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BIOREGIONAL ASSESSMENTS

CSIRO

Hydrogeology of the Cooper 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 development of selected unconventional hydrocarbon plays on water and the environment. The geological and environmental data and tools produced by the Program will assist governments, industry, landowners and the community to help inform decision making and enhance the coordinated management of potential impacts.

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

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ISBN-PDF 978-1-921069-21-5

Citation

Evans TJ, Martinez J, Lai ÉCS, Raiber M, Radke BM, Sundaram B, Ransley TR, Dehelean A, Skeers N, Woods M, Evenden C and Dunn B (2020) Hydrogeology of the Cooper GBA region. Technical appendix for the Geological and Bioregional Assessment Program: Stage 2. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia.

Authorship is listed in relative order of contribution.

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

Cover photograph

Cooper Creek in flood, 4 km east of Windorah, March 2018.
Credit: Geological and Bioregional Assessment Program, Russell Crosbie (CSIRO)
Element: GBA-COO-2-343

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Executive summary

Three major hydrostratigraphic sequences occur in the Cooper GBA region. These are the Cooper Basin, the Eromanga Basin and Lake Eyre Basin. The Cooper Basin is comprised of the Gidgealpa Group and the overlying Nappamerri Group. Where shale, tight, and deep coal gas accumulations occur in the Gidgealpa Group, the rocks are likely to be relatively dry as the contained gas displaces the groundwater. However, at shallower levels (less than about 2800 m), the Gidgealpa Group becomes increasingly water saturated and the hydrocarbon accumulations become more discrete. Whilst the Nappamerri Group can also contain hydrocarbon reservoirs and groundwater, regionally it acts as the seal (aquitard) to the underlying Gidgealpa Group.

The Eromanga Basin sequence is up to 2800 m thick and covers the entirety of the Cooper Basin. It includes a sequence of aquifers and aquitards that comprise a part of the Great Artesian Basin (GAB). From bottom to top these include the artesian GAB aquifers (e.g. Hutton Sandstone and Cadna-owie–Hooray aquifer), the Rolling Downs aquitard and the Winton–Mackunda partial aquifer. Regionally, groundwater flow in artesian GAB aquifers across the region are in a south-westerly or southerly directions. Groundwater flow rates and hydraulic gradients in more deeply buried parts these aquifers approach near-stagnant conditions, particularly in western parts of the Cooper GBA region. Higher groundwater flow tends to occur preferentially at shallower levels in areas of higher porosity and permeability, around the margins of the Cooper GBA region.

The Rolling Downs aquitard is the regional aquitard that separates artesian GAB aquifers from shallower aquifers. Groundwater flow in the sub-artesian Winton-Mackunda partial aquifer is topographically controlled. Local flow directions is towards major drainage lines, whilst more regional flow is to the southwest, out of the Cooper GBA region and towards Lake Blanche. Hydrochemistry suggests that hydrodynamics of the Winton-Mackunda partial aquifer may be more complex and compartmentalised than what is currently conceptualised.

The Lake Eyre Basin is up to 300 m thick and encompasses several locally important aquifer systems. Groundwater flow patterns are similar to the Winton-Mackunda partial aquifer, which suggests potential connectivity between the two systems. Sparse salinity data suggests that there are two aquifer systems, a shallow system, approximately 60 - 80 m thick with highly variable salinity and a deeper system with more consistent salinity down to about 300 m.

Due to the drilling depth required, far fewer bores target the artesian GAB aquifers in the Cooper GBA region than the Winton-Mackunda partial aquifer or aquifers in the Lake Eyre Basin. However, artesian GAB aquifers generally provide more consistent and higher quality groundwater, as well as yield higher and more sustainable flow rates than what can be obtained from other aquifers found nearer to the surface.

Springs with an artesian GAB aquifer source are found about 20 km to the west of the Cooper GBA region, near Lake Blanche. These springs primarily source water via faults conduits from the Coorkiana Sandstone and Cadna-owie–Hooray aquifer. In the vicinity of the springs groundwater flow in the Cadna-owie–Hooray aquifer is relatively poorly constrained, leaving open the possibility that some groundwater flow out of the Cooper GBA region may contribute to the springs. The lack of springs that have an artesian GAB source within the region suggests that

Rolling Downs aquitard is for the most part competent enough to impede the natural vertical movement of groundwater to surface.

Existing hydrogeological studies on groundwater-surface water interactions in aquifers in Lake Eyre Basin have focused on the top 20 m and are limited to only few waterholes on the Cooper Creek floodplain and Coongie Lakes, with less information available on deeper aquifers in the Lake Eyre Basin. There is evidence to suggest that connectivity between numerous permanent waterholes and floodplain or bedrock aquifers is more spatially and temporarily diverse and complex than what is indicated by the current knowledge found in the literature.

Surface water – groundwater interactions require further investigation and the use of environmental tracers, hydrochemistry and remote sensing data will fill gaps in understanding of the distribution of water in the landscape, flux exchanges, floodplain and riparian vegetation dynamics, and land use.

Hydrological connectivity between the Cooper and Eromanga basins is likely where: the Gidgealpa Group sequence subcrops beneath the Eromanga Basin, where sandier units of the Nappamerri Group are in contact with the Eromanga Basin, or where faulting and structuring is significant enough to affect groundwater flow. Formation pressure and salinity data suggest that there is some degree of connection between artesian GAB aquifers in the Eromanga Basin and parts of the Cooper Basin.

Five potential hydrological connectivity pathways from stressors (unconventional gas reservoirs and prospective aquifers as a potential source of groundwater to support gas development) to near surface environmental assets in the three basins system cannot be ruled out, based on the development of conceptual hydrogeological models. The potential hydrological connectivity pathways are: 1. vertical migration via dilation faults; 2. migration through porous aquifers; 3. migration through partial aquifers/aquitards; 4. migration due to contact between gas plays and overlying aquifers near the basin margin and 5. Vertical migration at catchment constrictions where steep hydraulic gradients exist between alluvial aquifers and underlying GAB formations.

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

Knowledge gaps exist in understanding the hydrogeology of the Cooper GBA region, in particular in the geological architecture and hydrodynamics of the Lake Eyre Basin and Winton–Mackunda partial aquifers. Baseline waterlevel and hydrochemistry data (including isotopes) would improve understanding source of recharge, aquifer compartmentalisation and connectivity. This information will inform the conceptualisation of and provide a better framework for future management of shallow aquifer systems. For artesian GAB aquifers and Cooper Basin, salinity, hydrochemistry and environmental tracers from groundwater, including water produced as part of petroleum production, may improve the understanding of deep groundwater processes and inform future management and re-use options for the produced water.

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Acknowledgements

This Cooper Stage 2 technical product was reviewed by several groups:

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  Geoscience Australia: Richard Blewett, Merrie-Ellen Gunning, Robert Langford, David Robinson and Martin Smith.
- Technical Peer Review Group: Andrew Boulton, Peter McCabe, Catherine Moore and Jenny Stauber.
- State Government Science Technical Review: This group includes scientists from the Queensland and South Australian governments.

Abbreviations and acronyms

Abbreviation/acronym	Definition
CSG	Coal seam gas
DEA	Digital Earth Australia
DEM	Digital elevation model
DST	Drill stem test
EPBC Act	*Environment Protection and Biodiversity Conservation Act 1999*
GAB	Great Artesian Basin
GBA	Geological and Bioregional Assessment
GDE	Groundwater-dependent ecosystem
HCA	Hierarchical cluster analysis
NGMA	National Geoscience Mapping Accord
NSW	New South Wales
NT	Northern Territory
OGIA	Office of Groundwater Impact Assessment
QPED	Queensland petroleum exploration data
PFS	Polygonal fault system
SA	South Australia
SWL	Standing water level
TCW	Tasselled cap wetness index
TOC	Total organic carbon
WAP	Water allocation plan
WOfS	Water Observations from Space
WRP	Water resource plan

Units

Unit	Description
μg/L	Microgram per litre
μS/cm	Microseimens per centimetre
km	Kilometre
m	Metre
m/sec	Metres per second
mg/L	Milligrams per litre
ML/day	Megalitres per day
mm	Millimetres
mm/year	Millimetres per year
MPa	Mega pascals
o	Degrees (referring to an angle)
oC	Degrees Celsius
psi	Pounds per square inch

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 Cooper 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 Cooper GBA region are:

- Owens R, Hall L, Smith M, Orr M, Lech M, Evans T, Skeers N, Woods M and Inskeep C (2020) Geology of the Cooper GBA region.
- Lech ME, Wang L, Hall LS, Bailey A, Palu T, Owens R, Skeers N, Woods M, Dehelean A, Orr M, Cathro D and Evenden C (2020) Shale, tight and deep coal gas prospectivity of the Cooper Basin.
- O'Grady AP, Herr A, MacFarlane CM, Merrin LE and Pavey C (2020) Protected matters for the Cooper GBA region.
- Kirby JK, Golding L, Williams M, Apte S, Mallants D and Kookana R (2020) Qualitative environmental risk assessment of drilling and hydraulic fracturing chemicals for the Cooper GBA region.
- Kear J and Kasperczyk D (2020) Hydraulic fracturing and well integrity for the GBA regions.

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

1 Introduction

The hydrogeology technical appendix provides regional hydrogeological analysis and conceptualisation of the Cooper GBA region in the context of shale, tight and deep coal gas developments. It provides hydrogeological baseline datasets and information that is relevant to understanding the potential impacts on water resources and water-dependent assets.

The hydrogeology technical appendix includes the following components:

- Groundwater data inventory (Section 2.1 and 2.2)
- Legislation and groundwater use (Section 2.3)
- Regional groundwater system conceptualisation (Section 3). The regional groundwater system conceptualisation is underpinned by the: Hydrostratigraphic framework (Section 3.1); hydrodynamics (Section 3.2); hydrochemistry (Section 3.3); potential basin inter-connectivity (Section 3.4) and conceptualisation of groundwater–surface water interactions (Section 3.5)
- Potential hydraulic connectivity (Section 4)
- Regional hydrogeological conceptual model for assessing the potential impacts (Section 5)
- Conclusions (Section 6). This consists of a summary of the key findings (Section 6.1) and the identification of data and knowledge gaps and recommendations for future work (Section 6.2).

2 Groundwater data inventory

This section builds on the data inventory in the geology technical appendix of (Owens et al., 2020). Data from South Australia and Queensland are included, as the Cooper GBA region crosses state borders. Key publicly available data, including groundwater bore data and pressure and temperature data from petroleum wells were compiled to investigate the hydrogeology of the Cooper GBA region. Data for Groundwater bores is often missing information such as hydrostratigraphy, waterlevels, salinity or hydrochemistry. It is the first time that temperature and formation pressure data compiled from petroleum wells in Queensland has been compiled into one publically available dataset.

2.1 Source datasets

For this study, "source" (or "origin") datasets represent data that are derived externally to the GBA program that is, data held by government agencies or companies. Some key source datasets for hydrogeology are outlined in the following sub-sections.

2.1.1 Borehole data

For all bore databases, data quality can vary considerably from bore to bore. Influences on bore record data quality include: the original purpose for which the bore was drilled (e.g. groundwater, coal or petroleum); when the bore was drilled (data vintage); drilling method; the care with which data were collated and reported; the relative experience of the well site personnel; and if other types of data collected can be used for comparison and results validation (e.g. downhole geophysics logs, biostratigraphy, lithological descriptions).

For the Cooper GBA region, groundwater bore data can be found in a number of sources including the National Groundwater Information System ("NGIS", Bureau of Meteorology, 2016) as well as state groundwater databases. For this study, groundwater data were compiled from Queensland and South Australian Government bore databases as these contain additional detail, including information on chemistry, pump tests, and detail on bore status.

The primary source for groundwater data in Queensland is the Queensland groundwater database (Queensland Government, 2018a). It includes information on registered groundwater bores in the state of Queensland. Department of Natural Resources and Mines (Qld) (2015) provides detail on database structure and content. The bore database includes: bore registration details (location information); bore construction; stratigraphy, lithology; waterlevels; aquifer tests; water quality data; as well as other bore-related information.

Groundwater data for South Australia is available through the South Australian Government website, 'WaterConnect' (South Australian Government, 2018b). Aside from types of information described for the Queensland groundwater database, SA data also includes a summary table of relevant information for each bore. Further detail on the database structure and codes are available through the 'Help' page of the website (South Australian Government, 2018b).

The Queensland and SA groundwater databases were compiled into a composite dataset (Geological and Bioregional Assessment Program, 2019b) for the Cooper GBA region, a summary of which are presented in Figure 1 and Table 1.

In total, there are 4652 registered bore locations in the combined dataset. However, this count includes locations of petroleum wells as well groundwater bores. Of the 4652 bore locations, 2137 are classed as water bores. Whilst the majority of unsuccessful petroleum wells were plugged and abandoned, a small proportion (65) are completed as water supply bores, predominantly in artesian GAB aquifers. These bores are also included in the total count of water bores. Not all of the registered groundwater bores are still in operation (Table 1).

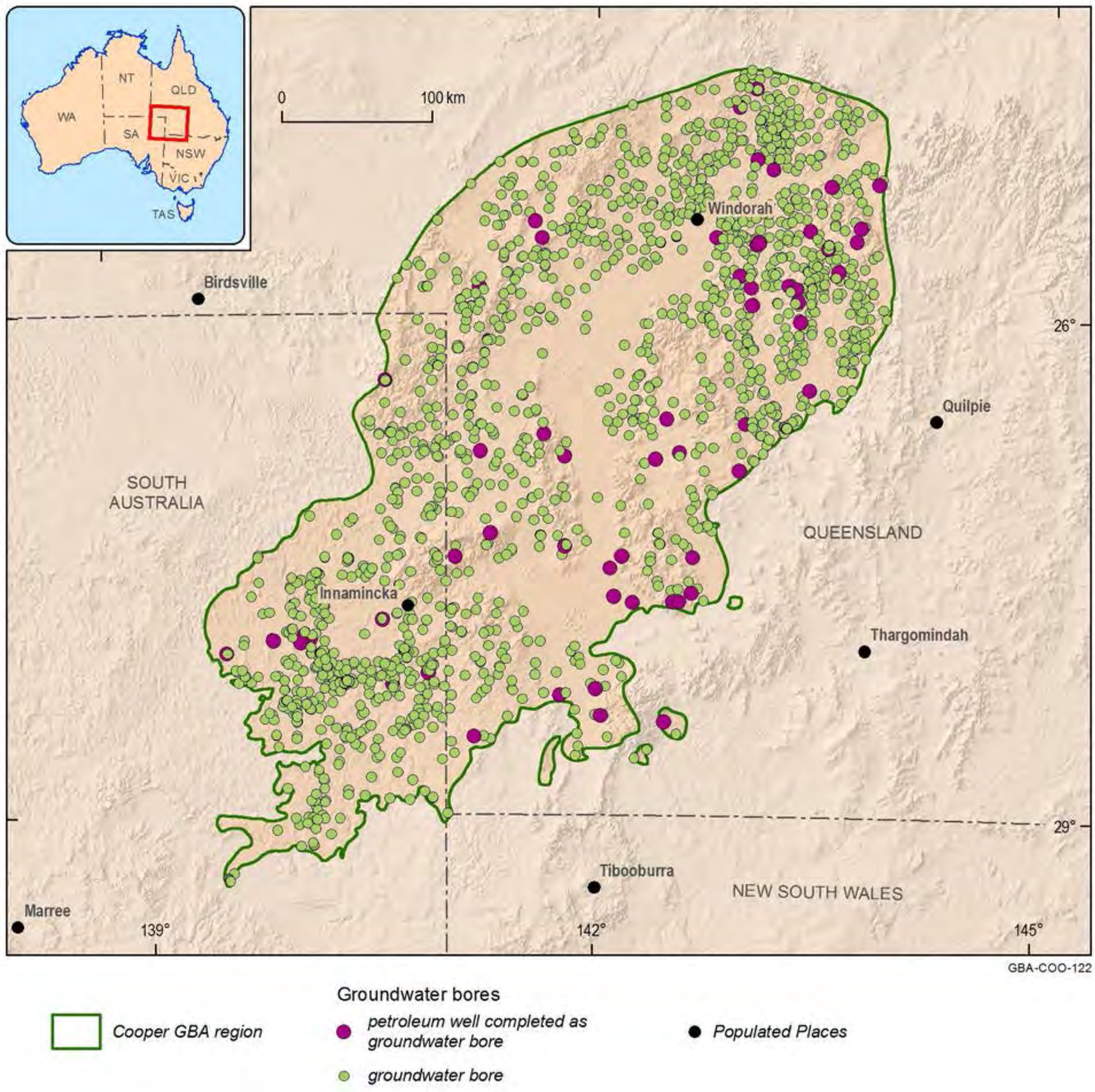

Figure 1 Location of groundwater bores within Cooper GBA region

Data: Geological and Bioregional Assessment Program (2019b)
Element: GBA-COO-122

Table 1 Number of existing and abandoned groundwater bores in Cooper GBA region per state

	Groundwater bore	Petroleum wells completed as a groundwater bore	Subtotal
Queensland	1245	52	1297
Abandoned and destroyed	412	7	419
Existing	833	45	878
South Australia	827	13	840
Abandoned and destroyed	156	4	160
Existing	671	9	680
Total	2072	65	2137

Data current as of June 2018
Data: Geological and Bioregional Assessment Program (2019b)

2.1.2 Great Artesian Basin (Atlas)

Datasets for the GAB Atlas (Ransley et al., 2015a) include interpreted geological and hydrogeological data for the Eromanga Basin and Lake Eyre Basin, which overlie the Cooper Basin (Owens et al., 2020).

2.1.3 State Petroleum Well

Information about petroleum well datasets is outlined in Owens et al. (2020). Petroleum well data that is of particular interest for hydrogeological studies includes well stratigraphy, formation pressure, temperature, water analyses, porosity-permeability measurements and well logs (geophysical and rock properties logs).

2.1.4 Queensland

The Queensland Petroleum Exploration Database (QPED, Queensland Government, 2018d) does not include formation pressure information. For the Queensland portion of the Cooper GBA region, formation pressure and temperatures were compiled for the Eromanga and Cooper basins from over 100 well completion reports as part of this project (Geological and Bioregional Assessment Program, 2018e, 2019c). Due to the number of petroleum wells in Queensland, the compilation undertaken for the Cooper GBA region focussed on pressure data from wireline formation tests (e.g. Repeat Formation Testers (RFT) or Modular Dynamic Testers (MDT)) conducted since 1995. Selected Drill Stem Test (DST) results were collated in areas where no wireline pressure surveys had been run. Wireline pressure survey data was collated in preference to DSTs, as often multiple measurements were undertaken in each formation, which provides a further crosscheck for pressure measurements and can be used to determine pressure gradients. For Queensland, all collated pressure and temperature data reference the gauge depth, as opposed to packer depth. Where appropriate packer intervals are included in the compilation for completeness.

2.1.5 South Australia

Aside from what is in the PEPS-SA database (outlined in Owens et al., 2020), another useful compilation of formation pressure and water salinity data from South Australian petroleum wells is Dubsky and McPhail (2001). This compilation is comprised of pressure and water analysis data for the Cooper and Eromanga basins from wells drilled prior to 1999. Dubsky and McPhail (2001) applied some quality control measures to flag pressure measurements influenced by the presence of hydrocarbons. Water analyses compiled by Dubsky and McPhail (2001) were assessed to determine the potential for contamination by drilling mud and fluids.

2.1.6 Digital Earth Australia – Landsat Archive

Remote sensing information can provide a nationally consistent tool for understanding the spatial and temporal patterns of surface water across Australia. Geoscience Australia has recently developed products from earth observation data as part of Digital Earth Australia (Lewis et al., 2017; Dhu et al., 2017; Geoscience Australia, 2018c).

Digital Earth Australia (DEA) is an analysis platform for satellite imagery and other earth observation data based on the Australian Geoscience Data Cube (Lewis et al., 2017). DEA holds an archive of 30 years of corrected and processed Landsat data, as well as time-series of other earth observation data, and provides tools to interact with the data through the Australian National Computational Infrastructure (NCI) high performance computing environments. Published DEA products to date based on remotely sensed data include Water Observations from Space (WOfS; Mueller et al., 2016). Other products derived from the DEA such as tasselled cap wetness index (TCW) and normalised difference vegetation index (NDVI) can be used to identify areas of persistent wetness or vegetation health. Section 3.5 provides some further detail on the use of DEA products for the Cooper GBA project.

2.2 Key derived datasets

For GBA, “derived” datasets are new datasets produced as a part of one of the GBA projects. A derived dataset may include data sourced from outside the GBA program, or it may be a new data compiled as part of the programme (See Section 2.1). Key hydrogeological datasets derived for the Cooper GBA region are detailed below.

2.2.1 Bore hydrostratigraphy

In the Cooper GBA region, bore stratigraphic data is available for some groundwater bores, and almost all petroleum and stratigraphic wells. In general, data from petroleum and stratigraphic wells represent the higher quality datasets because usually a more methodical and consistent approach is applied collecting a variety of data from each well. There is also often enough detailed information to validate stratigraphic picks, which may be derived from the various datasets (e.g. geophysical well logs, detailed lithology and biostratigraphy).

There is more variation in the availability and quality of stratigraphic data with groundwater bores. Sometimes more care is taken in the collection of data from deeper (and more expensive) groundwater bores than what is available from relatively shallow bores. Shallow groundwater bore locations may not have be surveyed or pinpointed using a GPS, which can confer some uncertainty on their actual location. Interpretation of their stratigraphy is commonly solely from drillers' logs, rather than from variety of data sources. However, the greater number of groundwater bores available offers a better regional coverage, if integrated carefully with stratigraphic information from more reliable data sources, such as deep stratigraphic and petroleum exploration wells.

For the Cooper GBA project, interpretation of the hydrostratigraphic unit(s) for a groundwater bore was undertaken using the following workflow:

- Bore construction details from groundwater databases were used to determine the screened intervals. Sometimes bores can have multiple ingress points for groundwater. In the GBA dataset, the screen 'From' measurement represents uppermost interval and screen 'To' represents the base of the interval at which groundwater can enter a bore. For bores with missing or incomplete screen interval data, the maximum recorded drilling depth was used as a proxy for the base of screened interval. In some cases using total depth as a proxy for base of screens may not be representative of the screened interval. For example, a bore may be uncased below a certain depth and the open interval large and intersect multiple aquifers.
- Determine which hydrostratigraphic unit(s) coincide with the screened interval (or maximum depth for a bore, if no screened interval was available). Stratigraphic information derived from state groundwater databases was crosschecked against other data, such as information from nearby bores. If it were found to be consistent, then hydrostratigraphic information from the state groundwater databases would be utilised. Inconsistent hydrostratigraphic interpretations would be checked against other available data (e.g. surface geology), as it may be suggestive of occurrence of a fault or geological contact. If there were no geological reason then the bore hydrostratigraphy would be adjusted to be consistent with adjacent bores. For bores that draw groundwater from multiple aquifers, all aquifers were included in the interpretation. For example, "Mackunda–Hooray" would signify that that bore was open and could draw water over a large interval that included the Hooray Sandstone up to Mackunda Formation.

Where a groundwater bore lacked stratigraphic data, an assessment was made as to whether the gap could be infilled by using stratigraphic data from other sources including GAB atlas dataset, surface geology or nearby petroleum wells or groundwater bores. Once stratigraphy was assigned, it was then crosschecked against nearby bores to ensure consistency in interpretation.

Hydrostratigraphic interpretations for groundwater bores from Queensland and South Australia cab be found in (Geological and Bioregional Assessment Program, 2018h) . Hydrostratigraphic interpretation for waterlevel and hydrochemistry data for Cooper GBA project were derived from these two datasets.

The distribution of bores across the Cooper GBA region is outlined in Figure 1. The vast majority (92%) of these bores are less than 300 m deep and around 8% (176) of water bores have no recorded depth data ('0' on Figure 2). Table 2 details number of bores with interpretable hydrostratigraphy as well basic information such as screen depth.

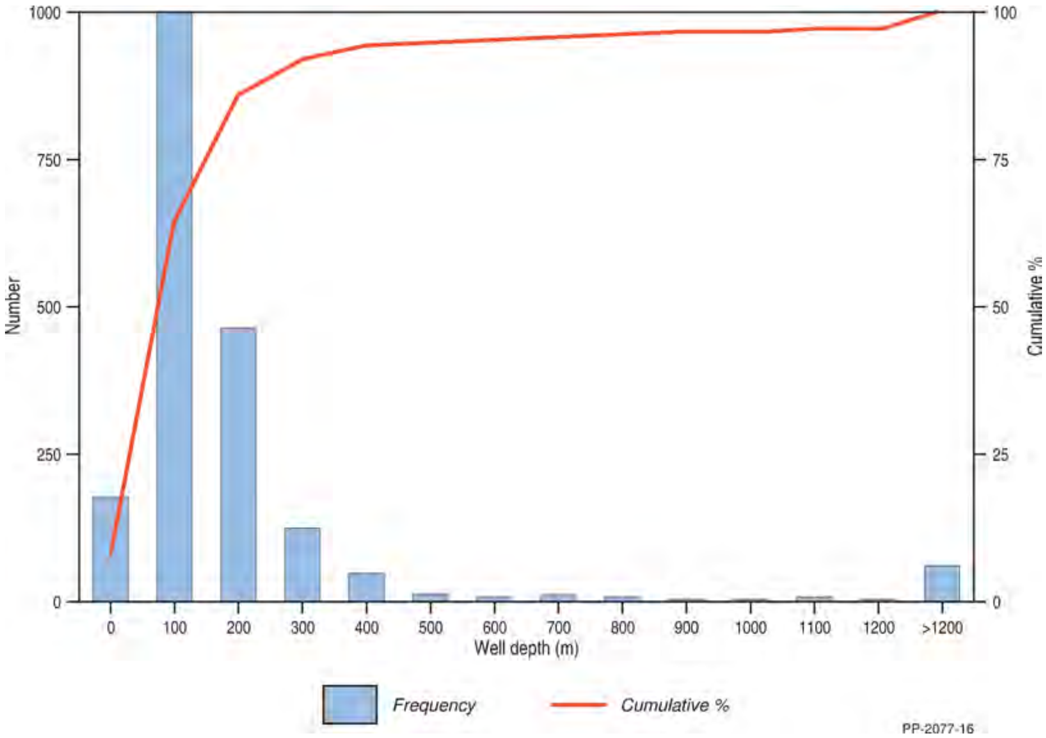

Figure 2 Histogram of groundwater bore depths

Data current as of June 2018. "0" = bores with no available data to indicate the bore was drill depth
Data: Geological and Bioregional Assessment Program (2019b)
Element: GBA-COO-2-282

Table 2 Groundwater bore data inventory for aquifers in the Eromanga Basin and Cenozoic

Major hydrostratigraphic grouping	Total number of bores	Number of existing bores	Number of bores with a waterlevel measurement	Number with screen data	Average maximum depth (m)
Lake Eyre Basin (Cenozoic)	1025	779	573	415	92
Winton–Mackunda partial aquifer	827	570	466	374	158
Artesian GAB aquifers	54	43	34	39	1715
Cannot interpret hydrostratigraphy with available data	242	174	2	0	258
Cannot interpret and no depth data	176	NA	0	0	NA
Total	2313	1566	1075	828	NA

Data current as of June 2018. "NA" = Not Applicable
Data: Geological and Bioregional Assessment Program (2019b)

From a comparison of the major hydrostratigraphic groups (Table 2), it is apparent that the majority of groundwater bores are screened in the Lake Eyre Basin (Cenozoic) or Winton–Mackunda partial aquifer. Only a relatively small number of bores draw from artesian GAB aquifers. A number of bores in the artesian GAB aquifer were originally drilled as petroleum wells, but then abandoned and completed as deep groundwater bores. No groundwater bores have been drilled or completed in the Cooper Basin. Whilst numerically the number of bores tapping artesian GAB aquifers is low, these bores can generally sustain higher flow rates that are often artesian (Table 3), as well as have more consistent water quality than bores extracting groundwater from aquifers at shallower levels.

Table 3 Groundwater bore yield for aquifers in the Eromanga Basin and Lake Eyre Basin (Cenozoic)

Major hydrostratigraphic grouping	Number of measurements	Minimum yield (L/sec)	Average yield (L/sec)	Maximum yield (L/sec)
Lake Eyre Basin (Cenozoic)	383	0.06	3.1	22.7
Winton–Mackunda partial aquifer	149	0.01	2.3	17
Artesian GAB aquifers	27	0.01	32.7	258
Total	559	NA	NA	NA

Data current as of June 2018.
There are often multiple yield measurements from bores in artesian GAB aquifers. Also, the yield can vary with time and is dependent on a number of factors including condition of the bore and the aquifer pressure. "NA" = Not Applicable.
Data: Geological and Bioregional Assessment Program (2019b)

2.2.2 Standing waterlevels and hydraulic head

Standing waterlevel (SWL) is a measurement of the depth below a reference point to water in a groundwater bore. SWL data were converted to hydraulic head Geological and Bioregional Assessment Program (2018h). Hydraulic head is groundwater level above a reference point, which in this instance is the Australian Height Datum (AHD). Hydraulic head was calculated as follows:

- For groundwater bores, the elevation of ground level at the bore collar was derived from the 1-second digital elevation model (DEM, Geoscience Australia, 2011). The assumption here is that the reference point for measurement to depth of water is ground-level and that the bore location co-ordinates are accurately recorded in the databases. This may not necessarily be the case. For instance, reference measurement point may be the top of the casing and is not generally recorded. Furthermore, the bore location may be estimate rather than an accurate measure of its final (drilled) position. Generally casing height above ground is generally no more than 1 m however, the amount casing sticks up above ground level is usually not available. Whilst approach will introduce a level of error, it is not likely to affect interpretation of regional trends. It may cause a level of uncertainty in interpretation of trends at local scale (e.g. less than 5 km). There are also inherent errors in the 1 second DEM that need to be taken into consideration when using these data to investigate subtle trends.
- Standing waterlevel measurement was subtracted from local ground level to derive the hydraulic head relative to sea level.

Where required, freshwater equivalent hydraulic head was calculated using methods outlined in Post et al. (2007). For the Winton-Mackunda partial aquifer and aquifers in Lake Eyre Basin, waterlevel data were not density corrected due to variable salinity and that salinity data was often lacking. For more local studies, density corrections could be warranted, particularly in areas of known high salinity (see Section 3.3 for salinity). For future studies having a better understanding of salinity distribution in these aquifers would allow for a more reliable conversion to freshwater equivalent hydraulic head.

2.2.3 Salinity and hydrochemistry

Two facets of groundwater hydrochemistry been analysed in this study: (i) estimates of salinity or the aggregate amount of matter dissolved in the water; and (ii) estimates of the relative abundance of major ions that comprise this salinity. These are based upon various groundwater samples from bores compiled from relevant state groundwater databases (Section 2.1). These databases contain hydrochemical parameters including electrical conductivity (EC), total dissolved solids (TDS) and acidity (pH); however, not all bores had these three parameters, so EC, as the most common, was selected for further analysis. The hydrostratigraphy for various samples was determined as described in Section 3.

A total of 1545 records were compiled from the databases Geological and Bioregional Assessment Program (2018h) . However, many bores did not have sufficient information to ascertain the hydrostratigraphic position of the screened interval (removing 835 records), and some further records (91) did not have an EC value. In total salinity data for statistical analysis consists of 619 records from 319 unique bores (Table 4). This includes some bores with multiple salinity measurements.

For the purposes of this hydrochemical analysis, the hydrostratigraphic attribution has been simplified into four components related to the hydrostratigraphy presented in Figure 10:

- Cenozoic (Lake Eyre Basin) aquifers
- Winton–Mackunda partial aquifer, which includes the Winton Formation and Mackunda Formation. Bores assigned “Cenozoic/Winton–Mackunda” is also included in this grouping.
- Rolling Downs aquitard, consisting of the Allaru Mudstone, Toolebuc Formation, Wallumbilla Formation, Oodnadatta Formation, Coorikiana Sandstone and Bulldog Shale

Artesian GAB aquifers: focussed on the Cadna-owie–Hooray aquifer and equivalents, as this is the main artesian GAB aquifer utilised in the Cooper GBA region. However, some of these bores are screened in multiple aquifers, as well as the Cadna-owie–Hooray aquifer (See Section 3.1.2 for detail).

It should be noted that many of the sample depths represent the maximum bore depth, rather than depth of the screened/open interval. This could have a bearing on interpretation when assessing hydrochemical data against depth, as sometimes the screen depth may not coincide with maximum bore depth.

Table 4 Summary of available hydrochemical data

	Number of salinity (EC) readings	Number of bores with salinity data	Number of major ion analyses	Number of bores with major ion analysis
Cenozoic aquifers	234	168	101	90
Winton–Mackunda partial aquifer	129	88	452	343
Rolling Downs aquitard	14	2	29	17
Artesian GAB aquifers	242	61	150	59
Total	619	319	732	509

Data current as of June 2018.
Data: Geological and Bioregional Assessment Program (2018h)

In addition to salinity, other groundwater hydrochemical data is available for some bores. Major ions include: sodium (Na), potassium (K), magnesium (Mg) and calcium (Ca) cations and chloride (Cl), carbonate (CO_3), bicarbonate (HCO_3) and sulphate (SO_4) anions). Samples with sufficient major ionic data and an ionic balance within ±10% were extracted and correlated with their hydrostratigraphic grouping. This resulted in a composite dataset of 732 records from 509 unique bores (Table 4). Some bores have multiple records, which may relate to sampling at different dates.

Table 4 shows that for many bores EC data was available but no hydrochemistry, and vice-versa. If a further comparison is made between Table 2 and Table 4, it becomes apparent that some bores have hydrochemistry but no waterlevel (and visa-versa).

2.2.4 Petroleum pressure data and hydraulic head

With the exception of information in Dubsky and McPhail (2001), the various pressure and temperature data outlined in Section 2.1 were compiled into one dataset (Geological and Bioregional Assessment Program, 2019c), the ranges of which are summarised in Table 5. While these data are considered to be of suitable quality for a regional study, some aspects would need further evaluation, if more local scale studies were to be undertaken.

Some variance may be attributable to the archival nature of the dataset, for instance, the types of pressure gauge and methodologies used to obtain a pressure measurement. However, as outlined by Dubsky and McPhail (2001), there appears to be consistency between pressures measured using different types of gauges and data of different vintages. Unlike what was the case for groundwater bores where the bore elevation was determined from a DEM (Section 2.2.2), the location and elevation of the reference point for depth measurements for petroleum wells is accurately surveyed (as well as ground level). Hence, for petroleum well data the conversion from downhole depths to heights above sea level (m AHD) is likely to be more accurate.

Some known data gaps and potential issues with petroleum pressure data include:

- Pressures measurements were made using a variety of tools of different vintages, which may influence measurement precision (e.g. quartz strain gauges versus mechanical pressure gauge).
- South Australian data is predominantly from DSTs, whereas Queensland data is primarily from MDTs and RFTs. While there is the possibility of discrepancies due to different pressure measurement methods and techniques, Dubsky and McPhail (2001) suggest that overall between data collated from various methods is consistent.
- Depths are not consistent: South Australian DSTs reference the depth at which the packers were set down the well whereas, pressure data from petroleum wells in Queensland reference the depth of the pressure gauge down the well. The depth difference can be in the order of several metres. Gauge depths are preferred for data analysis and for conversion from pressure to an equivalent hydraulic head.
- Final shut-in pressures for DSTs recorded in the well completion reports are often just the field reading. Field readings have not always been corrected to reservoir pressure. However, for the purposes of this regional study field pressure was used as a proxy for reservoir pressure if corrected pressures were not available. For detailed studies, further quality control and corrections may be required.
- Stratigraphic interpretation is based on well completion reports, which has not been validated against other sources.
- Some pressure measurements are influenced by presence of hydrocarbons, in particular gas.
- Temperature data was not corrected for localised cooling effects caused by the circulation of drilling mud in the well. Lower temperatures will influence calculations of equivalent hydraulic head, as temperature is one variable in these calculations. Also, limited availably of salinity data for some aquifers means that salinity often to be estimated for most formations.

Future pressure data collations could focus on data gaps in this dataset including:

- Queensland: incorporating pressure/temperature data from pre-1995 wireline pressure surveys and DST pressure/temperature data.
- South Australia: incorporating post-1998 wireline pressure survey data (pre 1998 RFT data are included in Dubsky and McPhail (2001)) and converting to gauge depths for pressure data derived from the PEPS-SA database, assessment of DST data quality.

Whilst some basic quality control of pressure data was undertaken, unlike the methodologies followed by Dubsky and McPhail (2001), pressure measurements influenced by presence of hydrocarbons or production were not been removed from this dataset. This is because hydrocarbons and production will influence pressure regime. This may be important, as local fluid pressures will influence the potential for fluids to migrate and the direction of migration.

