially high concern' to aquatic organisms due to their persistence and bioaccumulative and highly toxic nature (Geological and Bioregional Assessment Program, 2018f). The three cyclic siloxanes, octamethylcyclotetrasiloxane (CAS RN 556-67-2), decamethylcyclopentasiloxane (CAS RN 541-02-6) and dodecamethylcyclohexasiloxane (CAS RN 540-97-6) are likely to volatilise or degrade in water (via hydrolysis) but, due to their hydrophobic nature, are also likely to strongly associate with sediments / suspended solids where they can persist. Furthermore, there are currently conflicting ERAs on the cyclic siloxanes due to difficulties in conducting aquatic toxicity tests because of their volatility, making the toxicity assessments highly uncertain (ECHA, 2018; Environment Canada and Health Canada, 2008; Fairbrother et al., 2015; Fairbrother and Woodburn, 2016; Government of Canada, 2012b, 2012a). The National Industrial Chemicals Notification and Assessment Scheme (NICNAS, 2018) conducted a Tier 2 ERA on these chemicals and found all three to be persistent, two to be bioaccumulative (octamethylcyclotetrasiloxane and decamethylcyclopentasiloxane) and one (octamethylcyclotetrasiloxane) to have 'uncertain toxicity'. Therefore, a more detailed quantitative ERA will need to be undertaken for these chemicals if they are used at shale gas operations. The quantitative ERA must assess and model the likelihood and consequence of a risk event occurring, identify and evaluate control and mitigation measures (e.g. what controls are in place to address the identified risk and how effective are these controls), and monitor to ensure controls and management strategies are adequate to prevent impacts on the environment.

6.3.2.2 Laboratory-based based tests on powdered rock samples from the Isa GBA region – geogenic chemicals

The leachate tests conducted with dilute hydrochloric acid and in-house hydraulic fracturing fluid mobilised the highest element concentrations into solutions compared with synthetic groundwater (SGW) (see chemical screening technical appendix (Kirby et al., 2020)). This demonstrates the role that acidity and chemical constituents of hydraulic fracturing fluid (e.g. chelating agents, surfactants, solvents, etc.) can play in mobilising elements from powdered rocks. The elements showing substantial mobilisation (>50-fold median increase compared with SGW) in hydraulic fracturing fluid include aluminium, barium, cadmium, cerium, cobalt, copper, iron, lanthanum, manganese, neodymium, nickel, lead, yttrium, and zinc. It was noted that there was variability between rock types in formations in terms of both the total content of elements and the concentrations of elements mobilised into solution. Further studies are needed to determine the underlying relationships between element content and physico-chemical properties of the formations and the fate of chemicals in the hydraulic fracturing fluid.

Higher pressure led to substantially increased mobilisation into solutions of elements such as thorium, cobalt, and boron and decreased mobilisation for elements such as antimony, barium, phosphorus, lead and molybdenum (see chemical screening technical appendix (Kirby et al., 2020)). The findings highlight the important role pressure can play in the mobilisation of geogenic chemicals from powdered rocks during hydraulic fracturing. Further work is needed to determine the relationship between pressure (and temperature) on the hydraulic fracturing fluid and mobilisation of geogenic chemicals from powdered rocks in shale gas formations in the Isa GBA region.

Targeted priority organic compounds such as PAHs and TRHs were detected in extracts of powdered rock samples (see chemical screening technical appendix (Kirby et al., 2020)). PAHs were detected in six of nine sample extracts. The highest concentrations of PAHs were found in extracts from Desert Creek Lawn Hill (chrysene, 105 µg/g; phenanthrene, 40.6 µg/g), AMOCO 83/2 Termite Range (pyrene, 34.9 µg/g; phenanthrene, 20.5 µg/g) and AMACO 83/2 Lawn Hill (chrysene, 31.9 µg/g). Phenols were not detected (below reporting limits) in powdered rock sample extracts. The highest concentrations of TRHs were found to be associated with the >C16–C34 NEPM TRHs (54 to 134 mg/kg; 41% to 46% TRHs) and TRHs C15–C28 (26 to 105 mg/kg; 19% to 34% TRHs) fractions for all sample extracts. Targeted analysis of PAHs represented a small fraction of the total organic geogenic compounds present in the sample extracts (i.e. <0.1% for all samples analysed). Hence, most geogenic organic compounds (as TRHs) in sample extracts were unidentified and their potential risk (individuals and mixtures) to aquatic environments is unknown.

6.3.2.3 Fate and behaviour of chemicals in the environment

The ecotoxicity of chemicals released during shale, tight and deep coal gas operations will likely be affected by reactions and processes in environments that can modify their fate and bioavailability (e.g. exposure concentrations) (Adriano, 2001; ANZECC/ARMCANZ, 2000; Neilson, 1994). Organic chemicals can be volatilised, photodegrade, undergo abiotic and biotic degradation and transformations, and complex/adsorb to a range of solid phases (e.g. organic matter). Inorganic chemicals can undergo neutralisation, displacement, ionisation, redox and precipitation reactions, biotransform (e.g. arsenic methylation), and complex/partition to a range of solid phases (e.g. clays, oxides/hydroxides and organic matter). These reactions and processes will be influenced by the physical and chemical properties of the receiving environment such as pH, salinity, redox conditions, microbial populations and organic matter content.

Chemical additives used in hydraulic fracturing fluids may also be lost in wells and formations to solid surfaces and/or degrade or be transformed, leading to lower concentrations than what was initially added. For example, polymers can degrade/decompose, biocides can degrade and complex/adsorb onto solid surfaces, and surfactants can be adsorbed onto solid surfaces in formations. In addition, chemical concentrations from source zones can be attenuated in surface water and groundwater through dilution and volatilisation processes.

The Tier 1 qualitative ERA used aquatic acute ecotoxicity data representing three trophic levels – a freshwater alga, a water flea and a fish species – using standard testing protocols (Geological and Bioregional Assessment Program, 2018e). Acute toxicity data may not be sufficient in assessing the environmental risk of persistent and bioaccumulative chemicals that could result in effects on biota due to long-term exposure (chronic effects) in the environment. Chronic toxicity data on aquatic organisms from a range of trophic levels (and sensitive species) are needed to accurately assess effects due to long-term exposure of these chemicals to aquatic organisms. In addition, the approach of single-chemical acute toxicity test data provides a highly uncertain assessment when there is limited detailed knowledge on the interactions that modify toxicity and on the modes of toxicity of the chemicals in the mixture to aquatic biota. A direct toxicity approach where aquatic biota are exposed to dilutions of a complex chemical mixture (e.g. a hydraulic fracturing fluid, flowback and produced water) would provide a more relevant environmental exposure assessment that incorporates chemical interactions/mixtures. Further, these assessments do not consider pulse discharges and dispersion of chemicals (individual and mixtures) into aquatic ecosystems.

6.3.3 Conclusions

A total of 116 chemicals were identified for use in drilling and hydraulic fracturing at shale, tight and deep coal gas operations between 2011 and 2016 (see chemical screening technical appendix (Kirby et al., 2020)). A Tier 1 qualitative (screening) ERA of the identified chemicals found that 42 chemicals are of ‘low concern’ and are considered to pose minimal risk to surface water and groundwater aquatic ecosystems; 33 chemicals are of ‘potentially high concern’; and 41 are of ‘potential concern’.

Further site-specific quantitative chemical assessments of the identified chemicals of potential concern and potentially high concern would need to be performed to determine risks from specific gas operations to aquatic ecosystems.

The chemicals used in drilling and hydraulic fracturing are expected to change with time as the gas industry adapts to site-specific conditions, improves gas extraction efficiency, and endeavours to use ‘greener, safer’ options. A Tier 1 qualitative (screening) ERA should be undertaken on new chemicals (and chemical not previously assessed) used in shale, tight and deep coal operations in Australia to determine if a potential environmental risk exists (‘yes/no’). If a risk exists, the questions will change to 'what', 'where' and 'how great' is the risk (i.e. Tier 2 and 3 quantitative ERAs).

Laboratory-based leachate and extraction tests on powdered rock samples collected from formations in the Isa GBA region identified many elements that could be substantially mobilised by hydraulic fracturing fluids including aluminium, barium, cadmium, cerium, cobalt, copper, iron, lanthanum, manganese, neodymium, nickel, lead, yttrium and zinc. Phenols were not detected (below reporting limits) in powdered rock sample extracts. Priority organic chemicals such as PAHs and TRHs were detected in sample extracts from powdered rock samples. Targeted analysis of PAHs represented a small fraction of the total organic geogenic compounds present in the sample extracts. Hence, the majority of organic compounds in sample extracts (as TRHs) were unidentified and their risk (individual and mixtures) to aquatic environments is unknown.

