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BIOREGIONAL ASSESSMENTS

CSIRO

Hydrogeology and groundwater systems of the Isa GBA region

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

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Cover photograph

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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Executive summary

This technical appendix focuses on the hydrogeology and groundwater systems of the Isa GBA region in north-west Queensland. This region includes part of the Isa Superbasin, a Paleoproterozoic to earliest Mesoproterozoic superbasin of the North Australian Craton. The Isa GBA region is in the Northern Lawn Hill Platform, an area where petroleum exploration (for both conventional and unconventional resources) has previously occurred.

The Isa GBA region is host to two groundwater systems that are potentially connected:

1. groundwater associated with the Proterozoic rock units of the Isa Superbasin and South Nicholson Basin – typically the deeper groundwater system in the region

2. groundwater associated with the overlying Jurassic to Cretaceous Carpentaria Basin (part of the Great Artesian Basin or GAB) and Karumba Basin.

The supersequences of the Isa Superbasin and South Nicholson Basin rocks extend from outcrop in the west of the Isa GBA region and dip southwards to depths of over 9 km. These older basin sequences are overlain by younger sediments of the Mesozoic Carpentaria and Cenozoic Karumba basins in central and eastern parts of the region.

The Proterozoic units of the Isa Superbasin and South Nicholson Basin are generally highly lithified fine-grained rocks, typically with aquitard properties, and include the prospective shale gas plays of the Lawn and River supersequences. Groundwater exploration of these units has been limited; however, some of the carbonate-dominated lithofacies, particularly the Lady Loretta Formation (Loretta Supersequence) and to a lesser degree the Paradise Creek Formation and Esperanza Formation, exhibit aquifer properties, potentially under artesian pressure.

The Carpentaria Basin (GAB) overlies the Proterozoic units and covers most of the assessment area. The basin consists of a variably confined groundwater system comprising a multi-layered complex of aquifers of variable character within predominantly continental sandstones. Within the assessment area are two regionally recognised aquifers of the GAB:

1. The Gilbert River Formation and underlying basal Jurassic to Cretaceous aquifer system of the Eulo Queen Group

2. The Late Cretaceous Normanton Formation aquifer.

These two groundwater systems are separated by the Rolling Downs Group aquitard, which forms a substantial low-permeability zone that is up to about 500 m thick in eastern parts of the region.

Overlying the Carpentaria Basin is the Cenozoic Karumba Basin, a thin (typically less than 50 m thick in the region) sedimentary basin hosting a series of partial aquifers and leaky aquitards. The aquifers of the Carpentaria and Karumba basins are more widely utilised than the Proterozoic groundwater systems in the region. Of the 190 registered groundwater bores within the assessment area for this study, 152 are in the Carpentaria and Karumba basins, providing the shallowest and most economically important groundwater resources. The

remaining 38 bores (all in the west of the region) access groundwater from the Proterozoic rock units of the Isa Superbasin and South Nicholson Basin.

The regional watertable aquifer, which lies in the Karumba Basin across most of the region, flows to the north-east towards the Gulf of Carpentaria. Groundwater in the confined Gilbert River Formation aquifer is typically under artesian pressure and the direction of groundwater flow is uncertain. The groundwater flow direction in the Proterozoic units has not been established due to the lack of available water level data and the potential influence of major fault structures in compartmentalising groundwater flow systems. Groundwater within all of the aquifers in the region is of low to moderate salinity, with median total dissolved solid (TDS) concentrations typically of 600 to 1400 mg/L.

The potential exists for intra-basin groundwater connectivity throughout the region, both within the Proterozoic units of the Isa Superbasin and South Nicholson Basin as well as the overlying Carpentaria and Karumba basins. In addition, five hydrological connectivity pathways that can potentially link shale gas reservoirs to overlying aquifers or near-surface environmental and economic assets cannot be ruled out as occurring in the region, based on development of conceptual hydrogeological models for this study. Although there is very little direct evidence currently available to verify the existence of these pathways, they can conceptually be recognised as: 1. direct stratigraphic connections, 2. deep-seated faults, 3. aquifers of sufficient porosity and permeability, 4. partial aquifers and aquitards, and 5. catchment constrictions where steep hydraulic gradients exist between alluvial aquifers and underlying formations.

The interactions between groundwater and surface water are key components of the hydrogeological system and are important for supporting many ecosystems in the region. Approximately one-third of the Isa GBA region has terrestrial and aquatic groundwater-dependent ecosystems, including springs, nationally important wetlands and strategic environmental areas. Groundwater interacts with surface waters through a variety of mechanisms. These interactions are dynamic in nature due to the seasonal rainfall regime.

Based on analysis of available datasets, the ‘floodplain and alluvium’ landscape class (MacFarlane et al., 2020) in the region has the greatest potential for surface water – groundwater interactions, arising from hydraulic connection between the Karumba Basin sediments and surface water features. Spring ecosystems in the south-west (both within and just outside the region boundary) are potentially supported by Proterozoic sandstone aquifers in contact with deeper shale gas units. Given the connectivity between groundwater and surface waters, future groundwater use will need to consider the potential impacts on shallow aquifers and surface water systems.

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- Internal Peer Review Group: Geoscience Australia – Jessica Northey, Robert Langford
- Discipline Leaders: Tim Ransley (Hydrogeology)
- Basin Leaders: Steven Lewis (Isa Superbasin)
- Technical Peer Review Group: Andrew Boulton, Catherine Moore
- State Government Science Technical Review: This group includes scientists with expertise in hydrogeology from the Queensland Government.

Abbreviations and acronyms

Abbreviation/acronym	Definition
AEP	annual exceedance probability
AHD	Australian Height Datum
ASS	assumed datum
CH_4	methane
CSG	coal seam gas
DEA	Digital Earth Australia
EC	electrical conductivity
EPBC Act	*Environment Protection and Biodiversity Conservation Act 1999*
GAB	Great Artesian Basin
GABORA	Great Artesian Basin and Other Regional Aquifers
GBA	Geological and Bioregional Assessment
GDE	groundwater-dependent ecosystem
HCA	hierarchical cluster analysis
HRS	hydrologic reference station
IBRA	Interim Biogeographic Regionalisation of Australia
ILUA	Indigenous Land Use Agreement
Ma	millions of years before present
MSL	mean sea level
MNES	Matters of National Environmental Significance
NABRE	Northern Australian Basins Resource Evaluation
PFS	polygonal fault system
RN	registered number
SAR	sodium absorption ratio
SRTM	shuttle radar topographic mission
SWIR	short-wave infrared
TCI	tasselled cap index
TCW	tasselled cap wetness
TDS	total dissolved solids
WOfS	Water Observations from Space

Units

Unit	Description
AHD m	Australian Height Datum (metres)
D	darcy
GL/year	gigalitres per year
kPa	kilopascals
L/s	flow rate in litres per second
L/min	flow rate in litres per minute
m	metres
mbgl	metres below ground level
mD	millidarcy
mg/L	milligrams per litre
ML	megalitres
mm/year	millimetres per year
TDS mg/l	total dissolved solids in milligrams per litre
µg/L	micrograms per litre
µS/cm	microSiemens per centimetre

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 NT. In early 2018, deep coal gas was added to the assessment for the Cooper GBA region, as this play is actively being explored by industry.

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

The GBA Program aims to:

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

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

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

Presented in this technical appendix is a description of the hydrogeology of the Isa GBA region. It provides more detailed information regarding the depositional and tectonic history, groundwater system conceptualisation, and conceptual models of potential connectivity pathways. The structure and focus of the synthesis report and technical appendices reflect the needs of government, industry, landowners and community groups.

Technical appendices

Other technical appendices that support the geological and environmental baseline assessment for the Isa GBA region are:

- 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 Superbasin.
- Bailey AHE, Bradshaw BE, Palu TJ, Wang L, Jarrett AJM, Orr M, Lech M, Evenden C, Arnold D, Reese B, Skeers N, Woods M, Dehelean A, Lawson C and Hall L (2020) Shale gas prospectivity of the Isa GBA region.
- MacFarlane CM, Herr A, Merrin LE, O'Grady AP and Pavey C (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 review for the GBA regions.

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

1 Introduction

This appendix reviews and assesses the hydrogeology and groundwater systems of the Isa GBA region in north-west Queensland. This is part of the technical component of Stage 2 of the Geological and Bioregional Assessment (GBA) Program, providing a geological and environmental baseline assessment of the region.

The Isa GBA region (Figure 1) is the area of the Isa Superbasin containing identified shale gas plays, where future development of these resources could result in delivery of gas to the East Coast Gas Market. This appendix draws on several other technical appendices developed for the Isa GBA region, including the shale gas prospectivity assessment of Bailey et al. (2020) and the regional geology review (Orr et al., 2020). Further information about how the Isa GBA region has been defined is in Orr et al. (2020).

The aims of this appendix are to:

1. provide details of the groundwater and connected surface water systems as they are currently understood in and around the Isa GBA region
2. describe potential hydrological connectivity between these systems, with particular reference to potential changes in system connectivity that could occur due to shale gas development
3. provide baseline datasets to underpin the future development of shale gas development activities
4. outline recommendations for future data collection and assessment to improve the baseline system understanding.

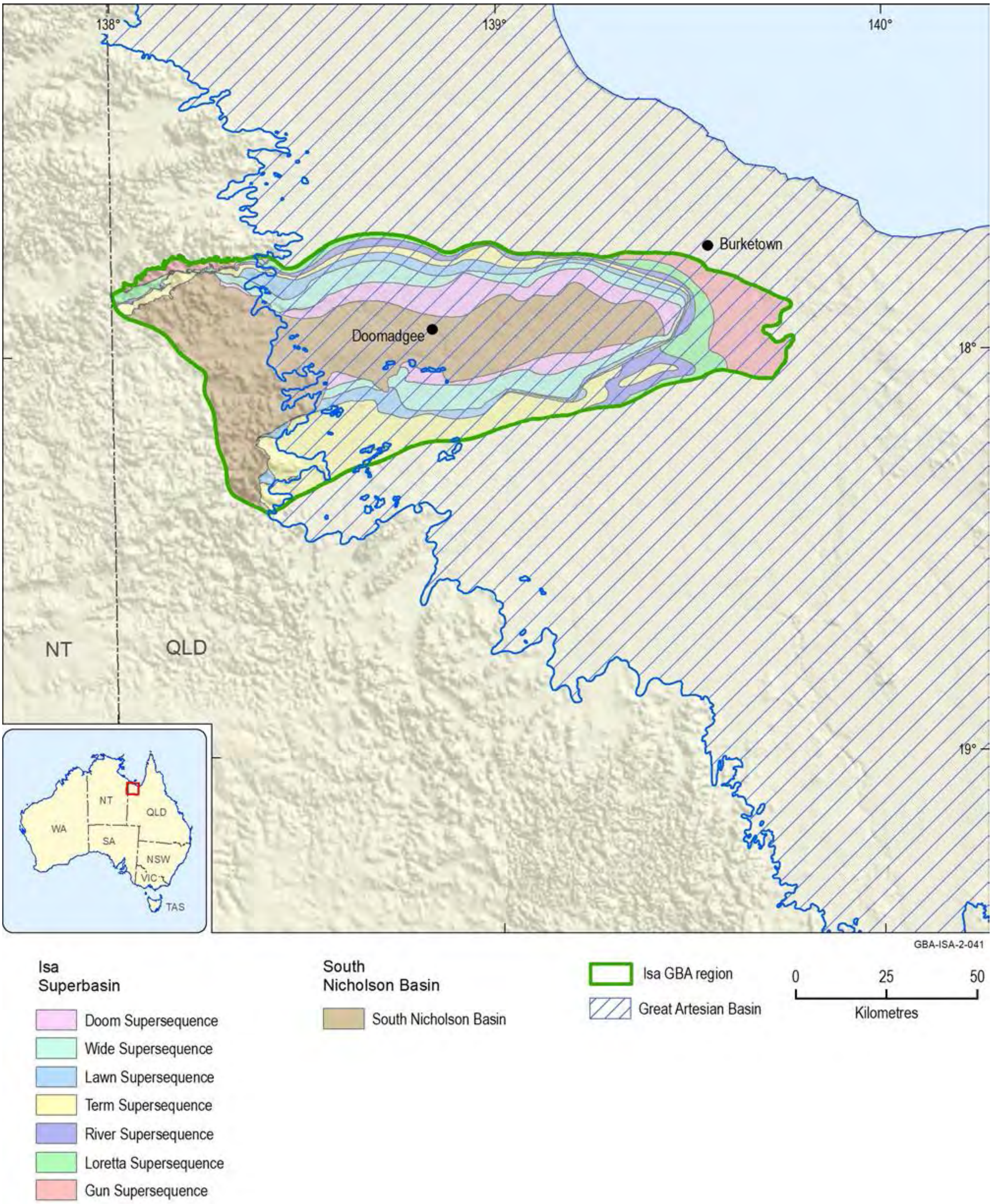


Figure 1 Extent of the Great Artesian Basin (GAB), showing the underlying Proterozoic rocks of the Isa Superbasin and the South Nicholson Basin in the Isa GBA region

The Proterozoic units outcrop in the west of the Isa GBA region, but are buried by younger cover sediments of the Carpentaria Basin (part of the Great Artesian Basin) and the Karumba Basin in the central and eastern part of the region.
Data: Isa Superbasin and South Nicholson Basin geology (Bradshaw et al., 2018a); GAB extent (Ransley et al., 2015b)
Element: GBA-ISA-2-041

1.1 Hydrogeological terminology

Hydrostratigraphy is the identification of mappable geological units based on their hydraulic properties. Where consecutive lithological units have similar hydrological properties, they may be aggregated and referred to as a single hydrostratigraphic unit. Typically, hydrostratigraphic units are classified as: aquifers, partial aquifers, aquitards, leaky aquitards and aquicludes. Aquifers are defined as an underground layer or layers of water-bearing permeable rock, rock fractures or unconsolidated materials (gravel, sand, or silt). An aquitard is a layer of underground material which impedes the movement of water; an aquiclude is one which prevents movement of water. If a confining layer (aquitard or aquiclude) overlies an aquifer, the aquifer is said to be confined. If the pressure in this aquifer is such that the resultant groundwater level is above the natural ground level, artesian conditions exist. A well or groundwater spring fed by such an aquifer will naturally flow at the land surface. Where the groundwater level does not reach the surface, sub-artesian conditions exist. The potentiometric surface is a hypothetical surface that defines the height to which the artesian water may rise. These hydrogeological concepts are illustrated in Figure 2.

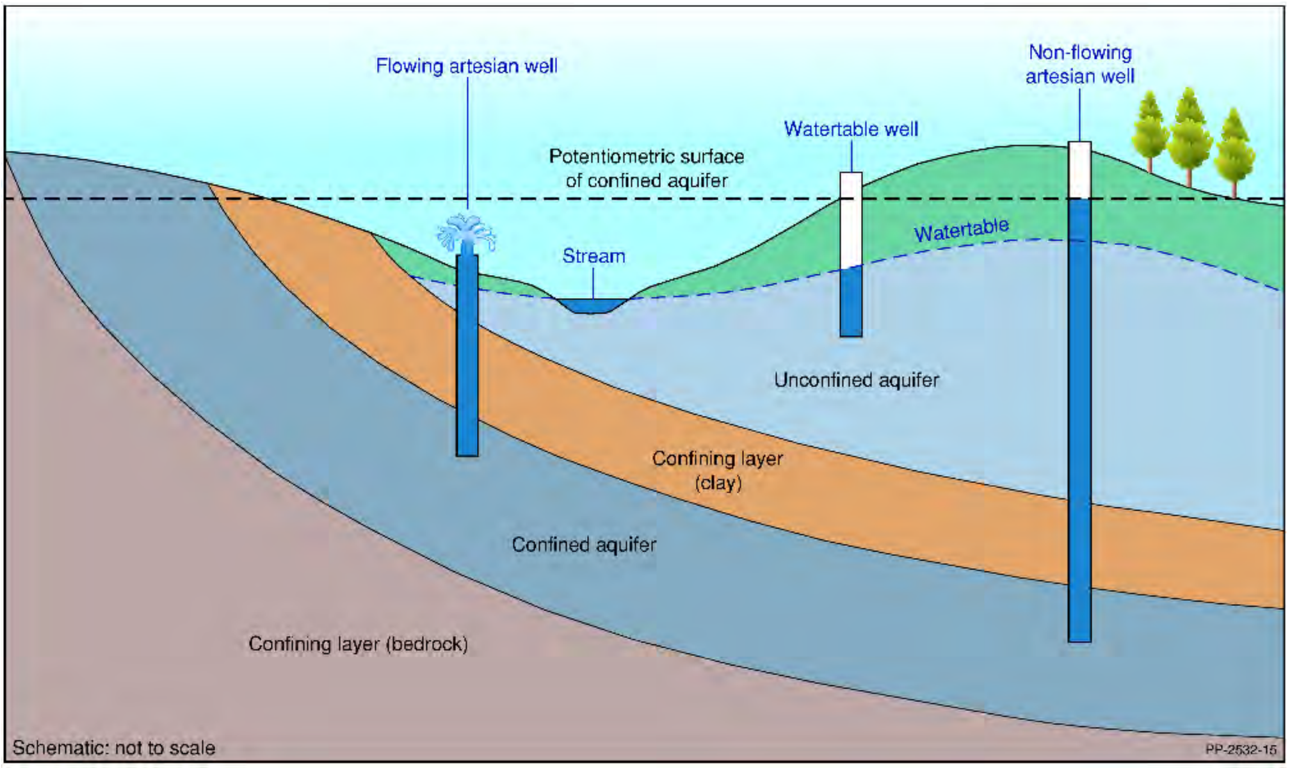


Figure 2 Schematic example of hydrogeological units, including unconfined aquifers, aquitards (confining layers), confined aquifers and the potential effect of these on groundwater levels/pressures

Source: after Figure 3 in DSEWPAC (2016)
Element: GBA-ISA-2-152

2 Depositional and tectonic history

This section presents a brief summary of the depositional and tectonic history of geological basins in the Isa GBA region, providing context relevant to this hydrogeological assessment. A detailed account of the depositional and tectonic history is presented in the geology technical appendix (Orr et al., 2020).

2.1 Isa Superbasin and South Nicholson Basin

The Isa Superbasin is a Paleoproterozoic to earliest Mesoproterozoic superbasin of the North Australian Craton. It contains a mixed assemblage of clastic and carbonate rock sequences that formed during the period from 1670 to 1575 million years ago (Ma). Superbasins are understood to be originally very large single depositional systems that have been disrupted internally by later tectonism to form numerous structural basins and other structural features. The full extent of the Isa Superbasin has not yet been defined. It is primarily identified and described from the Lawn Hill Platform in the Mount Isa Inlier in Queensland, although extends under cover for potentially several hundred kilometres (Betts et al., 2006; Scott et al., 2000) and has been recognised in McArthur Basin sequences in the NT (Abbott et al., 2001; Southgate et al., 2000).

In the west of the Isa GBA region, the geological units of the Paleoproterozoic to Mesoproterozoic Isa Superbasin are exposed on the northern and southern margins of an eastward extension of Mesoproterozoic South Nicholson Basin rocks. The Isa Superbasin and South Nicholson Basin rocks extend from outcrop in the west of the region and dip southwards under a gradual thickening of cover of the Mesozoic Carpentaria and Cenozoic Karumba basins. Figure 1 presents the outcrop and subcrop extents of the Proterozoic Isa Superbasin and South Nicholson Basin within the region and the overlying extent of the Carpentaria and Karumba basins. This is presented in cross-section in Figure 3.

From a hydrogeological perspective, the main groundwater-bearing units of the region occur in the overlying Jurassic to Cretaceous Carpentaria and Cenozoic Karumba Basins. The following section presents an overview of the key aspects of the depositional and tectonic history of these younger basins. A comprehensive discussion of the depositional and tectonic history of these basins can be found in several recent publications (Ransley and Smerdon, 2012; Ransley et al., 2015b; Smerdon et al., 2012b; Radke et al., 2012).

2.2 Carpentaria Basin

The Jurassic to Cretaceous Carpentaria Basin is a broad north-trending intracratonic depression up to 1800 m deep in the offshore part of the basin. It is separated from contiguous geological basins by basement highs (Smerdon et al., 2012b). The basin is the northernmost of a number of geological basins, including the Eromanga and Surat basins (and a portion of the Clarence-Moreton Basin), which collectively are known as the Great Artesian Basin (GAB). The Isa GBA region is near the boundary of the southern Staaten Sub-basin and the Western Gulf Sub-basin of the GAB, and west of the Burketown Depression, a poorly defined Jurassic (or older) erosional feature (Figure 4).

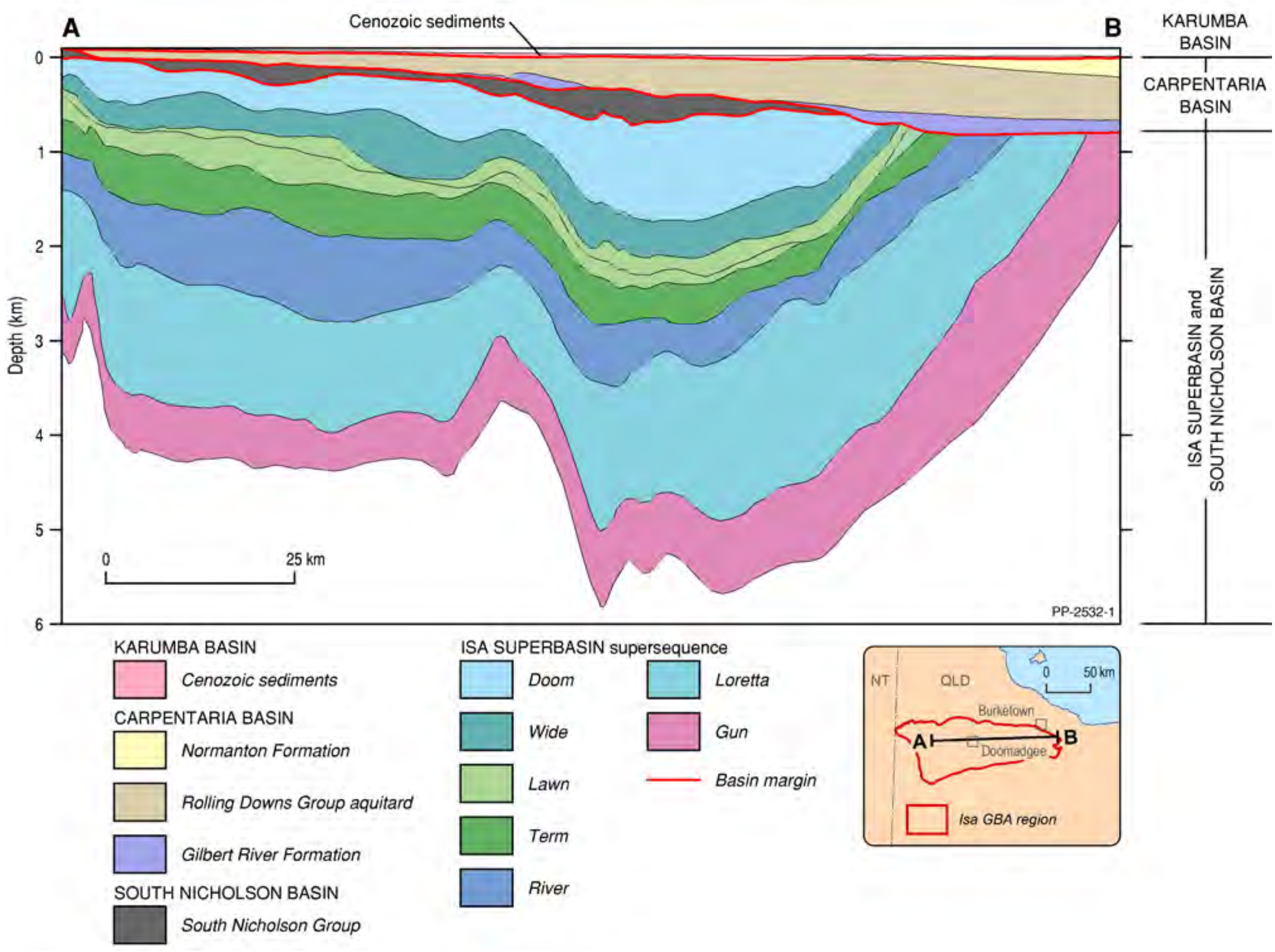


Figure 3 Geological cross-section (west to east) of the Isa GBA region

The Carpentaria Basin (part of the Great Artesian Basin) and Karumba Basin overlie the rocks of the South Nicholson Basin and Isa Superbasin (supersequences shown). Other geological cross-sections provided later in this report show the subsurface structure and architecture of these basins in other parts of the Isa GBA region – see Figure 10, Figure 11, Figure 60, Figure 61 and Figure 62 for further details.
Source: geological cross-section (Bradshaw et al., 2018a)
Element: GBA-ISA-2-138

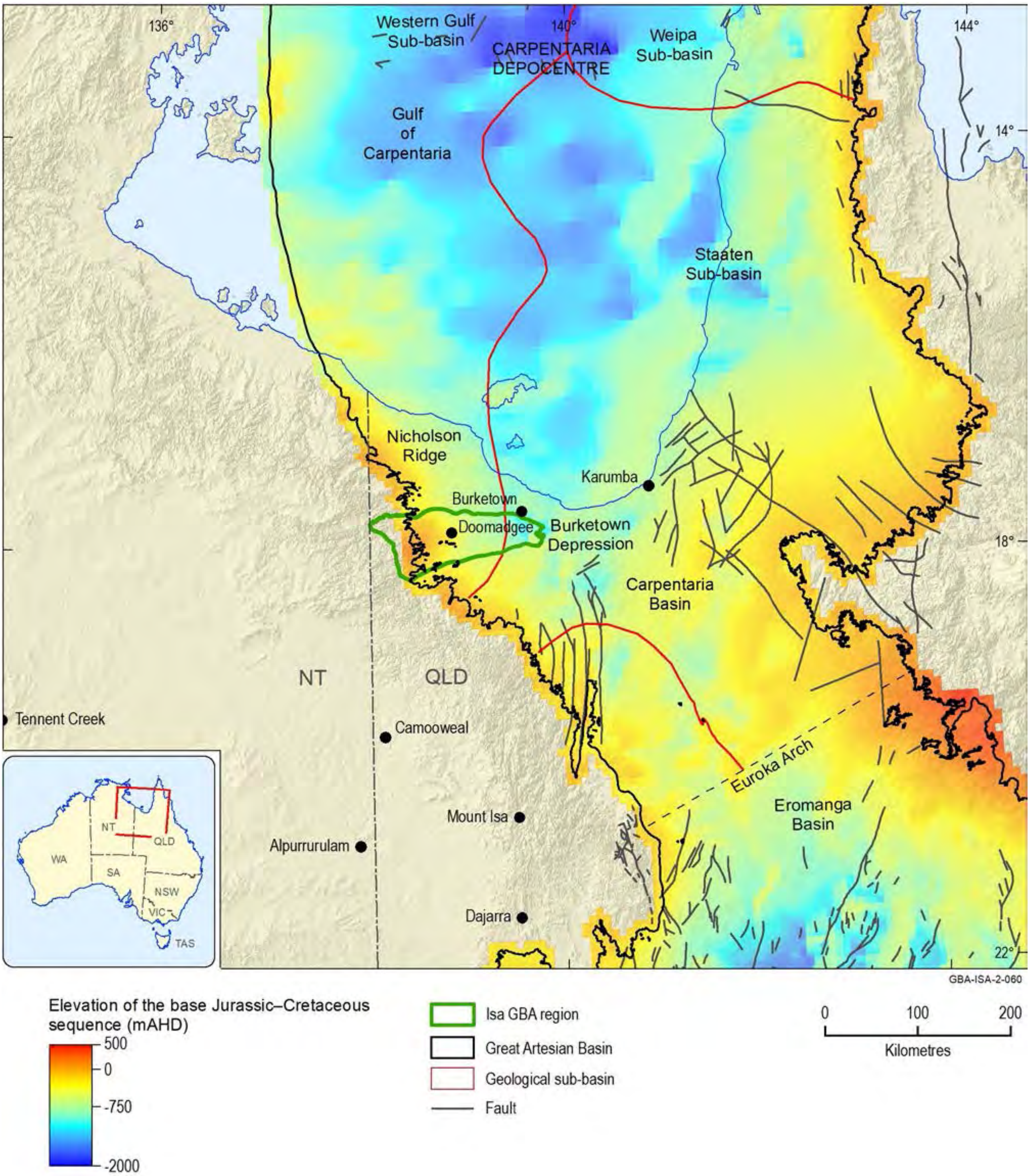


Figure 4 Structural features and sub-basins of the Great Artesian Basin

Source: Ransley et al. (2015b)
Element: GBA-ISA-2-060

Deposition in the Carpentaria Basin (Orr et al., 2020) began in the Jurassic with fluvial quartzose sandstones of the Eulo Queen Group, principally restricted to paleotopographic valleys in southern parts of the Weipa and Staaten sub-basins (McConachie et al., 1990). Deposition recommenced with fluvial quartzose sandstones of the Gilbert River Formation. This unit is glauconitic towards the top of the formation, marking a shift to marine conditions through relative sea-level rise in the Early Cretaceous (Smerdon et al., 2012b). Marine conditions became more widespread in the middle Cretaceous, resulting in deposition of fine-grained clastic sediments (silts and muds) of the upper Wallumbilla Formation. Input from terrestrial sources was highly variable, possibly introduced through actively shifting deltaic lobes infilling a shallow shelf sea (Smerdon et al., 2012b). The overlying and organic-rich Cretaceous Toolebuc Formation shows gradually decreasing organic content towards the north, as open marine conditions began to dominate. Shallow marine conditions in the Southern Carpentaria Basin deposited fine-grained siltstones and mudstones of the Allaru Mudstone.

At approximately 90 Ma, a phase of uplift led to the formation of the highlands on the eastern margin of the Eromanga Basin (Figure 4). The resultant increase in erosion in the highlands and corresponding deposition down-gradient formed the Normanton Formation. This represented the final phase of Cretaceous sedimentation within the Carpentaria Basin. During this period, deposition occurred under basin-wide progradation infilling shallow seas. The Normanton Formation is a relatively extensive body of glauconitic sandstone and siltstone. Together with the Allaru Mudstone, Toolebuc Formation and Wallumbilla Formation, these units comprise the Rolling Downs Group (Smerdon et al., 2012b).

2.3 Karumba Basin

The Cenozoic Karumba Basin unconformably overlies the Carpentaria Basin in much of northern Queensland, and extends into eastern parts of the NT. It formed as a broad and shallow intracratonic sag basin, with its development divided into three major cycles, all of which are characterised by similar sequences of erosion, deposition and weathering. The active phase of each cycle was tectonic warping, providing an erosional surface for material to be transported to lower downwarped regions. As the gradient between these regions flattened, a passive phase was entered during which both erosion and deposition greatly reduced. Weathering of this ’terminal surface’ continued until renewed tectonism initiated another cycle (Doutch, 1976; Cook and Jell, 2013).

The three cycles (Doutch, 1976) recognised in the Karumba Basin are the:

1. Bulimba Cycle
2. Wyaaba Cycle
3. Claraville Cycle

Bulimba Cycle

The Bulimba Cycle was initiated with the uplift of the eastern margins of the Karumba Basin in the Late Cretaceous or early Paleogene. The resultant deposition produced the Bulimba Formation, consisting of interbedded clayey sandstone, conglomerate and sandy claystone. The Bulimba surface was deeply weathered and has given rise to the siliceous duricrusts in the Isa GBA region.

Wyaaba Cycle

According to Doutch (1976), the Wyaaba Cycle was initiated by Oligocene tectonism resulting in uplift of the present Great Dividing Range and the southerly margin of the basin. Erosional destruction of significant portions of the Aurukun Surface occurred during this time. The Wyaaba beds comprise primarily fluvial clayey sandstone, conglomerate and interbedded clayey sandstone, thickening towards the present coast and extending offshore. Marine deposits exist near the coast and extend offshore. The facies of the Wyaaba beds are similar to the Bulimba Formation, reflecting the similar depositional environment. The Pliocene Kendall Surface (and equivalents) is a deeply weathered terminal surface at the end of the Wyaaba Cycle and occurs over most of the Karumba Basin (Grimes and Sweet, 1979).

Claraville Cycle

The Claraville Cycle commenced with uplift in the Pliocene and underwent several stages of upwarp with eustatic and climate fluctuations. This cycle produced the Armraynald beds. The sediment composition of these stages typically comprises quartzose sands with minor silts and clays.

3 Data inventory

3.1 Key datasets

The following datasets (listed alphabetically) have been drawn on for this report:

Depth structure and isochore data

The depth structure and isochore (true vertical thickness) data for the: River Supersequence; Term Supersequence; Lawn Supersequence; Lawn 4 Sequence; Wide Supersequence, Doom Supersequence; South Nicholson Basin; and Carpentaria Basin that were used in this assessment are sourced from the recently published Geoscience Australia update (Bradshaw et al., 2018b) to the original Northern Australian Basins Resource Evaluation (NABRE) seismic interpretations over the Northern Lawn Hill Platform (Bradshaw and Scott, 1999).

Environmental assets data

Data on environmental assets within the region were obtained from the Queensland Government springs database (Department of Environment and Science (Qld), 2018), the Groundwater Dependent Ecosystems Atlas (Bureau of Meteorology, 2017) and WetlandInfo (Department of Environment and Science (Qld), 2017).

Geological data

The surface geological data used in this study are from the 'surface geology of Australia' dataset (Geoscience Australia, 2012). The structural features used for mapping surface and subsurface faults and other structural elements are from the Geological Survey of Queensland (2011); Geoscience Australia (2013).

Hydrochemistry data

Available groundwater chemistry data were sourced from Bardwell and Grey (2016), the Water Monitoring Information Portal (Department of Natural Resources, Mines and Energy (Qld), 2018a) and EHS Support (2014).

Queensland groundwater database

This database holds records of all known groundwater bore records registered with the Queensland Government (Department of Natural Resources, Mines and Energy (Qld), 2018d). The database was interrogated for information situated beyond the Isa GBA region to allow for the analysis of a greater number of bores, so as to provide additional information on regional hydrogeological conditions (for example, lithology, groundwater yield, salinity, groundwater levels). Data from 190 bores within an area of about 24,000 km^2 were extracted from the database and used in this assessment. Of these 190 bores, 53 are within the Isa GBA region. The broader assessment region was selected to include a number of bores (and hence stratigraphic information) that were set in the deeper units of the GAB. Of these bores, 60 had sufficient stratigraphic information to allow attribution of a source aquifer. The location of all bores extracted from the Queensland groundwater database for use in this study is in Figure 5.

Many bores were re-assigned a source aquifer, based on analysis by the Isa GBA research team of the aforementioned Geoscience Australia update to seismic interpretations over the Northern Lawn Hill Platform (Bradshaw et al., 2018b). The derived dataset for the Isa GBA region is herein known as the interpreted groundwater database (Geoscience Australia, 2018f).

Mesozoic and Cenozoic aquifer and aquitard intervals

The Mesozoic and Cenozoic hydrostratigraphic unit data (Geoscience Australia, 2018c) for the Carpentaria Basin were re-interpreted from the previously published regional-scale Great Artesian Basin mapping of Smerdon et al. (2012c). The methodology used for this update involved:

- Interpreting the base of Carpentaria Basin (top Proterozoic), top of Gilbert River Formation and base of Normanton Formation and top of Normanton Formation on seismic data using well log interpretations and time-depth data from available exploration bores.
- Converting the seismic two-way time interpretations into depth below seismic datum (MSL) using the same workflow documented by Bradshaw et al. (2018b) using their Mesozoic velocity model.
- Merging the depth-converted seismic grid with the regional grids of Smerdon et al. (2012c) over the groundwater assessment area defined for this study.
- Verifying and refining the merged grids using all available stratigraphic tops in borehole data over the assessment area.
- Estimating the thickness of Karumba Basin sediments by subtracting the top of the Normanton Formation from surface elevation data.

Petroleum exploration wells

Where relevant, petroleum well completion reports have been used to assist hydrogeological interpretation. Figure 5 shows the location and names of the key petroleum exploration wells used in this assessment.

Remote sensing data

All of the remotely sensed satellite data used in this study were obtained from Digital Earth Australia (Geoscience Australia, 2018e). A number of different remote sensing products were used to investigate the persistence of water and/or wetness in the landscape (see Section 4.5.6).

Stream gauge data

The available stream gauge data within and surrounding the Isa GBA region were sourced from Water Monitoring Information Portal (WMIP) (Department of Natural Resources, Mines and Energy (Qld), 2018a) and Water Data Online (Bureau of Meteorology, 2015) for the hydrologic reference station (HRS) gauges.

Elevations of stream gauges (zero gauge) were obtained from WMIP (Department of Natural Resources, Mines and Energy (Qld), 2018a) as well as estimated from the national digital elevation model (1 second Shuttle Radar Topography Mission, SRTM) (Gallant et al., 2011). The surveyed zero gauge height is in metres relative to the Australian Height Datum (AHD) or Assumed Datum (ASS).

Surface elevation data

Surface elevation data from the national-scale digital elevation model (Gallant et al., 2011) were used to convert groundwater and stream levels to a standard datum (mAHD). Zero-gauge elevations were also obtained from the Queensland database (Department of Natural Resources, Mines and Energy (Qld), 2018d).

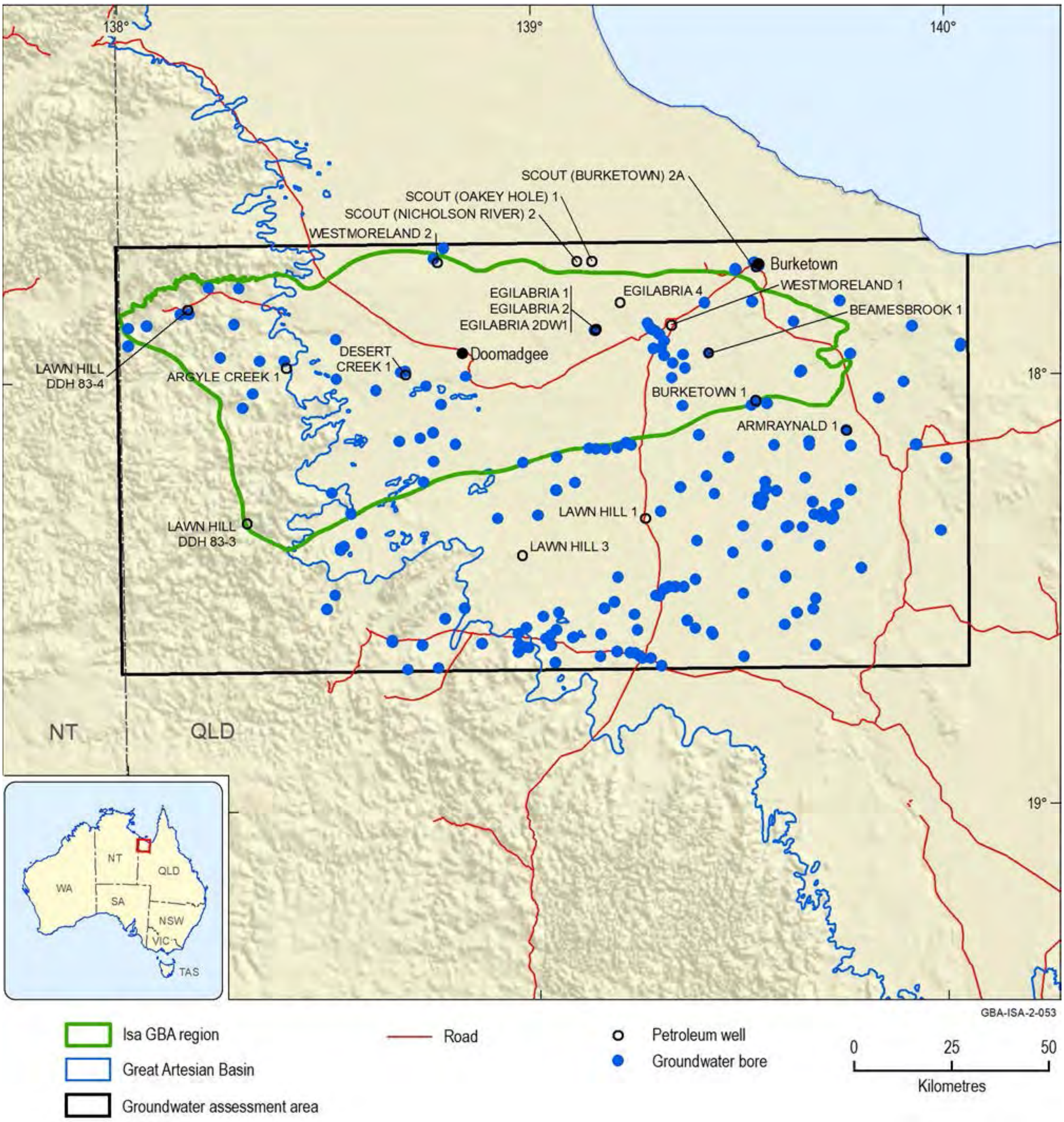


Figure 5 Registered groundwater bores and petroleum exploration wells within and near the Isa GBA region

Due to the low number of groundwater bores in the Isa GBA region (green polygon) additional bores from the surrounding area (black box) were used in this assessment to increase the information available for interpretation.
Data: Groundwater bores (Department of Natural Resources, Mines and Energy (Qld), 2018d); petroleum well locations – Queensland (Department of Natural Resources, Mines and Energy (Qld), 2018e)
Element: GBA-ISA-2-053

3.2 Groundwater use

3.2.1 Existing 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, 2017a) and the *Water Plan (Gulf) 2007* (Queensland Government, 2007). The GABORA plan manages groundwater in identified regional aquifers, and also applies to GAB springs (although there are no GAB springs in or near the Isa GBA region). The GABORA Plan has 16 constituent groundwater units, and three of these intersect the Isa GBA region: the Hooray, Normanton and Rolling Downs units (Figure 6). 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. These groundwater sub-areas occur over much larger parts of Queensland than the extent of the Isa GBA region.

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, 2017). 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:

- 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 several 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 Islanders economic reserve available 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.

Current Queensland Government policy suggests that capping and piping of existing (non-watertight) bores and bore drains in the GAB would be encouraged in the first instance as the preferred way to access groundwater, prior to consideration of granting any further release under the general or state reserves. Notably, most of the opportunities available to cap and pipe existing bores do not actually occur in the Isa GBA region or the immediate surrounds, but rather exist in areas that may be up to hundreds of kilometres distant (and potentially even over a thousand kilometres away from the region).

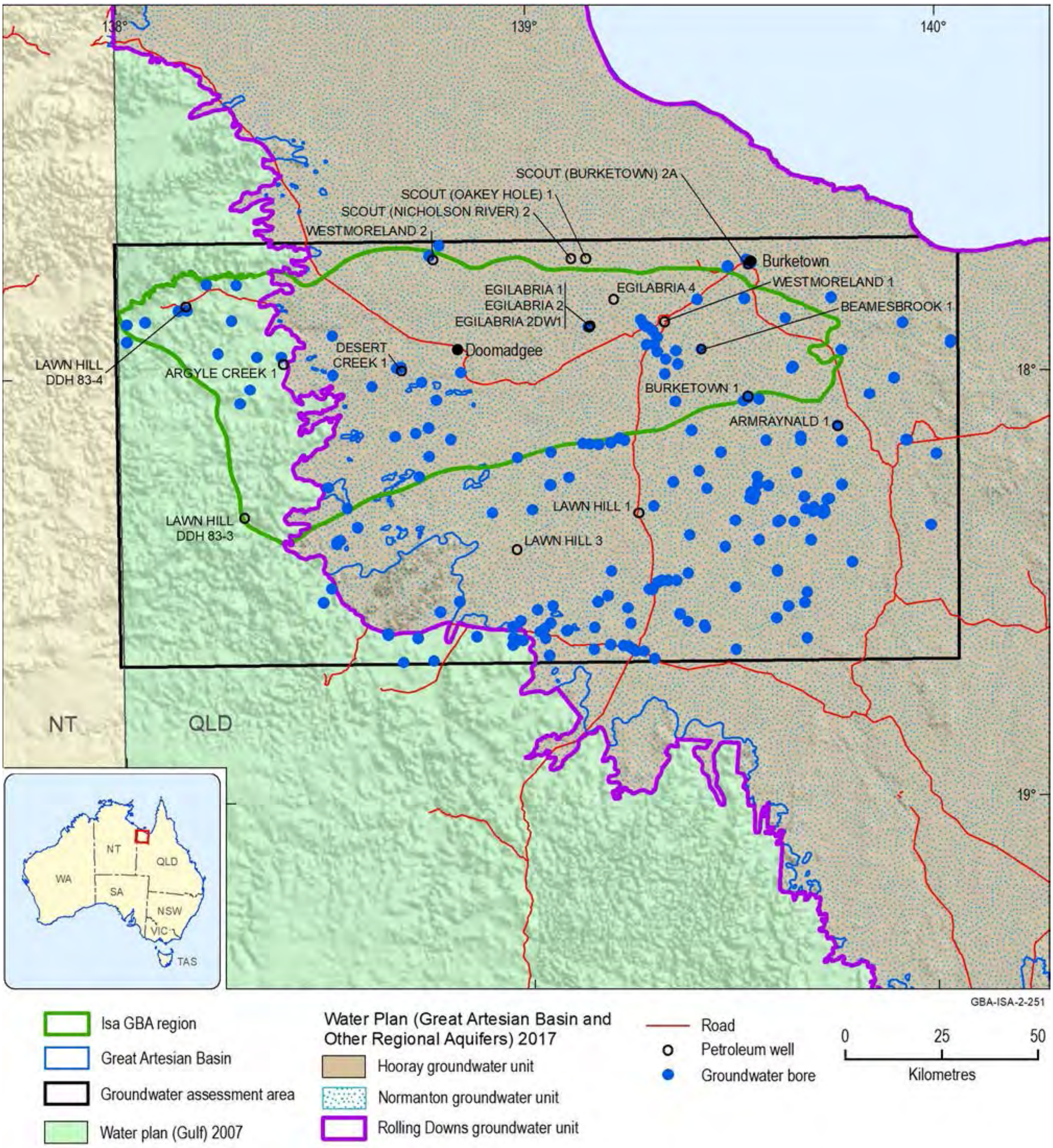


Figure 6 Groundwater management areas and registered bores in the Isa GBA region

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

In addition to the GABORA Plan, the *Water Plan (Gulf) 2007* (Queensland Government, 2007) (Gulf Plan) is relevant to the management of 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 Isa GBA region. The Gulf Plan also includes the Nicholson groundwater management area (GMA), which applies to non-GAB groundwater resources hosted in either the Cenozoic Karumba Basin (which overlies the GAB in central and eastern parts of the Isa GBA region) or in various Proterozoic fractured rock aquifers. These Proterozoic aquifers may underlie the GAB aquifers within the central and eastern parts of the region, and may also exist in areas to the 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 the groundwater resources administered under the Gulf Water Plan (for example, groundwater from Proterozoic fractured rock aquifers beneath the GAB) can be accessed without needing a water licence.

3.2.2 Groundwater use

Groundwater use in the Southern Carpentaria Basin (part of the GAB) was estimated as part of a detailed hydrogeological assessment undertaken by consultants Klohn Crippen Berger in 2016 for the Queensland Government (Klohn Crippen Berger, 2016a). The Isa GBA region, which occurs in the far north-west of this assessment area covers about 10% of the Southern Carpentaria Basin that was assessed for this investigation. The Klohn Crippen Berger (2016a) work highlighted that 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. 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 aquifer of the Gilbert River Formation. The estimated water use (in 2016) in the Southern Carpentaria Basin is shown in Table 1.

As discussed in Section 3.1, the Isa GBA region has 53 bores recorded in the Queensland groundwater database (Department of Natural Resources, Mines and Energy (Qld), 2018d). 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 in the region. 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 in the region. However, Klohn Crippen Berger (2016a) 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 for the region, particularly if some registered bores are no longer operational or do not extract at the assumed rate.

Within the entire catchment area of the Nicholson River there are currently 35 water licences, consisting of 20 groundwater licences and 15 surface water licences. About half (45%) of the groundwater licences are administered under the GABORA plan (either the Carpentaria South Gilbert River Aquifer or groundwater sub-area or Carpentaria South Wallumbilla groundwater sub-areas), with the remainder under the Gulf Plan.

Table 1 Estimated water use for the Southern Carpentaria Basin, Queensland

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	3913	3,914	386	10,339
Total	2,935	3956	4,510	386	11,787

Additional to these estimated water use volumes, Klohn Crippen Berger (2016b) also estimated that 209 ML/year is used for stock and domestic purposes from the Bulimba Formation, part of the Cenozoic Karumba Basin overlying the Carpentaria Basin
Source: Klohn Crippen Berger (2016a)

3.2.3 Potential future groundwater 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 all major life-cycle stages, particularly during the gasfield development phase when most production wells are drilled and hydraulically fractured. Water is also needed for many other activities across the life of the field, such as construction and maintenance of access roads, pipelines and gas production facilities, as well as site decommissioning and rehabilitation.

Data from US shale gas fields which have been developed over the past 15 to 20 years indicates that there is considerable regional variability in the volume of water needed to hydraulically fracture shale gas wells. A variety of factors, such as local geological conditions, average vertical drilling depths and horizontal well lengths, and the number of hydraulic fracturing stages per well will all influence the total volume of water required. For example, Kondash and Vengosh (2015) demonstrated that the median volume of water needed for hydraulic fracturing of a US shale gas production well can range from 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, is more than 20 ML/well (Fayetteville (Arkansas) and Woodford (Oklahoma) shales). These data are similar to work published by Nicot and Scanlon (2012) which investigated water use in shale gas wells across several basins in Texas.

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 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). In the Isa GBA region, the only hydraulic fracturing undertaken to date was for Armour Energy's exploratory drilling and fracturing program at Egilabria 2DW1 (see the prospectivity technical appendix, Bailey et al. (2020)). The investigative nature of Armour Energy's Egilabria 2DW1 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 the 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 further work is required to better understand the future development profile (including water use requirements) of this region.

3.2.3.1 Groundwater and surface water resources

There are several groundwater and surface water sources potentially available to supply the water required for future shale gas development in the Isa GBA region, e.g. water needed for drilling, hydraulic fracturing and civil construction activities. These options include possible access to water resources of the GAB (i.e. through the GABORA Plan), as well as surface water and groundwater resources administered under the Gulf 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 Water Plan. Consultation with water policy staff from the Queensland Government's Department of Natural Resources, Mines and Energy indicates that the most likely GAB water supply options available to cater for future 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) could be used 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 GAB groundwater units that intersect the Isa GBA region (as discussed in Section 3.2.1)
- Water permits for activities of limited duration, which may be available for initial exploration and appraisal operations prior to development.

In addition to accessing GAB water resources, shale gas proponents could potentially access water reserves available through the Gulf Plan. For example, licences may be granted to extract available surface water reserves 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 to the Isa GBA region. In particular, within the Nicholson GMA there are available groundwater resources that could be sourced from the shallow aquifers of the Karumba Basin, or the Proterozoic fractured rock aquifers that underlie the GAB or occur to the west of the GAB boundary. Shale gas proponents may also be able 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.

3.2.3.2 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 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 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 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 reservoirs, or CSG reservoirs. Kondash and Vengosh (2015) highlighted the variable volume of produced water from different US shale gas fields, 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 and 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 and flowback water, typically 5 to 6 ML/well. These examples illustrate the variability of produced water volumes associated with shale gas development.

Depending on the volume of produced water recovered during gas production operations it may be possible for produced water to be treated and reused as a water source for subsequent 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 develop an improved understanding of shale gas reservoir characteristics, including produced water volumes, water quality parameters and any temporal production trends.

In the Isa GBA region, reusing any produced or flowback water that may be captured as part of shale gas extraction 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 *Environment Protection Act*.

4 Groundwater system conceptualisation

This section summarises the current understanding and available baseline data for the groundwater systems and hydrogeological processes in and around the Isa GBA region.

The region hosts two regional-scale groundwater systems, as illustrated in the conceptual block diagram in Figure 7:

- groundwater associated with the Proterozoic units of the Isa Superbasin and South Nicholson Basin – typically the deeper groundwater system in most of the region
- the overlying groundwater system of the Carpentaria Basin (part of the Great Artesian Basin (GAB)) and Karumba Basins. The GAB covers most of the Isa GBA region (except the far western part, as shown in Figure 1).