Table 5 Petroleum well formation pressure and temperature data for the Cooper GBA region

	Number of measurements	Depth (m)		Final Shut in Pressure (PSIG)		Temperature (°C)	
Formation/Group	Count	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Eromanga Basin							
Rolling Downs Group	2	1002.79	1057.35	1436.0	1523.0	82.4	84.7
Cadna-owie–Hooray aquifer	217	655.83	1898.90	188.0	2930.4	60.2	117.4
Westbourne–Adori	46	985.00	1874.52	1560.3	2711.4	79.0	133.7
Birkhead Formation	118	1012.50	2162.86	298.0	3137.0	78.9	135.1
Hutton–Poolowanna sandstones	222	1097.00	2479.56	296.0	3757.3	76.8	139.5
Cooper Basin							
Nappamerri Group	92	1735.53	2906.59	385.0	4298.2	80.5	159.9
Toolachee Formation	395	1619.71	2991.92	289.0	4895.6	69.7	161.3
Daralingie Formation	19	1959.86	2606.04	266.0	4171.0	115.6	161.3
Roseneath Shale	15	1887.32	2656.03	299.0	3898.0	104.6	151.9
Epsilon Formation	112	1690.95	3029.41	379.0	6743.0	96.7	178.5
Murteree Shale	21	1966.57	3295.19	308.0	5522.0	101.9	149.7
Patchawarra Formation	829	1751.38	3246.12	289.0	7015.0	87.4	193.5
Tirrawarra–Merrimelia formations	25	2177.19	3029.71	476.0	4416.0	99.7	144.6
Grand Total	2113						

PSIG = Pounds per square inch gauge

For an individual measurement depth may refer to either packer depth or gauge depth, and depends on which state the data was derived.

Data: Geological and Bioregional Assessment Program (2019c)

2.2.4.1 Calculation of equivalent hydraulic head from pressure data

Corrected equivalent hydraulic head derived from formation pressure measurements (Geological and Bioregional Assessment Program, 2019c) were used as a measure of waterlevels in deeper formations where no groundwater data was available. Pressure data was converted to hydraulic head utilising gauge temperature and an estimate of salinity. For the Eromanga Basin, salinity was estimated from data compiled in Ransley et al. (2015a). For the Cooper Basin, the average salinity of a formation as reported in (e.g. Dubsky and McPhail, 2001) was utilised as proxy for salinity. Section 3.3 includes further information on salinity.

Additional steps are required to obtain a freshwater equivalent hydraulic head from formation test pressure measurements. This process is:

- Basic quality control. Some examples are as follows:
  - For DSTs: Only DSTs classed as successful by the operator were used and where the final shut-in pressure was less than final hydrostatic pressure.
  - For wireline pressure data (RFT's MDTs): only tests classified as "good" in the relevant well completion report were utilised in GBA analysis. While compiled in the dataset for completeness, wireline pressures tests reported as "curtailed", "no seal", or having some other issue, were not converted to equivalent hydraulic head. Further detail on formation test quality control methods are outlined in (Hortle et al., 2013).
- Where data passed quality assurance checking, pressure measurements reported in pounds per square inch absolute (PSIA) were converted to pounds per square inch gauge (PSIG) pressure according to Equation 1:

$$PSIG = PSIA - 14.7 \quad (1)$$

- Pressure was assumed to represent a predominantly single-phase fluid.
- Pressures were converted to environmental hydraulic head and equivalent freshwater hydraulic head using methods in Post et al. (2007).
- Fluid density corrections for temperature were calculated based on gauge temperatures. Salinities were estimated from available groundwater salinity data. The density calculation component references formulas presented in McCutcheon et al. (1993). Whilst not explicitly discussed, there are possibly some limitations with the McCutcheon et al. (1993) equations, including that they are in part derived from the equations for the "state of seawater" (UNESCO, 1981). The equations in UNESCO (1981) are valid to temperatures of 40°C. Often groundwater's temperatures in Cooper GBA region exceed this threshold. For more detailed studies, potentially this could be a further source of error worth considering in the derivation of equivalent hydraulic head using for a given pressure and salinity.

2.3 Groundwater use

Groundwater planning and management is undertaken by South Australia (SA) and Queensland (Qld) State government agencies for groundwater resources in their jurisdiction. The Great Artesian Basin (GAB) not only crosses state borders, but is special in that groundwater typically is managed for pressure and not by extractive volumes (Klohn Crippen Berger, 2016b; Lai et al., 2016; SA Department for Water, 2011; Queensland Government, 2017; South Australian Arid Lands Natural Resources Management Board, 2009a, 2009b)).

This section provides a brief overview of the legislation and water plans for South Australia and Queensland. Water management in the Cooper Basin falls within a number of water management areas as shown in Figure 3. A summary of the key legislation and water management plans including major water users for South Australia and Queensland is presented in Table 6.

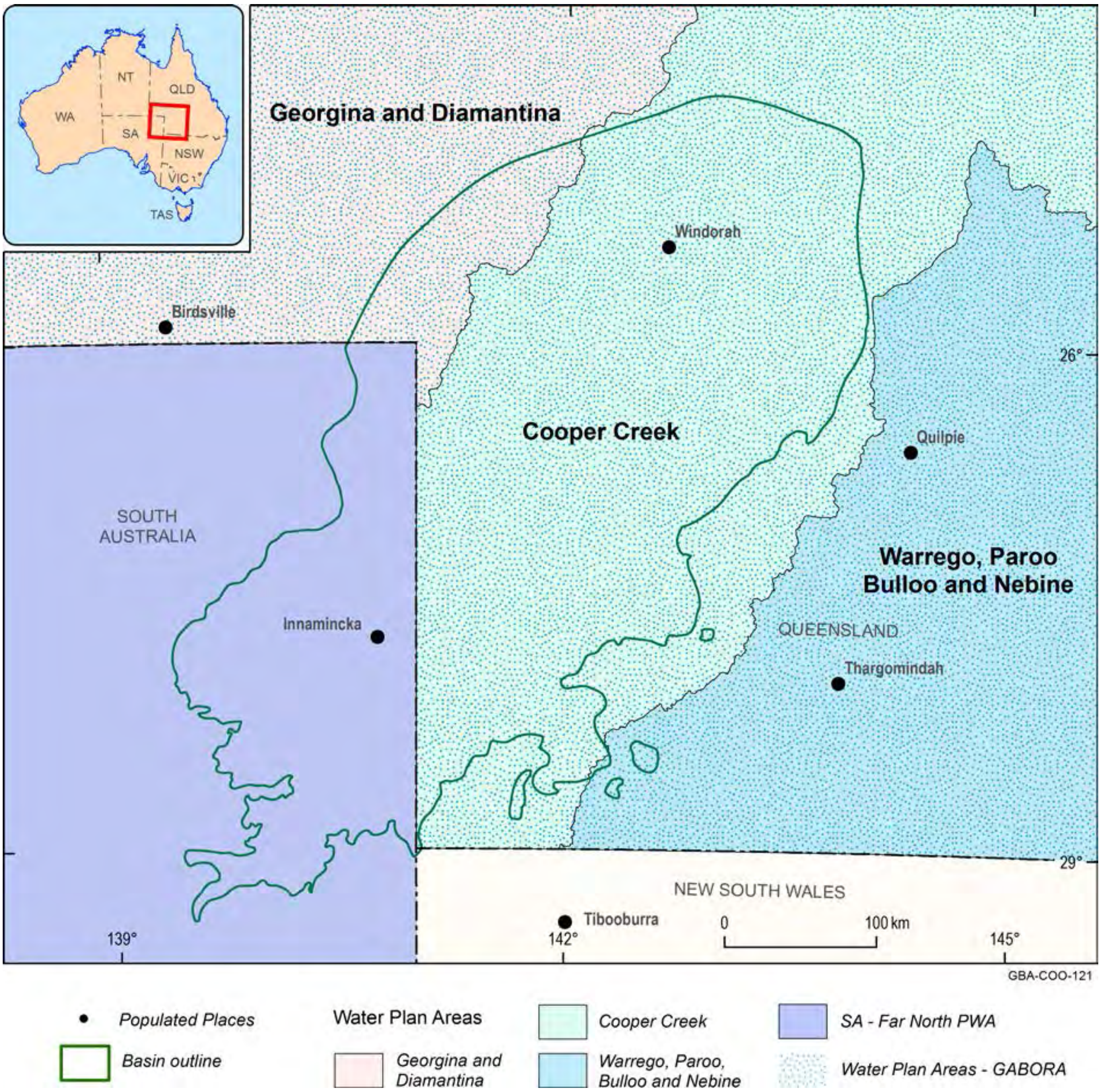

Figure 3 Map of the Cooper Basin showing the areas covered by water resources plans

State borders are the primary division of water management. In South Australia, prescribed wells areas occur – the Far North PWA covers the South Australian Cooper Basin region. Three near-surface water plan areas (Georgina and Diamantina; Cooper Creek; and Warrego, Paroo, Bulloo and Nebine), and one entirely subsurface water plan (the Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017, also known as "GABORA") manage parts of the Queensland Cooper Basin region.
Data: Queensland Government (2018b, 2018c); South Australian Government (2018a)
Element: GBA-COO-121

Table 6 Summary of relevant State water management legislation and water use

	South Australia	Queensland
Water act	*Natural Resources Management Act 2004* (South Australian Legislation, 2004)	*Water Act 2000* (Queensland Government, 2000)
Water plan(s)	• *Water Allocation Plan for the Far North Prescribed Wells Area* (South Australian Arid Lands Natural Resources Management Board, Feb 2009) - This covers all groundwater within the plan extent, and therefore all of the SA Cooper Basin	• *Water Resource (Georgina and Diamantina) Plan 2004* - Surface water and Cenozoic groundwater, northwest portion of Queensland Cooper Basin • *Water Plan (Cooper Creek) 2011* - Surface water and Cenozoic groundwater, majority of Queensland Cooper Basin • *Water Resource (Warrego, Paroo, Bulloo and Nebine) Plan 2016* - Surface water and Cenozoic groundwater, south-eastern corner of Queensland Cooper Basin • *Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017* (also known as "GABORA") - Groundwater from Queensland Great Artesian Basin
Limits on produced water	Allocated 60 ML/day	
Limits on other petroleum industry water use	Separately licensed	Requires short-term permits or long-term licenses
Other major water users	• Stock and/or domestic - 30-90 ML/day • Mining industries - ~ 45 ML/day • Town water supplies - ~ 4 ML/day (Department of Environment Water and Natural Resources (SA), 2017; SA Department for Water, 2011)	• Stock and/or domestic - ~ 13 ML/day • Town water entitlements - ~11 ML/day • Bore drain discharge and uncontrolled artesian well discharge - ~ 65 ML/day (Klohn Crippen Berger, 2016b)
Government water monitoring online detailed information	• SA WaterConnect, https://www.waterconnect.sa.gov.au - Department of Environment, Water and Natural Resources (South Australian Government, 2018b)	• Water Monitoring Information Portal, https://water-monitoring.information.qld.gov.au/ - Department of Natural Resources (2018)

The volumes of water compiled in this table do not specifically relate to the Cooper GBA region. Rather they are specific to the area encompassed by their associated water plan.

2.3.1 South Australia

Groundwater in SA is managed under SA's *Natural Resources Management Act 2004* (South Australian Legislation, 2004). Areas where there is development or stakeholder concern can be declared as a prescribed water resources area (Golder Associates, 2015). Water Allocation Plans

(WAPs) are developed by natural resource management (NRM) boards for each prescribed resource in their region. The WAP covering the SA portion of the Cooper GBA region, is the *Water Allocation Plan for the Far North Prescribed Wells Area* (or WAP for the Far North PWA). This WAP sets out the requirements to manage and protect both non-artesian and artesian water resources within the area and provides a framework for allocating groundwater for various users and uses (Golder Associates, 2015; Lai et al., 2016). The current WAP is under review in 2018, with draft plans to be consulted on prior to adoption planned for July 2019 (South Australian Arid Lands Natural Resources Management Board, 2017). This section describes the existing 2009 WAP.

The extent of the Far North WAP does not match the Cooper GBA region hence, some stated volumes may not directly relate to the region. Groundwater in the SA Great Artesian Basin is used for a variety of purposes, including stock and/or domestic uses, petroleum, mining, town water supplies, power generation, industrial, tourism, and road maintenance (South Australian Arid Lands Natural Resources Management Board, 2009a).

As detailed in Table 1 above, 840 registered bores are located in the SA portion of the Cooper GBA region, of which 680 are still in existence. The majority of these bores do not tap into artesian GAB aquifers. However, artesian bores and associated infrastructure are generally far more productive than non-artesian bores.

The three largest groundwater uses for are stock and domestic, petroleum industries and mining industries purposes (SA Department for Water, 2011; South Australian Arid Lands Natural Resources Management Board, 2009a). Mining is estimated to be the largest consumer of water resources, while the greatest number of bores is for stock and domestic purposes (Keppel et al., 2013b). Mining operation water extraction from GAB aquifers in SA are located outside the Cooper GBA region (e.g. Beverley is 85 km away from the edge of the Cooper GBA region boundary and Olympic Dam bore field is over 100 km away). Although these are relevant to the SA Arid Lands Natural Resources management (SAAL NRM) area, mining water use is not directly relevant to the Cooper GBA region water usage. Non-anthropogenic users including springs are also considered in accounting water demands (South Australian Arid Lands Natural Resources Management Board, 2009a).

A total of 128 ML/day was allocated for licenses in the Far North PWA (SA Department for Water, 2011). This includes 60 ML/day for “water used as a by-product of petroleum production” or petroleum produced water (South Australian Arid Lands Natural Resources Management Board, 2009a). Average production of produced water has risen since 2003 from less than 20 ML/day, to up to 43 ML/day in 2016 (Department of the Premier and Cabinet (SA), 2017).

SAAL NRM Board estimated 90 ML/day for stock and domestic uses and 4 ML/day for town water supplies (Department of Environment Water and Natural Resources (SA), 2017). It is assumed that all stock and domestic use is groundwater rather than surface water, with approximately two-thirds from artesian systems and one-third from non-artesian bores (South Australian Arid Lands Natural Resources Management Board, 2009a).

Total water use is projected to increase over time, with the proportional use by each purpose varying (South Australian Arid Lands Natural Resources Management Board, 2009a). Increasing demand for town water supplies, tourism, and the petroleum industry are expected; while new commercial uses may appear in the future (South Australian Arid Lands Natural Resources Management Board, 2009a). There may be opportunity for increased reuse of produced water, such as for civil works, drilling, treatment and re-injection where excellent water quality is not vital (South Australian Arid Lands Natural Resources Management Board, 2009b)

2.3.2 Queensland

Groundwater in Queensland is managed under Queensland's *Water Act 2000* (Queensland Government, 2000). Water Resource Plans (WRPs) in Queensland have been established to manage water resources from artesian groundwater, sub-artesian groundwater and surface water systems. The allocation and licensing of water are subject to these water resource plans.

In the Cooper GBA region, the following WRPs apply:

- *Water Resource (Georgina and Diamantina) Plan 2004* – (Queensland Government, 2004b)
- *Water Plan (Cooper Creek) 2011* – (Queensland Government, 2011)
- *Water Resource (Warrego, Paroo, Bulloo and Nebine) Plan 2016* – (Queensland Government, 2016)
- *Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017* – also known as "GABORA" (Queensland Government, 2017).

The first three cover non-overlapping areas of Queensland that focus on surface water and near-shallow groundwater. In contrast, the *Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017* focuses on deeper groundwater systems.

The *Water Resource (Georgina and Diamantina) Plan 2004* and *Water Plan (Cooper Creek) 2011* both cover surface water as well as shallow groundwater (Queensland Government, 2004b, 2011). These plans define water rights, both for surface water as well for non-GAB groundwater systems from the Cenozoic units. The W*ater Resource (Warrego, Paroo, Bulloo and Nebine) Plan 2016* covers an area mostly outside the extent of the Cooper GBA region, but a small area on the south eastern edge of the region extent lies within the plan area (Queensland Government, 2016). Like the Georgina/Diamantina and Cooper Creek WRP, the Warrego/Paroo/Bullo/Nebine WRP manages aquifers classed as non-GAB groundwater systems from the Cenozoic units.

Groundwater from the Queensland part of the Eromanga Basin is considered part of the Great Artesian Basin, and managed under the *Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017* ("GABORA", Queensland Government, 2017). This replaces the former *Water Plan (Great Artesian Basin) 2006* (Queensland Government, 2006). The GABORA plan includes both sub-artesian (e.g. Winton Mackunda) and artesian (e.g. Cadna-owie, Hooray, and Hutton) groundwater units of the Eromanga Basin.

Queensland's *Petroleum and Gas (Production and Safety) Act 2004* (Queensland Government, 2004a) and *Petroleum Act 1923* provides a legislative framework for petroleum exploration, production and pipelines (Golder Associates, 2015). Under these acts, groundwater may be extracted as part of petroleum production. The *Water Act 2000* requires petroleum tenement holders to "make good" any impairment of groundwater supply for other users. These obligations are described further in OGIA (2016).

As detailed in Table 1, 1292 registered bores are located in the Queensland portion of the Cooper GBA region, of which 878 are still in existence.

Currently in the Queensland Eromanga Basin, groundwater is dominantly used for stock and domestic purposes through private water bores, which accounts for about 70% of total water extraction; however quantification has proven difficult in the past as many bores do not have licensed extraction volumes (Klohn Crippen Berger, 2016b, 2016a).

A recent estimate of 142 GL/year for the total groundwater use in the Queensland Eromanga Basin included stock and domestic use, bore drain discharge and uncontrolled artesian well discharge, entitlements outside stock and domestic uses, and petroleum and gas extraction by-products (Klohn Crippen Berger, 2016b).

Although there is the potential for increased stock and domestic demands, other emerging demands have also been identified:

- Large scale agriculture and stock intensive applications
- Mining projects, both for direct consumptive use and for dewatering
- Petroleum and gas industries, both for direct consumptive use and for consequential take.

Across these three sectors, a total of 47 GL/year of consumptive use and 45 GL/year dewatering have been estimated across the whole Queensland Eromanga Basin, of which a few proposals are located near the Cooper GBA region. These include possible new shale and tight gas projects in the Queensland Cooper Basin have the potential for up to 1660 ML/year demand from the Cenozoic and Winton–Mackunda aquifers, with perhaps up to 1300 ML/year coming from Santos projects (Klohn Crippen Berger, 2016b). In addition, increasing demands from mining (e.g. Warrego West, ~300 ML/year), geothermal (e.g. Windorah, ~500 ML/year), and agriculture (e.g. Central Agriculture, ~400 ML/year) may also require further water resources from the GAB (Klohn Crippen Berger, 2016b).

3 Regional groundwater system conceptualisation

The regional groundwater system conceptualisation for the Cooper GBA region is outlined in the introductory portions of this section. The conceptualisations focus on three major facets. 1. Interactions between the tight, shale and deep coal gas plays and groundwater in the Cooper Basin 2. Artesian GAB aquifers and Rolling Downs aquitard in the Eromanga Basin 3. Shallow aquifers in the Cooper GBA region: Lake Eyre Basin (Cenozoic) and the Winton–Mackunda partial aquifer

Each of these conceptualisations encompass key aspects that are discussed in detailed in sections on hydrostratigraphy, hydrodynamics, hydrochemistry, potential basin inter-connectivity and surface water – groundwater interactions. Further detail over and above what is outlined in the conceptualisations is also included in these five subsections.

The following conceptualisations synthesise some of the current understanding outlined in Section 3.1 to Section 3.5 of this report. Holland et al. (2020) also provides a summary of these aspects.

Tight, shale and deep coal gas plays and groundwater in the Cooper Basin

Figure 4, Figure 8 and Figure 9 outline some pertinent aspects of regional hydrogeology and its relationship with the tight, shale and deep coal gas plays outlined in (Lech et al., 2020). These include:

- The Cooper Basin consists of the Gidgealpa Group and Nappamerri Group (Section 3), both of which are deeply buried by the overlying Eromanga and Lake Eyre basins.
- Tight, shale and deep coal gas reservoirs in the Gidgealpa Group occur predominantly at significant depths in Cooper Basin depocentre(s) such as the Patchawarra, Nappamerri and Windorah troughs (Lech et al., 2020). Low permeability unconventional reservoirs are over-pressured; gas charged with no gas-water contact. Here, traditional aquifer/aquitard concepts may not be applicable as the natural in-situ reservoir conditions have a tendency to drive out free water, and disrupt pre-existing groundwater systems (Section 3).
- Where tight, shale and deep coal gas plays do not dominate, aquifer/aquitard concepts may apply in the Cooper Basin (Section 3.2.1). Areas where this may be case include:
    1. The Nappamerri Group
    2. Where the Gidgealpa Group occurs at relatively shallow depths (e.g. <2800 m deep, see Section 2.1 in (Lech et al., 2020).
    3. Where the Gidgealpa Group subcrops beneath the Eromanga Basin (see Figure 11)
    4. At depths where more conventional petroleum plays tend to dominate instead of the unconventional resource plays (see Section 2 in (Lech et al., 2020).
- Depleted reservoir pressures can occur in the Gidgealpa Group, particularly near areas of ongoing petroleum production (Section 3.2.1). If pressures (and equivalent hydraulic head) are greater in overlying units, then this is likely to reduce the potential for migration of fluids (and any entrained contaminants) out of the reservoir area.

- The deeper Eromanga Basin aquifers (e.g. the Hutton Sandstone aquifer) are for the most part, separated from the Gidgealpa Group by the Nappamerri Group. The main potential for connectivity between the Eromanga and Cooper basins is where the Gidgealpa Group subcrops beneath the Eromanga Basin, where sandy facies in the Nappamerri Group are in contact with the Eromanga Basin, or where major faults significantly offset aquifer sequences (Section 3).
- The separation between the Cadna-owie–Hooray aquifer (the main producing artesian GAB aquifer in the Cooper GBA region) and unconventional resource plays is often in excess of 600 m (Section 3). Furthermore, the Birkhead and Westbourne formations separate the Cadna-owie–Hooray aquifer from the underlying Hutton Sandstone aquifer. The Birkhead and Westbourne formations can impede flow between different aquifer units in the Eromanga Basin. The basin margin lateral equivalents of Hutton Sandstone to Cadna-owie–Hooray aquifer sequence is the Algebuckina Sandstone.
- The thick Rolling Downs aquitard separates the deeper predominantly artesian GAB aquifers from the sub-artesian Winton–Mackunda partial aquifer. There are potential leakage pathways across this regional aquitard through lithological changes; structural complexities and polygonal fault systems (see Section 3.4.3).
- The majority of current groundwater bores (90%) are less than 300 m deep and draw groundwater from the Winton–Mackunda partial aquifer and Cenozoic aquifers (Section 2.2). There is significant lateral and vertical separation between these shallow aquifers and unconventional resource plays.
- Likely future water sources include Cenozoic aquifers, Winton–Mackunda partial aquifer, artesian GAB aquifers, or produced water from petroleum production (Section 3, Section 2.3 and Section 6).

Artesian GAB aquifers and Rolling Downs aquitard in the Eromanga Basin

Figure 4, Figure 8, Figure 9 and Figure 23 (as well as Section 3.2) outline some pertinent aspects of regional hydrogeology of the GAB aquifers and Rolling Downs aquitard. These include:

- The Cadna-owie–Hooray aquifer (and equivalents) is the main artesian GAB aquifer utilised in the Cooper GBA region. It can provide consistently good quality groundwater with relatively high flow rates, when compared to groundwater from the Winton–Mackunda partial aquifer.
- A zone of very low flow / stagnant groundwater (groundwater sink) occurs in the south-western part of the Cooper GBA region appears to coincide with reduced porosity at depth. One result is that regional groundwater flow tends to skirt around the margins of Cooper GBA region at shallower depths in areas of higher porosity and permeability such as along the Birdsville Track Ridge.
- The Cadna-owie–Hooray aquifer can be artesian. Sub-artesian pressure can develop in relatively topographically elevated areas (e.g. Innamincka Dome), or where water production has significantly lowered aquifer pressures. Artesian pressures in the Cadna-owie–Hooray aquifer may induce upward vertical leakage across the Rolling Downs aquitard towards the sub-artesian Winton–Mackunda partial aquifer. Potential for downward leakage

may occur where pressures in underlying GAB aquifers are less than pressures in the Cadna-owie–Hooray aquifer. These conditions could potentially where there are petroleum fields producing from underlying aquifers e.g. the Hutton Sandstone aquifer.

- The thick Rolling Downs aquitard (Figure 23) separates the deeper artesian GAB aquifers from the sub-artesian Winton–Mackunda partial. There are potential leakage pathways across this regional aquitard through lithological variation, structural complexities and polygonal faulting systems. Recent regional water balance estimates for the Eromanga Basin suggests that there has been up to a 30% decline in the upward leakage potential across the Rolling Downs aquitard in Queensland, due to long term groundwater production from free flowing artesian bores (Klohn Crippen Berger, 2016b).

Shallow aquifers in the Cooper GBA region: Lake Eyre Basin (Cenozoic) and the Winton–Mackunda partial aquifer

Figure 5 and Figure 6 outline some pertinent aspects of Cenozoic, many of which apply to Winton–Mackunda partial aquifer

- Thicker Cenozoic sequences occur in in South Australia, particularly in the Callabonna Sub-basin, but also in under parts of the Cooper Creek floodplain in Queensland.
- Winton-Mackunda partial aquifer is ubiquitous across the Cooper GBA region and can be over 500 m thick. Its aquifer characteristics and water quality can vary significantly over short distances. Many aspects of its water balance are poorly known, including the amount of recharge and degree of upwards leakage from underlying aquifers and discharge processes.
- Topographically controlled groundwater flow in Lake Eyre Basin and Winton-Mackunda partial aquifer occurs from elevated areas towards major drainage lines. Overall, regional groundwater flow direction appears to be to the south-west out of the Cooper GBA region.
- There are at least two groundwater systems in the Cenozoic (Section 3.3.3): a shallow local system with highly variable salinity above 60-80 m, and deeper, possibly fresher and regional scale groundwater system down to 300 m. The highly variable salinity in shallow system may relate to bores water quality been influenced by local recharge and discharge processes, with more saline water quality being intersected near areas of discharge. The deeper aquifer systems may be fresher and potentially relate (in part) to older palaeo-recharge. It should be noted that there could also be bias in available salinity data, as there may be no data from areas where deeper aquifers in the Lake Eyre Basin discharge. Only further sampling will clarify these issues.
- There are many unknowns, including degree of compartmentalisation, the nature of the boundary between the shallow and deeper Cenozoic aquifer, recharge sources and amount of upward leakage from underlying Winton-Mackunda partial aquifer. Also, there is not a robust water balance estimate.

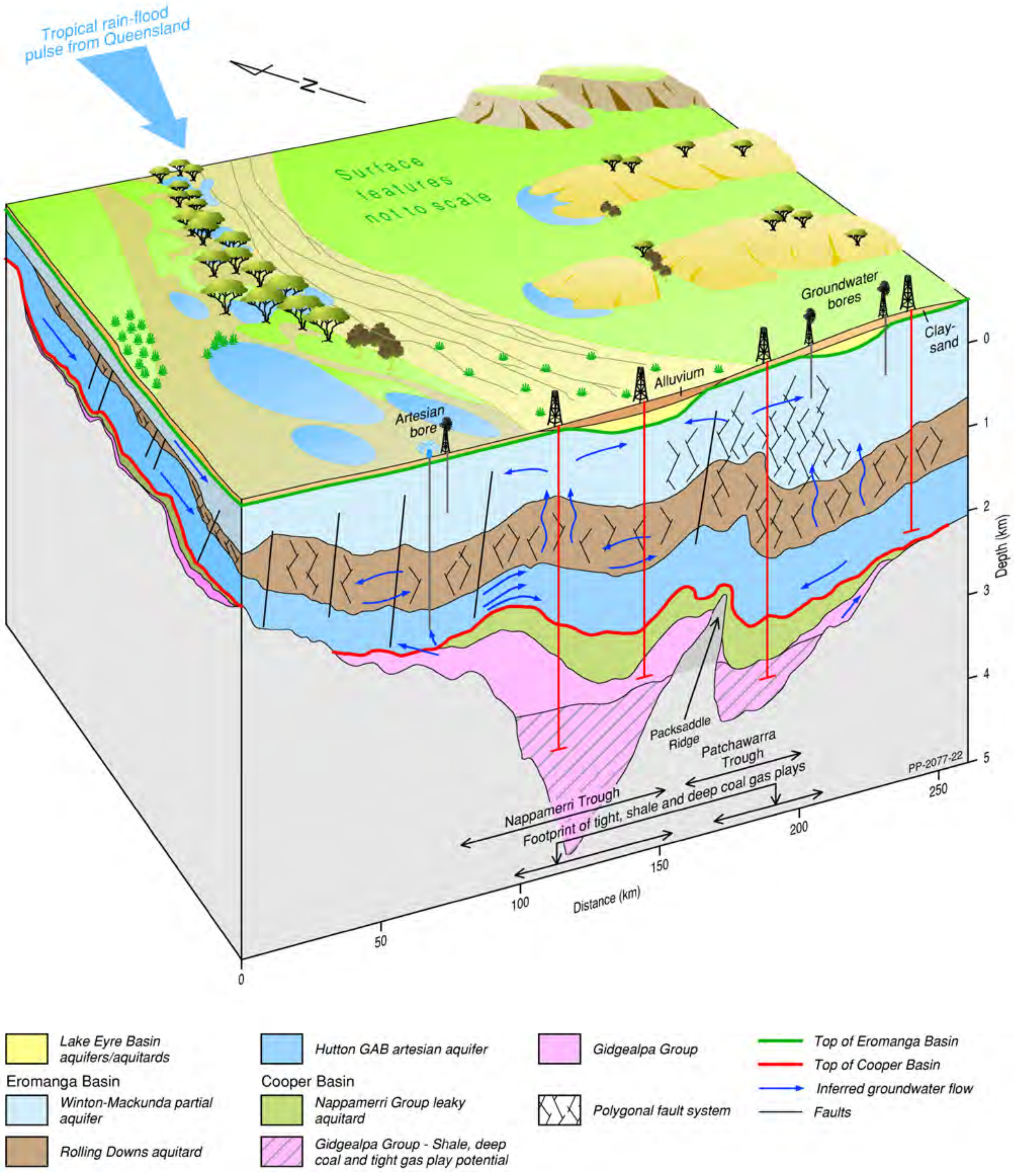

Figure 4 Conceptualisation of Cooper and Eromanga basins

Interactions include: leakage from rivers and lakes recharging regional aquifers during flood events; leakage to perched aquifers above the regional water table; leakage from shallow Cenozoic aquifers to deeper Cenozoic aquifers; regional south-westward directed groundwater flow in Cenozoic and Winton-Mackunda partial aquifers; upwards leakage from via polygonal faulting pathways; shallow groundwater extracting groundwater.
Element: GBA-COO-2-330

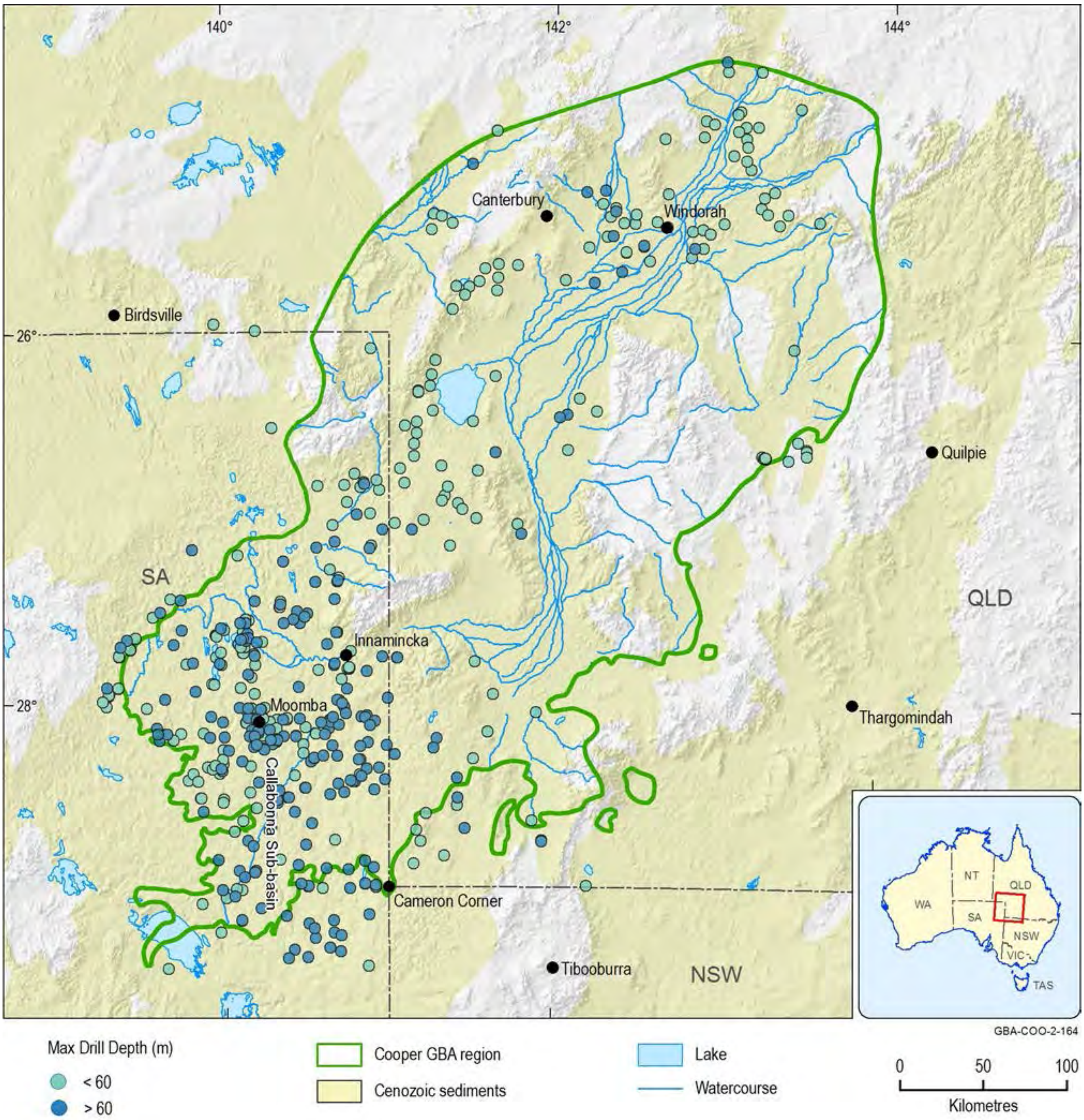

Figure 5 Potential distribution of the deeper aquifer using maximum drilling depth for groundwater bores in the Lake Eyre Basin

Data: Geological and Bioregional Assessment Program (2018a)
Element: GBA-COO-2-164

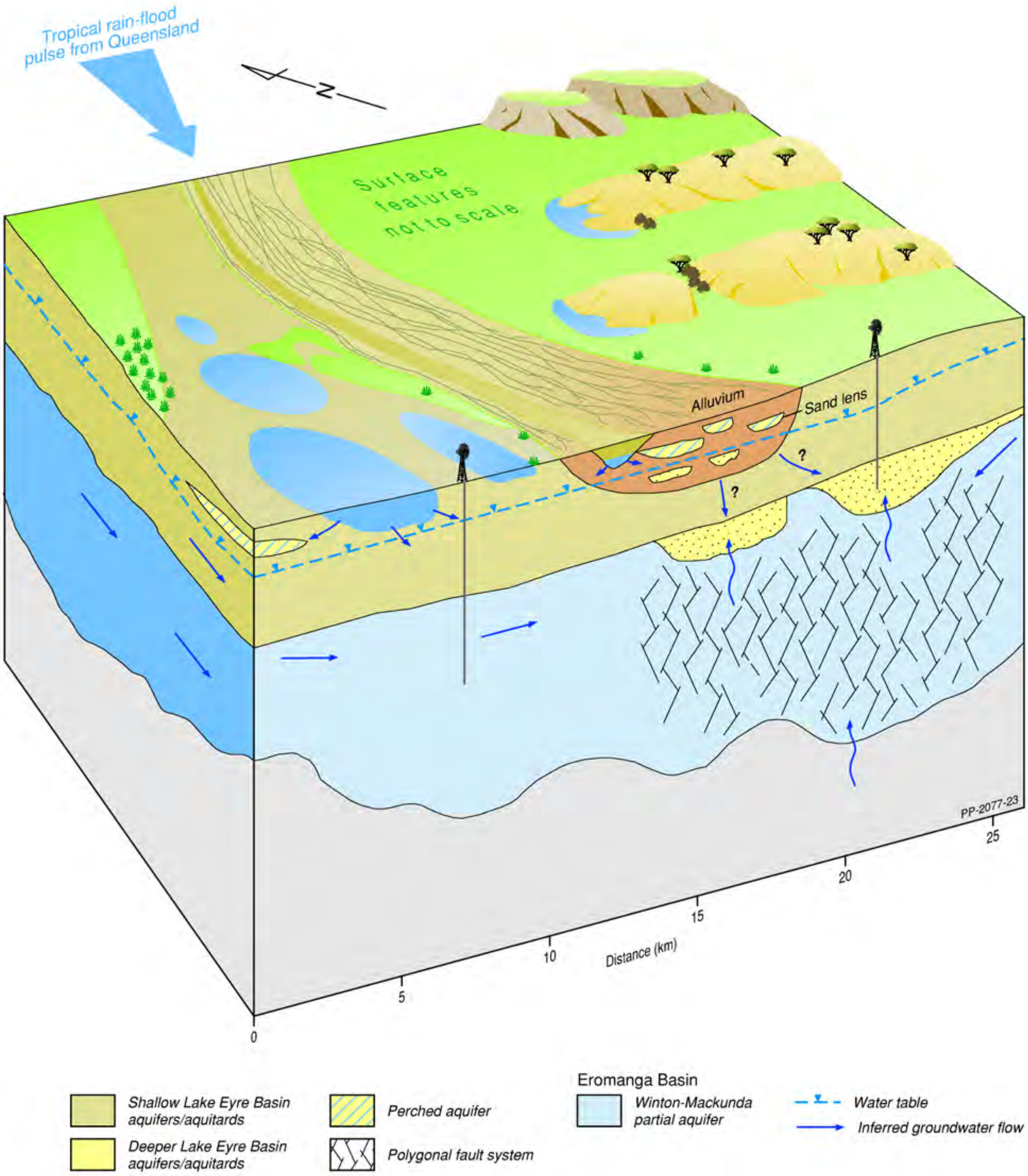

Figure 6 Shallow aquifer interactions with surface water features including lakes and drainage

Interactions include: leakage from rivers and lakes recharging regional aquifers during flood events; leakage to perched aquifers above the regional water table; leakage from shallow Cenozoic aquifers to deeper Cenozoic aquifers; regional south-westward directed groundwater flow in Lake Eyre Basin (Cenozoic) and Winton-Mackunda partial aquifers; upwards leakage from via polygonal faulting pathways; shallow groundwater extracting groundwater.
As outlined in Section 3.5, potentially the connectivity of the waterholes with groundwater may vary in part depending on their position in the floodplain. However, more work is required to determine whether this this actually the case.
Element: GBA-COO-2-283

3.1 Hydrostratigraphic framework

The geology of the Cooper GBA region is detailed in Owens et al. (2020) and (Lech et al., 2020). Figure 7 outlines the distribution of petroleum fields and facilities in the Cooper GBA region.