The composition and concentration of geogenic chemicals in flowback and produced waters will depend on many factors, including: (i) geology and mineralogy of formations; (ii) surface area of the fracture network exposed to hydraulic fracturing fluids; (iii) composition and concentration of chemicals used in hydraulic fracturing; (iv) residence time of hydraulic fracturing fluids in formations; (v) operational and environmental conditions (e.g. volumes added and recovered, temperature, pressure); and (vi) chemical and physical reactions (e.g. adsorption, complexation, precipitation, aggregation, degradation and transformations).

Companies undertake an ERA process of gas operations (in consultation with government agencies) that identifies potential hazards (e.g. chemical transport and storage, hydraulic fracturing fluid injection, flowback and produced water storage), determines the likelihood and consequence of a risk occurring, identifies and evaluates control and mitigation measures (e.g. what controls are in place or need to be in place to address the identified risk and how effective are these controls), and develops a monitoring program to ensure controls and management strategies are adequate/effective and for compliance. Despite undertaking these detailed ERAs, there is still public concern surrounding the potential environmental impacts of hydraulic fracturing – particularly the threats posed by the mixture of industrial chemicals and geogenic chemicals that could be mobilised and their impacts on water quality.

6.4 Knowledge gaps

6.4.1 Hydraulic fracturing and compromised well integrity

Qualitative assessments of hydraulic fracturing and compromised well integrity completed in Stage 2 for the Isa GBA region identified knowledge gaps including the following:

- The potential environmental risks from hydraulic fracture stimulation are generally considered manageable to a suitably low level but there is heightened community concern in the Isa GBA region (and more broadly) around the use of hydraulic fracturing. A conceptual analysis which showed the likelihood of a hydraulic fracture growing into an aquifer in the Isa GBA Region could serve to address the identified knowledge gap between engineering risk assessments and community concerns of specific risks in the region. Therefore, one impact mode, 'F1: hydraulic fracture growth into aquifer', is recommended for further analysis based on heightened community concerns around hydraulic fracturing and the regional geological characteristics.

- Quantification of the likelihood and potential rate of subsurface flow of fluids along compromised wells in the Isa GBA region was identified as a priority and a knowledge gap. Further assessment of two impact modes would help to address this knowledge gap: 'W3 – migration of fluids between different geological layers along a failure of the well casing' and 'W4 – failure of well integrity after well decommissioning/abandonment'.
- It is difficult to observe potential impacts from hydraulic fracture stimulation and compromised well integrity, which leads to difficulty in validating assessments of environmental risks. The uncertainty caused by the lack of validation data cannot be fully overcome within the scope of GBA.
- Activity-focused risk assessments undertaken in other GBA regions will inform consequences of fluid flow into aquifers in the Isa GBA region, enabling a quantitative assessment of the risks for each assessed impact mode.

6.4.2 Screening of drilling and hydraulic fracturing chemicals

The assessment of chemicals associated with shale, tight and deep coal operations in GBA regions identified knowledge gaps including the following:

- Chemicals used in drilling and hydraulic fracturing are expected to change with time as industry adapts to site-specific conditions, improves gas extraction efficiency and endeavours to use 'greener, safer' options. A Tier 1 qualitative (screening) ERA should be undertaken on new chemicals (and chemicals not previously assessed) used in shale, tight and deep coal operations in Australia to determine if a potential environmental risk exists ('yes/no'). If a potential risk exists, the questions should change to 'what', 'where' and 'how great' is the risk (Tier 2 and 3 quantitative ERAs). The chemical assessments should be undertaken in the context of the risk management framework that determines the likelihood and consequence of a risk event occurring, identifies and evaluates control and mitigation measures (e.g. what controls are in place or need to be in place to address the identified risk and how effective are these controls) and develops a monitoring program to ensure controls and management strategies are adequate/effective and for compliance.
- Comprehensive baseline surface water and groundwater quality data used for targeted aquifers, irrigation and drinking water, and groundwater-dependent ecosystems, should be collected prior to shale, tight and deep coal gas developments.
- The Tier 1 qualitative ERA relied mainly on aquatic acute ecotoxicity data representing three trophic levels – a freshwater alga, a water flea and a fish species. Acute toxicity data may not be sufficient for assessing the environmental risks of persistent and bioaccumulative chemicals that could have effects on aquatic organisms due to long-term exposure. Chronic toxicity data using a range of aquatic organisms and trophic levels are needed to accurately assess the effects of long-term exposure of chemicals to aquatic organisms. In addition, ecotoxicity data on drilling and hydraulic fracturing chemicals for Australian species are limited and ecotoxicity endpoints are currently not available for groundwater organisms (e.g. stygofauna).

- Publicly available data on the composition and concentration of chemicals in hydraulic fracturing fluids, flowback and produced water, and wastes (e.g. muds, brines) from shale, tight and deep coal operations in Australia are limited. The fate, transformations and toxicity of chemicals present in hydraulic fracturing fluids, and flowback and produced water (individual chemicals and mixtures) in the environment, are also unknown.
- The majority of organic compounds present in sample extracts from powdered rock samples were unidentified and their potential risk (if present in flowback and produced waters) to aquatic environments is unknown.
- Despite the very low likelihood of a well integrity failure (refer to Section 6.2) or failure of surface infrastructure (ponds, tanks, pipelines, etc.) (refer to Section 5.2) associated with shale, tight and deep coal gas operations in Australia (i.e. constructed to highest industry standards, high level of government regulation and compliance), there is still public concern about the consequences for water quality (drinking, livestock, aquatic ecosystems and cultural) if fluids are released. Surface water and groundwater monitoring and modelling using site-specific conditions and exposure scenarios would improve public understanding of potential impacts and consequences for water quality (i.e. localised event) and the adequacy of control and management plans to prevent environmental impacts.

7 Conclusions

7.1 Key findings

Stage 2 of the geological and bioregional assessment of the Isa GBA region is a geological and environmental baseline analysis in the context of possible future shale gas development. The potential hazards and causal pathways that this industry may pose to the quality, quantity and availability of water resources (both surface water and groundwater) and the environment have also been identified and prioritised for further investigation. Importantly, the work presented here incorporates feedback and insights from a spectrum of people – representing local communities, landowners, the gas industry and governments – who have a strong interest in understanding how shale gas development in the Isa GBA region may affect water and the environment.

The compilation of baseline data and information for the Isa GBA region, combined with recognition of high-priority hazards and the development of preliminary conceptual models, are key building blocks for any future assessment of the potential impacts of shale gas development. The data and information compiled here for Stage 2 (and within the detailed technical appendices) provides a solid foundation to support and inform any future shale gas impact assessments in the region. The outputs from this Stage 2 work can be used by industry and government regulators alike as a common starting point for further assessment, and should help to focus any new investigations or research on the key uncertainties identified through this baseline analysis.

7.1.1 About the region

The Isa GBA region is the focus of the Stage 2 analysis and has been defined specifically from work undertaken for the Program. This 8223-km^2 region in the subtropical Gulf Savannah country of north-west Queensland is centred on the remote community of Doomadgee, with Burketown just outside the northern boundary. This region does not represent the entire extent of the poorly defined geological Isa Superbasin. However, it is known to host shale gas in several organic-rich Proterozoic sequences, such as the Lawn and River supersequences.

As of December 2019, only limited unconventional gas exploration focusing on shale gas plays has been undertaken in the Isa Superbasin. The Isa GBA region includes the greatest concentration of geoscientific data collected during several previous hydrocarbon exploration campaigns, with the most recent being Armour Energy Limited's (Armour Energy) drilling and hydraulic fracturing operations at the Egilabria prospect in 2013 and 2014.

A much broader area of hydrocarbon potential is also identified based mainly on interpretation of recently released geoscience datasets. However, the relative lack of suitable data (such as petroleum well and seismic reflection data) to evaluate unconventional gas resources has restricted any further evaluation of this broader area as part of Stage 2.

The Isa GBA region occurs mostly within the Nicholson River catchment and, at its nearest point, is less than 40 km from the southern coastline of the Gulf of Carpentaria. The countryside is typically flat and low-lying and mostly covered by vast and well-vegetated alluvial and near-coastal plains. Only along the far western edge of the region is the terrain slightly more rugged, in areas where the older Proterozoic rocks outcrop. The region has a very low population density, with fewer than 2000 residents (mostly at Doomadgee). The traditional lands of the Gangalidda, Garawa and Waanyi peoples occur within and around the region, and over half of the area has had native title rights determined.