Key observations about these groundwater systems are that:

- Groundwater of suitable quality and quantity supports existing stock and domestic use within and around the Isa GBA region, particularly for the pastoral (beef cattle) industry. Any future water supply demands for shale gas operations in the region are likely to be substantially greater than the current level of extractions. Although there are several possible water supply options to support shale gas industry demands (Section 3.2), more detailed investigations are required to assess their sustainability and potential impacts.
- There is limited connectivity between the deeper unconventional shale gas targets in the Proterozoic rock units and the shallower aquifers of the GAB and watertable. However, there may be potential for hydrological connectivity pathways to exist between these systems; preliminary identification and discussion of these potential pathways are provided in this section.
- Relevant groundwater and hydraulic property data for the main aquifer systems in this region are relatively scarce, which means that many aspects of the hydrogeological system conceptualisation presented in this section remain speculative.

Groundwater potentially interacts with surface waters in and around the Isa GBA region through a variety of mechanisms, including:

- groundwater discharge as baseflow to streams intersecting an aquifer
- groundwater discharge at spring vents connected to stream channels
- off-channel groundwater discharge as isolated springs, wetlands and other surface water features
- offshore groundwater discharge to the Gulf of Carpentaria
- groundwater recharge by streams at certain times of the year, resulting in variably gaining and losing stream reaches.

Shallow groundwater from the Karumba Basin sediments supports terrestrial and aquatic groundwater-dependent ecosystems on the alluvial floodplains, while deeper Proterozoic aquifers potentially support springs within and outside the south-west margin of the Isa GBA region.

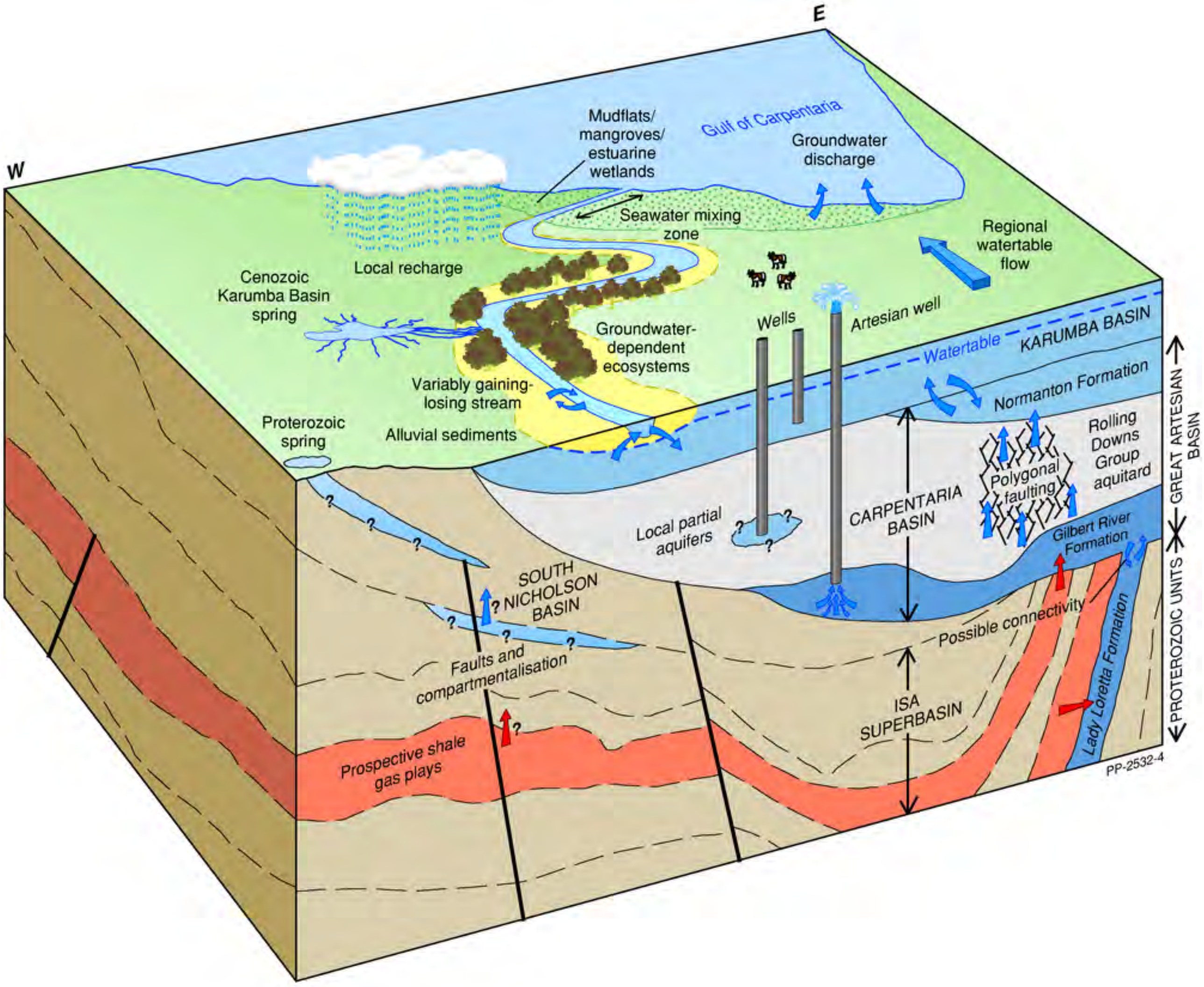


Figure 7 Key components of the groundwater systems of the Isa GBA region and potential connectivity pathways between aquifers and the surface water system

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 44) and potential hydrogeological connections (Figure 60, Figure 61 and Figure 62) for more detailed conceptual diagrams of potential mechanisms for connectivity.
This diagram is not to scale and has been vertically exaggerated to show key features and processes.
Element: GBA-ISA-2-141

4.1 *Hydrostratigraphic framework*

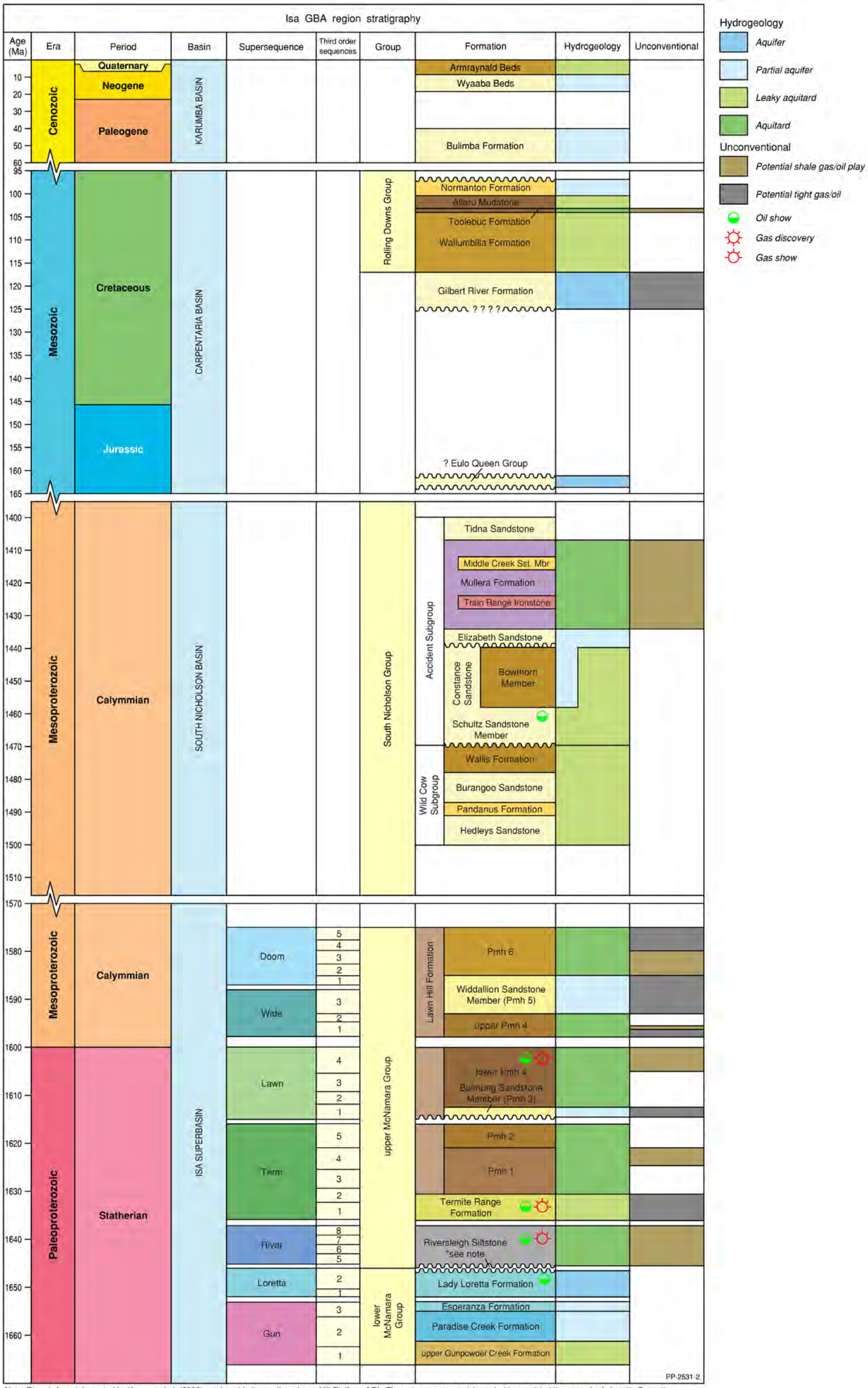
The hydrostratigraphic framework for the Proterozoic Isa Superbasin and South Nicholson Basin is shown in Figure 8. This has been developed based on the lithostratigraphic column presented in the geology technical appendix (Orr et al., 2020) and Gorton and Troup (2018).

Seven second-order supersequences are recognised within the sedimentary rock package of the Isa Superbasin, subdivided into 26 third-order sequences in the Isa GBA region. These are the Gun 1 to 3, Loretta 1 to 2, River 5 to 8, Term 1 to 5, Lawn 1 to 4, Wide 1 to 3 and Doom 1 to 5 sequences.

The Gun and Loretta supersequences collectively form the lower McNamara Group; the River, Term, Lawn, Wide and Doom supersequences collectively comprise the upper McNamara Group. Where these sedimentary rocks outcrop in the north of the Isa GBA region, they are collectively known as the Fickling Group.

In general, there is scant information relating to the hydrogeological characteristics of the Proterozoic rock units. This is primarily because these units are typically deep and overlain by other water-bearing units, and have therefore not been extensively explored for groundwater. Where groundwater bores have been installed, the stratigraphic information from the Queensland groundwater database has been used to help infer aquifer properties. Hydrogeological characteristics have also been inferred from petrophysical information and well completion reports for petroleum exploration wells (Dunster et al., 1989; Perryman, 1964).

The hydrostratigraphic framework for the Carpentaria and Karumba basins is based on the work of Ransley et al. (2015b).



Note: River 1-4 are interpreted by Krassay et al. (2000) as absent in the northern Lawn Hill Platform AOI. These sequences are interpreted to consist of the upper Lady Loretta Formation (Pmlt, River 1) the Shady Bore Quartzite (River 2-3), and the lower Riversleigh Siltstone (Pmr, River 3-4).

Figure 8 Lithology and hydrostratigraphy of the Isa GBA region

The chart breaks at 1300 to 840 Ma and 480 to 120 Ma are for display purposes.
Source: Isa Superbasin and South Nicholson Basin after Gorton and Troup (2018); Carpentaria Basin after Cook et al. (2013) and McConachie et al. (1997); Karumba Basin after Cook and Jell (2013)
Element: GBA-ISA-2-113
This figure has been optimised for printing on A3 paper (297 mm x 420 mm).

4.1.1 Hydrogeology of Proterozoic units

The supersequences are thinner in the Isa GBA region compared with much of the known Isa Superbasin. The outcropping McNamara Group sediments are exposed to the north and south of South Nicholson Basin rocks that form the axis of a regional synform (Figure 1). These rocks extend from outcrop in the west of the region, dipping southwards under a gradual eastward thickening cover of the Mesozoic Carpentaria and Cenozoic Karumba basins (Figure 3).

4.1.1.1 Gun Supersequence (lower McNamara Group)

Within the basal Gun Supersequence are the Paradise Creek and Esperanza Formations (Figure 8). The Paradise Creek Formation is characterised by stromatolitic dolostone, dolomitic siltstone, some limestone interbeds and dolostone with chert nodules. The Esperanza Formation contains dolomite, dolomitic siltstone and quartzose to lithic sandstone. Although permeability is expected to be low in these formations due to strong lithification, they are considered partial aquifers, with at least one groundwater bore (RN109203) reported in the Paradise Creek Formation (Table 2). The Gunpowder Creek Formation (basal formation in the Gun Supersequence) consists typically of laminated siltstone and is considered an aquitard.

4.1.1.2 Loretta Supersequence (lower McNamara Group)

In the Isa GBA region, the Loretta Supersequence is comprised of the Lady Loretta Formation and its lateral equivalents (e.g. Walford Dolomite) which thin to the north, primarily due to erosion of the River Supersequence boundary due to onlap (Bradshaw and Scott, 1999). The platform carbonates of the Loretta Supersequence are a possible source of groundwater for the Northern Lawn Hill Platform. There are no potential unconventional hydrocarbon source rocks identified within the Loretta Supersequence (Gorton and Troup, 2018).

The original porosity of the Loretta Supersequence has been modified during diagenesis. In drilled intersections, porosity is commonly low (0.5% to 5%) (Gorton and Troup, 2018) although may be up to 15% to 20% in zones with extensive dissolution cavities and vughs, and also in zones of moldic porosity in oolitic grainstones (Moultrie, 1991). Measured permeability is generally low, with values ranging from less than 1 milliDarcy (mD) to 3.4 mD.

Where the Loretta Supersequence occurs close to surface (shallow subcrop), it has markedly higher aquifer potential. For example, below the base of the Mesozoic Carpentaria Basin sequence in exploration well Burketown 1, 1328 m of dolostone from the Loretta Supersequence includes a lower 53-m thick cavernous dolostone with extremely high transmissivity (Perryman, 1964). This zone produced hot artesian groundwater at a rate of about 1 litre per second (L/s) when first drilled, indicative of connectivity between this lower cavernous zone and the basal sandstone aquifer of the overlying Carpentaria Basin through a complex cavernous fracture network that exists within the upper 275 m of the Loretta Supersequence. The seismic character of the Loretta Supersequence indicates that enhanced cavernous permeability occurs commonly across the region (especially in areas of subcrop). Accordingly, such zones may offer a conduit for groundwater flow, and potentially any fugitive gas migration where it directly underlies the shale gas plays of the prospective Riversleigh Siltstone.

The Loretta Supersequence is the most widely accessed unit of the Isa Superbasin for groundwater. According to the Queensland groundwater database, there are five bores (Table 2) screened in dolomite or limestone that are inferred to access the Loretta Supersequence (Lady Loretta Formation and equivalent Walford Dolomite). Groundwater yields of up to 6.5 (L/s) have been reported. The location of the wells, depth to the screened interval and the solid geology interpretation are presented in Figure 9.

Of particular note is bore RN72582 which, along with the Burketown 1 well, exhibited artesian conditions during drilling in 1991. However, no additional groundwater observations have been recorded from this bore since it was installed, so it is not possible to comment upon the temporal characteristics of artesian conditions within this unit.

Table 2 Characteristics of groundwater bores tapping Proterozoic aquifers of the Isa Superbasin and South Nicholson Basin in and around the Isa GBA region

Bore registered number[1]	Unit	Bore elevation (mAHD)	Bore screen (mbgl)	Bore screen (mAHD)[2]	Lithology	Groundwater yield (L/s)	Bore diameter (mm)
3349	unknown	121.9	21.9	100.0	nd	nd	nd
16177	unknown	92.0	30.8	61.2	nd	0.25	152
16444	unknown	85.1	36.6	48.5	nd	0.9	152
17421	Lawn Hill Formation	104.4	39.6	64.8	limestone/carbonate /shale	nd	152
17422	Lawn Hill Formation	91.9	24.3	67.6	limestone/carbonate /shale	nd	152
23245*	unknown	116.1	nd	nd	nd	nd	nd
26174	unknown	69.6	nd	nd	nd	nd	nd
36343*	unknown	82.0	nd	nd	nd	nd	nd
45203	unknown	96.3	31	65.3	nd	1	127
45204	unknown	80.6	16	64.6	nd	6.5	127
45205	unknown	84.6	18	66.6	nd	6.3	127
45468	unknown	95.2	30.5	64.7	nd	nd	141
45469	unknown	84.8	24.4	60.4	nd	nd	141
45578	unknown	114.5	nd	nd	nd	nd	nd
45581	unknown	111.3	nd	nd	nd	nd	nd

Bore registered number[1]	Unit	Bore elevation (mAHD)	Bore screen (mbgl)	Bore screen (mAHD)[2]	Lithology	Groundwater yield (L/s)	Bore diameter (mm)
45583	unknown	109.3	nd	nd	nd	nd	nd
45588	unknown	98.9	nd	nd	nd	nd	nd
45589	unknown	72.0	nd	nd	nd	nd	nd
45618	unknown	127.8	nd	nd	nd	nd	nd
45624	unknown	105.3	nd	nd	nd	nd	nd
45625	unknown	142.3	nd	nd	nd	nd	nd
45630	unknown	110.8	31	79.8	nd	nd	127
45884	unknown	87.7	39.6	48.1	nd	nd	141
72498*	Walford Dolomite	107.9	200	-92.1	Mixed dolomite, siltstone shale	1.2	75
72499	unknown	82.7	nd	nd	nd	nd	nd
72500	unknown	98.2	nd	nd	nd	nd	nd
72582*	Walford Dolomite	158.6	129	29.6	Dolomitic siltstone	nd	75
72620*	Walford Dolomite	131.1	259	-127.9	Mixed dolomite, siltstone, shale	nd	nd
72621*	Walford Dolomite	146.9	172	-25.1	Siltstone, sandstone, dolomite	1	nd
100067*	unknown	88.4	nd	nd	nd	nd	nd
109203	Paradise Creek Formation	122.0	90	32.0	Limestone	nd	140
109204	unknown	128.1	20	108.1	Black shale	nd	141
109223	Lady Loretta Formation	112.0	38	74.0	Weathered chert	nd	200
139379	South Nicholson Basin	102.0	42	60.0	Sandstone	nd	160
139380	South Nicholson Basin	110.9	72	38.9	Sandstone	nd	355
171074	Lawn Hill Formation	139.6	24	115.6	Shale, grey	nd	140

nd=no data; mAHD=metres relative to Australian Height Datum; mbgl=metres below ground level; L/s=litres per second
[1] numbers in bold are for bores with water level data (shown in Figure 19); artesian bores are marked with an asterisk *
[2] negative values relate to screened depths below mean sea level
Data: bore data (Geoscience Australia, 2018f)

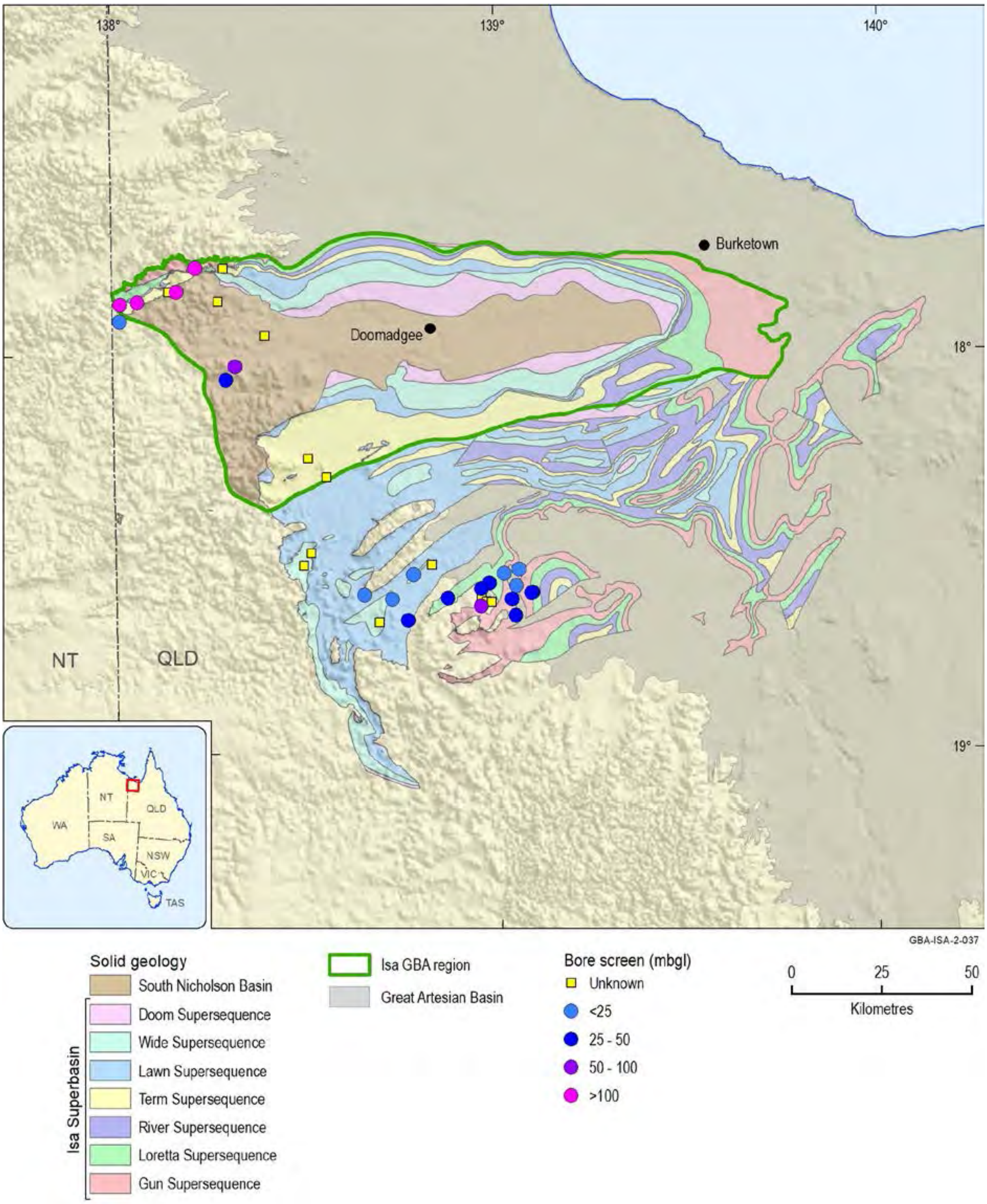


Figure 9 Groundwater bores tapping Proterozoic units in and near the Isa GBA region, showing depth to screened interval

Data: Geology: outside Isa GBA region (Department of Natural Resources, Mines and Energy (Qld), 2018c), inside Isa GBA region (Bradshaw et al., 2018a), bores (Geoscience Australia, 2018f)
Element: GBA-ISA-2-037

4.1.1.3 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 that are mostly present in the upper Lawn Hill Formation (Lawn 4 Sequence) and the Riversleigh Siltstone (River Supersequence). The basal part of the intervening Termite Range Formation (lower Term Supersequence) has some reservoir characteristics with known gas and oil shows (Bailey et al., 2020).

4.1.1.3.1 River Supersequence

The organic-rich shales of the Riversleigh Siltstone (River Supersequence) are among the main shale gas source rocks for the Isa Superbasin, having over 100 m gross thickness and generally uniform composition across the Lawn Hill Platform (Gorton and Troup, 2018). The typically fine-grained nature of these rocks results in aquitard properties.

4.1.1.3.2 Term Supersequence

The Term Supersequence comprises the Termite Range Formation, and units Pmh 1 and Pmh 2 of the Lawn Hill Formation. Typically, these formations consist of interbedded sandstone, siltstone, shale and tuffaceous sandstone and siltstone, and are considered aquitards. However, turbiditic sandstones of the Termite Range Formation commonly have measured porosity of 0.5% to 5% and, in some isolated zones porosity may be up to 16% (Gorton and Troup, 2018), indicative of leaky aquitard properties.

4.1.1.3.3 Lawn Supersequence

The Lawn Supersequence comprises the Bulmung Sandstone Member (Pmh 3) and the lower Pmh 4 unit of the Lawn Hill Formation. The shallow marine Bulmung Sandstone Member (Pmh 3) has measured porosities typically between 2% and 9%, with up to 25% rarely observed. Permeability is generally low (less than 1 mD), although locally can be three orders of magnitude greater, up to 2 D (Gorton and Troup, 2018). Partial aquifer status is attributed to this sandstone member, which directly underlies the shale gas-prospective carbonaceous rocks of the Lawn 4 Sequence. As such it is potentially a conduit for natural gas emissions from adjoining source rocks. The lower Pmh 4 unit is characterised by organic-rich shale, with minor sandstone, siltstone, tuffaceous sandstone and siltstone. It is considered an aquitard.

4.1.1.3.4 Wide Supersequence

The Wide Supersequence comprises the upper Pmh 4 unit and part of the Widdallion Sandstone Member (Pmh 5). The Widdallion Sandstone Member is dominantly thickly cross-bedded, medium- to coarse-grained, and granule-rich with minor pebbles. This unit contains volcanolithic sands which have a diagenetically modified porosity ranging from 1% to 15% in a 40 m thick unit of stacked sandstones (Gorton and Troup, 2018) and can be accorded partial aquifer to aquifer status. This aquifer has potential to be a conduit for natural gas emissions from the underlying shale gas source rocks of the Lawn Supersequence. Gorton and Troup (2018) considered that wrench-faulting during deposition of the Wide and Doom supersequences could have formed excellent structural traps to contain migrating hydrocarbons.

The Queensland groundwater database (Department of Natural Resources, Mines and Energy (Qld), 2018d) indicates that three groundwater bores access water from the Lawn Hill Formation (and equivalent Doomadgee Formation), as shown in Table 2. These bores likely draw groundwater from either the Widdallion Sandstone Member or the Bulmung Sandstone.

4.1.1.3.5 Doom Supersequence

The Doom Supersequence consists of the upper Widdallion Sandstone Member (Pmh 5) and the Pmh 6 unit of the Lawn Hill Formation. The Pmh 6 unit is characterised by sandstone, siltstone, shale and carbonate with log-derived porosity of 1% to 15%. These rocks are typically considered aquitards. Some sandstone-dominated intervals in the upper part of the Pmh 6 unit are up to 40 m thick, with log-derived total porosity of 8% to 15% (up to maximum of 21%).

4.1.1.4 South Nicholson Group

The South Nicholson Basin sequence in the Isa GBA region (Orr et al., 2020) is composed entirely of sedimentary rocks that were deposited fluvial to shallow marine environments (Figure 8). Typically, these units have hydraulic properties characteristic of leaky aquitards or aquitards. The exceptions to this are the thick-bedded quartz-arenites of the Constance and Elizabeth sandstones. These units are generally tight with porosity between 0.5% and 5%, although much higher porosity occurs in places (up to about 16%). Permeability is equally variable, ranging from <1 mD to nearly 7 D. There is a clear relationship between porosity and permeability, with zones of higher porosity and permeability likely relating to microfractures (Gorton and Troup, 2018). Testing of the Constance Sandstone at well DDH83-3 produced water at a rate of over 10 L/s (Dorrins et al., 1983).

Two groundwater bores are known to source water from rocks of the South Nicholson Basin (RN139380 and 139379), as shown in Table 2.

A north-trending cross-section of the Isa GBA region showing the Proterozoic rock units and their hydraulic properties is in Figure 10.

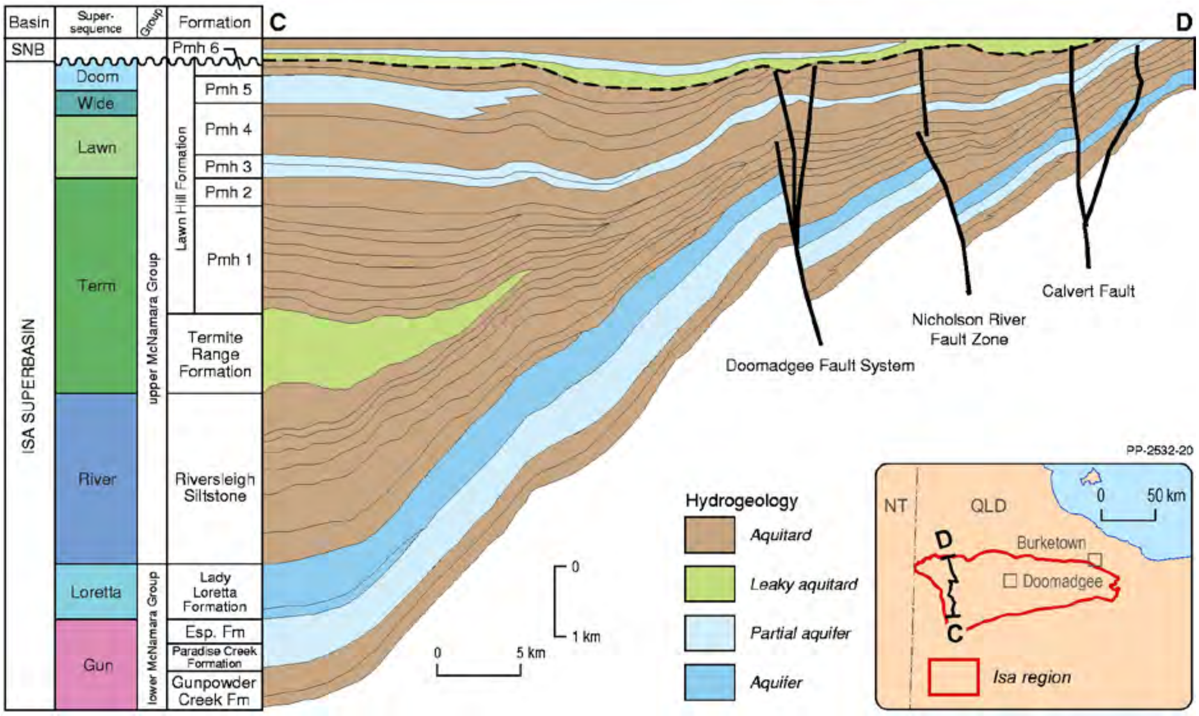


Figure 10 North-trending cross-section through Proterozoic units of the Isa Superbasin showing inferred hydrogeological properties

This section illustrates that the Loretta Supersequence (Lady Loretta Formation) has the greatest aquifer potential of all the Proterozoic units in the Isa GBA region. SNB = South Nicholson Basin; Esp. Fm = Esperanza Formation
Data: after Bradshaw et al. (1999) and Krassay et al. (1999)
Element: GBA-ISA-2-154

4.1.2 Hydrogeology of the Carpentaria Basin

Within the Isa GBA region, the Carpentaria Basin (part of the GAB) consists of a variably confined groundwater system comprising multi-layered aquifers of variable hydraulic characteristics, hosted within predominantly continental sandstones. The basin aquifers are separated and centrally confined by aquitards of both fluvial and marine mudstone (Smerdon et al., 2012b). The Carpentaria Basin is structurally separated from the Eromanga Basin to the south by the Euroka Arch, which forms a major groundwater divide (Figure 4).

The Isa GBA region spans the western margin of the Carpentaria Basin, with sedimentary sequences thickening towards the regional depocentre in the north-east (which is now within the Gulf of Carpentaria). The GAB margins used in this report are those defined in the GAB Atlas (Ransley et al., 2015b). Recent studies (Smerdon et al., 2012b) revised the western margin of the Carpentaria Basin to be approximately 35 km further west than previously identified by Habermehl and Lau (1997). This revised margin is based on the mapped structural boundaries between the Proterozoic basement rocks and the Karumba and Carpentaria basins, as shown on the 1:250,000 geological maps for Lawn Hill (Hutton and Grimes, 1983) and Westmoreland (Grimes and Sweet, 1979). Although lithostratigraphic units of the Carpentaria Basin occur as outliers further west of the basin boundary, these are considered hydrogeologically isolated from the GAB. Any groundwater system that may occur in these outlier units does not contribute to regional Carpentaria Basin flow, and are only subject to local hydrogeological influences.

Within the study area for this assessment there are two regional aquifer systems hosted in the Carpentaria Basin, namely the:

- deeper Gilbert River Formation aquifer (and potentially underlying basal Jurassic to Cretaceous aquifer system of the Eulo Queen Group)
- shallower Late Cretaceous Normanton Formation aquifer (the upper part of the Rolling Downs Group).

These two aquifer systems are separated by the relatively thick aquitard sequence of the Rolling Downs Group, which comprises the Wallumbilla Formation, Toolebuc Formation and Allaru Mudstone (Figure 11).

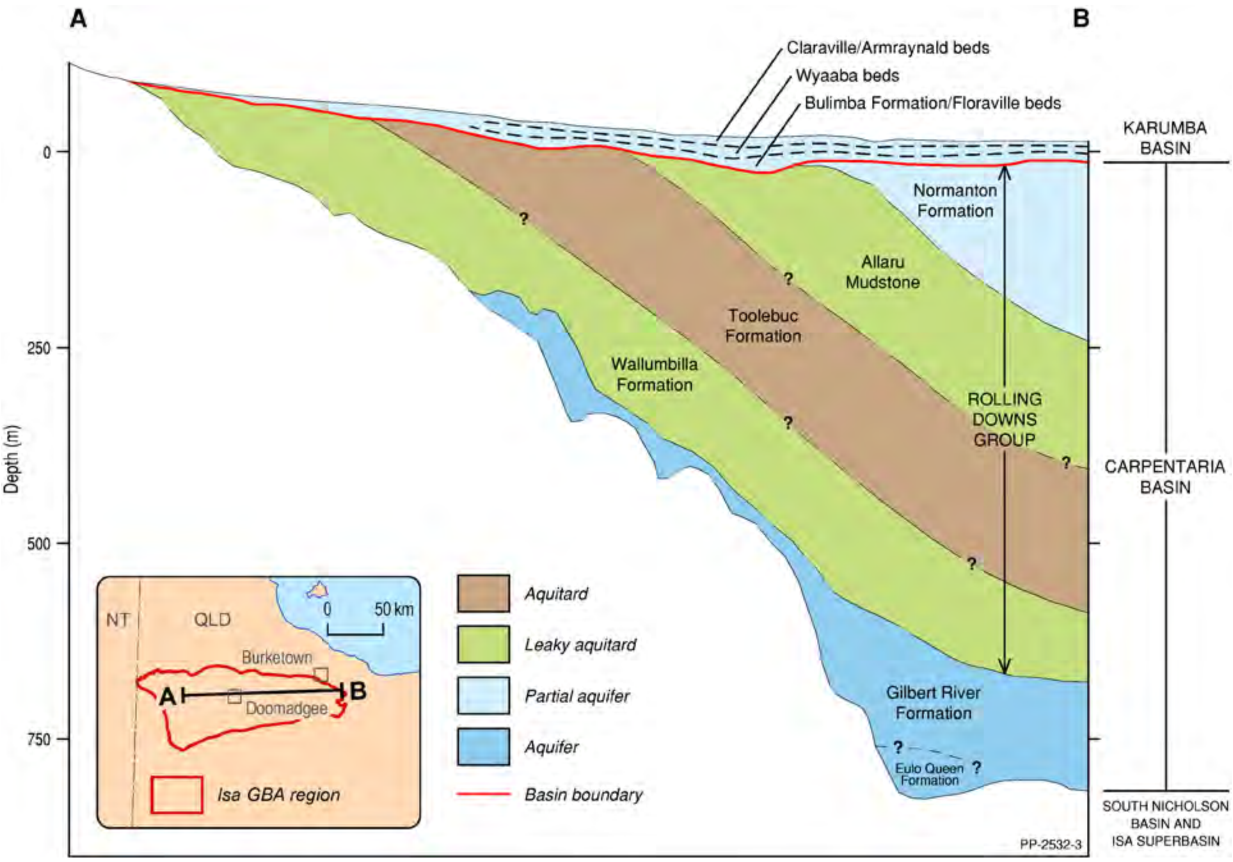


Figure 11 Cross-section of the Carpentaria and Karumba basins in the Isa GBA region

Inset shows cross-section location.
Data: Geoscience Australia (2018c)
Element: GBA-ISA-2-140

4.1.2.1 Gilbert River Formation aquifer

The basal GAB sandstone sequence in the Isa GBA region is the Gilbert River Formation (referred to as the Gilbert River Formation aquifer in this report). This formation typically comprises sandstones with minor shale lenses and overall has characteristic aquifer properties. This aquifer is relatively widespread over the central and eastern Isa GBA region, and typically occurs east of Doomadgee. Along the axis of the synform in basement rocks, this aquifer has a convoluted western extent as it appears to infill paleovalleys incised into the South Nicholson Basin (Figure 12).

The basal aquifer of the Carpentaria Basin is typically the deepest aquifer accessed for groundwater use in the Isa GBA region. Bores are typically screened at a depth of 150 m to over 500 m below ground level, and groundwater within this aquifer is commonly under artesian pressure (discussed further in Section 4.3.2). Based on measurements in the northern Carpentaria and Laura basins, the hydraulic conductivity of the Gilbert River Formation is estimated as 2m/day (ranging from 0.1 to 10 m/day) (Klohn Crippen Berger, 2016a).

Bores completed in this aquifer in the Burketown region initially produced at flow rates of between 31 and 300 L/s, but over time the flow rate for some bores has diminished to a trickle (Ingram, 1972). According to the Queensland groundwater database (Table 3), there are 22 bores attributed to the Gilbert River Formation in the area, although only three of these are actually within the Isa GBA region, with the rest nearby to the east and south (Figure 12). Groundwater yields in this aquifer are variable, ranging from 0.3 L/s (RN45979) to 6.4 L/s (RN109264). Artesian conditions are indicated where the column 'Bore yield' in Table 3 shows flow rates with reference to pressure (kilopascals, kPa), where 100 kPa is approximately equivalent to 10 m of groundwater head.

An artesian bore at Burketown drilled into the Gilbert River Formation is producing methane gas, interpreted to have migrated from the underlying Proterozoic shale gas reservoirs of the River and Lawn supersequences across an unconformable contact (EHS Support, 2014).

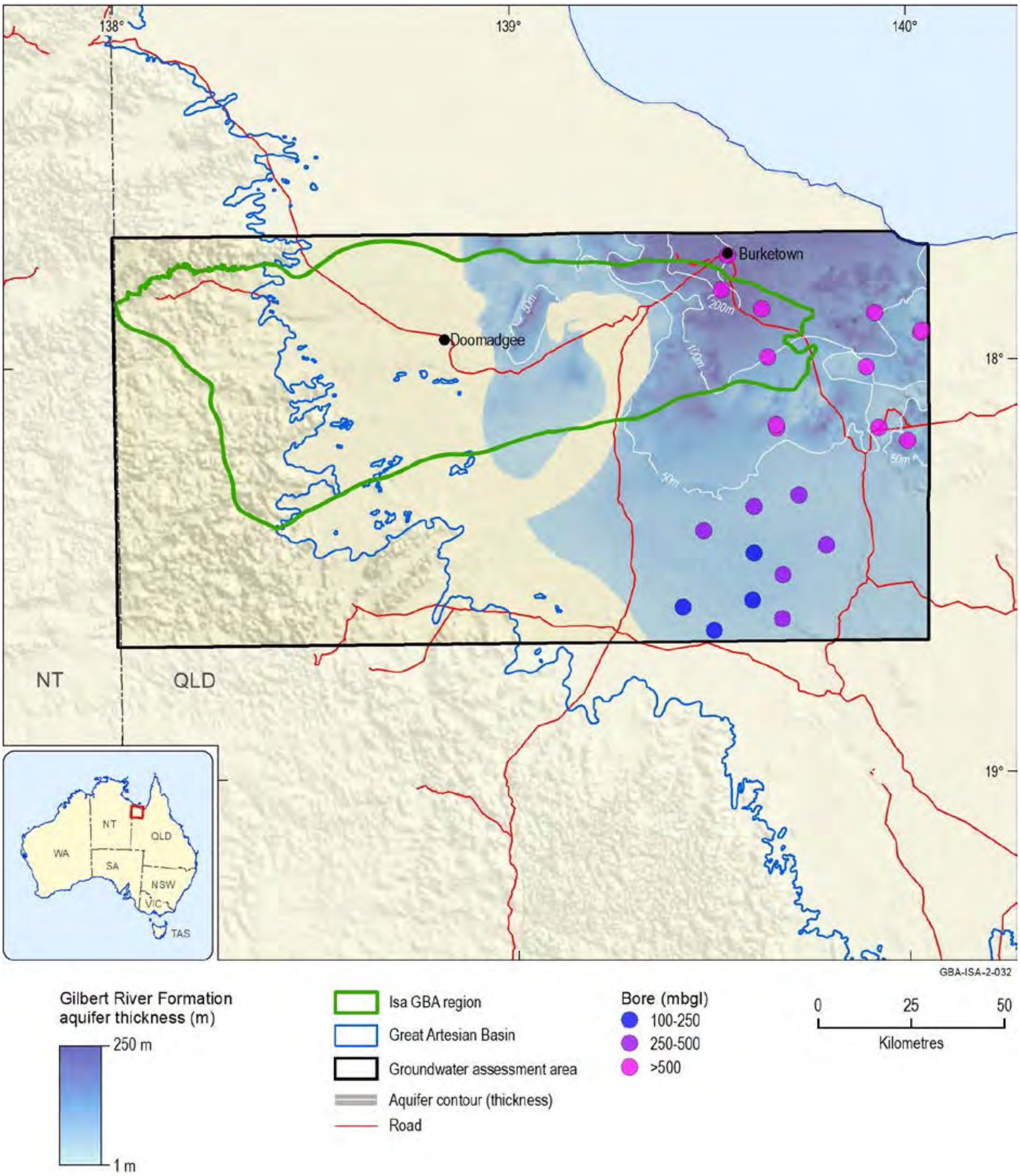


Figure 12 Gilbert River Formation aquifer extent, thickness and groundwater bore locations

mbgl=metres below ground level
Data: aquifer (Geoscience Australia, 2018c); bores (Geoscience Australia, 2018f)
Element: GBA-ISA-2-032

Table 3 Characteristics of bores that access the Gilbert River Formation in and around the Isa GBA region

Bore registered number	Unit	Bore elevation (mAHD)	Bore screen (mbgl)	Bore screen (mAHD)[1]	Lithology	Groundwater yield (L/s)	Bore diameter (mm)
330	Gilbert River Fm	3.7	702.7	-699.0	nd	nd	nd
3030	Gilbert River Fm	31.0	701	-670.0	Sandstone	nd	152
7572	Gilbert River Fm	45.6	339	-293.4	Sandstone	0.63	152
16407	Gilbert River Fm	45.6	229	-183.4	Sandstone	nd	
16447	Gilbert River Fm	61.0	231	-170.0	Sandstone	nd	152
16490	Gilbert River Fm	51.0	201.2	-150.2	Shale and sandstone	nd	127
34051	Gilbert River Fm	42.5	400.2	-357.7	Sandstone	nd	127
45180	Gilbert River Fm	22.4	583	-560.6	Soft sandstone	1.6 (at 172 kPa)	127
45181	Gilbert River Fm	13.4	601.5	-588.1	Soft sandstone	0.5 (at 137 kPa)	101
45979	Gilbert River Fm	34.1	469	-434.9	Tight, grey sandstone	0.3 (bailer)	
72002	Gilbert River Fm	14.5	667	-652.5	Sandstone	nd	171
92812	Gilbert River Fm	64.7	228	-163.3	Grey clays	2.4 (airlift)	168
109264	Gilbert River Fm	47.6	405	-357.4	Sandstone	6.4 (airlift)	168
109309	Gilbert River Fm	30.2	482	-451.8	Shale beds	nd	168
109649	Gilbert River Fm	7.5	585	-577.5	Sandstone and shale	2.5 (at290 kPa, 59 °C)	127
109811	Gilbert River Fm	6.7	595	-588.3	Hard, fine-grained sandstone	0.7 (at245 kPa, 58 °C)	127
126658	Gilbert River Fm	22.0	572	-550.0	Grey sandstone	nd	127
126659	Gilbert River Fm	19.7	611.3	-591.6	Coarse siltstone	nd	168
171028	Gilbert River Fm	39.5	491.4	-451.9	Sand, coarse-grained with quartz grains	nd	127
171260	Gilbert River Fm	28.3	671	-642.7	Shale, trace sandstone	nd	140
171269	Gilbert River Fm	32.4	600	-567.6	Sandstone	nd	140
171340	Gilbert River Fm	27.8	700	-672.2	Sandstone	nd	140

mAHD=metres relative to Australian Height Datum; mbgl=metres below ground level; L/s=litres per second; nd=no data; Fm = Formation

[1] negative values relate to screened depths below mean sea level

Data: bore data (Geoscience Australia, 2018f)

4.1.2.2 Rolling Downs Group

The Rolling Downs Group comprises the Wallumbilla Formation, Toolebuc Formation, Allaru Mudstone and Normanton Formation. Of these, the Normanton Formation is considered a partial aquifer, and other units are generally considered aquitards (Ransley et al., 2015b).

4.1.2.2.1 Rolling Downs Group aquitard

The Rolling Downs Group aquitard (comprised of the Wallumbilla and Toolebuc formations and the Allaru Mudstone) is widespread across the Isa GBA region and areas to the east and south. The boundary of this aquitard corresponds to the western margin of the Carpentaria Basin, and it thickens eastwards across the Isa GBA region (Figure 13). The Rolling Downs Group aquitard is considered the most effective aquitard in the Carpentaria Basin because of its substantial lateral extent, significant thickness and the very low permeability of its constituent mudstones and other fine-grained sediments.

The lithology of the units and the hydraulic properties of the Rolling Downs Group aquitard are summarised in Table 4.

Table 4 Stratigraphic units of the Rolling Downs Group aquitard

Unit	Typical lithology	Hydraulic properties
Allaru Mudstone	Mudstone with calcareous concretions, some siltstones. Shale and siltstone in northern areas	Leaky aquitard
Toolebuc Formation	Calcareous, bituminous shale, limestone, sandstone, siltstone	Aquitard
Wallumbilla Formation	Mudstone and siltstone with calcareous concretions; glauconitic labile sandstone, particularly in lower sections	Leaky aquitard

Lithofacies in the Wallumbilla Formation and Allaru Mudstone are spatially variable (Smerdon et al., 2012b). Due to the dominance of non-radiogenic clays in the mudstone, and the presence of radiogenic glauconitic sands in the aquitard, there remains considerable uncertainty about establishing the sand-shale characteristics based on gamma response in the area of investigation and more broadly in the Staaten Sub-basin.

An important feature of this aquitard is the ubiquitous, intraformational, polygonal faulting that pervades the entire sequence with small vertical displacements in the order of tens of metres. The structural overprint of the Rolling Downs Group aquitard is further discussed in Section 5.5.

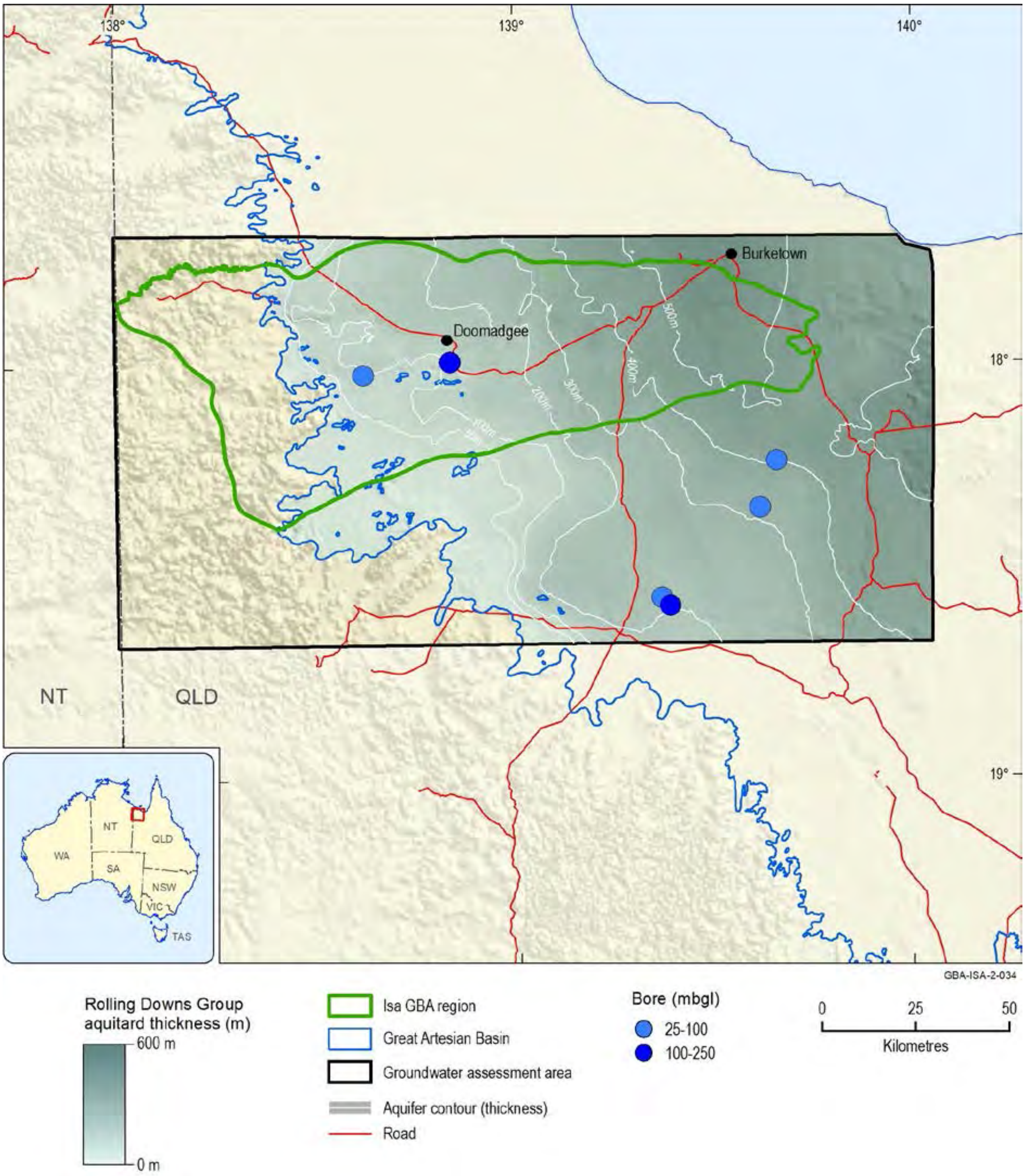


Figure 13 Rolling Downs Group aquitard extent, thickness and groundwater bore locations

mbgl=metres below ground level
Data: aquifer (Geoscience Australia, 2018c); bores (Geoscience Australia, 2018f)
Element: GBA-ISA-2-034

Although these units are typically aquitards, small supplies of generally saline water have been obtained from what are inferred to be minor isolated lenses of sandstone and shale (Smart et al., 1980). Given the general lack of groundwater data from this region, there is a relatively high level of uncertainty surrounding the spatial distribution of these lenses. Based on information within the Queensland groundwater database (Department of Natural Resources, Mines and Energy (Qld), 2018d), six bores access the Rolling Downs Group aquitard within or close to the Isa GBA region. A summary of the available hydrogeological data for these bores is in Table 5.

Table 5 Features of bores that access the Rolling Downs Group aquitard in and around the Isa GBA region

Bore registered number	Unit	Bore elevation (mAHD)	Bore screen (mbgl)	Bore screen (mAHD)[1]	Strata information	Groundwater yield (L/s)	Bore diameter (mm)
36255	Allaru Mudstone	39.2	70.1	-30.9	Blue shale	1.3	152
38649	Allaru Mudstone	28.3	57.91	-29.6	Blue shale	0.4	152
45878	Rolling Downs Group aquitard	45.5	105	-59.5	Sandstone	nd	161
72580	Rolling Downs Group aquitard	51.4	45	6.4	Coarse-grained sand	4.4	141
92915	Wallumbilla Formation	67.1	192	-124.9	Firm broken grey/white rock	4.0	168
92952	Toolebuc Formation	66.8	72	-5.2	Grey shale	1.0	200

mAHD=metres relative to Australian Height Datum; mbgl=metres below ground level; L/s=litres per second; nd=no data
[1] negative values relate to screened depths below mean sea level
Data: bore data (Geoscience Australia, 2018f)

4.1.2.2.2 Rolling Downs Group – Normanton Formation

The Lower Cretaceous Normanton Formation, the uppermost unit of the Rolling Downs Group, is a relatively extensive unit of glauconitic sandstone and siltstone that has a fringing near-coastal distribution around the Carpentaria Basin. The Normanton Formation typically has partial aquifer characteristics onshore but transitions into a low-permeability aquitard offshore, generally increasing in thickness towards the main depocentre in the central part of the Gulf of Carpentaria. Median bore yields are 2 L/s, ranging from less than 1 to about 4 L/s (Klohn Crippen Berger, 2016a).