Smith et al. (2015) provided an overview of the hydrogeology of the Cooper GBA region as part of the Cooper Bioregional Assessment programme. Substantial information about the overlying GAB has been compiled in other projects including: the Great Artesian Basin Water Resources Assessment ("GABWRA", Ransley and Smerdon, 2012); Allocating Water and Maintaining Springs in the Great Artesian Basin ("AWMSGAB", Keppel et al., 2013a) and the Hydrogeological Atlas of the Great Artesian Basin ("GAB Atlas", Ransley et al., 2015a).

The hydrogeological properties of a formation vary in different parts of the Cooper GBA region. This variation in properties is due to one or a combination of the following: sediment source, lithological changes, rates of basin subsidence during deposition, diagenesis, structural modification, erosion and weathering since the time of deposition (Kellett et al., 2012b). The hydrostratigraphic framework (Figure 10) for the Cooper GBA region is in part based on the lithostratigraphic column presented in Orr et al. (2020) and other studies mentioned above. It shows the distinction of aquifers, partial aquifer, leaky aquitard, and aquitard. It also distinguishes on a regional scale, between formations with different hydraulic properties and varying lithological compositions, from sandstone dominated regional scale aquifers with good conductivity, to partial aquifers (variable lithological composition, local scale aquifers), leaky aquitards and aquitards (mudstone-siltstone dominated lithologies). It also identifies formations with variable hydrostratigraphic status due to other factors such as presence of extensive hydrocarbon plays.

The Cooper GBA region encompasses three major hydrostratigraphic subdivisions: Cooper Basin (Section 3.1.1), Eromanga Basin (Section 3.1.2) and Lake Eyre Basin (Section 3.1.3).

The following sections provide a summary of salient aspects of the hydrostratigraphy of the Cooper GBA region. Cross sections shown in Figure 8 and Figure 9 provide 2-dimensional representation of the distribution of these units.

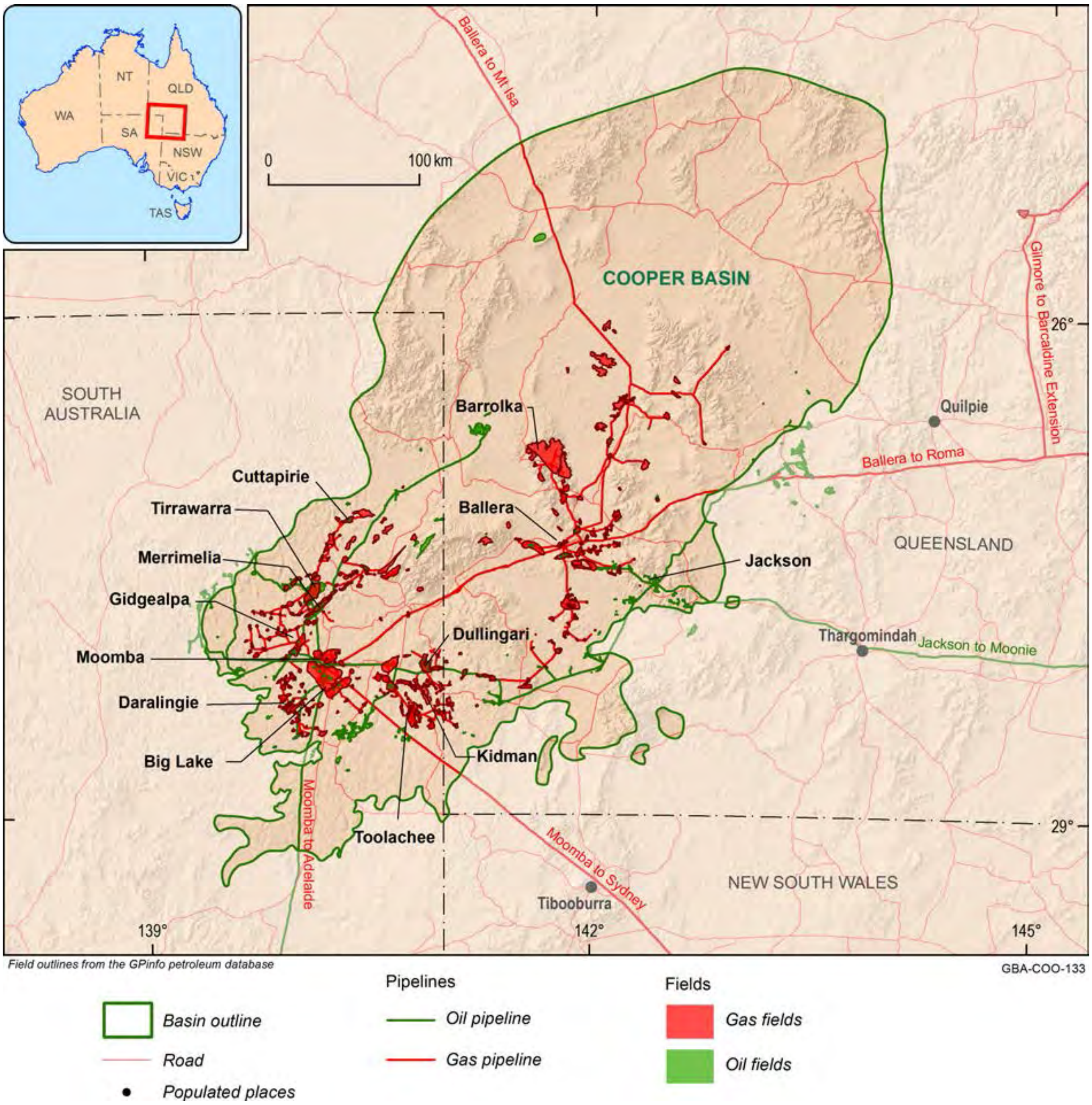

Figure 7 Cooper GBA region: petroleum fields, pipelines and production facilities

Data: oil and gas field outlines and pipeline routes from the GPinfo petroleum database – a Petrosys Pty Ltd product (Petrosys Pty Ltd, 2019)
Element: GBA-COO-133

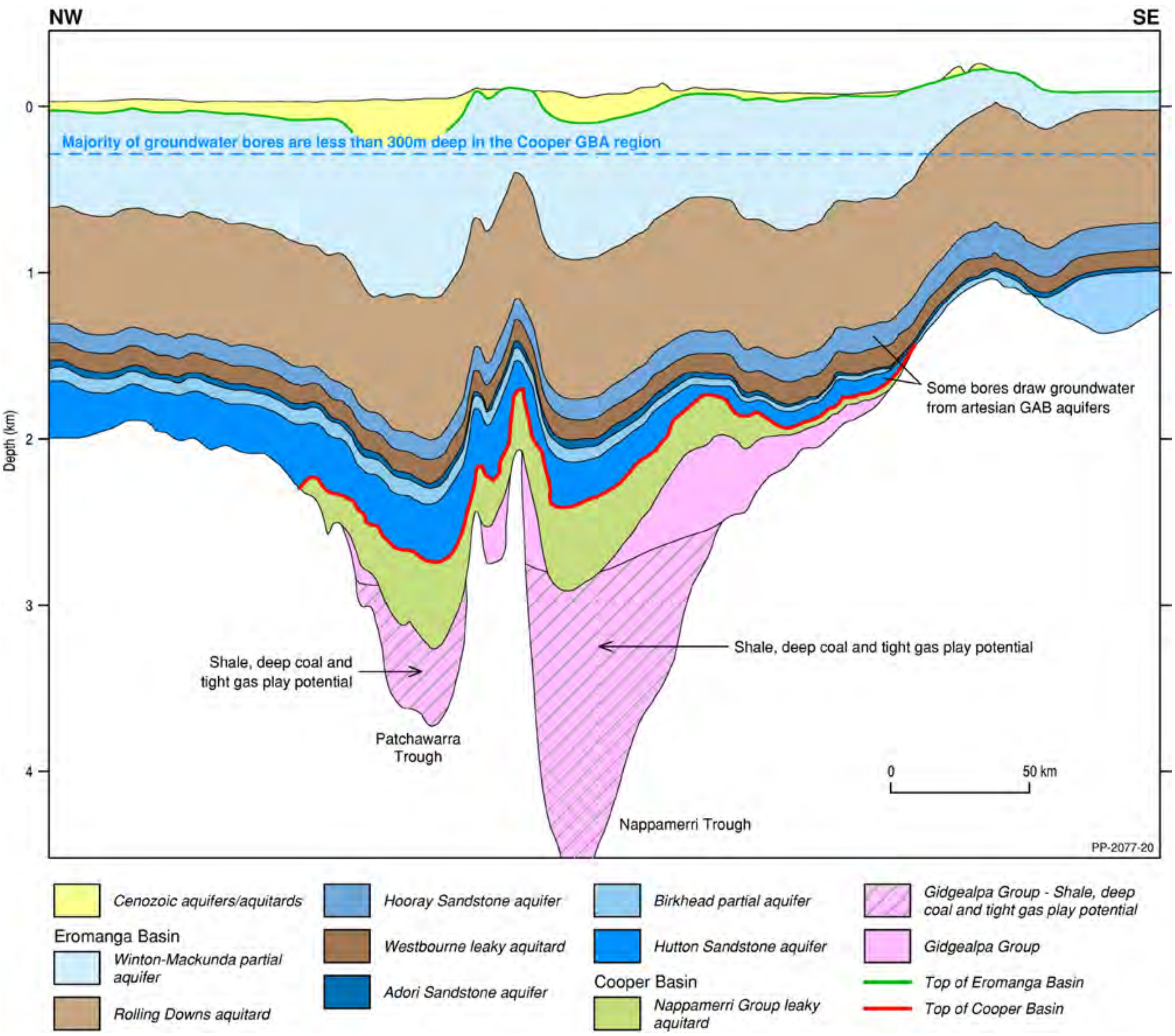

Figure 8 Cooper GBA region cross-section in South Australia - conceptualisation of relationships between tight, shale and deep coal gas plays in Cooper Basin and overlying aquifers and aquitards

Figure 11 outlines the location of the section.
Source: surfaces from Hall and Palu (2016)
Element: GBA-COO-2-284

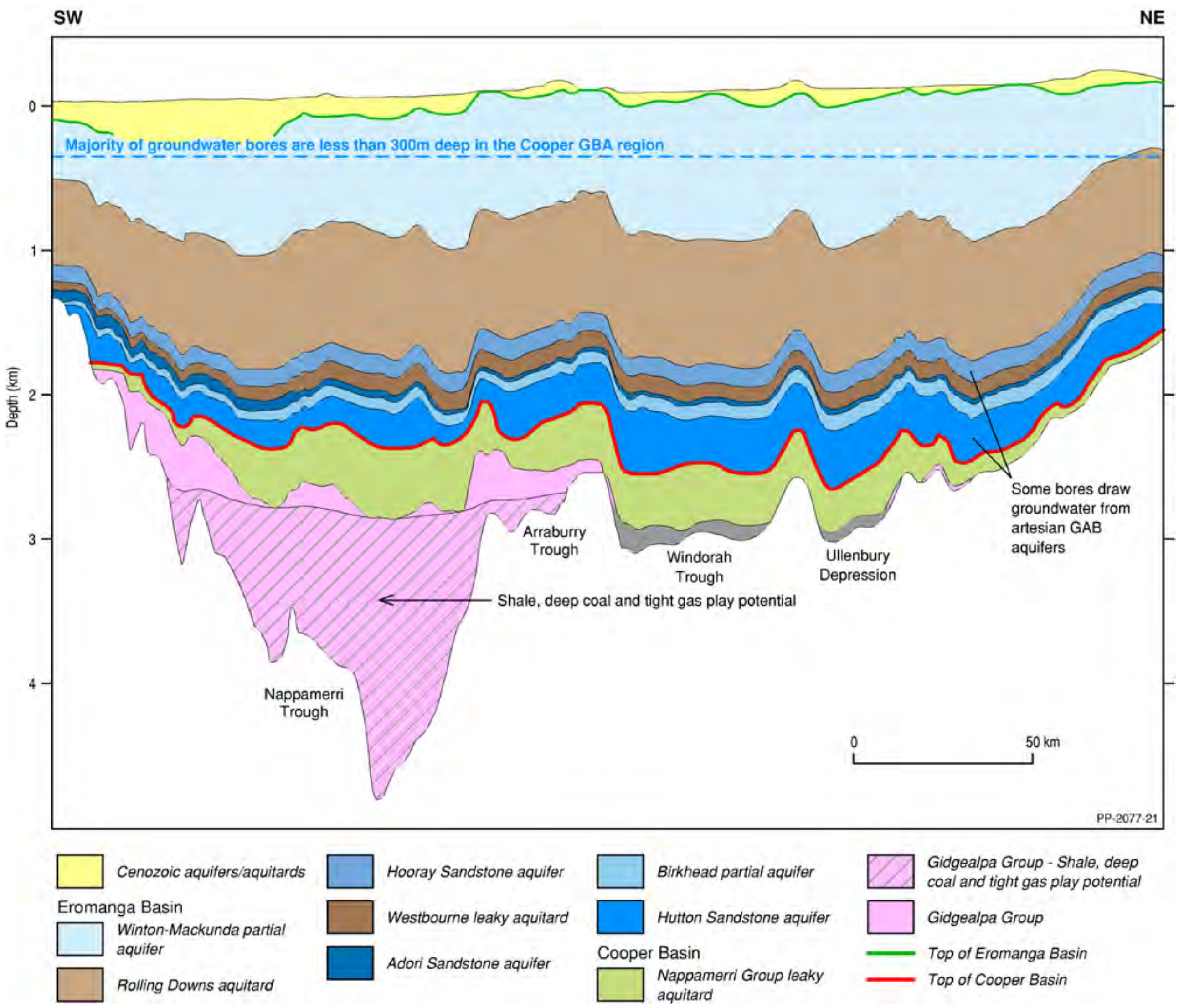

Figure 9 Cooper GBA region long-section in South Australia and Queensland - Conceptualisation of relationships between tight, shale and deep coal gas plays in Cooper Basin and overlying aquifers and aquitards

Figure 11 outlines the location of the section.
Source: surfaces from Hall and Palu (2016)
Element: GBA-COO-2-194

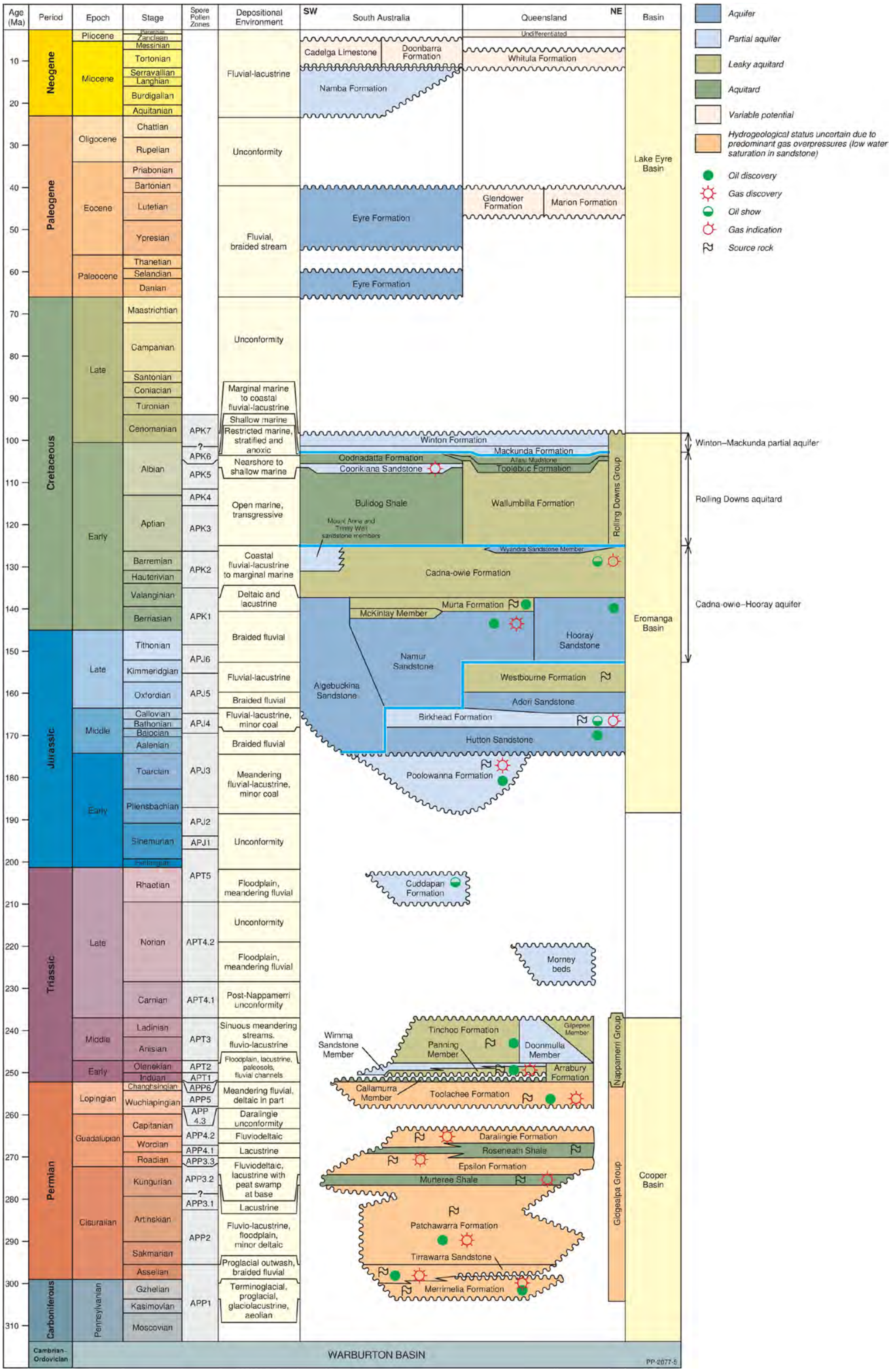

Figure 10 Hydrostratigraphic column for the Cooper GBA region

This figure has been optimised for printing on A3 paper (420 mm x 297 mm).
Element: GBA-COO-2-285

3.1.1 Cooper Basin

The Carboniferous–Triassic Cooper Basin is up to 2500 m thick and occurs at depths below surface from about 1000 m to 4500 m. As outlined in Owens et al. (2020) the extent of the Cooper Basin is defined by the occurrence of two stratigraphic groups. These are the late Carboniferous to late-Permian Gidgealpa Group and the late Permian to Middle-Triassic Nappamerri Group (Figure 11, Figure 12). Whilst a summary is provided here on Cooper Basin stratigraphy and depositional environments, further detail can be found in Owens et al. (2020), Lech et al. (2020), and Hall et al. (2015).

Conventional petroleum resources occur in both Gidgealpa and Nappamerri groups, whilst tight, shale, deep coal gas plays only occur in the Gidgealpa Group. A defining feature of these types of gas accumulations is that there is no gas-water contact (Lech et al., 2020). Furthermore, as outlined in Owens et al. (2020), lithology can vary considerably within individual formations, thus making a simplified lithological based categorisation of hydraulic properties problematic. These aspects have a bearing on hydrogeological status of a formation.

Within the Gidgealpa Group, variable over-pressuring in source rocks and adjoining sandstones has expelled much of the free water to render them gas-charged units. With little to no water saturation, assigning a hydrogeologic categorisation is less applicable. Therefore, a category "Hydrogeological status uncertain due to predominant gas over-pressures (low water saturation in sandstones)" are assigned to some of the formations that comprise the Gidgealpa Group (Figure 10, Figure 12). This situation negates any relevant consideration of hydrogeological inter- and intra-aquifer connectivity within much of the Cooper Basin sequence.

Where tight, shale and deep coal gas hydrocarbon plays do not dominate, aquifer/aquitard concepts may apply in the Cooper Basin. Areas where this may be the case include:

- The Nappamerri Group.
- Where the Gidgealpa Group occurs at relatively shallow depths (e.g. < less than 2800 m deep).
- Where the Gidgealpa Group subcrops beneath the Eromanga Basin (Figure 11).
- At depths where conventional petroleum plays tend to dominate instead of the unconventional resource plays (Lech et al., 2020).

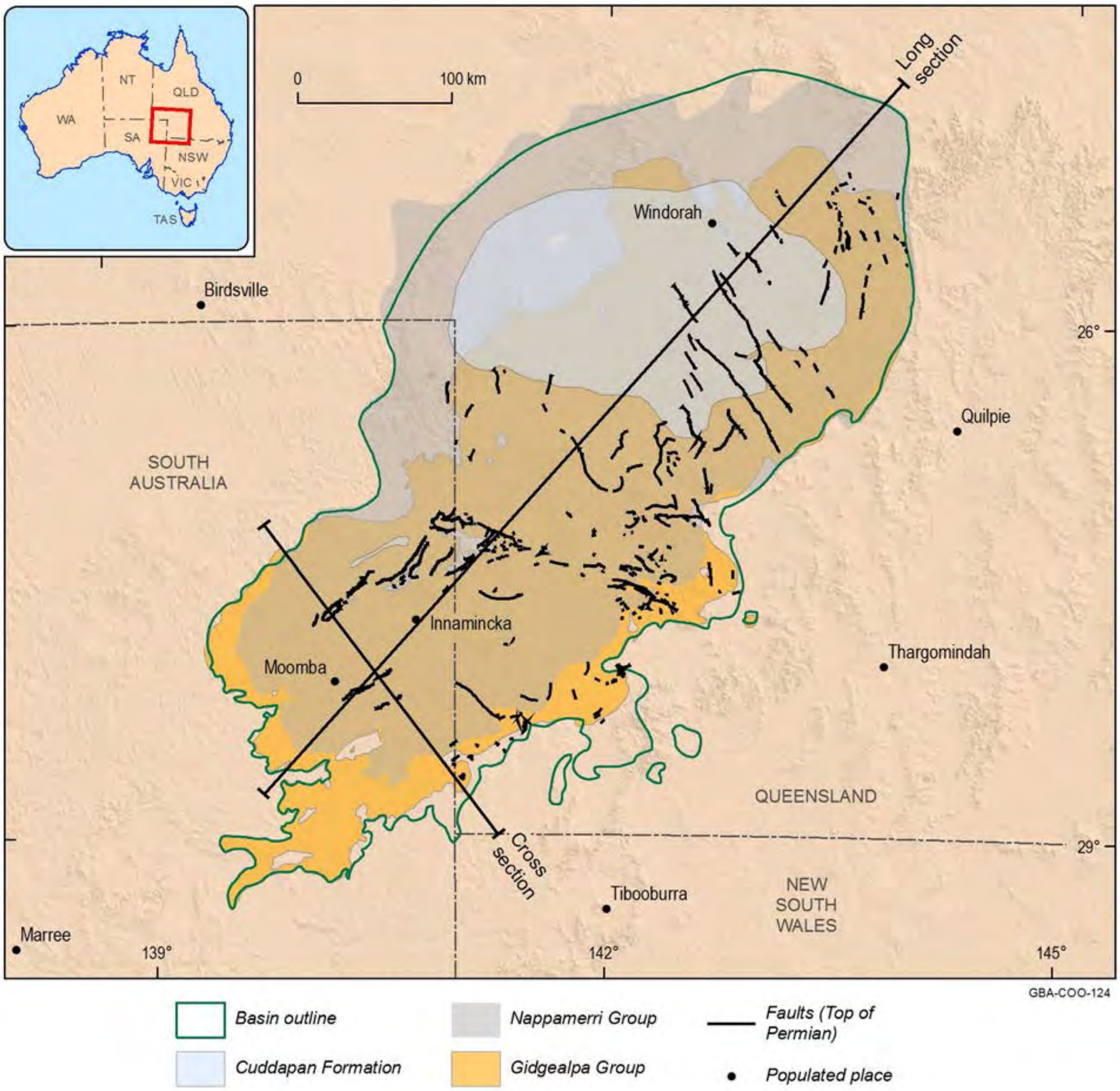

Figure 11 Distribution of Gidgealpa and Nappamerri groups and Cuddapan Formation underneath the Eromanga Basin cover

Subcrop of the Gidgealpa Group occurs underneath the Eromanga Basin, in areas where the Nappamerri Group is not present. Sections lines are detailed in Figure 8 and Figure 9.
Data: Hall and Palu (2016): Extent of Gidgealpa and Nappamerri groups; Geoscience Australia (2018a): Extent of Cuddapan Formation
Element: GBA-COO-124

Deposition of the Cooper Basin sequence commenced within mountainous terrain created by structurally controlled ridges. Underlying rocks belong to either the: Warburton Basin, Thomson Orogen or the Delamerian Orogen (Owens et al., 2020). The lowermost units of the Cooper Basin are paraglacial deposits with aeolianites (Merrimelia Formation) or glacial outwash sediments (Tirrawarra Sandstone). Depositional processes then changed to predominantly fluvio-lacustrine environments interspersed with coal swamps. The fluvial formations (Patchawarra and Toolachee formations in the Gidgealpa Group, and Arrabury and Tinchoo formations in the Nappamerri Group) include sandstones, which have in the past been considered to be partial aquifers (Smith et al., 2015). With rapid basement subsidence and high accommodation rates for fluvial deposition, there was minimal reworking of sediments, thus many river channel sands were buried as individual channels, with little or no development of planar sand bodies as would be expected with slower subsidence. Consequently, fluvial formations have a highly variable vertical and lateral character of fine-grained sediments (seals) interspersed with sand channels (aquifers-reservoirs). Hydrogeological properties would depend on lithofacies rather than having a single formation-wide character.

Due to the dominance of fine-grained lithologies, the Murteree and Roseneath shales are regional aquitards (Figure 12). Deposited in broad lake bodies, these shale units are limited to depressions in the south-western portion of the Cooper Basin (see Owens et al. (2020) for distribution). The Epsilon and Daralingie formations overlying the lacustrine units have deltaic, shore face and beach deposits in addition to fluvial sequences, and so are likely to have a highly variable hydrogeological character.

The overlying Triassic Nappamerri Group, although of fluvial origin, is relatively devoid of the coal that typifies the fluvial sequences of the Gidgealpa Group. Where the Gidgealpa Group is covered by the Nappamerri Group sequence (Figure 11), the Gidgealpa Group is predominantly over-pressured environment due to gas (Lech et al., 2020). The Nappamerri Group is not over-pressured however; sandy facies (e.g. the Wimma Sandstone Member) do host conventional hydrocarbon accumulations. The current conceptualisation is that the Nappamerri Group has diverse lithologies that includes a series of discrete intra-formational seals (Dragomirescu, 2002; Gravestock et al., 1998).

The Cuddapan Formation (Figure 10) unconformably overlies the Nappamerri Group. It is regarded as a partial aquifer, and may be comparable to the overlying Poolowanna Formation. Whilst this unit is more extensive in Queensland, in South Australia, only eroded remnants up to 64 m thick are preserved in a small area of the Patchawarra Trough (Figure 11).

Where the Cuddapan Formation is not present, the Nappamerri Group is directly covered by the basal units of the Eromanga Basin sequence. In most circumstances, this would be the Poolowanna Formation, but in other areas, it would be in direct contact with the Hutton Sandstone. The Poolowanna Formation is similar in lithology to the Cuddapan Formation, which makes it difficult to differentiate between the two formations without chronologic evidence.

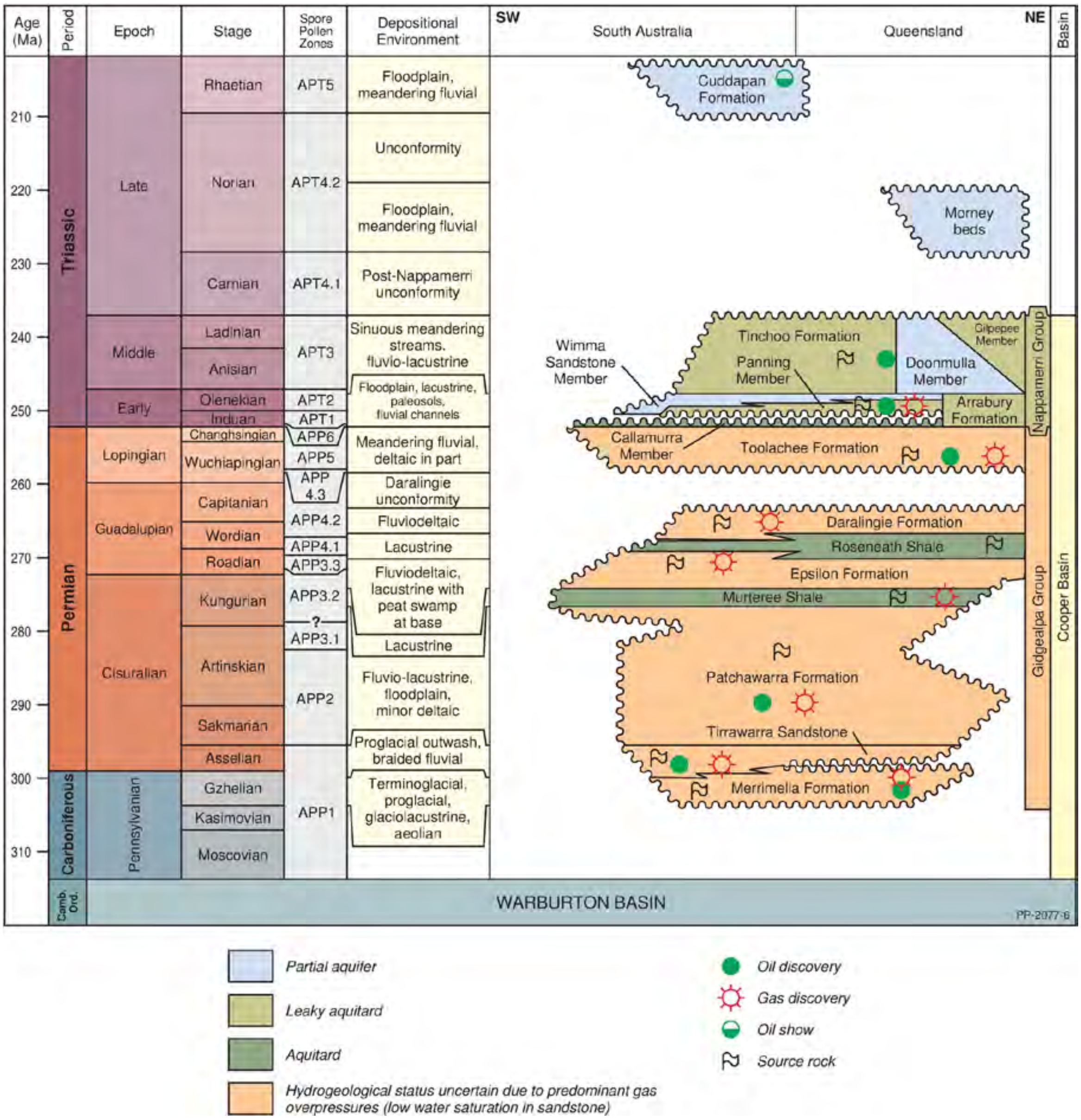

Figure 12 Cooper Basin hydrostratigraphy

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3.1.2 Eromanga Basin

The Jurassic–Cretaceous Eromanga Basin covers the entirety of the Cooper Basin, and varies in thickness from around 1000 m (near the Cooper Basin margins) to 2800 m over the Cooper Basin depocentres (Owens et al., 2020; SA Department for Water, 2011). The lithostratigraphy and depositional environments for the Eromanga Basin are outlined in Owens et al. (2020). The hydrostratigraphic equivalents of these lithostratigraphic units (Figure 13) form a sequence of aquifers and aquitards that comprise a part of the Great Artesian Basin (GAB) (Ransley and Smerdon, 2012). As was the case for the Cooper Basin, for some formations the lithology can vary considerably, thus making a simplified lithological based categorisation of hydraulic properties on a regional basis difficult in some cases (e.g. the Birkhead Formation). These have a bearing on hydrogeological status of a formation across the Cooper GBA region.

Broadly, the GAB aquifer sequence in the Eromanga Basin consists of the following (from bottom to top):

- Predominantly artesian GAB aquifers, of which the most widely utilised is the Cadna-owie–Hooray aquifer and equivalents.
- The Rolling Downs aquitard.
- The sub-artesian Winton–Mackunda partial aquifer.

The Cadna-owie Formation (including the Wyandra, Mount Anna, and Trinity Well sandstone members), Murta Formation (including the McKinlay Member), Hooray, Namur and Algebuckina sandstones (Figure 13) constitute the uppermost, predominantly artesian, GAB aquifer sequence (Ransley and Smerdon, 2012; Ransley et al., 2015a). This aquifer is the most widely used and most studied component of all the GAB aquifers (For examples refer Ransley et al. (2015a); Klohn Crippen Berger (2016b); Keppel et al. (2013a); and Hasegawa et al. (2016)). As outlined in Section 2.3 and Section 3.2.2, due to depth constraints this is predominantly the main artesian GAB aquifer utilised in the Cooper GBA region and is thought to source aquifer for some of the artesian GAB springs (Section 3.5). For this report, it is referred to as the Cadna-owie–Hooray aquifer.

Underlying the Cadna-owie–Hooray aquifer are a series of aquifers and regional aquitards. These include: the Adori Sandstone (Adori–Springbok Aquifer in Ransley et al., 2015a), Birkhead partial aquifer and Westbourne leaky aquitard, and the Hutton Sandstone and Poolowanna Formation (Hutton and equivalents aquifer). These underlying aquifers as well as the Cadna-owie–Hooray aquifer, all pinch out westwards into the Algebuckina Sandstone (Figure 13), towards the margin of the Eromanga Basin in South Australia.

Although the Birkhead Formation is classed in this report as a partial aquifer due to presence of sandstone reservoirs, it could also be classed as a leaky aquitard. Reason being is that the Birkhead Formation contains sandstone reservoirs as well as intra-formational shale seals (Boult, 1993) and can act as a regional seal to the underlying Hutton Sandstone. The Birkhead Formation reaches a thickness in excess of 150 m in the Patchawarra and Nappamerri troughs (Ransley et al., 2015a) and shales can act as aquitards. The Westbourne Formation is a leaky aquitard that has comparable extent to the Birkhead Formation, with thicknesses from 30 to 140 m. it is generally over 100 m thick (Ransley et al., 2015a) along the axis of the Cooper GBA region in Queensland.