The region has distinct wet and dry seasons typical of tropical northern Australia. Most rainfall occurs from December to February, with hot summer temperatures and relatively warm and dry winter months. Annual rainfall totals may vary significantly from year to year, particularly due to the unpredictable influence of tropical cyclones and associated low-pressure, high-rainfall events.

7.1.2 Geology and shale gas resources

The Isa Superbasin is a poorly defined Paleoproterozoic to Mesoproterozoic geological province known from limited surface outcrops and subsurface drilling across parts of north-western Queensland (north and north-west of Mount Isa). The superbasin formed over a period of around 100 million years (from about 1670 to 1580 Ma), during multiple stages of continental-influenced extension and contraction. Although available geoscience evidence is relatively sparse, the Isa Superbasin is also likely to occur in parts of the eastern NT, buried beneath younger geological basins such as the South Nicholson and Georgina basins. The Isa GBA region hosts the best-studied subsurface part of the Isa Superbasin due to the previous focus of both hydrocarbon and base metal mineral exploration.

In central and eastern parts of the region, the Isa Superbasin is buried by up to several kilometres of younger sedimentary basin infill, mainly from the Carpentaria Basin. There is also a thinner cover of fluvial, lacustrine and shallow marine sediments associated with the Karumba Basin. The Proterozoic rocks of the Isa Superbasin and the overlying South Nicholson Basin only outcrop sporadically in the far western part of the region.

The Isa Superbasin is one of Australia's remaining frontier petroleum provinces. The most recent exploration campaign by Armour Energy (2012 to 2014) confirmed the presence of shale gas hosted in organic-rich rocks of the Lawn and River supersequences. Armour Energy successfully flowed shale gas from a multistage, hydraulically fractured lateral well in the Lawn Supersequence, which represented an Australian first for the shale gas industry. Analysis of important shale gas data currently available, such as net source rock thickness and thermal maturity, was used to characterise areas of the Isa GBA region where shale gas plays are both likely and unlikely to occur. This play fairway mapping indicates that the River Supersequence is potentially prospective for shale gas over most of the Isa GBA region. Parts of the Lawn Supersequence are also considered prospective, albeit over a slightly smaller area focused in the central and eastern parts of the region.

The relatively early stage of unconventional gas exploration in the Isa Superbasin means that considerable further exploration and appraisal work is required by industry before any commercial production could occur. The remoteness of the Isa GBA region and lack of existing infrastructure are major impediments to future commercialisation of shale gas resources from the superbasin. However, the existing data suggest potential for significant gas resources to occur within the identified unconventional gas plays in the region. Further, the recent connection of the Northern Gas Pipeline between Tennant Creek and Mount Isa may help to increase interest in the broader region and lead to renewed exploration activities in future years (e.g. across other parts of the area of hydrocarbon potential), building upon the initial encouraging results from past exploration activities.

7.1.3 Water resources

Groundwater resources are critically important within the Isa GBA region and sustain a range of environmental, economic and sociocultural values. For example, groundwater bores provide reliable year-round watering points to support the region's multi-million-dollar beef cattle industry. It also supports a range of terrestrial and aquatic ecosystems associated with wetlands, streams and vegetation communities.

The main regional groundwater system occurs in the Carpentaria Basin (part of the much larger Great Artesian Basin (GAB)) and Karumba Basin. The GAB covers the central and eastern parts of the Isa GBA region and consists of multiple stacked aquifers with intervening aquitards (e.g. of the Rolling Downs Group). The main GAB aquifers in the region are the artesian Gilbert River Formation (the basal unit of the GAB) and the Normanton Formation. In the Karumba Basin, the shallow Bulimba Formation is the most commonly accessed unit. In the eastern part of the region, the sedimentary sequence of the GAB may be over 500 m thick. The GAB sequences progressively thin westwards and have been completely removed (due to erosion) over the westernmost part of the Isa GBA region (Figure 31).

Groundwater systems in the deeper Proterozoic rock units of the region are not as well understood as those of the GAB, although they are the main source of groundwater in the western part of the region, where the GAB does not occur. Several dolostone-rich units in the lower McNamara Group of the Isa Superbasin, including the Lady Loretta Formation and the quartz-arenite Constance Sandstone in the South Nicholson Basin, are the most productive aquifers. Approximately 20% of groundwater bores in the region access aquifers hosted in either the South Nicholson Basin or the Isa Superbasin.

Most of the Isa GBA region occurs in the catchment of the Nicholson River. The headwaters of the Nicholson River occur farther westwards in the NT before the river enters the region near the Queensland–NT border and flows eastwards past Doomadgee to its junction with the Gregory River near Burketown. Upstream of this junction the Nicholson River is ephemeral, with consistent flow for only 50% to 60% of the year, and is heavily dependent upon rainfall during the wet season. Once the Gregory River joins the Nicholson River, flow becomes perennial due to the year-round groundwater-fed streamflow of the Gregory River. The Nicholson River discharges into the Gulf of Carpentaria after it flows through the nationally listed wetlands of the Nicholson Delta Aggregation.

There has been little previous work to understand surface water – groundwater interactions within the Isa GBA region, despite the importance of such hydrological connections in supporting a range of ecosystems. This is particularly the case in the south-west of the region, where groundwater sourced from Proterozoic rocks supports a number of springs (both within and just outside the region boundary). In addition, in the alluvial floodplains of the region, groundwater discharge from the regional watertable aquifer may, at times, contribute to streamflow and likely supports many groundwater-dependent ecosystems (GDEs).

7.1.4 Protected matters

The Isa GBA region may contain up to 24 different species (and two subspecies) identified as Matters of National Environmental Significance (MNES) under the EPBC Act. These include various species of birds (ten), reptiles (eight), mammals (four) and fish (four) which are nationally listed as threatened (critically endangered, endangered or vulnerable). There are an additional 21 migratory species that occur or potentially occur within the Isa GBA region, many of which are also listed as marine species (e.g. the osprey, streaked shearwater and oriental plover). Fifteen of these migratory species are birds, and there are also three species of fish, two mammals and one reptile (saltwater crocodile).

Matters of State Environmental Significance also occur within the Isa GBA region. These include two state reserves near the Lawn Hill National Park, as well as part of the designated precinct of the Gulf Rivers Strategic Environmental Area and four important wetlands. There is also one endangered regional ecosystem (*Eucalyptus camaldulensis* woodland on channels and levees) and two species listed as vulnerable under Queensland's *Nature Conservation Act 1992* (the purple-crowned fairy wren (*Malurus coronatus*) and the plant *Solanum carduiforme*).

A prioritisation and screening process (Section 4.4) identified the protected matters that are most likely to be at potential risk from any future shale gas development in the region. This includes 11 species of national environmental significance, comprising five endangered species (three birds, one mammal and one reptile) and six vulnerable species (two birds, two mammals, one reptile and one fish species). These 11 species, along with the two state protected matters, are recommended as the main focus of further impact and risk analysis in the Isa GBA region, prior to any potential shale gas development.

There are no world heritage or national heritage places within the Isa GBA region, although the renowned Australian Fossil Mammal Site (Riversleigh) is about 50 km south of the region (and within the broader area of hydrocarbon potential).

7.1.5 Potential impacts of shale gas development

The development of any future shale gas industry in the Isa Superbasin is most likely to occur (at least initially) in the Isa GBA region. Understanding the geological and environmental baseline of this region is an important focus of the GBA Program and comprises much of the focus of this report. However, the Stage 2 work has gone beyond this baseline analysis and has started to evaluate the potential impacts to the environmental, economic and sociocultural values of the region by investigating the hazards and causal pathways posed by shale gas development. This is an important preliminary step for any subsequent impact and risk analysis and has helped GBA researchers to better understand the variety of potential hazards and linkages that may arise due to operations typically associated with shale gas development.

The comprehensive assessment of hazards associated with shale gas operations, starting from construction activities and going through the main development and production stages before final decommissioning and rehabilitation, has identified 222 individual hazards that may occur during various life-cycle stages. Qualitative assessment of the potential environmental severity and recurrence interval of each hazard was used to derive individual hazard scores and develop a relative ranking of hazards to help prioritise and focus future efforts. The sixty-eight priority 1 hazards are recommended for further evaluation, along with the priority 2 hazards for which other lines of evidence (such as evidence from relevant national or international research) suggest further attention is warranted.