Within the Isa GBA region, the boundary of the Normanton Formation runs approximately north to south about 10 km west of Burketown (Figure 14). The aquifer thickness increases to the east reaching a maximum thickness of around 300 m near the coastline. Within the study area, only one bore (RN109352) is identified as accessing water from the Normanton Formation at a depth of 39.5 m below ground level.

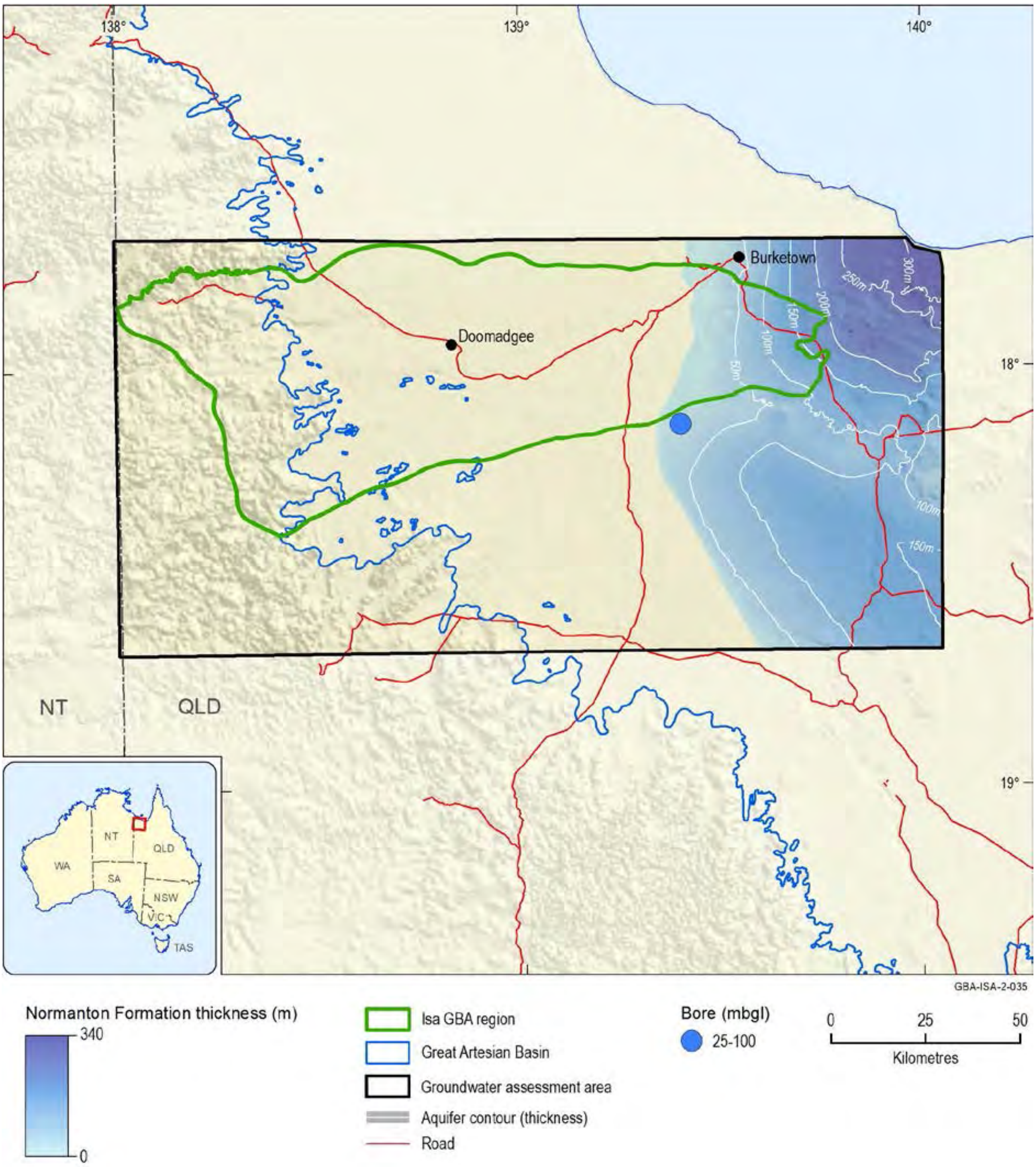


Figure 14 Normanton Formation extent, thickness and groundwater bore locations

Data: aquifer (Geoscience Australia, 2018c); bores (Geoscience Australia, 2018f)
Element: GBA-ISA-2-035

4.1.3 Hydrogeology of the Karumba Basin

The Cenozoic Karumba Basin (Orr et al., 2020) is widespread in the Isa GBA region, pinching out approximately 45 km to the west of Doomadgee, corresponding to the edge of the Carpentaria Basin (Figure 15). The lithostratigraphic units, weathering cycles, and hydrostratigraphic designations for the Karumba Basin are summarised in Table 6.

Table 6 Major lithology and hydraulic properties of the units of the Karumba Basin

Cycle	Age	Unit	Typical lithology	Thickness	Hydraulic properties
Claraville Cycle	Pliocene-Pleistocene	Armraynald beds	Silt, clay, sand and gravel	up to 25 m	Leaky aquitard
Wyaaba Cycle	Miocene	Wyaaba beds	Clayey quartzose sand and sandstone, granule to (locally) pebble gravel, conglomerate	unknown	Partial aquifer
Bulimba Cycle	Paleocene to Eocene	Bulimba Formation	Cross-bedded fine-grained quartzose clayey sandstone; local conglomerate, thin chalcedonic limestone and siltstone	40 m max	Partial aquifer

The sediments associated with the three primary cycles of Cenozoic deposition (Bulimba, Wyaaba and Claraville cycles) each have variable aquifer characteristics. The basal Bulimba Formation of the Bulimba Cycle consists of fine-grained quartzose and is typically the most productive aquifer of the Karumba Basin. The overlying units contain minor sand-rich zones but overall have leaky aquitard properties. Localised aquitard zones of the Gregory Downs Limestone (Wyaaba Cycle) create a variable semi-confined system (Radke et al., 2012).

The lithology of the Bulimba Formation is highly variable, ranging from shale (bore RN45347) to sandy ferricrete (bore RN45350). There are correspondingly variable groundwater yields for this unit (Table 7), with an average yield of 1 L/s ranging from 0.25 L/s to 4.5 L/s. According to the GAB water resource assessment (Smerdon et al., 2012c) the hydraulic conductivity of the Bulimba Formation ranges from 150 to 300 m/day and the specific yield is 0.1. The Bulimba Formation is the most commonly accessed unit of the Karumba Basin in the Isa GBA region, with nine bores identified in the Queensland groundwater database (Department of Natural Resources, Mines and Energy (Qld), 2018d). Bore inlet screen depths range from 29 to 45 m below ground level. Formation thickness is typically about 40 m north of Doomadgee, around 25 m in the Burketown region and 18 m in the south (Grimes and Sweet, 1979).

The Armraynald beds consist of brown and grey clays (commonly silty), minor beds of sandstone and clay-bound gravel, and limestone nodules. Within the Isa GBA region, outcrop is restricted to stream banks, so lithological information is limited, and derived mainly from drillers' logs. Smart et al. (1980) suggested that unit thickness varies from about 10 m in the south of the region, to 25 metres in the north. One registered bore accesses groundwater from the Armraynald beds, producing water at a rate of about 2.5 L/s (Queensland groundwater database). This groundwater bore is screened at a depth of 30 m in red and yellow sandstone.

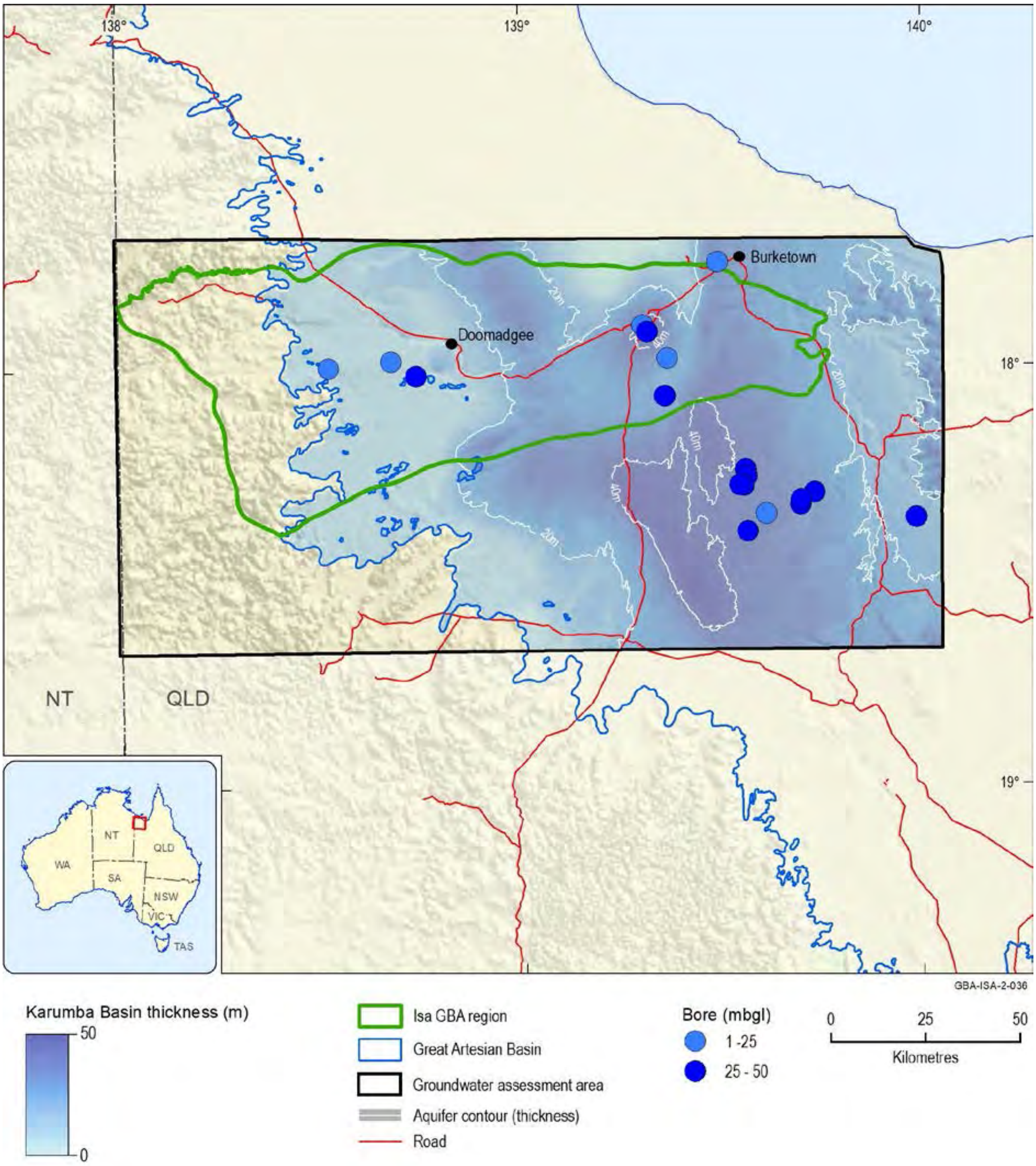


Figure 15 The Karumba Basin extent, thickness and groundwater bore locations

mbgl = metres below ground level
Data: aquifer (Geoscience Australia, 2018c); bores (Geoscience Australia, 2018f)
Element: GBA-ISA-2-036

Table 7 Groundwater bores inferred to access water from the Karumba Basin and alluvial deposits

Bore registered number	Unit	Bore elevation (mAHD)	Bore screen (mbgl)	Bore screen (mAHD)[1]	Lithology	Bore yield (L/s)	Bore diameter (mm)
15937	Alluvium	18.1	21	-2.9	Loose gravel	1.3	152
34586	Alluvium	4.9	4.6	0.3	Fine-grained brown sand	0.6	152
34587	Alluvium	5.1	4.3	0.8	Fine-grained brown sand	0.6	152
34588	Alluvium	4.9	4.7	0.2	Clean brown sand	0.6	152
34589	Alluvium	5.0	5.3	-0.3	Brown sand	0.6	152
45347	Bulimba Fm	45.0	40	5.0	Black shale	~0.5	152
45348	Bulimba Fm	32.9	38	-5.1	Clay, red mottled sandstone	~0.73	152
45349	Bulimba Fm	37.0	45	-8.0	White sandstone	~0.56	152
45350	Bulimba Fm	35.3	42	-6.7	Ferricrete, sandy	~0.56	152
45449	Bulimba Fm	30.5	36	-5.5	Grey mudstone	4.5	152
45471	Alluvium	39.4	24	15.4	Sand	0.2	
45628	Bulimba Fm	26.5	28	-1.5	yellow clay	0.25	150
45766	Bulimba Fm	34.2	38	-3.8	Sand	nd	161
45879	Armraynald Beds	21.0	30	-9.0	Red and Yellow Sandstones	2.5	161
72518	Bulimba Fm	36.9	42	-5.1	sandstone	0.58	161
72519	Bulimba Fm	35.8	29	6.8	Red, white and brown sandstone	0.63	161
72578	Karumba Basin	42.1	40	2.1	Mudstone, sandstone and gravel layers	3.4	141
72579	Karumba Basin	63.0	22	41.0	Mudstone with gravel layers	1.5	141
72581	Karumba Basin	75.2	25	50.2	Sandstone with clay matrix	1	141
91210024	Alluvium	16.1	12.5	3.6	Grey sands with Ironstone bands	nd	50

mAHD=metres relative to Australian Height Datum; mbgl=metres below ground level; L/s=litres per second; nd=no data
[1] negative values relate to screened depths below mean sea level
Data: bore data (Geoscience Australia, 2018f)

4.1.3.1 Unconsolidated deposits

Colluvial and sheetwash deposits are widespread in the region and form a thin cover over the Bulimba Formation and other sediments of the Karumba Basin. These unconsolidated deposits, which may include surficial Holocene sands, are commonly underlain by ferricrete at shallow depth.

Alluvial deposits mainly occur on lower gradients in areas of relatively lower elevation. They are generally poorly sorted and typically comprise silts and very fine-grained sands. They are relatively widespread aquifers, with seven bores in the Queensland groundwater database (Department of Natural Resources, Mines and Energy (Qld), 2018d) identified as accessing alluvial deposits. Bore screen depths are generally shallow, typically around 5 m, although may be up to 21 m below ground level. Yields for this aquifer are generally low, ranging from 0.2 to 1.3 L/s.

4.2 Recharge

4.2.1 Proterozoic units

Recharge mechanisms to aquifers of the Isa Superbasin and South Nicholson Basin are primarily limited to diffuse recharge at formation outcrops to the west of the GAB margin. Due to the highly lithified nature of the Proterozoic rock units, any recharge rates are expected to be low and limited to areas where meteoric weathering or fracture zones may provide a preferential pathway at the surface for recharge waters to enter the groundwater system.

Where the Proterozoic units are covered by the GAB, recharge may potentially occur through inter-basin groundwater flow, particularly between the Loretta Supersequence and the basal aquifer of Carpentaria Basin. However, the direction of groundwater flow between aquifers of different basins will depend on relative groundwater pressures within the respective aquifers. There is little data currently available to quantify such flow rates or directions. Inter-basin hydrological connectivity is further discussed in Section 5.

4.2.2 Carpentaria Basin

Diffuse recharge occurs where rainfall directly recharges downwards into an aquifer. This is thought to be the main recharge mechanism for the Normanton Formation, where it occurs beneath shallow Cenozoic cover sediments (Smerdon et al., 2012a). Due to the scarcity of groundwater data, recharge rates have not been directly calculated for the Isa GBA region. However, according to a recent hydrogeological assessment of the GAB (Klohn Crippen Berger, 2016a), recharge to the Normanton Formation (within the Southern Carpentaria sub-basin), is 38 GL/year on average, ranging from 19 to 96 GL/year.

Recharge from rivers may contribute to groundwater recharge of the Karumba Basin aquifers and (indirectly) the Normanton Formation, particularly during the wet season when ephemeral rivers in the region typically flow. However, recharge from the streambed is not expected to be a large contributor (DSITIA, 2014). Estimates of this type of recharge are hampered by a lack of temporally matched river stage and groundwater depth measurements. In cases where suitable data are available, hydrograph analysis has been undertaken as part of this study and these results are discussed further in Section 4.5.2.

The primary source of recharge to the deeper confined GAB aquifer system, the Gilbert River Formation, is through intake beds where the aquifer outcrops and receives direct infiltration from rainfall. However, there are no outcrop areas of the Gilbert River Formation within or near to the Isa GBA region. Instead, the main recharge beds for the Gilbert River Formation are approximately 600 km to the east of the Isa GBA region, on the western slopes of the Great Dividing Range. 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, 2016a). The combined recharge rate to the Carpentaria Basin is about 60 GL/year on average, ranging from 27 to 127 GL/year (Table 8).

Table 8 Estimated recharge rates for the main aquifers of the Karumba and Carpentaria basins in the Southern Carpentaria sub-basin

	Average (ML/yr)	Minimum (ML/yr)	Maximum (ML/yr)
Karumba Basin	160,000	80,000	400,000
Normanton Formation	38,400	19,200	96,000
Gilbert River Formation	21,700	7,750	31,000
Southern Carpentaria sub-basin total	**220,100**	**106,950**	**527,000**

Source: Klohn Crippen Berger (2016a)

4.2.3 Karumba Basin

Diffuse recharge and river recharge (to a lesser extent) drive groundwater movement in the Karumba Basin. The laterites of the Bulimba Formation have a particularly high vertical permeability and are capable of receiving considerable diffuse recharge during the wet season. Although estimates are not yet available for recharge rates in the Isa GBA region, net recharge rate to the Bulimba Formation in outcrop areas is estimated as 4 mm/year in the Southern Carpentaria sub-basin (incorporating the Isa GBA region) compared to a much higher rate in the northern extent of the Carpentaria Basin of 25 mm/year which has higher wet-season rainfall (Klohn Crippen Berger, 2016a). Warner (1968) suggested that the Wyaaba beds may receive some local recharge from stream leakage in addition to diffuse recharge.

A large proportion of total recharge in the Karumba Basin is expected to enter the surface water system as baseflow to rivers, spring discharge, overland flow or evapotranspiration losses (DSITIA, 2014). According to a recent hydrogeological assessment of the GAB (Klohn Crippen Berger, 2016a), the total recharge volume to the main aquifer of the Karumba Basin (within the Southern Carpentaria sub-basin) is 160 GL/year on average, ranging from 80 to 400 GL/year (Table 8).

For the Southern Carpentaria sub-basin the average net recharge rate is estimated as 10 mm/year, with a range of 5 to 20 mm/year (Klohn Crippen Berger, 2016a). The combined total recharge for the Karumba and Carpentaria basins within the Southern Carpentaria sub-basin averages about 220 GL/year, ranging from 107 to 527 GL/year (Table 8).

4.3 Groundwater hydrodynamics

4.3.1 Structural controls on groundwater flow

4.3.1.1 Isa Superbasin and South Nicholson Basin

Recent publications by the Geological Survey of Queensland (Frogtech Geoscience, 2018) and Geoscience Australia (Bradshaw et al., 2018a) include maps of geological structures that integrate surface and subsurface features. These maps show that the moderately deformed rocks of the Isa Superbasin are structurally segmented into a series of fault-bound troughs in the Isa GBA region, which variably trend east-south-easterly to east-north-easterly. The major structural elements of the region are presented in Figure 16.

Analysis of seismic reflection data indicates significant fault offsets and thickness changes within the Proterozoic units of the Isa Superbasin. Synsedimentary fault movement, particularly along steeply north-dipping, largely north-east-trending normal faults, partition the depositional system into local sub-basins (Krassay et al., 2000).

The structural architecture of the Isa GBA region, as well as displacement of aquifers along individual fault systems, have potential implications for groundwater flow in the main aquifers of this area. For example, where fault offsets are significant enough to displace a potential aquifer by more than the unit thickness of the aquifer, the potential exists for compartmentalisation of groundwater flow. This situation is depicted in Figure 10, where the amount of displacement along structures such as the Doomadgee and Nicholson River fault zones is such that potential lateral hydrological connectivity within the Loretta Supersequence may be reduced due to fault offsets.

On the basis of existing information compiled for this study, the level of control that the regional fault zones have on groundwater flow systems is largely speculative and requires more detailed hydrogeological investigations. Further analysis of the potential influence of geological structures on groundwater flow in the Isa GBA region, especially as possible hydrological pathways connecting the deep (Proterozoic) and shallow (GAB) aquifer systems, is presented in Section 5.

4.3.1.2 Carpentaria Basin

Structural elements at the base of the Carpentaria Basin include a series of north-easterly trending faults with relatively small throws over the western basin margin around Doomadgee, and a series of north-east to northerly trending major faults and associated horst and graben structures within the main axis of the Carpentaria Basin (to the east of the Isa GBA region (Figure 17)). Based on the relatively smooth groundwater flow contours and lack of short-scale variation in groundwater pressure head (Figure 19 and Figure 20), there does not appear to be any significant impact on groundwater flow from these structural elements (albeit from limited available pressure data). The implications of geological structures on hydraulic connectivity are discussed further in Section 5.

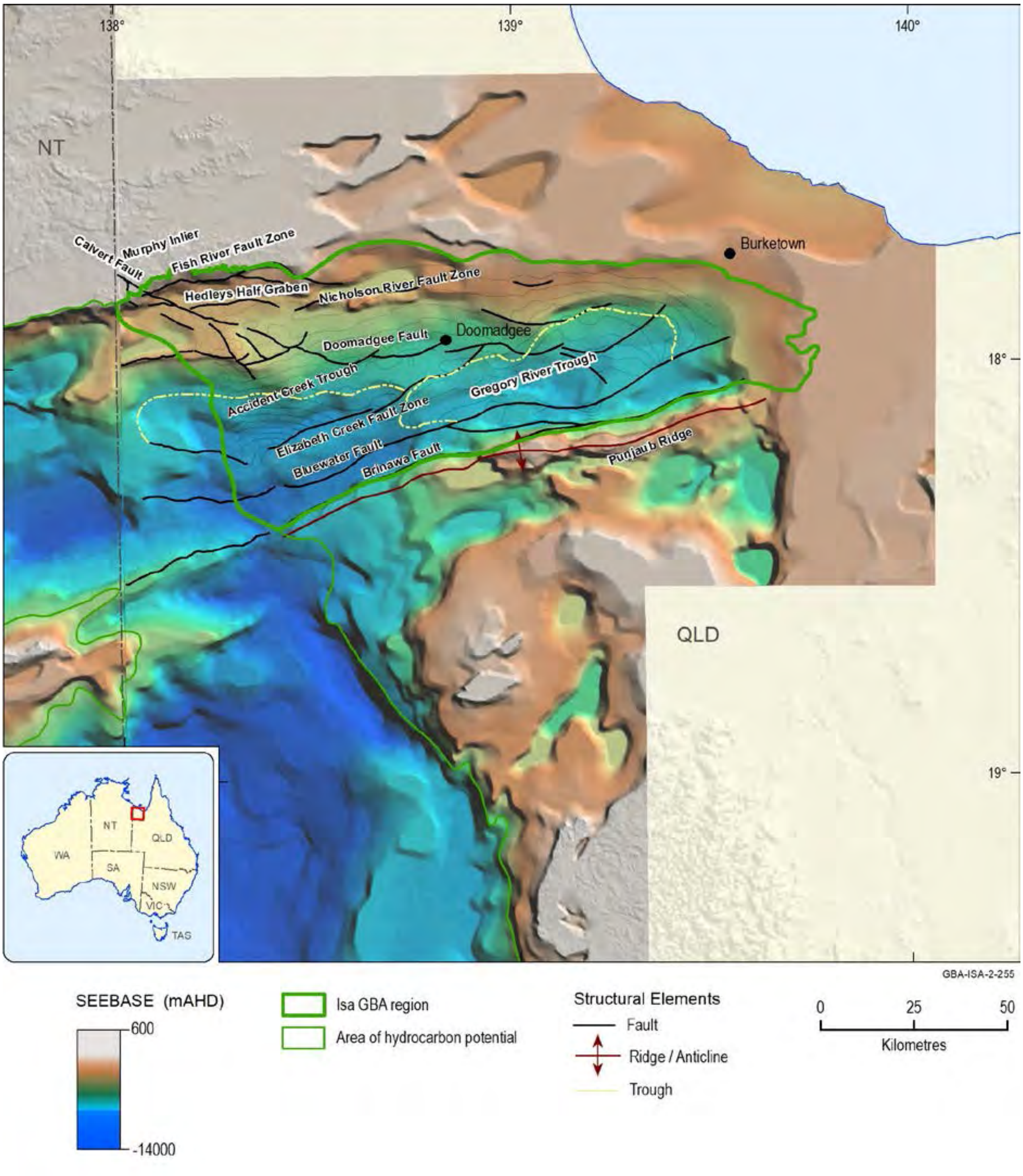


Figure 16 Major structural elements of the South Nicholson Basin and Isa Superbasin in the Isa GBA region

Data: structural elements are derived from the base River Supersequence and Base Term Supersequence depth-structure maps of Bradshaw et al. (2018b). Queensland SEEBASE® image sourced from Frogtech Geoscience (2018). NT SEEBASE® image sourced from Frogtech Geoscience (2018)
Element: GBA-ISA-2-255

Within the Rolling Downs Group aquitard, intraformational polygonal faults are widespread and pervasive, although typically have relatively minor offsets (Smerdon et al., 2012b). Analysis of seismic reflection data (for example, Figure 32 in the geology technical appendix

(Orr et al., 2020)) indicates that these faults are especially common within the Toolebuc Formation. Polygonal faults in the Rolling Downs Group may provide tortuous fluid pathways with enhanced vertical permeability, and potentially permit inter-formational flow (i.e. aquifer leakage) within the Carpentaria Basin. However, there is no clear information currently available to quantify the magnitude, rate or direction of any inter-aquifer flow that may exist within the Carpentaria Basin.

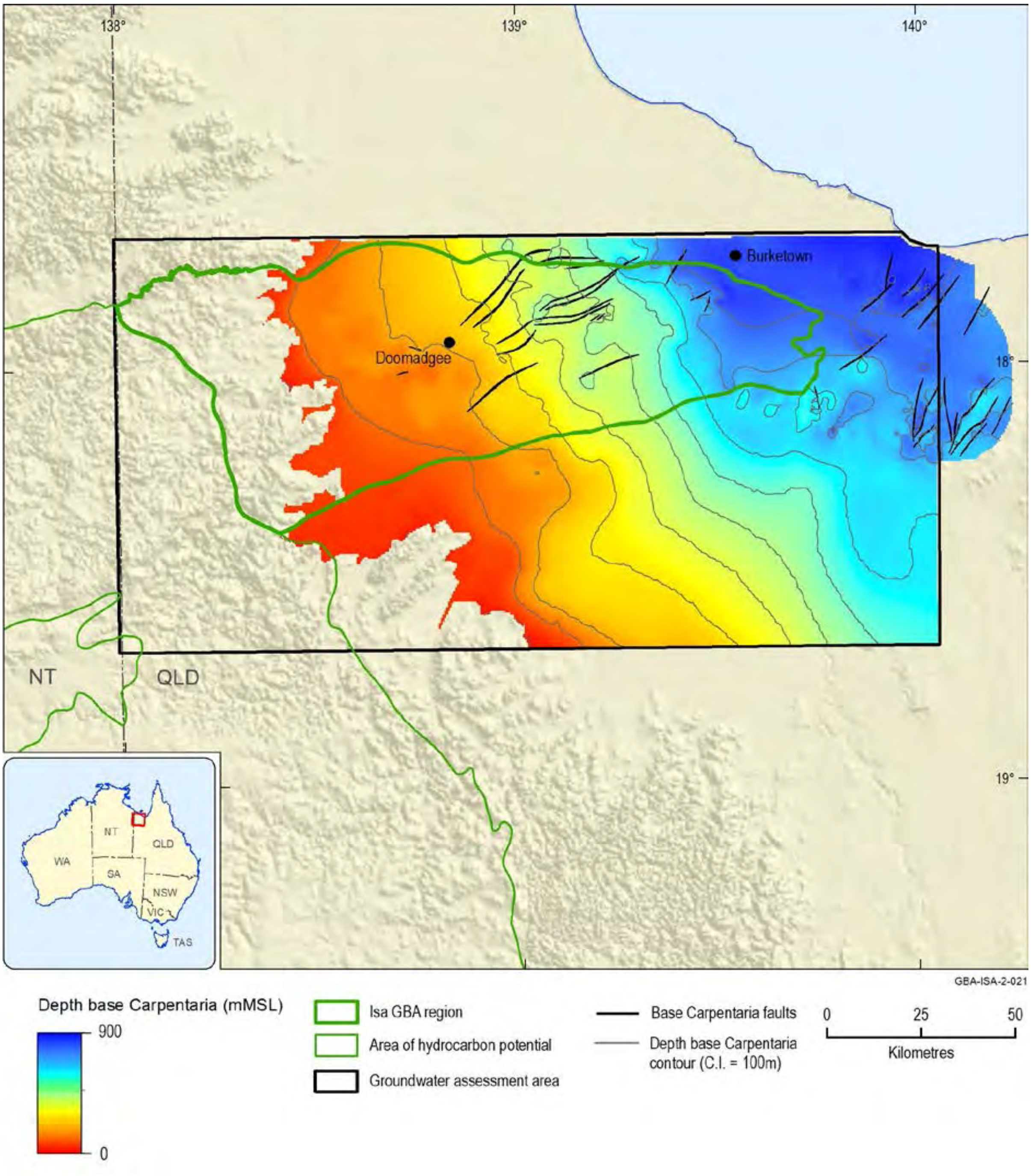


Figure 17 Major structural elements of the Carpentaria Basin

Datum = mean sea level (MSL); contour interval (C.I.) = 100 m
Data: depth-structure grid, contours and faults from Bradshaw et al. (2018b)
Element: GBA-ISA-2-021

4.3.2 Groundwater levels and pressures

Accurate inferences of groundwater dynamics, such as the seasonal changes in groundwater levels or analysis of long-term trends, are predicated on sufficient spatial and temporal coverage of groundwater data. Groundwater level records from bores within and around the Isa GBA region are generally poor. Measurements have been collected at irregular intervals and only a small number have been made. Based on the Queensland groundwater database (Department of Natural Resources, Mines and Energy (Qld), 2018d), for all of the aquifer and aquitard units in the Isa GBA region, groundwater levels have only been measured on average twice or less (Table 9). The most frequently measured bore (RN91210024) has 16 groundwater level measurements collected since it was first installed.

Table 9 Summary statistics for groundwater levels in geological units in and near the Isa GBA region

	Number of bores sampled	Average number of measurements	Max. number of samples	Latest sample date
Proterozoic aquifers	9	1.3	2	3/09/2015
Gilbert River Formation	12	1.7	5	14/03/2016
Rolling Downs Group	5	1.0	1	5/07/1998
Normanton Formation	1	1.0.	1	20/11/2006
Karumba Basin sediments	15	2.0	16	14/06/1985

Data: bore data (Geoscience Australia, 2018f)

4.3.2.1 South Nicholson Basin and Isa Superbasin

Groundwater levels and pressures in the aquifers of the South Nicholson Basin and Isa Superbasin show significant spatial variation in and around the Isa GBA region. This may be due to the influence of faulting, which may contribute to compartmentalisation within water-bearing units. For this reason, and due to the paucity of bores with groundwater measurements, no attempt has been made for this study to interpolate the groundwater elevation surface between the available point-scale measurements. Groundwater levels in the Isa Superbasin range from 68.6 mAHD to 134.6 mAHD. Groundwater levels from the two bores inferred to be in the South Nicholson Basin were 91.9 mAHD and 97.0 mAHD when measured (Figure 19).

Most (29) Proterozoic bores listed in the Queensland groundwater database (Department of Natural Resources, Mines and Energy (Qld), 2018d) are sub-artesian (Table 2), with none of the groundwater measurements in Figure 19 indicative of artesian conditions. Furthermore, there has been no reported overpressure during exploration drilling which may suggest such hydrological conditions. However, within the region of investigation artesian conditions were recorded at the time of drilling of several bores (Table 2), although the subsequent status of these bores is unknown. In addition, artesian conditions were reported during drilling of the Burketown 1 bore (which flowed at a rate of 63 L/min when first drilled) 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). As no further groundwater observations have been recorded to understand the long-term pressure changes in this aquifer, the classification of this aquifer as confined and displaying artesian characteristics is highly uncertain.

4.3.2.2 Gilbert River Formation aquifer

Groundwater pressure in the Gilbert River Formation aquifer appears to have remained relatively constant for the period where data has been collected. Groundwater pressure from the two most regularly measured bores (RN3030 and RN4180) is shown in Figure 18.

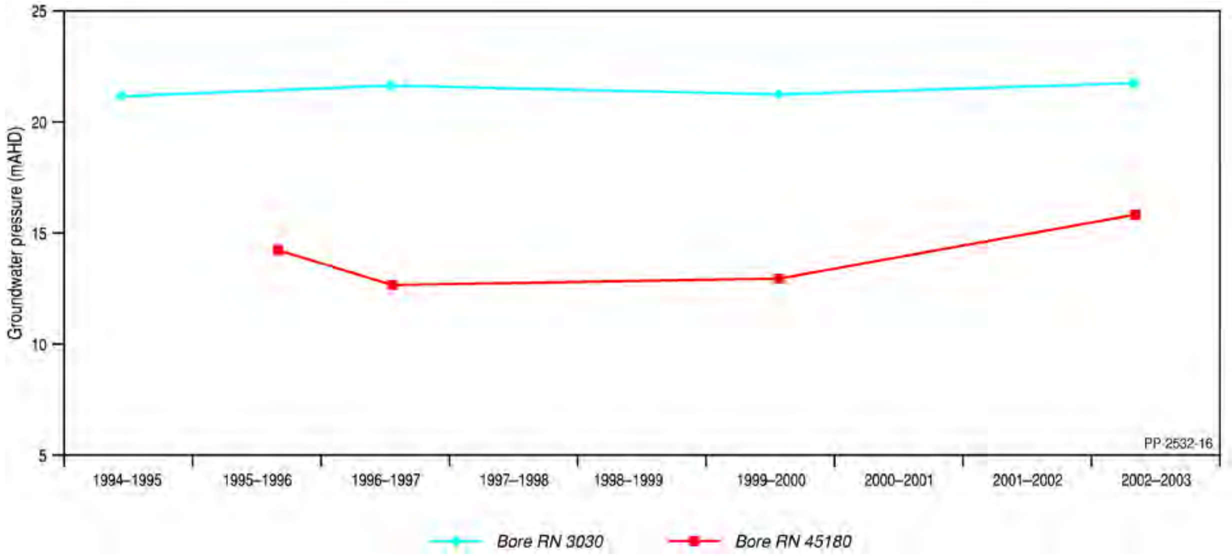


Figure 18 Groundwater pressures in the Gilbert River Formation

Data: Geoscience Australia (2018f)
Element: GBA-ISA-2-153

Eight artesian bores tapping the Gilbert River Formation aquifer are in the north-east of the groundwater area of investigation, with recorded artesian pressures during well completion ranging from 137 kPa to 290 kPa (approximately 15 to 30 mAHD) (Department of Natural Resources, Mines and Energy (Qld), 2018d). Other flowing artesian bores are known to exist in the area, including the Burketown Bore (RN330), although groundwater levels for these bores are not documented (and so have not been presented on Figure 19).

Based on available data, groundwater levels (above mean sea level) in the confined Gilbert River Formation aquifer range from 27.4 to 46.8 m AHD (Figure 19). In this region the Gilbert River Formation occurs only in subcrop. Due to insufficient groundwater measurements, no attempt has been made in this study to generate a potentiometric surface for this aquifer (noting that groundwater level contours are included in Ransley et al. (2015b)).

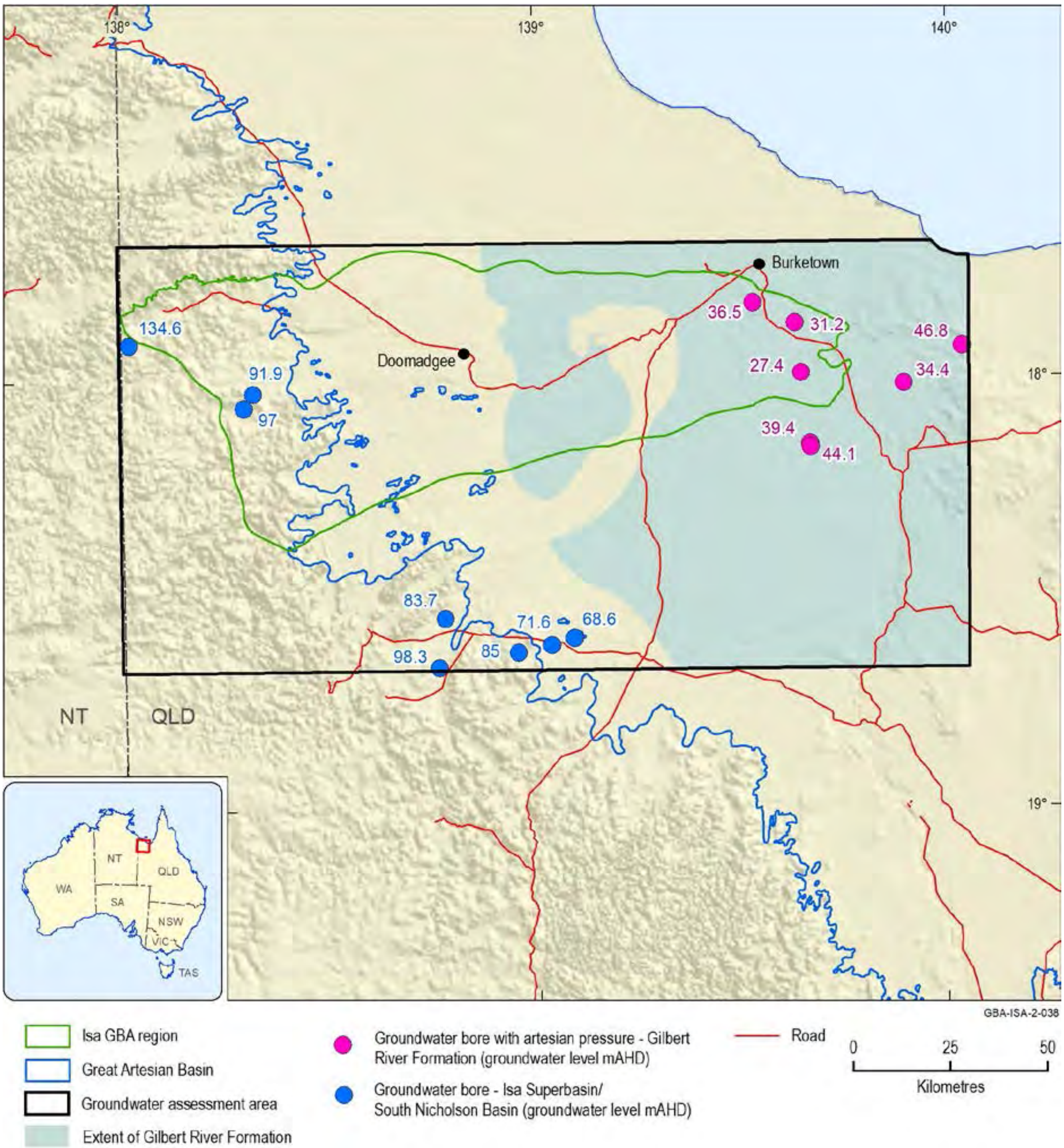


Figure 19 Groundwater levels in the Isa Superbasin and South Nicholson Basin and Gilbert River Formation aquifer of the Great Artesian Basin

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

4.3.2.3 Regional watertable

Within the Isa GBA region, the regional watertable ranges from an elevation of about 60 mAHD on the western margin of the GAB to zero mAHD near the coast, where it occurs in Karumba Basin sediments (Ransley et al., 2015b) (Figure 20). The groundwater flow direction generally follows this north-easterly gradient, although it may be locally influenced by topographic features. The zero watertable contour (zero mAHD) is up to 30 km inland from the coast.

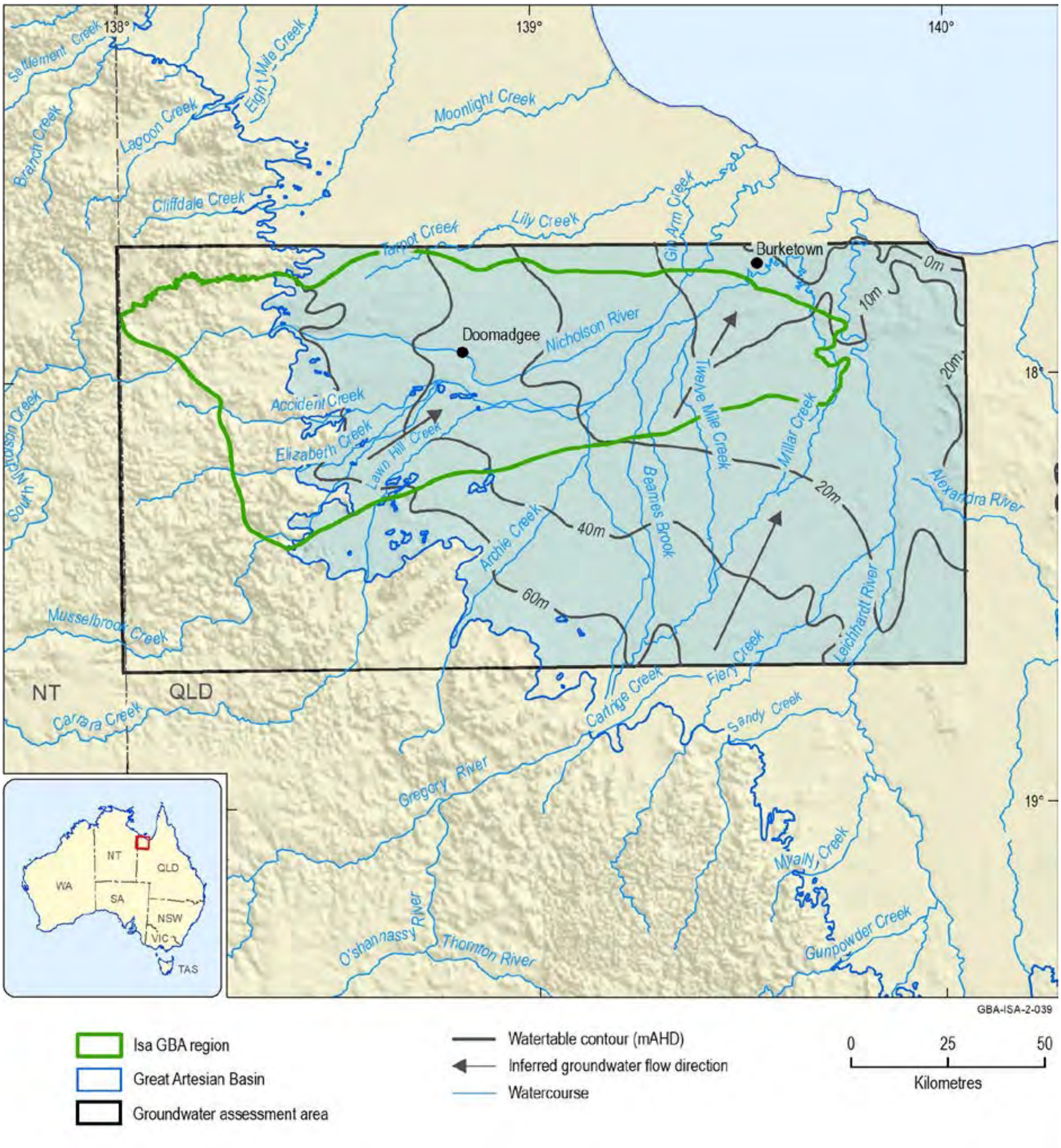


Figure 20 Groundwater level and inferred flow direction in the regional watertable of the Karumba Basin

Data: geology (Geoscience Australia, 2018c); groundwater contours (Ransley et al., 2015b)
Element: GBA-ISA-2-039

The extent of seawater intrusion in the watertable in this region remains unknown, due to a lack of groundwater bores and salinity data near the coast. However, given the zero gradient of groundwater around the coastal areas, the potential for seawater intrusion exists if the watertable is lowered in the coastal region.

4.4 Groundwater hydrochemistry

Groundwater and surface water hydrochemical datasets were analysed for this study to characterise the chemical composition of groundwater for the main aquifers and surface water systems of the Isa GBA region. In addition, these data have been used to examine potential groundwater flow between aquifers, and potential surface water – groundwater interactions. Hydrochemical data from the Queensland groundwater database (Department of Natural Resources, Mines and Energy (Qld), 2018d) were combined with surface water chemistry data from the Water Monitoring Information Portal (Department of Natural Resources, Mines and Energy (Qld), 2018a) and augmented by data from EHS Support (2014). The following section presents the results of hierarchical cluster analysis (HCA) based on groundwater and surface water samples, as well as analyses of groundwater quality including data on salinity. A more detailed discussion on surface water chemistry is presented in Section 4.5.4.

4.4.1 Hierarchical cluster analysis

Hierarchical cluster analysis (HCA) was undertaken on available groundwater data from within and near the Isa GBA region to characterise the various water sources and identify any distinct hydrochemical patterns. HCA is a useful technique commonly adopted in groundwater hydrochemical studies as it allows detection of 'spatial patterns in large datasets and enhances the understanding of physical and chemical catchment processes' (e.g. Güler et al., 2002; Raiber et al., 2012). Where available, a large number of variables should be used in HCA to characterise groundwater chemistry and its controlling processes. The selection of the parameters used in HCA requires balance between selecting a wide range of variables but also aiming for a large number of complete cases to ensure comprehensive spatial coverage, as HCA considers only cases where a value exists for each variable (e.g. Raiber et al., 2012).

Due to the limited spatial coverage of available data, surface water sites were selected both within and outside of the Isa GBA area (Figure 21). Repeated surface water chemistry data were available for eight gauging stations (two sites within the Isa GBA region) for the complete set of parameters considered in the HCA analysis. Despite the poor temporal coverage of available data (predominantly from 1973 to 1993), subsets of 'high' and 'low' salinity surface water samples were used in the analysis to represent possible end-member compositions of surface waters from this region.

To avoid skewing of the dataset (due to the greater number of time series measurements available for surface water sites compared to the relatively small number of groundwater hydrochemical records), only selected surface water hydrochemical records with the lowest measured electrical conductivity (EC) (representing wet-season flows) and the highest EC (representing baseflow conditions during the dry season) were included in the HCA. Furthermore, due to the small number of groundwater hydrochemical records from the Isa GBA region, records from locations near to the Isa GBA region were also included in the analysis (Figure 21) to provide a better representation of regional groundwater chemistry.

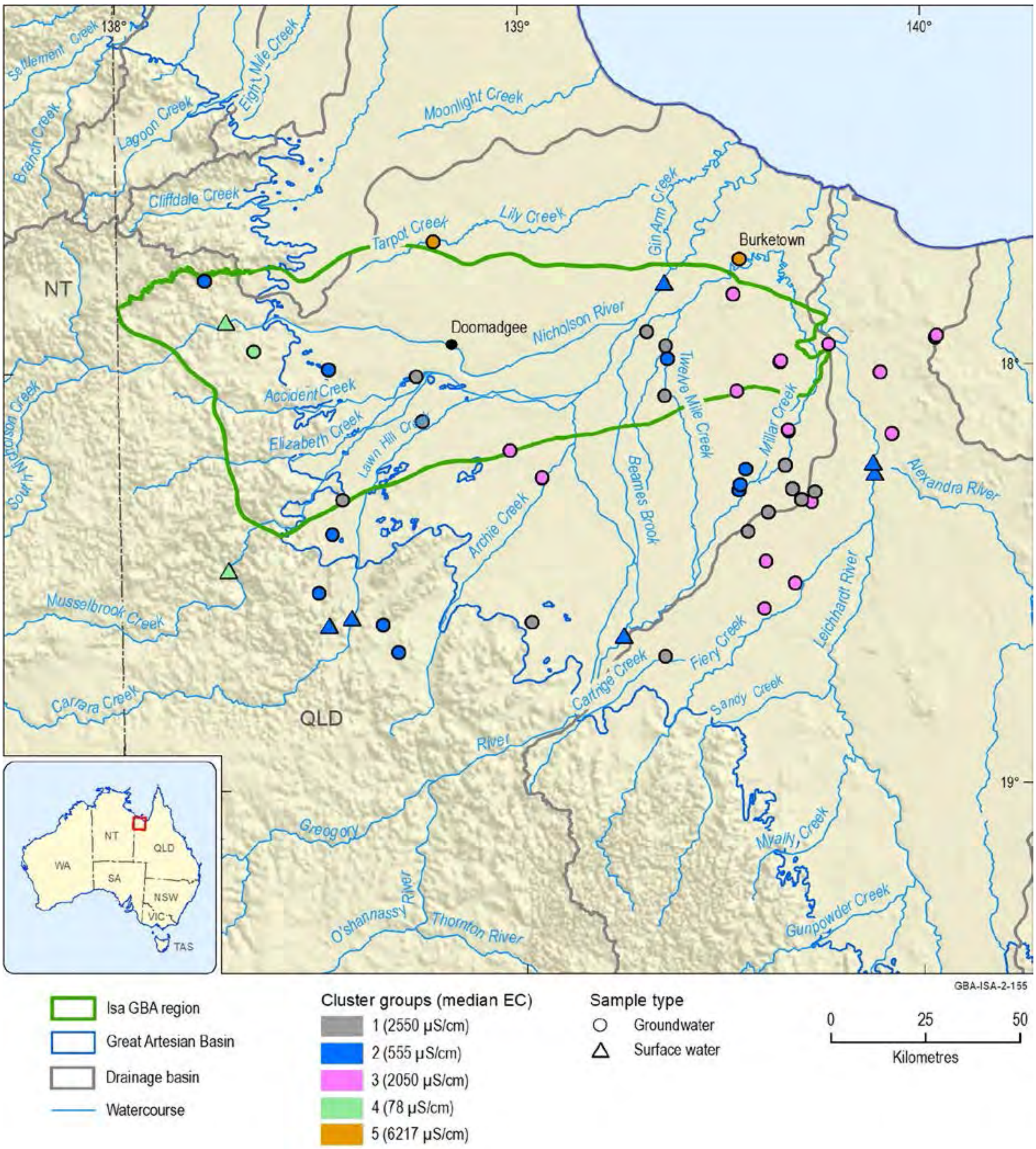


Figure 21 Spatial distribution of hydrochemical cluster groups for groundwater and surface water samples

Data: Geological and Bioregional Assessment Program (2019)
Element: GBA-ISA-2-155

Ten variables were selected for HCA (Ca, Mg, Na, K, HCO_3, Cl, F, SO_4, pH and EC) as they were measured across most sites. Temperature was not included as no field temperature measurements were available for many bores. In total, 71 hydrochemical records from groundwater bores and 16 records from surface water gauging stations were included in the multivariate statistical analysis using the methodology described in Martinez et al. (2015); Raiber et al. (2019).

The results of the HCA are presented in Table 10 and Figure 22, showing that there are five major clusters with distinct median values for different parameters. A chi-square test was used to test for independence between aquifers and clusters and assess whether the cluster attribution of hydrochemical records is related to aquifer (or surface water) membership. Since the P-value is less than 0.05, the hypothesis that the aquifer and cluster classifications are independent can be rejected at the 95% confidence level. A cross-tabulation (Figure 22a) also highlights the relationship between cluster and aquifer or surface water during dry or wet periods, respectively.

Median values for different parameters (Figure 22) were used to determine the characteristics of the different water chemistry clusters.