The Rolling Downs Group comprises a thick basal aquitard and upper unconfined partial aquifer. The aquitard, termed the Rolling Downs aquitard (Ransley et al., 2015a), consists of the Wallumbilla and Toolebuc formations, Allaru Mudstone, Bulldog Shale, Coorikiana Sandstone and Oodnadatta Formation. The Coorikiana Sandstone forms a thin, discrete aquifer along the south-western margin of the Eromanga Basin, and is considered to be a source aquifer for some springs near the western margin of the Cooper GBA region (Keppel et al., 2016) (Section 3.5). Whilst regionally, the Wallumbilla Formation is a leaky aquitard, at more local scale sandstone units in it can act as aquifers (Klohn Crippen Berger, 2016b; Radke et al., 2012). In general, the stratigraphy of the Rolling Downs aquitard is complex and is an active area of research. For instance, the Bellinger Sandstone has recently being recognised as thin aquifer unit that overlies the Bulldog Shale in SA (ASUD, 2019).

The sub-artesian Winton–Mackunda partial aquifer is the uppermost GAB aquifer system (Section 3.2; (Klohn Crippen Berger, 2016b; Ransley and Smerdon, 2012; Smith et al., 2015). Unlike the artesian GAB aquifers, this aquifer is not confined by a regional aquitard, except perhaps where overlain by thick sequences of the Lake Eyre Basin (Smith et al., 2015). At more local scales, sandstone lithologies within Winton–Mackunda partial aquifer can be confined by finer grained sediments such as siltstones and mudstones.

The marginal marine sediments of the Mackunda Formation provide the more permeable and consistent aquifer. Higher in the sequence, especially in the fluvial Winton Formation, the distribution of sand bodies becomes more heterogeneous in fine-grained sediments. This results in disconnected and lensoidal aquifers and aquitards. The basal parts of the Winton Formation and the Mackunda Formation tend to have higher yields (Radke et al., 2012; Ransley and Smerdon, 2012; Ransley et al., 2015a). It can be difficult to identify the contact between the two formations (Department of Natural Resources and Mines (Qld), 2016).

The Winton–Mackunda partial aquifer is an important source of water for the Cooper GBA region, as a result of its shallow depth mitigating the costs of drilling into deeper artesian GAB aquifers (Department of Natural Resources and Mines (Qld), 2016). Although these sub-artesian aquifers are relatively highly utilised, there are significant knowledge gaps (Department of Natural Resources and Mines (Qld), 2016; Ransley and Smerdon, 2012), as much of the previous work has focussed on artesian GAB aquifers.

It was often difficult to interpret the boundary between the Cenozoic and Winton Formation from groundwater bore data, due to a lack of reliable stratigraphic picks. The lack of stratigraphic picks may be due to the difficulty in differentiating the weathered Winton and Mackunda formations from overlying Cenozoic sequences based on lithology alone, or no interpretation was undertaken at the time of drilling. Distinguishing between sandstones of the Winton Formation and the Eyre Formation is difficult, and past interpretation of formation boundaries has varied dramatically (for example see Moussavi-Harami and Alexander, 1998; and Alexander et al., 2006). In contrast, Gravestock et al. (1995) reports that there is a distinct colour change between overlying Cenozoic and Winton Formation. Stratigraphic picks derived from downhole geophysical logs, stratigraphic dating, airborne electromagnetic surveys, and other data collected in future may further refine the boundary between the Cenozoic sequences and Winton and Mackunda formations. This would assist with unravelling shallow aquifer hydrodynamics in the Cooper GBA region.

Picking which aquifer a bore was drawing water was further complicated by a lack of screen interval information. Sometimes the only potential discriminator was bore depth. For example, in areas of Cenozoic cover, bores less than 50 m would be interpreted as sourcing water primarily from the Cenozoic. Where a bore lacked stratigraphic data, in areas of Cenozoic cover, the Palaeogene-Neogene thickness model of Ransley et al. (2015a) was used to determine whether a bore's maximum depth exceeded the thickness of Cenozoic sediments and intersected the Winton or Mackunda formations. In these instances, bores were assigned as "Cenozoic/Winton–Mackunda". A bore would be assigned to the Winton–Mackunda partial aquifer hydrostratgraphic unit if a distinction was apparent under areas of cover, or where the bore was located on areas of outcropping Winton or Mackunda formations.

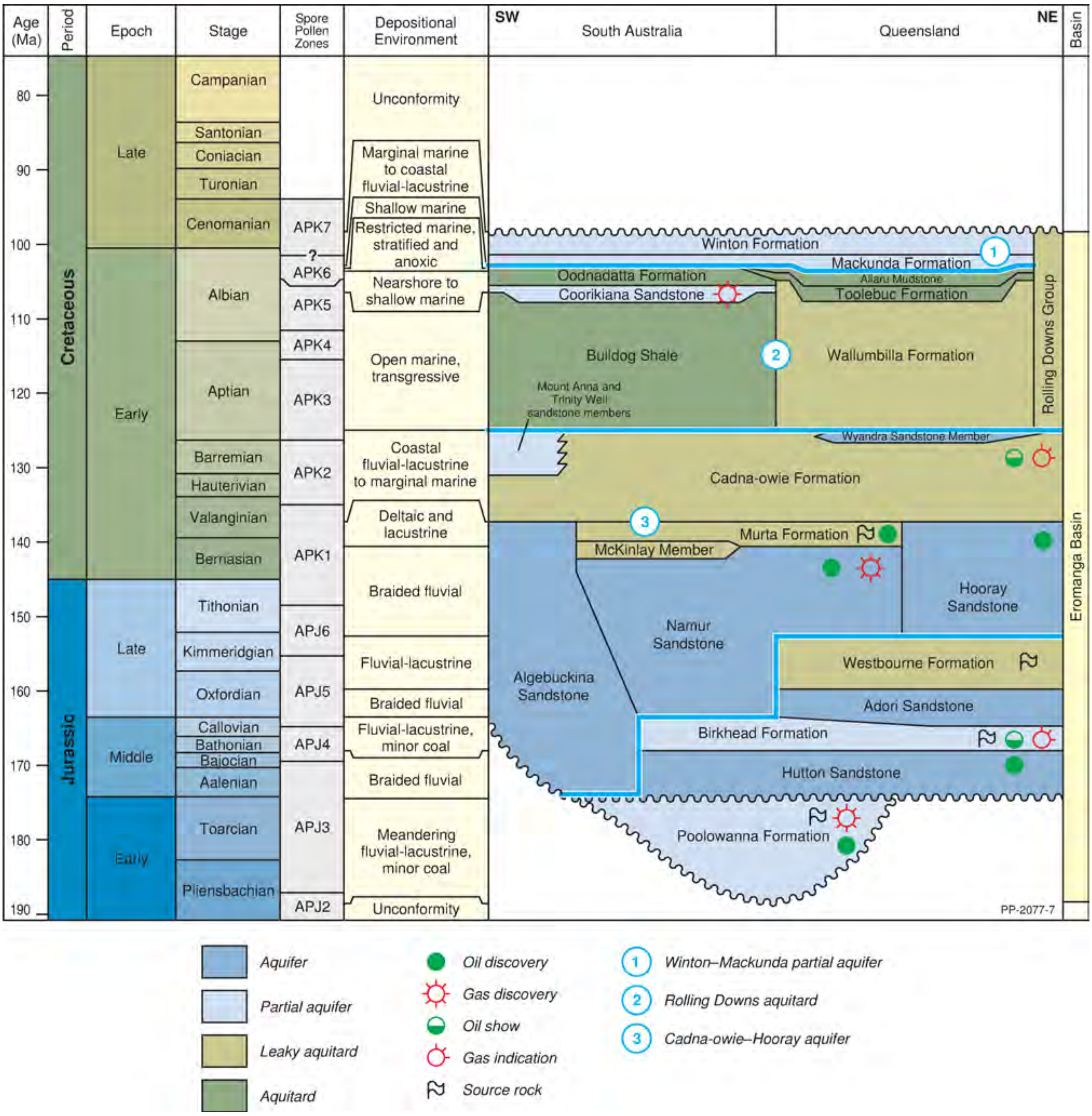

Figure 13 Eromanga Basin hydrostratigraphy for the Cooper GBA region

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3.1.3 Lake Eyre Basin

For the Cooper GBA region, the distribution and thickness of Cenozoic-aged Lake Eyre Basin sediments is outlined in Owens et al. (2020). Lake Eyre Basin sequences can be up to 300 m thick in the Callabonna Sub-basin. In other areas, such as under the Cooper Creek floodplain in Queensland and Strzelecki desert plains, the thickness reach up to 100 m. An extensive cover of Quaternary sediments associated with present day geomorphologic features blanket much of the pre-Quaternary sequence.

Recent studies into geological history of the Lake Eyre Basin have tended to focus on Quaternary geology and geomorphology, as it contains an excellent record of how climatic and active interplate tectonics influence sedimentation and geomorphology. Examples include: Jansen et al. (2013); Cohen et al. (2010) and Habeck-Fardy and Nanson (2014). In contrast, only one study (e.g. Cendón et al., 2010) is focussed on shallow hydrogeology of the Cooper GBA region.

Figure 14 details the hydrostratigraphy of the Lake Eyre Basin. The Eyre and Namba formations are aquifers in South Australia, but relatively few bores access equivalents across the border in Queensland (Klohn Crippen Berger, 2016b). The Eyre Formation is dominated by sandstone, lignite and conglomerate deposited in braided river channel environments along with clay and silt deposited on floodplain (SA Department for Water, 2011; Coleman, 2002). Up to 140 m thick, it is characterised as a variably confined to unconfined aquifer, depending on the nature of overlying material (SA Department for Water, 2011). This widespread formation is the basal unit in the Callabonna Sub-basin (Coleman, 2002).

The widespread Glendower Formation, dominated by fluvial quartzose sandstones and conglomerates up to 70 m thick, is considered an eastern equivalent to the Eyre Formation; however the hydrogeological properties of the Glendower Formation are variable (Department of Natural Resources and Mines (Qld), 2016; Radke et al., 2012; Ransley and Smerdon, 2012).

The Namba Formation overlies the Eyre Formation. It is generally less than 200 m thick, and consists of poorly sorted and alternating fine to medium grained sand, silt and clay, as thin dolomitic/limy interbeds (Radke et al., 2012; SA Department for Water, 2011). With a variable sedimentological nature, the Namba Formation acts as either an aquitard in many places or an aquifer in others; it can be considered a tight aquitard containing enclosed channel aquifers within the formation, leading to an overall leaky aquitard to partial aquifer status (Keppel et al., 2016; Radke et al., 2012; SA Department for Water, 2011). Other equivalent units include the Whitula Formation, Cadelga Limestone and the Doonbara Formation are considered to have quite variable hydraulic properties as well (Alley, 1998; Ransley et al., 2015a; Coleman, 2002; Smith et al., 2015).

To date, hydrogeological investigations into the Lake Eyre Basin aquifers tend to be at a local scale and focused on groundwater-surface water interactions rather than looking at the whole-aquifer system (e.g. Cendón et al., 2010). This study has found that the quality of available hydrostratigraphic data from groundwater bores (Section 2.2) coupled with extensive Quaternary cover make it difficult to differentiate specific Cenozoic units in the sub-surface environment. Data gaps that hamper interpretation include reliable stratigraphic picks, well depths and screen intervals. Hence, individual units for groundwater bores sourcing water from Lake Eyre Basin aquifers (unless otherwise designated in the dataset) are not generally distinguishable and are hydrostratigraphically assigned to “Cenozoic”. A lack of understanding of hydrostratigraphic framework can have implications for management, such as over drawing water or salinisation.

As discussed in Section 3.1.2 above, the boundary between Winton Formation and overlying Cenozoic is poorly defined. Furthermore, some of the bores have very long screen open hole/screen intervals, so there is potential that a number of bores source water from both Lake Eyre Basin and underlying Winton–Mackunda formations.

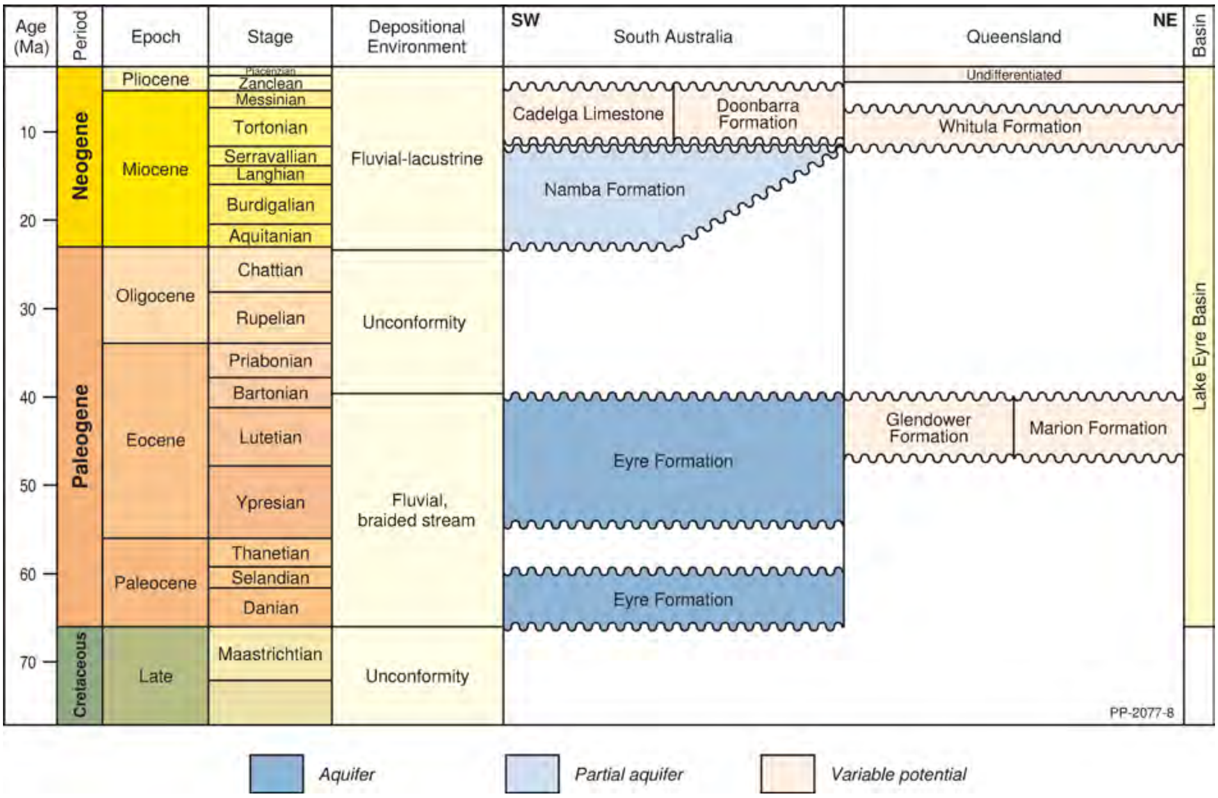

Figure 14 Lake Eyre Basin hydrostratigraphy for the Cooper GBA region

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3.2 Hydrodynamics

Groundwater underpins activities in the Cooper GBA region and provides a water source for pastoral industry, population centres, mining activities, and other extractive industries. Most bores target aquifers in the Lake Eyre Basin and the Winton–Mackunda partial aquifer (Table 2) as these aquifers are relatively shallow when compared to the artesian GAB aquifers. However, the relatively small number of groundwater bores tapping into artesian GAB aquifers have higher flow rates and more consistent water quality. The most studied aquifer in the Cooper GBA region is the Cadna-owie–Hooray aquifer, which is one of the confined artesian aquifers that make up the iconic GAB aquifer system.

3.2.1 Cooper Basin

The Cooper Basin is not utilised as a groundwater source (Section 2.2.1). Hence, petroleum industry data is required to understand the hydrogeology of the Cooper Basin. Water produced as part of hydrocarbon production can be: re-used for petroleum related activities, a water source for local pastoral activities or evaporated. For this report, formation pressure data from petroleum wells was utilised to inform discussion around hydrodynamics of the Cooper Basin.

A number of factors (see also Section 3.1.1) influence groundwater systems in the Cooper. Aside from hydrocarbons, other influences include distribution of sandstone porosity and permeability, subsequent diagenetic effects and structures. Sandstone porosity and permeability varies considerably and can depend on original mineralogy, subsequent diagenesis and burial history (Schulz-Rojahn and Phillips, 1989). Quartz and carbonate cements, clay infill and secondary dissolution of lithics often heavily modify the porosity in the Cooper Basin. Some deeper sections of Cooper Basin, for instance in the lower parts of the Nappamerri Trough, have been subjected to low grade regional metamorphic temperatures and pressures (Schulz-Rojahn and Phillips, 1989), which has destroyed much of the original porosity and permeability. This has had a bearing on hydrocarbons in deep parts of the Cooper Basin as well as the development of engineered geothermal systems in the underlying Warburton Basin (see Section 3.4.1).

3.2.1.1 Potentiometry of the Nappamerri Group, Toolachee-Daralingie and Patchawarra formations

Hydrostatic pressure (Figure 15) refers to the pressure that a static (i.e. not moving) column of fluid at a given density exerts at a given depth. Pressures that fall below calculated hydrostatic pressure are termed “under-pressured” whereas, those greater than the calculated hydrostatic pressure are classed as “over-pressured”. Section 2.2 includes discussion on potential data quality issues that may occur when utilising archival formation pressure data.

Aside from depth, pressures can vary from hydrostatic due to a number of factors. These include the presence of hydrocarbons, whether the fluids are in flux (moving), fluid composition and density (if groundwater the density is controlled by temperature and salinity), stress regime, lithology, porosity, permeability and pressure compartmentalisation, and whether nearby producing wells have drawn pressures down. Some under-pressured measurements may also be due the influence of low permeability and the duration of test, resulting in a measurement prior to pressure stabilisation.

This section will focus on the Nappamerri Group, the Toolachee-Daralingie formations and the Patchawarra Formation for the following reasons:

- The Nappamerri Group is the regional seal for petroleum systems found in the underlying Gidgealpa Group (Lech et al., 2020).
- The Toolachee-Daralingie formations comprise the uppermost sequences in the Gidgealpa Group and have potential for tight, shale and deep coal gas (Lech et al., 2020). For these formations, pressure data was combined as there is evidence they are connected across the intervening unconformity (Figure 12).
- The Patchawarra Formation has significant potential for extensive tight, shale and deep coal gas plays (Lech et al., 2020).

Figure 15 shows that there can be considerable variation from the calculated hydrostatic pressure for a particular depth across all formations. While some individual pressure measurements may potentially be influenced by data quality issues, overall the trends are consistent with hydrostatic pressure. For instance, pressures in the Nappamerri Group tend to fall largely within the calculated hydrostatic pressure range for a given depth. Some of the under-pressured measurements in the Nappamerri Group (i.e. pressures less than calculated hydrostatic) may be attributable to past or on-going production of hydrocarbons or low permeability.

Pressures in the Toolachee, Daralingie and Patchawarra formations (Figure 15) show considerably more variation with depth in comparison to the overlying Nappamerri Group. Over-pressuring (i.e. above hydrostatic) is evident with increasing depth, which supports the interpretation of the

Nappamerri Group as a regional seal for hydrocarbons (Lech et al., 2020). Some under-pressure measurements could be due to reduction in pressure from hydrocarbon extraction. Pressures around 300 – 500 PSIG (pounds per square inch), appear to form a highly under-pressured trend from about 1900 m to 3100 m below surface. A hypothesis for this trend is that it may relate to pressures in depleted reservoirs. Further investigation would be required to confirm whether this is case.

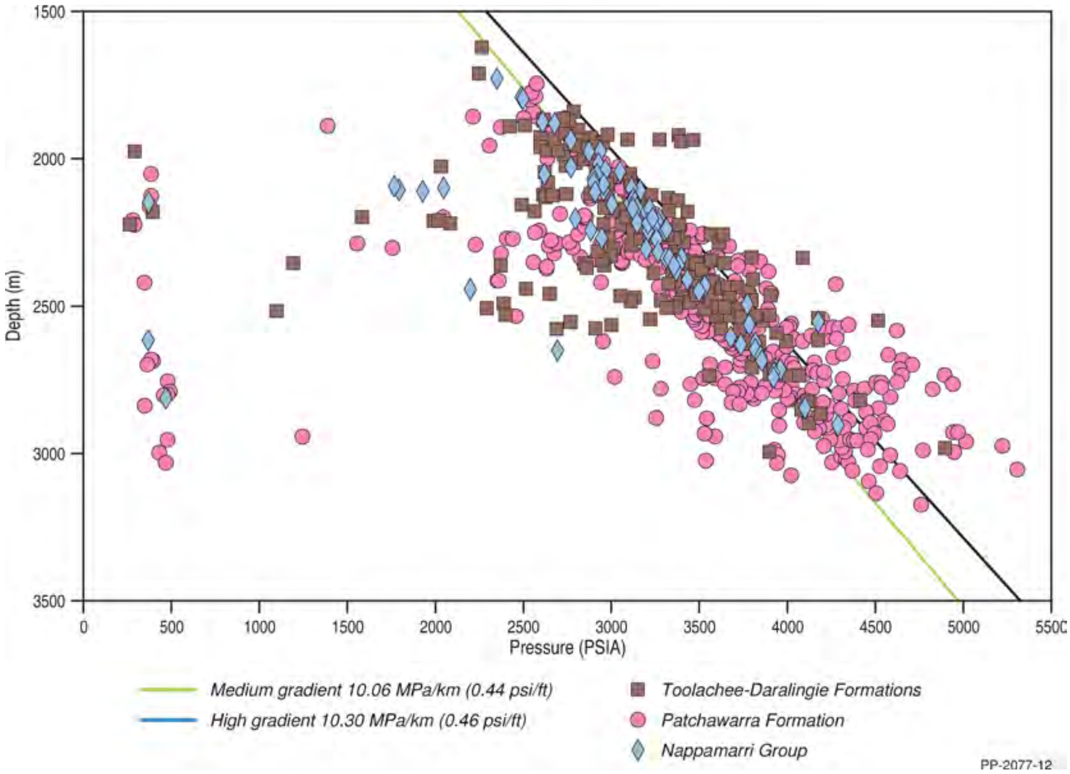


Figure 15 Final shut in pressures from formation tests for selected formations in the Cooper Basin

Medium gradient/ High gradient: these related to hydrostatic pressures trend relative to a given fluid density. These respectively relate to water with salinities of 2500 mg/L and 5000 mg/L respectively. Pressure values are "under-pressured" or "over-pressured" depending on if it sits to the left or right of the zone defined by the gradient lines (i.e. the expected range of pressures for a given depth).
Data: Geological and Bioregional Assessment Program (2019c)
Element: GBA-COO-2-289

Converting pressure data to freshwater equivalent hydraulic head accounts for temperature and salinity (see Section 2.2). Hydraulic head references height relative to an elevation datum, usually Australian Height Data (m AHD), which equates to metres above sea level. The presence of hydrocarbons, in particular gas, will influence formation pressures, which can result in over-pressuring and subsequently very high equivalent hydraulic heads.

Hydraulic heads are important for understanding potential flow directions both horizontally and vertically in a stacked aquifer-aquitard sequence. For instance, fluids have potential to flow vertically between units if a pathway and pressure differential exists. For instance, if hydraulic head in Nappamerri Group is lower than that found in the overlying Hutton Sandstone, the potential flow will be downwards into the Nappamerri Group. Conversely, upward potential flow depends on hydraulic head being lower in Hutton Sandstone, when compared to underlying units. Actual flow will only occur if a suitable connective pathway exists.

Figure 16, Figure 17 and Figure 18 outline how freshwater equivalent hydraulic head varies spatially for the Nappamerri Group, Toolachee-Daralingie formations and the Patchawarra Formation. Often there can be multiple measurements in a formation at different depths in each petroleum well. To simplify display of equivalent freshwater hydraulic head data in a spatial extent the points on these figures represents the top most (i.e. the shallowest) measurement taken in a formation in a particular well. Future work could investigate variations in hydraulic head and pressure that may occur vertically within a formation.

In the Nappamerri Group (Figure 16), the distribution of hydraulic head measurements are biased towards locations of well fields and structural highs in the Cooper Basin, with few data points occurring off major structural trends towards basin centres. Significant variations in hydraulic head are apparent, but it is difficult to identify distinct trends at a regional scale. The Nappamerri Group encompasses a series of units with a range of lithologies. However, for many petroleum wells, the stratigraphy for the Nappamerri Group is not segregated down to the formation level, which makes an assessment of this factor difficult. Hydraulic head variations could also be due to: structural complexity around highs, lithological variations between and within formations (i.e. lithofacies changes due to changing depositional environments), diagenetic effects post deposition, presence of hydrocarbons, or petroleum production.

Whilst there is significant variation over short distances, the majority of hydraulic head measurements occur between 0 – 200 m along structural highs or near the margin of the Cooper Basin. Very low hydraulic head (i.e. below sea level) is likely to be due to petroleum production. Very high (i.e. greater than 200 m) hydraulic head could be due to the presence of hydrocarbons or aquifer compartmentalisation. Due to the flat topography and low elevations, hydraulic heads greater than 200 m will be artesian in the Cooper GBA region.

Near the petroleum fields situated on the western flank of the Cooper Basin, the Toolachee-Daralingie and Patchawarra formations show varying degrees of depressurisation due to production (Figure 17, Figure 18). Variable hydraulic head levels on the western flank may also be due to a combination of affects including: changes in pressures due to production as development of the petroleum reservoirs progress with time, reservoir compartmentalisation, or effect of low permeability on pressure measurement (see also Section 2.2.4). Sparse data suggests that that hydraulic heads in Toolachee-Daralingie (Figure 17) into Queensland can be relatively high. In the Patchawarra Formation (Figure 18) hydraulic heads vary considerably over short (km scale) distances, which again will be largely be due to production and pressure compartmentalisation. As with the Nappamerri Group, at regional scales there are no obvious trends in hydraulic head in either Patchawarra, Toolachee-Daralingie formations.

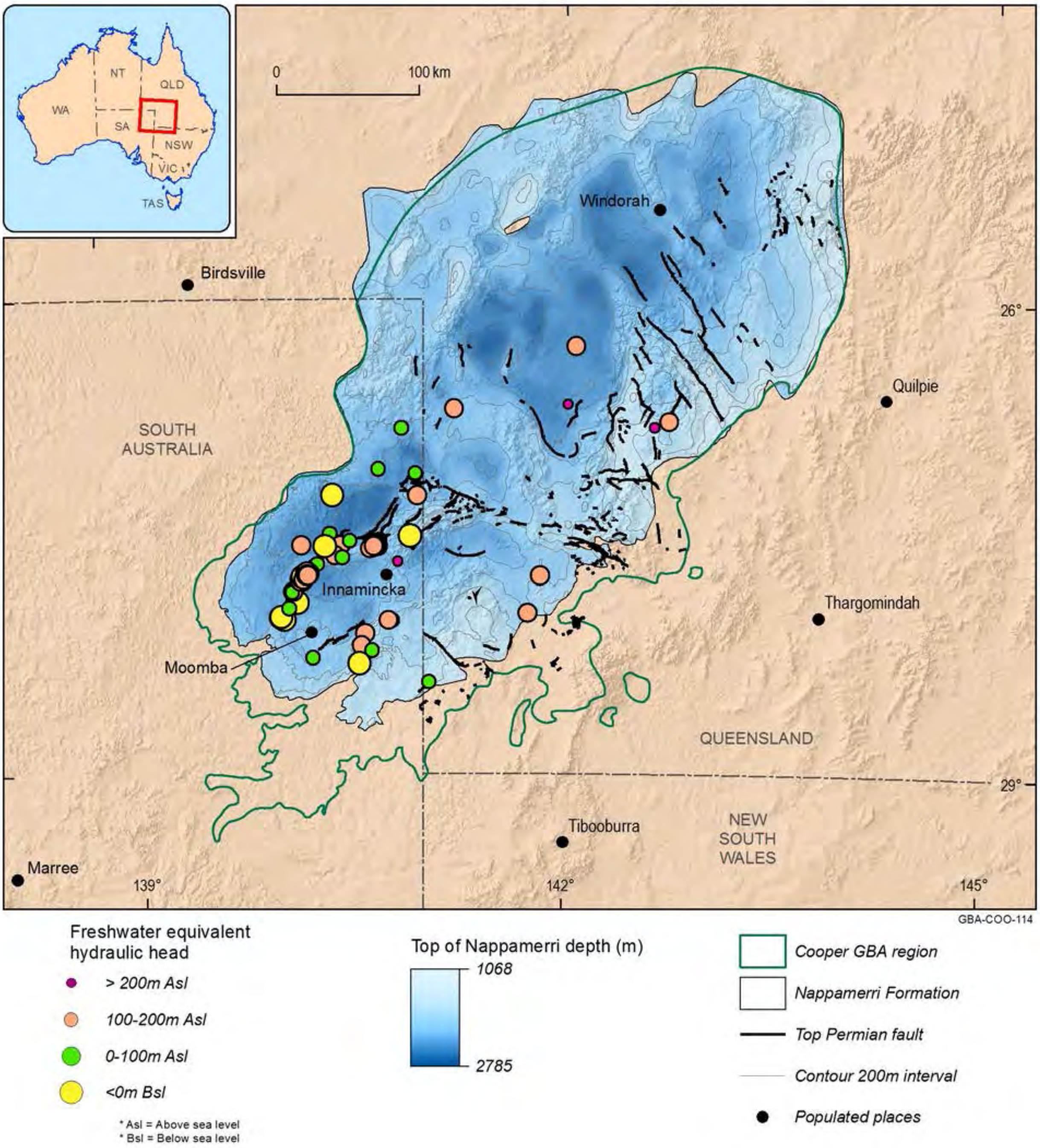


Figure 16 Nappamerri Group – hydraulic head overlain on depth to the top of formation

Data: Geological and Bioregional Assessment Program (2018c) freshwater equivalent hydraulic head; Hall and Palu (2016): Top of Formation and contours
Element: GBA-COO-114

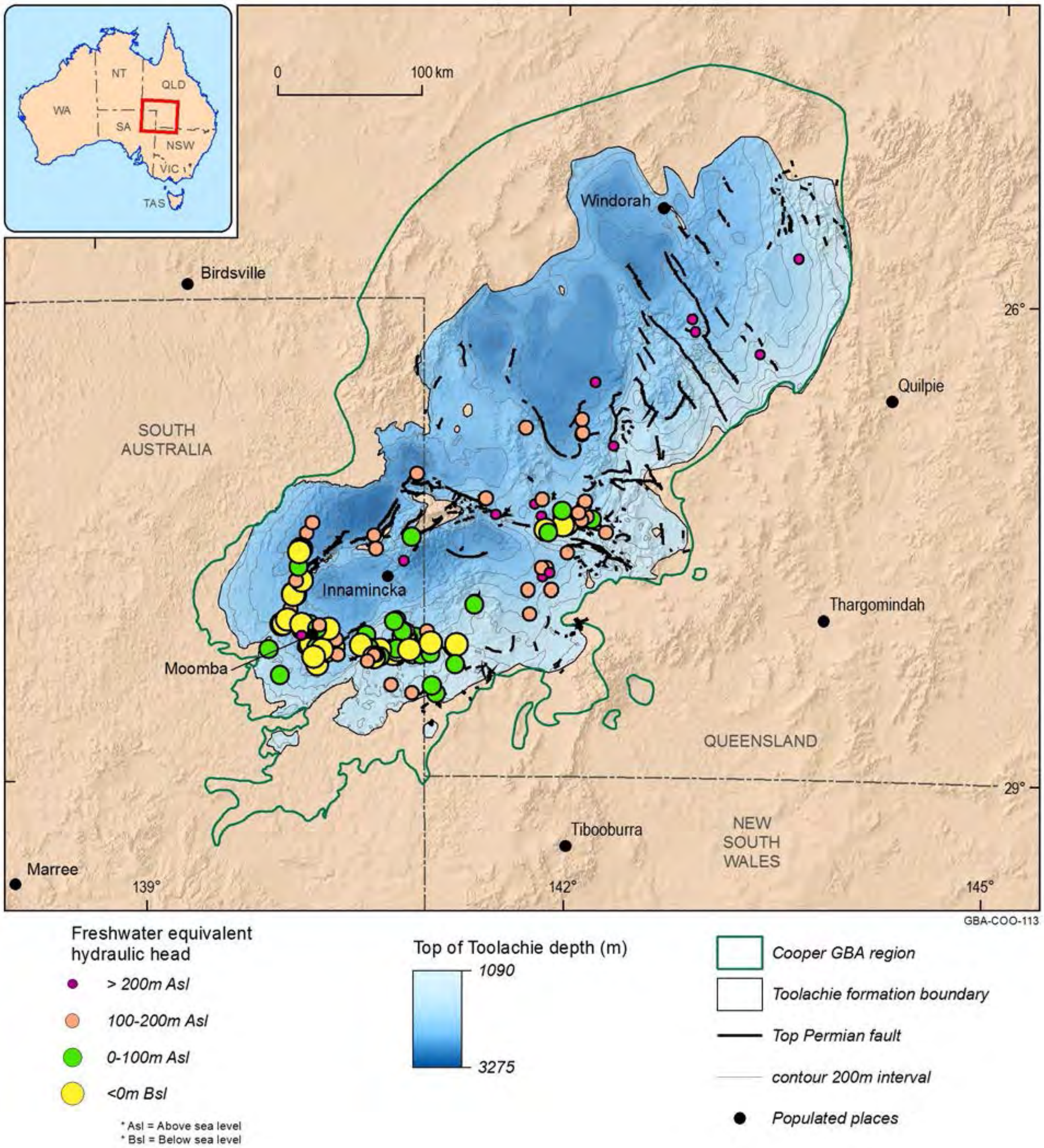


Figure 17 Toolachee-Daralingie formations – hydraulic head overlain on depth to top of formation

Data: Geological and Bioregional Assessment Program (2018c) freshwater equivalent hydraulic head; Hall and Palu (2016): Top of Formation and contours
Element: GBA-COO-113

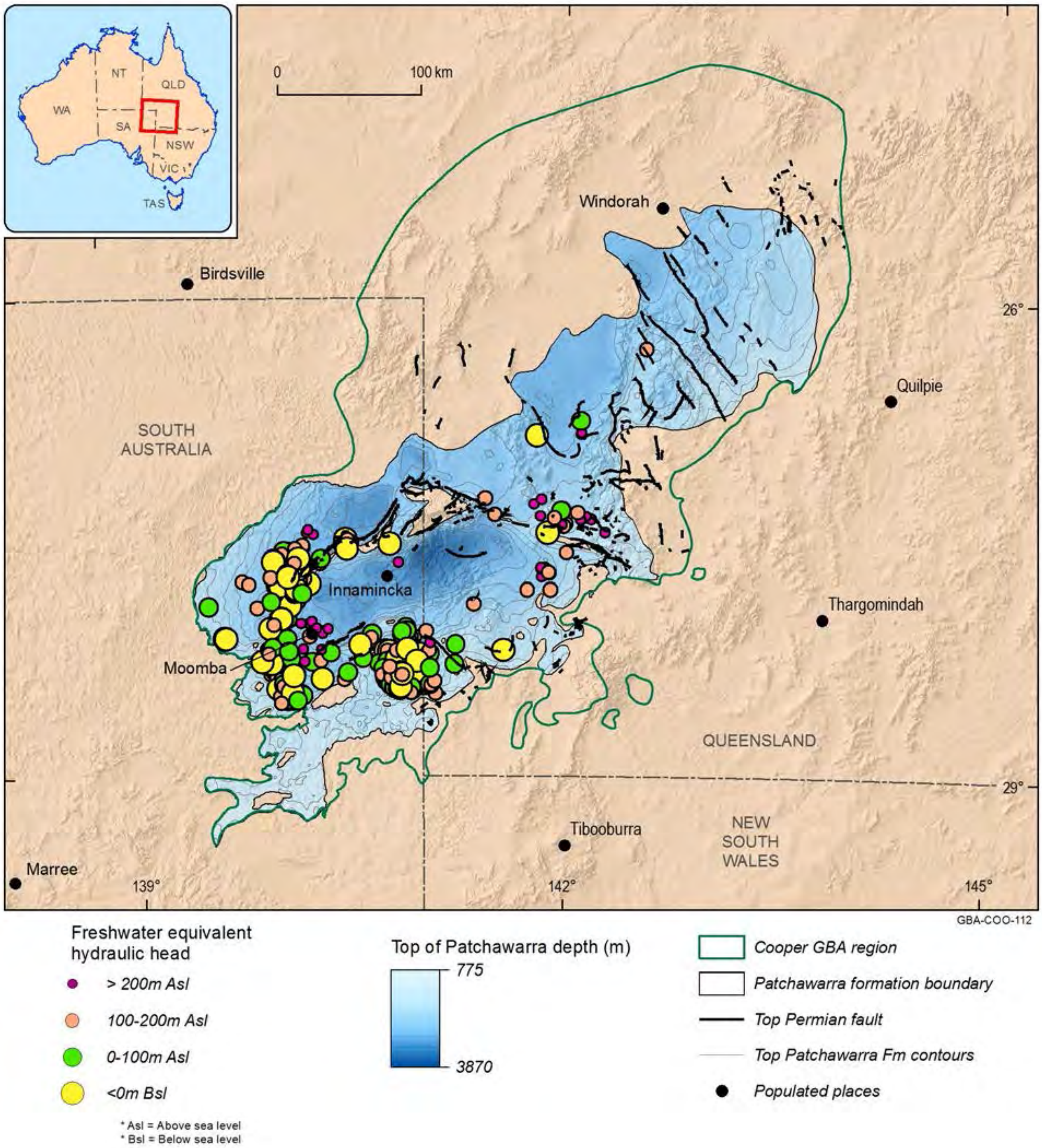


Figure 18 Patchawarra Formation – hydraulic head overlain on depth to top of formation

Data: Geological and Bioregional Assessment Program (2018c) freshwater equivalent hydraulic head; Hall and Palu (2016): Top of Formation and contours
Element: GBA-COO-112

As outlined in Section 3.1.1 and Figure 12, the hydrodynamics of the Gidgealpa Group in the Cooper Basin is likely to be quite variable, and may not necessarily fit neatly into a traditional aquifer/aquitard classification. Some of the factors that lead to the breakdown in classification include:

- Depth and over-pressures – As demonstrated in Figure 15 and detailed in Lech et al. (2020), from about 1900 m below surface, the Gidgealpa Group becomes increasingly over-pressured with depth. Increasing over-pressures tend to drive free water (i.e. groundwater) out of the pore space.