Causal pathways describe the chain of events that link shale gas development with potential impacts on water and the environment. For GBA purposes the identified hazards have been classified into 14 different causal pathways, aggregated into three main causal pathway groups:

- landscape management
- subsurface flow paths
- water and infrastructure management.

The process of aggregating and prioritising hazards, and understanding the causal pathways that may arise from shale gas development, helps to focus future attention by ruling out hazards deemed to be of low concern. It also ensures that future modelling and related investigations are targeted towards the highest priority hazards that are likely to be of greatest severity and highest likelihood.

Additional to identifying and prioritising hazards and causal pathways, Stage 2 has also examined in greater detail three of the most contentious issues raised by the Isa GBA user panel in relation to shale gas development:

1. hydraulic fracturing
2. compromised well integrity
3. industrial chemicals associated with drilling and hydraulic fracturing of shale gas wells.

Due to the limited amount of early-stage shale gas exploration in the Isa GBA region (e.g. only one shale gas exploration well has previously been hydraulically fractured in the region), these reviews have taken a broader approach and include various Australian and international examples. However, the findings from these reviews largely support the results of the hazard identification analysis undertaken for the Isa GBA region and provide further justification for specific investigations that are recommended as part of any future shale gas impact assessment.

7.2 Gaps, limitations and opportunities

7.2.1 Geology and shale gas resources

The results of the shale gas play fairway mapping for the Isa GBA region identify areas where further data acquisition and geological modelling are warranted. However, this type of regional geological analysis is at a relatively coarse scale and is largely unsuitable for more detailed play or prospect-scale evaluation (e.g. of the type that a gas company may undertake within their tenement). Local geological variations, which may not be adequately captured by the regional-scale input data, mean that not all areas identified as likely to contain play fairways will result in future gas discoveries.

In addition to cultural and environmental considerations, the large capital outlay required to commercialise shale gas plays depends heavily on the economic viability of the resource. To better inform future development scenarios for the Isa GBA region, and better understand associated hazards and impacts, it is important to consider development of each play in the context of likely economic viability. While the play fairway maps inform where the plays are most likely to occur, they do not provide the economic context required to effectively inform future development scenarios. Additional work to place the fairway mapping in an economic context could include:

- resource assessments to estimate total volume of gas-in-place for priority plays, based on the geological understanding outlined in this report
- estimation of the proportion of gas-in-place that is technically recoverable
- analyses to understand which plays are economic to commercialise, based on current and expected future market conditions.

There is also an opportunity to evaluate several recently acquired geoscience datasets collected in northern Australia as part of Geoscience Australia's Exploring for the Future program (Geoscience Australia, 2019). This includes regional seismic reflection data acquired over areas of western Queensland and neighbouring parts of the NT, which may provide new information on the extent of the Isa Superbasin in parts of the broader area of hydrocarbon potential (to the west and south of the Isa GBA region). Further, new regional airborne electromagnetic data collected as part of the AusAEM component of Exploring for the Future may help to improve understanding of the geological architecture and groundwater systems of the Isa GBA region.

7.2.2 Water resources

The relatively low level of groundwater development and extraction in the Isa GBA region and surrounds means that many aspects of the region's hydrogeology remain poorly understood. For example, there is very little knowledge about groundwater systems in the older and deeper Proterozoic units of the Isa Superbasin and the South Nicholson Basin, as most bores and ecosystems access shallower groundwater from the overlying GAB.

Improved knowledge of the region's groundwater systems is vital to better understand and predict potential impacts associated with future shale gas development. This is particularly the case given that groundwater is one of the likely sources of water to support drilling and hydraulic fracturing of new shale gas wells. Further research could help address key aspects relating to the degree of hydrological connectivity within and between the two main groundwater systems (i.e. Proterozoic-hosted groundwater and the GAB), as well as improving knowledge of surface water – groundwater interactions. Additional work could focus on improving understanding of baseline water quality for key regional aquifers (i.e. through targeted fieldwork and sampling), as well as help validate preliminary interpretations of remotely sensed data.

7.2.2.1 Groundwater dynamics and baseline data

Uncertainty about groundwater dynamics exists for most aquifers of the region, including factors such as the seasonal variation in groundwater levels, groundwater flow directions and lag time in response to rainfall and streamflow events. Additional baseline groundwater data (i.e. prior to any shale gas development), such as additional groundwater level data collected from the main aquifers of the region, are needed to improve this knowledge base. Data collection at both the end of the dry season and the end of the wet season across multiple years would further improve understanding of seasonal trends in water levels.

Faulting within the Isa Superbasin and South Nicholson Basin may contribute to groundwater flow compartmentalisation, with potential implications for groundwater recharge rates, accessibility of groundwater and the potential for subsurface impacts (e.g. associated with shale gas development) to propagate away from the gas reservoirs and affect aquifers. Targeted hydrochemical sampling across suspected fault boundaries would further elucidate potential structural controls on groundwater flow and aquifer interaction.

A new phase of baseline water sampling is recommended, targeting available bores that access groundwater from multiple aquifers within or near the Isa GBA region. This sampling could focus on hydrochemical and isotopic 'fingerprinting' of these groundwater systems and potentially include gas analyses (e.g. helium and methane) as well as selected natural groundwater tracers such as strontium, carbon-14 and tritium. A more comprehensive network of hydrogeochemical data would provide additional knowledge about various groundwater processes and flow characteristics, such as improving understanding of the potential hydrological connectivity pathways proposed in Stage 2.

7.2.2.2 Surface water – groundwater interactions

There is considerable uncertainty about surface water – groundwater interactions in the region due to sparse groundwater and streamflow data. Long-term streamflow and groundwater time-series data, coupled with accurate stream gauge and bore elevations (as well as detailed lithological information), would enable enhanced assessment of the magnitude and dynamics of surface water – groundwater connectivity. There is also limited mapping of springs and insufficient data to confidently assign source aquifers for the spring cluster in the south-west of the region.

Collecting targeted hydrochemistry data from bores, along streams and from springs would greatly improve understanding of water sources that support GDEs in the region. In particular, targeted hydrochemical sampling of springs and along stream transects during the dry season would help identify source aquifers contributing to surface waters – for example, sampling at several sites along the length of the Nicholson River. In addition, surveying of bore and stream gauge elevations and data logging of selected groundwater wells near monitored streams are recommended approaches to enhance the temporal resolution of data to inform understanding of surface water – groundwater dynamics.

Analysis of remote sensing data (Section 3.3.1.2) has enabled a rapid, consistent approach to mapping parts of the landscape that have potential dependence on groundwater. However, field validation in selected areas is needed to confirm these interpretations. Additional remote sensing data products and assessment methods could be integrated with other datasets to further enhance understanding of surface water – groundwater interactions at both local and regional scales in the Isa GBA region.

7.2.2.3 Potential hydrological connections

Assessing potential hydrological connections in Stage 2 identified several important data and knowledge gaps, as well as generated hypotheses for further testing. The key knowledge gaps are:

- limited understanding of vertical variation of in-situ stress orientation, fault reactivation and fault dilation tendencies, particularly in the deeper Proterozoic units and in places where faults occur near surface (close to assets)
- sparse aquifer and aquitard characterisation datasets, including groundwater pressure, hydrochemistry, dissolved methane and isotope data, and biased distribution along the major depositional centres
- limited knowledge of the role that polygonal faulting in the Rolling Downs Group aquitard may play in connecting the artesian Gilbert River Formation with the near-surface aquifer of the Normanton Formation and sediments of the Karumba Basin
- lack of evidence supporting assigned aquifer sources for non-GAB springs in and near the region.

Table 13 summarises the five potential hydrogeological connections that may occur in the Isa GBA region, including the supporting evidence base, the priority research questions to address and recommendations for further work.

7.2.3 Protected matters

Accurate records of the distribution and biology of MNES, particularly for threatened species and migratory species, are important knowledge gaps for the Isa GBA region. Many species are currently identified as ‘likely to occur’ or ‘may occur’, rather than ‘known to occur’ within the region. To identify those species that may be impacted by future shale gas development, the question of whether individual species occur (or did occur) – and, if so, when and where – must be resolved. In addition, there is currently limited information about the preferred habitat and food sources of many of the MNES species in the region, as well as their trophic interactions (including interactions with invasive species).

Most species listed under Queensland legislation have not had known or potential threatening processes identified (as has been done for MNES). This information is important to understand how existing threatening processes may interact with activities undertaken as part of future shale gas development and potentially result in cumulative impacts.