Table 10 Median values of the variables considered in the cluster analysis for each sample group

Cluster	Number of samples	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	17	2550	7.6	330	61	70.0	7.0	509.0	170	0.3	405.0
2	26	555	8.0	8.0	34.5	28.9	2.5	8.5	5	0.2	304.5
3	33	2050	8.3	484	4.8	0.9	6.4	290.0	50	5.3	690.0
4	5	78	6.9	5.2	1.6	1.5	2.1	7.0	5	0.1	24.5
5	6	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 (2019)

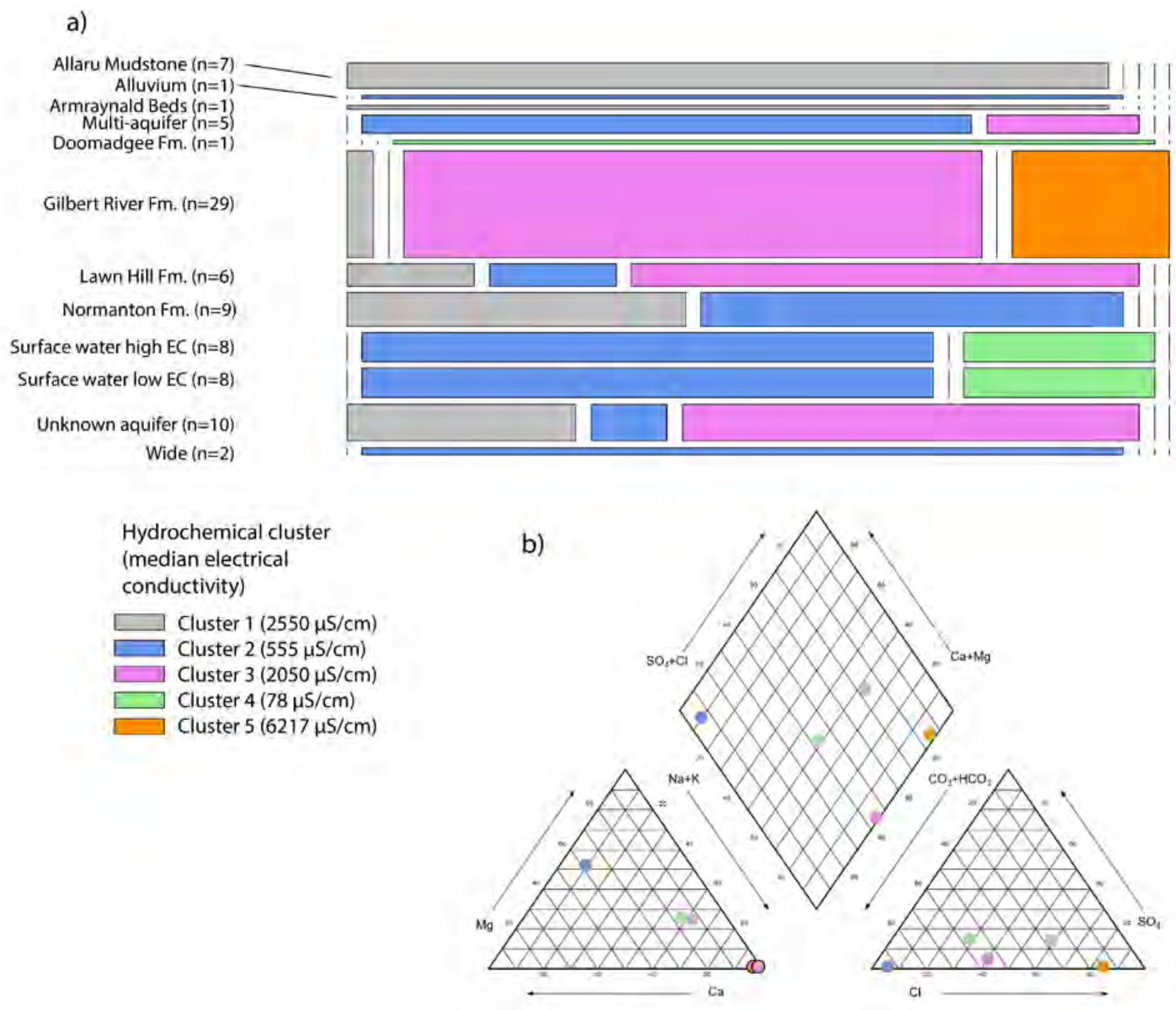


Figure 22 Cluster membership of aquifers in the Isa GBA region

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

The major characteristics of each cluster are:

- **Cluster 1:** this group contains groundwater chemistry records from the Carpentaria Basin aquifers, represented mostly by the Allaru Mudstone and Normanton Formation. These groundwaters are slightly brackish (median EC of 2550 µS/cm), with a dominance of Cl over HCO_3, and relatively high levels of Ca, Mg and SO_4. Fluoride concentrations are relatively low.
- **Cluster 2:** water chemistry records in this group include both groundwater and surface water. Surface water chemistry records are from both dry and wet seasons, with groundwater records assigned to the alluvium, Normanton Formation and Lawn Hill Formation. No records from the Gilbert River Formation were assigned to this cluster. Water chemistry records assigned to this cluster are generally fresh (with an EC of 555 µS/cm), have very high HCO_3/Cl ratios and a dominance of Ca and Mg over Na.

- **Cluster 3:** water chemistry records in this group are exclusively sourced from groundwaters (mostly from the Gilbert River Formation). They are slightly brackish (median EC of 2050 µS/cm), and are marked by a dominance of HCO_3 over Cl, very low Ca and Mg concentrations and high concentrations of F (high F concentrations in other sedimentary basins are commonly considered a potential indicator of interaction with coal or organic matter within the sedimentary sequences).
- **Cluster 4:** water samples assigned to this group contain the lowest median salinity within the Isa GBA region. It is composed primarily of surface water samples with only one groundwater chemistry record from the Doomadgee Formation. Samples within this cluster have a high HCO_3/Cl ratio and otherwise low concentrations of all ions.
- **Cluster 5:** this group exclusively contains groundwater samples from the Gilbert River Formation. This cluster is marked by the highest salinity groundwater in the Isa GBA region (median EC of 6217 µS/cm based on six samples). It also has low HCO_3/Cl ratios, high Na, low Mg and SO_4 and high F concentrations. Overall, groundwaters assigned to this cluster are highly evolved, and are potentially groundwaters with long residence times.

Based on the available hydrochemical records, the key observation from the HCA is that the Gilbert River Formation and the Normanton Formation are hydrochemically very different. This provides evidence to indicate that the Rolling Downs Group forms a competent aquitard that precludes widespread hydrological connection between these two aquifers (Figure 22), although areas of local connection may occur, e.g. as evidenced through localised occurrences of elevated gas levels in some groundwater samples (Section 4.4.2). Importantly though, hydrochemistry data are sparse for the Isa GBA region, and there are no multi-level observation bores where both formations are monitored simultaneously.

4.4.2 Gas occurrences

Dissolved gas concentration data are available for nine groundwater samples collected from existing private bores tapping the alluvium, Gilbert River Formation and Normanton Formation aquifers. These samples were collected as part of a baseline hydrological assessment conducted for Armour Energy in 2014 (EHS Support, 2014), and were collected from bores within Armour's gas exploration tenement Authority to Prospect (ATP) 1087, which covers most of the Isa GBA region (see the petroleum prospectivity technical appendix (Bailey et al., 2020) for further information about ATP 1087). The dissolved gas concentration data were used to provide preliminary assessment of potential gas migration pathways from deep shale gas reservoirs to the shallower groundwater system.

An increasing body of literature from studies on conventional and unconventional gas fields in Australia (e.g. Currell et al., 2017) and North America has demonstrated the value of using methane isotopes as tracers to determine the origin of methane (CH_4) that may occur in aquifers overlying gas plays. The analysis of these data can also be used to identify mechanisms of methane migration (e.g. Sherwood et al., 2016; Nicot et al., 2017; Humez et al., 2016; Harkness et al., 2017; Mallants et al., 2018b), particularly when combined with other tracer methods such as noble gas isotopes and helium, or other lines of evidence such as data from geophysical techniques (Harkness et al., 2017; Mallants et al., 2018b).

Together with noble gases (such as helium) and trace element concentrations, methane isotope data (δ^2H and $\delta^{13}C$ of methane) can help to better understand the origin of the gas and possible diffusive and advective pathways for gases from unconventional gas reservoirs to underlying or overlying sedimentary bedrock aquifers. Within the Isa GBA region, such information could be relevant to understanding the origin of elevated methane levels that may occur in groundwater within the GAB aquifers (e.g. Gilbert River Formation or Normanton Formation) as well as the Cenozoic aquifers of the Bulimba Formation and Wyaaba beds. However, there are currently no analyses of methane isotope data publicly available for groundwater samples from the Isa GBA region.

Detection of dissolved methane in aquifers can be an indicator for the presence of seal bypass systems, and it can be considered a precursor of other organic or even inorganic contaminants derived from coal. The presence of dissolved methane in sedimentary basins is not unusual, and concentrations measured in the Eromanga Basin within the Cooper GBA region, for example, ranged from 150 to 216,500 μg/L (Holland et al., 2020).

Concentrations of dissolved methane in groundwater from the Isa GBA region ranged from less than 10 to 7320 μg/L (EHS Support, 2014), which is relatively low compared to measurements taken in other Australian sedimentary basins. However, this is based on only nine measurements (refer to Figure 58), and there is a need for additional methane baseline data, including samples from shallow aquifers to better characterise the source of methane in the Isa GBA region.

Three samples collected from one of the GAB aquifers (Gilbert River Formation) had dissolved methane (CH_4) measurements up to 4880 μg/L (EHS Support, 2014). As previously mentioned, this is the basal GAB aquifer in this region, and is known to directly overlie and be in contact with several of the underlying Paleoproterozoic sequences, including (in places) the gas-bearing Lawn Supersequence. Of note is bore RN330A, located in Burketown, which is an artesian bore tapping the Gilbert River Formation aquifer (EHS Support, 2014) with total depth of approximately 700 m and dissolved methane concentration of 2310 μg/L.

The maximum methane concentration dissolved in groundwater (7320 μg/L) among all nine samples collected by EHS Support (2014) was from a bore that sources water from the Normanton Formation, a partial aquifer in the Rolling Downs Group (Figure 11). The elevated gas concentration in the Normanton Formation was interpreted by EHS Support (2014) as originating from the underlying Lawn Supersequence (Lawn Hill Formation), which is the uppermost shale gas play in the Isa Superbasin.

Methane migration from the source reservoir can occur through seal bypass mechanisms, such as along faults or other permeable structural features. However, when there is no pathway between the hydrocarbon source rocks and a groundwater aquifer (i.e. when no seal bypass systems exist), methane concentrations in shallow aquifers are more likely due to a relatively shallow methane source (such as near-surface coal seams or other in situ biogenic gas production processes) unrelated to the target unconventional gas plays. The analysis of methane isotopes and other environmental tracers in groundwater (e.g. noble gases) can provide additional insights into potential connectivity pathways, and can help to determine the most likely source of gas within an aquifer (i.e. a deep or shallow methane source).

4.4.3 Major cation and anion compositions

Using the Peeters (2014) colour scheme for Piper plots, map-based representations of hydrochemical signatures have been compiled for this study. The hydrochemical composition data from available groundwater samples (Bardwell and Grey, 2016) are presented in Figure 23, Figure 24 and Figure 25. These figures depict the hydrochemical signature of groundwater from the South Nicholson Basin and Isa Superbasin aquifers, the Gilbert River Formation aquifer and the regional watertable aquifer, respectively.

The Proterozoic aquifers show significant spatial variability in groundwater chemistry (Figure 23), ranging from Mg-Ca-HCO_3 to Na-SO_4-Cl as the dominant ions. The variability is probably indicative of local-scale recharge processes and a variety of water-rock interactions. Mg-Ca-HCO_3 type groundwater is consistent with interactions with dolomite and other carbonate-rich rocks, which are known to occur in the sedimentary sequences of the Isa Superbasin.

The groundwater of the Gilbert River Formation aquifer varies from sodium-bicarbonate-chloride (Na-HCO_3-Cl) to sodium-chloride-bicarbonate (Na-Cl-HCO_3) type (Figure 24). This is typical of groundwater in the GAB that has migrated a considerable distance (e.g. hundreds of kilometres) from the point of recharge and has undergone extensive hydrochemical evolution along its flow path (see also Section 4.4.7). This supports the conceptual understanding of recharge to this deeper GAB aquifer system occurring on the western edge of the Great Dividing Range, and then flowing westwards into deeper parts of the basin (as discussed in Section 4.2).

The chemistry of the regional watertable aquifer is spatially variable, particularly outside of the Isa GBA region (Figure 25). Within the region, groundwater is dominated by Na-HCO_3 or Na-Cl; outside of the region Mg-Ca-HCO_3 and Mg-Na-HCO_3 types also occur. Groundwater accessed from different units within the Karumba Basin as well as localised interaction with surface waters may contribute to the variability in water type in this shallow aquifer.

In terms of interconnectivity between aquifers, the cation-anion compositions support the results of the HCA and suggest that there is no widespread hydrological connection between the different aquifer systems. Distinct hydrochemical signatures characterise the major aquifer groups of the regional watertable, Gilbert River Formation and the South Nicholson Basin and Isa Superbasin aquifers. However, the locations of the existing samples are spread over a relatively wide area, and are generally not within the Isa GBA region. Consequently, the level of uncertainty about potential hydrological connectivity between groundwater systems remains very high. Furthermore, the sparse data does not provide information on the potential for fault-controlled and more localised connectivity pathways that may exist between the different basins (Section 4.3.1). Targeted groundwater sampling (in the future) would be required to develop an improved understanding of the potential for more localised connectivity to exist within parts of the Isa GBA region.

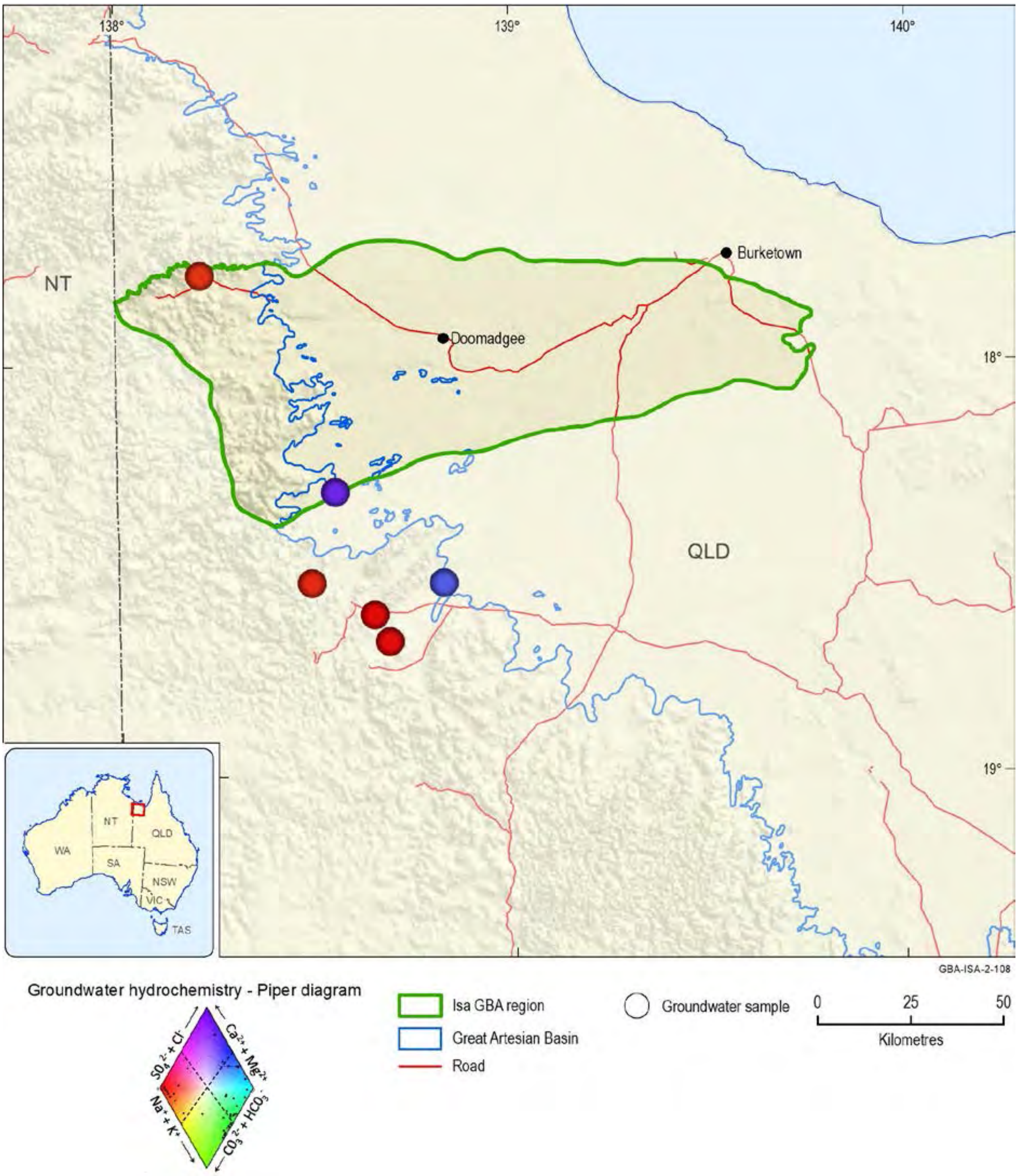


Figure 23 Groundwater hydrochemistry for bores accessing groundwater from Proterozoic rock units in the Isa Superbasin and South Nicholson Basin

Data: Bardwell and Grey (2016)
Element: GBA-ISA-2-108

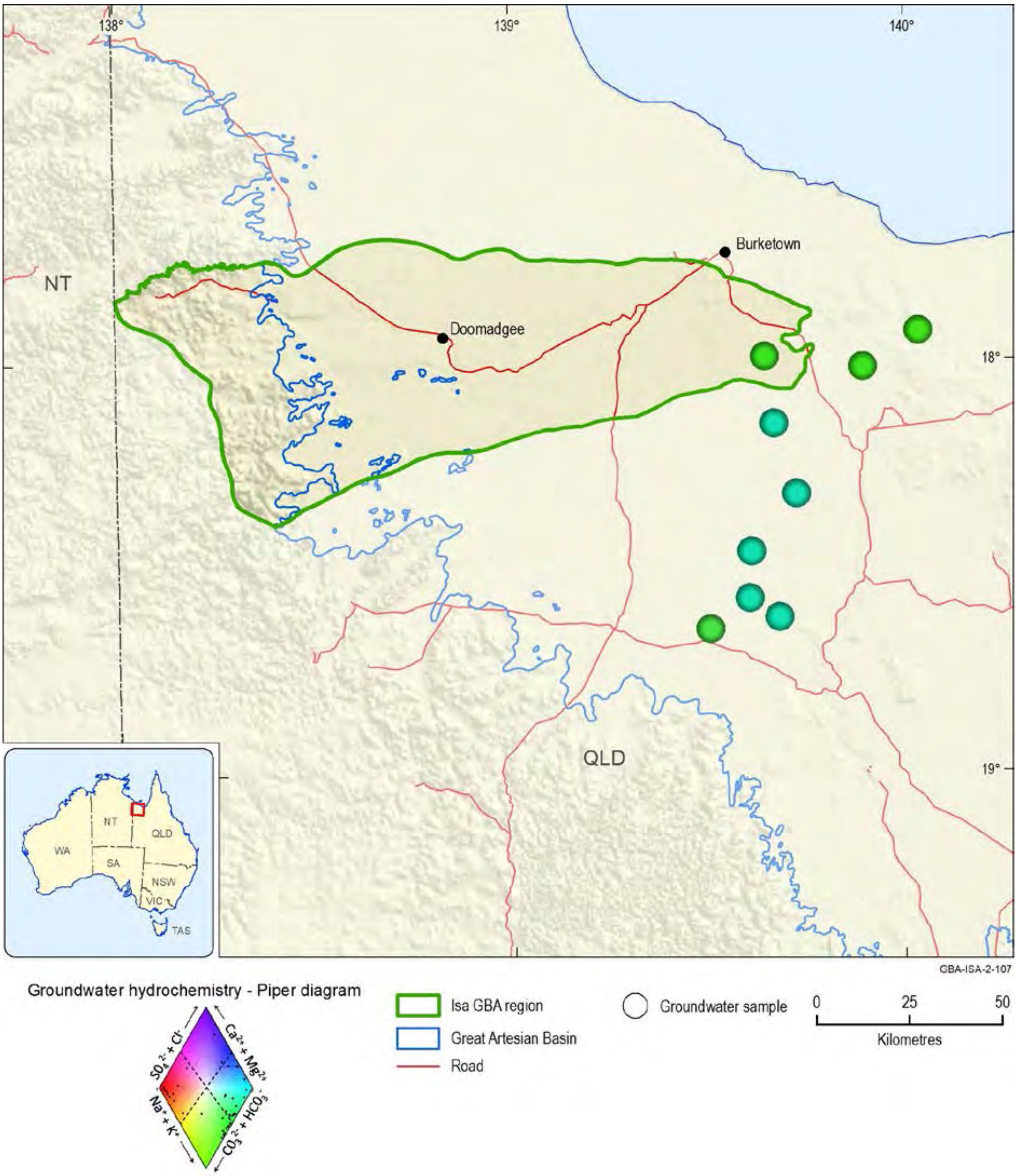


Figure 24 Groundwater hydrochemistry for bores in the Gilbert River Formation aquifer

Data: Bardwell and Grey (2016)
Element: GBA-ISA-2-107

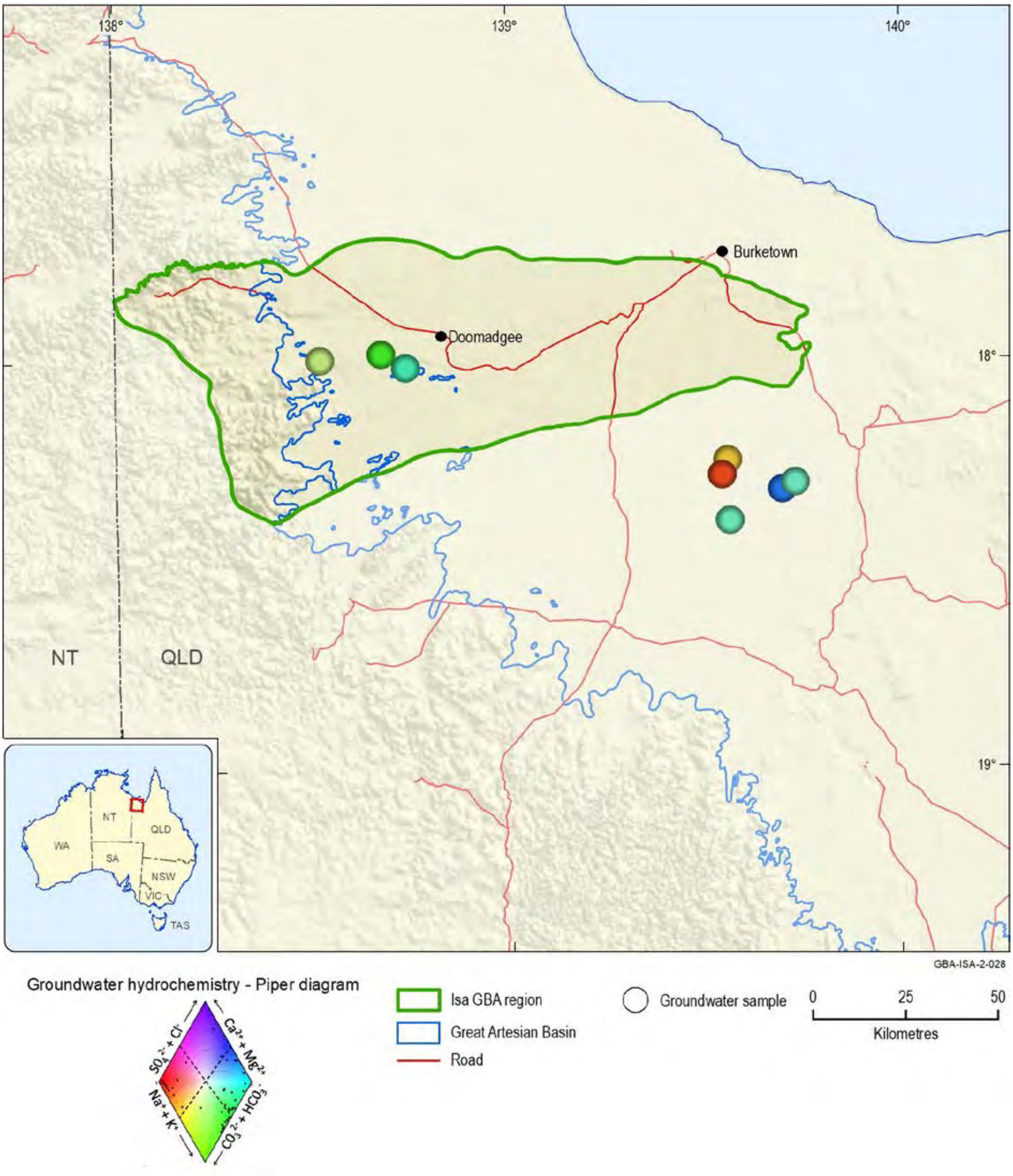


Figure 25 Groundwater hydrochemistry for bores in the regional watertable aquifer

Data: Bardwell and Grey (2016)
Element: GBA-ISA-2-028

4.4.4 Salinity of Isa Superbasin and South Nicholson Basin aquifers

Groundwater salinities in the Isa Superbasin and South Nicholson Basin aquifers are moderately variable, with total dissolved solids (TDS) ranging from 90 mg/L to 4614 mg/L, with a median 663 mg/L (Figure 26). As for groundwater levels, only the actual values have been presented on the map with no attempt to contour. This is due to the significant structural and stratigraphic complexity of the Proterozoic units, which is likely to cause groundwater flow systems to be locally variable with limited regional connectivity. This interpretation is further supported by the high level of spatial variability in the available salinity data, for example, groundwater samples with relatively high salinity occur nearby to samples with much lower salinity.

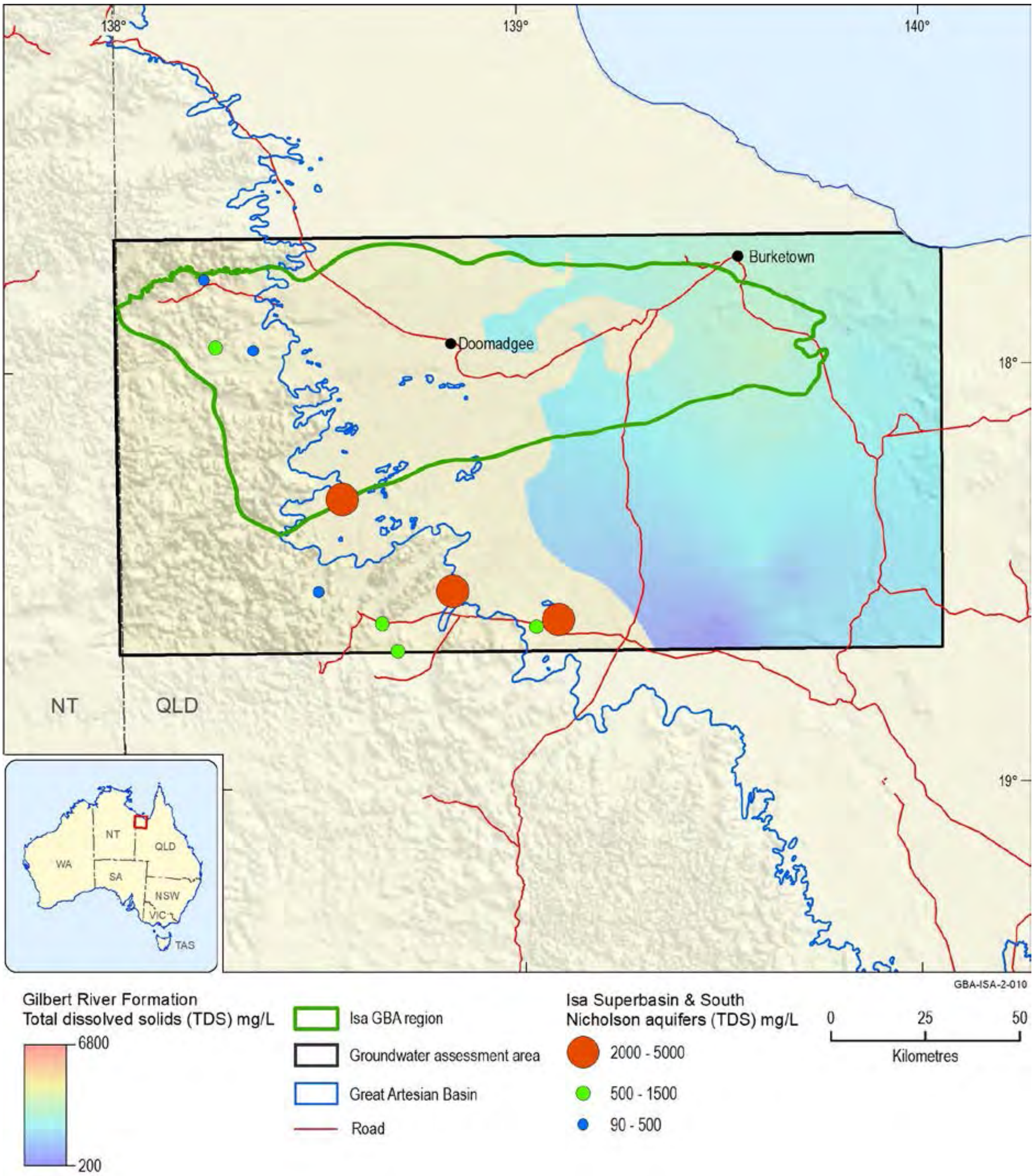


Figure 26 Groundwater salinity in the Gilbert River Formation aquifer (contours) and Proterozoic aquifers

Proterozoic units shown as TDS concentration-dependant circular symbols.
Data: Geoscience Australia (2018g). Data contoured using Inverse Distance Weighting.
Element: GBA-ISA-2-010

4.4.5 Salinity of Gilbert River Formation aquifer

The median salinity level is higher in the Gilbert River Formation aquifer than the regional watertable; however, it is still classed as only slightly saline groundwater (Figure 26). There is less spatial variation in salinity in the Gilbert River Formation aquifer than for the regional watertable, although this may be due to fewer sample points. The TDS values from the 29 available samples range from 367 mg/L to 1638 mg/L, with a median of 1324 mg/L.

4.4.6 Salinity of regional watertable aquifer

Groundwater salinity is spatially variable in the regional watertable aquifer; however, most samples are slightly or moderately saline. The TDS values from the 11 available samples range from 191 mg/L to 6912 mg/L, with a median of 790 mg/L. The spatial distribution of TDS (derived by contouring) is presented in Figure 27.

Compared with the GAB, the TDS concentrations of the watertable aquifer are relatively low. This likely reflects the relatively high wet-season rainfall which results in regular pulses of freshwater recharge and groundwater flux. The high salinity hotspot observed towards the east could be due to less flushing of the groundwater in that area, although this is speculative and would require further investigation.

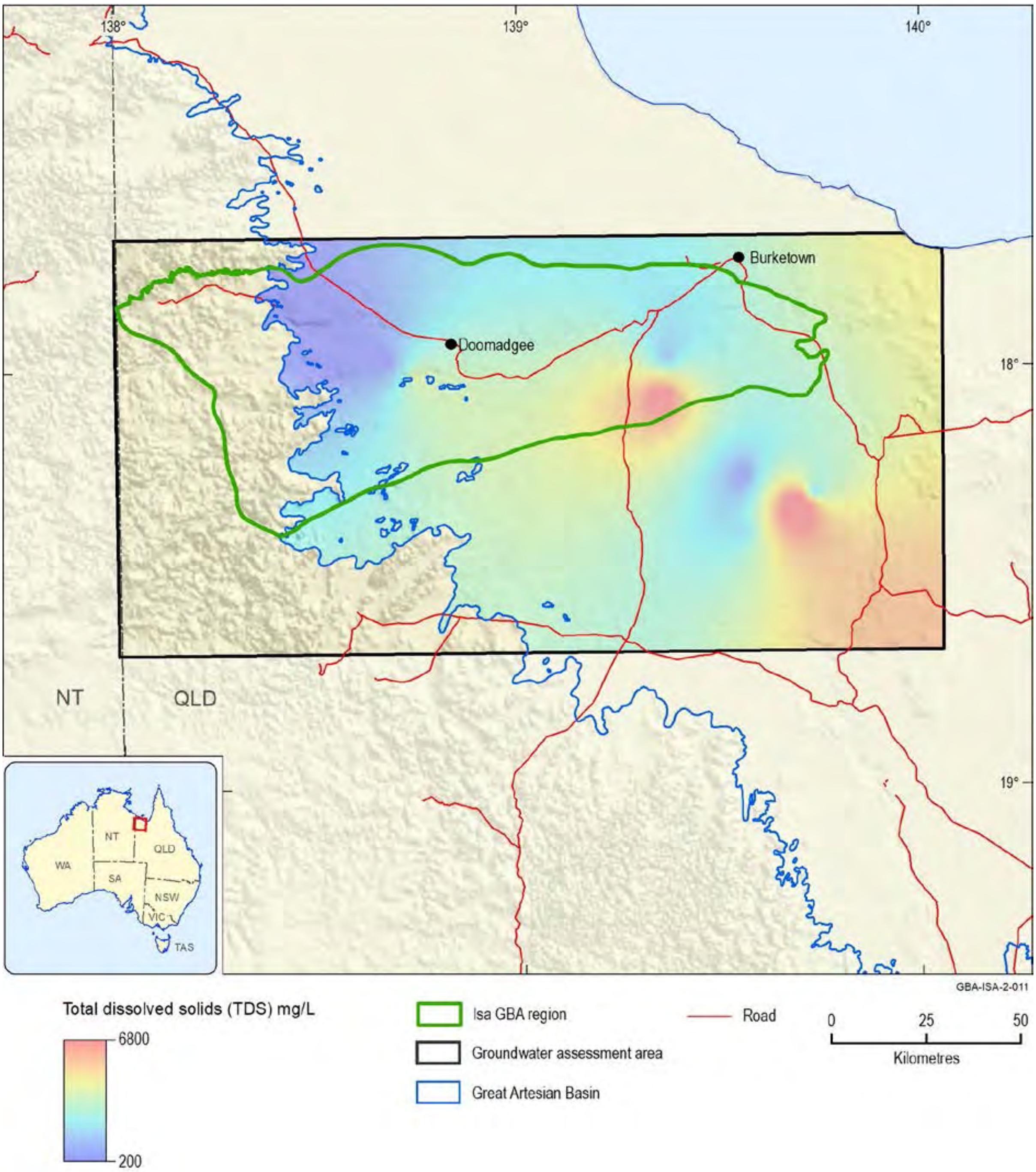


Figure 27 Salinity of the regional watertable aquifer in areas of the Carpentaria and Karumba basins

Data: Geoscience Australia (2018g). Data contoured using Inverse Distance Weighting.
Element: GBA-ISA-2-011

4.4.7 Sodium adsorption ratio

The sodium adsorption ratio (SAR) is a measure of the amount of sodium (Na^{+}) relative to calcium (Ca^{2+}) and magnesium (Mg^{2+}) in groundwater. This ratio can be used to help understand groundwater flow paths and also identify areas where the use of groundwater may have negative impacts on the land (for example, application of irrigation water). Figure 28 shows that the SAR values are typically less than 20 for all groundwater samples in the watertable aquifer, as well as the aquifers of the South Nicholson Basin and Isa Superbasin. However, the Gilbert River Formation aquifer has much higher SAR with values commonly greater than 45.

Low SAR values may indicate more local-scale recharge processes for the watertable aquifer and Proterozoic aquifers (Section 4.2). In contrast, the high SAR values in the Gilbert River Formation aquifer imply that groundwater has undergone significant chemical exchange since the point of recharge. Radke et al. (2000) characterised the chemistry of groundwater in the eastern recharge areas of the GAB as Ca/Mg-HCO_3/Cl type, and to a lesser extent Ca/Mg-Cl/SO_4 type. As this groundwater moves basin-wards from recharge areas (and eventually into the Isa GBA region), cation exchange occurs, whereby sodium ions in the aquifer matrix are exchanged for dissolved Ca and Mg ions. These reactions lead to the subsequent conversion of Na-smectite-rich clays to kaolinite-rich clays, thereby releasing Na^+ into groundwater. This leads to increasingly elevated SAR in more evolved groundwaters. The use of groundwater (for example, in irrigation) with high SAR may lead to degradation of soil properties, including dispersion of organic matter and clay particles, and reduced saturated hydraulic conductivity.

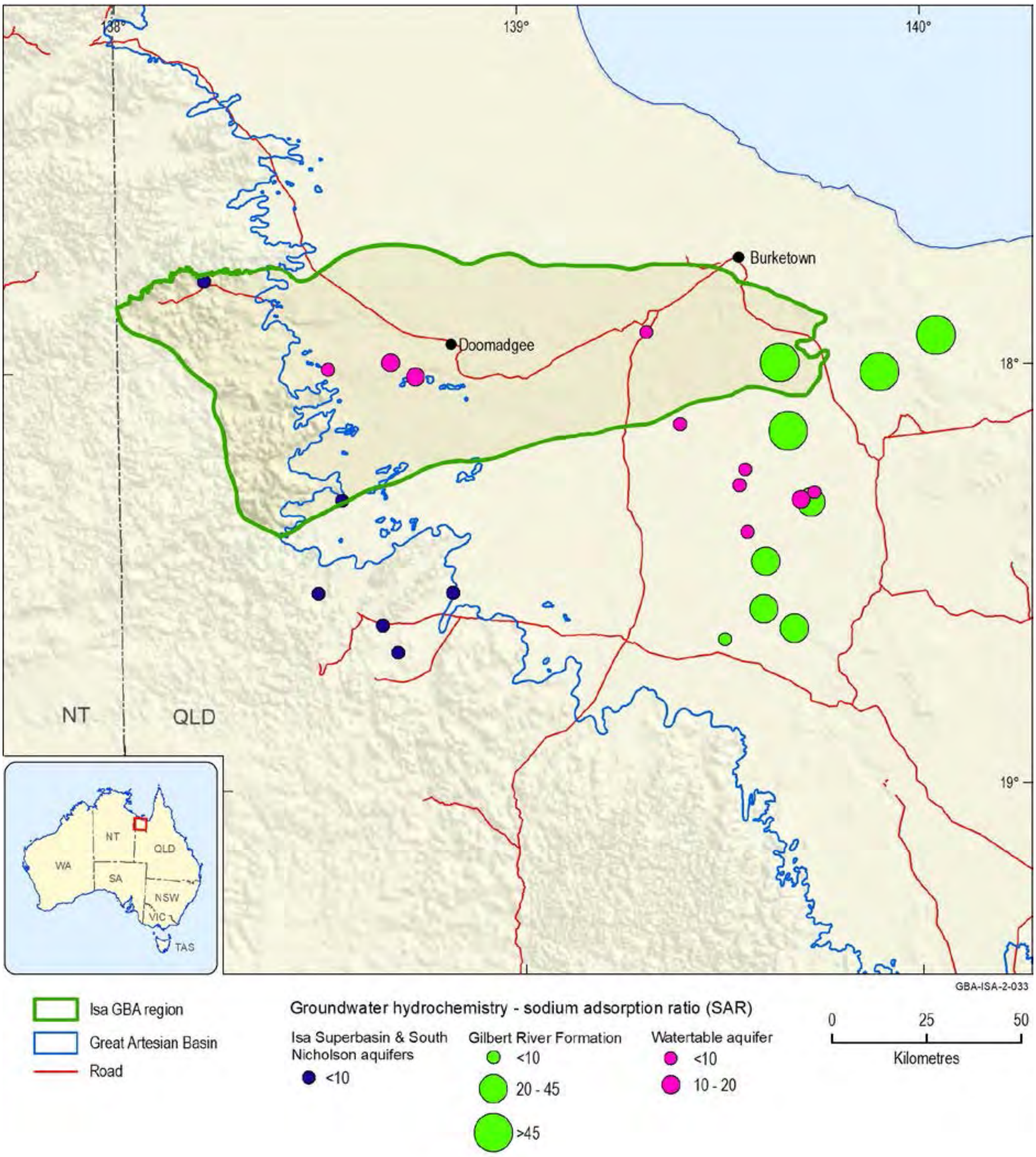


Figure 28 Groundwater sodium adsorption ratio

Data: Bardwell and Grey (2016)
Element: GBA-ISA-2-033

4.4.8 Fluoride

Fluoride in groundwater is mainly derived from the weathering and leaching of rocks and is a commonly used environmental tracer (Kumar et al., 2017). Fluoride concentrations (Figure 29) are significantly higher in the Gilbert River Formation aquifer than the other aquifers in the Isa GBA region, with median and maximum concentrations of 3.1 mg/L and 6.2 mg/L, respectively. Within the watertable aquifer the median and maximum concentrations are 0.4 mg/L and 0.9 mg/L, respectively. The South Nicholson Basin and Isa Superbasin aquifers have average and maximum concentrations of 0.35 mg/L and 0.73 mg/L, respectively. These relatively low concentrations suggest that groundwater within the Proterozoic aquifers has interacted with rocks that contain minimal fluoride, in contrast to the Gilbert River Formation.

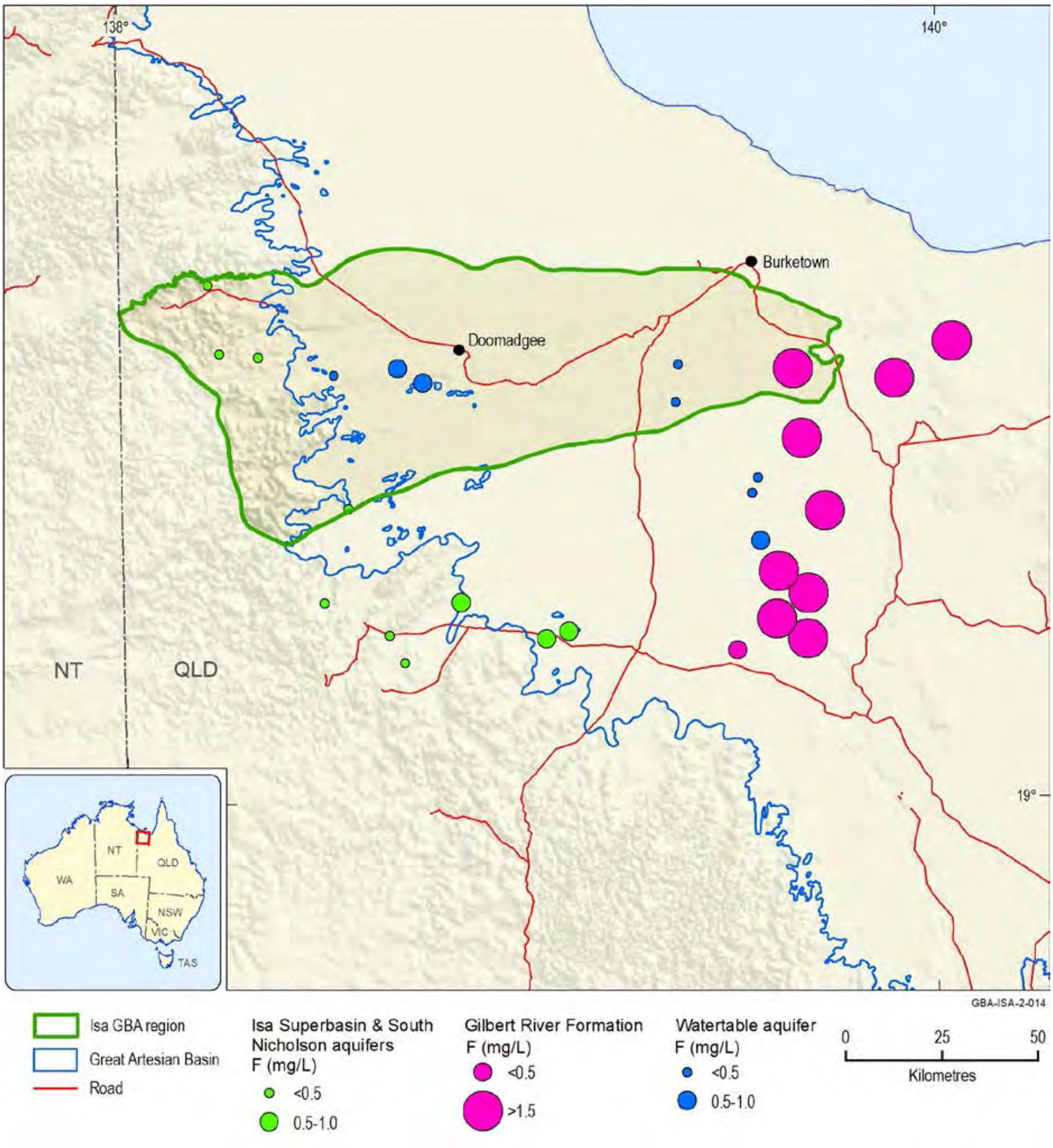


Figure 29 Fluoride concentrations in groundwater

Data: Bardwell and Grey (2016)
Element: GBA-ISA-2-014

4.4.9 Sulfate

Sulfate concentrations (Figure 30) are lowest in the Gilbert River Formation aquifer, with average, median and maximum concentrations of 38.4 mg/L, 36.4 mg/L and 75.6 mg/L, respectively. Within the watertable aquifer the average, median and maximum are 171.2 mg/L, 12 mg/L and 735 mg/L, respectively. The Proterozoic aquifers have average, median and maximum concentrations of 270.1 mg/L, 25.6 mg/L and 1500 mg/L, respectively.

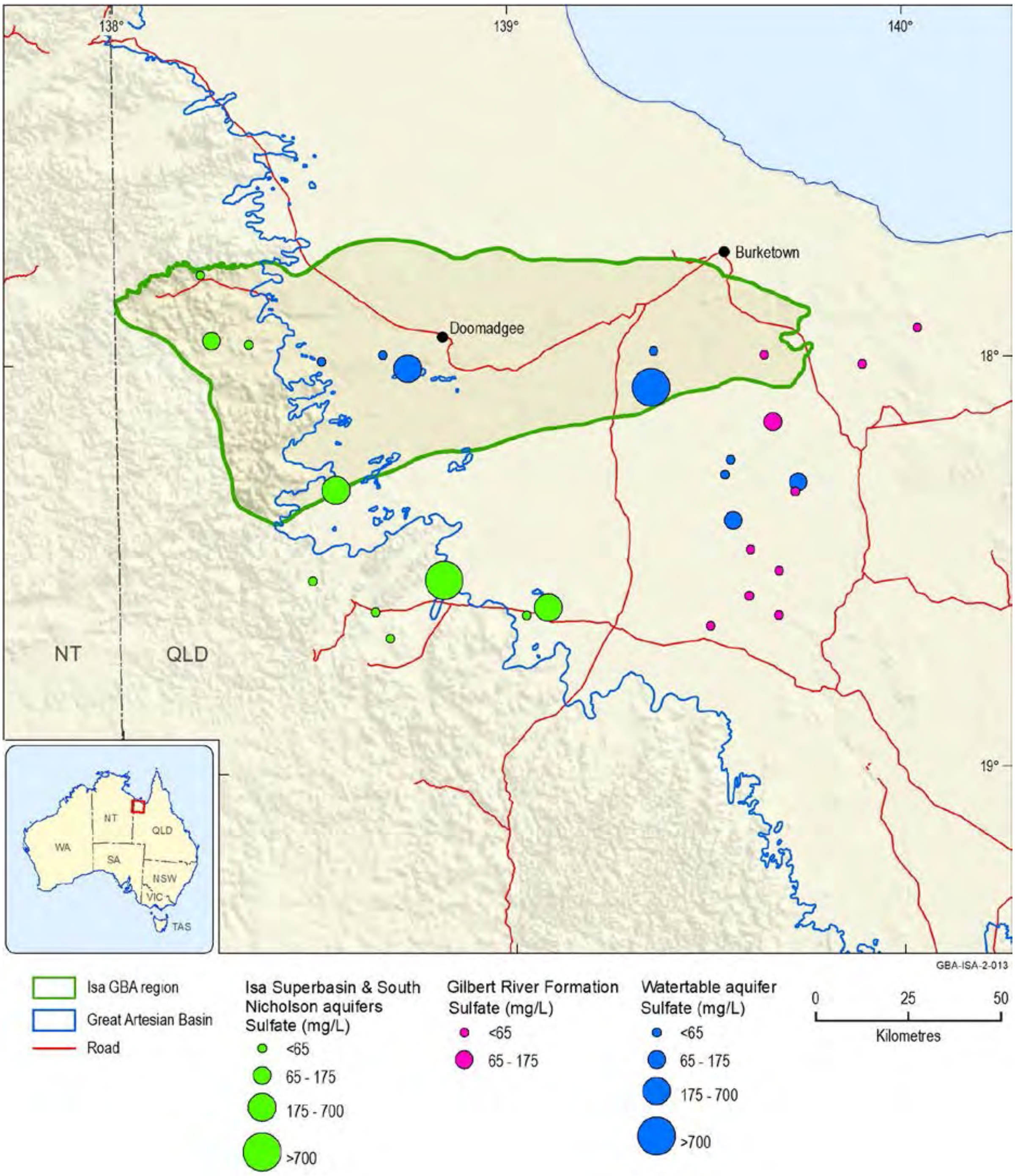


Figure 30 Sulfate concentrations in groundwater for various aquifer systems

Data: Bardwell and Grey (2016)
Element: GBA-ISA-2-013

4.5 Surface water – groundwater interactions

The Isa GBA region lies within a summer-dominant rainfall area. Streamflow is sustained in many streams during the dry season by groundwater input, either directly where streams incise an aquifer, or where groundwater discharges at spring vents adjacent to stream channels. Groundwater also supports a range of aquatic and terrestrial groundwater-dependent ecosystems (GDEs) associated with springs, instream waterholes, wetlands, lakes and vegetation communities in and around the region (refer to the protected matters technical appendix (MacFarlane et al. (2020)) for further details).

The interactions between groundwater and surface water are an important component of the hydrogeological system in the Isa GBA region. Existing datasets used to assess these interactions include streamflow, hydrogeological, hydrochemical, geological and remote sensing products. The results and interpretations of these analyses are reported in this section.

4.5.1 Streamflow dynamics

The Isa GBA region is located almost entirely within the Nicholson River drainage basin, which contains a number of operational and non-operational stream gauges (Figure 31). The network of stream gauges includes several hydrologic reference station (HRS) gauges with relatively long and high-quality streamflow records (Bureau of Meteorology, 2015). A summary of stream gauge characteristics for streams that intersect the region is in Table 11.

There are no currently operational stream gauges within the Isa GBA region and therefore analysis of stream gauge data is based on historical records. Depending on the available data, stream discharge, stream level or stage heights have been examined for several streams in the region (Nicholson River, Gregory River, Elizabeth Creek, Musselbrook Creek and Lawn Hill Creek) to assess perenniality and dependence on groundwater sources.

Mean stage heights and daily mean stream levels for the three gauges along the Nicholson River are shown in Figure 32 and Figure 33. There is a decrease in mean stream elevation of approximately 70 m from upstream (gauge 912107A) to downstream (gauge 912109A). The Nicholson River flows intermittently at the upstream gauge (44% of the time based on the historical record) and ceases to flow towards the end of the dry season. The Nicholson River also flows intermittently near Doomadgee (gauge 912116A), although permanent waterholes are observed (refer to Section 4.5.6). In contrast, there has been continuous flow downstream (gauge 912109A) throughout the available historical record. However, it is noted that weir construction on the Nicholson River at Doomadgee has significantly altered the flow regime such that the river can be dry or have isolated pools downstream of the weir. Although there is limited temporal stream gauge data, remote sensing analysis (Section 4.5.6) indicates that the Nicholson River is perennial downstream of its confluence with the Gregory River (Figure 31).