- Over-pressuring is primarily due to increasing gas saturation and the development of continuous basin-centred gas accumulations with increasing depths. These accumulations include deep CSG plays, shale gas, and tight sandstone reservoirs, which are essentially dry due to the contained gas (Lech et al., 2020; Menpes et al., 2013);, with free water being largely driven out due to hydrocarbon presence. A defining factor for continuous gas accumulations is the lack of a defined gas/water contact. This suggests that any remaining groundwater may be compartmentalised and not connected.
- The hydrostratigraphy of the Gidgealpa Group is further complicated by the range of depositional environments, including fluvial lacustrine, braided river systems, peat swamps, and deltaic depositional environments. This results in complex lithologies and compartmentalised reservoirs. Further complexity is added by subsequent burial history and diagenetic overprints, including the development of silica and carbonate cements and clays (Green et al., 1989; Radke et al., 2000). All of these processes modify the distribution of porosity and permeability within a formation.
- At shallower depths, groundwater systems may occur in the Gidgealpa Group where over-pressures and continuous gas accumulations do not dominate. Evidence for this includes the historical and continuing production of produced water associated with conventional reservoirs at shallow depths. This is particularly evident along the southern and western margins of the Cooper Basin where the Gidgealpa Group subcrops beneath the Eromanga Basin.

Some of complexities in groundwater that occur near the south-western margin of the Cooper Basin are detailed in Smith et al. (2015). Here, coals in the Patchawarra Formation in the Weena Trough can be saturated with gas and contain little to no groundwater. However, sandstones adjacent to the coals can be water-saturated (i.e. contain groundwater). For the same reasons that geological and structural complexities already described introduce compartmentalisation in petroleum reservoirs, groundwater systems in shallow parts of the Cooper Basin are likely to be compartmentalised.

As shown in Figure 16, Figure 17 and Figure 18, due to the sparseness and distribution bias in the data towards structural highs, it is difficult to draw any conclusions about horizontal and vertical pressure gradients and potential flow directions on a regional scale. Future studies at more local scales may uncover details on intra-formational pressure variations in different reservoirs. More regional studies to understand if there are cumulative pressure changes occurring across the basin as various petroleum fields develop over time. This may assist with understanding the degree of groundwater leakage and interaction between Cooper and overlying basins.

3.2.2 Eromanga Basin

The Eromanga Basin comprises a part of the Great Artesian Basin (GAB) and its hydrostratigraphy are detailed in Section 3.1.2. In summary, the hydrostratigraphy of Eromanga Basin in the Cooper GBA region comprises:

- Artesian GAB aquifers in the Lower Eromanga Basin (generally not utilised in the Cooper GBA region for groundwater production). These include Poolowanna aquifer to the Westbourne Formation (Figure 13)

- Cadna-owie–Hooray aquifer (the most utilised artesian GAB aquifer in the Cooper GBA region)
- Rolling Downs aquitard (includes the Wallumbilla Formation and Coorikiana Sandstone)
- Winton–Mackunda partial aquifer (sub-artesian GAB aquifer).

Inputs to the water balance for GAB aquifers in the Cooper GBA region include recharge from rainfall or episodic flooding in areas of outcrop, intra-aquifer leakage, aquifer throughflow from outside the region, as well as leakage from underlying or overlying basins, such as the Cooper or Lake Eyre basins.

Of all the Eromanga Basin sequences, only the Winton Formation outcrops within the Cooper GBA region. Outcrop of the artesian GAB aquifers (the "recharge beds") occurs outside the Cooper GBA region, along margins of the Eromanga Basin. Along the western margin recharge to artesian GAB aquifers occurs through three pathways: diffuse recharge; ephemeral river recharge and mountain system recharge (Love et al., 2013a). Along the western margin longer-term diffuse recharge derived from precipitation are generally less than 1 mm/year. Ephemeral river recharge from rivers such as Finke and Plenty rivers, was much higher (380-850 mm/year from the Finke River) but dependent on significant flow events. No rates were given for mountain system recharge to artesian GAB aquifers, but hydrochemistry and environmental tracer data suggest that it is an important mechanism, and that this type of recharge may occur if the monthly rainfall was above about 180 mm (Love et al., 2013a).

Outcrop along the eastern margin coincides in part with the Great Dividing Range (Ransley et al., 2015a), located some 300 km east of the Cooper GBA region in Queensland. Here, Kellett et al. (2003) established that diffuse recharge rates to artesian GAB aquifer outcrop range from 0.03 mm/year to 2.4 mm/year using the chloride mass balance method. Subsequent investigations (e.g. Evans et al., 2018) suggest that earlier calculations over-estimated diffuse recharge to GAB aquifers by as much as 25 – 50%, due to the presence of clay-rich Cenozoic cover and deep weathering profiles impeding recharge to underlying Eromanga Basin aquifers. Evans et al. (2018) only considered diffuse recharge using the chloride mass balance method, and did not take into account other recharge processes such as episodic recharge, which may occur where surface drainage has incised into aquifer outcrop (for an example, see Love et al., 2013a).

Whilst outcrop of the artesian GAB aquifers is relatively distant from the Cooper GBA region, significant changes to recharge rates here are likely to have a bearing on the water balance of artesian GAB aquifers due to aquifer throughflow into the region. Furthermore, episodic recharge has been found to be an important process in other areas of the GAB, such as along western margin of the Eromanga Basin in South Australia (Keppel et al., 2013b). Future estimates of recharge (particularly for the eastern margin) should consider all potential recharge processes for GAB aquifers.

Discharge from aquifer systems in the Cooper GBA region can be through inter-aquifer leakage, groundwater extraction, spring discharge or throughflow out of the region or evapotranspiration from aquifers in the Winton Formation. Inter-aquifer leakage can occur between GAB aquifers. Aquifer throughflow in and out of the GBA region is likely to be a significant component of the water balance where aquifer boundaries extend beyond Cooper GBA region boundary.

Whilst GAB springs do not occur in Cooper GBA region, some significant springs do occur within 20 km its boundary, near Lake Blanche. Further detail on the springs is available in Section 3.5. Diffuse discharge from GAB aquifers may take the form of evaporation or evapotranspiration where groundwater levels are at shallow enough depths below ground surface (generally less than 20 m, Lewis et al., 2018). Bore discharge (particularly free flowing discharge from bores tapping artesian GAB aquifers) can be significant over extended periods. Water produced, as part production of hydrocarbons is another source of artificial discharge, and again can be significant (see Section 2.3).

Artesian GAB aquifers are managed for pressure and not volume (Klohn Crippen Berger, 2016b; Lai et al., 2016). In the Cooper GBA region, 54 bores have screens in the artesian GAB aquifers, including Cadna-owie–Hooray aquifer (Table 2). A number of these bores were originally petroleum wells completed as deep groundwater bores. Some bores are discretely screened in the Cadna-owie–Hooray aquifer, whereas others have very large open/screened intervals, which can be open from the Winton–Mackunda partial aquifer down to artesian aquifers in Lower Eromanga Basin. This leads to considerable variation in the depth of screened intervals. On average, the top of the screened/open interval in the artesian GAB aquifers is 1090 m with an average depth of base around 1355 m. However, some intervals can extend down to 2000 m. Overall aquifer bore depths are much deeper than bore depths for the Winton–Mackunda partial aquifer (Table 2).

3.2.2.1 Aquifers in the Lower Eromanga Basin

For this study, the Lower Eromanga Basin includes all hydrostratigraphic units below the Cadna-owie–Hooray aquifer and equivalents. These are the Westbourne–Adori–Birkhead sequence, Hutton Sandstone and Poolowanna Formation. Little data are available for these hydrostratigraphic units in the groundwater database as these units are not usually tapped for groundwater supply (due to depth constraints). However many of these units contain petroleum resources, hence the availability of pressure data from petroleum activities.

Final shut in pressures from petroleum wells (Figure 19) demonstrate that pressures in the Lower Eromanga aquifers follow a hydrostatic pressure gradient similar to that of the overlying Cadna-owie–Hooray aquifer as well as the underlying Nappamerri Group (Cooper Basin). This suggests that Eromanga Basin and Nappamerri Group operate under the same pressure regime. Additionally, as outlined in Dubsky and McPhail (2001), the average salinity of the Nappamerri Group (3090 ppm) is similar to that of the overlying Hutton Sandstone (2800 ppm) and Poolowanna Formation (3140 ppm). Again, this suggests there is some degree of connection between the Eromanga and Cooper basins' hydrogeological systems, and that there has been some degree of flushing of the Nappamerri Group by groundwater from overlying artesian GAB aquifers.

As noted previously for the Cooper Basin, depleted pressures evident on Figure 19 may be due to depressurisation from petroleum production whereas, over-pressures may relate to hydrocarbons, or suggest some degree of compartmentalisation within the aquifers. Hydrocarbon production from the Hutton Sandstone around the southern margin of the Nappamerri Trough may locally reduce groundwater pressures, which in turn would influence the groundwater flow potentials both laterally and vertically.

Figure 20 outlines hydraulic head near the top of the Hutton Sandstone aquifer. Data tends to be concentrated along major structural trends or near petroleum fields. Higher hydraulic heads (>100 m) appear to be more prevalent in Queensland, whilst in South Australia hydraulic heads tend to more variable. Lower hydraulic heads (<100 m) in South Australia occur along structural trends and near basin margins. This could be a natural phenomenon, or the effects of ongoing petroleum production, (or both, see discussion for Hooray Sandstone aquifer and Figure 22).

It is not readily apparent in Figure 20, if regional structuring influences hydrodynamics of the Hutton Sandstone in the Cooper GBA region. However, it is likely to be the case. For example, as outlined in Figure 8 and Figure 9, there are several instances where the Hutton Sandstone thins significantly, or is even faulted/pinched out against structural highs around the margins of the Cooper GBA region. Depending on degree of local permeability, these offsets and pinch outs are likely to have an effect, by either ponding or redirecting ground flow.

Aquifer porosity and permeability (in particular the artesian GAB aquifers) in the Eromanga Basin sequence have been shown to vary due to depth of burial and diagenetic history. For instance, Green et al. (1989) interpreted three regional scale diagenetic zones that in part varied with depth for a portion of the Hutton Sandstone in southwest Queensland. This area includes the Qld portion of the Cooper GBA region. The zones defined by Green et al. (1989) in the Hutton Sandstone are: a “dissolution zone” (porosities > 25%), a quartz overgrowth zone (porosity between 10-25% and the “compaction zone” (porosity < 10%). Green et al. (1989) concluded that porosity and permeability could be significantly diminished by burial compaction and pore occlusion, in particular in central parts of the Eromanga Basin. More recently, Dillinger et al. (2016) found that diagenetic clays (kaolinite and illite) in conjunction with silica cements had significantly reduced the porosity and permeability of the Hutton Sandstone in the Nappamerri Trough in SA. This resulted in anomalously low flow rates for a hot sedimentary aquifer geothermal play in the region. The work of Dillinger et al. (2016), appears to correspond with earlier work by Radke et al. (2000), who concluded that groundwater flow approached near-stagnant conditions in artesian GAB aquifers where they directly overlay the Cooper Basin depocentres. Essentially porosity and permeability variations can influence the hydrodynamic regime. Whilst there are strong indications of regional controls on porosity, permeability and hydrodynamics some caution is required in extrapolating these findings over broader areas due to variability of the basin history across the Cooper GBA region.

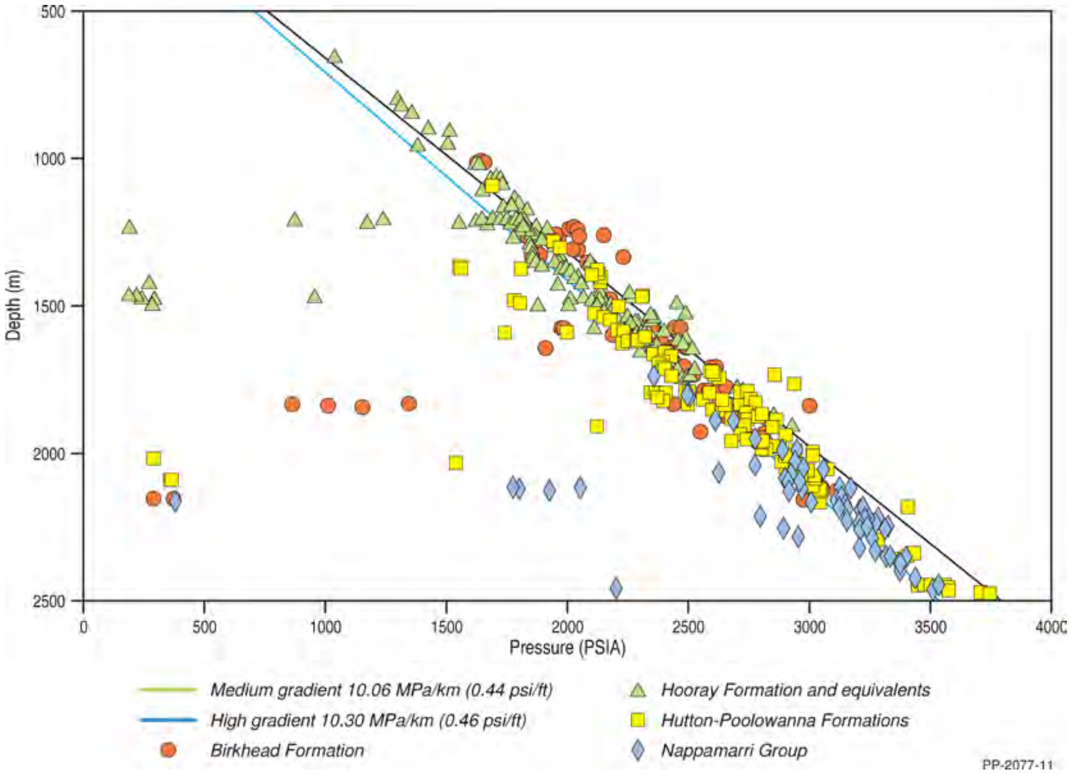


Figure 19 Final shut in pressures from formation tests in Eromanga aquifers and underlying Nappamerri Group

Medium gradient/ High gradient: these related to hydrostatic pressures trend relative to a given fluid density. These gradient trends respectively relate to water with salinities of 2500 mg/L and 5000 mg/L. Pressure values are considered “under-pressured” or “over-pressured” depending on if it sits to the left or right of the zone defined by the gradient lines (i.e. the expected range of pressures for a given depth).
Data: Geological and Bioregional Assessment Program (2019c)
Element: GBA-COO-2-290

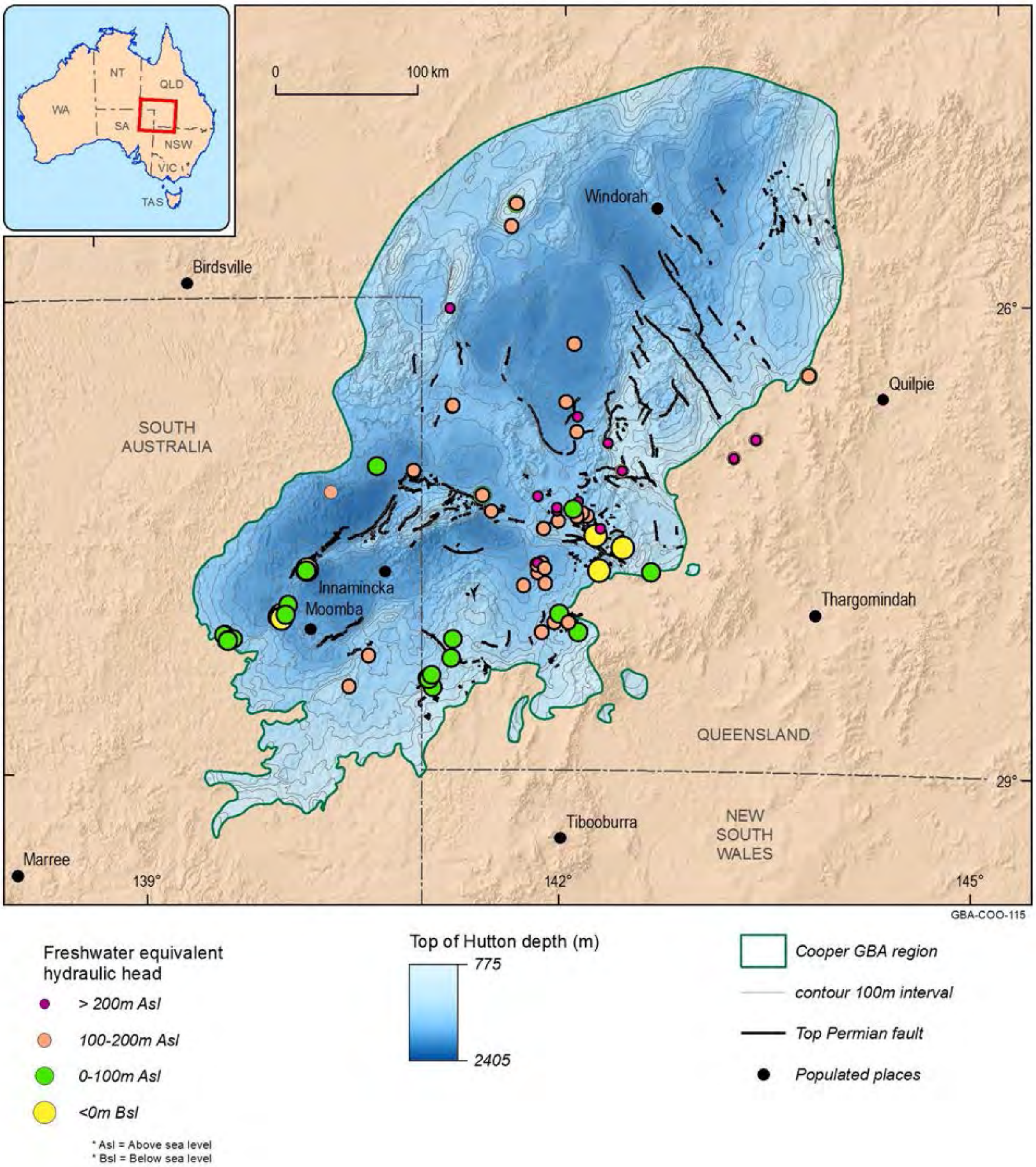


Figure 20 Hutton Sandstone aquifer – hydraulic head overlain on depth to top of Hutton Sandstone for the Cooper GBA region

Data: Geological and Bioregional Assessment Program (2018c) freshwater equivalent hydraulic head; Hall and Palu (2016): Top of Formation and contours
Element: GBA-COO-115

3.2.2.2 Cadna-owie–Hooray aquifer

Hydrostratigraphic units included as part of the "Cadna-owie–Hooray aquifer" are outlined in Section 3.1.2. The monitoring bore network in Cadna-owie–Hooray aquifer is shown on Figure 21. Figure 21 is based on the density corrected regional potentiometric mapping for the Cadna-owie–Hooray Sandstone aquifer from Ransley et al. (2015a), which is derived from hydraulic head measurements from groundwater bores whereas potentiometric mapping in Figure 22 is derived from hydraulic head measurements from groundwater petroleum well data collated as part of this investigation. Overall, there are similarities between the potentiometric mapping shown in Figure 21 and Figure 22, which suggests that there is some degree of continuity between pressures in regional groundwater and more locally around petroleum fields, and that the two different datasets tend to complement each other. As outlined in Figure 13, many of the Cadna-owie–Hooray aquifer also include conventional petroleum accumulations (primarily oil), which has migrated predominantly from Cooper Basin source rocks (Lech et al., 2020).

Regional groundwater flow (Figure 21 and Figure 22) is from the east to south-west across the Cooper GBA region, with potentiometric sinks occurring in SA, over the Nappamerri and Patchawarra Troughs. These potentiometric sinks also in part coincide with petroleum production from the Eromanga Basin sequence (for example fields around Moomba). Hydraulic head is highest in the east (greater than 300 m AHD) dropping to 50 to 100 m in western parts of Cooper GBA region.

Potentiometric mapping in Figure 22 suggests some southerly directed flow may occur between Quilpie and Thargomindah. While there are broad trends, there is considerable variability across the Cooper GBA region, including potentiometric sinks (with sub-artesian hydraulic head pressures) near petroleum fields on the south-western flank of the Cooper GBA region. Very high hydraulic heads could be due to presence hydrocarbons, or to some broader hydrodynamic change such as aquifer compartmentalisation or changes to transmissivity. Overall, the broadly spaced contours suggest sluggish groundwater flow and presence of a groundwater sink, particularly around western portion of the Cooper Basin in SA.

Kulikowski et al. (2018) demonstrates that structuring in the overlying Eromanga Basin is influenced by underlying Cooper Basin structures. As shown in Figure 22, the geometry of the top of the Cadna-owie–Hooray aquifer is cross-cut by some significant faults (e.g. Canaway Fault). Also, it is apparent that depocentres in the Hooray Sandstone correlate with underlying Cooper basin structural features and depositional centres.

Other than the Canaway Fault (see discussion in Muller (1989), at a regional scale it is not clear if specific faults are influencing groundwater flow potentials within the Cooper GBA region. In other parts of the Eromanga Basin, Moya et al. (2016) and Evans et al. (2018) have inferred from hydrochemical and geological data, that inter-aquifer leakage is occurring, where the Hutton Sandstone is in direct contact with coal measures in the Galilee Basin in the vicinity of some major faults.

For the Cadna-owie–Hooray aquifer, modelled horizontal fluxes varied across the Cooper GBA region, from 20 to 50 mm/year at the north-eastern end in Qld, dropping to 0 to 20 mm/year at the south-western end in SA (Welsh, 2000). Such low rates of horizontal flow and distinctive higher salinity groundwater compositions in the central parts of the aquifer over the Cooper GBA region argue for near- stagnant conditions (Radke et al. (2000). This is in contrast to higher horizontal flow of lower salinity waters in the same aquifer around the periphery of the Cooper GBA region (for example around the western margin along the vicinity of the Birdsville Track Ridge). This suggests a much less permeable aquifer within in more deeply buried portions of the aquifer than in shallower, less-compacted regions around the margins. Radke et al. (2000) postulated that the degree of diagenesis within the aquifer might influence lateral and vertical groundwater flow in the Cadna-owie–Hooray aquifer. Radke also suggested that diagenetic processes, such as those as outlined by Green et al. (1989) for the Hutton Sandstone (see also Section 3.2.2.1), may go some way to explaining near-stagnant groundwater flow noted in the central parts of the Cadna-owie–Hooray aquifer.

Recharge rates and processes for the Cadna-owie–Hooray aquifer are outlined previously in Section 3.2.2. Discharge from the Cadna-owie–Hooray aquifer can occur via lateral through-flow out of the Cooper GBA region, upward leakage into the Rolling Downs aquitard, or as discharge through groundwater extraction. Potentially, downward leakage towards underlying aquifers (e.g. Hutton Sandstone aquifer) could occur if pressures in the underlying unit are significantly lower and a conductive pathway exists. The Cadna-owie–Hooray aquifer is also a source aquifer for GAB springs, found to the west of the Cooper GBA region in the vicinity of Lake Blanche (See Section 3.5 for further detail and (Keppel et al., 2016). Diffuse discharge derived from GAB aquifers may occur at surface near large salt lake complexes such as Lake Blanche (Gotch, 2013; Gotch et al., 2016; Keppel et al., 2016).

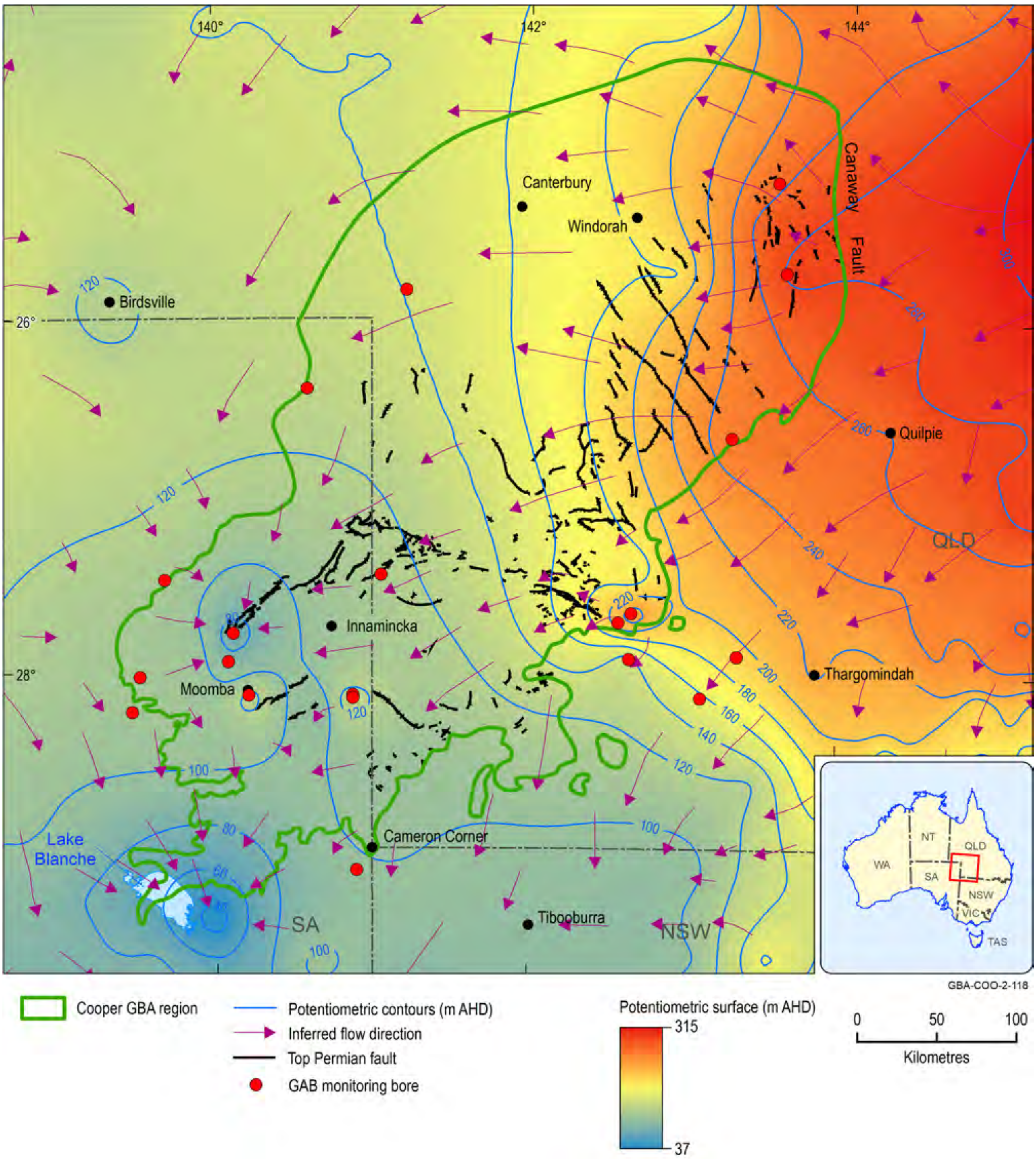


Figure 21 Cadna-owie–Hooray Sandstone aquifer – potentiometric mapping and monitoring bores

Data: Potentiometric mapping derived from Ransley et al. (2015a)
Element: GBA-COO-2-118

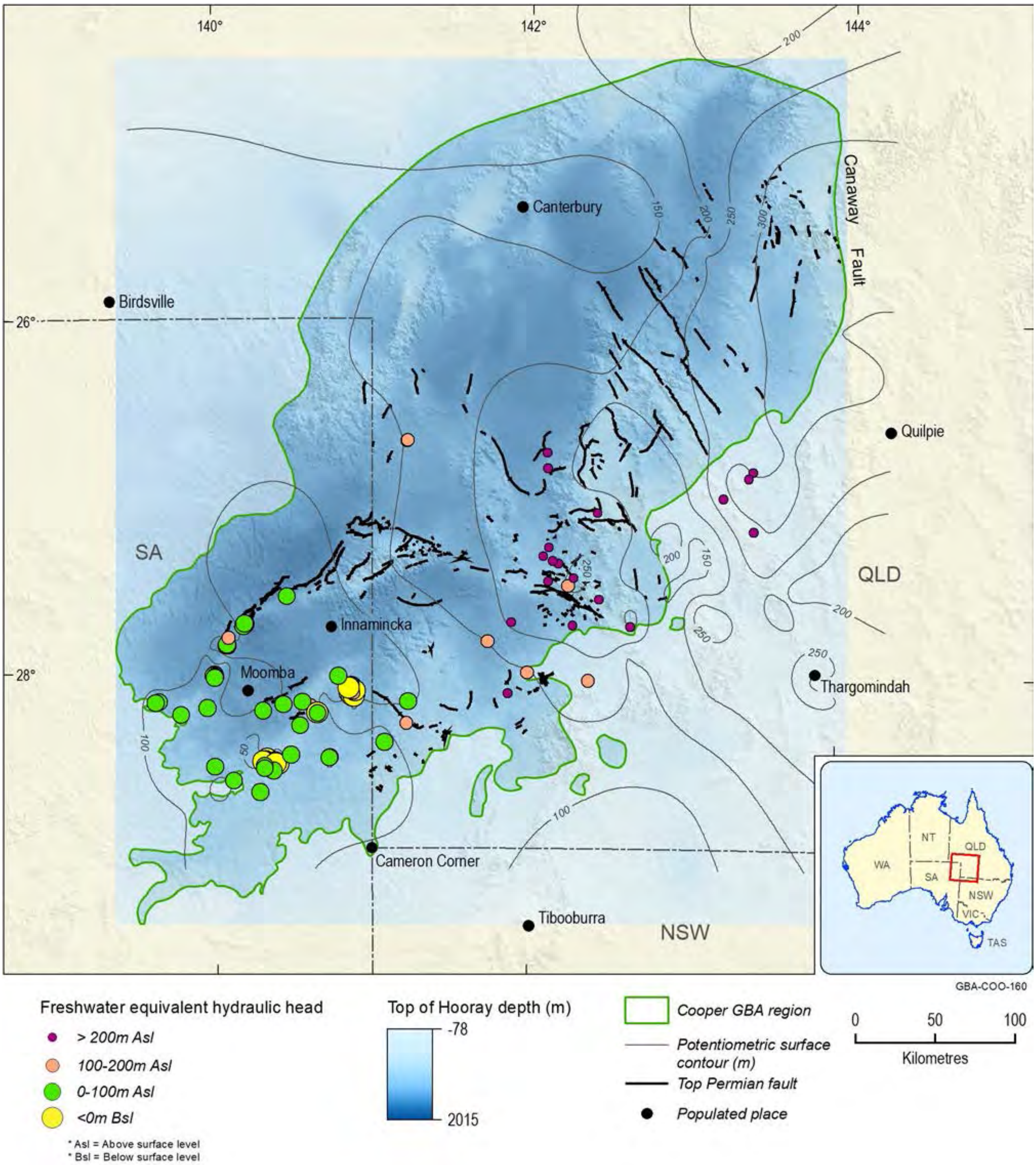


Figure 22 Cadna-owie–Hooray aquifer – potentiometric mapping derived from petroleum and groundwater bore data, and depth to top of formation

Data: Geological and Bioregional Assessment Program (2018c) freshwater equivalent hydraulic head; Hall and Palu (2016): Top of Formation and contours; Geological and Bioregional Assessment Program (2018g) Potentiometric contours derived utilising groundwater bore data and petroleum industry pressure data
Element: GBA-COO-160

3.2.2.3 Rolling Downs Group aquitard

There is very little outcrop of the Rolling Downs aquitard (Figure 25) and very few bores utilise it as a source of groundwater in the Cooper GBA region. Figure 23 outlines some of the conceptual leakage pathways where Rolling Downs aquitard outcrops including polygonal faulting systems

(PFS) and diffuse discharge. Whilst in the Cooper GBA region the Rolling Downs aquitard is buried by the Winton–Mackunda formations and in places, the Lake Eyre Basin, as demonstrated by the work of Kulikowski and Amrouch (2018a) conceptual leakage mechanisms via fault networks would still be applicable at depth below the Winton-Mackunda partial aquifer.

Estimates of diffuse discharge through the Rolling Downs aquitard have been made to the west of Cooper GBA region (Gotch, 2013). These estimates may provide an order of magnitude guide in the absence of more region specific information. Towards the western margin of the GAB, upward leakage may be the dominant groundwater discharge mechanism. Vertical conductivity estimated by various methods ranges from 3 to 10 mm year^{-1} (~1.6 x10^{-10} m/sec Woods (1990); 5 x 10^{-11} m/sec Gardner et al. (2012); <1 x 10^{-12} m/sec Harrington et al. (2013); 0.4 x 10^{-13} m/sec Smerdon et al. (2012b)).

In addition to diffuse discharge, another potential but unquantified leakage mechanism is through polygonal faulting, which is prevalent in parts of the Rolling Downs aquitard. Recognition of polygonal fault systems (PFS) in this region is quite recent (Watterson et al., 2000; Nicol et al., 2003). Leakage through PFS has been proposed as a pathway across the aquitard (Ransley et al., 2015a; Ransley et al., 2012). Depending on the stress field acting on a PFS there are a subset of favourably-oriented individual faults that will tend to dilation, and hence offer the potential for vertical fluid movement (Kulikowski and Amrouch, 2018a; Kulikowski et al., 2018).

PFS have also been recognised in parts of the overlying Winton-Mackunda partial aquifer (Ransley et al., 2015a). Whilst PFS occur in the Rolling Downs aquitard and parts of Winton Formation, fluid pathways through these fault networks is likely to be convoluted and diffuse due to inherent nature of the polygonal faulting system. Whilst these fault networks are prevalent, the lack of GAB springs in the Cooper GBA region, as well as artesian pressures in the Winton-Mackunda partial aquifer, suggest that overall the Rolling Downs aquitard does impede (but not completely prevent) vertical leakage and pressure transfer from underlying artesian GAB aquifers.

Any vertical leakage from artesian GAB aquifers would be accommodated by either local sandstone aquifers in the Rolling Downs aquitard (e.g. Coorikiana Sandstone; sandstone layers Wallumbilla Formation) or the overlying Winton–Mackunda partial aquifer. A recent regional water balance for the Queensland portion of the Eromanga Basin (Klohn Crippen Berger, 2016b), suggests that there has been up to a 30% decline in the upward leakage potential across the Rolling Downs aquitard due to long term groundwater production from free flowing artesian bores. Specifically for the Cooper GBA region, how much actual vertical leakage has declined is yet to be determined.