The landscape classification developed for the Isa GBA region is limited by the quality of the available input datasets, including surface geology, elevation, vegetation and landform mapping, and extent and quality of ground observations. Although this landscape classification is likely to be suitable for regional-scale investigations, any finer scale assessments may require use of other land resource datasets such as aerial photography and satellite imagery as well as targeted field-based observations.

7.2.4 Potential impacts

Further impact and risk analysis efforts are recommended to build upon the preliminary conceptual models of causal pathways developed in Stage 2 that link development-related activities and hazards with landscape classes and endpoints specific to the region. This work could also seek to better identify how risks from shale gas development may affect protected matters within the environment, including how shale gas development may interact with threatening processes such as changing climate patterns; land clearing; and biodiversity impacts due to introduced pests, such as weeds and feral animals.

Conceptualisation of the regional geology and hydrogeology, as well as the potential hydrological connections from shale gas reservoirs to near-surface assets such as the regional watertable aquifer, includes substantial uncertainties and alternative conceptual models. These uncertainties could be captured, represented and tested using simple screening models that propagate uncertainty through the modelling chain by basing predictions on plausible distributions of model parameters rather than fixed values. The preliminary conceptualisations presented here for each causal pathway should be updated if used as part of future impact and risk analysis using a range of approaches, including expert elicitation and more detailed literature reviews.

Effective future monitoring, mitigation and management of selected shale gas plays will be informed by assessment of the adequacy of current regulatory controls and qualitative or quantitative assessment of potential impacts. The conceptual models reflect the beliefs that experts hold about the ways in which shale gas development might affect ecological, economic and sociocultural values.

7.2.4.1 Hydraulic fracturing and compromised well integrity

Potential environmental risks from hydraulic fracture stimulation are generally considered manageable to a suitably low level. However, there are heightened community concerns around the use of hydraulic fracturing in many places, including the local communities of the Isa GBA region. To help address these concerns, the impact mode ‘hydraulic fracture growth into aquifer’ is recommended for further analysis.

Quantification of the likelihood and potential rate of subsurface fluid flow along compromised wells in the Isa GBA region was identified as a priority impact mode and knowledge gap. Further investigations are recommended for two relevant impact modes: ‘migration of fluids between different geological layers along a failure of the well casing’ and the ‘failure of well integrity after well decommissioning / abandonment’.

A critical knowledge gap is the difficulty in directly observing potential impacts from hydraulic fracture stimulation and compromised well integrity. This makes it challenging to validate assessments of environmental risks. The uncertainty due to the lack of validation data cannot be fully overcome within the scope of the GBA program.

7.2.4.2 Screening of drilling and hydraulic fracturing chemicals

Public concern about potential environmental impacts on water quality from hydraulic fracturing remains heightened. In particular, the community is concerned about potential impacts on water quality from the mixture of industrial chemicals and geogenic chemicals that could be mobilised during shale gas resource development. While it is beyond the scope of this assessment of the Isa GBA region, the independent collection and open and transparent reporting of water quality data before, during and after hydraulic fracturing would improve community and government understanding in the ERA process, controls and monitoring of chemicals; and inform wastewater management and treatment options.

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Glossary

The register of terms and definitions used in the Geological and Bioregional Assessment Program is available online at https://w3id.org/gba/glossary (note that terms and definitions are respectively listed under the 'Name' and 'Description' columns in this register). This register is a list of terms, which are the preferred descriptors for concepts. Other properties are included for each term, including licence information, source of definition and date of approval. Semantic relationships (such as hierarchical relationships) are formalised for some terms, as well as linkages to other terms in related vocabularies. Many of the definitions for these terms have been sourced from external glossaries – several from international sources; spelling variations have been preserved to maintain authenticity of the source.

2C: best estimate of contingent resources

abandonment: a process which involves shutting down the well and rehabilitating the site. It includes decommissioning the well.

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

activity: for the purposes of Impact Modes and Effects Analysis (IMEA), a planned event associated with unconventional gas resource development. For example, activities during the exploration life-cycle stage include drilling and coring, ground-based geophysics and surface core testing. Activities are grouped into ten major activities, which can occur at different life-cycle stages.

adsorption: the capability of all solid substances to attract to their surfaces molecules of gases or solutions with which they are in contact

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

anticline: an arch-shaped fold in rock in which rock layers are upwardly convex. The oldest rock layers form the core of the fold and, outward from the core, progressively younger rocks occur.

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

aquitard: a saturated geological unit that is less permeable than an aquifer, and incapable of transmitting useful quantities of water. Aquitards commonly form a confining layer over an artesian aquifer.

artesian aquifer: an aquifer that has enough natural pressure to allow water in a bore to rise to the ground surface

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

barrel: a standard unit of measurement for all production and sales of oil. It has a volume of 42 US gallons [0.16 m^3].

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

basement: the oldest rocks in an area; commonly igneous or metamorphic rocks of Precambrian or Paleozoic age that underlie other sedimentary formations. Basement generally does not contain significant oil or gas, unless it is fractured and in a position to receive these materials from sedimentary strata.

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

bioaccumulation: a process by which chemicals are taken up by a plant or animal either directly through exposure to a contaminated medium (soil, sediment, water) or by consuming food or water containing the chemical

biogenic gas: hydrocarbon gases (which are overwhelmingly (greater than or equal to 99%) methane) produced as a direct consequence of bacterial activity

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

brittleness: a material is brittle if, when subjected to stress, it breaks without significant plastic deformation

carbonaceous shale: organic-rich shales that contain less total organic carbon (TOC) than coals (50 wt.% TOC)

casing: a pipe placed in a well to prevent the wall of the hole from caving in and to prevent movement of fluids from one formation to another

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

causal pathway group: causal pathways with similar attributes (e.g. landscape management) that are grouped for further analysis

cementing: the application of a liquid slurry of cement and water to various points inside and outside the casing

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

clastic: sedimentary rock that consists of fragments or clasts of pre-existing rock, such as sandstone or shale cleat: the vertical cleavage of coal seams. The main set of joints along which coal breaks when mined.

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

coal seam gas: coal seam gas (CSG) is a form of natural gas (generally 95% to 97% pure methane, CH_4) extracted from coal seams, typically at depths of 300 to 1000 m. Also called coal seam methane (CSM) or coalbed methane (CBM).

compression: lateral force or stress (e.g. tectonic) that tends to decrease the volume of, or shorten, a substance

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

condensate: condensates are a portion of natural gas of such composition that are in the gaseous phase at temperature and pressure of the reservoirs, but that, when produced, are in the liquid phase at surface pressure and temperature

confined aquifer: an aquifer saturated with confining layers of low-permeability rock or sediment both above and below it. It is under pressure so that when the aquifer is penetrated by a bore, the water will rise above the top of the aquifer.

conglomerate: a sedimentary rock dominated by rounded pebbles, cobbles, or boulders

consequence: synonym of impact

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

contingent resources: those quantities of petroleum which are estimated, on a given date, to be potentially recoverable from known accumulations but which are not currently considered to be commercially recoverable

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

Cooper Basin: the Cooper Basin geological province is an Upper Carboniferous – Middle Triassic geological sedimentary basin that is up to 2500 m thick and occurs at depths between 1000 and 4400 m. It is overlain completely by the Eromanga and Lake Eyre basins. Most of the Cooper Basin is in south-west Queensland and north-east SA, and includes a small area of NSW at Cameron Corner. It occupies a total area of approximately 130,000 km^2, including 95,740 km^2 in Queensland, 34,310 km^2 in SA and 8 km^2 in NSW.

craton: the old, geologically stable interior of a continent. Commonly composed of Precambrian rocks at the surface or covered only thinly by younger sedimentary rocks.

crude oil: the portion of petroleum that exists in the liquid phase in natural underground reservoirs and remains liquid at atmospheric conditions of pressure and temperature. Crude oil may include small amounts of non-hydrocarbons produced with the liquids.

crust: the outer part of the Earth, from the surface to the Mohorovicic discontinuity (Moho)

cumulative impact: for the purposes of geological and bioregional assessments, the total environmental change resulting from the development of selected unconventional hydrocarbon resources when all past, present and reasonably foreseeable actions are considered

current controls: the methods or actions currently planned, or in place, to detect hazards when they occur or to reduce the likelihood and/or consequences of these hazards should they occur

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

deep coal gas: gas in coal beds at depths usually below 2000 m are often described as 'deep coal gas'. Due to the loss of cleat connectivity and fracture permeability with depth, hydraulic fracturing is used to release the free gas held within the organic porosity and fracture system of the coal seam. As dewatering is not needed, this makes deep coal gas exploration and development similar to shale gas reservoirs.