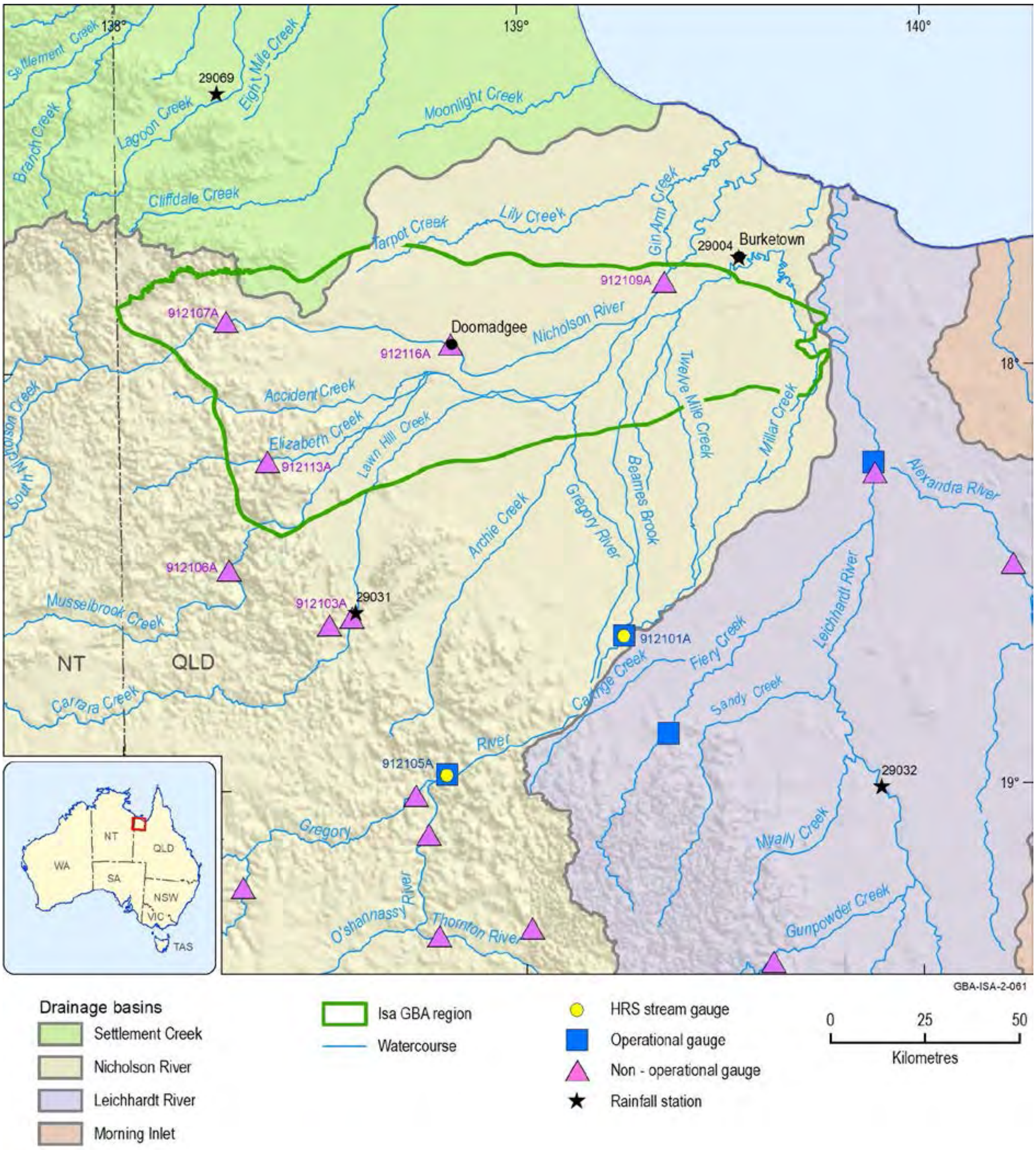


Figure 31 Surface water features and rainfall stations

Selected stream gauges and long-term rainfall stations assessed for this study are labelled.
Data: stream gauging network (Queensland Department of Natural Resources Mines and Energy, 2016); groundwater bores (Geoscience Australia, 2018f); rainfall stations (Geoscience Australia, 2018h); drainage basins (Geoscience Australia, 2018a)
Element: GBA-ISA-2-061

Based on available information, stream levels are intermittently very low or below detection along Elizabeth Creek and Musselbrook Creek. Both of these streams have their headwaters to the west of the Isa GBA region, but flow eastwards into the region before joining the Gregory River. Streamflow along Lawn Hill Creek was continuous prior to 1980 (1973 to 1980) and intermittent from 1980 to 1988; the reason for this change is unknown and would require further investigation. According to Carter and Opik (1961), the Gregory River has high dry-season flows where it enters the plains and diminishing surface flow downstream. Stream gauge data indicates that streamflow is continuous at both gauges along the Gregory River, south of the Isa GBA region, consistent with a perennial stream (Figure 34 and Figure 35). Remote sensing analysis confirms that the river is perennial in the lower reaches (downstream of gauge 912101A) but may be a losing stream due to downwards leakage to the groundwater system and/or very high rates of evapotranspiration (Section 4.5.2).

Table 11 Summary of stream gauge information for streams that intersect the Isa GBA region

Site no.	Site name	Date commenced	Date ceased	Zero gauge[1] (m)	Datum[2]	Surface elevation (mAHD)
912101A	Gregory River at Gregory Downs	11/12/1969	-	62.59	AHD	76
912105A	Gregory River at Riversleigh No.2	1/05/1968	-	112.77	AHD	135
912107A	Nicholson River at Connollys Hole	2/11/1968	23/10/1988	19.78	ASS	84
912109A	Nicholson River at 5 Mile Hut	20/01/1970	23/10/1988	87.65	ASS	13
912116A	Nicholson River at Doomadgee Mission	5/10/1973	31/01/1979		AHD	43
912103A	Lawn Hill Creek at Lawn Hill No 2	01/07/1919	25/10/1988	22.127	ASS	108
912106A	Musselbrook Creek at Stockyard Creek	08/11/1968	01/10/1988	10.753	ASS	112
912113A	Elizabeth Creek at Mining camp	02/06/1974	21/10/1988	20.742	ASS	112

[1, 2] The surveyed zero gauge height in metres relative to the Australian Height Datum (AHD) or Assumed Datum (ASS)

Sustained flow along stream reaches, including during the dry season, is consistent with baseflow contributions from groundwater sources. Groundwater discharges directly, where the streambed intercepts an aquifer, or indirectly, where groundwater discharges at spring vents adjacent to stream channels. Groundwater-fed stream reaches can also be tributaries of other streams. Based on analysis of the limited streamflow data alone it is difficult to reliably assess the extent of surface water – groundwater interactions in the region. However, groundwater is likely to contribute to streamflow, including to the lower Nicholson River, in at least the eastern part of the region via the Gregory River. The availability of continuous long-term streamflow data for the major streams would help to quantify volumetric baseflow contributions to surface waters at different times of the year.

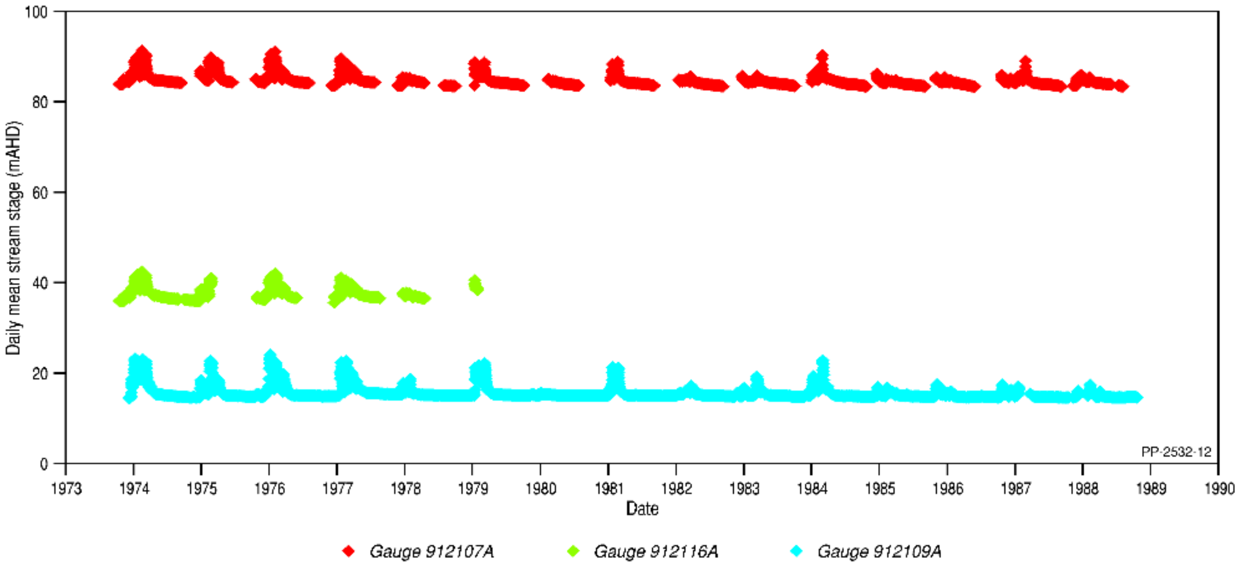


Figure 32 Daily mean stage height (metres above the zero gauge, mAHD) at stream gauges on the Nicholson River

The gauges are ordered from upstream (912107A) to downstream (912109A).
Data: stream stage (Department of Natural Resources, Mines and Energy (Qld), 2018a)
Element: GBA-ISA-2-149

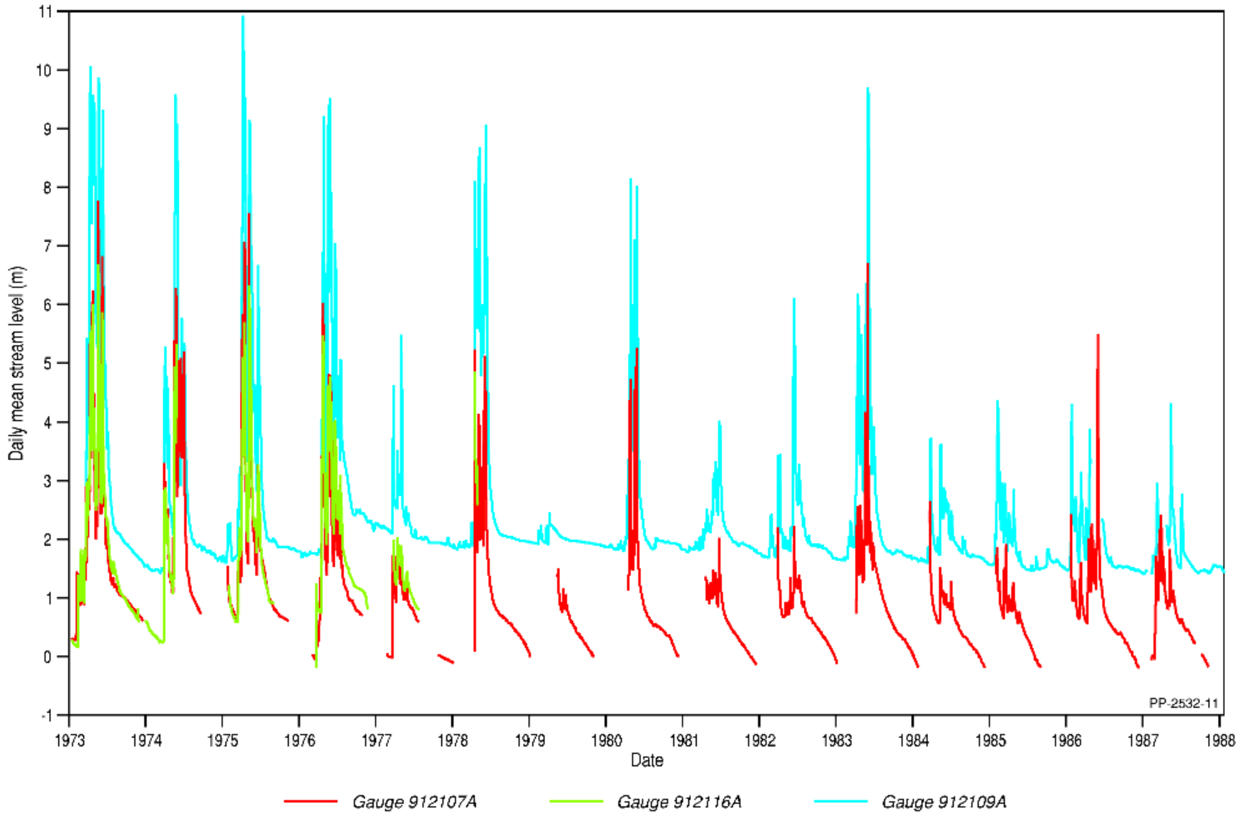


Figure 33 Daily mean stream level (m) at the stream gauges on the Nicholson River

The gauges are ordered from upstream (912107A) to downstream (912109A).
Data: stream level (Department of Natural Resources, Mines and Energy (Qld), 2018a)
Element: GBA-ISA-2-148

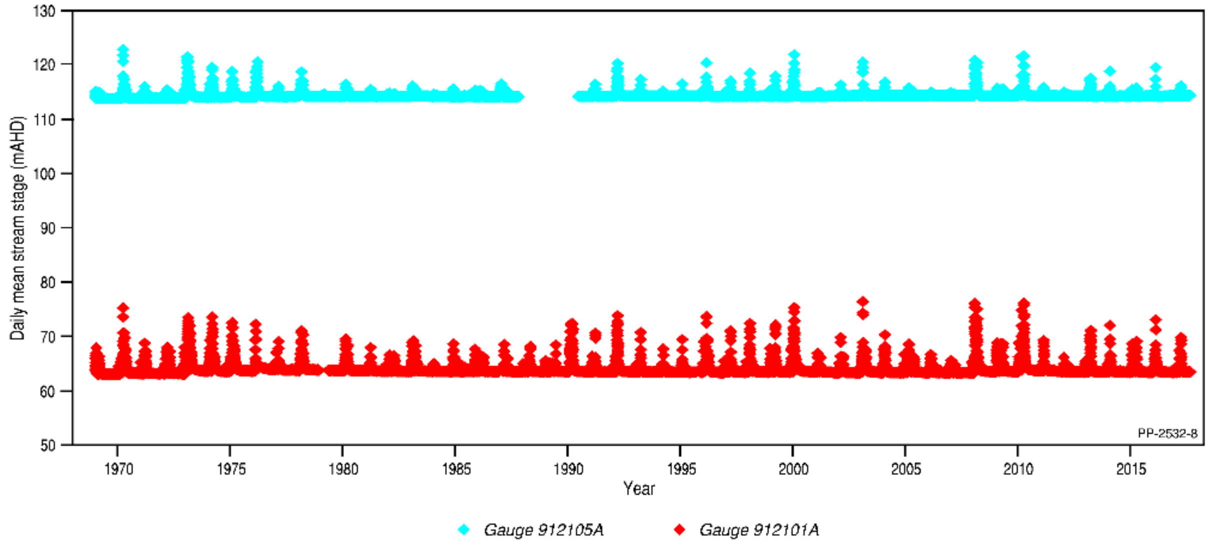


Figure 34 Daily mean stream stage at stream gauges on the Gregory River

Stream stage is in metres above the zero gauge. The gauges are ordered from upstream (912105A) to downstream (912101A).
Data: stream stage (Department of Natural Resources, Mines and Energy (Qld), 2018a)
Element: GBA-ISA-2-145

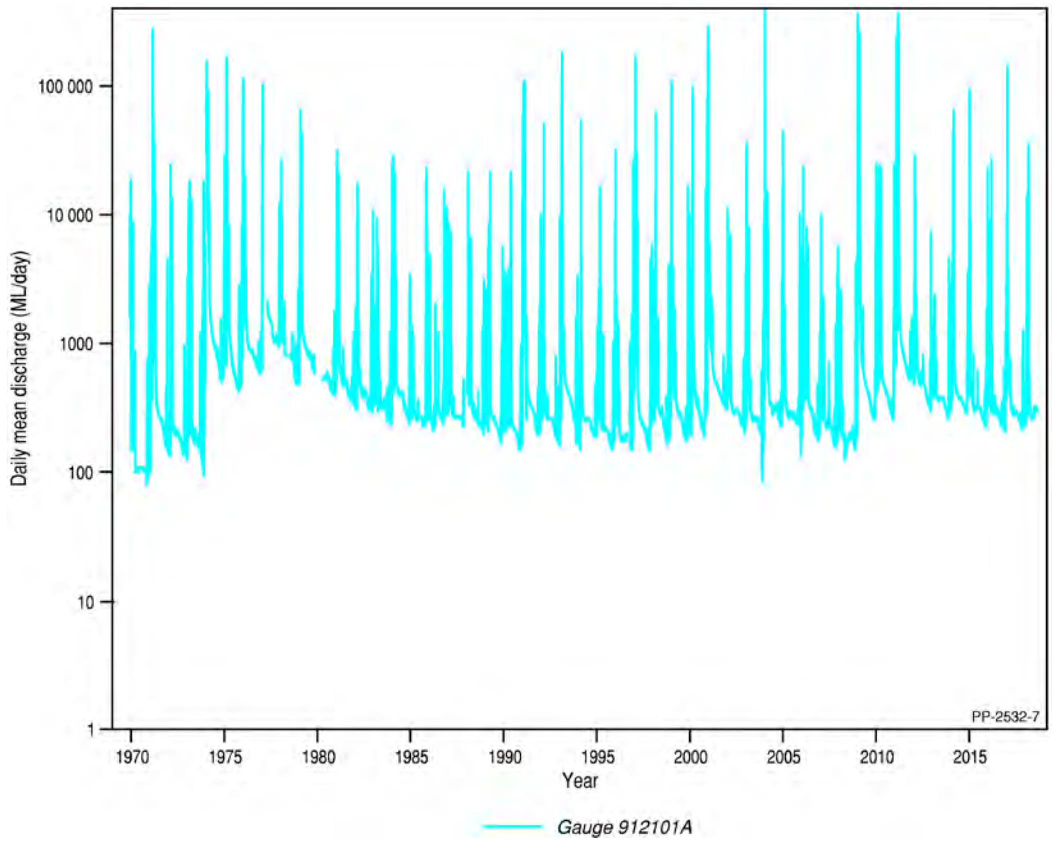


Figure 35 Daily mean stream discharge at the downstream gauge along the Gregory River

Stream discharge is shown in log units, indicating that flow is above zero throughout the record.
Data: stream discharge (Department of Natural Resources, Mines and Energy (Qld), 2018a)
Element: GBA-ISA-2-144

4.5.2 Stream – groundwater dynamics

Coupled stream and groundwater data were examined to assess the dynamics of surface water – groundwater interaction. Shown in Figure 36 are groundwater monitoring bores in and around the Isa GBA region located within 10 km of the stream gauges, or adjacent to gauged stream reaches, that have at least one groundwater level record.

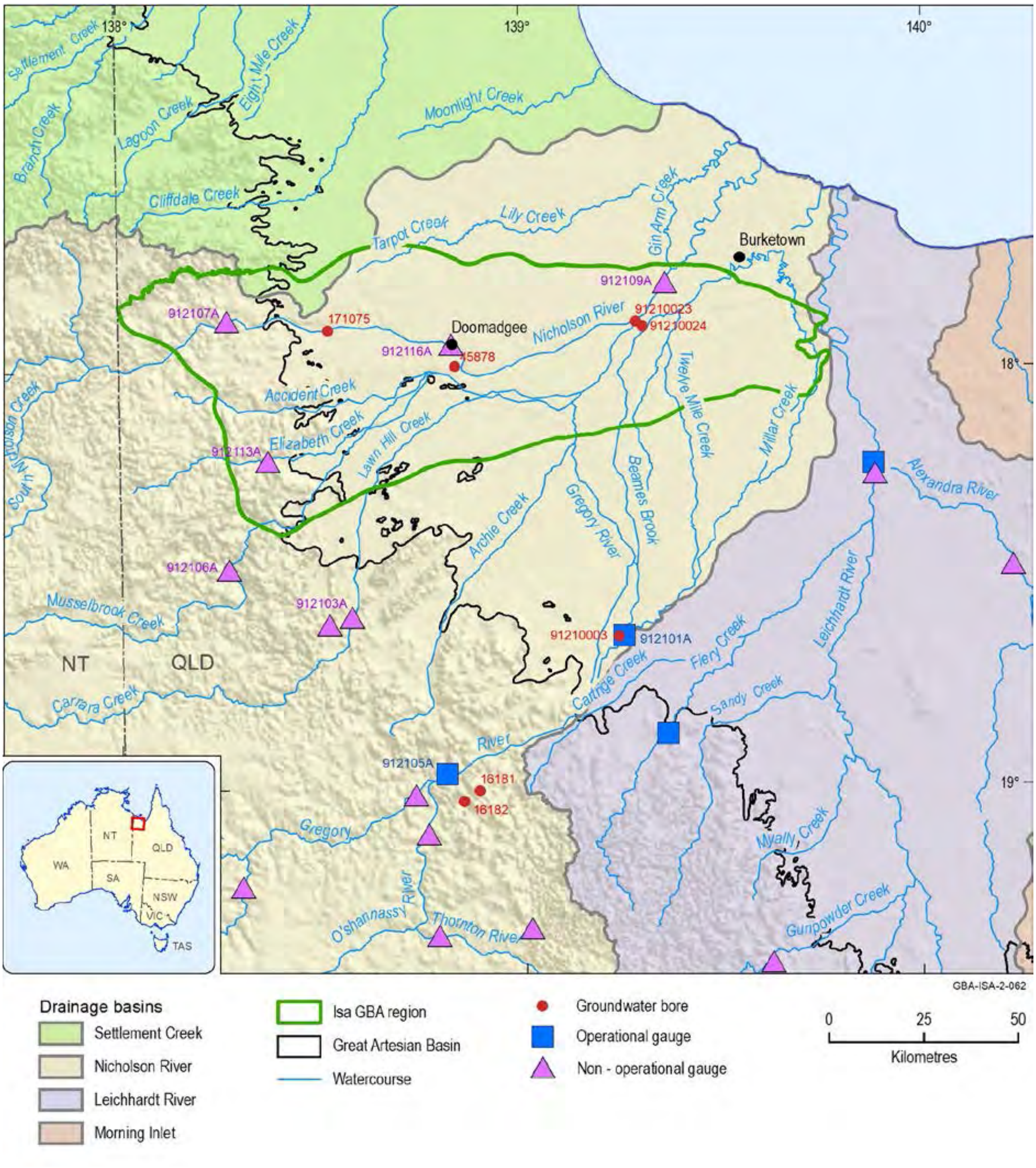


Figure 36 Major streams, stream gauges and nearby groundwater monitoring bores

Selected stream gauges and bores (with at least one water level record) that were assessed are labelled.
Data: stream gauging network (Department of Natural Resources, Mines and Energy (Qld), 2016); groundwater bores (Geoscience Australia, 2018f); drainage basins (Geoscience Australia, 2018h)
Element: GBA-ISA-2-062

Methods snapshot: comparing surface water and groundwater levels

Time series stream and groundwater level data were analysed by comparing stream stage heights with groundwater elevations, in metres relative to the Australian Height Datum (mAHD). The surveyed zero gauge height (mAHD) or, where absent, the surface elevation at the gauge (derived from the 1 arc second Australian digital elevation model from the Shuttle Rader Topographic Mission, or SRTM) (Gallant et al., 2011), was used to generate stream stage (mAHD) from stream level measurements (m). Similarly, bore elevations at the surface (mAHD) were derived from the SRTM data (Gallant et al., 2011) and used to generate groundwater level elevations (mAHD) from water level measurements below ground level (mbgl). Comparison of relative surface water and groundwater elevations at the same location provides an indication of the potential direction of surface water – groundwater interaction, i.e. gaining or losing streams, but has to be interpreted in the context of the local geology and hydrogeology, and incision depth of the river to determine the likelihood of connectivity.

Based on the available data, paired stream gauge and corresponding groundwater bore(s) (Figure 36) have been assessed:

1. Gauge 912116A (middle Nicholson River) and bores RN171075 and RN45878 (Figure 37):
   a. Bore RN171075 (located about 0.5 km from the Nicholson River and upstream of the stream gauge) has a groundwater elevation (51 mAHD) above the maximum stream stage (42 mAHD) based on a single groundwater level measurement during the dry season.
   b. Bore RN 45878 (located 1.5 km from the Nicholson River and 5 km downstream of the gauge) has a groundwater elevation (27.5 mAHD) below the minimum stream stage (35.5 mAHD) based on a single groundwater level measurement during the dry season.
   c. There are insufficient data to determine the potential direction of surface water – groundwater connectivity along this stream reach.
2. Gauge 912109A (lower Nicholson River) and bores RN91210023 and RN91210024 (Figure 38).
   a. Bore RN91210023 (adjacent to the Gregory River near the junction with Nicholson River) and bore RN91210024 (2 km from the Gregory River) are approximately 12 km upstream of the stream gauge and have groundwater elevations below the stream stage over the available period of data.
   b. If there is surface water – groundwater connection, there is potential for downwards leakage from the Nicholson River to groundwater upstream of the gauge i.e. losing stream condition.
3. Gauge 912105A (upper Gregory River) and bores RN16181 and RN16182 (Figure 39):

   a. Bores RN16181 and RN16182 (less than 8 km from Gregory River) have groundwater elevations (165 and 236 mAHD) above minimum stream stage (114 mAHD), based on a single groundwater level measurement at each bore during the dry season.
   b. There are insufficient data to determine the potential direction of surface water – groundwater connectivity.
4. Gauge 912101A (Gregory River) and bore RN91210003 (Figure 40):
   a. Bore RN91210003 (less than 0.5 km from the Gregory River) generally has a groundwater elevation more than 14 m below the stream stage over the available period of data. However, there are some measurements during dry-season months with higher groundwater elevations.
   b. If there is surface water – groundwater connectivity, the Gregory River upstream of the gauge is predominantly a losing system and has the potential to recharge groundwater. Further measurements in the wet season would be required to assess whether there is potential for groundwater to discharge to the stream during periods of high groundwater levels, i.e. variably gaining/losing stream.

Given the paucity of data and potential errors in the elevations of stream gauges and bore elevations, the analysis of coupled groundwater and streamflow data is not considered to be very reliable for assessing surface water – groundwater interactions in the region. More detailed lithological information at each bore (including screened intervals) and of the streambed at the gauge, together with longer and current groundwater and streamflow time series data, would also be required to better assess the direction and potential for surface water – groundwater interactions using this approach.

Recent modelling work suggests that a large proportion of total recharge to the Karumba Basin is expected to enter the surface water system as baseflow to rivers, springs discharge, overland flow or evapotranspiration losses (DSITIA, 2014).

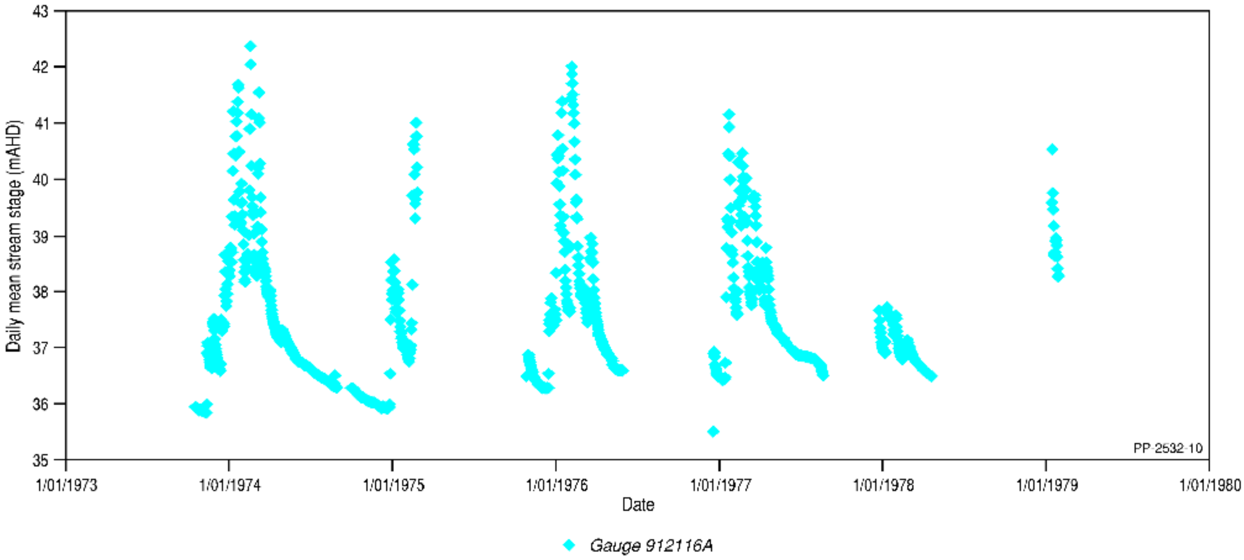


Figure 37 Time series stream stage (mAHD) at gauge 912116A along middle reaches of the Nicholson River

Refer to Figure 36 for stream gauge location.
Data: stream stage (Department of Natural Resources, Mines and Energy (Qld), 2018a)
Element: GBA-ISA-2-147

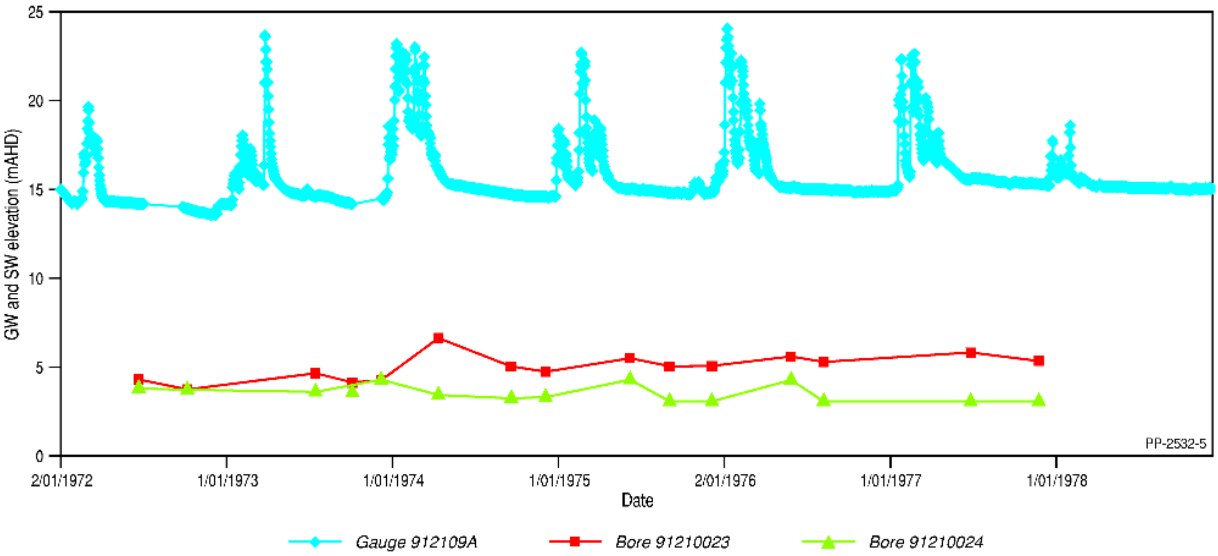


Figure 38 Comparison of groundwater and surface water elevations (mAHD) in the lower Gregory River

The groundwater bores are located approximately 12 km downstream of the stream gauge; bore 91210023 is located adjacent to the Gregory River and 91210024 is located approximately 2.5 km from the Nicholson/Gregory River junction (refer to Figure 36).
Data: stream stage (Department of Natural Resources, Mines and Energy (Qld), 2018a); groundwater elevation (Geoscience Australia, 2018f)
Element: GBA-ISA-2-142

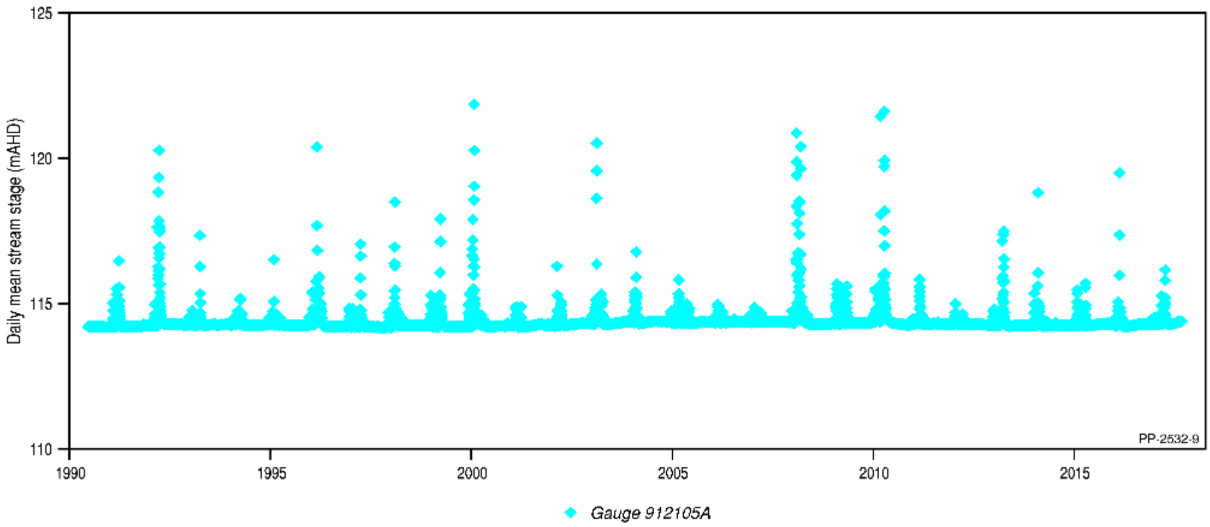


Figure 39 Time series stream stage (mAHD) at gauge 912105A along the upper Gregory River

Refer to Figure 36 for stream gauge location.
Data: stream stage (Department of Natural Resources, Mines and Energy (Qld), 2018a)
Element: GBA-ISA-2-146

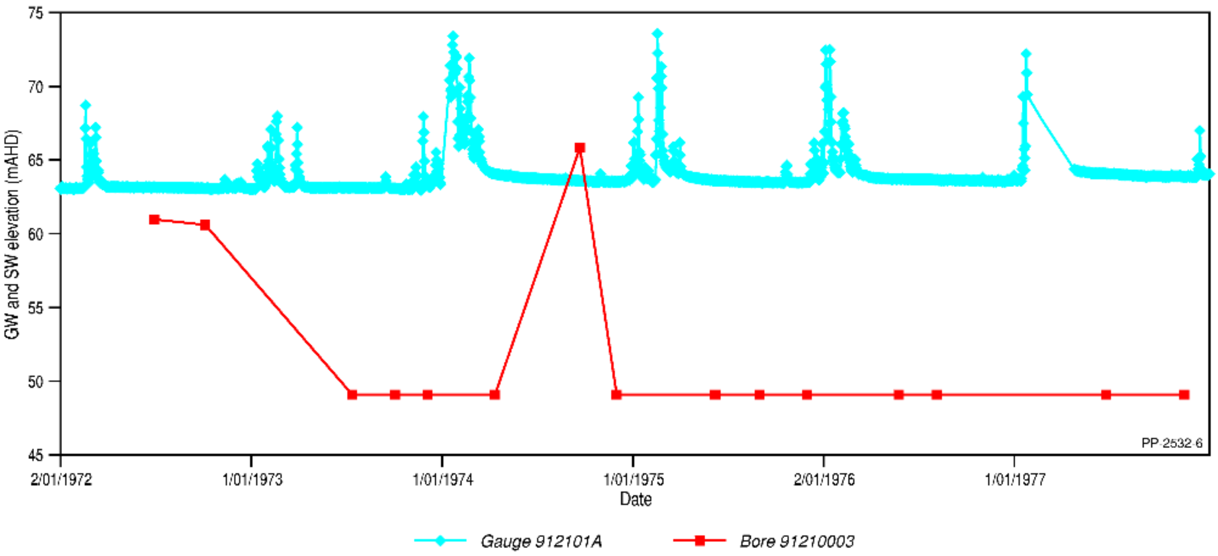


Figure 40 Comparison of groundwater and surface water elevations (mAHD) in the middle reaches of the Gregory River

The groundwater bore is located approximately 500 m from the Gregory River (refer to Figure 36).
Data: stream stage (Department of Natural Resources, Mines and Energy (Qld), 2018a); groundwater elevation (Geoscience Australia, 2018f)
Element: GBA-ISA-2-143

4.5.3 Geological indicators of surface water – groundwater connectivity

The surface geology in the Isa GBA region has been examined for this study as an indicator of source aquifers that may interact with surface waters. Most of the Isa GBA region is underlain by aquifers of the GAB, with groundwater systems hosted in the Mesozoic Carpentaria Basin and the overlying Cenozoic Karumba Basin. Throughout most of the region, the GAB overlies Proterozoic rocks of the Isa Superbasin and South Nicholson Basin

(Figure 10 and Figure 11), although Proterozoic units outcrop in the western part (Figure 1). The ground surface of the Isa GBA region consists mainly of Paleoproterozoic sandstones of the upper McNamara Group, the Mesoproterozoic Constance Sandstone (South Nicholson Group), the Cenozoic Armraynald beds, as well as sand plains, ferruginous duricrust and Quaternary colluvium and alluvium (Figure 41).

In the west, within the upland region outside of the GAB, the upper Nicholson River and other streams such as Elizabeth and Musselbrook creeks traverse the Constance Sandstone (South Nicholson Group), which is regarded as a partial aquifer (Figure 8). The occurrence of springs at the south-western margin of the region is also consistent with groundwater discharge in the area from underlying Proterozoic sedimentary rock aquifers (see also Section 4.5.5.2). However, based on available streamflow data and the ephemeral nature of the upper Nicholson River (Section 4.5.1), groundwater discharge from South Nicholson Group aquifers does not sustain flow in these streams throughout the year. The drivers of potential groundwater discharge from deeper units are not presently well understood due to lack of relevant data. However, one possible mechanism could be that groundwater discharge is driven by gas overpressure from the shale-rich sequences in the Isa Superbasin (further discussed in Section 5.7).

Within the alluvial floodplains of the region (i.e. the landscape class ‘floodplain and alluvium’ (MacFarlane et al., 2020)) streams are incised into sediments of the Karumba Basin (Grimes and Sweet, 1979). Despite their variable lithological characteristics, these sediments are generally considered to be partial aquifers (Figure 8). Overlying unconsolidated alluvial deposits also form widespread shallow aquifers (Section 4.1.3.1) and are associated with terrestrial GDEs in the centre of the region (Figure 43). According to Smerdon et al. (2012b) groundwater discharge as baseflow originates from the Cenozoic aquifers of the Karumba Basin. In addition, water level data indicates that there is the potential for groundwater recharge from streams (Section 4.5.2). 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. It is therefore plausible that the Karumba Basin sediments and alluvium have a direct hydraulic connection to streams, with the potential for both gaining and losing stream reaches in different parts of the region and at different times of the year, e.g. wet-season characteristics may differ from the dry season.

According to Grimes and Sweet (1979), there may be extensive shallow groundwater below the ferricrete zone on the Doomadgee Plain, which is thought to give rise to springs at the head of some stream channels. This shallow groundwater may also directly contribute flow to the Nicholson River west of Doomadgee, where ferricrete has been incised by the stream, although the contribution may not be sustained throughout the year (refer to gauge 912116A in Figure 32). Alternatively, upwards groundwater leakage through the Rolling Downs Group via structural conduits (Figure 45) may be a source of this underlying groundwater rather than a perched watertable. According to draft material prepared for the Southern Gulf of Carpentaria Aquatic Conservation Assessment (Department of Environment and Science (Qld), In press) there are permanent waterholes on the Nicholson

River, sourced from a combination of upstream spring-fed flows and seeps from adjoining sand units.

Based on the mapped surface geology, the perennial streams of Gregory River and Lawn Hill Creek likely receive baseflow from Cambrian dolomitic limestone, which outcrops extensively to the south of the Isa GBA region (unit El in Figure 41). This limestone aquifer is within the Georgina Basin and has not been assessed in this study. The Gregory River is the main contributor of flow to the lower Nicholson River in the Isa GBA region, downstream of the junction in the east of the region (Figure 41).

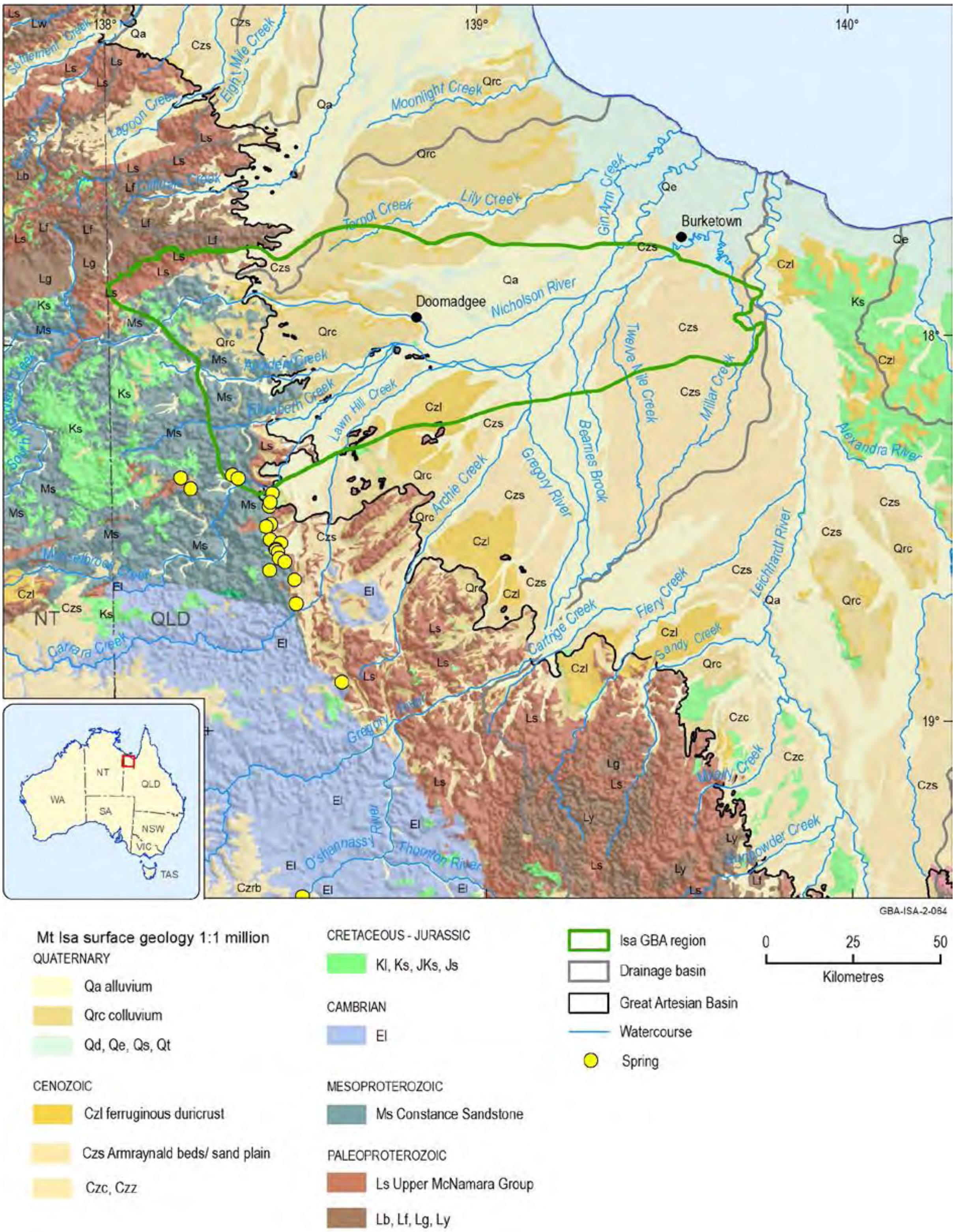


Figure 41 Simplified surface geology in and around the Isa GBA region

To simplify presentation, only the main geological units in the Isa GBA region are labelled.
Data: surface geology (Geoscience Australia, 2012); springs (Department of Environment and Science (Qld), 2018)
Element: GBA-ISA-2-064

4.5.4 Surface water hydrochemistry

Based on the HCA described in Section 4.4.1, surface waters in and around the Isa GBA region are generally fresh, with two sample clusters recognised; Cluster 2 has median salinity (EC) of 555 µS/cm, whereas Cluster 4 has median EC of 78 µS/cm. Cluster 2 surface waters from Lawn Hill Creek, Gregory River and the lower Nicholson River overlap hydrochemically with groundwaters from alluvium, Normanton Formation (Rolling Downs Group) and Lawn Hill Formation (upper McNamara Group) (Figure 21 and Figure 22). These surface water samples are located within areas of surficial alluvium and sand plains.

Cluster 4 surface waters are associated with the upper Nicholson River and Musselbrook Creek and overlap hydrochemically with groundwater from the Proterozoic Doomadgee Formation (Lawn Hill Formation equivalent) (Figure 21 and Figure 22). The surface geology at these sample locations is the Constance Sandstone (South Nicholson Group), noting that no groundwater samples were available to characterise hydrochemistry of the South Nicholson Group. The observations based on available stream and groundwater hydrochemistry are consistent with the variation in regional surface geology (Section 4.5.3) and indicate that there is little to no groundwater contribution to streams from the hydrochemically distinct Gilbert River Formation aquifer at these locations (Figure 22).

4.5.5 Environmental assets

Many environmental assets are recognised in the Isa GBA region (Table 12, Figure 42 and see MacFarlane et al. (2020)). Although there are no Ramsar-listed wetlands (Department of the Environment and Energy, 2016b), nationally important wetlands (Department of the Environment and Energy, 2010) within the region include Bluebush Swamp and the Aggregations of Musselbrook Creek, Nicholson Delta and Southern Gulf. Part of the Lawn Hill (Widdallion) and Lawn Hill (Arthur Creek) protected areas (Department of the Environment and Energy, 2016a) also fall within the region's south-western boundary and are linked with the springs shown in Figure 43. Strategic environmental areas, including the Gulf Rivers strategic environmental area designated precinct, also occur in the region, as well as a number of riverine waterbodies (instream waterholes) with important cultural and biodiversity values (Department of Environment and Science (Qld), In press). Both aquatic and terrestrial GDEs (Bureau of Meteorology, 2017) are identified in the region (Section 4.5.5.1), including springs (Section 4.5.5.2).

Table 12 Key environmental assets in the Isa GBA region

Environmental assets		
Ramsar wetlands	None	
Nationally important wetlands (area km²)	Musselbrook Creek Aggregation	389
	Nicholson Delta Aggregation	168
	Southern Gulf Aggregation	46
	Bluebush Swamp	9
	Total area	**612**
Protected areas (area km²)	Lawn Hill (Widdallion) Resources Reserve	51
	Lawn Hill (Arthur Creek) Resources Reserve	6
	Total area	**57**
Strategic environmental area designated precinct (area km²)	Gulf Rivers strategic environmental area **Total area**	**1480**
Aquatic and terrestrial GDEs of known, high and moderate potential (area km²)	**Total area**	**2892**

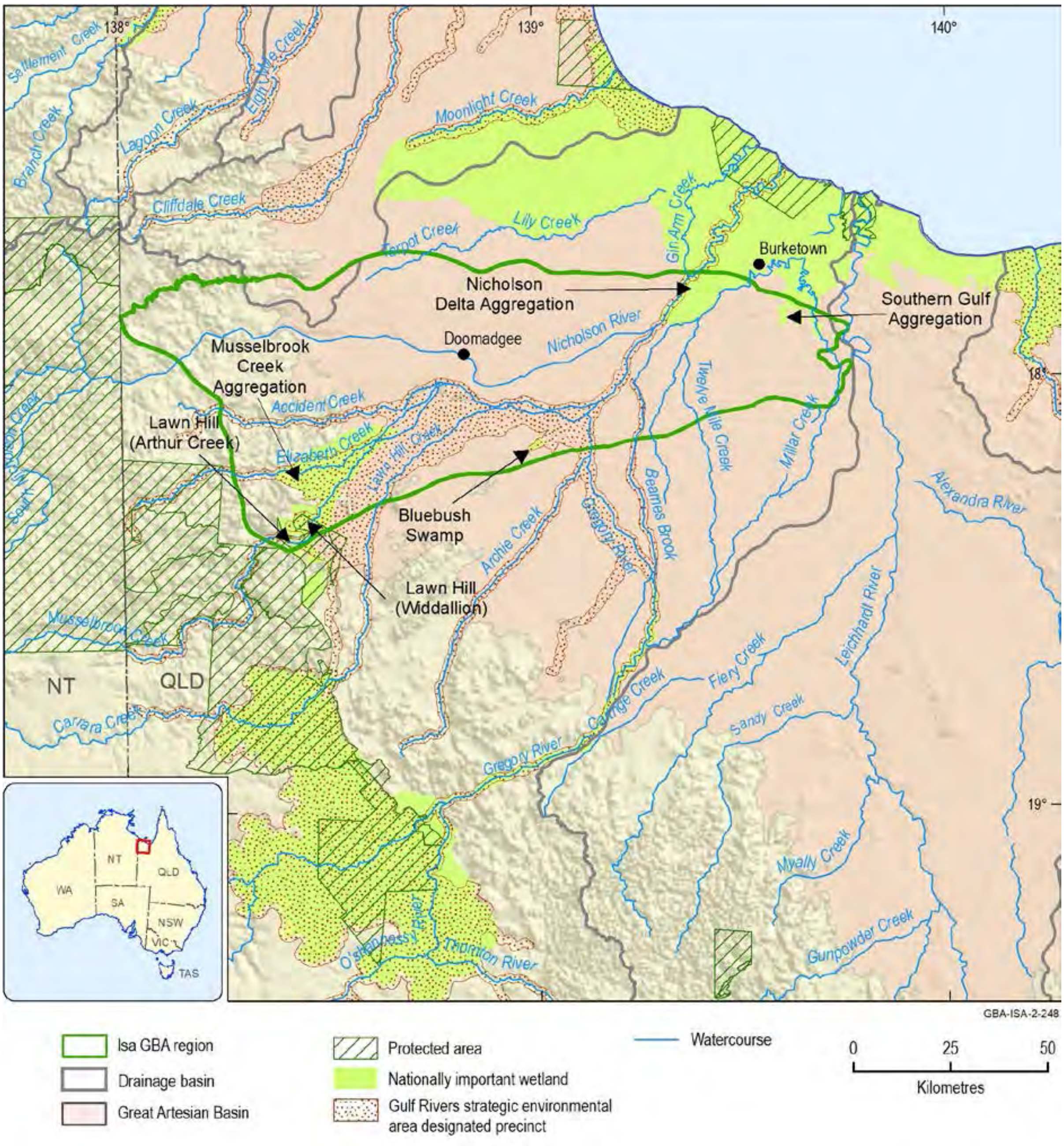


Figure 42 Nationally important wetlands and protected areas in the Isa GBA region

Data: wetlands (Department of the Environment and Energy, 2010); protected areas (Department of the Environment and Energy, 2016a)
Element: GBA-ISA-2-248

4.5.5.1 Groundwater-dependent ecosystems

GDEs rely on access to groundwater on a permanent or intermittent basis for some or all of their water requirements (Queensland Government, 2018). Consequently, GDEs may be vulnerable to changes in the hydrological cycle, such as those caused by excessive groundwater extraction or groundwater contamination. There are numerous conceptual models for GDEs (relevant to the Isa GBA region) based on their hydrological and landscape setting (Queensland Government, 2018), and the GDE Atlas (Bureau of Meteorology, 2017) provides a national GDE dataset based on a range of different sources.

In the GDE Atlas (Bureau of Meteorology, 2017), the degree of confidence in the mapped location, extent and type of GDE varies from low to high, reflecting the use of various national or regional datasets. GDEs are classified according to their likely potential to rely on groundwater. For the purposes of this assessment, aquatic, terrestrial and subterranean GDEs with known, high and moderate potential have been mapped (Figure 43). Terrestrial GDEs are the dominant type in areas associated with the floodplains of major watercourses (extent of alluvium in Figure 41). These GDEs occur particularly to the east of Doomadgee where they are associated with the Nicholson and Gregory rivers, and around Elizabeth and Musselbrook creeks in the south-west of the region (Figure 43). Aquatic GDEs are associated with some streams and other waterbodies. A subset of aquatic GDEs associated with permanently flowing streams is identified in the GDE Atlas along Lawn Hill Creek and Gregory River. Parts of the identified GDE areas correspond with nationally important wetlands and protected areas (Figure 42). A schematic diagram summarising the key relationships between GDEs and surface water – groundwater interactions in alluvial systems, such as those of the Isa GBA region, is shown in Figure 44. This diagram shows that GDEs may be associated with areas of alluvial sediments (terrestrial GDEs), within stream channels (surface expression GDEs) and within alluvial aquifers (subterranean GDEs). The movement of water from the surface to the subsurface, and the mixing of groundwater and surface water, support the various types of GDEs. The availability of these water sources for different GDE types also varies between wetter and drier periods, as depicted in Figure 44. Refer to the protected matters technical appendix (MacFarlane et al., 2020) for further information about this GDE conceptual model.