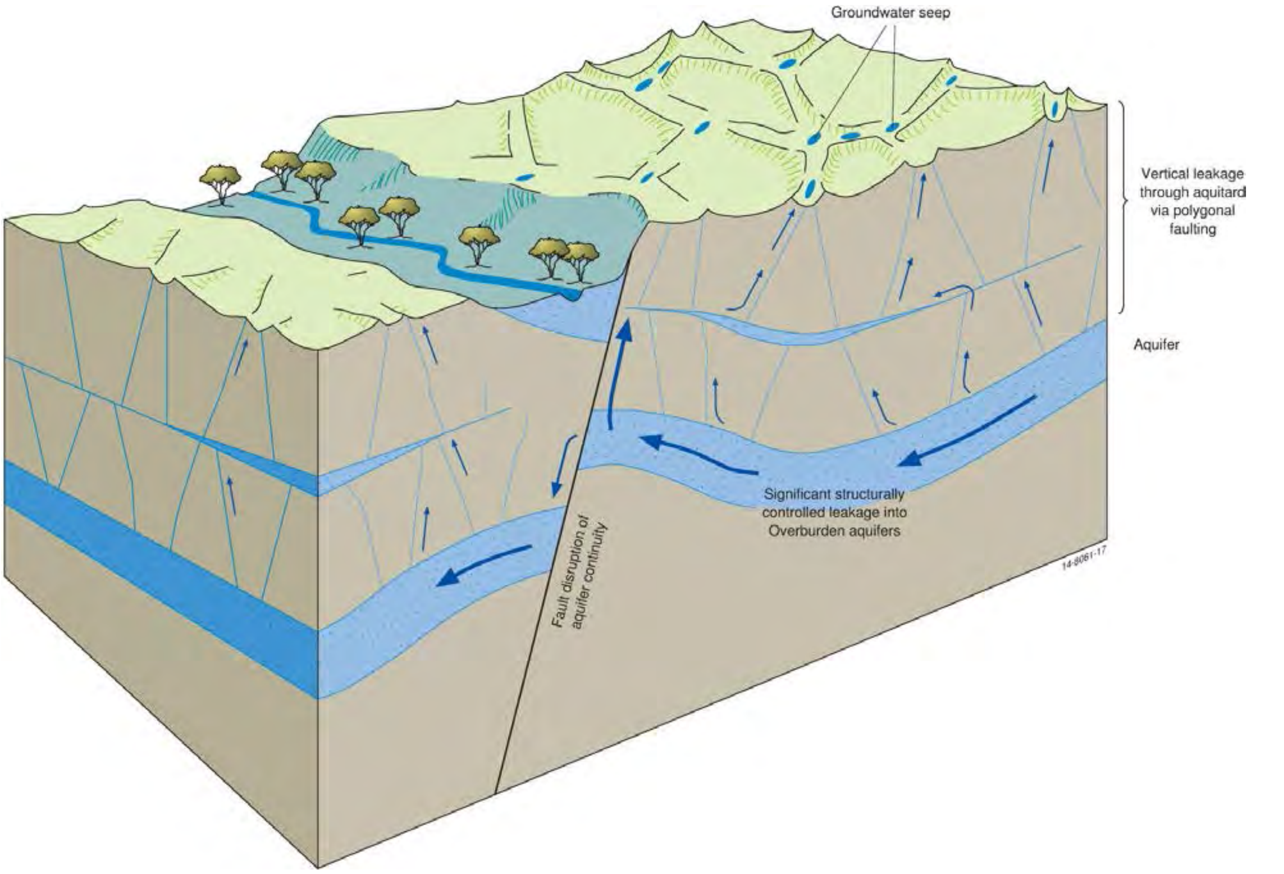


Figure 23 Potential leakage pathways across the Rolling Downs aquitard

Dilated faults as implied from surface expression in gaining streams with anomalous Evapotranspiration Index, polygonal faults, interlinked by internal aquifers within the aquitard (from Ransley et al., 2015a).
Conceptual model is shows pathways for outcrop areas. Even, where buried though, the leakage pathways via faults and polygonal fault systems are still valid.
Source: Ransley et al., 2015a
Element: GBA-COO-2-291

3.2.2.4 Winton–Mackunda partial aquifer

Aquifers in the Winton and Mackunda formations are hydraulically connected (Ransley and Smerdon, 2012), and are considered regionally to comprise a single aquifer system. As shown in Map 24 of Ransley et al. (2015a), these formations can cumulatively be more than 500 m thick, particularly in the Cooper GBA region.

Regional watertable mapping presented in Ransley et al. (2015a) are derived from a compilation of hydraulic head measurements from a number of near-surface aquifers that crop out across the GAB region, including the Winton–Mackunda partial aquifer and aquifers of the Lake Eyre Basin. However, for this project, waterlevel data from the Lake Eyre Basin and the Winton–Mackunda partial aquifer was partitioned in order to assess if there were differences, as aquifers in the Lake Eyre Basin are locally an important groundwater source.

The Winton–Mackunda partial aquifer is in general an unconfined to semi-confined aquifer system. However, It may be confined in places where overlying Lake Eyre Basin cover is thick (see Figure 23 in Owens et al., 2020). In addition, intra-formational siltstones and mudstones may act as local confining layers for sandstone aquifers within these formations. Varying bore yields and water quality in the Winton and Mackunda formations have been in part attributed to highly varied lithologies that comprise these units, in particular the Winton Formation (Ransley and Smerdon, 2012).

No groundwater monitoring or time-series waterlevel data are available for the Winton–Mackunda partial aquifer. Often the only waterlevel data available are isolated readings taken around the time of construction. Depth to water and watertable mapping outlined in Figure 24, Figure 25 and Figure 26, are derived from measurements taken in different years and thus may not represent the watertable at a particular point in time. However, these types of maps may be useful for identifying potential flow direction trends in the groundwater system, assuming that there are not significant waterlevel fluctuations from year to year (i.e. greater than 5 to 10 m).

The Winton–Mackunda partial aquifer is ubiquitous across the Cooper GBA region with many bores drawing water from it (Figure 25 and Table 2). There is little relationship between depth to groundwater and bore depth (Figure 24) and it is evident from the density of bores (Figure 25) that this aquifer is more frequently utilised in Queensland than in SA. The average depth to groundwater (from 466 samples) is 25 m, with 90% of bores having a standing waterlevel less than 49 m. Average bore depth is 140 m with 90% having a depth less than 305 m. While the Winton–Mackunda partial aquifer is not artesian, depth to groundwater is such that there is potential for groundwater to rise to a level where it could leak into overlying aquifers in the lake Eyre Basin, if a connectivity pathway were to exist. Overall, no particular pattern in the depth to groundwater is evident for the Winton–Mackunda partial aquifer. Increases in depth to groundwater noted to the north-east of Windorah and south-east of Innamincka are attributed to increases in topographic elevation. This suggests that in these areas the aquifer is unconfined.

As outlined in Ransley et al. (2015a) and Figure 26, watertable contours for the Winton–Mackunda partial aquifer are strongly influenced by local and regional topography. Regionally, the inferred groundwater flow direction is from north-east to south-west, towards regional topographic low points around Lake Blanche and Lake Gregory in South Australia. However, whether upward leakage from Winton-Mackunda partial aquifers towards these lakes occurs is unknown. At more local scales, groundwater mounding is evident under elevated topographic areas. Inferred groundwater flow is from elevated areas to low lying areas, thus any flow would tend to be directed towards major drainage lines, such as those found in the Cooper Creek floodplain. However, sparse waterlevel data suggests it is unlikely for discharge to occur from the Winton–Mackunda partial aquifer would directly discharge to Cooper Creek, as overlying Lake Eyre Basin sediments are relatively think on the Cooper Creek floodplain and the depth to groundwater is around about 10 to 20 m below surface (Figure 25). There is potential though for upwards leakage into the overlying Lake Eyre Basin aquifers.

Recharge rates and processes have not been investigated in any detail for the Winton-Mackunda partial aquifer. Diffuse recharge is thought to be very low in areas of outcrop, less than 1 mm/year (Klohn Crippen Berger, 2016b) in the Queensland portion of the Cooper GBA region. It is plausible that recharge processes such as diffuse and episodic recharge, (as discussed in the introduction to Section 3.2.2 for artesian GAB aquifers) are also appropriate for the Winton-Mackunda partial aquifer.

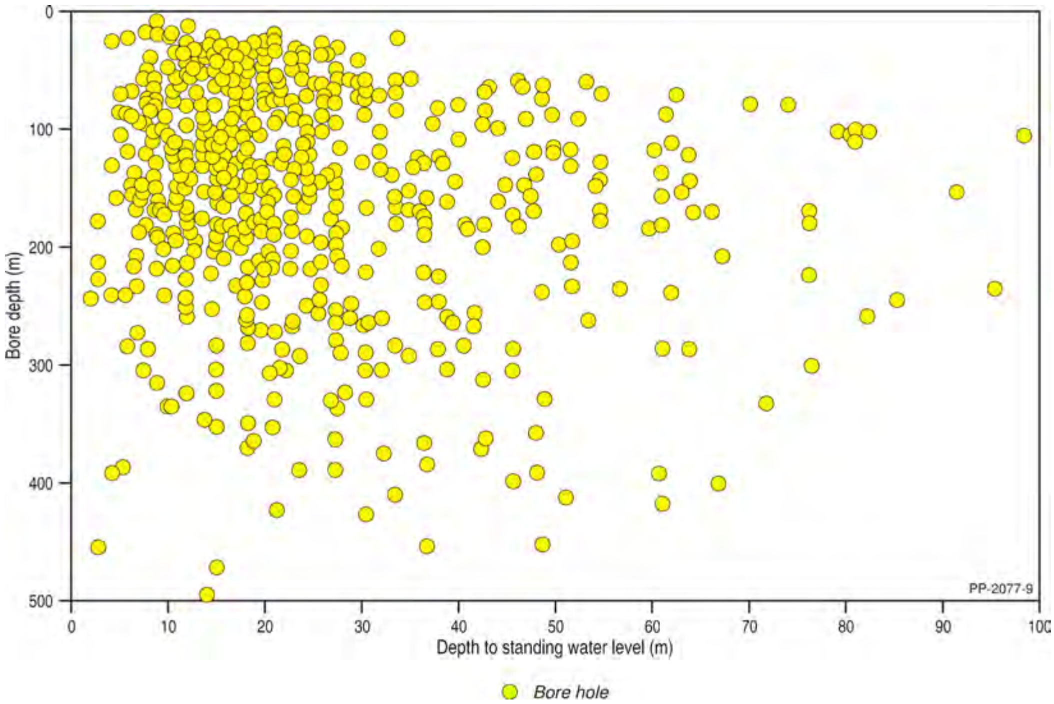


Figure 24 Winton–Mackunda partial aquifer depth to groundwater versus bore depth

Locations of bores outlined on Figure 25. Bore depth may not necessarily represent actual depth of the screens. Depending on bore data available, it may represent the maximum bore depth. See Section 2.2.1 for further detail.
Data: Geological and Bioregional Assessment Program (2018h) depth to standing waterlevel
Element: GBA-COO-2-292

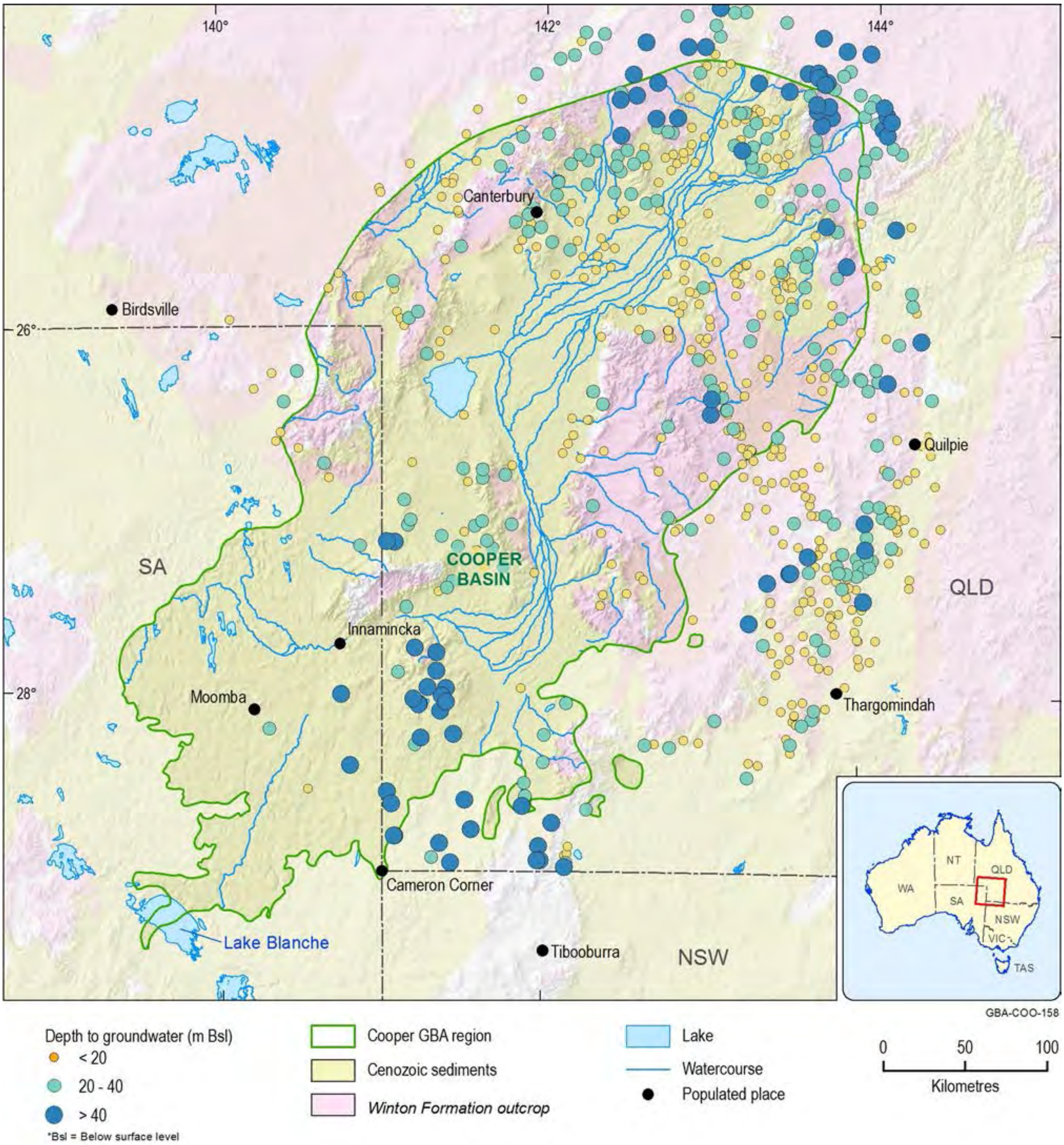


Figure 25 Winton–Mackunda partial aquifer – depth to groundwater in the Cooper GBA region

Data: Geological and Bioregional Assessment Program (2018g) depth to groundwater

Element: GBA-COO-158

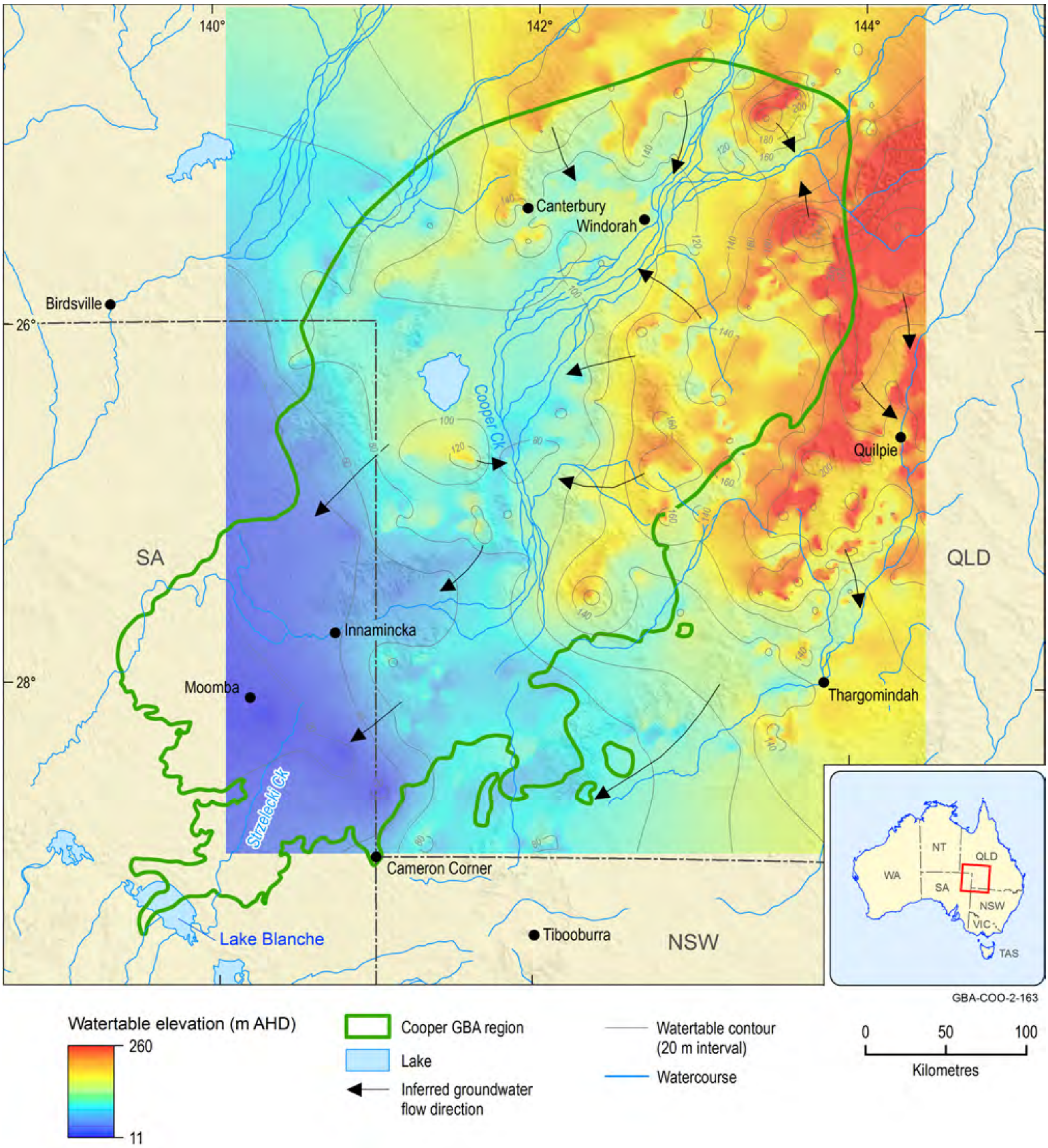


Figure 26 Winton–Mackunda partial aquifer – watertable elevation and inferred flow paths

Distribution of Winton Formation outcrop and data points are outlined on Figure 25.
Due to a lack of salinity data density corrections were not applied to waterlevels.
Data: Geological and Bioregional Assessment Program (2018g) watertable elevation
Element: GBA-COO-2-163

3.2.3 Lake Eyre Basin

As outlined in Section 3.1.3, the hydrostratigraphic units that comprise the Lake Eyre Basin sequences could not be differentiated in the subsurface, thus for this report the generic term "Cenozoic" is used. The Cenozoic sequences encompass several locally important aquifer systems, including aquifers in the Namba and Eyre formations in South Australia and the Glendower

Formation in Queensland. These older units (Figure 14) are often obscured by a veneer of younger Pliocene to Quaternary aged sediments at surface, which are associated with present day landscape features including drainage, dune fields and lakes.

Figure 27 and Figure 28 detail the distribution of depth to groundwater for aquifers in Lake Eyre Basin. From 567 bores, the average bore depth is 55m with 90% of bores being less than 95 m deep. The average depth to groundwater for Cenozoic sequence aquifers across the Cooper GBA region is 20 m, with 10% bores having a depth to groundwater of less than 7.5m. As was the case with the Winton–Mackunda aquifer, again there is a region where the depth to groundwater is relatively deep, south-east of Innamincka (east of Strzelecki Creek) where the Namba Formation (and equivalents) outcrop in an topographically elevated area, along the Qld-SA border.

Shallow standing waterlevels (less than 20 m to the watertable) coupled with subdued hydraulic gradients occur west of the Queensland State border in areas dominated by Quaternary alluvium, dunes and salt lakes. As outlined in Section 3.2, highly saline groundwater occurs here, particularly near salt lakes. Salinity data also suggests there are at least two groundwater systems in the Cenozoic. These two systems comprise a shallow system with highly variable salinity above 80 m (this includes groundwater in sediments of Quaternary age) and a deeper system with relatively fresher groundwater below 80 m.

As with the Winton–Mackunda partial aquifer, Cenozoic watertable mapping (Figure 29) suggests groundwater flow are strongly influenced by local topography. Overall, there is a regional south-westerly flow trend towards regional topographic low points in the landscape, such as large salt lakes (e.g. Lake Blanche and Lake Gregory). It is possible that during dry periods these lakes act as regional discharge zones for Cenozoic aquifers.

Across the Cooper GBA region, recharge to groundwater in the Cenozoic and Winton–Mackunda partial aquifer of the Eromanga Basin, is driven by regional diffuse recharge during rain events or localised recharge from watercourses and lakes during flood-events. Whilst the magnitude of recharge is yet to be quantified, studies such as Love et al. (2013a) suggest that recharge from episodic events could be significant. The contribution from upward leakage of artesian GAB groundwater to shallower aquifers (Kellett et al., 2012b) remains to be quantified. It should be noted that in the Cooper GBA region any leakage from artesian GAB aquifers would have pass through Rolling Downs aquitard as well as the Winton-Mackunda partial aquifer to reach the Lake Eyre Basin. As outlined in Section 3.2.2.3, the Rolling Downs aquitard is likely to be acting as a readably competent aquitard, in part due to lack of artesian GAB springs and artesian pressures in Winton-Mackunda partial aquifer (and for that matter aquifers in Lake Eyre Basin) in the Cooper GBA region.

Existing hydrogeological studies have only investigated groundwater in the top 20 m. In addition, recharge rates have not been quantified for the Lake Eyre Basin and it is uncertain whether episodic recharge leaks into more deeply buried aquifers in the Cooper Creek floodplain or Callabonna Sub-basin. Alternatively, relatively fresher groundwater at depth could be the result of paleo-recharge from past climatic events.

In the top 20 m of the Cenozoic, Cendón et al. (2010) identified lenses of relatively fresh groundwater (less than 5000 mg/L TDS) that appear to sit on top of a shallow more saline, regional groundwater (10,000-40,000 mg/L TDS) around Goonbabinna waterhole on the Cooper Creek floodplain. Localised recharge within watercourses are thought to occur through the floor of freshly scoured waterholes during floods, in contrast to no recharge through the mud-dominant sediments out on the floodplain. The presence or absence of sand dunes appears to have no significant effect on recharge. After each flood event, the floor of the waterholes is thought to self-seal minimising leakage, as clays suspended in the water column settle out. This form of localised recharge is dependent on and consistent with monsoonal flooding events (Cendón et al., 2010) with limited interaction between surface water in waterholes and groundwater occurring during no-flow conditions (i.e. dry periods).

Discharge from Cenozoic can take the form of evapotranspiration, diffuse discharge from shallow groundwater, evaporation around salt lakes, groundwater pumping or leakage into the underlying Winton–Mackunda partial aquifer. Potentially another form of discharge could be bank discharge to waterholes and baseflow to surface drainage around could occur when creeks have been flowing (so waning stages, or just post a flood event).

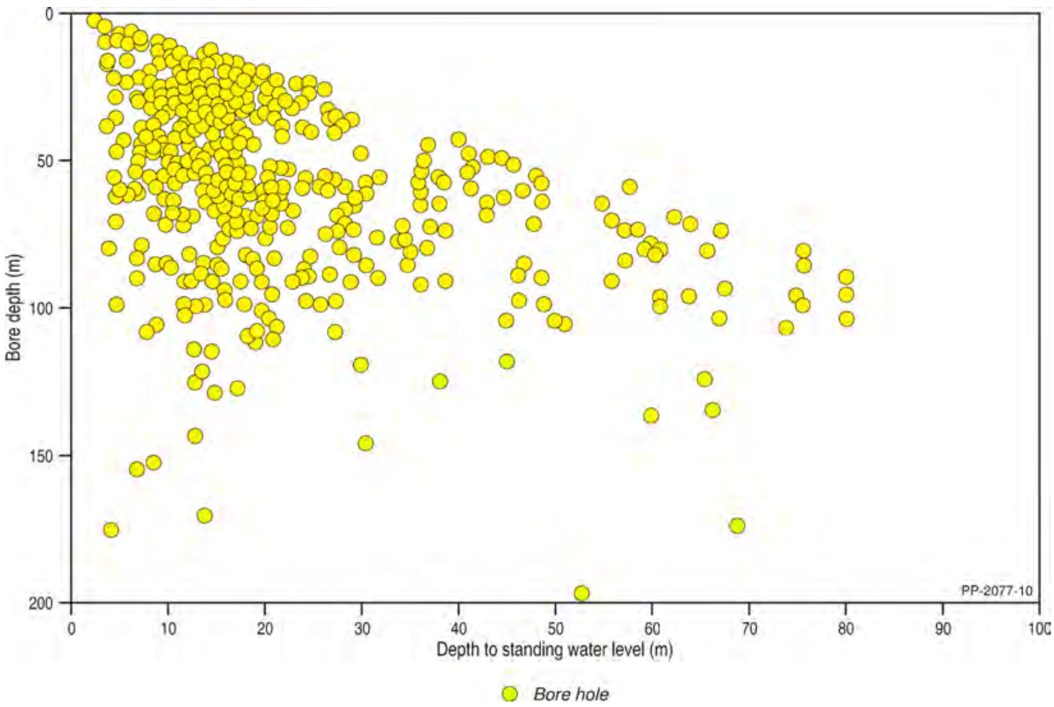


Figure 27 Cenozoic aquifer – depth to groundwater versus maximum bore depth

Bore depth may not necessarily represent actual depth of the screens. Depending on bore data available, it may represent the maximum bore depth. See Section 2.2.1 for further detail.
Data: Geological and Bioregional Assessment Program (2018h) depth to standing water level
Element: GBA-COO-2-293

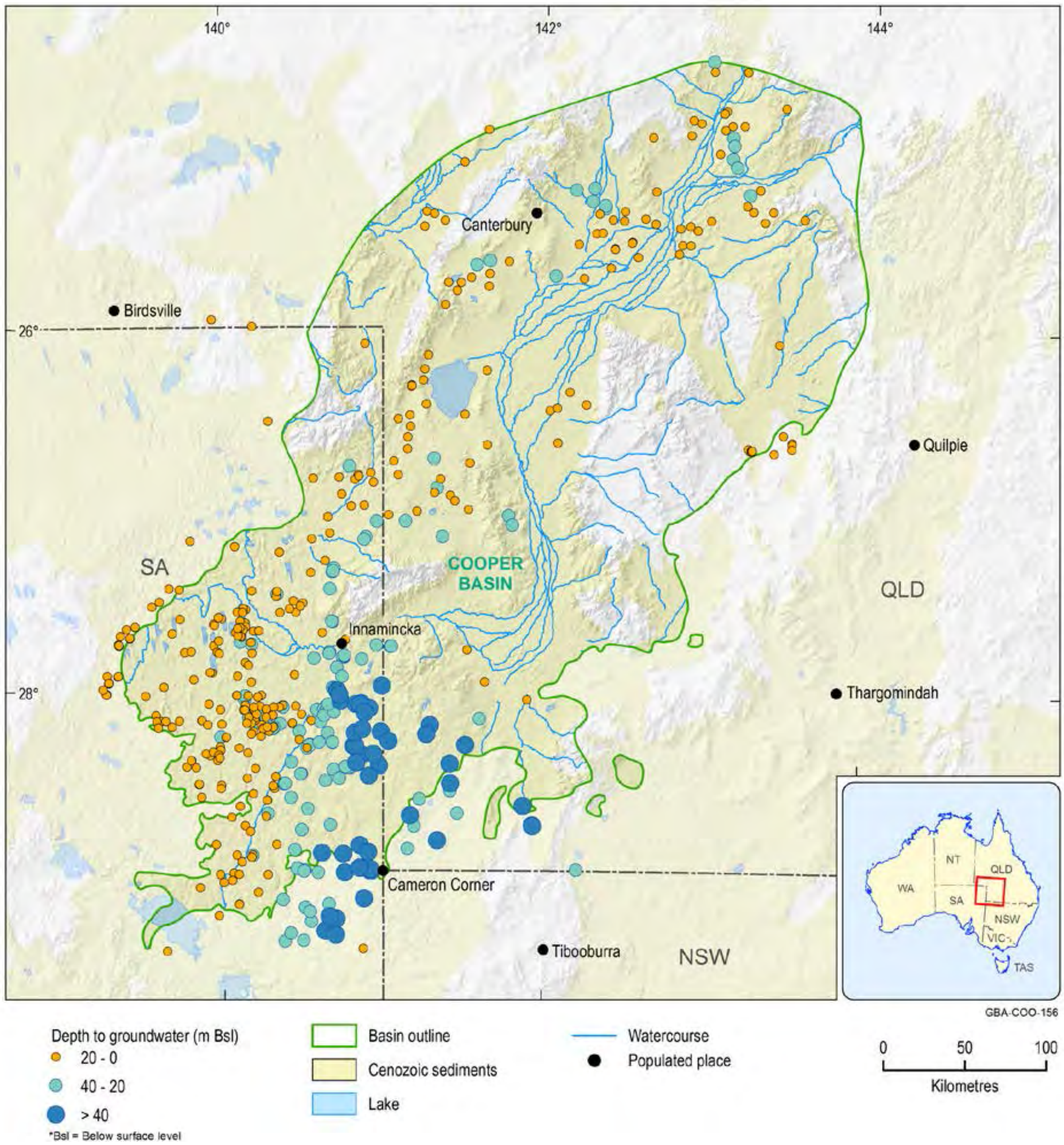


Figure 28 Depth to groundwater for the Cenozoic aquifer

Data: Geological and Bioregional Assessment Program (2018g) depth to groundwater
Element: GBA-COO-156

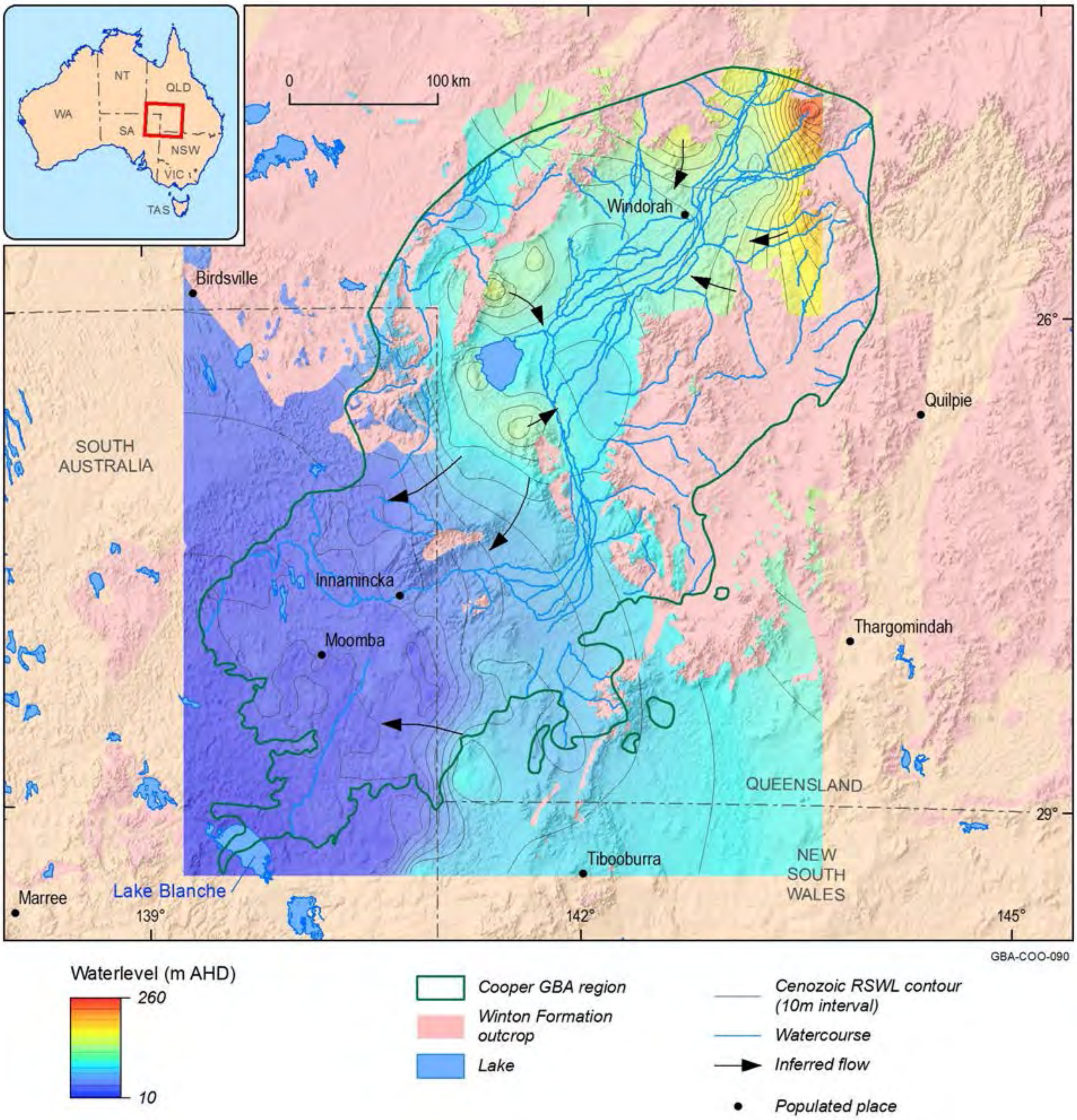


Figure 29 Lake Eyre Basin – watertable elevation relative to sea-level

Figure 28 outlines the distribution of Lake Eyre Basin waterlevel data. Waterlevels for Lake Eyre Basin have not density corrected due to a lack of salinity information across much of the region. This be an issue for areas where high salinity may occur e.g. around salt lakes to the west of Innamincka.
Data: Geological and Bioregional Assessment Program (2018g) watertable elevation
Element: GBA-COO-090

3.3 Hydrochemistry

For this section, aquifer hydrochemistry is utilised to characterise groundwater processes within the aquifer. Whereas the focus of Section 4 is to investigate the potential for inter aquifer and inter basin connectivity.

Salinity

For many hydrostratigraphic units, salinity data are sparse or lacking across much of the Cooper GBA region. Table 7 compiles salinity estimates from previous studies. Main sources used here for Cooper and Eromanga basins are respectively Dubsky and McPhail (2001) and Ransley et al. (2015a).

Based on the compilation from state groundwater databases (Geological and Bioregional Assessment Program, 2018h), 619 salinity values, recorded as electrical conductivity (EC), can be attributed to a hydrostratigraphic unit. Summary statistics for EC are presented in Table 8. The maximum and minimum values should be used with caution often represent extreme outliers in the data. For instance, extremely low values of EC (e.g. 2 µS/cm) are likely to be the result of operator errors or equipment malfunction. Unless maximum and minimum values are verified, then the 5th or 10th percentiles should be considered as been more representative of lower bounds, whereas the 90th and 95th percentiles may be more useful to consider as upper bounds for salinity.

An estimate of salinity, as total dissolved solids (TDS), can be derived from by assuming a linear relationship with EC and multiplying by a constant factor (Carlson, 2005; Hubert and Wolkersdorfer, 2015; Rusydi, 2018). However, the value of this constant varies depending on the dominant major ionic composition of various waters, sampling locations and seasons. The value typically ranges between 0.54 and 1.1, with 0.65 commonly used for this analysis (Carlson, 2005; Hubert and Wolkersdorfer, 2015). This relationship is more complicated in reality, with various ionic species and proportions affected the actual TDS value, so that often in saline waters the relationship is not truly linear (Hubert and Wolkersdorfer, 2015; Rusydi, 2018). For the Cooper GBA region, EC converted to TDS values are shown in Table 8.

EC was converted to TDS using Equation 2

$$TDS = EC \times 0.65 \tag{2}$$

For the whole of the GAB, the salinity for artesian GAB aquifers is outlined in Ransley et al. (2015a). From these datasets, the salinity of Cadna-owie–Hooray aquifer is outlined in Figure 30 for the Cooper GBA region. With only 14 EC readings (at two bores), data coverage is insufficient to map the groundwater salinity distribution within the Rolling Downs aquitard in the Cooper GBA region. Salinity for the Winton–Mackunda partial aquifer (Figure 31) and Lake Eyre Basin aquifers (Figure 32) are derived from data compiled for this project. Further discussion relating to salinity distributions and water quality are outlined in Sections 3.2.2 and 3.2.3.