deformation: folding, faulting, shearing, compression or extension of rocks due to the Earth's forces

delta: a low, nearly flat area near the mouth of a river, commonly forming a fan-shaped plain that can extend beyond the coast into deep water. Deltas form in lakes and oceans when sediment supplied by a stream or river overwhelms that removed by tides, waves, and currents

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

deposition: sedimentation of any material, as in the mechanical settling of sediment from suspension in water, precipitation of mineral matter by evaporation from solution, and accumulation of organic material

depositional environment: the area in which, and physical conditions under which, sediments are deposited. This includes sediment source; depositional processes such as deposition by wind, water or ice; and location and climate, such as desert, swamp or river.

detection score: for the purposes of Impact Modes and Effects Analysis (IMEA), the expected time to discover a hazard, scored in such a way that a one-unit increase (or decrease) in score indicates a ten-fold increase (or decrease) in the expected time (measured in days) to discover it

development: a phase in which newly discovered oil or gas fields are put into production by drilling and completing production wells discovered: the term applied to a petroleum accumulation/reservoir whose existence has been determined by its actual penetration by a well, which has also clearly demonstrated the existence of moveable petroleum by flow to the surface or at least some recovery of a sample of petroleum. Log and/or core data may suffice for proof of existence of moveable petroleum if an analogous reservoir is available for comparison.

diversion: see extraction

dolomite: a rhombohedral carbonate mineral with the formula $CaMg(CO_3)_2$

dolostone: a carbonate sedimentary rock that contains over 50% of the mineral dolomite [$CaMg(CO_3)_2$]

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

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

drill bit: a drilling tool that cuts through rock by a combination of crushing and shearing

drill stem test: an operation on a well designed to demonstrate the existence of moveable petroleum in a reservoir by establishing flow to the surface and/or to provide an indication of the potential productivity of that reservoir. Drill stem tests (DSTs) are performed in the open hole to obtain reservoir fluid samples, static bottomhole pressure measurements, indications of productivity and short-term flow and pressure buildup tests to estimate permeability and damage extent.

drilling fluid: circulating fluid that lifts rock cuttings from the wellbore to the surface during the drilling operation. Also functions to cool down the drill bit, and is a component of well control.

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

economic values: values associated with agriculture, aquaculture, drinking water supply, industry or intensive development and tourism activities

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

ecosystem asset: an ecosystem that may provide benefits to humanity. It is a spatial area comprising a combination of biotic and abiotic components and other elements which function together.

effect: for the purposes of Impact Modes and Effects Analysis (IMEA), a change to water or the environment, such as changes to the quantity and/or quality of surface water or groundwater, or to the availability of suitable habitat. An effect is a specific type of an impact (any change resulting from prior events).

effective porosity: the interconnected pore volume or void space in a rock that contributes to fluid flow or permeability in a reservoir. Effective porosity excludes isolated pores and pore volume occupied by water adsorbed on clay minerals or other grains. Effective porosity is typically less than total porosity.

effective water saturation: the fraction of water in the pore space corresponding to the effective porosity. It is expressed in volume/volume, percent or saturation units. Unless otherwise stated, water saturation is the fraction of formation water in the undisturbed zone. The saturation is known as the total water saturation if the pore space is the total porosity, but is called effective water saturation if the pore space is the effective porosity. If used without qualification, the term water saturation usually refers to the effective water saturation.

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.

ephemeral stream: a stream that flows only briefly during and following a period of rainfall, and has no baseflow component

Eromanga Basin: an extensive geologic sedimentary basin formed from the Early Jurassic to the Late Cretaceous that can be over 2500 m thick. It overlies several older geological provinces including the Cooper Basin, and is in part overlain by the younger Cenozoic province, the Lake Eyre Basin. The Eromanga Basin is found across much of Queensland, northern SA, southern NT, as well as north-western NSW. The Eromanga Basin encompasses a significant portion of the Great Artesian Basin.

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

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

exploration approvals: all operational approvals under the Schedule and all environmental approvals under the Petroleum Environment Regulations granted on an exploration permit for an exploration activity

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

facies: the characteristics of a rock unit that reflect the conditions of its depositional environment

fairway: a term used in geology to describe a regional trend along which a particular geological feature is likely to occur, such as a hydrocarbon fairway. Understanding and predicting fairways can help geologists explore for various types of resources, such as minerals, oil and gas.

fault: a fracture or zone of fractures in the Earth's crust along which rocks on one side were displaced relative to those on the other side

field: in petroleum geoscience, a 'field' refers to an accumulation, pool, or group of pools of hydrocarbons or other mineral resources in the subsurface. A hydrocarbon field consists of a reservoir with trapped hydrocarbons covered by an impermeable sealing rock, or trapped by hydrostatic pressure.

floodplain: a flat area of unconsolidated sediment near a stream channel that is submerged during or after high flows

flowback: the process of allowing fluids and entrained solids to flow from a well following a treatment, either in preparation for a subsequent phase of treatment or in preparation for cleanup and returning the well to production. The flowback period begins when material introduced into the well during the treatment returns to the surface following hydraulic fracturing or refracturing. The flowback period ends when either the well is shut in and permanently disconnected from the flowback equipment or at the startup of production.

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

fluvial: sediments or other geologic features formed by streams

fold: a curve or bend of a formerly planar structure, such as rock strata or bedding planes, that generally results from deformation

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

formation fluid: any fluid within the pores of the rock. It may be water, oil, gas or a mixture. Formation water in shallow aquifers can be fresh. Formation water in deeper layers of rock is typically saline.

formation water: water that occurs naturally in sedimentary rocks

fracking: see hydraulic fracturing

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

free gas: the gaseous phase present in a reservoir or other contained area. Gas may be found either dissolved in reservoir fluids or as free gas that tends to form a gas cap beneath the top seal on the reservoir trap. Both free gas and dissolved gas play important roles in the reservoir-drive mechanism.

gas cap: part of a petroleum reservoir that contains free gas

gas hydrate: naturally occurring 'ice-like' combinations of natural gas and water that have the potential to provide an immense resource of natural gas from the world's oceans and polar regions. Gas hydrates are known to be widespread in permafrost regions and beneath the sea in sediments of outer continental margins. It is generally accepted that the volume of natural gas contained in the world's gas hydrate accumulations greatly exceeds that of known gas reserves.

gas-in-place: the total quantity of gas that is estimated to exist originally in naturally occurring reservoirs

gas saturation: the relative amount of gas in the pores of a rock, usually as a percentage of volume

geogenic chemical: a naturally occurring chemical originating from the earth – for example, from geological formations

geological architecture: the structural style and features of a geological province, like a sedimentary basin

geological formation: stratigraphic unit with distinct rock types, which is able to mapped at surface or in the subsurface, and which formed at a specific period of geological time

groundwater: water occurring naturally below ground level (whether stored in or flowing through aquifers or within low-permeability aquitards), or water occurring at a place below ground that has been pumped, diverted or released to that place for storage there. This does not include water held in underground tanks, pipes or other works.

groundwater-dependent ecosystem: ecosystems that require access to groundwater on a permanent or intermittent basis to meet all or some of their water requirements

groundwater discharge: water that moves from a groundwater body to the ground surface or surface water body (e.g. a river or lake)

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

groundwater system: see water system

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

hazard score: for the purposes of Impact Modes and Effects Analysis (IMEA), one of two ranking systems that indicate the relative importance of a hazard. It is the sum of the severity score and likelihood score.

horizontal drilling: drilling of a well in a horizontal or near-horizontal plane, usually within the target hydrocarbon-bearing formation. Requires the use of directional drilling techniques that allow the deviation of the well on to a desired trajectory.

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

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

hydraulic fracturing stage: hydraulic fracture stimulation conducted at a defined interval along a well. Hydraulic fracture stimulation of horizontal wells will often involve multiple hydraulic fracture stages so as to create hydraulic fractures at multiple locations along the length of the well.

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

hydrogen index: the amount of hydrogen relative to the amount of organic carbon present in kerogen (organic matter). Gross trends of hydrogen indices (HIs) can be used as an indication of maturity.

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

hydrological connectivity: a descriptive measure of the interaction between water bodies (groundwater and/or surface water)

hydrostatic pressure: equal pressure in all direction, equivalent to the pressure which is exerted on a portion of a column of water as a result of the weight of the fluid above it

impact: the difference between what could happen as a result of activities and processes associated with extractive industries, such as shale, tight and deep coal gas development, and what would happen without them. Impacts may be changes that occur to the natural environment, community or economy. Impacts can be a direct or indirect result of activities, or a cumulative result of multiple activities or processes.

impact cause: an activity (or aspect of an activity) that initiates a hazardous chain of events

impact mode: the manner in which a hazardous chain of events (initiated by an impact cause) could result in an effect (change in the quality and/or quantity of surface water or groundwater). There might be multiple impact modes for each activity or chain of events.