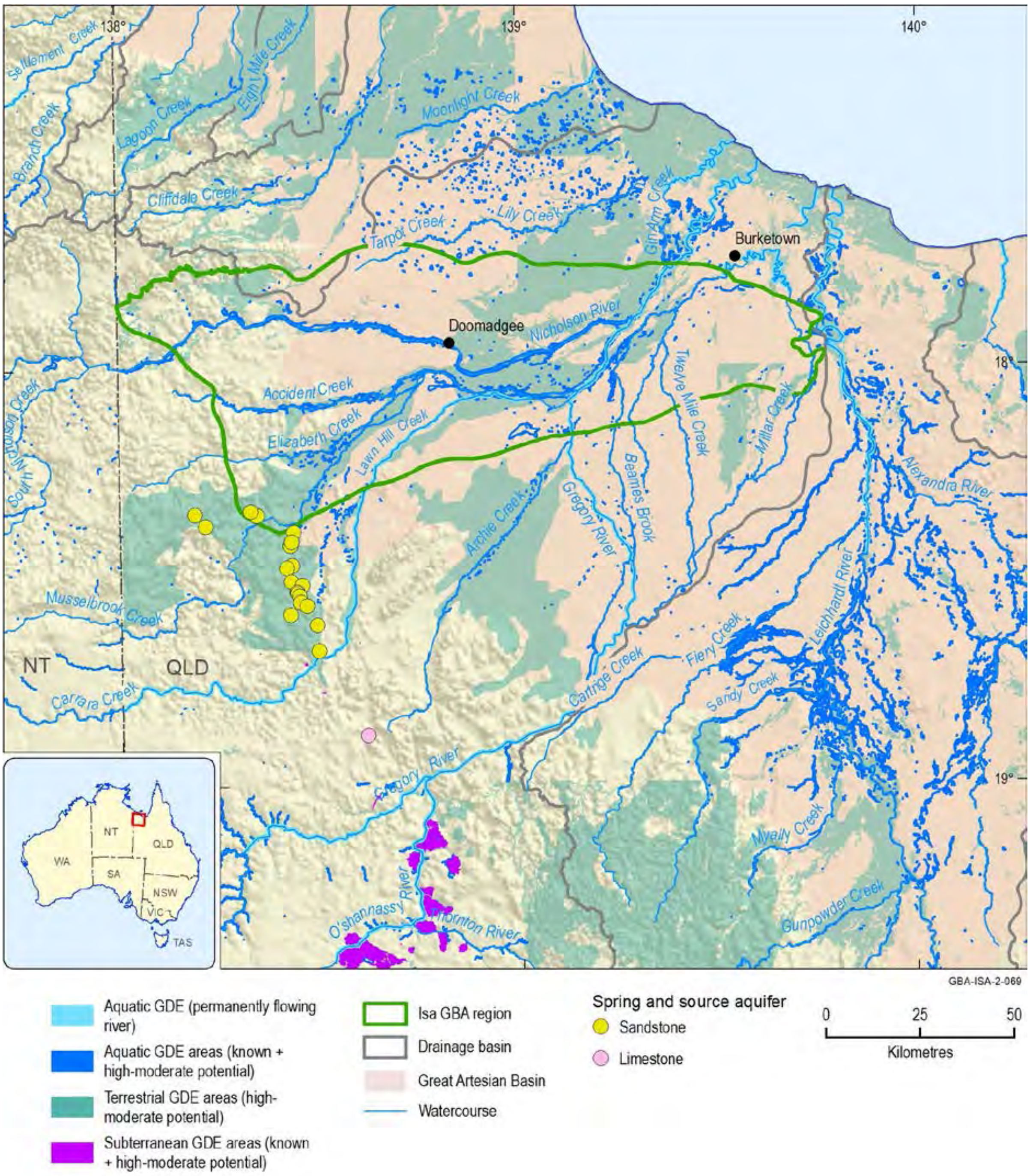


Figure 43 Potential for groundwater-dependent ecosystems in and around the Isa GBA region

Aquatic GDEs associated with permanently flowing streams and mapped springs with identified source aquifers are also shown.

Data: Groundwater Dependent Ecosystems Atlas (Bureau of Meteorology, 2017); springs (Department of Environment and Science (Qld), 2018)

Element: GBA-ISA-2-069

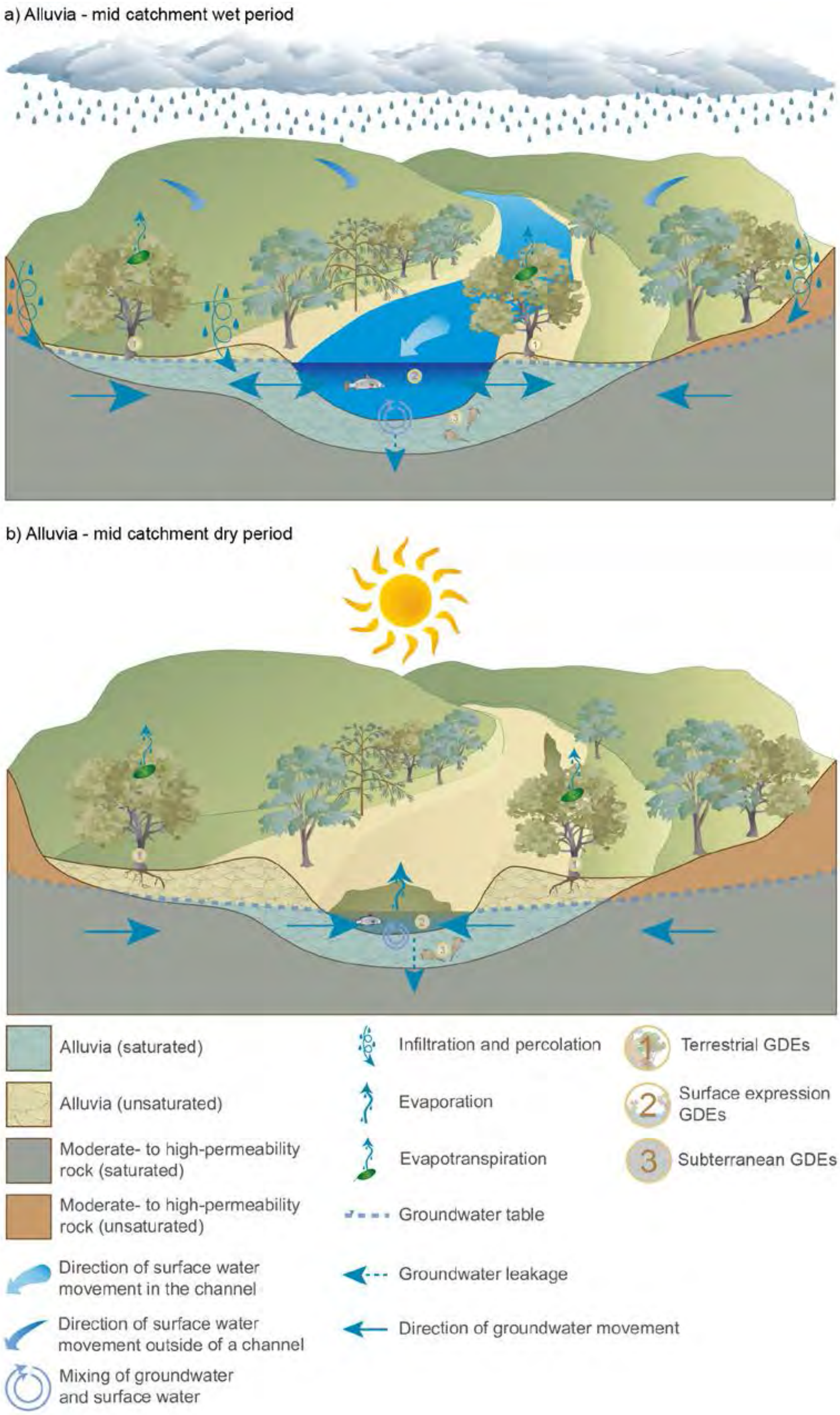


Figure 44 Relationship between groundwater-dependent ecosystems (GDEs) and surface water – groundwater interactions in an alluvial system

Source: adapted from the 'alluvia mid-catchment' conceptual model of Queensland Government (2013) and (Queensland Government, 2017b)
Element: GBA-ISA-2-259

4.5.5.2 Springs

In addition to the network of streams, the Isa GBA region contains numerous natural surface water features including wetlands, lakes, swamps, waterholes and springs. Many ecosystems depend on groundwater from springs in the GAB and range in size from small vents to large mounds (Freeze and Cherry, 1979; Smerdon et al., 2012c). 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.

No GAB springs are identified in the Isa GBA region, with the nearest GAB-fed springs over 200 km away to the south-east. However, there are two non-GAB recharge springs which have been mapped in the Isa GBA region, and related spring clusters occur to the south and south-west of these (just outside the boundary of the Isa GBA region (Figure 41)). All but one of these springs coincide with the area of identified terrestrial GDEs centred on the floodplain of Musselbrook Creek (Figure 43). Although only two springs are located within the region, activities associated with the development of shale gas resources may have the potential to impact on surrounding environmental assets. Therefore, all springs within and surrounding the region have been assessed for this study.

According to the Queensland springs database (Department of Environment and Science (Qld), 2018), all of the 22 springs clustered in or near the south-west of the Isa GBA region are permanently saturated and hydrologically active. The source aquifer for most of these springs is assigned (in the database) to the Lawn Hill Formation (upper McNamara Group), with only the southernmost spring interpreted to be sourced from a Proterozoic limestone aquifer. However, based on the available surface geology mapping (Geoscience Australia, 2012), the springs within the Isa GBA region occur within an outcropping area of the Constance Sandstone (South Nicholson Group), which is interpreted to be a partial aquifer (Figure 8). Other springs to the south and south-west of the region are also associated with the South Nicholson Group (Constance Sandstone or Mullera Formation) as well as the upper McNamara Group (Paleoproterozoic sandstone in Figure 41). Note that the hydrochemical signature of streams crossing the Constance Sandstone resembles that of the Doomadgee Formation (Lawn Hill Formation equivalent) (Section 4.5.4) and therefore a groundwater source for the springs from Proterozoic units within the Isa Superbasin cannot be discounted (at least on the basis of current evidence).

Many of the springs to the south of the Isa GBA region are aligned along a geological contact between the South Nicholson and upper McNamara Groups (see Figure 41). The location of these springs also corresponds with a marked change in elevation of approximately 100 m from west to east, consistent with groundwater discharge at a break in slope (Figure 45). The linear alignment of the springs could be related to the Termite Range Fault situated to the south which has a similar orientation, although the fault has not been explicitly mapped in the vicinity of the springs. Other surface faults and regional structural features occur near the springs, for example, the Brinawa Fault System and Punjaub Ridge (Figure 45). Depending on their depth and the underlying geology, geological structures may influence the occurrence of the springs and the potential aquifer sources. Importantly, the geological structures may provide natural connectivity pathways between surface water features and Proterozoic aquifers, which are potentially in contact with deeper shale gas reservoirs (see Section 5 for further discussion on potential connectivity pathways in the region).

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. Based on the Queensland springs database (Department of Environment and Science (Qld), 2018), only basic field survey parameters such as the pH and temperature of water have been measured for the identified springs, and these are insufficient data to confidently assign source aquifers. There is also uncertainty in the potential source aquifers for the springs based on the surface geology. The collection of hydrochemical data such as environmental tracers would assist in determining the source waters of the springs. Furthermore, there are likely to be additional springs in the area that have not been mapped but can be identified through analysis of remote sensing data (Section 4.5.6).

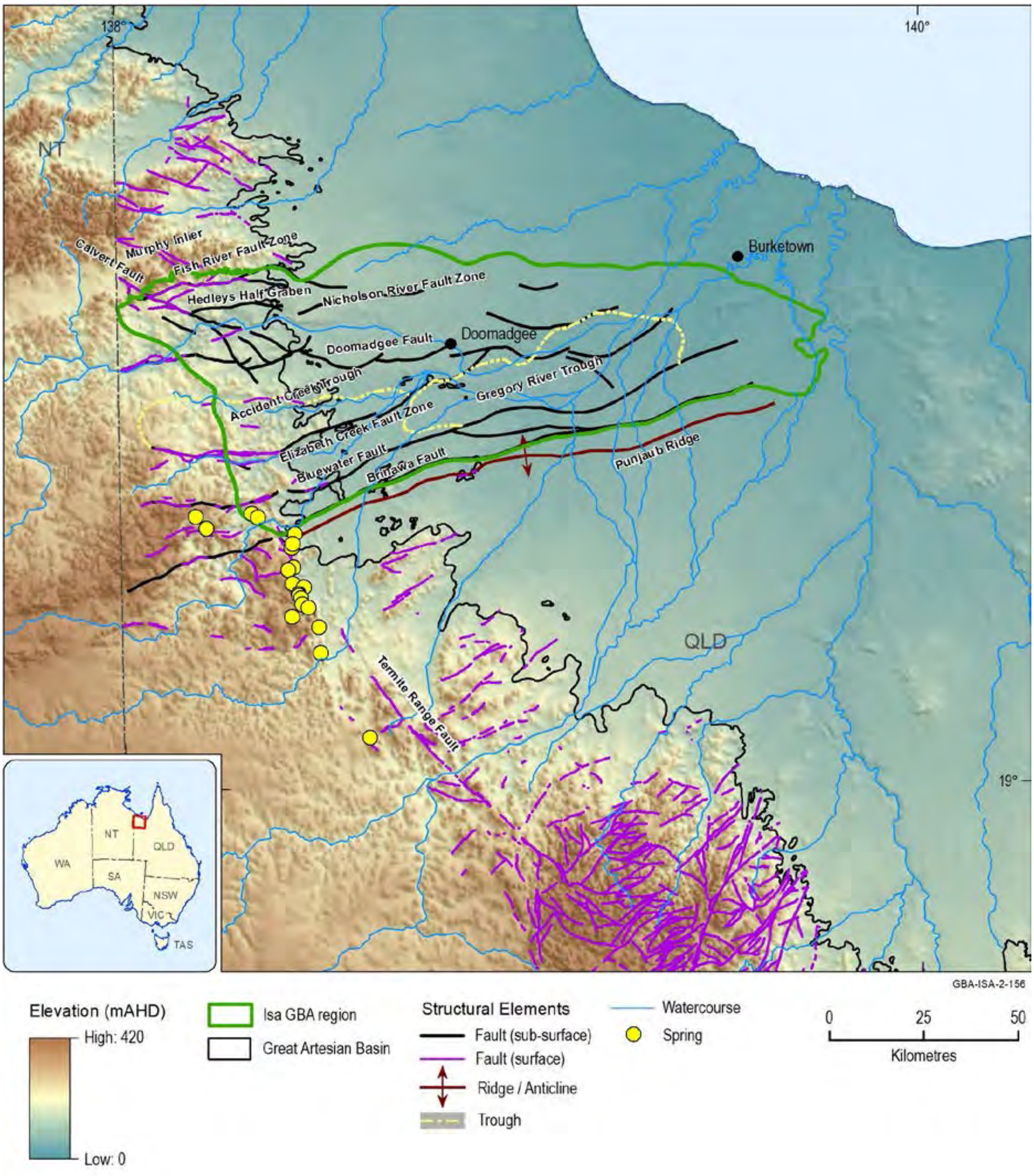


Figure 45 Relationship between mapped springs, elevation (DEM) and major geological structures within and near the Isa GBA region

Data: structural elements (Geoscience Australia, 2013); surface faults (Geological Survey of Queensland, 2011); springs (Department of Environment and Science (Qld), 2018)
Element: GBA-ISA-2-156

4.5.5.3 Coastal and marine ecosystems

As discussed in Section 4.3.2.3, the regional watertable aquifer, associated with the Karumba Basin sediments, has a zero mAHD contour up to 30 km inland from the coast. The direction of groundwater flow within the watertable is towards the coast, providing a potential source of shallow groundwater to support coastal and estuarine ecosystems, such as wetlands and mangroves. Groundwater discharge from the watertable aquifer into the Gulf of Carpentaria is also likely to 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.

4.5.6 Remote sensing analysis

To complement the information available from the GDE Atlas (Bureau of Meteorology, 2017), a number of new remote sensing products (e.g. from satellite-based sensors) allow a consistent approach to identify and map potential GDEs (discussed in Section 4.5.5.1). Remotely sensed data from Digital Earth Australia (DEA) (Geoscience Australia, 2018e) were used to map potential GDEs and hence enhance understanding of surface water – groundwater interactions in the Isa GBA region. Based on available Landsat imagery during the period 1987 to 2018, two remote sensing products (Water Observations from Space (WOfS) summary statistics and Tasselled Cap Index (TCI) wetness exceedance composite) were used to investigate the persistence of surface water and/or wetness in the landscape and hence identify perennial streams and other parts of the landscape that may rely on groundwater.

DEA is an organised, processed and maintained collection of Earth observation data along with the structures and tools necessary to enable analysis through a high-performance computing environment (Lewis et al., 2017). The DEA datasets used to produce the summary products in this study were surface reflectance (the way the Earth's surface reflects sunlight), pixel quality (per-pixel cloud masking) and rainfall grids from the Bureau of Meteorology (Jones et al., 2009).

4.5.6.1 Rainfall

The analysis of spatial variability in rainfall helps inform the selection of appropriate time periods for analysis of Earth observation data. Rainfall stations were selected with the longest and most continuous rainfall records available, including the period of available Landsat 8 satellite data (since 2013) and covering a broad area surrounding the Isa GBA region (Figure 31 and Table 13).

Analysis of monthly rainfall data indicates a seasonal rainfall pattern in this region, with the highest and lowest rainfall periods being October/November to April and May to September/October, respectively (Figure 46). The dry season, when surface runoff to streams is minimal, is particularly useful for identifying and mapping groundwater-fed streams, springs and other GDEs.

Table 13 Long-term rainfall stations near the Isa GBA region

Site[1]	Name	Latitude	Longitude	Start
29004	Burketown Post Office	-17.743	139.548	May 1887
29013	Donors Hill Station	-18.714	140.547	Jun 1889
29031	Lawn Hill	-18.581	138.581	Feb 1889
29032	Lorraine	-19.007	139.896	Jan 1909
29063	Normanton Airport	-17.687	141.073	Apr 2001
29069	Westmoreland Station	-17.338	138.251	Jan 1965

[1] Refer to Figure 31 for locations of rainfall stations

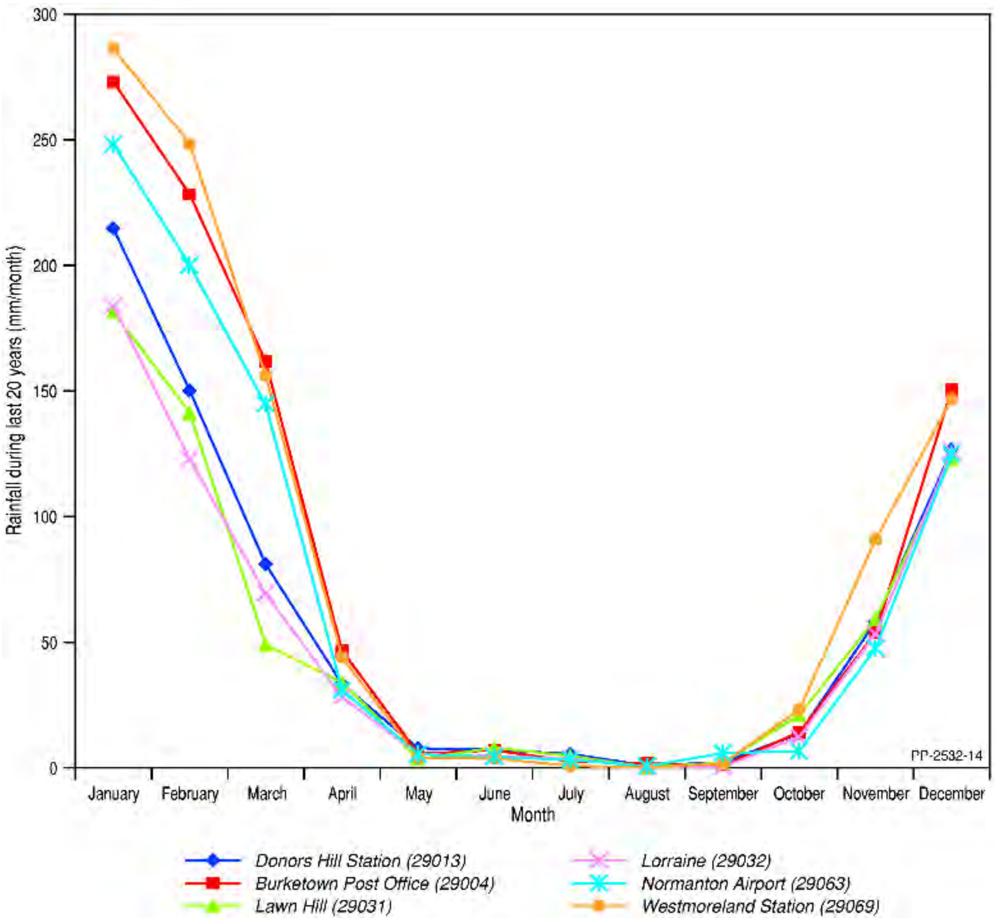


Figure 46 Monthly rainfall in and near the Isa GBA region based on rainfall records from 1998 to 2018

Data: rainfall data (Geoscience Australia, 2018a)
Element: GBA-ISA-2-151

Historical periods of increased or decreased rainfall over time can be observed by comparing the cumulative deviation of monthly rainfall from the long-term mean (rainfall residual mass curve) (Figure 47). Remote sensing imagery associated with declining phases in residual rainfall, particularly within the dry-season months, provides an ideal opportunity for investigating surface water – groundwater interactions because it is assumed that groundwater will be the primary water source at these times. The dry season of 2015 (May to October) was selected for analysis of Earth observation data due to the availability of

Landsat 8 satellite data (post 2013), low rainfall totals in the months preceding this dry season and the overall below-average rainfall conditions (decline in rainfall residual mass; Figure 47).

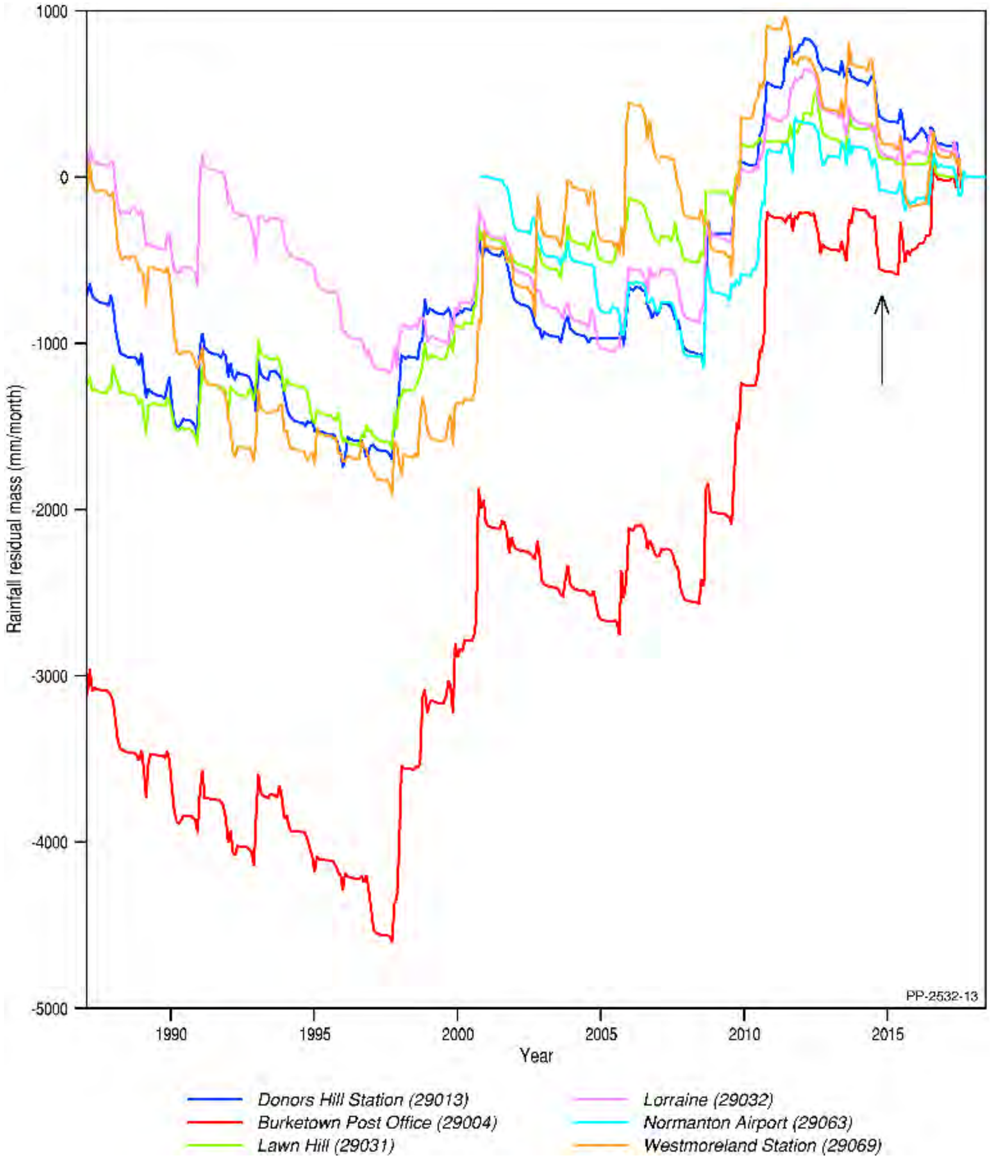


Figure 47 Combined rainfall residual mass curves for rainfall stations surrounding the Isa GBA region

The period since the availability of Landsat satellite data (1987 to present) is shown. The selected dry season in 2015 is also highlighted with the arrow.
Data: rainfall data (Geoscience Australia, 2018a)
Element: GBA-ISA-2-150

4.5.6.2 Water Observations from Space

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-m by 25-m pixel size of Landsat data, only features at least 25 m wide are detected. The WOfS summary statistic was produced over the Isa GBA region for the entire period of available data (1987 to 2018). Areas with the highest frequency of observed open water based on the historical record (i.e. observed water/clear observations) are shown in blue. In contrast, red areas represent the lowest frequency of observed water at the surface.

Pixels have been polygonised and classified in order to visually enhance key data in the imagery. The WOfS polygons shown in maps in this section are exaggerated in size and represent the location of observed surface water rather than their actual size.

The WOfS summary products were used to investigate the occurrence and perenniality of surface water features, and the potential extent of flooding and floodplain areas associated with the main stream network.

4.5.6.3 Perenniality of surface water features

The WOfS summary shows that most of the Isa GBA region has a low frequency (red) of open water over time (Figure 48). However, close examination of the data highlights small areas with a high frequency (blue) of open water along particular river reaches and off-channel sections (Figure 49). Within the region, the WOfS analysis confirms that the lower reaches of the Nicholson River (refer to Section 4.5.1) and Albert River are perennial. Surface water is maintained in these lower reaches more than 95% of the time based on the available 1987 to 2018 Landsat imagery (Figure 50). The WOfS analysis also indicates that permanent pools may be present along the upper and middle reaches of the Nicholson River, Elizabeth Creek and Musselbrook Creek, which cannot be identified using stream gauge data. Further supporting this evidence, draft material prepared for the Southern Gulf of Carpentaria Aquatic Conservation Assessment (Department of Environment and Science (Qld), In press) indicates that there are permanent waterholes on the Nicholson River, as well as the main channel of the Gregory River above the confluence of the Nicholson and Gregory rivers (see also Section 4.5.7.2).

In addition to discriminating perennial streams/pools along stream channels, the WOfS product highlights other persistent surface water features not associated with major streams, such as reservoirs, lakes and springs. These are shown in Figure 50 as points in between the major streams, and include both natural and artificial features in the landscape. For instance, a number of off-channel sites within the region, identified as perennial, are pastoral dams (e.g. inset boxes in Figure 50).

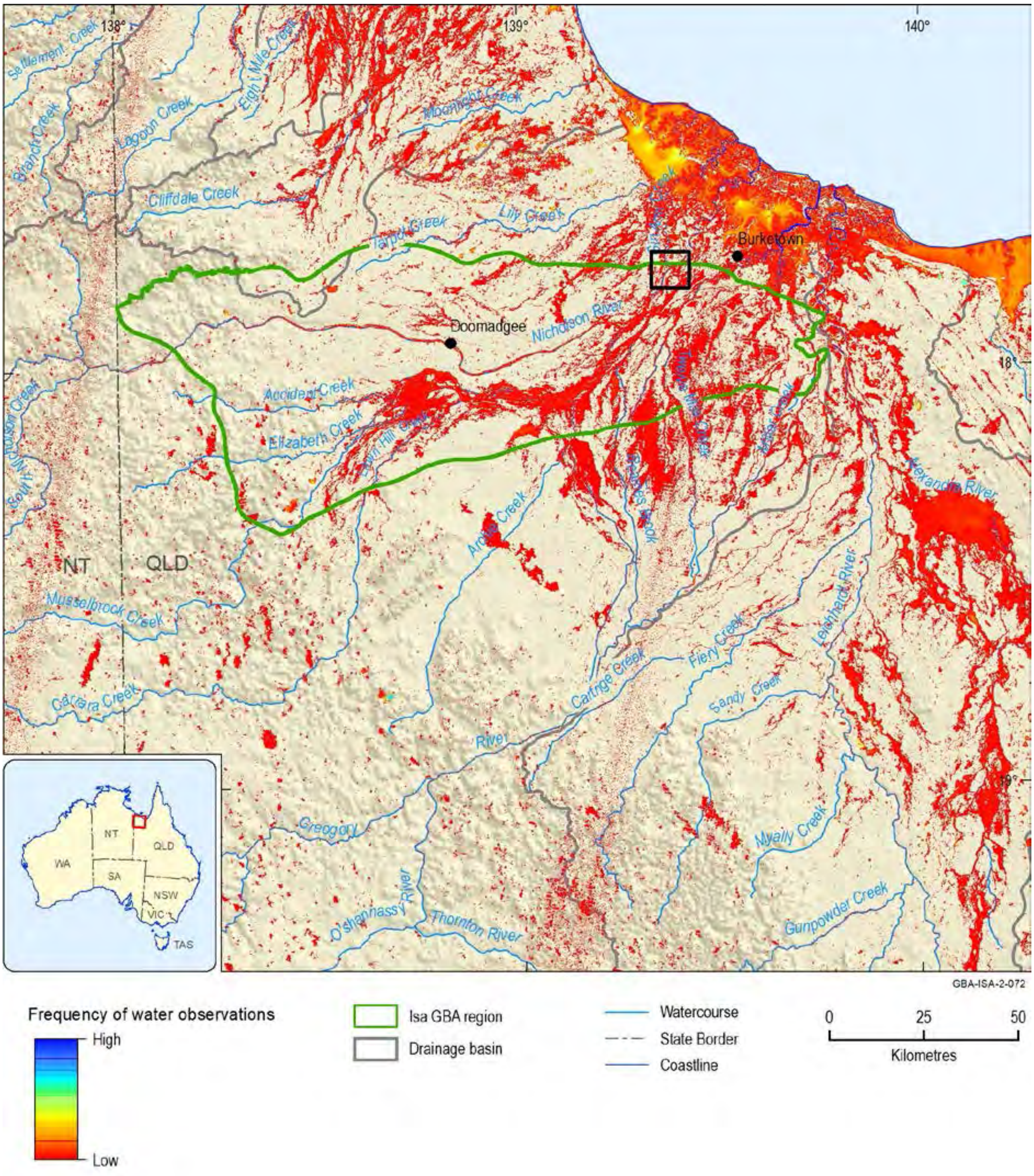


Figure 48 Water Observations from Space summary statistic based on available Landsat imagery during the period 1987 to 2018

The inset (black box) is zoomed-in in Figure 49.
Data: WOfS summary statistic (Geoscience Australia, 2018e)
Element: GBA-ISA-2-072

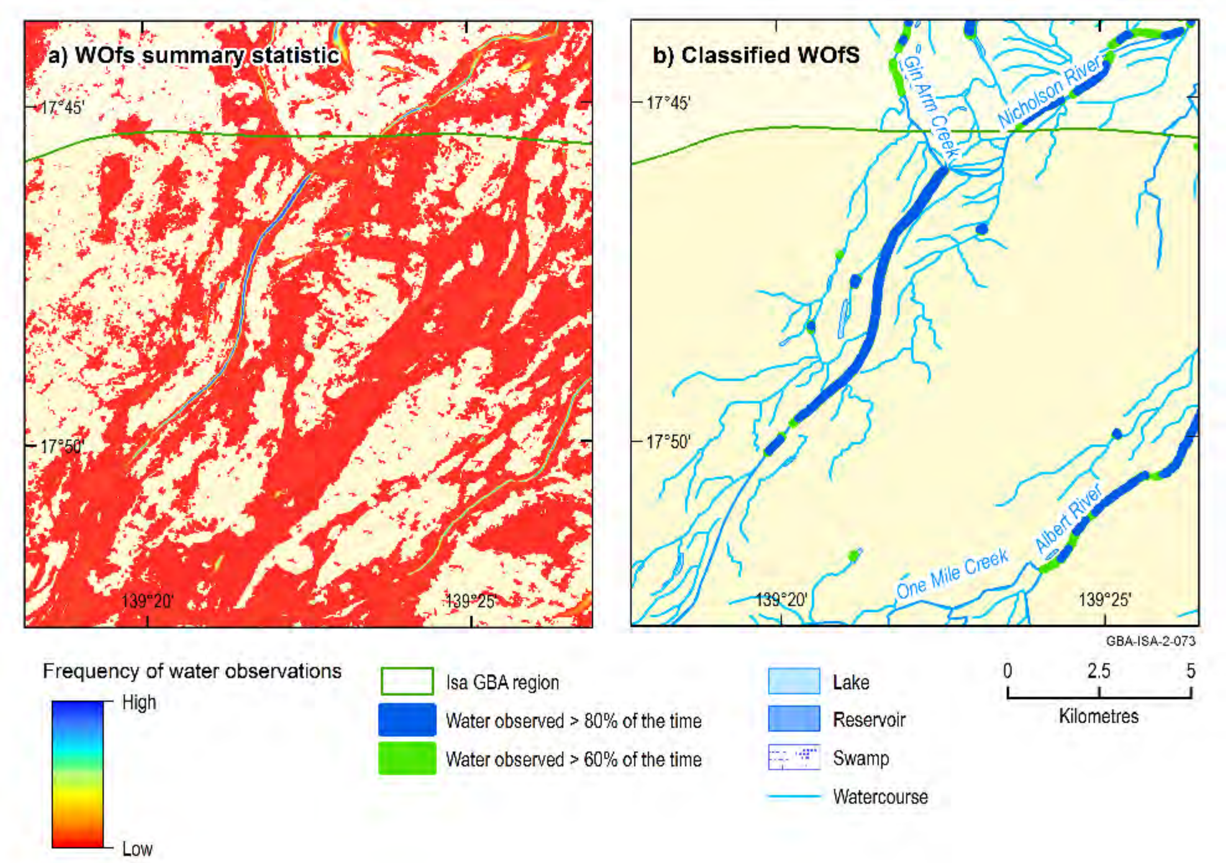


Figure 49 a) WOfS summary statistic (1987 to 2018) for the inset in Figure 48 showing the frequency of water observations in the lower Nicholson and Albert river region (blue) and other surface water features (yellow/green); b) classified WOfS where water has been observed more than 60% and 80% of the time

Pixels have been polygonised to visually exaggerate selected WOfS values.

Data: WOfS summary statistic (Geoscience Australia, 2018e); WOfS classified (Geoscience Australia, 2018b)

Element: GBA-ISA-2-073

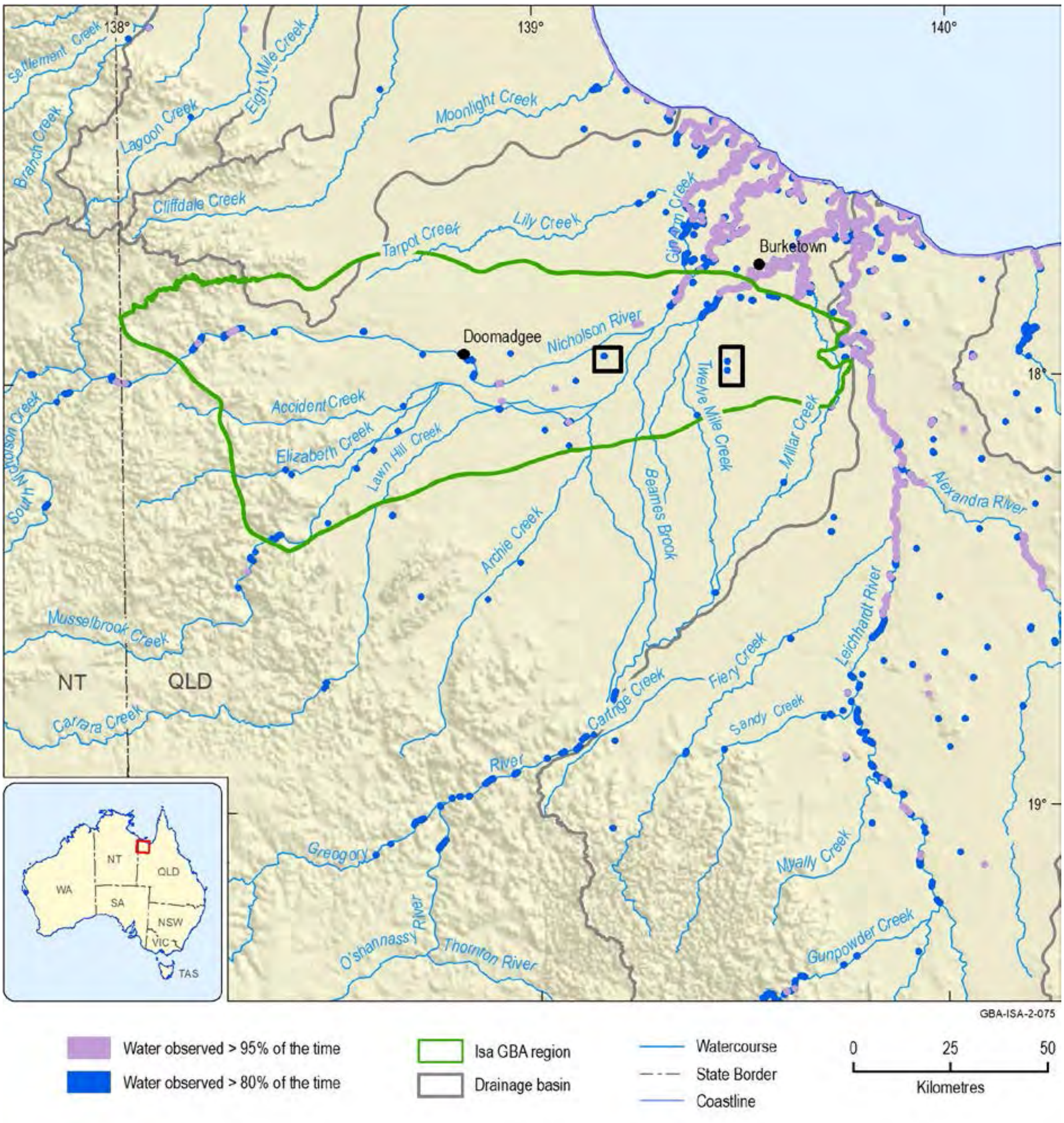


Figure 50 Classified WOfS summary statistic (1987 to 2018) highlighting perennial surface water features based on where water has been observed more than 80% and 95% of the time

Locations in purple are a subset of those shown in blue. The inset boxes highlight areas where artificial features (pastoral dams) occur in between the major streams. Pixels have been polygonised to visually exaggerate selected values.
Data: WOfS classified (Geoscience Australia, 2018b)
Element: GBA-ISA-2-075

The WOfS summary statistic also enables identification of ephemeral (non-permanent) surface water features. An example is shown in Figure 51, highlighting that surface water is observed over a greater spatial extent 10% to 30% of the time compared to 80% of the time (Figure 50). The fringe around the coastline with observed surface water greater than (or equal to) 10% of the time provides an indication of the extent of tidal influence, ranging from approximately 3 to 22 km inland from the coast (Figure 51).

As a first-pass assessment, areas that are most likely to support GDEs include streams and other surface water features which retain surface water for at least 80% of the time. Given the highly seasonal rainfall pattern (Section 4.5.6.1) these areas are likely to have a reliable groundwater source or access to groundwater that maintains surface water during periods of limited rainfall. Retention of surface water (from rainfall) in areas of depression on clay soils is also possible and would require further investigation. In contrast, areas of low frequency of observed surface water (e.g. 10% to 30% of the time) represent more ephemeral surface water features that are less likely to be associated with GDEs.

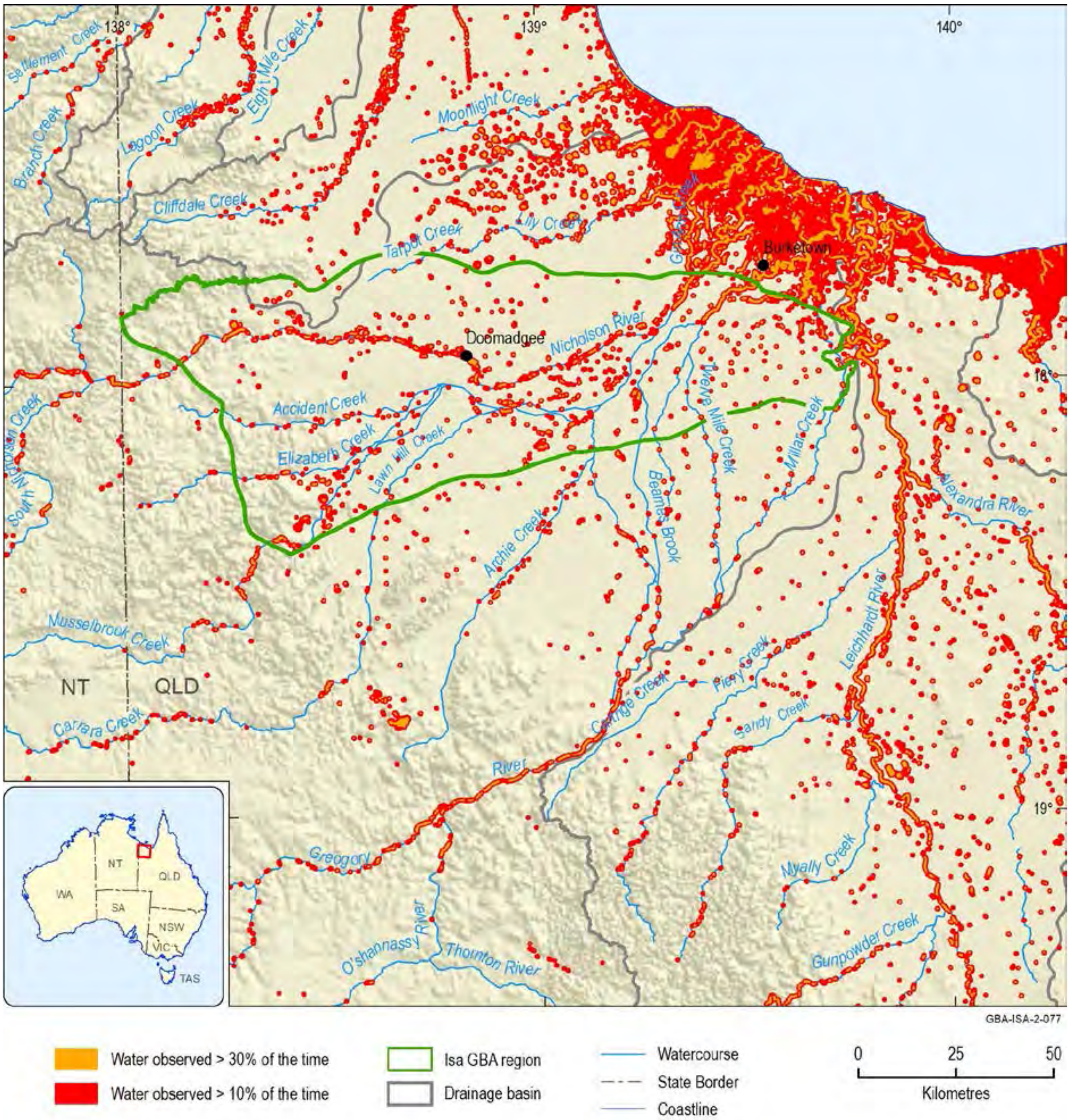


Figure 51 WOfS summary statistic (1987 to 2018) highlighting ephemeral surface water features based on where water has been observed more than 10% and 30% of the time

Pixels have been polygonised to visually exaggerate selected values.
Data: WOfS classified (Geoscience Australia, 2018b)
Element: GBA-ISA-2-077

4.5.6.4 Flood extents

To investigate the potential maximum extent of flood inundation of streams in the Isa GBA region and surrounding catchments, the WOfS summary statistic was classified for areas that have observed surface water greater than (or equal to) 1% of the time relative to the historical record (Figure 52). Areas with the lowest frequencies of surface water occurrence are concentrated around the major stream channels and most likely correspond to overbank flooding during heavy wet-season rain events. It is evident within the region that the Nicholson River and streams to the south such as Elizabeth Creek and its tributaries are potentially flood-prone areas.

A flood investigation study has previously been conducted around the township of Doomadgee (study extent shown in Figure 52) to identify high-level flood risks to rural townships using historical data and hydraulic modelling of the river and floodplain areas (Engeny Water Management, 2013). The results of the regional-scale flood modelling indicated that with an Annual Exceedance Probability (AEP) of 2% (i.e. the chance of flooding within any year), flows on a section of the Nicholson River would be contained within the main channel and would not affect infrastructure. However, for a rarer flooding event of 0.2% AEP, the town of Doomadgee would eventually be inundated, and all critical infrastructure potentially affected.

Based on the WOfS analysis and flood investigation (Engeny Water Management, 2013), it is noted that there are areas in the region that may experience flooding. Understanding the potential extent of flood inundation on floodplain areas is important when considering the location of any future shale gas wells.

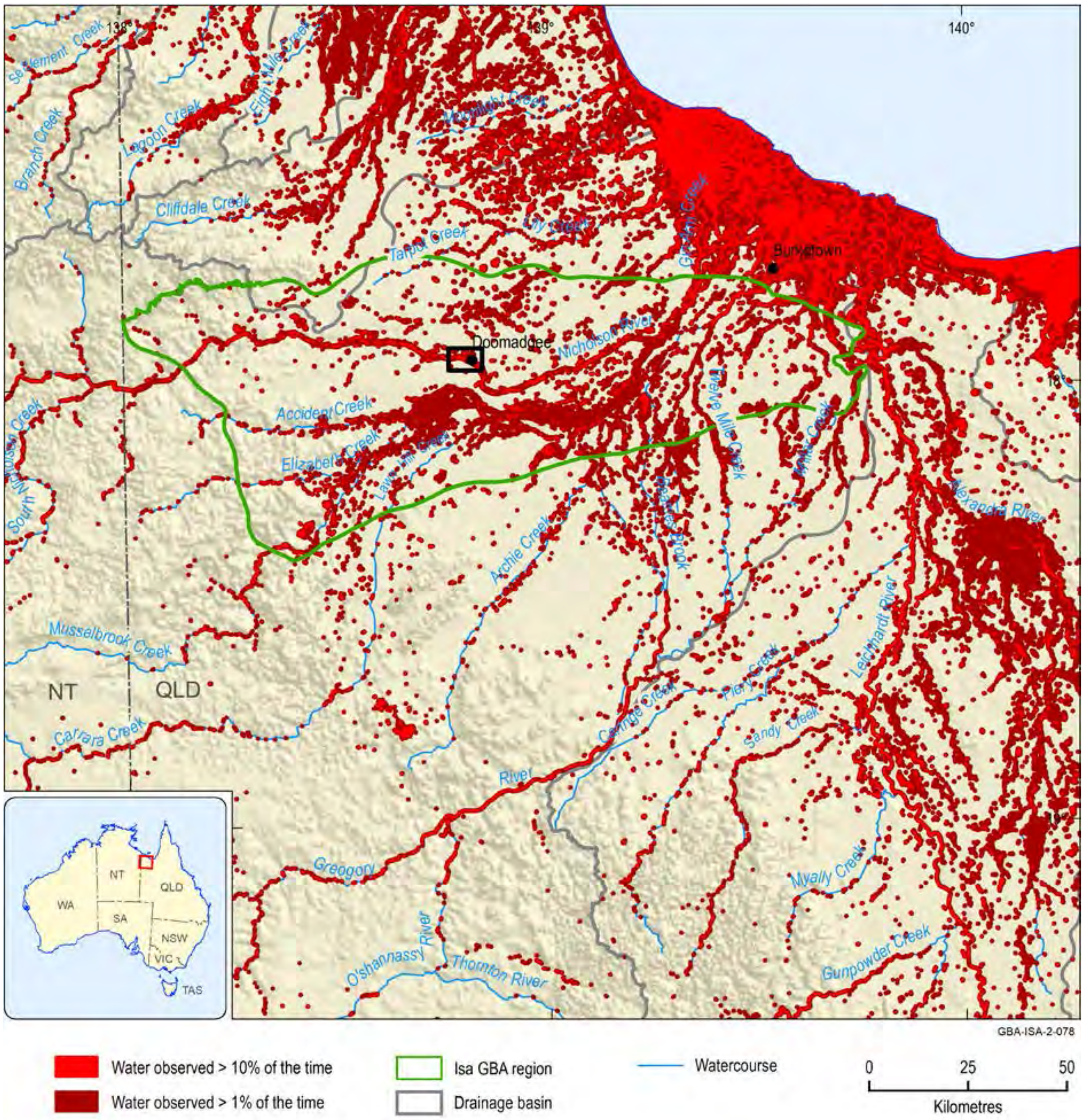


Figure 52 WOfS summary statistic (1987 to 2018) highlighting the potential flood extent based on where water has been observed more than 1% of the time

The spatial extent of the previous flood study (Engeny Water Management, 2013) is shown in the black box around Doomadgee. The potential tidal extent of the Gulf of Carpentaria is also shown as areas with water observed >10% of the time. Pixels have been polygonised to visually exaggerate selected values.
Data: WOfS classified (Geoscience Australia, 2018b)
Element: GBA-ISA-2-078

4.5.7 Tasselled Cap Index (TCI)

The Tasselled Cap Index (TCI) is a method of reducing 6 bands of satellite data (BLUE, GREEN, RED, NIR, SWIR1, SWIR2) to 3 bands (Brightness, Greenness, Wetness) using a Principal Components Analysis (PCA) and Procrustes' Rotation (Roberts et al., 2018). The published coefficients of Crist (1985) are applied to DEA's Landsat data to generate a TCI composite. The resulting Tasselled Cap bands are a linear combination of the original surface reflectance bands that correlate with the Brightness (bare earth), Greenness and Wetness of the landscape. The 'Tasselled Cap' refers to the shape of the distribution of the transformed data (Kauth and Thomas, 1976) which resembles a hat with a tassel on it.

Compressing the original surface reflectance data into Brightness, Greenness and Wetness bands makes changes in the landscape easier to interpret and identify, particularly if changes in surface cover, vegetation condition or surface water and vegetation are of interest.

Two products have been created for this study using the TCI:

1. The TCI percentage exceedance composite (Figure 53) is the percentage of observed scenes where the Tasselled Cap transform results are above a chosen threshold (i.e. a summary of the behaviour of the pixel throughout the time period in Brightness, Greenness and Wetness). The Tasselled Cap Index thresholds were set at Brightness: 4000, Greenness: 700 and Wetness: -600 to calculate the percentage exceedance. These thresholds are set based on Australian conditions and enable the display of the percentage of the time series where Wetness, Greenness or Brightness has been the dominant spectral response within the pixel.
2. The TCI wetness percentage exceedance composite (or Tasselled Cap Wetness (TCW) exceedance composite) (Figure 54) is a subset of the TCI percentage exceedance composite representing the behaviour of water in the landscape, as defined by the presence of water, moist soil or wet vegetation at each pixel through time. The summary shows the percentage of observed scenes where the Wetness layer of the Tasselled Cap transform is above the threshold, i.e. where each pixel has been observed as 'wet' according to the TCI.

4.5.7.1 TCI percentage exceedance composite (dry season)

The WOfS product analysed in this study (Section 4.5.6.2) is a summary statistic over the entire Landsat period (1987 to 2018). In comparison, TCI composite products were generated for a representative dry season (May to October 2015) characterised by relatively low rainfall totals during the previous 2014 to 2015 wet season and within a declining period of residual rainfall (Section 4.5.6.1). The TCI percentage exceedance composite for the 2015 dry season (Figure 53) shows the areas which are Bright (red), Green (green) and Wet (blue), or a combination of these, based on the chosen thresholds (Brightness: 4000, Greenness: 700, Wetness: -600). Areas of potential groundwater dependence during a period of low rainfall are shown in blue (representing persistent wet areas through time), green (representing persistent green vegetation through time), or a combination of blue and green (cyan) that represent areas that transition between wetness and greenness in the landscape through time (inset boxes in Figure 53). Red areas represent parts of the landscape that remain Bright over the selected dry period; purple and yellow are combinations of red and blue and red and green, respectively.