Table 7 Salinity ranges compiled from literature for aquifers in the Cooper GBA region

	Hydrostratigraphic unit(s) / group	Min salinity (mg/L)	Max salinity (mg/L)	Average salinity (mg/L) of produced water (*)	Source
Cenozoic	Local freshwater lenses, generally Quaternary	798	5,000		(Cendón et al., 2010)
	"Regional" near-surface Cenozoic groundwater	5,000	38,178		(Cendón et al., 2010)
	Eyre Formation	3,000	12,000		(SA Department for Water, 2011)
Eromanga	Winton–Mackunda partial aquifer	600	20,000		(Department of Natural Resources and Mines (Qld), 2016; Santos, 2016)
	Rolling Downs aquitard	1,140	2,950		(Ransley et al., 2015a)
	Cadna-owie–Hooray aquifer	1,080	9,000	2,192-2,436	(Ransley et al., 2015a)
	Westbourne Formation	–	–		–
	Adori Sandstone	1,060	2,600		(Ransley et al., 2015a)
	Birkhead Formation	2,000	3,000	2,826	(Hydrogeologic Pty Ltd, 2014)
	Hutton Sandstone	1,060	3,800	2,826	(Dubsky and McPhail, 2001; Ransley et al., 2015a)
	Poolowanna Formation	3,085	9,245	3,265	(Dubsky and McPhail, 2001)
Cooper	Cuddapan Formation and Morney beds	–	–		–
	Nappamerri Group	2,600	7,000	4,821	(Dubsky and McPhail, 2001; Hydrogeologic Pty Ltd, 2014)
	Toolachee–Daralingie formations	4,000	13,000	8,404	(Dubsky and McPhail, 2001; Hydrogeologic Pty Ltd, 2014)
	Roseneath Shale	–	–		–
	Epsilon Formation	2,200	10,000	7,695	(Dubsky and McPhail, 2001; Hydrogeologic Pty Ltd, 2014)
	Murteree Shale	–	–		–
	Patchawarra Formation	2,000	18,000	10,768	(Dubsky and McPhail, 2001; Hydrogeologic Pty Ltd, 2014)
	Tirrawarra Sandstone / Merrimelia Formation	5,000	17,000	10,404	(Dubsky and McPhail, 2001; Hydrogeologic Pty Ltd, 2014)

(*) Average salinity of produced waters from petroleum production are as reported in Dubsky and McPhail (2001).

Table 8 Summary statistics for salinity for Eromanga and Lake Eyre basins from groundwater bore data in the Cooper GBA region

		Cenozoic	Winton–Mackunda partial aquifer	Rolling Downs aquitard	Artesian GAB aquifers
Count	Number of records with EC values	234	129	14	242
EC (µS/cm)	Average	17,120	6,814	9,442	3,092
	Minimum	2	502	1,578	2
	5th percentile	1,236	1001	4,430	885
	10th percentile	1,892	1639	5,993	1,123
	50th percentile	10,013	4,973	10,532	2,348
	90th percentile	49,780	15,534	12,270	5,625
	95th percentile	57,557	18,336	12,384	6,277
	Maximum	99,800	24,000	12,400	22,527
Est. TDS (mg/L)	Average	11,000	4,400	6,100	2,000
	Minimum	1	330	1,000	1
	5th percentile	800	650	2,900	580
	10th percentile	1,200	1,100	3,900	730
	50th percentile	6,500	3,200	6,800	1,500
	90th percentile	32,000	10,000	8,000	3,700
	95th percentile	37,000	12,000	8,000	4,100
	Maximum	65,000	16,000	8,100	15,000

Values in Table 8 are as per what it in the bore databases. Unless verified, minimum and maximum values should only be used with caution. These values may not be representative due to sampling or data transcription errors (see text).
Data: Geological and Bioregional Assessment Program (2018h)

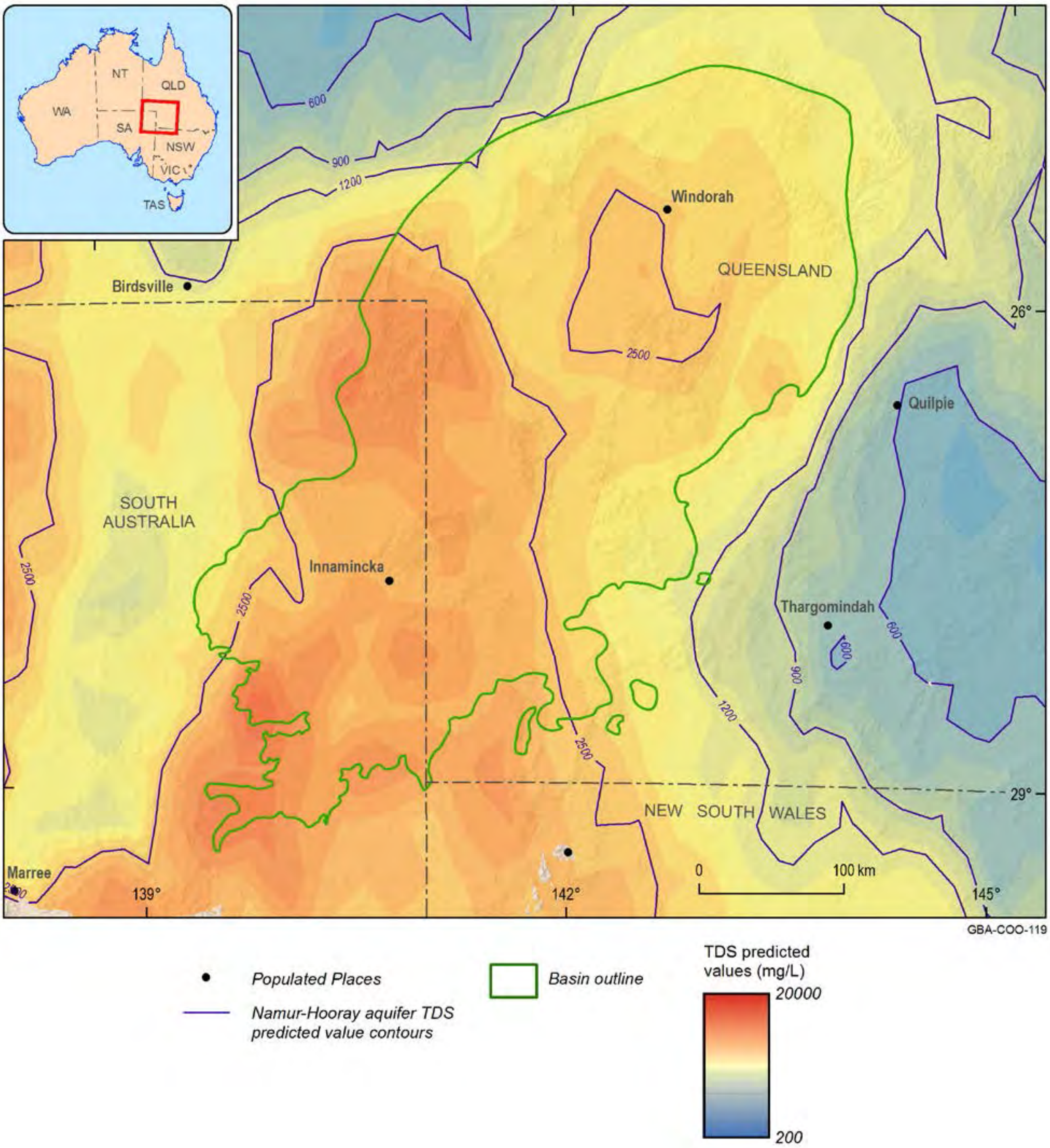


Figure 30 Salinity of the Cadna-owie–Hooray aquifer

Data: After Map 36 of Ransley et al. (2015a)
Element: GBA-COO-119

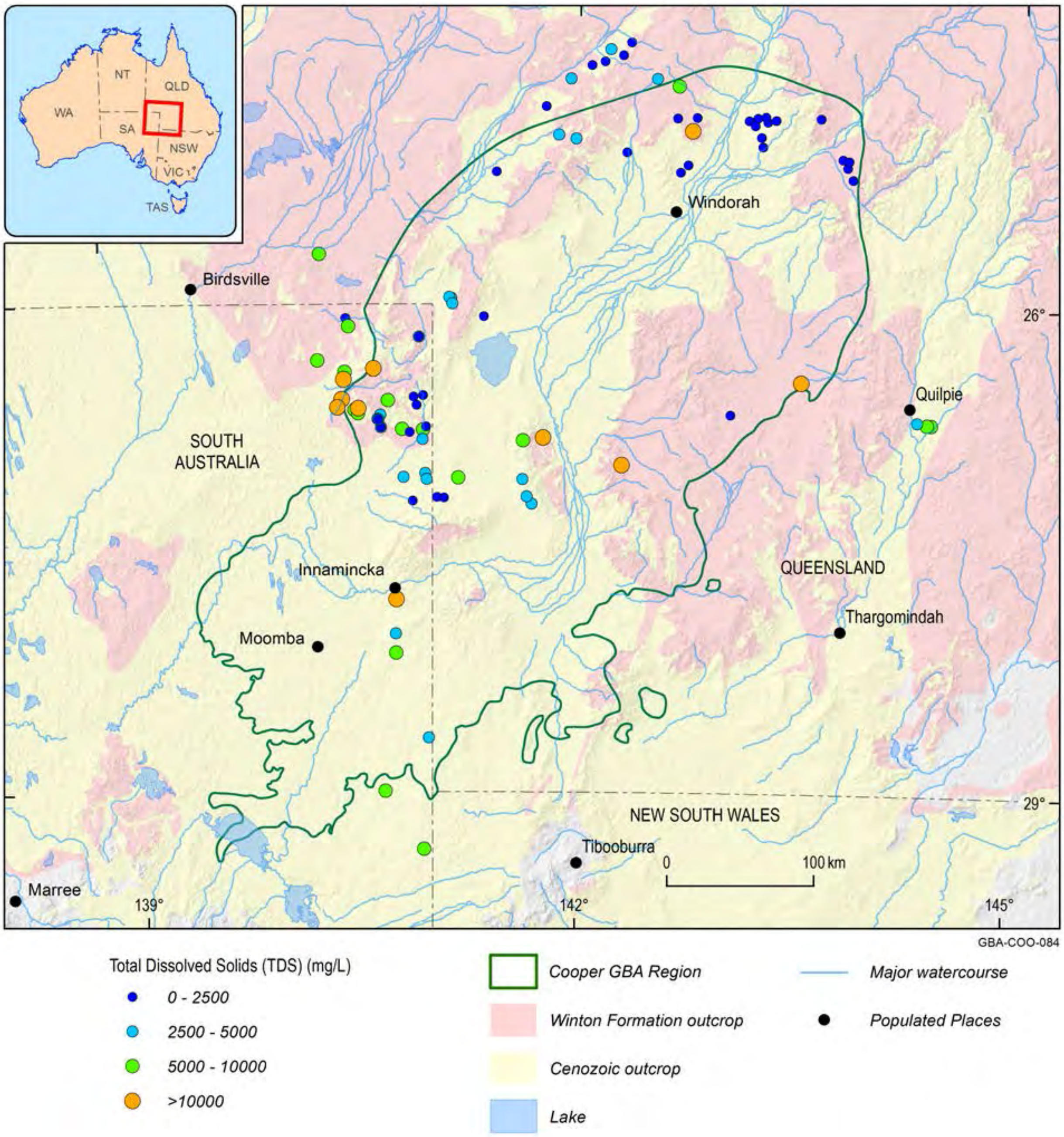


Figure 31 Spatial distribution of salinity in the Winton–Mackunda partial aquifer

Data: Geological and Bioregional Assessment Program (2018f)
Element: GBA-COO-084

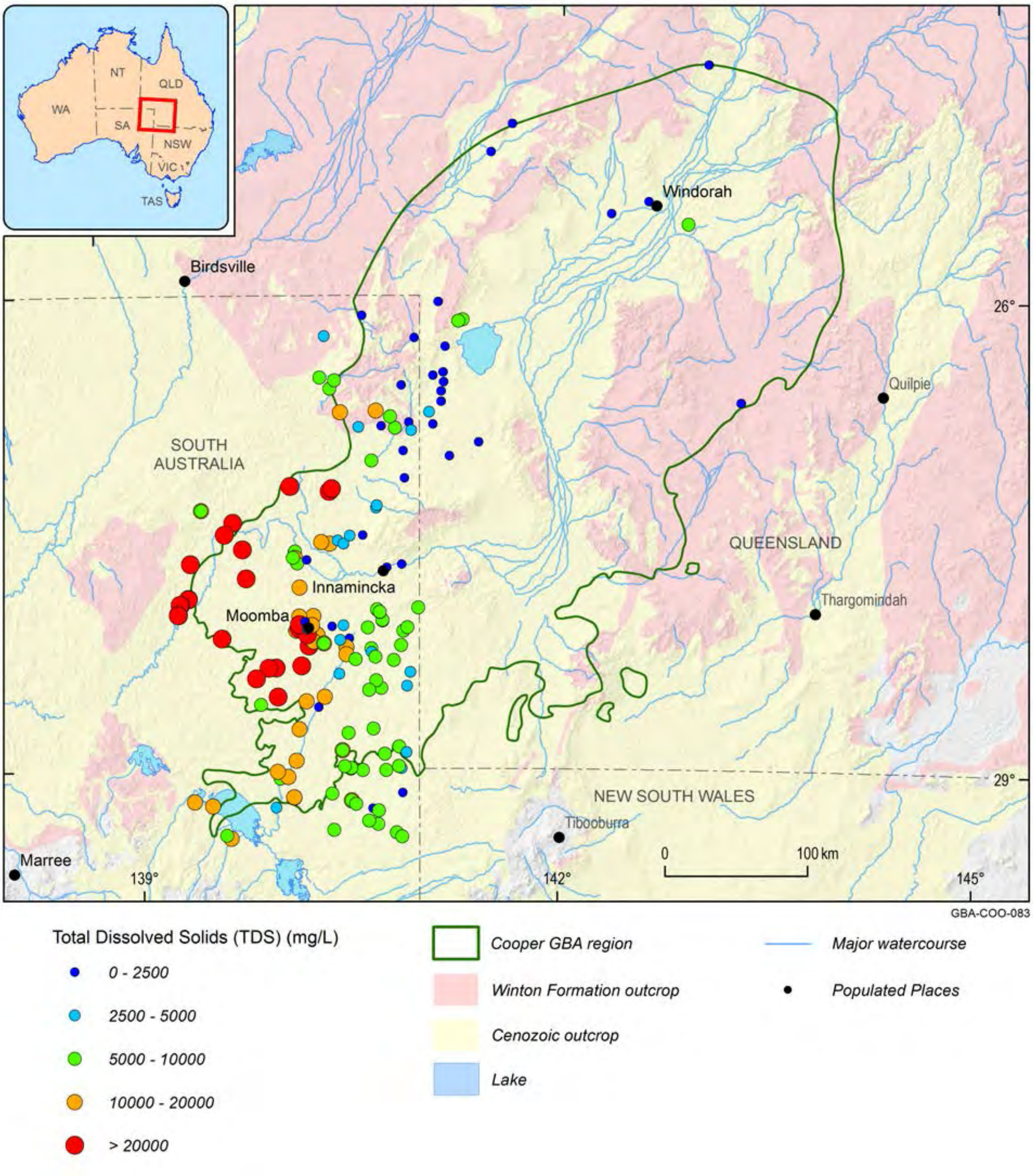


Figure 32 Spatial distribution of salinity in the Lake Eyre Basin aquifers

Data: Geological and Bioregional Assessment Program (2018f)
Element: GBA-COO-083

Hydrochemical facies

In addition to total salinity, other groundwater hydrochemical data is available for some bores. To better understand water types found in the various aquifers, major ion hydrochemical parameters (Na, K, Mg and Ca cations and Cl, CO_3, HCO_3 and SO_4 anions). As mentioned previously (Section 2.2) some caveats on interpretation of these data include:

- Due to a lack of screen data, sample depths may relate to maximum bore depth and not screen depth

- There is often little information on how the sample was taken or quality control at time of sampling
- Groundwater samples are assumed not to be contaminated during drilling, and that sampling occurred after the groundwater bore had been developed (i.e. flushed post drilling)
- Bore integrity was not taken into account.

For this section, piper plots (Piper, 1944) were used to characterise different water types are prevalent for different aquifers. These plots categorise water types according to the major ion composition. To provide a spatial perspective the characterise samples were then displayed on maps using the method described in Peeters (2014).

Overall, the Piper plots (Figure 34, Figure 35, Figure 37 and Figure 39 and the derived water types indicate that the confined GAB groundwater and Cenozoic aquifer are distinct. Na-Cl type water is typical in the Cenozoic aquifers. In contrast, confined GAB groundwater are dominated by Na or K cations with very little SO_4, leading to Na-HCO_3 type waters dominating over Na-Cl type water. The hydrochemistry of the Winton–Mackunda partial aquifer system is more complicated and contains distinct populations of Na-HCO_3 and Na-Cl type waters.

To assess distribution of the two populations further, the anion concentrations were plotted relative to depth. Given the two main water types found (Na-Cl and Na-HCO_3) are differentiated by their anion composition, and that SO_4 is insignificant, the position in the Piper plot can be reduced to the anion ratio shown in Equation 3. Low values of this ratio are associated with Na-HCO_3 type waters (points included within green boxes on Figure 33), while high ratio values represent Na-Cl type waters (points included within blue boxes on Figure 33). Some caution though is required when interpreting these data, as due to a lack of data screened intervals for many wells the sample depth related to maximum depth.

$$Ratio = \frac{Cl}{Cl + (CO_3 + HCO_3)} \tag{3}$$

By plotting this anion ratio against depth, clusters become evident. In the Cenozoic aquifers, Na-Cl type waters are prevalent at all depths (0 – 160 m), but Na-HCO_3 type water is found only in the 15 – 90 m depth range. The relatively shallow Na-HCO_3 waters may relate to recharge. In contrast, depth does not appear to have strong control on water type for the Winton–Mackunda partial aquifer and artesian GAB aquifers. This suggests that occurrence of Na-Cl waters in these aquifers may relate to other pathways, such as groundwater evolution laterally along a flow path or compartmentalisation of the aquifer system (for instance, by a physical barrier, such as a fault or change in lithology, or a hydrodynamic barrier). Section 3.3.2 and Section 3.3.3 include further detail on these aspects.

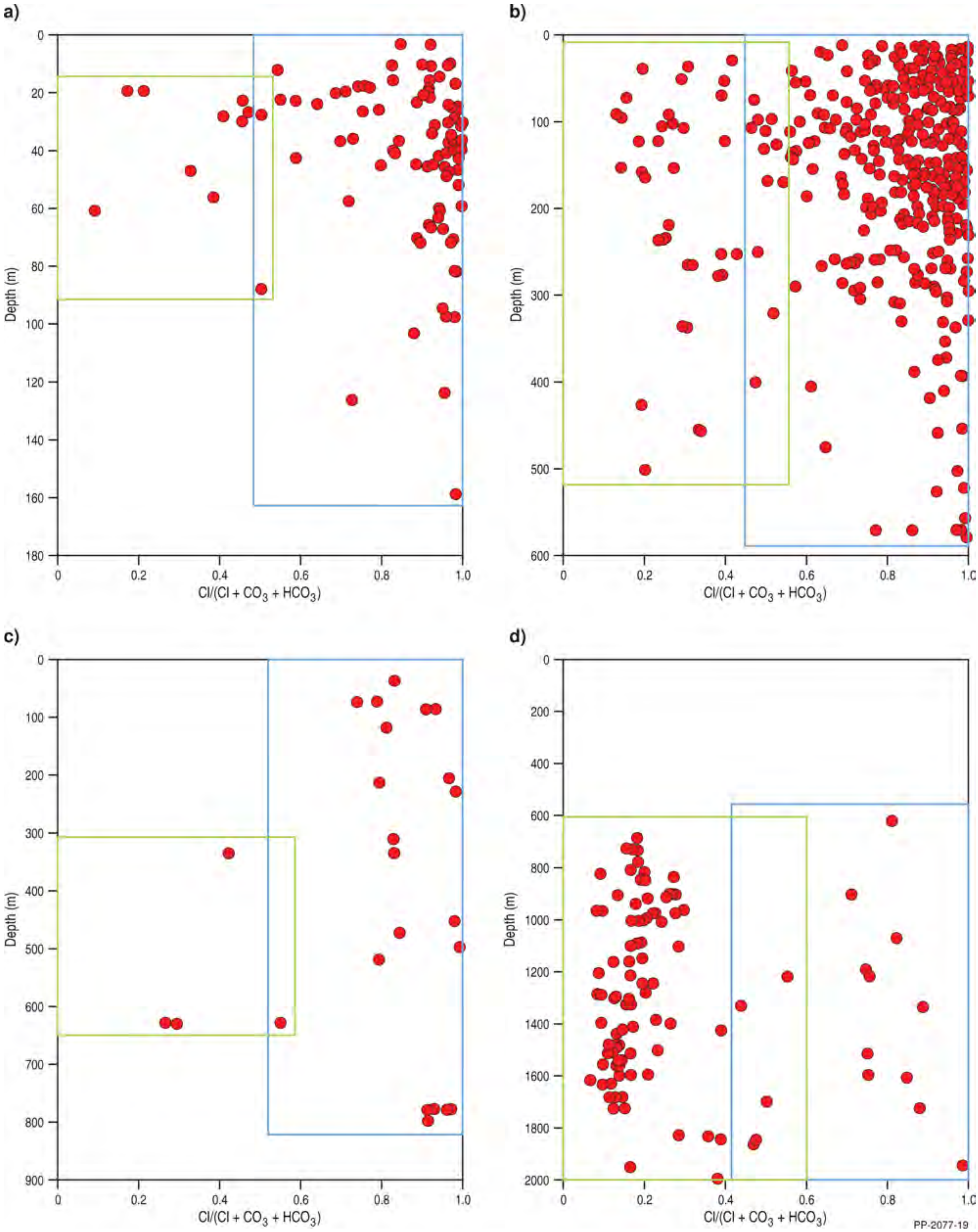


Figure 33 Anion ratio to highlight water types, plotted against depth, according to hydrostratigraphic groups. (a) Lake Eyre Basin; (b) Winton–Mackunda partial aquifer; (c) Rolling Downs aquitard; (d) artesian GAB aquifers

Bore depths do not necessarily represent actual depth of the screens. Depending on bore data available, it may represent the maximum bore depth. See Section 2.2.1 for further detail.
Data: Geological and Bioregional Assessment Program (2018h)
Element: GBA-COO-2-294

3.3.1 Cooper Basin

Publically available groundwater hydrochemistry data for the Cooper Basin is largely limited to salinity (Table 7), derived predominantly from wells located in South Australia. (Keppel et al., 2016) described groundwater from Patchawarra Formation as Na-Cl type waters that are relatively old, when comparable to waters from deeper parts of the GAB in the overlying Eromanga Basin.

3.3.2 Eromanga Basin

Previous studies into the hydrochemistry of the GAB aquifers have primarily focused on the artesian aquifers (e.g. Ransley et al., 2015a; Love et al., 2013a; Radke et al., 2000).

3.3.2.1 Artesian GAB aquifers

In artesian GAB aquifers (Table 7, Table 8), relatively higher salinities generally away from recharge zones or areas of sluggish groundwater flow (Radke et al., 2000; Ransley et al., 2015a). Furthermore, complications arising from hydraulic heterogeneity, structural geological features and variable stratigraphy contribute to hydrochemical variation within artesian GAB aquifers (Ransley and Smerdon, 2012; Welsh et al., 2012).

Previous work (Radke et al., 2000; Ransley et al., 2015a) identified that the salinity of the Cadna-owie–Hooray aquifer is relatively fresher around the margins of the Cooper GBA region and along the Birdsville Track Ridge, north-west of the Cooper GBA region. Salinity increases towards basin centre, particularly in the vicinity of the Nappamerri and Patchawarra Troughs (Figure 30) in the southwest of the Cooper GBA region. Radke et al. (2000) suggested that this relates to deeper burial leading to reduced porosity and permeability, resulting in sluggish flow rates approaching stagnation, and therefore containing older groundwater. Near-stagnant old groundwater were characterised by higher concentrations of Cl, Na, Ca and Mg (Radke et al., 2000), which were thought to be due to a mixture over time of downward diffusion of ions from overlying marine sediments in the Rolling Downs aquitard and partly from water-rock interactions. Other work (e.g. Love et al., 2013a; Keppel et al., 2016) has found that most groundwater in the western Eromanga Basin (west of Cooper GBA region) is of a Na-HCO_3 type, with carbonate dissolution and ion exchange processes affecting the hydrochemical evolution. These types of hydrochemical reactions and mixing are naturally occurring processes operating on very long time-scales, in the order of tens of thousands of years.

Groundwater from the artesian GAB aquifers are typically dominated by Na or K with very little SO_4, so tend to cluster in the lower right edge of the central diamond in the Piper plot (Figure 39b). This leads to the groundwater from these aquifers being almost exclusively of Na-HCO_3 type in the Cooper Basin region. With limited variation in the hydrochemical facies for the artesian GAB aquifers, there is also minimal spatial variation (Figure 39a). Although Na-HCO_3-type waters are dominant in the artesian GAB aquifers, some Na-Cl-type waters are also present. Depth is not a controlling factor on water types (Figure 33).

Environmental tracers such as chlorine-36 (^{36}Cl) has been used to characterise aquifer processes and estimate age of groundwater in artesian GAB aquifers. The density of ^{36}Cl data is much less than for other hydrochemical parameters (Ransley et al., 2015a). High ^{36}Cl values are present in the major recharge zones of the artesian GAB aquifers, decreasing towards the central portions of the aquifer in the Cooper GBA region, (Ransley et al., 2015a) and with depth (Hasegawa et al., 2016).

Studies through ^{14}C, ^{36}Cl and noble gas data suggest that the present artesian groundwater flow directions in the GAB have been in place for at least one million years (Ransley and Smerdon, 2012). Around Lake Blanche, $^{36}Cl/Cl$ ratios suggest that groundwater from the Cadna-owie–Hooray aquifer is generally older than those from either overlying (e.g. Coorikiana Sandstone and Cenozoic aquifers) or deeper crystalline basement, but is comparable to that in the Patchawarra Formation in the Cooper Basin (Keppel et al., 2016).

A transition to low-flow/stagnant conditions in the Central Eromanga depocentre is apparent from low $^{36}Cl/Cl$ values and high alkalinity (Ransley and Smerdon, 2012). Near-stagnant groundwater flow in the central Eromanga Basin has been inferred from ^{36}Cl and ^{4}He data (Radke et al., 2000; Ransley and Smerdon, 2012), which suggests that the groundwater could be in excess of 1 million years old. It is suggested that groundwater flow diverts around the Cooper GBA region through zones of higher porosity and permeability to avoid the zone of very low flow (Radke et al., 2000) (see also Section 3.2.2 above). Here groundwater could be more in order of 300-500 thousand years old (Radke et al., 2000; Ransley and Smerdon, 2012).

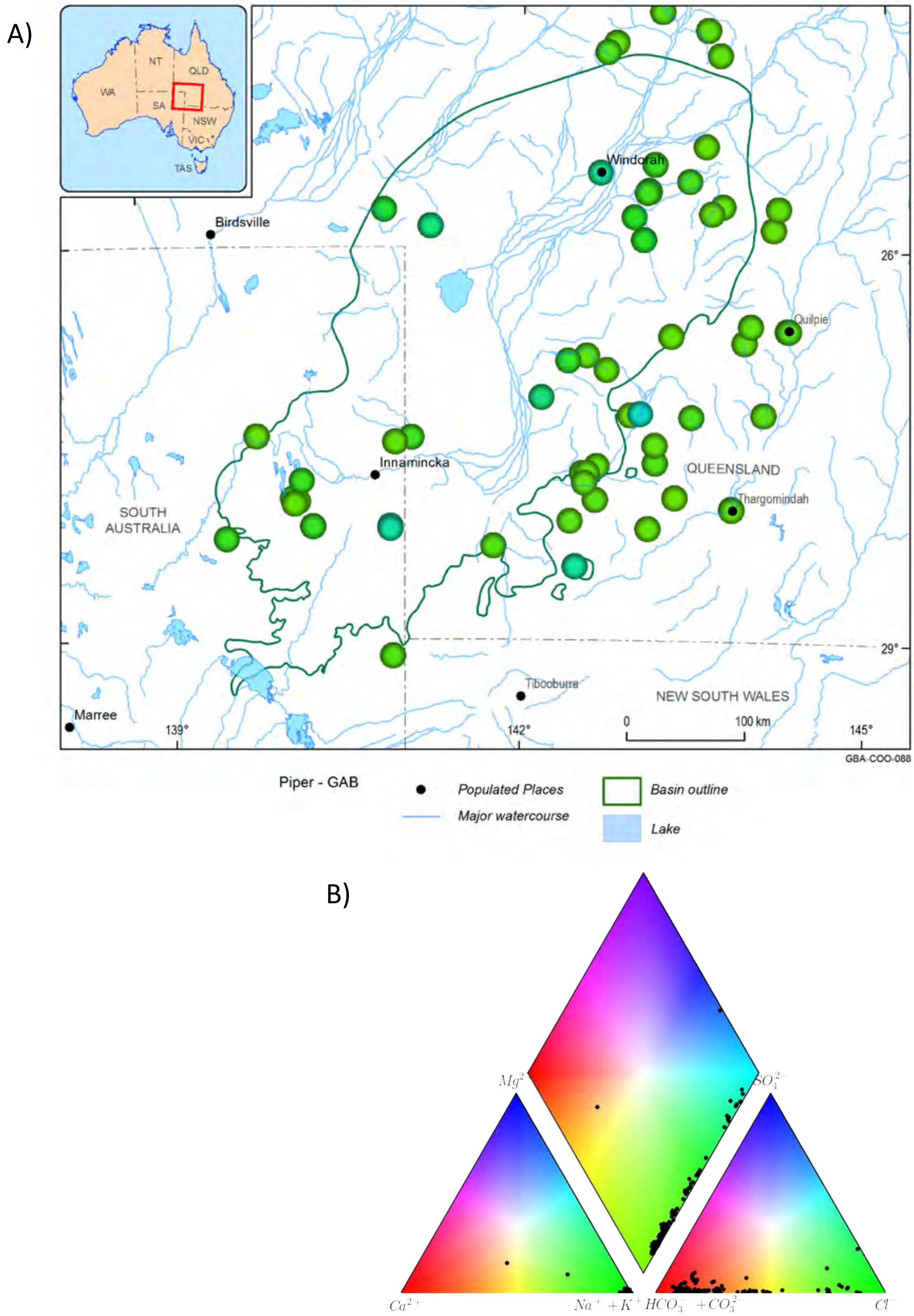


Figure 34 Piper plot and map of hydrochemistry for the artesian GAB aquifers (A) Map of hydrochemical facies, (B) Piper plot

Plot shows the hydrochemical facies, colours of points in the maps correlate to the colours shown in the Piper plot central diamond, as per the method described by Peeters (2014).
Colour of points in Figure 34A corresponds with colour of where point plots on central diamond in Figure 34B
Data: Geological and Bioregional Assessment Program (2018d)
Element: GBA-COO-088 (A); GBA-COO-2-323 (B)

3.3.2.2 Rolling Downs aquitard

There is limited information on salinity (14 data points including bores with multiple readings) and major ions (29 data points including bores with multiple readings) available for the Rolling Downs aquitard within the vicinity of the Cooper GBA region. Groundwater salinity ranges from 1000 – 8100 mg/L (Figure 35) and are of Na-Cl-HCO_3 water type (Figure 35b). Other studies from areas predominantly outside the Cooper GBA, suggest that groundwater in the Rolling Downs aquitard may be Na-HCO_3-Cl or Na-HCO_3 type (Golder Associates, 2013; Moya et al., 2016), or Na-Cl type (Keppel et al., 2016), but this information is also based on small number of samples.

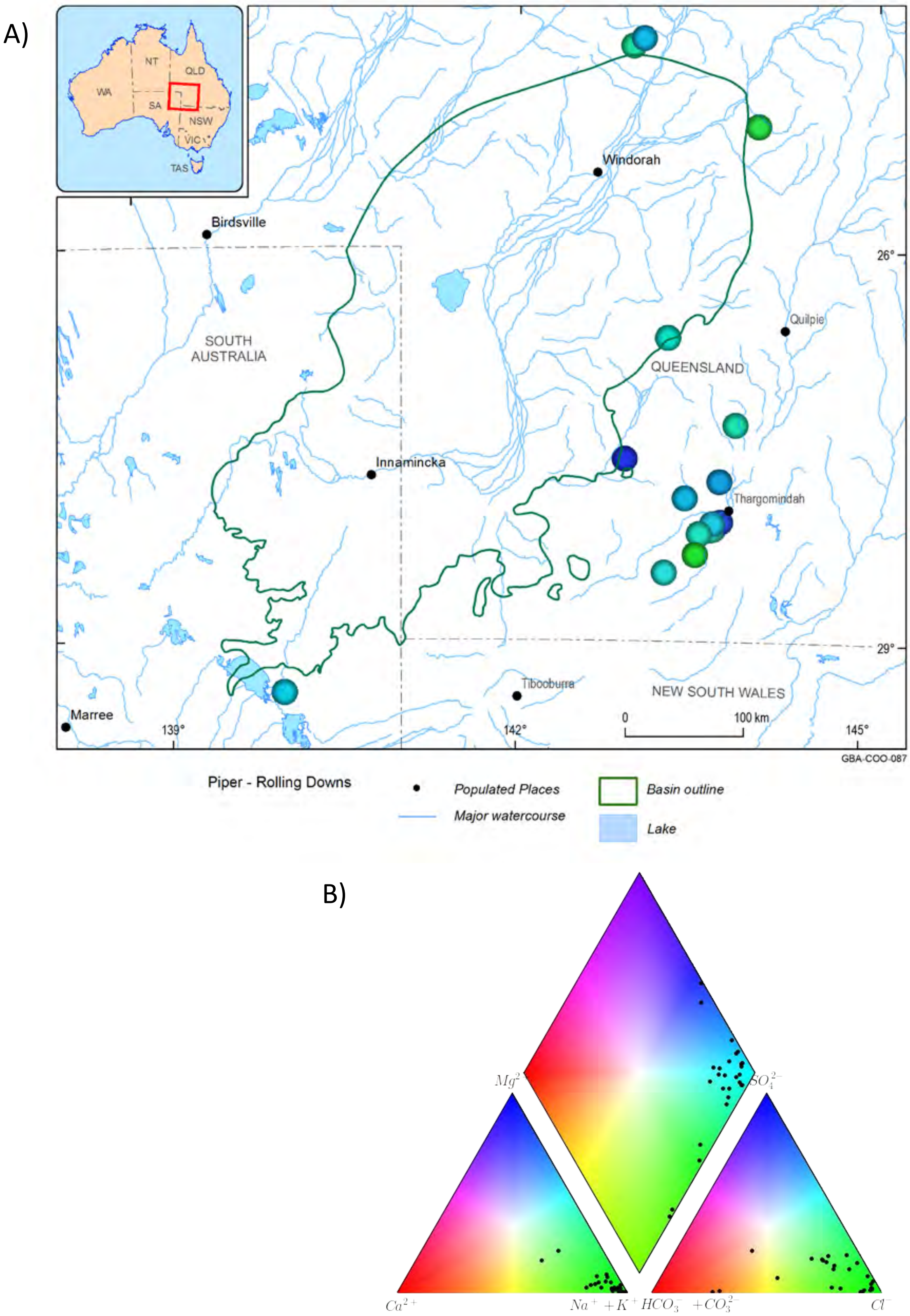


Figure 35 Piper plot and map of hydrochemistry for the Rolling Downs aquitard (A) Map of hydrochemical facies, (B) Piper plot

Plot shows the hydrochemical facies, colours in the maps correlate to the colours shown in the Piper plot, as per the method described by Peeters (2014).
Colour of points in Figure 35A corresponds with colour of where point plots on central diamond in Figure 35B
Data: Geological and Bioregional Assessment Program (2018d)
Element: GBA-COO-087 (A); GBA-COO-2-278 (B)

3.3.2.3 Winton–Mackunda partial aquifer

Salinity data for the Winton–Mackunda partial aquifer (Figure 31) has a patchy and sparse distribution. Furthermore, (Department of Natural Resources and Mines (Qld), 2016) and Muller (1989) noted that the salinity and chemistry of groundwater from Winton-Mackunda partial aquifer could be highly variable, which was presumed to be due to discontinuous nature of the sandstones in the Winton Formation and variable recharge pathways. In some areas (e.g. Innamincka Dome), the occurrence of groundwater mounds underneath areas of Winton Formation outcrop, suggest that recharge can be enhanced, possibly through near surface fractures (Ransley et al. (2015a).