Impact Modes and Effects Analysis: a systematic hazard identification and prioritisation technique based on Failure Modes and Effects Analysis

injection: the forcing or pumping of substances into a porous and permeable subsurface rock formation. Examples of injected substances can include either gases or liquids.

kerogen: insoluble (in organic solvents) particulate organic matter preserved in sedimentary rocks that consists of various macerals originating from components of plants, animals, and bacteria. Kerogen can be isolated from ground rock by extracting bitumen with solvents and removing most of the rock matrix with hydrochloric and hydrofluoric acids.

kerogen type: kerogens are classified into five types: I, II, IIS, III, and IV

known accumulation: the term accumulation is used to identify an individual body of moveable petroleum. The key requirement to consider an accumulation as known, and hence contain reserves or contingent resources, is that each accumulation/reservoir must have been penetrated by a well. In general, the well must have clearly demonstrated the existence of moveable petroleum in that reservoir by flow to surface or at least some recovery of a sample of petroleum from the well. However, where log and/or core data exist, this may suffice, provided there is a good analogy to a nearby and geologically comparable known accumulation.

Lake Eyre Basin: a geologic province containing Cenozoic terrestrial sedimentary rocks within the Lake Eyre surface water catchment. It covers parts of northern and eastern SA, south-eastern NT, western Queensland and north-western NSW. In the Cooper GBA region, the basin sedimentary package is less than 300 m thick.

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

leaky aquitard: a semi-permeable geological material that can transmit groundwater. Although regionally non-productive, it may be classed as a very low yielding aquitard that is sometimes used to produce groundwater where no other source is available.

life-cycle stage: one of five stages of operations in unconventional gas resource development considered as part of the Impact Modes and Effects Analysis (IMEA). These are exploration, appraisal, development, production, and rehabilitation. Each life-cycle stage is further divided into major activities, which are further divided into activities.

likelihood: probability that something might happen

likelihood score: for the purposes of Impact Modes and Effects Analysis (IMEA), the annual probability of a hazard occurring, which is scored so that a one-unit increase (or decrease) in score indicates a ten-fold increase (or decrease) in the probability of occurrence

lithology: the description of rocks, especially in hand specimen and in outcrop, on the basis of characteristics such as colour, mineralogic composition and grain size

material: pertinent or relevant

mature: a hydrocarbon source rock that has started generating hydrocarbons metamorphic rock : a rock formed from pre-existing rock due to high temperature and pressure in the Earth's crust, but without complete melting

methane: a colourless, odourless gas, the simplest parafin hydrocarbon, formula CH4. It is the principal constituent of natural gas and is also found associated with crude oil. Methane is a greenhouse gas in the atmosphere because it absorbs long-wavelength radiation from the Earth's surface.

migration: the process whereby fluids and gases move through rocks. In petroleum geoscience, 'migration' refers to when petroleum moves from source rocks toward reservoirs or seep sites. Primary migration consists of movement of petroleum to exit the source rock. Secondary migration occurs when oil and gas move along a carrier bed from the source to the reservoir or seep. Tertiary migration is where oil and gas move from one trap to another or to a seep.

Moho: the Mohorivicic discontinuity (seismic reflector) at the base of the crust

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

natural gas: the portion of petroleum that exists either in the gaseous phase or is in solution in crude oil in natural underground reservoirs, and which is gaseous at atmospheric conditions of pressure and temperature. Natural gas may include amounts of non-hydrocarbons.

naturally occurring radioactive materials: radioactive elements and their decay products found in the environment that have been generated from natural processes

net thickness: the accumulated thickness of a certain rock type of a specified quality which is found within a specific interval of formation

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

oil-prone: organic matter that generates significant quantities of oil at optimal maturity

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

organic matter: biogenic, carbonaceous materials. Organic matter preserved in rocks includes kerogen, bitumen, oil and gas. Different types of organic matter can have different oil-generative potential.

orogeny: the process of mountain building; the process whereby structures within fold-belt mountainous areas formed

outcrop: a body of rock exposed at the surface of the Earth

overpressure: occurs when the pore pressure is higher than the hydrostatic pressure, caused by an increase in the amount of fluid or gas in the rock, or changes to the rock that reduce the amount of pore space. If the fluid cannot escape, the result is an increase in pore pressure. Overpressure can only occur where there are impermeable layers preventing the vertical flow of water, otherwise the water would flow upwards to equalise back to hydrostatic pressure.

partial aquifer: a permeable geological material with variable groundwater yields that are lower than in an aquifer and range from fair to very low yielding locally

pay: a reservoir or portion of a reservoir that contains economically producible hydrocarbons. The term derives from the fact that it is capable of 'paying' an income. Pay is also called pay sand or pay zone. The overall interval in which pay sections occur is the gross pay; the smaller portions of the gross pay that meet local criteria for pay (such as minimum porosity, permeability and hydrocarbon saturation) are net pay.

pay zone: see pay

percentile: a specific type of quantile where the range of a distribution or set of runs is divided into 100 contiguous intervals, each with probability 0.01. An individual percentile may be used to indicate the value below which a given percentage or proportion of observations in a group of observations fall. For example, the 95th percentile is the value below which 95% of the observations may be found.

permeability: the measure of the ability of a rock, soil or sediment to yield or transmit a fluid. The magnitude of permeability depends largely on the porosity and the interconnectivity of pores and spaces in the ground.

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

petroleum system: the genetic relationship between a pod of source rock that is actively producing hydrocarbon, and the resulting oil and gas accumulations. It includes all the essential elements and processes needed for oil and gas accumulations to exist. These include the source, reservoir, seal, and overburden rocks, the trap formation, and the hydrocarbon generation, migration and accumulation processes. All essential elements and processes must occur in the appropriate time and space in order for petroleum to accumulate.

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

play fairway analysis: sometimes referred to as play fairway mapping, play fairway analysis is used to identify areas where a specific play is likely to be successful, and where additional work on a finer scale is warranted in order to further develop an understanding of a prospect. The phrasing 'fairway' is used as prospective areas on the map are often visually similar to fairways on a golf course. Play fairway maps are created at a regional scale, often tens to hundreds of kilometres in scale, from multiple input sources that vary based on what information is available and relevant based on the requirements of the creator.

plug: a mechanical device or material (such as cement) placed within a well to prevent vertical movement of fluids

porosity: the proportion of the volume of rock consisting of pores, usually expressed as a percentage of the total rock or soil mass potential effect: specific types of impacts or changes to water or the environment, such as changes to the quantity and/or quality of surface water or groundwater, or to the availability of suitable habitat

produced water: a term used in the oil industry to describe water that is produced as a by-product along with the oil and gas. Oil and gas reservoirs often have water as well as hydrocarbons, sometimes in a zone that lies under the hydrocarbons, and sometimes in the same zone with the oil and gas. The terms 'co-produced water' and 'produced water' are sometimes used interchangeably by government and industry. However, in the geological and bioregional assessments, 'produced water' is used to describe water produced as a by-product of shale and tight gas resource development, whereas 'co-produced water' refers to the large amounts of water produced as a by-product of coal seam gas development.

producing: a well or rock formation from which oil, gas or water is produced

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

production well: a well used to remove oil or gas from a reservoir

progradation: movement of the shoreline into a sedimentary basin when clastic input exceeds the accommodation space, as might occur due to reduced basinal subsidence or increased erosion and sediment supply

proppant: a component of the hydraulic fracturing fluid system comprising sand, ceramics or other granular material that 'prop' open fractures to prevent them from closing when the injection is stopped

prospective resources: estimated volumes associated with undiscovered accumulations. These represent quantities of petroleum which are estimated, as of a given date, to be potentially recoverable on the basis of indirect evidence but have not yet been drilled. This class represents a higher risk than contingent resources since the risk of discovery is also added.

prospectivity assessment: the assessment of an area to determine the likelihood of discovering a given resource (e.g. oil, gas, groundwater) by analysing the spatial patterns of foundation datasets. The key objective is to identify areas of increased likelihood of discovering previously unrecognised potential. Sometimes referred to as ‘chance of success’ or ‘common risk segment’ analysis.