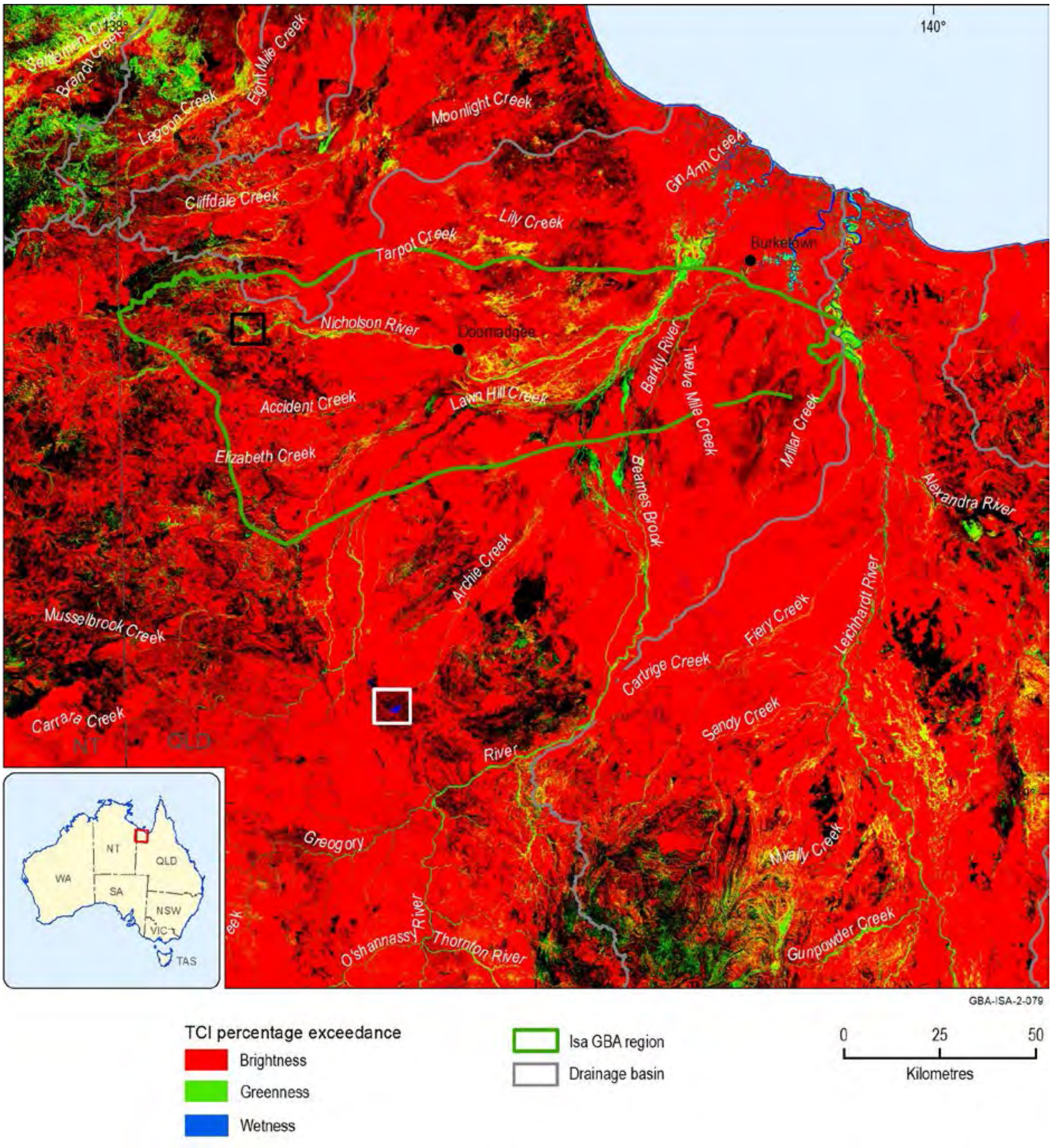


Figure 53 TCI percentage exceedance composite for the dry season (May to October 2015) based on Landsat 8 data

The small inset boxes highlight examples of open water (white box) and potential groundwater-dependent vegetation (black box).
Data: Tasselled Cap Index (Geoscience Australia, 2018d)
Element: GBA-ISA-2-079

Most of the Isa GBA region has a dominant brightness response during the dry season, consistent with soil or rock with little greenness or wetness. The greenness response along streams, particularly for reaches that are ephemeral, is indicative of groundwater-dependent vegetation. Some stream reaches are also cyan or blue, consistent with the presence of wetness in the landscape or open water.

4.5.7.2 *Tasselled Cap Wetness exceedance composite (dry season)*

To assist with visualisation, the wetness layer was isolated to examine the TCW percentage exceedance composite (wetness threshold of -600). Using a similar approach to the WOfS analysis (Section 4.5.6.2), the TCW exceedance composite was classified to distinguish areas that were wet for different proportions of time during the 2015 dry season (Figure 54). 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 (shadow can also show up as wetness). 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, or in areas where wetness in the landscape is expressed as moist soil rather than open water. For instance, the analysis indicates that there are additional ‘wet’ locations not detected by the WOfS summary statistic that indicate the presence of shallow groundwater in the region, such as along the middle and lower reaches of Nicholson River, Elizabeth Creek, Lawn Hill Creek and the lower Gregory River (for example, compare Figure 54 with Figure 50).

The ‘wetness’ signal in the TCW exceedance composite apparent along streams to the west of Doomadgee (Figure 54) possibly represents soil moisture or pools of water rather than continuous streamflow, consistent with the available stream gauge data (Section 4.5.1). Field evidence would be required to confirm this observation, although permanent waterholes have been noted on the Nicholson River on the Gulf Plains (Department of Environment and Science (Qld), In press). In addition, the numerous small wet areas observed in the TCW exceedance composite in the south-west, within and outside of the Isa GBA region, are in the vicinity of the currently mapped springs and associated with terrestrial GDEs (Figure 41 and Figure 43). Some of these ‘wet’ areas are likely to represent additional springs that have not been mapped in the Queensland springs database (Department of Environment and Science (Qld), 2018). Future field observations and groundwater sampling would enable the presence and characteristics of these potential springs to be determined.

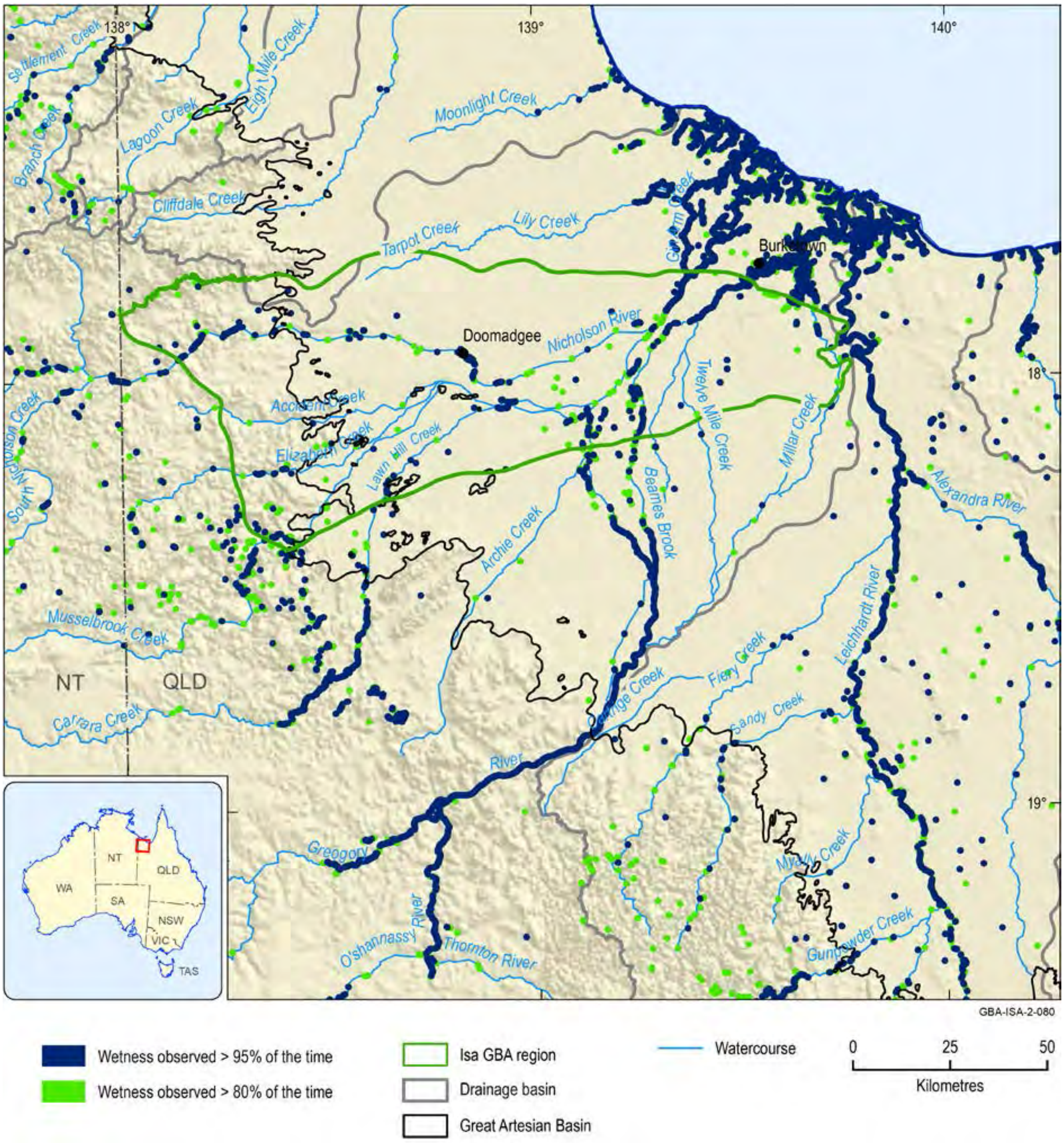


Figure 54 Tasselled Cap Wetness exceedance composite for the dry season (May to October) in 2015 showing locations where wetness in the landscape has been observed more than 80% and 95% of the time based on 1987 to 2018 Landsat imagery

Pixels have been polygonised to visually exaggerate selected values.
Data: TCW classified (Geoscience Australia, 2018g)
Element: GBA-ISA-2-080

The composite map shown in Figure 55 highlights that although the Gregory River has observed surface water in only the upper reaches according to WOfS, wetness is observed more than 80% of the time according to the TCW exceedance composite. Given that the Gregory River is known to be perennial, the observed TCW exceedance and WOfS signals are consistent with narrowing of the stream channel or loss of visibility of the channel due to riparian vegetation (below the detection limit of 25 m); a losing stream situation; high evapotranspiration or various combinations of these. Field observations and surface water flow measurements along the lower reaches of the Gregory River (within the Isa GBA region) would be required to ascertain the flow contribution of the Gregory River to the Nicholson River, as well as to terrestrial GDEs in the Nicholson River floodplain.

The most likely areas for GDEs to develop are where moisture is retained in the landscape. The composite map of Figure 55, including previously mapped springs (Department of Environment and Science (Qld), 2018), is a first-pass representation of areas that are most likely to rely on groundwater during the dry season. Importantly, there may be additional areas of groundwater-dependent vegetation not depicted that remain green and healthy throughout the dry season but do not show a ‘wetness’ signal (for example, GDEs that access deeper groundwater or are not always reliant on groundwater sources). Despite the limitations of the remote sensing products, the analyses presented here provide reasonable mapping at the regional-scale of parts of the landscape that have a reliance on groundwater and where there is greatest potential for surface water – groundwater interactions and GDE development to occur.

Comparison of the WOfS and TCW exceedance composite products with the GDE Atlas (Bureau of Meteorology, 2017) indicates that there is generally good agreement between the two mapping approaches in relation to aquatic GDEs. For example, overlaying the TCI wetness exceedance composite (≥95%) for the dry season on the mapped extent of high and moderate potential GDEs shows that the wettest parts of the landscape align with the aquatic GDE areas (Figure 56). Wet areas identified in the south-west align within the mapped extent of terrestrial GDEs according to the GDE Atlas. However, other areas of terrestrial GDE potential (for example, north of the Nicholson River) are not indicated as groundwater dependent by the remote sensing analysis (Figure 56). Further analysis of Earth observation data, including assessment of different spectral bands such as the greenness band or vegetation indices (e.g. normalised difference vegetation index, NDVI) during a range of time periods, would enable a more comprehensive and consistent assessment of other GDE types and their locations in the landscape.

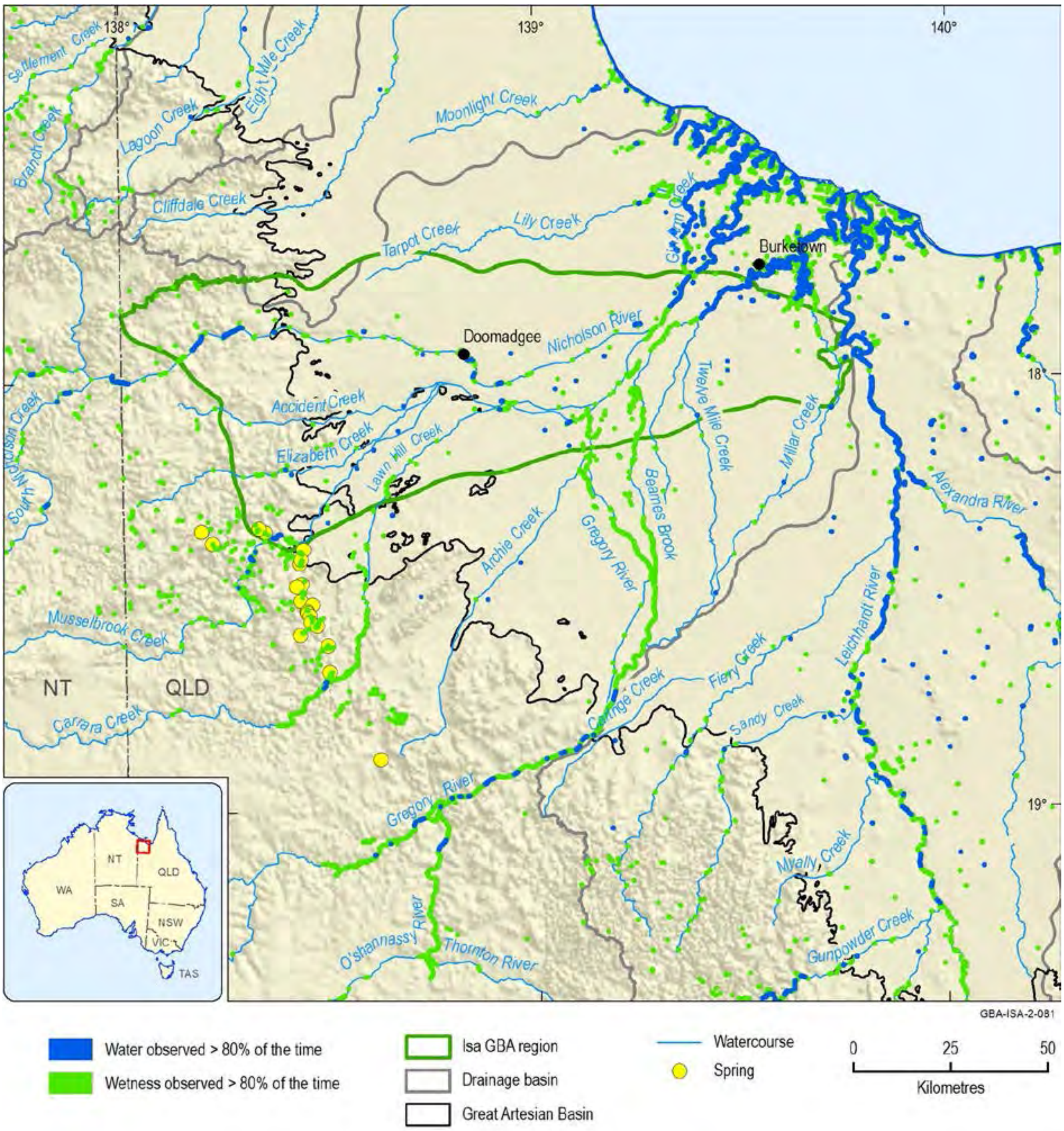


Figure 55 Composite of WOfS summary statistic (blue) and TCW (green) exceedance analyses, with mapped springs from the Queensland springs database

This map represents locations with open water observed for ≥80% of the time (WOfS summary for 1987 to 2018) combined with wetness in the landscape observed >80% of the time (TCI wetness exceedance composite for May to Oct 2015). Pixels have been polygonised to visually exaggerate selected values.

Data: TCW classified (Geoscience Australia, 2018g); WOfS classified (Geoscience Australia, 2018b); springs (Department of Environment and Science (Qld), 2018)

Element: GBA-ISA-2-081

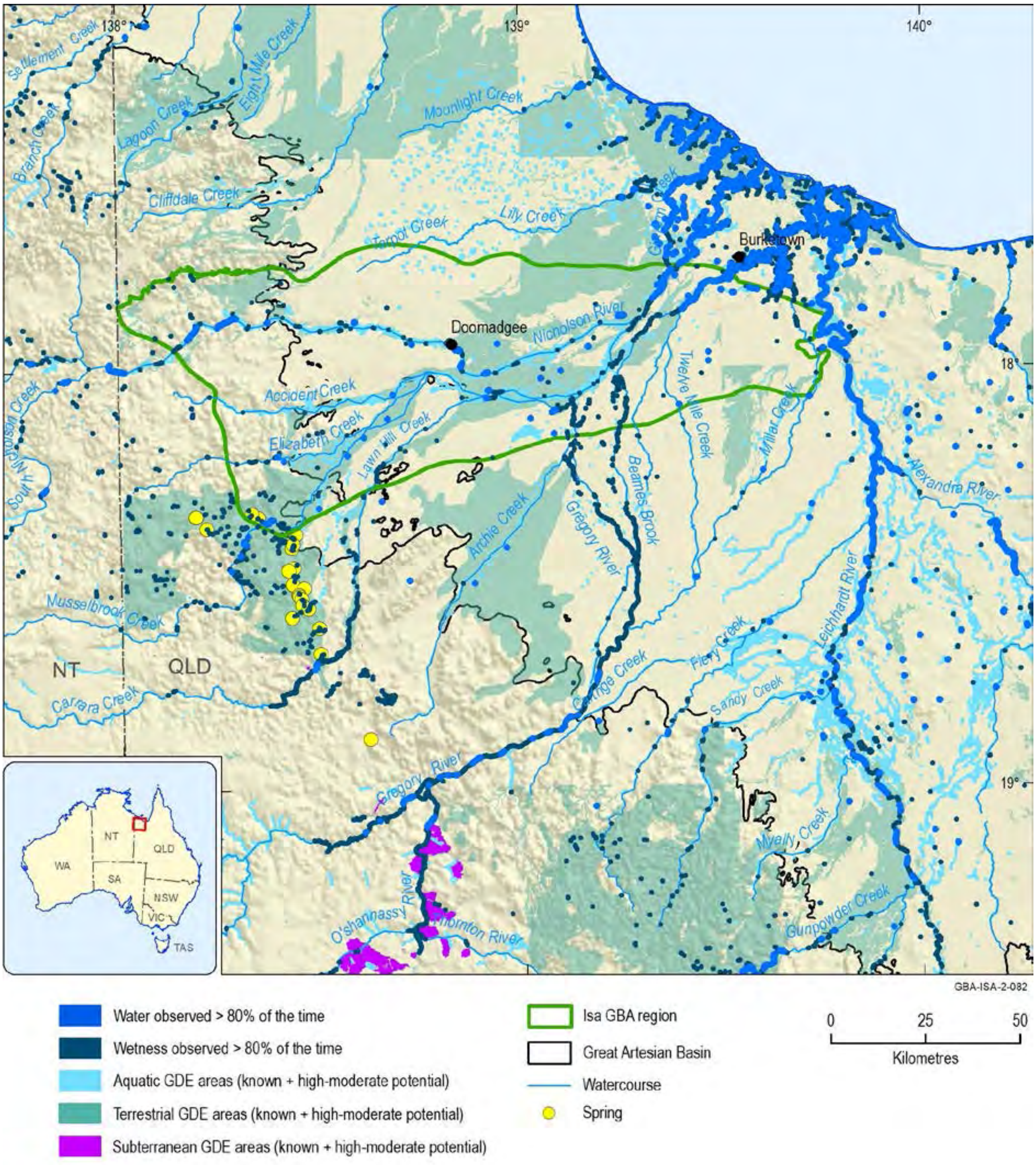


Figure 56 Composite of remote sensing analyses and mapped GDEs, including springs

Remote sensing products include Water Observations from Space (WOfS) summary statistic (medium blue) (1987 to 2018) and Tasselled Cap Wetness (TCW) exceedance composite (dark blue) (May to 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, 2018b); TCW classified (Geoscience Australia, 2018g); Groundwater Dependent Ecosystems Atlas (Bureau of Meteorology, 2017); springs (Department of Environment and Science (Qld), 2018)
Element: GBA-ISA-2-082

4.5.8 Summary of remote sensing methods

The application of remote sensing methods has enabled a rapid and consistent approach to mapping parts of the landscape in and around the Isa GBA region with potential dependence on groundwater. Importantly, the analysis of remote sensing data has helped assess surface water – groundwater interactions in the region where the availability of other datasets (such as surface water and groundwater data) has been limited. Field validation of the remote sensing data products in targeted areas would be required to confirm the preliminary interpretations of this assessment, and develop an improved understanding of the strengths and limitations of these methods in the Isa GBA region.

Some of the known limitations with using Earth observation data include:

1. The use of remotely sensed data relies on the ability of the sensor (satellite) to 'view' the scene. Clouds can obscure pixels, particularly during wet periods, biasing the results toward dry periods. As the TCI is calculated on cloud-free composites, wet pixels are less likely to be observed.
2. The resolution of Landsat 8 data is 25 m (i.e. 25-m x 25-m pixels) and therefore limits the size of surface water features that can be confidently detected by WOfS. The minimum area repeatedly detectable as surface water is typically 2 x 2 pixels, and features smaller than this may not be reliably observed. However, the TCW exceedance composite product enables wet/moist areas in the landscape to be identified that may have a small surface water footprint.
3. Thresholds for the TCI have been set based on scientific judgment and are currently in research/testing phase. For example, the -600 threshold is thought to be conservative. Being 'above' or 'below' the threshold of wetness does not necessarily indicate open water. Soil moisture, in addition to shadow and leaf moisture, may also show up in the TCW as wetness.

Despite these limitations, DEA datasets provide a regional coverage that can inform and direct more detailed work. The WOfS and TCI composite products assessed are only a small part of the available data, and the products currently available through DEA and their interpretation provided here are preliminary. Further comprehensive analysis could include more detailed statistical and time series trend analyses of a range of DEA datasets, and integration with other data from disciplines spanning hydrology, hydrogeology and ecology. Areas identified for more intensive study, for example, within or near areas of most likely shale gas development, could also be examined in more detail.

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

5 Potential hydrological pathways from shale gas reservoirs to environmental assets

5.1 Introduction

An important focus of the baseline hydrogeological study for the Isa GBA region involved developing a conceptual understanding of potential hydrological pathways that may naturally exist in the subsurface. These pathways may preferentially focus groundwater flow between aquifers or basins, or potentially act as enhanced hydrological flow paths due to the influence of new system stressors, such as future shale gas development and groundwater extraction to support development. Consequently, recognising the presence of possible subsurface fluid pathways is critical prior to any gas development proceeding, to understand potential impacts to the region’s groundwater systems. For example, if there are major faults linking shale gas reservoirs to overlying GAB aquifers, it is important to be aware of the location and architecture of these structures, and their possible influence on groundwater flow systems, prior to development.

Building on the regional hydrogeological model presented in Section 4, multiple conceptualisations of potential connectivity pathways have been developed as part of this assessment. These models are built on the main hydrostratigraphic layers of the region (from surface downwards) that are likely to be penetrated by unconventional gas wells. The models provide the framework to investigate potential connectivity pathways between the vertically stacked geological basins, deep and shallow aquifers, and the surficial groundwater-dependent ecosystems (GDEs) such as springs, wetlands and streams. The conceptualisations incorporate knowledge of the hydrostratigraphic and structural framework (as presented in other sections of this report and in the geology technical appendix (Orr et al., 2020)), and build upon similar hydrological pathway studies undertaken for coal seam gas basins elsewhere in Australia, such as those of Mallants et al. (2018a).

The conceptual models summarise plausible hydrological connectivity pathways that may exist due to factors such as:

- spatial variations in aquitard thicknesses in the region
- proximity of shale gas reservoirs and hydrological assets to faults (both vertically and horizontally), and the likely subsurface continuity of these faults
- direct stratigraphic contacts between shale gas plays and aquifers
- geological heterogeneities near basin margins.

The conceptual models also highlight recognised data gaps and hypotheses to be tested in future studies, which will help improve understanding of the likelihood of identified pathways between new system stressors (i.e. development of shale gas wells and aquifers used to support the development) and the existing groundwater and surface water systems and their associated assets.

Multiple cross-sections (orientations are shown in Figure 57 and Figure 58) were developed for the conceptual models to represent the lateral and vertical extent of the regional stratigraphic architecture, the location of major geological structures in relation to existing data (such as hydrochemistry and methane concentration data) and environmental assets. These cross-sections have been used to identify and highlight plausible subsurface connectivity pathways in the Isa GBA region that may connect deeper shale gas plays with shallow aquifers and groundwater-dependent surface environments.

Ideally, for further testing of these conceptual models, multiple lines of evidence (using existing and new datasets) should be integrated to increase confidence in the likelihood that identified pathways directly connect stressors and environmental assets.

Key factors considered in the conceptualisation of potential connectivity pathways for the Isa GBA region include:

- footprint and thickness of the shale gas play intervals (River and Lawn supersequences) and their linear distance (predominantly vertical) to the intra-basin Lady Loretta Formation aquifer and Widdallion Sandstone partial aquifer, 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 overlying hydrostratigraphic units, which may be susceptible to pressure changes in the 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 the aquitards (potential stratigraphic seals) positioned between the shale gas reservoirs and the identified assets, including shallow aquifers
- anomalies identified in hydrochemical data in groundwater and surface water samples (Figure 57) and a limited number of dissolved gas measurements from groundwater bores (Figure 58)
- spatial location and extent of environmental assets, including GDEs, springs, stream reaches where baseflow is likely to occur and groundwater bores used for water supply.

Zones of higher likelihood for the occurrence of potential hydrological pathways were identified through the combination of factors favouring the existence of subsurface 'weakness points'. This includes, for example, areas where aquitards are thinner or where they may be compromised by faults with a dilational tendency under the current stress regime. This may be further influenced by upward hydraulic gradients between the deep hydrostratigraphic units and the shallow aquifers.

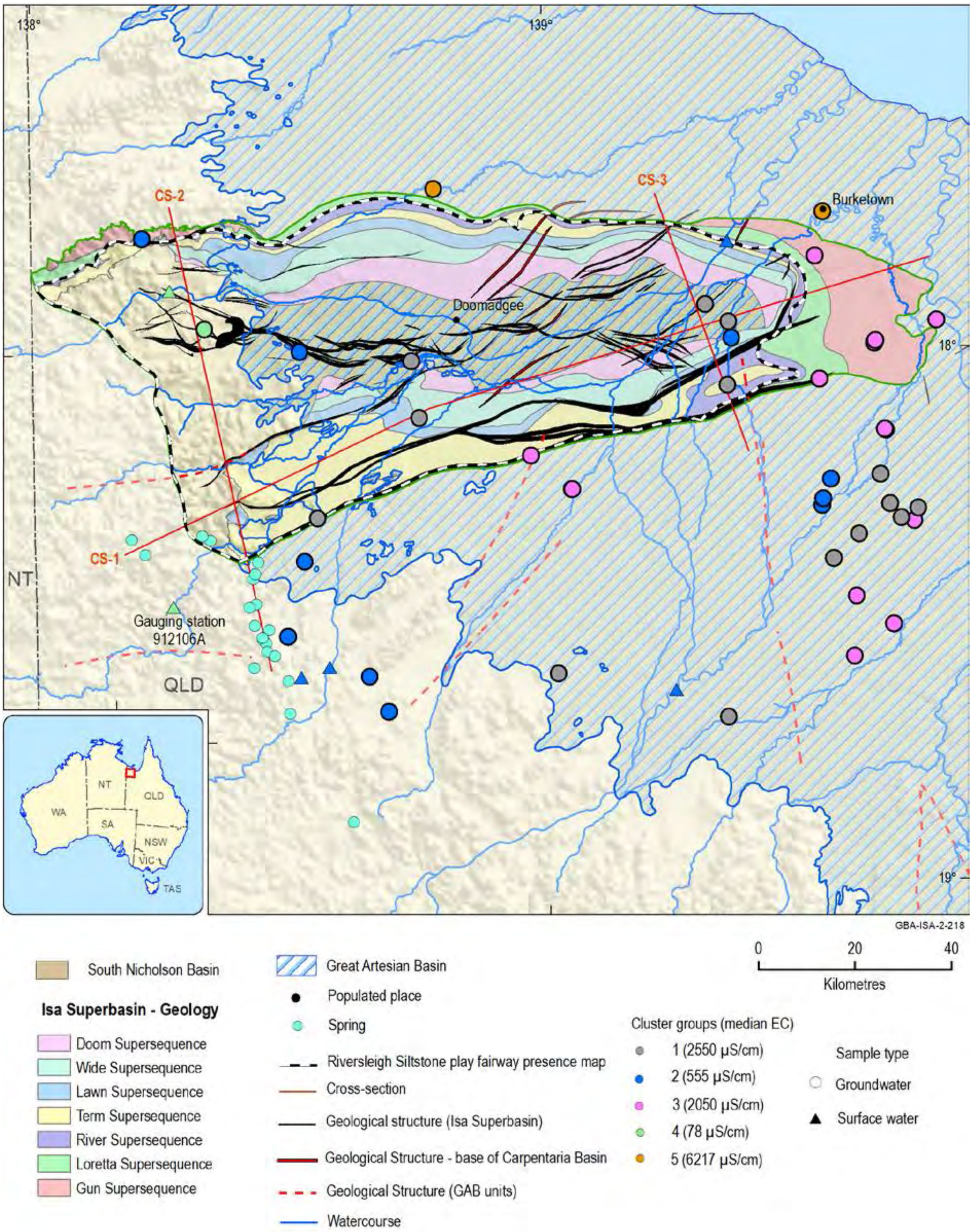


Figure 57 Isa GBA region with subsurface Proterozoic geological units, faults and position of cross-sections

The cross-section lines shown here are illustrated in Figure 60 (CS-1), Figure 61 (CS-2) and Figure 62 (CS-3) in Section 5.7. The five hydrochemical cluster groups shown here are discussed in Section 4.4.1.

Data: Isa Superbasin and South Nicholson Basin geology (Bradshaw et al., 2018a); GAB extent (Ransley et al., 2015b); faults associated with Isa Superbasin and to reach the base of Carpentaria Basin were sourced from Bradshaw et al. (2018b) and faults mapped within GAB units were sourced from Geoscience Australia (2013)

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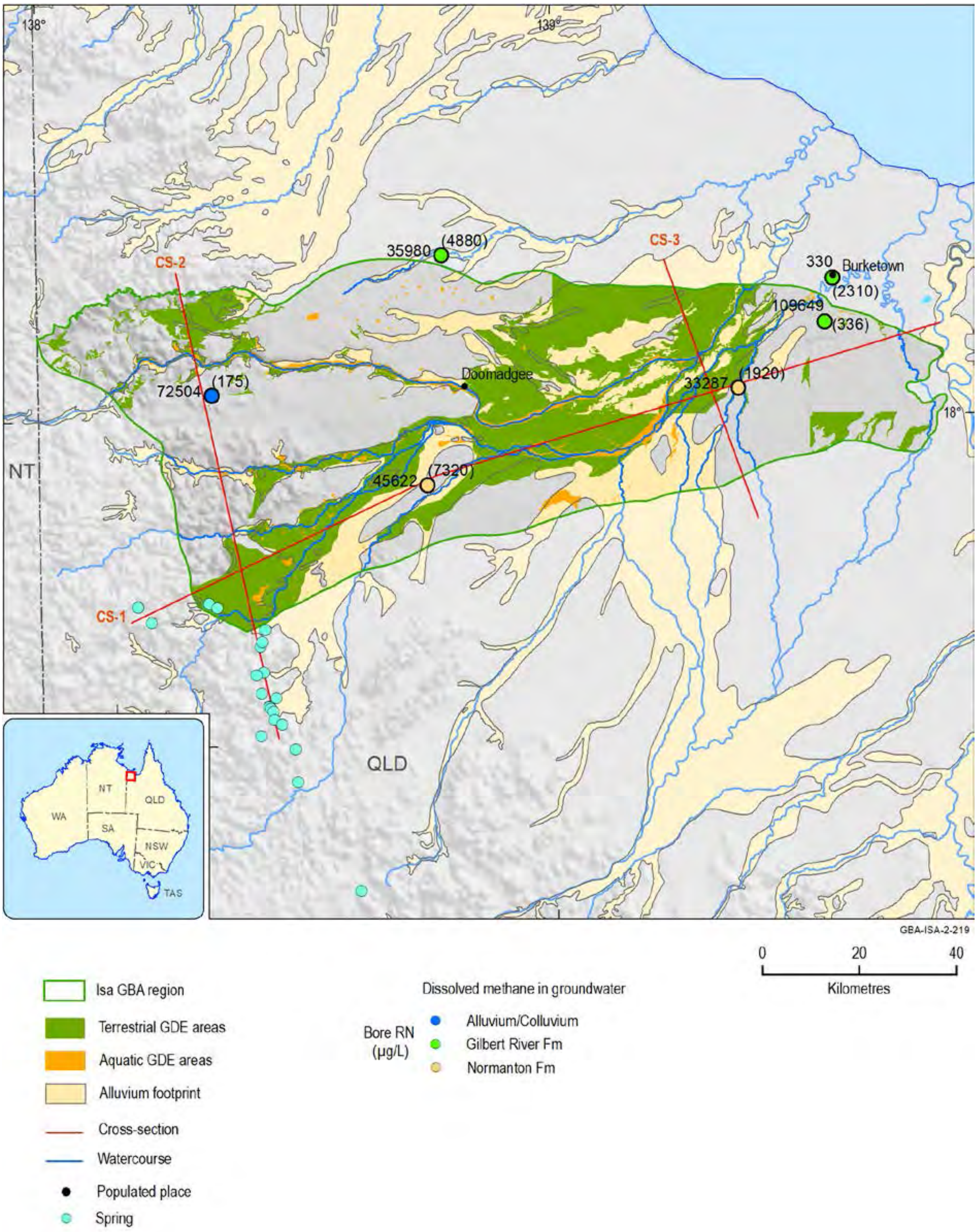

Figure 58 Isa GBA region with footprint of alluvial sediments, environmental assets (spring, watercourse and groundwater-dependent ecosystems), groundwater bores and dissolved methane (CH_4) in groundwater samples (in brackets)

The cross-section lines shown here are illustrated in Figure 60 (CS-1), Figure 61 (CS-2) and Figure 62 (CS-3) in Section 5.7. The terrestrial and aquatic GDEs shown here are based on the high to moderate potential GDE areas from the Bureau of Meteorology's GDE Atlas (Bureau of Meteorology, 2017).
Data: methane measurements (EHS Support, 2014), Groundwater Dependent Ecosystems Atlas (Bureau of Meteorology, 2017); springs (Department of Environment and Science (Qld), 2018); alluvium (Geoscience Australia, 2012)
Element: GBA-ISA-2-219

5.2 Datasets and methods

This section describes the approach used to analyse and integrate existing datasets, including the relationship between mapped geological structures and the characteristics of groundwater and surface water hydrochemistry data and dissolved gas concentrations. Also included is the rationale for developing multiple conceptual models using two-dimensional cross-sections that represent plausible hydrological pathways in the Isa GBA region.

5.2.1 Geological framework

The formation tops for key stratigraphic horizons obtained from the three-dimensional geological model of the Isa GBA region (see Bradshaw et al. (2018a)) were used to represent the contacts between the hydrostratigraphic units and support the assessment of the hydraulic sealing potential of aquitards and their ability to restrict migration of unconventional hydrocarbons.

From the detailed interpretation of aquitard thicknesses, representative cross-sections orthogonal to major structural elements were developed. These sections allowed the investigation of zones where existing seals (i.e. geological units of low permeability) between the shale gas resources (the potential future development of which represent the potential stressors of the system) and assets may be compromised, either via thinning of the seal unit, the influence of intrusive features such as dykes, or the occurrence of faults with dilation tendency.

5.2.2 Geological structures

Faults extend through different subsurface intervals of the Isa GBA region, including the Isa Superbasin, the South Nicholson Basin, Carpentaria Basin and Karumba Basin. Fault data were combined with physical-chemical property data, including dissolved methane (CH_4) concentrations in groundwater, to help interpret existing zones of potential preferential flow. The inferred faults associated with the Isa Superbasin were sourced from Bradshaw et al. (2018b) and those mapped within the GAB units were obtained from Geoscience Australia (2013).

For both datasets, faults are represented as lines on the horizontal plane of the spatial coordinate system displacements, with no associated dip values or vertical changes in orientation at depth. This shows where faults are in contact with different units, and where juxtapositions of hydrostratigraphic units may occur.

High-angle fault dips were inferred in parts of the Isa Superbasin, according to interpretation of seismic reflection data in the geology technical appendix (see Figure 29 to Figure 32 of Orr et al. (2020)). To better constrain whether these faults extend into the overlying sedimentary basins and most importantly to the main GAB aquifers, the vertical and lateral extent of the faults were compared to the changes in lateral continuity of the surfaces representing the major geological units in the three-dimensional geological model. Interpretation of these results is discussed in Section 5.5.

5.2.3 Hydrochemistry

The data used for HCA were integrated with other parameters such as groundwater methane concentrations and the assets located near mapped faults. The description of the hydrochemical data is in Section 4.4.1 and the results of this interpretation were integrated in the geological cross-sections discussed in Section 5.7. The data quality check and aquifer attribution for individual samples followed the procedures described in Section 3.1.

Methods snapshot: spatial data interpretation

Investigating plausible pathways for fluid migration from shale gas plays to near-surface environmental assets was based on conceptual models developed from a series of cross-sections produced within the Isa GBA region and its immediate vicinity (see Section 5.7).

These cross-sections intersect the stratigraphic architecture from the three-dimensional geological model prepared by Bradshaw et al. (2018a) and relevant geological structural elements mapped predominantly in the Isa Superbasin sequence (Bradshaw et al., 2018b) and the GAB aquifer/aquitard sequences (Geoscience Australia, 2013). One cross-section is parallel to the longest basin axis (roughly north-east to south-west), with a further two sections orthogonal to the basin axis, i.e. north-west to south-east. These sections were positioned across the Isa GBA region to intersect as many geological structures, groundwater bores and assets as possible, as well as to represent important geological structural elements such as basin troughs and ridges at their deepest and shallowest points, respectively, and associated fault zones.

Datasets used for the cross-section interpretations include a digital elevation model representing surface topography, as well as datasets of physical-chemical parameters, such as groundwater compositions, that may indirectly help to identify potential pathways.

5.3 Shale gas plays and prospective aquifers – potential system stressors

The potential stressors identified in the Isa GBA region are the Paleoproterozoic River and Lawn supersequences of the Isa Superbasin, which host shale gas plays that may be developed at some stage in the future (Figure 62).

The deepest shale gas play is the River Supersequence (Riversleigh Siltstone), an organic-rich upwards-deepening sequence composed of laminated siltstone, fine-grained sandstone, carbonaceous shale, dolomite and dolomitic siltstone. This supersequence has a gross thickness ranging from 800 to 3200 m across an area of about 5100 km^2, which occupies most of the Isa GBA region. The average unit thickness across the Northern Lawn Hill Platform is about 750 m. The thickness of the complete River Supersequence decreases from south to north, with localised thickening in extensional fault systems, e.g. between 2500 m to 3200 m within the Accident Creek Trough and Gregory River Trough, as represented in Figure 8(b) of Bailey et al. (2020).

The other shale gas play is the Lawn 4 Sequence, an organic-rich part of the Lawn Supersequence, which covers an area of about 3400 km^2. The maximum depth to the top of this sequence is 1610 m below surface, and it varies in thickness from 265 to 488 m. Pore pressure conditions in the Lawn Supersequence are interpreted as hydrostatic where it has been intersected; however, Gorton and Troup (2018) suggested that it may be over-pressurised where it reaches depths exceeding 2000 m. This is consistent with observations from other unconventional gas source rocks, as for example in the Cooper Basin, as described by Evans et al. (2020).

The Lawn Supersequence consists of black shale, siltstone, fine-grained sandstone and dolomitic siltstone deposited in a marine shelf environment, predominantly under wave base conditions. The Lawn 4 Sequence (lower Pmh 4 member of the Lawn Hill Formation) is dominated by organic-rich mudstone, and has the greatest identified shale gas potential. The Lawn Supersequence conformably overlies the Term Supersequence (Lawn Hill Formation Pmh 2 and Pmh 1, Termite Range Formation), which in turn unconformably overlies the River Supersequence (Riversleigh Siltstone), where there is a transition from fine-grained siltstones to thick-bedded turbidites (Bailey et al., 2020).

In addition, possible groundwater extraction from aquifers in the Carpentaria and Karumba basins to support the development activities comprise potential stressors to near-surface assets.

5.4 *Aquitards as potential hydraulic barriers*

A detailed characterisation of the groundwater system hydrodynamics within the Isa GBA region is in Section 4. For the investigation of potential connectivity pathways, it is crucial to understand the distribution, continuity and heterogeneity of low-permeability units (aquitards) that exist between the shale gas reservoirs (i.e. the potential system stressors when gas development starts) and the overlying assets (Underschultz et al., 2016). The purpose of this section is to describe the hydraulic characteristics of the main regional aquitards that form potential seals or barriers to any interaction between stressors and assets.

5.4.1 Isa Superbasin – upper McNamara Group

The geological unit identified as a potential aquitard/seal directly overlying the shale gas plays corresponds to the upper Mesoproterozoic Pmh 6 unit of the Lawn Hill Formation (part of the Doom Supersequence).

The partial aquitard of the Widdallion Sandstone Member (Pmh 5) lies between the Pmh 6 aquitard and the uppermost shale gas play (Pmh 4). This unit may provide a conduit for preferential fluid flow, mostly subparallel to the contact surfaces with underlying and overlying units.

There is very little information currently available on the thickness and spatial extent of the upper part of the Lawn Hill Formation (Pmh 6), which limits any inference about the capacity of this unit to impede fluid migration. East-directed geological structures occur predominantly in the central-west part of the Isa GBA region, whereas a sequence of north-east oriented faults are concentrated in the south-east part of the region. The latter set of structures form partial geological contacts between the Lawn and Term supersequences.

5.4.2 South Nicholson Basin – Accident Subgroup

Containment of fluid migration upwards from the shale gas reservoirs of the Isa Superbasin largely depends on the South Nicholson Basin sequence behaving as a regional aquitard. The main unit with aquitard properties (Figure 3) that lies between the shale gas plays and the basal GAB aquifer consists of deep marine siltstones and shales of the Mullera Formation (Sweet, 2017), part of the Accident Subgroup. However, there are localised areas of fracture- or fault-related permeability, for example, where this unit if locally folded along the Egilabria anticlinal structure. Available geological evidence indicates that the abundance of more hydraulically conductive fractures in these rocks is relatively greater near the Egilabria 1 and Egilabria 2 wells, in contrast to the Egilabria 4 site (Matthews, 2014).

The theoretical potential exists for connectivity to arise as a result of gas overpressure in the shales of the River and Lawn Supersequences, resulting in upwards leakage through the South Nicholson Basin in fracture zones and the Carpentaria and Karumba basin sequences. Gas overpressures may help explain the artesian groundwater pressures initially seen in the Lady Loretta Formation. However, there is only limited evidence for gas overpressure within the few exploration wells drilled in the region, and to date there have been no studies of formation pressure within the Isa Superbasin. Section 3.3.5 of the prospectivity technical appendix (Bailey et al., 2020) shows that using drilling mud weights as a proxy for formation pressure, the strata of the supersequences appear generally hydrostatic in nature and would not typically contribute to upwards flow. Consequently, this mechanism of potential groundwater movement is speculative and further data on formation pressures are required.

In most parts of the Isa GBA region, the South Nicholson Basin has an average thickness of less than 100 m (refer to Section 3.4.2 of the geology technical appendix (Orr et al., 2020)) and is dissected by a series of east-north-east to north-east geological structures (Figure 28 in Orr et al., 2020). These major fault zones form a series of horst and graben structures towards the east of the Isa GBA region. The structural complexity and heterogeneity evident in the South Nicholson Basin may influence preferential pathways for groundwater flow, although there is sparse direct evidence currently available to support this interpretation.

5.4.3 Carpentaria Basin – Rolling Downs Group aquitard

The basal part of the Rolling Downs Group consists of the Wallumbilla and Toolebuc formations, which combine to form a leaky aquitard across much of the Isa GBA region. These units are capped by the Allaru Mudstone, the uppermost aquitard in the combined hydrostratigraphic section of the Isa Superbasin, South Nicholson Basin, Carpentaria and Karumba basins. The characterisation of hydraulic properties and lateral continuity of this major aquitard is important for assessing potential regional connectivity between the shale gas plays (stressors) and the shallow groundwater and surface water systems (assets).

The Rolling Downs Group aquitard (Ransley et al., 2015b) forms a thick and laterally continuous low-permeability unit across most of the Isa GBA region. The average thickness is 310 m (Smerdon et al., 2012d), and in the east of the region near Burketown it is over 500 m thick (Ransley et al., 2015b), with a gradual westward trend of decreasing unit thickness at an approximate gradient of 0.3%. Around Doomadgee, the Rolling Downs Group aquitard is approximately 100 m thick and covers an extensive area (about 45 km wide) west of the town, although it eventually diminishes near the boundary of the GAB (Figure 13). Due to these properties, particularly its relatively homogenous thickness and very low permeability, this unit has been classified as a regional aquitard. In parts of the basin where this unit is not compromised by seal bypass structures (i.e. where no faults are present; Figure 17), it likely represents an effective regional aquitard that restricts vertical upwards fluid flow from deeper units (such as the Gilbert River Formation or the Proterozoic units of the Isa Superbasin or South Nicholson Basin).

The lateral extent of the Rolling Downs Group aquitard is represented by the interval between the red line representing the base of the Great Artesian Basin to the west and the Gilbert River Formation aquifer to the east, and the base of the Normanton Formation as shown in cross-section 1 (Figure 60). Although fault-induced displacements are not explicitly modelled by the three-dimensional geological model from the Carpentaria Basin, the subsurface geometry (as shown in the cross-sections) suggests that faults are likely to juxtapose different units in some depocentres. Such fault offsets may affect the lateral continuity of aquitards and adjacent aquifers, as observed in other basins such as the Galilee and Eromanga basins (e.g. Moya et al., 2014). There is currently no data available on the permeability of the faults that traverse the GAB and the geological units of the Isa Superbasin and South Nicholson Basin. Consequently, this knowledge gap increases uncertainty in quantitatively classifying the Rolling Downs Group as a regionally continuous aquitard.

Furthermore, pervasive intraformational faulting, identified as a polygonal fault system (PFS) (see Figure 7), may provide potential pathways for fluid migration through and within the Rolling Downs Group aquitard (Ransley and Smerdon, 2012; Ransley et al., 2015b; Ransley et al., 2015a). However, no quantification of fluid leakage through the PFS in the Rolling Downs Group is currently available in the literature. Instead, there is only a conceptual description of the likelihood that faults may disrupt the continuity of aquifers and act as possible conduits for leakage into other aquifers and gaining streams.

5.5 Structural geology framework

Fault zones may create conditions that enhance the vertical hydraulic connectivity between different hydrostratigraphic intervals. Faults and other geological structures may also compartmentalise strata and restrict lateral continuity of aquifers and aquitards. Evaluating the potential impacts of geological structures on groundwater flow systems thus requires a range of complementary assessment methods (Underschultz et al., 2018).

The structurally complex Proterozoic sequences of the Isa Superbasin and South Nicholson Basin have been affected by at least six tectonic events. The earliest tectonic event is inferred to have occurred about 1640 Ma (River Event as illustrated in Figure 34 of Orr et al. (2020)), and included wrench tectonics that generated the major structures of the Lawn Hill Platform, represented by oblique north-south extensional structures. Several subsequent fault reactivations have also variably affected these sequences, including the strike-slip Wide Event which initiated formation of local depocentres containing up to 500 m of Wide Supersequence in the western part of the Doomadgee Fault System (Figure 32; Orr et al. (2020)).

More recent tectonic events, including major faulting, are recorded as a PFS in the Rolling Downs Group (Geoscience Australia, 2013). These events are also inferred to affect other GAB aquifers and partial aquifers within the Isa GBA region, including the Gilbert River Formation, Normanton Formation, Bulimba Formation and Wyaaba beds.

The Rolling Downs Group aquitard provides up to 500 m of very low-permeability cover between the shale gas reservoirs and the shallow groundwater system of the Isa GBA region (Figure 13). This entire sequence is likely disrupted by intraformational polygonal faults, as described in Section 5.4. Although individual faults (that collectively form the PFS) may not always penetrate the entire aquitard sequence, evidence suggests that they may repropagate at sandier intervals within the aquitard (Watterson et al., 2000). Hence tortuous vertical pathways may exist through the Rolling Downs Group that potentially create enhanced vertical permeability and potential fluid leakage conduits. With the basic geometry of these polygonal fault systems, Kulikowski et al. (2018) have established (through geomechanical modelling of this aquitard sequence in the Eromanga Basin) the existence of fluid conduits. Under the current crustal stress regime of the Isa GBA region, maximum horizontal stress is oriented between 121° and 134° (Matthews, 2014). Thus, polygonal faults with orientations between 90° and 160° azimuth could be expected to be dilated and thus may provide localised vertical permeability. There are no quantified estimates of regional vertical permeability in this aquitard, but it is expected to have a wide range of values due to the degree of fracturing.

A regional assessment of potential cross-formational flow through the Rolling Downs Group aquitard was made by comparing the regional watertable and potentiometric pressures within Gilbert River Formation aquifer (Smerdon et al., 2012b). Pressure differentials within the region indicate that groundwater movement is mixed, with multiple bores showing artesian pressure in the Gilbert River Formation aquifer (generally in the north-east), indicating at least the potential for upward migration to occur through the Rolling Downs Group. In addition, enhanced connectivity between these aquifers through the Rolling Downs Group potentially occurs via vertical fluid transfer at a much-reduced rate where it has been compromised by polygonal fault systems.

5.6 Environmental and economic assets

Identified assets in the Isa GBA region that may interact with groundwater and fluids originating from deeper aquifers and shale gas reservoirs of the Isa Superbasin include (refer to Figure 58):

- GDEs such as springs and wetlands (see Sections 4.5.5.1 and 4.5.5.2)
- streams and large lakes, including the Gulf Rivers Strategic Environmental Area
- shallow groundwater bores used for domestic and stock water supply.

As discussed in section 4.5.5.1, a number of conceptual models have been developed by the Queensland Government to describe the processes and characteristics associated with GDEs (MacFarlane et al., 2020; Queensland Government, 2018). The main GDE models applicable to the Isa GBA region are:

- Alluvia – mid (moderate alluvial development) and lower (extensive alluvial development) catchment settings
- Catchment constrictions and stream diversions – identified during this study as occurring in the Nicholson River near Doomadgee, even though this type is not listed in WetlandInfo (Queensland Government, 2018)
- Permeable rocks (rocks with predominantly primary porosity), which can contain one or more unconfined aquifers
- Exclusion zones – formed by rocks with very low permeability, which limits the amount of rainfall that infiltrates to the watertable. These zones commonly consist of fine-grained sedimentary rocks or sediments, as well as metamorphic or igneous rocks. As a result, GDEs are uncommon
- Fractured rocks – formed by rocks that may have low to very low primary porosity (intergranular porosity) but can store and transmit groundwater through an interconnected fracture network (secondary porosity). Lacustrine and palustrine wetlands as well as rivers may depend on the surface expression of groundwater that commonly occurs in stream channels in the upper parts of these landscapes
- Cave ecosystems – identified predominantly where carbonate rocks occur (e.g. Lady Loretta Formation), which may present fractures and/or dissolution openings created by mechanical and chemical weathering (secondary porosity). Divided into four zones,

subterranean caves include the: i) entrance zone; ii) twilight zone; iii) transition zone and iv) deep zone.

Notably, terrestrial GDEs are widespread throughout many parts of both the Nicholson River and Elizabeth Creek floodplains. In particular, the Nicholson River floodplain downstream of Doomadgee (where a possible catchment constriction occurs, as discussed in Section 5.7) is extensively vegetated with terrestrial GDEs (Figure 58).

As described in Section 3.2, the groundwater users that can be considered potential environmental receptors include bores sustaining supplies for stock, domestic, town water, industrial, mining and road maintenance. The carbonates of the Loretta Supersequence (Lady Loretta Formation aquifer) exhibit aquifer properties due to localised high transmissivity and artesian conditions. However, the aquifers of the Carpentaria and Karumba basins (including shallow Cenozoic sediments), collectively identified as GAB aquifers, are the major target for most groundwater users in the region as these aquifers occur at relatively shallow depths (Section 4.1.3).

5.7 Conceptual models of potential connectivity pathways

Simplified conceptual models have been developed that highlight areas of the Isa GBA region where hydrological connectivity may exist between deep shale gas plays and shallower or near-surface assets (including various GAB aquifers, shallow alluvial aquifers, streams and springs). These models integrate key features of the structural and stratigraphic architecture of the region with other available datasets (such as hydrochemistry data) and help to identify important knowledge gaps (Section 7) which may be the focus of future investigations in the Isa Superbasin.

It is critical to recognise that the potential connectivity pathways described in this section are unlikely to exist simultaneously. Furthermore, even if a physical pathway does exist, it does not necessarily mean that the necessary hydrological conditions will occur to directly link fluids derived from the stressor activity (i.e. shale gas development) with any of the key assets that occur closer to or at the surface. Nevertheless, in light of the sparse data and many knowledge gaps previously discussed, it is important to consider all potential pathways as part of this baseline analysis. This section considers the possibility that connectivity may occur between different compartments of the basin, and that such connections may eventually result in changes to environmental or economically important assets (e.g. through fluid migration or changes of pressure gradients associated with extraction of groundwater to support gas development operations).

The analysis and interpretation of available data for the Isa GBA region has recognised that there are five potential hydrological connectivity pathways. These pathways could potentially allow the migration of fluids (such as deep groundwater or gas) from shale gas plays in the Isa Superbasin to overlying assets (such as shallower GAB aquifers and near-surface receptors), despite (in places) a combined thickness of approximately 900 m of overlying Carpentaria and Karumba basins.

The five potential pathways, which are depicted schematically in cross-sections shown in Figure 60, Figure 61 and Figure 62, are:

1. Potential connection via direct stratigraphic contacts
2. Potential connection via deep faults
3. Potential connection through porous aquifers
4. Potential connection through partial aquifers/aquitards
5. Potential connection at catchment constrictions and river diversions.

The key lines of evidence that support the existence of these potential connections include conceptual understanding of aquifer and aquitard geometry and architecture, proximity of assets to major faults that potentially have enhanced zones of vertical continuity, and the presence of direct stratigraphic contacts between unconventional gas plays and shallow aquifers. However, it must be stressed that these are preliminary conceptualisations that are based on relatively sparse geological and hydrological data from within the region. As discussed in Section 7, this work highlights that there is a need to collect additional baseline data to further test these conceptualisations and reduce the existing uncertainty.

In addition to the detailed descriptions below of the five potential connectivity pathways, there are also several other factors within and around the Isa GBA region that are relevant to this discussion:

- The GAB aquifers extend north, east and southwards beyond the boundary of the Isa GBA region. Thus, lateral migration of fluids or gas through these aquifers could potentially affect environmental or ecological assets that occur outside of the region
- Within the Isa GBA region, hydrocarbons are associated not only with the shale gas plays, but may also be associated with conventional petroleum reservoirs. For example, oil shows have been noted from the Schultz Sandstone Member of the South Nicholson Basin (Bailey et al., 2020). This unit is separated from the overlying Carpentaria Basin (which hosts the main GAB aquifers) by the Mullera Formation aquitard, composed of deeper marine siltstones and shales. Nevertheless, very limited information on the thickness and hydraulic properties of the Mullera Formation is currently available to assess its capacity to impede vertical fluid migration from the hydrocarbon reservoirs to GAB aquifers. This is relevant because in the event that tracers that indicate the presence of hydrocarbons are detected in the shallower aquifer systems (i.e. Gilbert River Formation, Normanton Formation, Cenozoic or alluvial) or even near environmental assets (e.g. springs, creeks and GDEs), the potential source of such hydrocarbons could be either associated with conventional or unconventional reservoirs.

Pathway ①: Potential connection via direct stratigraphic contacts

There are at least two plausible scenarios of potential hydraulic connection where direct stratigraphic contact exists between the shale gas plays of the River and Lawn supersequences and the overlying (Gilbert River Formation) and underlying (Lady Loretta Formation) aquifers.

There is limited, local-scale evidence from hydrochemistry data for the potential existence of this pathway, although the interpretation of these data remains equivocal (at least until further groundwater sampling and analyses can be undertaken). Methane concentrations of up to 7320 µg/L of dissolved methane have been recovered from groundwater in a bore screened in the Normanton Formation partial aquifer (EHS Support, 2014) within the region. Likewise, up to 4880 µg/L of dissolved methane has been sampled from a bore tapping the Gilbert River Formation. These 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. Additional methane and hydrochemistry data (ideally collected from multi-level groundwater bores) is required to help confirm or reject the existence of this connectivity pathway in the region. Furthermore, an additional number of bores should be tested in future (if possible) to better understand the spatial extent and variability of methane levels in the GAB aquifers.

The interpretation of potential stratigraphic connectivity between Proterozoic units and the overlying Mesozoic units was used to develop a regional connectivity map for this assessment (Figure 59). This map shows that the highest potential inter-basin connectivity exists in the east of the Isa GBA region where the main Proterozoic aquifer unit (Loretta Supersequence) is in direct contact with the basal aquifer of the Carpentaria Basin (Gilbert River Formation). This map also indicates that there is moderate potential for hydrological connection where an aquifer is in direct contact with an aquitard or a partial aquifer (i.e. central and eastern areas). The lowest potential inter-basin connectivity occurs where an aquitard or partial aquifer is in contact with an aquitard or partial aquifer, as occurs in most of the western part of the region (Figure 59).

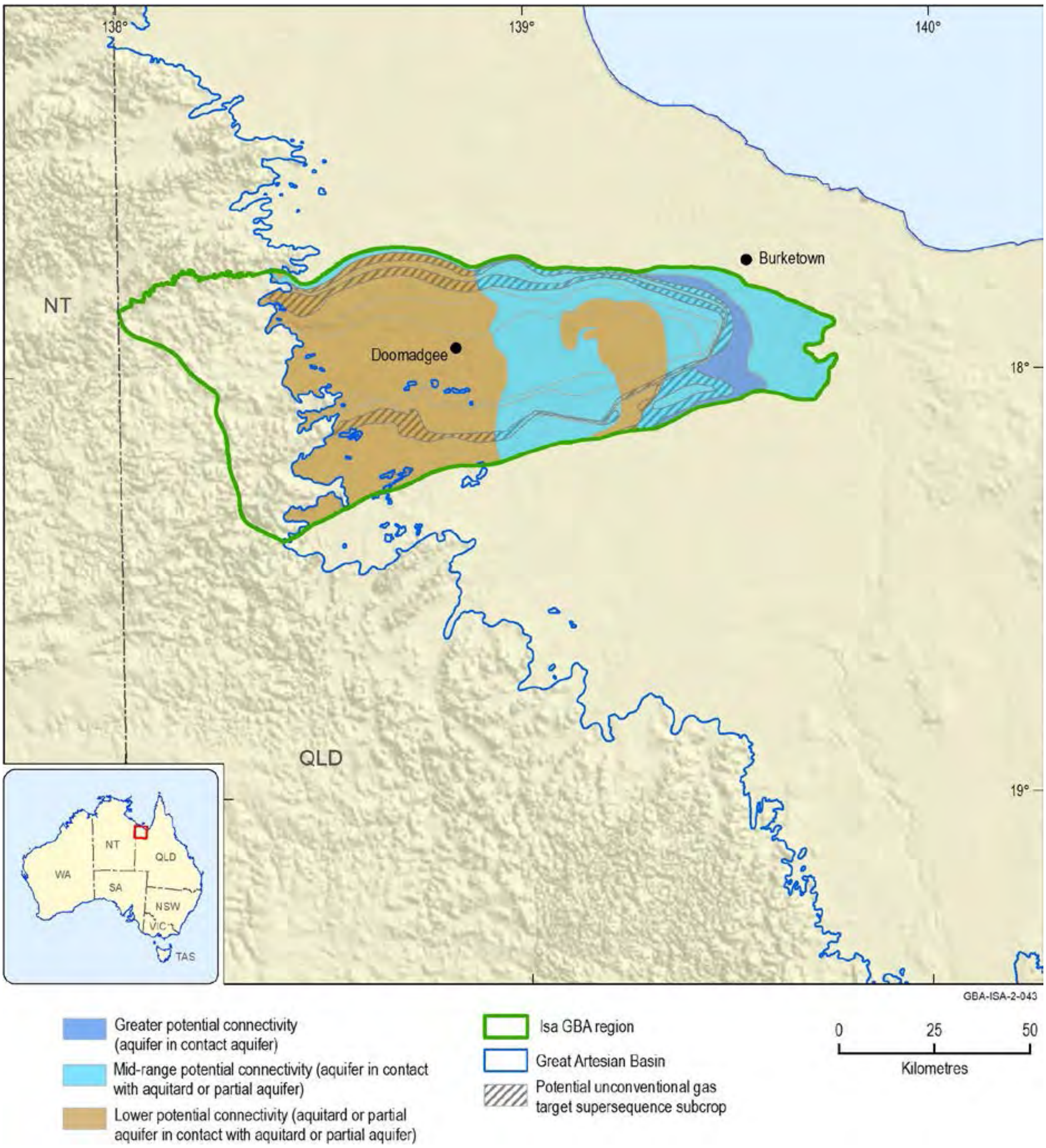

Figure 59 Qualitative interpretation of inter-basin hydrological connectivity between Mesozoic and Proterozoic units in the Isa GBA region

Data: after Bradshaw et al. (2018a)
Element: GBA-ISA-2-043

Pathway ②: Potential connection via deep faults

Faults can cause zones of direct vertical (or sub-vertical) hydraulic connection between different hydrostratigraphic layers (that would not otherwise be connected), and may also laterally compartmentalise hydrological units and associated groundwater flow systems. In the Isa GBA region, 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) and GAB aquifers (such as the Gilbert

River Formation). Such structures may extend upwards from depths of several thousand metres, potentially reaching the Cenozoic near-surface assets such as perched watertables, GDEs and springs. The remainder of the discussion of this particular pathway is focused on potential fault connectivity with springs in and near the region. However, a more comprehensive fault zone analysis that involves multiple complementary methods (e.g. geophysics, structural geology, hydrochemistry and environmental tracers) is recommended to assess the possibility of hydrological connections, and whether groundwater flow systems are preferentially directed along such structural conduits (Underschultz et al., 2018).

The Lawn Supersequence, which is known to host one of the main regional shale gas plays, outcrops approximately 6 km north-east of two springs located within the south-western limits of the Isa GBA region. The top and bottom surfaces of the Lawn Supersequence in the geological model used for this assessment do not extend to the springs in the south-west of the region. However, as shown in cross-section 1 (Figure 60), 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 is currently uncertain.

Three springs to the west of the Isa GBA region (part of the ‘Falling’ spring complex) are near an inferred fault represented in cross-section 1 (Figure 60). The reason for inferring a geological structure near these springs are twofold: firstly, there are sharp changes in the continuity of a geological unit that extends further west in the three-dimensional geological model, and there is also a sharp angle bend (about 90°) in the channel of Musselbrook Creek, which is south of these springs. Secondly, the north-north-west oriented geological structure, intersecting cross-section 1 semi-orthogonally, extends to near the surface, as suggested by the shape of the Musselbrook Creek channel, particularly upstream of its point of sharp inflexion near the surface water gauging station 912106A (Figure 36).

From the analysis of cross-section 2 (Figure 61), it is also possible to infer that three springs associated with the ‘Boodjamulla’ spring complex just outside the region are close to a set of geological structures, including Brinawa Fault and Punjaub Ridge, which may influence connectivity with deeper shale gas units. The fact that the three-dimensional geological model surfaces do not extend further south of Elizabeth Creek Fault is a current data gap in constraining the possible connectivity pathways that may potentially impact these springs.

The springs located south of cross-section 2 (Figure 61) outside of the Isa GBA region are semi-parallel and linearly distributed along an inferred fault in Figure 60, and orthogonal to the features described above (the Brinawa Fault and Punjaub Ridge). The combination of two sets of geological structures that may intersect semi-orthogonally may increase the likelihood for potential connectivity pathways to occur between deeper shale gas intervals and near-surface receptors.

The inferences above suggest that there is considerable uncertainty related to the potential source aquifers of the springs within or near the boundary of the Isa GBA region and that there is a lack of evidence on whether vertical migration of fluids sourced from deeper units is likely to occur along major geological structures. These are important knowledge gaps that would benefit from further investigation as part of future research activities in the Isa GBA region (see Section 7.3).

Pathway ③ Potential connection through porous aquifers

Some degree of groundwater flow (presently unquantified) is likely to occur in the Proterozoic hydrostratigraphic units immediately adjacent to the shale gas plays in the Isa GBA region. As depicted in Figure 60, the main Proterozoic aquifers of the Isa Superbasin are the partial aquifer of the Widdallion Sandstone Member (Pmh 5) and karstic zones of the Loretta Supersequence (Lady Loretta Formation aquifer). In addition, the Gilbert River Formation aquifer directly overlies the upper shale gas play in the east of the Isa GBA region.

Lateral and vertical connectivity within the Loretta Supersequence aquifer may be affected 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 61 and Figure 62. Nevertheless, the potential compartmentalisation of the Loretta Supersequence aquifer by structural elements does not rule out some degree of lateral and vertical fluid migration in this highly heterogeneous aquifer system.

Direct evidence for groundwater movement in the confined Gilbert River Formation aquifer is limited. Ransley et al. (2015b) produced a map indicating that regional groundwater flow in this aquifer is north-east from the Isa GBA region, towards the Gulf of Carpentaria. Hydraulic heads vary from 80 m to 40 mAHD with an approximate gradient of 0.03%. However, it is important to note that the Gilbert River Formation occurs only in subcrop in the region, and there is a high level of uncertainty associated with the location, extent and rate of its recharge processes (particularly evidence to support the inferred north-easterly flow direction proposed by Ransley et al. (2015b). Nevertheless, there is some evidence to confirm that the aquifer is porous and that sufficient hydraulic gradient exists to promote fluid migration, both laterally and vertically within this aquifer.

Figure 20 illustrates the inferred groundwater flow direction of the regional watertable aquifer. As such, this flow map indicates that hydraulic gradients are also likely to be present in the groundwater systems of the Normanton Formation and the overlying Cenozoic sediments of the Karumba Basin.

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 polygonal faulting, as previously discussed in Section 4.1.2.2. However, as shown in Figure 13, 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 pathway across its entire vertical thickness.

The Normanton Formation partial aquifer is considered part of the Rolling Downs Group and is in direct stratigraphic contact with the underlying aquitard. There is limited hydraulic data available for the Normanton Formation with only one bore registered in the groundwater database (Geoscience Australia, 2018f; Department of Natural Resources, Mines and Energy (Qld), 2018d). However, artesian pressure in the confined Gilbert River Formation aquifer suggests that an upward pressure gradient exists. Thus, if a sufficiently connected polygonal fault system exists in the Rolling Downs Group to have formed a coherent pathway for fluids to flow, there may be a hydraulic driver for groundwater to flow upwards from the lower GAB aquifer.

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. 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 underlying (and hydraulically connected) sedimentary rocks and upward groundwater pressure gradients may exist (Figure 61 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 associated streams. Hydraulic pressure reduction in the sub-alluvial bedrock, or conversely a water level drop in the alluvial aquifer, may 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 of 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 eastern flow direction further downstream) (Figure 57). Such stream diversions are commonly 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 61 inset), and the alluvial system becomes considerably thinner and narrower. As a result, there is potential for existing connectivity and for groundwater and/or gas migration pathways between sub-alluvial bedrock, alluvium and streams, and more baseline monitoring data are required to confirm the degree of connectivity.

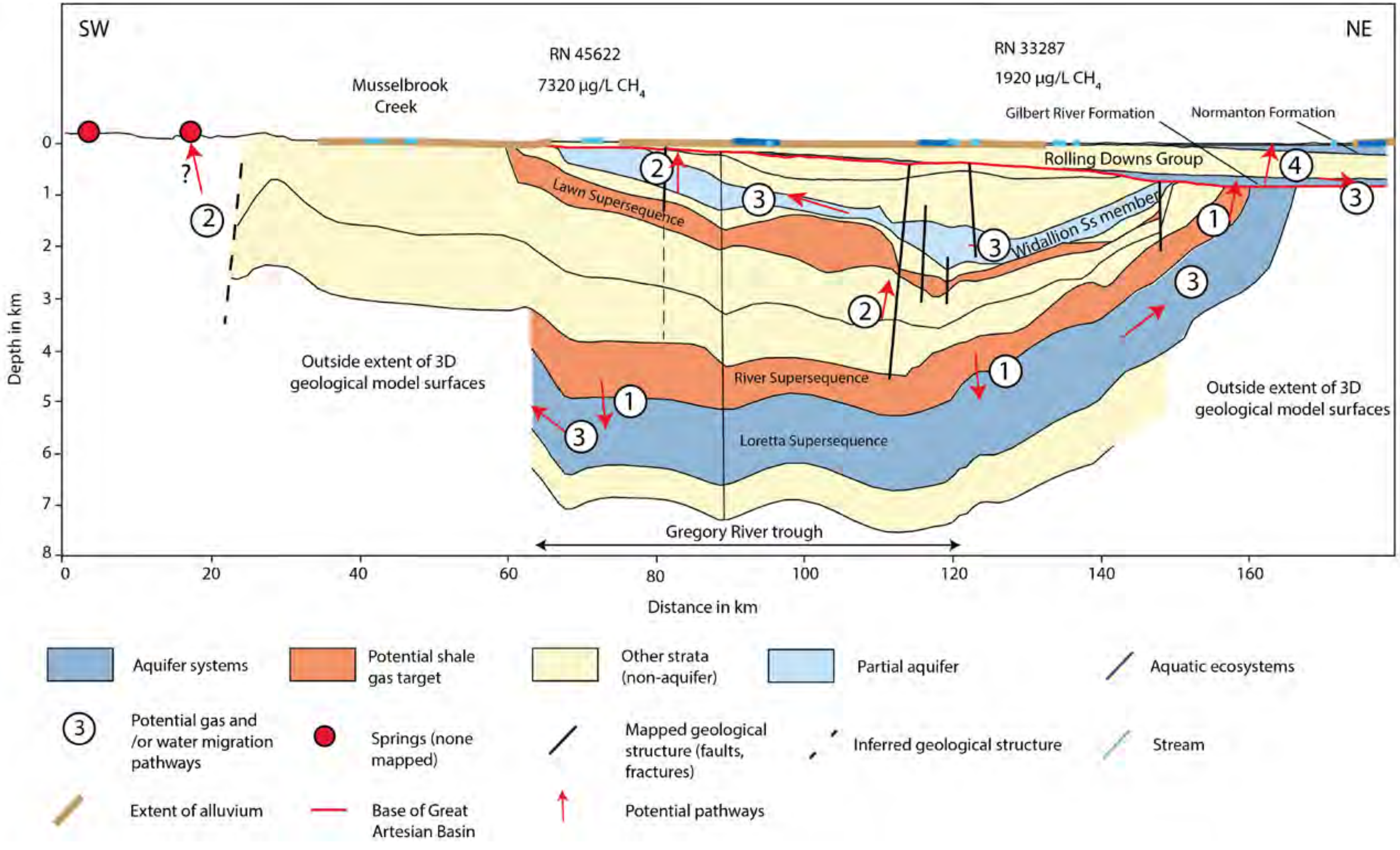

Figure 60 Cross-section 1 through the Isa Superbasin and South Nicholson, Carpentaria and Karumba basins, representing inferred Isa Superbasin margins and major geological structures, and potential natural connectivity pathways for water or gas migration

The four potential connectivity pathways shown here are: Pathway 1 –via direct stratigraphic contact, Pathway 2 –through deep-seated faults, Pathway 3 –through porous aquifers, and Pathway 4 –through partial aquifers/aquitards. See Figure 57 for location of this south-west to north-east cross-section.
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. (2018b), structural features obtained from Ransley et al. (2015b); Bradshaw et al. (2018b) and Geoscience Australia (2013)
Element: GBA-ISA-2-220

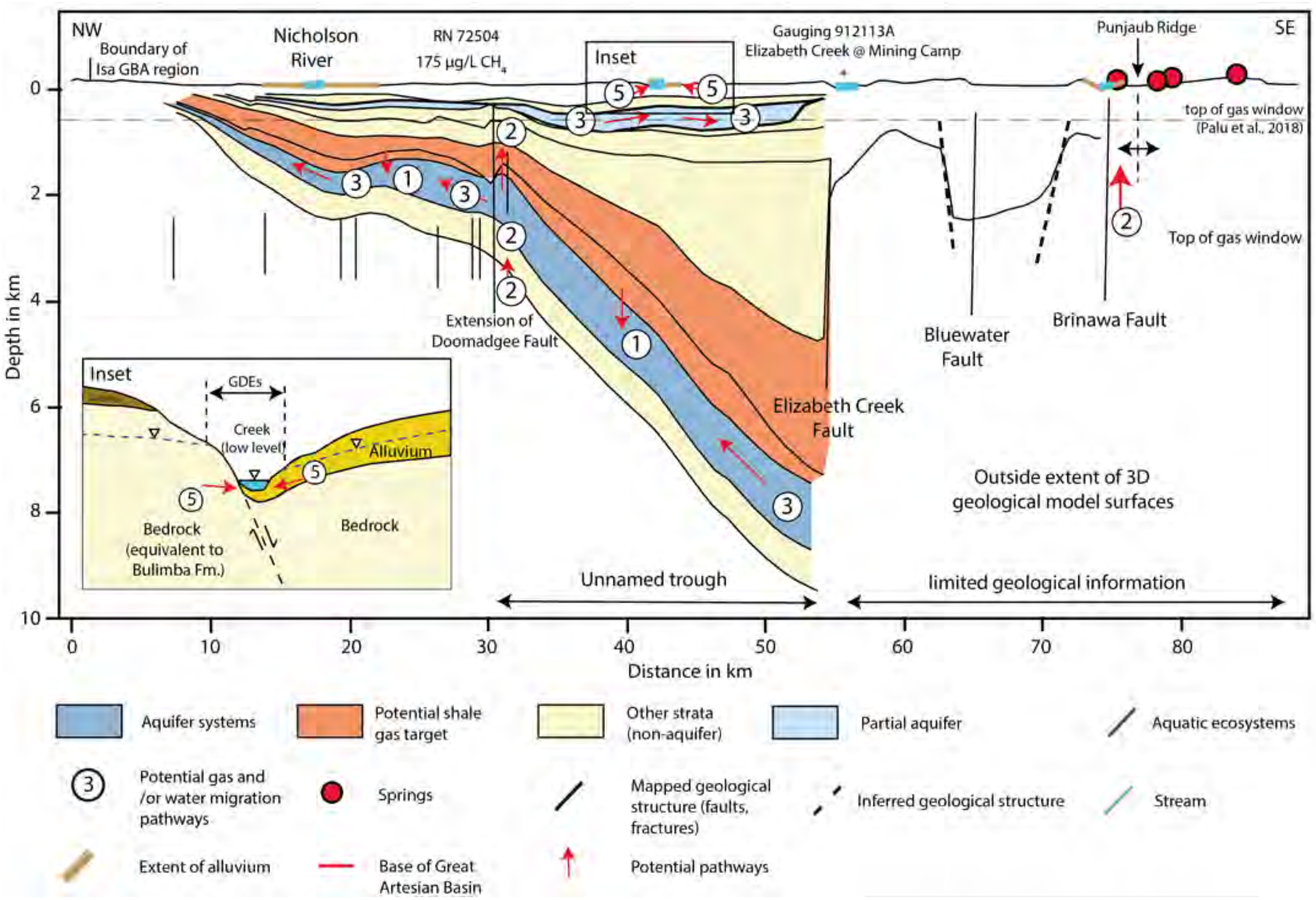

Figure 61: Cross-section 2, with NW – SE orientation, representing likely geological structural control of springs located to the south near the Punjaub Ridge

The potential connectivity pathways shown here are: Pathway 1 – via direct stratigraphic contact, Pathway 2 – through deep-seated faults, Pathway 3 – through porous aquifers, Pathway 4 – through partial aquifers/aquitards, and Pathway 5 – at catchment constrictions. See Figure 57 for location of this north-west to south-east cross-section.

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. (2018b), structural features obtained from Ransley et al. (2015b); Bradshaw et al. (2018b) and Geoscience Australia (2013)

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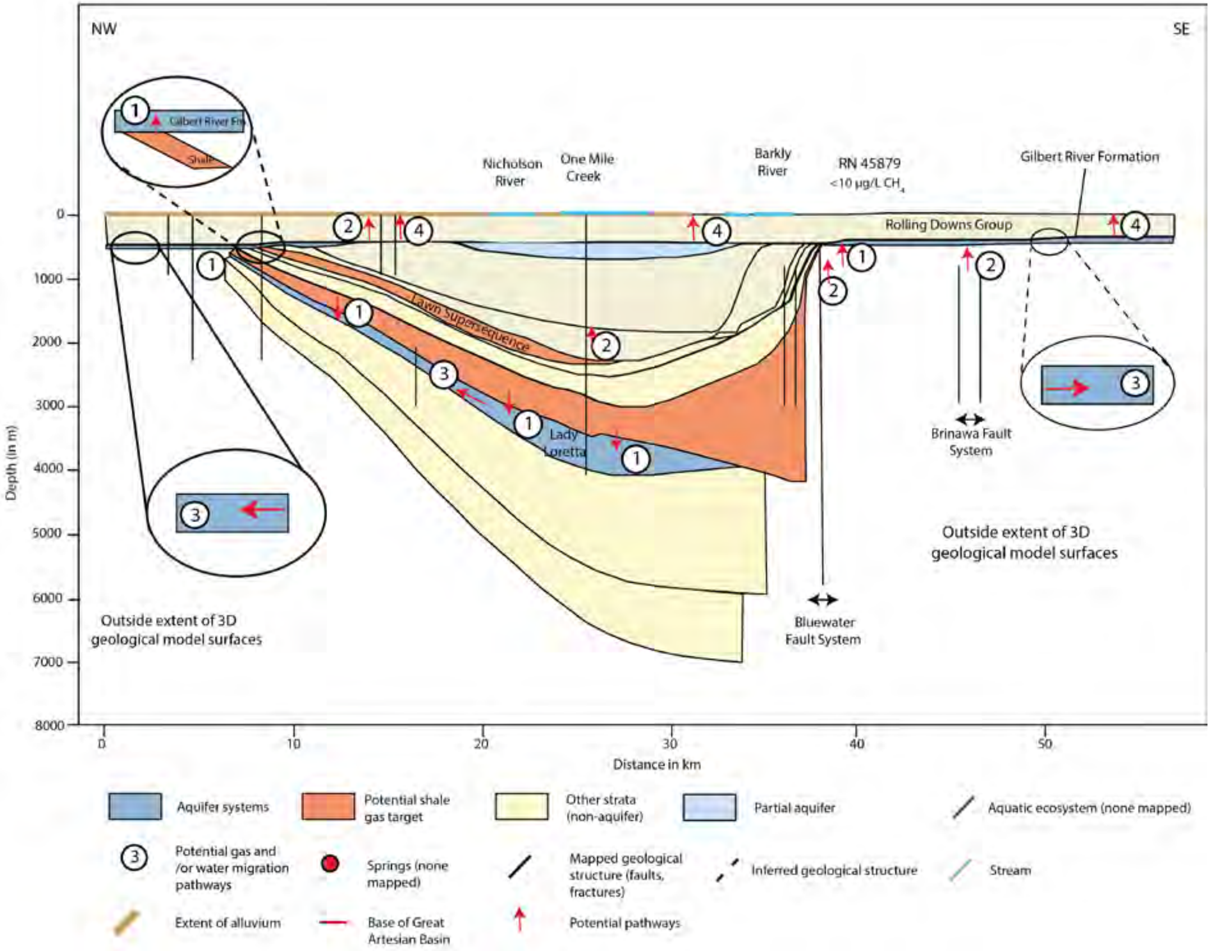

Figure 62 Cross-section 3 representing Gregory River Trough and major faults at the southern margin of Isa Superbasin, potentially controlling occurrence of pathways

The four potential connectivity pathways shown here are: Pathway 1 –via direct stratigraphic contact, Pathway 2 –through deep-seated faults, Pathway 3 –through porous aquifers, and Pathway 4 –through partial aquifers/aquitards. See Figure 57 for location of this south-west to north-east cross-section.

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. (2018b), structural features obtained from Ransley et al. (2015b); Bradshaw et al. (2018b) and Geoscience Australia (2013)

Element: GBA-ISA-2-221

6 Conclusions

Research into the hydrogeology and groundwater systems of the Isa GBA region has supported the baseline assessment (Stage 2) of the geological and bioregional assessment of the Isa GBA region. The key findings of this research, as presented within this document and based largely on the compilation and analysis of existing data, are summarised within this section for the main research themes of:

- groundwater systems
- groundwater data
- surface water – groundwater interactions
- connectivity pathways from shale gas reservoirs to assets.

6.1 Groundwater systems

Two broad and potentially connected groundwater systems exist in the Isa GBA region:

- The groundwater associated with the Proterozoic rocks of the Isa Superbasin and South Nicholson Basin – typically the deeper system.
- The overlying groundwater system of the Carpentaria Basin (part of the Great Artesian Basin (GAB)) and Karumba Basin.

The Carpentaria and Karumba basin aquifers, which include the regional watertable, are the most widely used aquifers in the Isa GBA region.

From the information available, the water required to support any future unconventional gas development (e.g. water for drilling and hydraulic fracturing) could be provided from groundwater sourced from the Carpentaria and Karumba basins. These basins host the relatively shallow near-surface aquifers that cover most of the Isa GBA region, and contain groundwater of suitable quality for these purposes.

6.1.1 Isa Superbasin and South Nicholson Basin groundwater systems

- Strata from the Isa Superbasin and South Nicholson Basin range in thickness from less than 1 km over the southern flanks of the Murphy Inlier where they outcrop, to a maximum of about 9 km in the south-west of the Isa GBA region.
- The Proterozoic rocks are typically highly lithified with low primary porosity and permeability, although there are some notable aquifers and partial aquifers are in the Isa Superbasin and South Nicholson Basin.
- The main Proterozoic aquifer is in the Loretta Supersequence (Lady Loretta Formation) which at subcrop is host to cavernous limestone.

- Other water-bearing units are classified as partial aquifers, including (along with their equivalents): Esperanza and Paradise Creek Formations of the Gun Supersequence; the Bulmung Sandstone of the Lawn Supersequence; Widdallion Sandstone Member of the Wide and Doom Supersequence and the Elizabeth and Constance sandstones of the South Nicholson Basin.
- The driver of reported artesian groundwater pressure in the Lady Loretta Formation remains unclear, although gas overpressure from the shale gas units is a possibility. Groundwater of the Isa Superbasin is directly connected with the Gilbert River Formation (the basal aquifer of the Carpentaria Basin).
- Limited hydrochemistry data indicates that the groundwater from the Isa Superbasin and South Nicholson basins do not share a common geochemical signature with the groundwater of the Gilbert River Formation, which suggests that inter-basin connectivity is not common or widespread.
- The two primary shale gas plays of the Isa Superbasin (River and Lawn supersequences) are classified as aquitards.
- The South Nicholson Basin is well-indurated and contains brittle rocks that may be more prone to localised fracture or fault-related permeability where folded. This includes the Constance and Elizabeth sandstones.
- Groundwater quality in the Proterozoic aquifers is spatially and chemically variable and is typically of low to moderate salinity.
- Groundwater flow dynamics are not well understood. This is both a result of the low number of bores in the region and the lack of groundwater level data from those that do exist. The available data suggests that there is significant short-scale variation in groundwater levels. The reasons for these variations remain uncertain, although one possibility is that they indicate fault-controlled groundwater compartmentalisation due to major geological structures associated with the Doomadgee Fault System, Nicholson River Fault Zone and the Calvert Fault.

6.1.2 Carpentaria Basin

The Isa GBA region is at the north-western margin of the Carpentaria and Karumba basins, and basin strata gradually thicken eastwards away from the region. Within the region, the Karumba Basin has a maximum thickness of approximately 50 m, whereas the Carpentaria Basin is up to 900 m thick.

The Carpentaria Basin hosts a variably confined groundwater system comprising multi-layered aquifers of variable character, within predominantly continental-derived sandstones.

Gilbert River Formation aquifer

- The basal aquifer of the Carpentaria Basin in the region is the Gilbert River Formation, a confined, typically artesian aquifer. Groundwater flow direction is inferred to be towards the north-east across the region, although the low sampling density means that there is considerable uncertainty about this interpreted flow direction.

- Re-interpretation of seismic data and exploration well reports indicates that the Gilbert River Formation is spatially restricted to the eastern part of the Isa GBA region.
- The thickness of the aquifer increases from west to east in the region, from a zero edge (i.e. aquifer boundary) in the Doomadgee area to over 200 m thick near Burketown.
- Average bore depth accessing water from the Gilbert River Formation is 472 m, with a maximum of 701 m. A total of 22 groundwater bores access the Gilbert River Formation within or near the Isa GBA region (Geoscience Australia, 2018f).
- The Gilbert River Formation has low to moderately saline groundwater. The hydrochemical signature is typical of groundwater in the GAB that has migrated a substantial distance (i.e. 100's of kilometres) from the point of recharge and undergone hydrochemical evolution along its flow path. This evidence supports the theory that recharge occurs on the eastern slopes of the Great Dividing Range.

Rolling Downs Group aquitard

- Re-interpretation of seismic data and exploration well reports indicates that the Rolling Downs Group aquitard (consisting of the Allaru Mudstone, Toolebuc Formation and Wallumbilla Formation) extends to the western margin of the Carpentaria Basin in the Isa GBA region. Maximum thickness is up to 600 m in the east of the region.
- The Rolling Downs Group aquitard has variable hydraulic properties, and is typically an aquitard or leaky aquitard. However, some thin and isolated sandier zones within the aquitard may yield limited volumes of groundwater.
- According to the Queensland groundwater database, six bores in or near the region access groundwater from this aquitard, with an average bore depth of 90 m and maximum depth of 192 m.
- Polygonal faulting is widespread in the Rolling Down Group aquitard, particularly within the Toolebuc Formation. It is conceptually possible (though equivocal) that polygonal faults may provide a conduit with enhanced vertical permeability that permits fluid leakage between the Gilbert River Formation (under artesian pressure) and the overlying Normanton Formation and Karumba Basin sediments.
- From limited sampling data, the hydrochemical signatures of the Gilbert River Formation aquifer (below the Rolling Downs Group aquitard) and the aquifers above the Rolling Downs Group aquitard are significantly different, indicating that widespread vertical movement of groundwater in the Carpentaria Basin is unlikely.

Rolling Downs Group – Normanton Formation aquifer

- The Normanton Formation, the upper unit of the Rolling Downs Group, is considered a partial aquifer.

- Through re-interpretation of seismic data and exploration well reports, the formation has a maximum thickness of approximately 300 m in the Burketown area and is present in the east of the Isa GBA region.
- According to the Queensland groundwater database one bore in the region accesses groundwater from the Normanton Formation at a depth of 39.5 metres below ground level.
- Groundwater in this formation interacts widely with the water-bearing units of the overlying Karumba Basin.
- Recharge is thought to occur mainly from infiltration through the overlying Karumba Basin. Also, the Gilbert River Formation may contribute minor recharge if some degree of leakage occurs through the polygonal faults of the Rolling Downs Group aquitard.

6.1.3 Karumba Basin

- The Cenozoic Karumba Basin is typically less than 50 m thick and is the uppermost sedimentary basin in the region, extending to the western edge of the Carpentaria Basin.
- The basin is comprised of three main hydrogeological units: the Armraynald beds (Pliocene to Pleistocene); Wyaaba beds (Miocene) and Bulimba Formation (Paleocene to Eocene), typically with leaky aquifer, partial aquifer and partial aquifer properties respectively.
- Localised patches of Gregory Downs Limestone (a unit of the Wyaaba beds) exhibit aquitard properties, creating a variably semi-confined system in the region.
- The Bulimba Formation is the most commonly used aquifer of the Karumba Basin (Queensland groundwater database) with nine bores installed in or near the region. Bore screen depth averages 37 m below ground level with a maximum of 45 m.
- Alluvial deposits are widespread in the lower gradient, lower elevation regions. A total of seven bores in the Queensland groundwater database access groundwater from alluvial deposits. Bores are generally shallow, typically around 5 metres below surface, although may be up to 21 m deep. Yields for this aquifer are generally low.
- Throughout the region, the watertable aquifer is mostly in the Karumba Basin. The elevation of the watertable varies from over 60 mAHD in the western margin of the basin to 0 mAHD to the east of Burketown. The watertable elevation remains relatively flat at 0 mAHD for over 30 km at which point it meets the Gulf of Carpentaria.
- The potential for seawater intrusion into the shallow groundwater system exists in the region to the east of Burketown, where only a small change in gradient (e.g. due to pumping) could lead to inland movement of seawater into the watertable aquifer.
- Recharge to this aquifer is through diffuse recharge from rainfall and also some degree of river recharge.

- Salinity levels show considerable spatial variability in the regional aquifer, and groundwater is generally slightly or moderately saline. Total dissolved solids (TDS) in groundwater range from 191 mg/L to 6912 mg/L with an average of 1791 mg/L.

6.2 Groundwater data

- Groundwater bore data are sparse within and near the Isa GBA region, with most bores missing some key information such as the depth at which groundwater is drawn (i.e. missing screened/open intervals depths), stratigraphy information and salinity data. Of the registered bores analysed for this study, 60 contained sufficient stratigraphic and other information to attribute a source aquifer.
- The number of groundwater depth measurements is very limited. On average, the registered bores had approximately two measurements for each bore, with a maximum number of measurements of 16 at a bore in the Karumba Basin.
- The 18 petroleum and stratigraphic exploration wells situated within and around the Isa GBA region provide additional stratigraphic and petrophysical information about the regional aquifers. However, there is very little direct hydrological information from these wells, such as pressure data or groundwater samples.

6.3 Surface water – groundwater interactions

The interactions between groundwater and surface water are a key component of the hydrogeological system and are important for supporting a variety of ecosystems in the Isa GBA region. Approximately one-third of the region has identified terrestrial and aquatic GDEs, including nationally important wetlands (such as Bluebush Swamp and the Musselbrook Creek Aggregation), protected areas, strategic environmental areas (Gulf Rivers) and a number of instream waterholes with important biodiversity values. Terrestrial GDEs in the region are associated with river floodplains, whereas aquatic GDEs are mostly associated with stream channels and springs. Non-GAB springs occur in the south-west, both within and outside the margins of the region. The source of the springs is unknown; however, geological structures may provide pathways that connect these surface water features with underlying Proterozoic aquifers. Activities associated with the development of shale gas have the potential to impact on some of the environmental assets of the region (see the Stage 2 synthesis report for the Isa GBA region for further discussion of potential impacts (Lewis et al., 2020)).

Based on analysis of available streamflow, groundwater, geology and remote sensing datasets, together with existing information on springs and other GDEs, the interactions between groundwater and surface water systems in the Isa GBA region can be summarised as:

- In the alluvial floodplains east of Doomadgee and to the south-west (Elizabeth and Musselbrook creeks), sediments of the Karumba Basin have the potential to be hydraulically connected with surface waters and support GDEs. At the coastal fringe, shallow groundwater also potentially supports coastal and estuarine ecosystems. The mechanisms of surface water – groundwater interaction are likely to vary temporally and spatially and lead to both gaining and losing stream reaches and seasonally variable wet/dry areas in the landscape.

- In the south-west of the region, outside of the GAB, there is potential for groundwater discharge from Proterozoic sandstone aquifers (either of the South Nicholson Group or the Isa Superbasin) to support aquatic ecosystems, including springs.
- Lawn Hill Creek and the Gregory River flow into the region from the south, both of which are perennial along their upper reaches due to Cambrian limestone source aquifers in the Georgina Basin (outside of the Isa GBA region). Streamflow is sustained in the lower Nicholson River by inflow from the Gregory River and possible baseflow contributions from the Karumba Basin sediments.
- Groundwater discharge from the regional watertable aquifer into the Gulf of Carpentaria potentially provides a source of freshwater for marine ecosystems, although very little knowledge exists about these processes.

The application of remote sensing methods has enabled a consistent approach to mapping parts of the landscape with potential dependence on groundwater, including identification of previously unmapped springs. This has enhanced understanding of surface water – groundwater interactions, complementing the analyses based on limited streamflow, groundwater and geological information.

6.4 Potential connectivity pathways from shale gas targets to assets

Multiple geoscientific datasets have been integrated to develop conceptual models that describe possible hydrological connections that exist between potential future system stressors (i.e. the development of shale gas plays in the Isa GBA region) and overlying environmental and economic assets (e.g. shallower groundwater systems, springs, surface water and ecosystems dependent on groundwater discharge).

These conceptual models are based on the interpretation of several two-dimensional cross-sections, developed during this study and based largely on a newly available three-dimensional geological model of the region (see the geology technical appendix (Orr et al., 2020)). The cross-sections extend vertically upwards from the deeper Proterozoic units of the Isa Superbasin to the near-surface Cenozoic sediments of the Karumba Basin, and their immediate vicinity. The conceptualisations integrate the currently available information about fault zone architecture and the regional stratigraphic framework, and compare geological architecture and structure with the spatial distribution of important surface assets.

At least five potential existing hydrological pathways may connect deeper shale gas reservoirs to shallower aquifers, surface water systems and environmental assets in the Isa GBA region. These naturally occurring hydrological connections are:

1. direct stratigraphic contact
2. deep-seated faults
3. through porous aquifers
4. through the Rolling Downs Group aquitard
5. at catchment constrictions and river diversions, potentially controlled by geological structures.

Dissolved gas concentrations within the Gilbert River Formation aquifer and Normanton Formation partial aquifer provide some evidence of potential existing connectivity between deep and shallow hydrogeological system components. Generally though, this assessment highlights that very considerable data and knowledge gaps exist, while emphasising important research questions that can be addressed in future studies to determine the likelihood of identified pathways from stressors to assets.

7 Data gaps, key uncertainties and possible research directions

From a hydrogeological perspective, the Isa GBA region is relatively unexplored. The paucity of information is largely due to the low number of groundwater bores, which typically are a primary source of hydrogeological information for any groundwater study. The average bore density in the region according to the Queensland groundwater database is one bore every 127 km^2 (190 bores in 24,000 km^2).

The level of uncertainty about many spatial and temporal characteristics of the groundwater systems in the region is relatively high as a result of the lack of hydrogeological data. This is particularly the case for the deeper groundwater systems of the Isa Superbasin and South Nicholson Basin, as most groundwater bores (and previous investigations) have focused on the shallower groundwater systems of the Carpentaria and Karumba basins.

To better inform future management of the region's groundwater resources, and as potential inputs to any future impact modelling and assessment, the GBA research team has identified several primary data gaps, and suggested a number of approaches to improve overall hydrogeological knowledge of the Isa GBA region.

7.1 Intra-basin and inter-basin groundwater connectivity

There is currently only limited understanding of intra-basin and inter-basin groundwater connectivity in the Isa GBA region. From the analysis of existing datasets and an integrated assessment of the structural geology and hydrogeological characterisation of the Isa Superbasin–South Nicholson–Carpentaria–Karumba basins, five potential natural hydrogeological pathways have been identified from this study. These pathways may link aspects of future shale gas development to environmental and economic assets at or near the surface. In summary, these are direct stratigraphic contact, fault pathways, connection through aquifers; migration through aquitards and enhanced connectivity at catchment constrictions and river diversions.

However, the degree to which the potential hydrological pathways may interact with or be affected by any future shale gas development is poorly understood. To better address this important knowledge gap and help reduce uncertainties relating to future management options, further prioritised data collection and analysis is required. Table 14 presents a summary of the five key potential hydrogeological pathways and proposed future data collection strategies required to address the most critical knowledge gaps recognised from this investigation.

7.2 Groundwater dynamics and baseline data

There are relatively high levels of uncertainty surrounding groundwater dynamics in most aquifers of the region, including the seasonal variation in groundwater elevation, groundwater flow directions and lag time in response to rainfall and associated streamflow events. To improve the understanding of system hydrodynamics, new baseline data with enhanced temporal and spatial resolution are required.

Given the existing knowledge gaps, the collection of additional groundwater level data for key aquifers (e.g. Karumba Basin aquifers, Gilbert River Formation) would improve the spatial and temporal coverage of existing baseline data. Ideally, the acquisition of these new datasets should occur at the end of the wet season, as well as at the end of the dry season, so as to better capture any distinctive seasonal trends. Data logging of selected bores proximal to monitored river stages or rainfall sensors is also recommended to develop high temporal resolution understanding of hydrological system dynamics. Furthermore, sampling these bores for selected hydrochemical analyses (e.g. isotopic tracers) would provide additional data to evaluate recharge sources and mixing processes.

7.3 Surface water – groundwater interactions

There are no active stream gauges in the Isa GBA region and therefore analysis of streamflow data has been based on historical information, which may or may not reflect the more recent hydrological conditions. The paucity of baseline groundwater and streamflow data has resulted in considerable uncertainty in the dynamics of surface water – groundwater interactions. The availability of continuous long-term time series streamflow data, at a number of gauges spaced along the main stream channels, would enable quantification of volumetric baseflow contributions to surface waters at different times of the year. Accurate bore and stream gauge elevations, together with relevant lithological information (i.e. of the bore screen and streambed), would also improve understanding of the potential for connectivity.

Hydrochemistry data, collected along stream transects, in waterholes and from springs, would improve understanding of source aquifers for important regional GDEs. These are critical data for spring characterisation and sustainable management of key aquifers, as well as monitoring potential impacts on environmental assets that may arise from future shale gas development.

Preliminary analyses of remote sensing data has helped assess surface water–groundwater interactions where the availability of other spatial and temporal datasets has been limited. In particular, remote sensing has enabled assessment of parts of the landscape that retain water during the dry season and are the most likely areas to support GDEs. This includes the identification of previously unmapped springs both within and near to the region. Additional remote sensing data products and assessment methods are available which could further enhance mapping of GDEs and the understanding of surface water–groundwater interactions. For example, assessment of different spectral bands (such as the greenness band or vegetation indices during a range of time periods) would enable a more comprehensive and consistent temporal assessment of GDEs. More detailed statistical and time series trend analyses of a range of datasets available from Digital Earth Australia (DEA), and integration with other data, could further improve understanding of regional and local-scale processes. Field validation of remote sensing data products in targeted areas would be required to confirm the interpretations made in this assessment. In particular, the use of hydrochemistry and environmental tracers to confirm areas where groundwater potentially discharges as springs and into streams, could help to reduce existing conceptual uncertainties.

Table 14 Summary table linking identified potential connectivity pathways, evidence based on current data and knowledge, key data and knowledge gaps and recommended future research activities

Potential hydrological connections		Hydrological and environmental assets potentially affected	Evidence base	Potential research questions	Possible focus areas for future research and investigation
Path way 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 Loretta Supersequence aquifer. The occurrence of mapped faults intersecting the Proterozoic units near their contact with the main GAB aquifer (eastern part of Isa GBA region) provides the potential for this connectivity pathway to occur (through hydraulic connectivity promoted by secondary permeability).	Water bores that access the GAB and shallower aquifers as well as cavernous parts of Loretta Supersequence aquifer, the Widdallion partial aquifer, and any surface water bodies and GDEs.	• Zones of direct stratigraphic contact between shale gas plays and groundwater assets (Widdallion partial aquifer, GAB and Loretta Supersequence aquifers) are represented in cross-sections (Figure 60, Figure 61, and Figure 62). • NW-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 the Loretta Supersequence aquifer is under artesian pressure and is the most widely accessed formation of the Isa Superbasin for groundwater use.	• What is the travel distance and travel time that water and/or gas can migrate from the Proterozoic shale gas reservoirs into the overlying GAB and underlying Loretta Supersequence 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 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 Loretta Supersequence aquifer will be reduced by depressurisation of the overlying gas plays, particularly the River Supersequence? What is the extent of potential impact 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 Loretta Supersequence aquifer due to shale gas development via depressurisation and hydraulic fracturing.
Path way ②	**Potential connection through deep-seated faults** that may intersect shale gas reservoirs in the River Supersequence and overlying Proterozoic partial aquifer (Widdallion Sandstone Member of Lawn Hill Formation – Pmh 5) and some 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-west 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 3D 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 a groundwater sampling campaign to better constrain the source of springs near mapped faults, with particular focus on groundwater tracers to evaluate potential source contribution from deeper geological units (e.g., 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 ^{87}Sr/^{86}Sr. • Perform shallow geophysical surveying (e.g. using transient electro-magnetic methods (TEM)) to locate and characterise geological structural features 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.
Path way ③	**Potential connection through 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. 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., 2015b). It is most likely to occur considering the high yields reported in the cavernous zones of the Loretta Supersequence 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		Hydrological and environmental assets potentially affected	Evidence base	Potential research questions	Possible focus areas for future research and investigation
Path way ④	**Potential connection through partial aquitards**, such as the Rolling Downs Group partial aquitard via polygonal fault systems (PFS).	Bores that access the overlying Normanton Formation partial aquifer.	• Groundwater under artesian pressure within the underlying Gilbert River Formation aquifer may promote upwards 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 polygonal fault systems?	
Path way ⑤	**Potential connection at catchment constrictions** and/or 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) 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.

2D = two-dimensional; 3D = three-dimensional; GAB = Great Artesian Basin; GDE = groundwater-dependent ecosystem; GW = groundwater; O&G = oil and gas; SW = surface water; TEM = transient electromagnetics

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Glossary

The register of terms and definitions used in the Geological and Bioregional Assessment Program is available online at http:/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

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

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.

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.

carbonaceous shale: organic-rich shales that contain less total organic carbon (TOC) than coals (50 wt.% TOC)

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

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).

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

confined aquifer: an aquifer saturated with confining layers of low-permeability rock or sediment both above and below it. It is under pressure so that when the aquifer is penetrated by a bore, the water will rise above the top of the aquifer.

conglomerate: a sedimentary rock dominated by rounded pebbles, cobbles, or boulders

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

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

Cooper Basin: the Cooper Basin geological province is an Upper Carboniferous – Middle Triassic geological sedimentary basin that is up to 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 km2, 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.

crust: the outer part of the Earth, from the surface to the Mohorovicic discontinuity (Moho)

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.

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.

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

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.

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.

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

effect: 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).

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

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

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.

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

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

geological architecture: the structural style and features of a geological province, like a sedimentary basin

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

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.

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

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

hydrological connectivity: a descriptive measure of the interaction between water bodies (groundwater and/or surface water) 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 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.

intrusion: the process of emplacement of magma into pre-existing rock

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.

likelihood: probability that something might happen

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

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.

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.

normal fault: a fault in which the hanging wall appears to have moved downward relative to the footwall, normally occurring in areas of crustal tension

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

organic matter: biogenic, carbonaceous materials. Organic matter preserved in rocks includes kerogen, bitumen, oil and gas. Different types of organic matter can have different oil-generative potential.

outcrop: a body of rock exposed at the surface of the Earth

overpressure: occurs when the pore pressure is higher than the hydrostatic pressure, caused by an increase in the amount of fluid or gas in the rock, or changes to the rock that reduce the amount of pore space. If the fluid cannot escape, the result is an increase in pore pressure. Overpressure can only occur where there are impermeable layers preventing the vertical flow of water, otherwise the water would flow upwards to equalise back to hydrostatic pressure.

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

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

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.

porosity: the proportion of the volume of rock consisting of pores, usually expressed as a percentage of the total rock or soil mass

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

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.

recharge: see groundwater recharge

reserves: quantities of petroleum anticipated to be commercially recoverable in known accumulations from a given date forward under defined conditions. Reserves must further satisfy four criteria: they must be discovered, recoverable, commercial and remaining (as of the evaluation date) based on the development project(s) applied.

reservoir: a subsurface body of rock having sufficient porosity and permeability to store and transmit fluids and gases. Sedimentary rocks are the most common reservoir rocks because they have more porosity than most igneous and metamorphic rocks and form under temperature conditions at which hydrocarbons can be preserved. A reservoir is a critical component of a complete petroleum system.

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)

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.

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.

siltstone: a sedimentary rock composed of silt-sized particles (0.004 to 0.063 mm in diameter)

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

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.

surface water: water that flows over land and in watercourses or artificial channels and can be captured, stored and supplemented from dams and reservoirs

tectonics: the structural behaviour of the Earth's crust

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.

terrane: an area of crust with a distinct assemblage of rocks (as opposed to terrain, which implies topography, such as rolling hills or rugged mountains) 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 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.

trap: a geologic feature that permits an accumulation of liquid or gas (e.g. natural gas, water, oil, injected CO_2) and prevents its escape. Traps may be structural (e.g. domes, anticlines), stratigraphic (pinchouts, permeability changes) or combinations of both.

unconfined aquifer: an aquifer whose upper water surface (watertable) is at atmospheric pressure and does not have a confining layer of low-permeability rock or sediment above it

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

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

water system: a system that is hydrologically connected and described at the level desired for management purposes (e.g. subcatchment, catchment, basin or drainage division, or groundwater management unit, subaquifer, aquifer, groundwater basin)

water use : the volume of water diverted from a stream, extracted from groundwater, or transferred to another area for use. It is not representative of 'on-farm' or 'town' use; rather it represents the volume taken from the environment.

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’.

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