prospectivity mapping: mapping or visualisation component of a prospectivity analysis which is used to determine the likelihood of discovering a given resource within a chosen area. See prospectivity assessment.

recharge: see groundwater recharge

regression: the retreat or contraction of the sea from land areas, and the consequent evidence of such withdrawal (such as enlargement of the area of deltaic deposition). Also, any change (such as fall of sea level or uplift of land) that brings nearshore, typically shallow-water environments to areas formerly occupied by offshore, typically deep-water conditions, or that shifts the boundary between marine and nonmarine deposition (or between deposition and erosion) toward the center of a marine basin.

reserves: quantities of petroleum anticipated to be commercially recoverable in known accumulations from a given date forward under defined conditions. Reserves must further satisfy four criteria: they must be discovered, recoverable, commercial and remaining (as of the evaluation date) based on the development project(s) applied.

reservoir: a subsurface body of rock having sufficient porosity and permeability to store and transmit fluids and gases. Sedimentary rocks are the most common reservoir rocks because they have more porosity than most igneous and metamorphic rocks and form under temperature conditions at which hydrocarbons can be preserved. A reservoir is a critical component of a complete petroleum system.

reservoir rock: any porous and permeable rock that contains liquids or gases (e.g. petroleum, water, CO_2), such as porous sandstone, vuggy carbonate and fractured shale

ridge: a narrow, linear geological feature that forms a continuous elevated crest for some distance (e.g. a chain of hills or mountains or a watershed)

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

risk: the effect of uncertainty on objectives (ASNZ ISO 3100). This involves assessing the potential consequences and likelihood of impacts to environmental and human values that may stem from an action, under the uncertainty caused by variability and incomplete knowledge of the system of interest.

runoff: rainfall that does not infiltrate the ground or evaporate to the atmosphere. This water flows down a slope and enters surface water systems.

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

seal: a relatively impermeable rock, commonly shale, anhydrite or salt, that forms a barrier or cap above and around reservoir rock such that fluids cannot migrate beyond the reservoir. A seal is a critical component of a complete petroleum system.

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

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

sedimentation: the process of deposition and accumulation of sediment (unconsolidated materials) in layers seismic survey: a method for imaging the subsurface using controlled seismic energy sources and receivers at the surface. Measures the reflection and refraction of seismic energy as it travels through rock.

sensitivity: the degree to which the output of a model (numerical or otherwise) responds to uncertainty in a model input

severity: magnitude of an impact

severity score: for the purposes of Impact Modes and Effects Analysis (IMEA), the magnitude of the impact resulting from a hazard, which is scored so that an increase (or decrease) in score indicates an increase (or decrease) in the magnitude of the impact

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

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

shear: a frictional force that tends to cause contiguous parts of a body to slide relative to each other in a direction parallel to their plane of contact

siltstone: a sedimentary rock composed of silt-sized particles (0.004 to 0.063 mm in diameter)

sociocultural values: values associated with aesthetic, cultural and spiritual beliefs, human health and recreation or amenity values

source rock: a rock rich in organic matter which, if heated sufficiently, will generate oil or gas. Typical source rocks, usually shales or limestones, contain about 1% organic matter and at least 0.5% total organic carbon (TOC), although a rich source rock might have as much as 10% organic matter. Rocks of marine origin tend to be oil-prone, whereas terrestrial source rocks (such as coal) tend to be gas-prone. Preservation of organic matter without degradation is critical to creating a good source rock, and necessary for a complete petroleum system. Under the right conditions, source rocks may also be reservoir rocks, as in the case of shale gas reservoirs.

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

stratigraphy: the study of the history, composition, relative ages and distribution of stratified rock strata, and its interpretation to reveal Earth's history. However, it has gained broader usage to refer to the sequential order and description of rocks in a region.

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

stressor: chemical or biological agent, environmental condition or external stimulus that might contribute to an impact mode

strike-slip fault: a type of fault whose surface is typically vertical or nearly so. The motion along a strike-slip fault is parallel to the strike of the fault surface, and the fault blocks move sideways past each other. A strike-slip fault in which the block across the fault moves to the right is described as a dextral strike-slip fault. If it moves left, the relative motion is described as sinistral.

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

subcrop: 1 - A subsurface outcrop, e.g. where a formation intersects a subsurface plane such as an unconformity. 2 - In mining, any near-surface development of a rock or orebody, usually beneath superficial material.

subsidence: the sudden sinking or gradual downward settling of the Earth's surface with little or no horizontal motion. The movement is not restricted in rate, magnitude, or area involved.

surface water: water that flows over land and in watercourses or artificial channels and can be captured, stored and supplemented from dams and reservoirs

tenement: an area of land held by an authority holder. May be an authority to prospect, a petroleum lease, a petroleum facilities lease or a petroleum pipeline lease.

thermal maturity: the degree of heating of a source rock in the process of transforming kerogen (derived from organic matter) into hydrocarbon. Thermal maturity is commonly evaluated by measuring vitrinite reflectance or by pyrolysis.

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

total organic carbon: the quantity of organic matter (kerogen and bitumen) is expressed in terms of the total organic carbon (TOC) content in mass per cent. The TOC value is the most basic measurement for determining the ability of sedimentary rocks to generate and expel hydrocarbons.

total porosity: total porosity is the total void space in the rock whether or not it contributes to fluid flow (i.e.the total pore volume per unit volume of rock). It is measured in volume/volume, percent or porosity units. The total porosity is the total void space and as such includes isolated pores and the space occupied by clay-bound water. It is the porosity measured by core analysis techniques that involve disaggregating the sample. It is also the porosity measured by many log measurements, including density, neutron porosity and nuclear magnetic resonance logs.

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

transgression: any change (such as rise of sea level or subsidence of land) that brings offshore, typically deep-water environments to areas formerly occupied by nearshore, typically shallow-water conditions, or that shifts the boundary between marine and nonmarine deposition (or between deposition and erosion) outward from the center of a marine basin.

transtension: the simultaneous occurrence of strike-slip faulting and extension, rifting, or divergence of the Earth's crust trap: a geologic feature that permits an accumulation of liquid or gas (e.g. natural gas, water, oil, injected CO_2) and prevents its escape. Traps may be structural (e.g. domes, anticlines), stratigraphic (pinchouts, permeability changes) or combinations of both.

unconfined aquifer: an aquifer whose upper water surface (watertable) is at atmospheric pressure and does not have a confining layer of low-permeability rock or sediment above it

unconformity: a surface of erosion between rock bodies that represents a significant hiatus or gap in the stratigraphic succession. Some kinds of unconformities are (a) angular unconformity – an unconformity in which the bedding planes above and below the unconformity are at an angle to each other; and (b) disconformity – an unconformity in which the bedding planes above and below the stratigraphic break are essentially parallel.

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

vitrinite: one of the primary components of coal and most sedimentary kerogen. Vitrinite is a type of maceral, where 'macerals' are organic components of coal analogous to the 'minerals' of rocks. It is derived from the cell-wall material or woody tissue of plants.

vitrinite reflectance: a maturation parameter for determining organic matter in fine-grained rocks

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

water-dependent asset: an asset potentially impacted, either positively or negatively, by changes in the groundwater and/or surface water regime due to unconventional gas resource development

water saturation: the fraction of water in a given pore space. It is expressed in volume/volume, percent or saturation units. Unless otherwise stated, water saturation is the fraction of formation water in the undisturbed zone. The saturation is known as the total water saturation if the pore space is the total porosity, but is known as effective water saturation if the pore space is the effective porosity. If used without qualification, the term usually refers to the effective water saturation.

water system: a system that is hydrologically connected and described at the level desired for management purposes (e.g. subcatchment, catchment, basin or drainage division, or groundwater management unit, subaquifer, aquifer, groundwater basin)

water use : the volume of water diverted from a stream, extracted from groundwater, or transferred to another area for use. It is not representative of 'on-farm' or 'town' use; rather it represents the volume taken from the environment.

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

weathering: the breakdown of rocks and other materials at the Earth's surface caused by mechanical action and reactions with air, water and organisms. Weathering of seep oils or improperly sealed oil samples by exposure to air results in evaporative loss of light hydrocarbons.

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

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

well barrier failure: when a single, specific barrier fails to contain fluids (remaining barriers maintaining containment)

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

well integrity failure: when all well barriers have failed and there is a pathway for fluid to flow in or out of the well

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

workover: well procedure to perform one or more remedial or maintenance operations on a producing well to maintain or attempt production increase. Examples of workover operations are downhole pump repairs, well deepening, plugging back, pulling and resetting liners, squeeze cementing and re-perforating.

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