Salinity has been plotted against bore depth (screened interval midpoint where available, maximum bore depth otherwise) in Figure 36. Less saline samples occur at all depths, but higher salinities (TDS > 6000 mg/L) are mostly restricted to depths shallower than 200 m. A few samples between 550 and 575 m depth also exhibit salinities greater than 5000 mg/L TDS. However, for these bores, the depth represents the maximum depth rather than screen depth. The actual depth at which these samples were taken is not accurately known.

From limited data, higher salinities in Winton Formation aquifers appear to be associated with shallow depths to groundwater (Figure 36b). This potentially could be a result of processes such as evapotranspiration concentrating salts in groundwater. Potentially areas where depth to groundwater is shallow and salinity is high may represent areas of discharge for Winton–Mackunda partial aquifer. However, it is evident from Figure 36 that the occurrence of bores with salinity data (Figure 36) when compared to amount of bores with waterlevel data (Figure 25) is far less.

Hydrochemical water types are variable in the Winton–Mackunda partial aquifer (Figure 37b). Whilst Na is the dominant cation, a distinct trend towards equal proportions of Ca-Mg is also apparent on the cation trilinear plot (lower left hand side of Figure 37b). The dominant anion for the majority of samples is Cl however, in an appreciable proportion of samples HCO_3 dominates. Depth does not appear to control which is the dominant anion (Figure 33b), which suggests that vertical flow.

The central diamond of the Piper plot (Figure 37b) shows two obvious trends, which demonstrates that a number of water types are present. The trend along the bottom right of the diamond is indicative of Na-HCO_3 type waters (sample points in the green hues), whereas the trend along top right of the central diamond (in the purple hues) is indicative of Ca-Mg-HCO_3 type waters. The large cluster of samples (in the blue hues) suggests that for the majority of samples (90%) groundwater are dominated by Na-Cl. Investigations using environmental tracers have not been undertaken for the Winton-Mackunda partial aquifer.

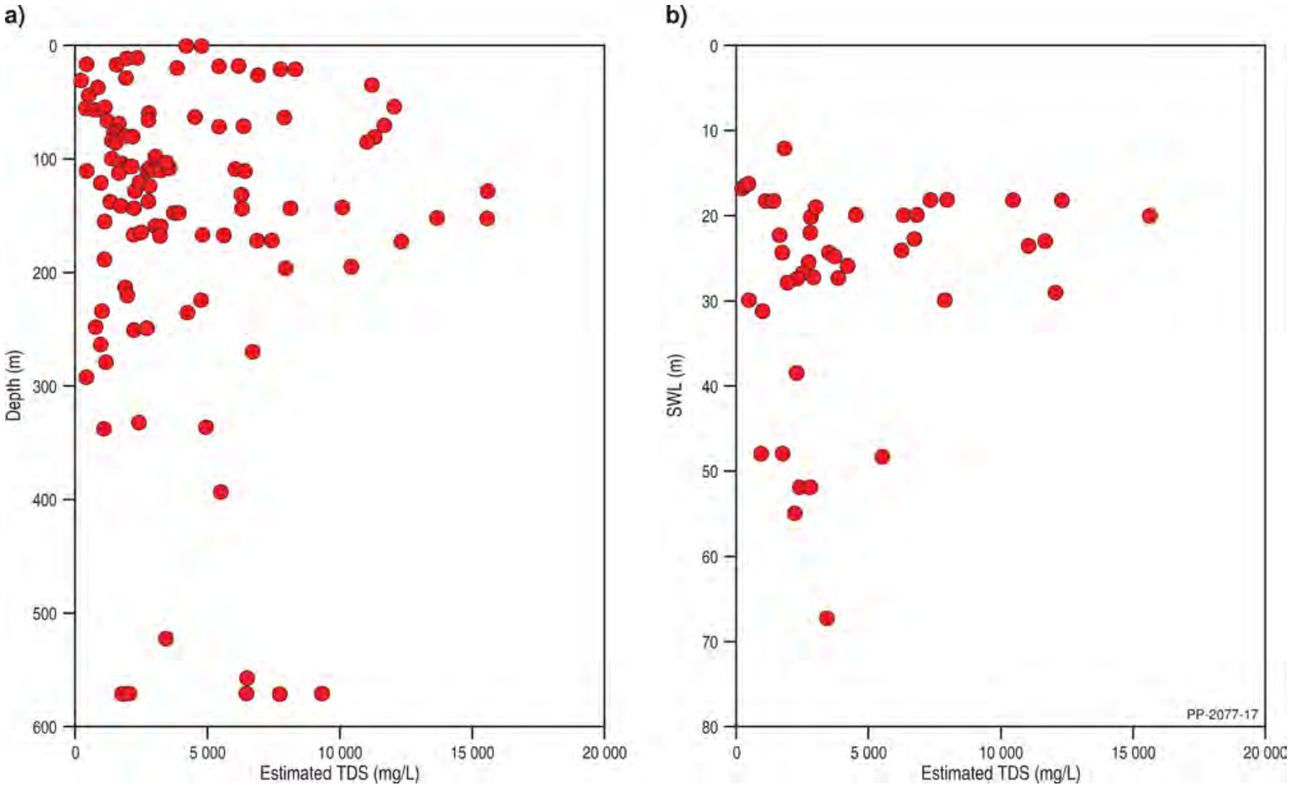
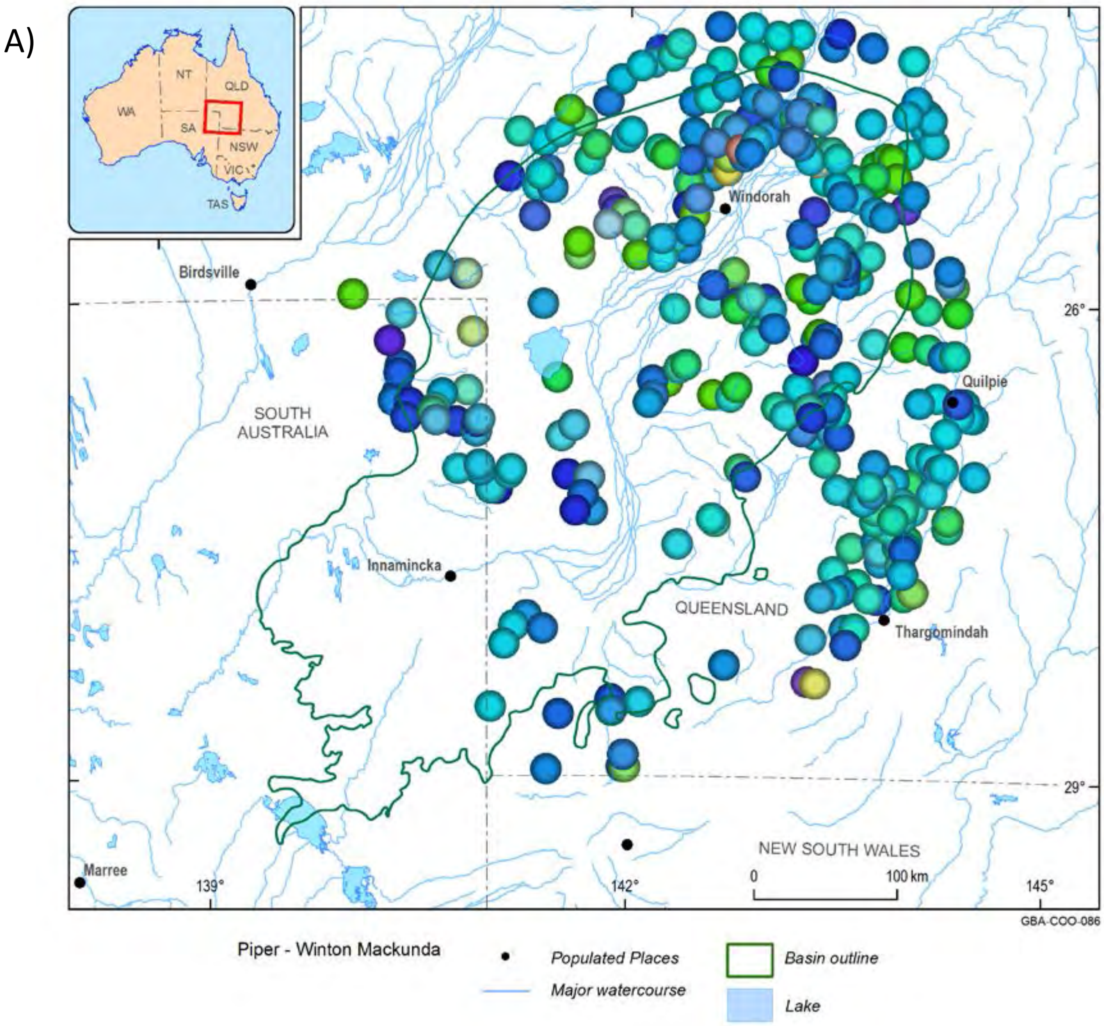


Figure 36 Salinity depth trends for Winton–Mackunda partial aquifer (a) Salinity versus bore depth. (b) Salinity versus depth to groundwater

Bore depth may not necessarily represent actual depth of the screens. Depending on bore data available, it may represent the maximum bore depth. See Section 2.2.1 for further detail.
Data: Geological and Bioregional Assessment Program (2018h)
Element: GBA-COO-2-295

The causes and process behind the hydrochemical trends in the Winton–Mackunda partial aquifer are not clear. Groundwater in the Winton–Mackunda partial aquifer has similarities to groundwater in both the Lake Eyre Basin (Na-Cl type) and artesian GAB systems (Na-HCO_3 dominated waters). These similarities have been noted previously (e.g. Radke et al., 2000; Golder Associates, 2013) and inter-aquifer leakage has been postulated as a possible mechanism, particularly around major structures such as the Canaway Fault. Due to proximity, there is likely to be a high degree of connection between aquifers in the Lake Eyre Basin and Winton–Mackunda partial aquifer. Upwards leakage from artesian GAB aquifers is also a possibility. However, this could be limited in the Cooper GBA region, due to the great thicknesses of Rolling Downs aquitard (usually greater than 500 m, see also discussion in Section 3.2.2.3) and the lack of artesian GAB springs across the region. Alternatively, it may be an oversimplification to consider the Winton–Mackunda partial aquifer as a single aquifer system based on the hydrochemistry presented here. There could well be a number of discrete aquifer systems within the Winton–Mackunda partial aquifer, with varying rates of recharge, hydraulic conductivity and water-rock interactions. Perhaps the Na-HCO_3 dominated water represent points of enhanced recharge or areas where there carbonate dissolution is occurring within the aquifer. The degree of lithological variation in the aquifer is also likely to be an influence. More work is required to unravel the groundwater pathways and hydrochemistry.



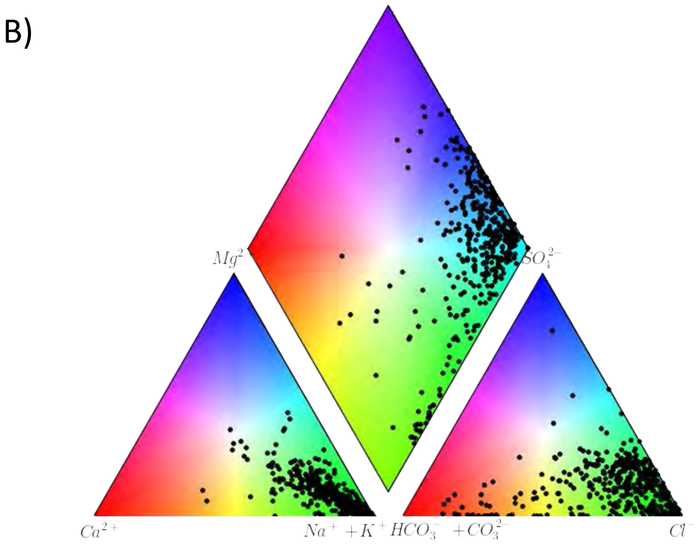


Figure 37 Piper plot and map of hydrochemistry for the Winton–Mackunda partial aquifer (A) Map of hydrochemical facies, (B) Piper plot

Plot shows the hydrochemical facies, colours of points in the maps correlate to the colours shown in the Piper plot central diamond, as per the method described by Peeters (2014).
Colour of points in Figure 37A corresponds with colour of where point plots on central diamond in Figure 37B
Data: Geological and Bioregional Assessment Program (2018d)
Element: GBA-COO-086 (A); GBA-COO-2-279 (B)

3.3.3 Lake Eyre Basin

As was the case for the hydrodynamics (Section 3.2.3), there is often not enough information to differentiate the hydrostratigraphy down to a formation level. Hence, the hydrostratigraphy is lumped together as “Cenozoic” for the hydrochemistry data. Furthermore, due to lack of screen interval data, many of sample depths often represent the maximum bore depth (Section 2.2) rather than screen depth.

Lake Eyre Basin groundwater is typically more saline than ground water from other aquifers in Cooper GBA region (i.e. 50% of samples exceed 10,000 mg/L TDS, see Table 8). Salinity depth plots for Cenozoic aquifers (Figure 33A) suggests that less saline groundwater (less than 10,000 mg/L TDS) can be found down to 200 m whereas the salinity is more variable above about 80 m. Very high salinities appear to be associated with shallow depth to groundwater (Figure 38B). Shallow highly saline groundwater tend to occur in SA (Figure 32) near a number of salt lakes. Potentially these lakes could be interacting with shallow groundwater. Groundwater is more likely to be fresher where depth to groundwater is greater than 20 m.

The stratification in salinity suggests that there may be at least two groundwater systems in the Lake Eyre Basin aquifers. A shallow system associated with local scale features such as waterholes and salt lakes and a deeper system with potentially less saline groundwater. Fresher groundwater at depth suggest that deeper aquifers (e.g. the Eyre Formation) may be in part confined and separated from shallow aquifers, or that there is some other process preventing salinisation of deeper groundwater. Also, it is indicative of various salinisation processes operating at a range of depths in the regional groundwater system. For instance evapotranspiration concentrating salts in soil profile, or the flushing of salt from ephemeral lakes into shallow groundwater during floods, could explain the high salinities in Lake Eyre Basin aquifers. Another contributing factor could also in part be due to bias in available salinity and waterlevel data. For example, many bores in the vicinity of the Cooper Creek floodplain lack salinity information (see Figure 32). Finally available salinity data may not necessarily be representative of all aquifer processes. Only further sampling and investigation will clarify these issues.

The Cenozoic aquifer shares some similarities in groundwater type with some groundwater in the Winton–Mackunda partial aquifer. The basal Eyre Formation appears to be in hydraulic connection to the Winton Formation (Ransley and Smerdon, 2012).

Piper plots show that Cenozoic groundwater hydrochemistry (Figure 39b) is distinct from the artesian GAB aquifers (Figure 34b). An apparent trend from the Na+K vertex towards the centre of the cation subplot, and anions dominated by Cl with highly variable contents results in a cluster near the top right of the central diamond. Furthermore, the spatial distribution of hydrochemical facies (Figure 39a) is relatively sporadic, although some more HCO_3-rich waters (green points) are found towards the southwest of the Cooper GBA region.

Major ion patterns and high salinities indicate that Cenozoic aquifers are hydrochemically distinct from the confined GAB aquifers. However, in some cases, shallower GAB aquifers such as the Winton–Mackunda partial aquifer show chemical similarities to the Cenozoic aquifers, with elevated Mg. This is consistent with previous investigations (Cendón et al., 2010; Tweed et al., 2011).

The anion ratio (Figure 33b), suggests that the majority of Na-Cl groundwaters from Lake Eyre Basin aquifers are prevalent at all depths. In contrast, Na-HCO_3 type water tend to occur at shallower levels above 80-90 m. Near-surface processes such as episodic recharge may account for the occurrence of Na-HCO_3 type waters with more regional groundwater being represented by the Na-Cl type. Such an explanation concurs with the hypothesis of Cendón et al. (2010), who suggested that bicarbonate may be associated with near-surface freshwater lenses, while regional groundwater would be dominated by chloride.

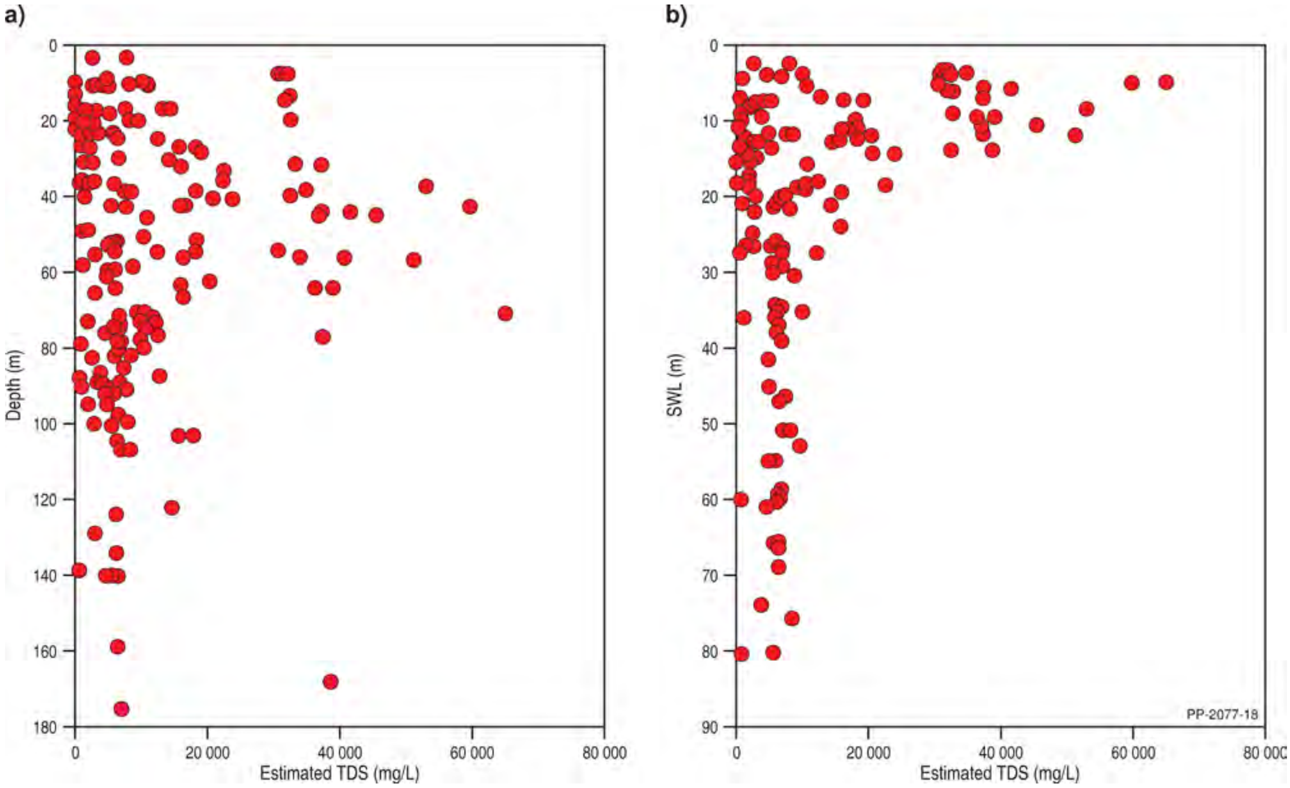
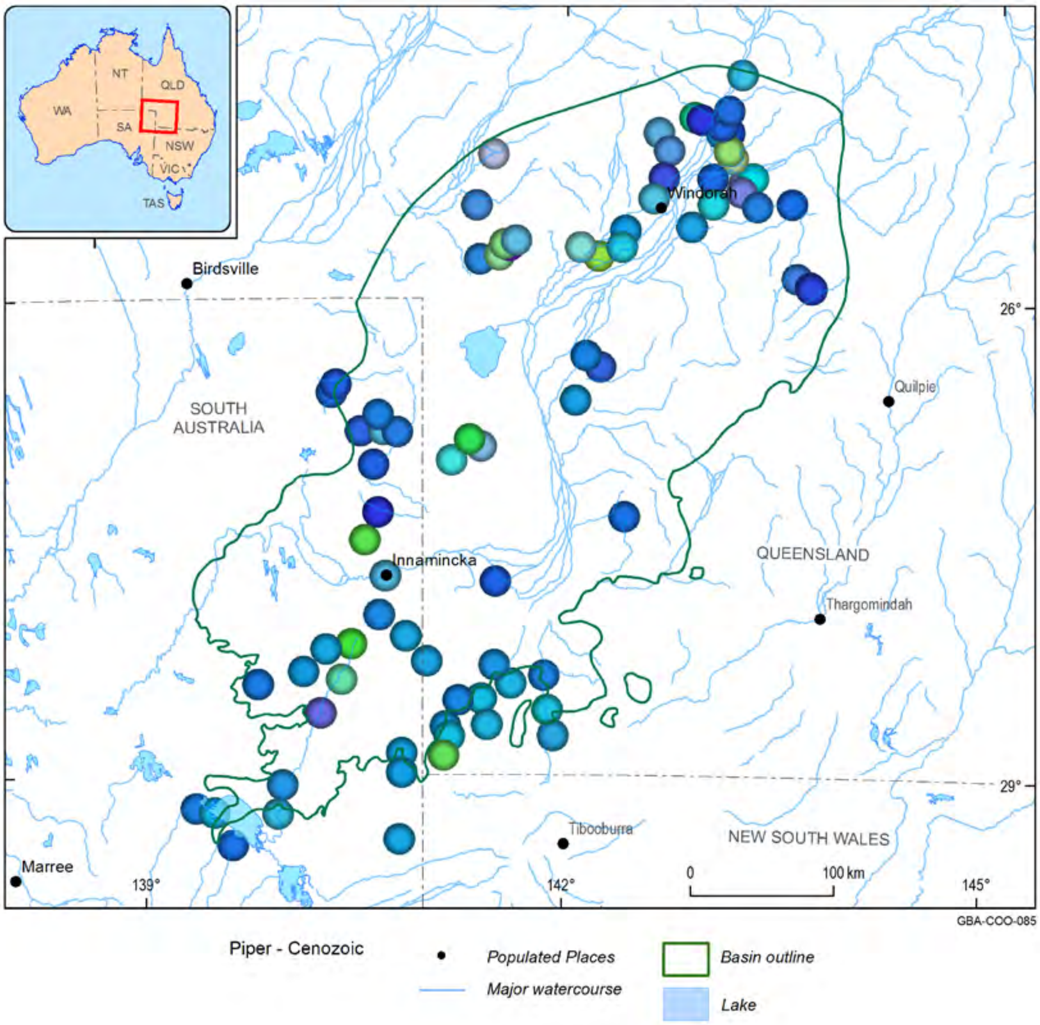


Figure 38 Salinity depth trends for Cenozoic aquifers (a) Salinity versus bore depth (b) Salinity versus depth to groundwater

Bore depth may not necessarily represent actual depth of the screens. Depending on bore data available, it may represent the maximum bore depth. See Section 2.2.1 for further detail.
Data: Geological and Bioregional Assessment Program (2018h)
Element: GBA-COO-2-296

A)



B)

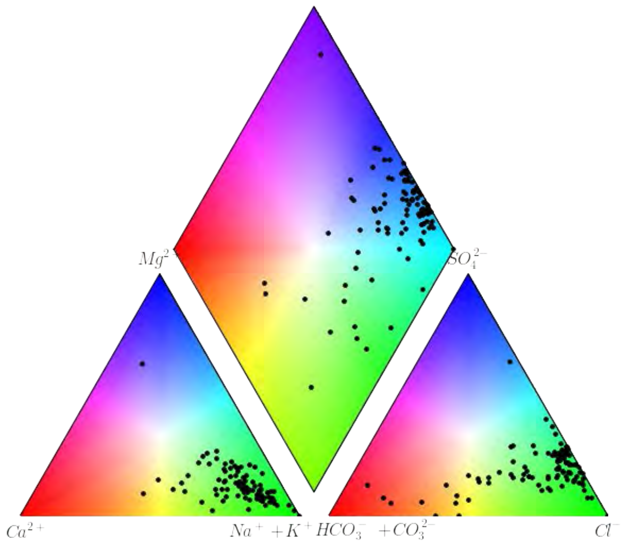


Figure 39 Piper plot and map of hydrochemistry for Cenozoic aquifers (A) Map of hydrochemical facies, (B) Piper plot

Plot shows the hydrochemical facies, colours of points in the maps correlate to the colours shown in the Piper plot central diamond, as per the method described by Peeters (2014).
Colour of points in Figure 39A corresponds with colour of where point plots on central diamond in Figure 39B
Data: Geological and Bioregional Assessment Program (2018d)
Element: GBA-COO-085 (A); GBA-COO-2-280 (B)

3.4 Potential basin inter-connectivity

Aspects on basin connectivity, some of which have been touched on in preceding sections can be summarised as follows:

- Complex distribution of lithologies and depositional environments in the Cooper Basin (Lech et al., 2020; Owens et al., 2020), Section 3.1.1). Being a fluvio-lacustrine basin sequence that experienced high accommodation rates, lithofacies for many of the formations in the Cooper Basin sequence tend to be diverse and repeatedly varied. This influences the original distribution of porosity and permeability and consequently geological architecture of aquifers and aquitards.
- Tendency of groundwater to be driven out of over-pressured, gas charged reservoirs, particularly where tight, shale and deep coal gas are present in deeper portions of the Cooper Basin (Sections 3.1.1 and 3.2.1; (Lech et al., 2020). This would displace and disrupt any pre-existing groundwater systems. Gas filled pore space over large areas (such as could be case for basin centred gas plays) would likely act as a regional aquitard. In addition in the past, vertical migration of oil upwards through the Cooper sequence into overlying structural traps in aquifers of the Eromanga Basin sequence has led to stacked reservoirs (Heath et al., 1989) Expulsion of original groundwater also occurred during inversion of the Cooper Basin and earlier hydrocarbon migration events.
- Diagenetic changes such as formation of silica and carbonate cements, clay minerals (e.g. kaolinite, illite) can modify or destroy pre-existing porosity and permeability by infilling pore space (Sections 3.2.1 and 3.2.2). Diagenetic affects are likely to be greater where rocks have been more deeply buried, which in turn can affect connectivity and groundwater flow paths (e.g. Hooray Sandstone in the Central Eromanga depocentre Radke et al., 2000).
- Influence of structural architecture on aquifer compartmentalisation, connectivity and fluid flow paths (e.g. Radke et al., 2000; Kulikowski et al., 2018); Sections 3.2.1 and 3.2.2).
- Current temperature, pressure and stress regime can influence fluid flow pathways in the Cooper and Eromanga basins (Lech et al., 2020; Toupin et al., 1997). For instance, whether a fault is conductive, a barrier to groundwater flow, or both can depend on characteristics of the fault and stress (Bense et al., 2013).

3.4.1 Hydraulic connectivity between the Cooper Basin and basement

Fluid and gas exchange between rocks of the Cooper and Eromanga basins and basement rocks have been a part of the geological evolution of the GBA region. For instance, dissolved gases in GAB groundwater are attributed to both crustal and mantle volatiles (Ring et al., 2016). Mantle derived helium (He) is specifically present over the Cooper Basin area. However, the crustal component signature of the He isotopes significantly masks the mantle contribution. Dissolved gases within geothermal waters in granite basement fractures can contain in excess of 13% He (Wyborn, 2012). Also, much of the CO_2 and nitrogen (N) in Cooper Basin hydrocarbon gases are attributed to mantle or igneous sources (Boreham et al., 2001). The presence of these volatiles indicates migration of gas over timeframes in the order of millions of years (Italiano et al., 2014).

The transfer upwards may be due to diffusion, with some thermal convective contribution where sufficient permeability exists.

The Warburton Basin, which underlies the Cooper Basin includes its own petroleum system, which has mixed upwards into the Cooper Basin sequence (Boreham and Summons, 1999). Subsequent generation of Cooper Basin sourced hydrocarbons has migrated laterally and downwards into Warburton Basin, presumably due to gas generation and over-pressuring that developed within the Cooper Basin.

In the central Nappamerri Trough, the granite basement underlying the Cooper Basin was targeted for the development of an engineered geothermal energy system (Wyborn, 2012) due to the presence of high temperature anomalies. Near-horizontal fractures intersected in the granite basement were fluid-filled and contained over-pressures in the order of 34.47 MPa (5,000 psi) above predicted hydrostatic pressure gradient. Such immense natural over-pressure was attributed to horizontal compressive stresses (Lech et al., 2020), as well as an overlying low permeability seal of shales and fine-grained sandstones near the base of the Cooper Basin (e.g. Merrimelia Formation, Tirrawarra Sandstone, Patchawarra Formation). This seal was the result of deep burial (> 3000 m) and diagenesis at high temperatures (>200 °C) destroying much of the original porosity and permeability. Monitoring during development of these engineered geothermal systems found that sympathetic pressure variations were occurring in geothermal reservoirs in the basement rocks, as well as gas reservoirs in the overlying Cooper Basin. This suggests that there was potential for pressures/stress changes in basement to influence pressures in the Cooper Basin (Wyborn, 2012). The connection may follow a direct pathway, or alternatively relate to stress induced pressure changes on pore fluids (the “poro-elastic effect”, see Domenico and Schwartz, 1997).

Sympathetic pressure changes noted by Wyborn (2012) suggest that there is potential for pressure changes in underlying sequences to influence pressures in overlying Cooper Basin. How much actual exchange occurs under present day conditions is unknown but is likely to be limited by low porosity and permeability in the Cooper Basin rocks at depth.

3.4.2 Hydraulic connectivity between the Cooper and Eromanga basins

Until regional dynamic modelling of all related processes is undertaken, any quantitative assessment of potential connectivity is speculative. Only limited data is available to test the interconnectivity of the entire hydrostratigraphy of the Cooper GBA region, and this is highly localised. However, the established regions of high prospectivity for tight gas, shale gas and much of the region for deep coal lie within the central regions of Cooper Basin troughs (Lech et al., 2020). Over much of the Cooper Basin, the Nappamerri Group reduces vertical connectivity between Gidgealpa Group and the Eromanga Basin.

Uplift and erosion of Cooper Basin sequence has resulted in a narrow band of Gidgealpa Group rocks to be in contact with overlying Eromanga Basin aquifers, along the south-western margin of the Cooper Basin (Figure 8, Figure 11 and Figure 40). Elsewhere Cooper Basin subcrop consists almost entirely of Nappamerri Group, which is primarily a leaky aquitard.

Subcrop extents of the underlying Gidgealpa Group, around the south-western periphery of the Cooper Basin (Figure 11 and Figure 40) occurs at relatively shallow depths (1100 – 1600 m below surface). Areas where the Gidgealpa Group are not covered by the Nappamerri Group are unlikely to be over-pressured with gas (Lech et al., 2020) and Section 3.1.1). Groundwater occurs in these zones; hence, at the relatively shallow levels much of the Gidgealpa Group is classed as partial aquifer and likely to contain some groundwater. At greater depths, the Gidgealpa Group is increasingly charged with gas, making its hydrostratigraphic status more uncertain (see Figure 12). Due to lithological considerations, regardless of depth the Murteree and Roseneath shales are regional aquitards and impede any inter-basinal groundwater flow.

Predominantly either the Poolowanna Formation or Hutton Sandstone aquifers overlie the Cooper Basin (Ransley et al., 2015a). The Poolowanna Formation is of comparable lithofacies to the Cuddapan Formation and is difficult to differentiate the two without chronologic evidence. These lowermost aquifers of the Eromanga Basin also host oil accumulations, mainly in structural traps. Vertical separation between aquifers in the Eromanga Basin and areas prospective for shale, tight, and deep coal gas in Gidgealpa Group of the Cooper Basin, varies considerably, and may range from 300 m for artesian aquifers to over 2000 m for the Winton–Mackunda partial aquifer.

Vertical leakage or cross-formational flow occurs at undetermined rates, but is presumed to be significant over timescales of thousands to millions of years. Measured pressure differences between aquifers are an indication of the vertical leakage or flow as are some hydrochemical indicators mentioned previously (Cresswell et al., 2012; Dubsky and McPhail, 2001; Love et al., 2013b; Toupin et al., 1997).

The absence of any identified deep faults or extensions of interpreted faults in the north-eastern corner of the Cooper Basin may be anomalous (Figure 11 and Figure 40). This apparently un-faulted region could be an artefact of relatively poor seismic coverage rather than the absence of major faults. In addition, thick coals in the Winton Formation were identified in this area by drilling and early seismic surveys. It is possible that the coals have prevented effective seismic penetration into the underlying Cooper Basin sequences. This region remains a gap in our knowledge of the structure and thickness of the Cooper Basin sequence.

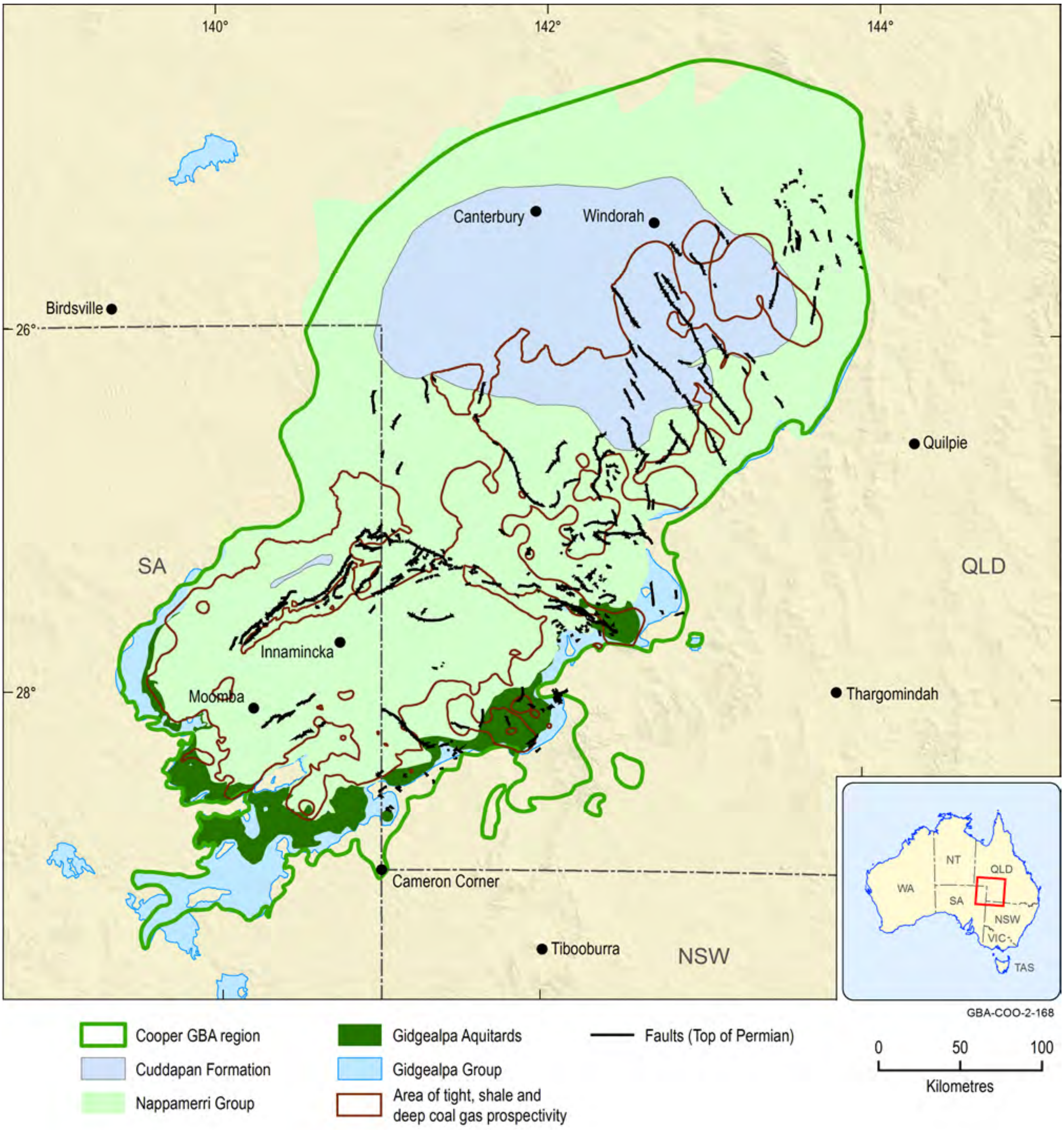


Figure 40 Potential connectivity across the Cooper Basin – Eromanga Basin contact

The Cuddapan Formation is a partial aquifer sandwiched between the Eromanga Basin aquifers and the Nappamerri Group leaky aquitard. The Nappamerri Group is predominantly a leaky aquitard.
Roseneath and Murteree shales are regional aquitards in the Gidgealpa Group.
All other units that comprise the Gidgealpa Group (See Figure 12) subcrops beneath the Eromanga Basin. At shallow levels, these units are likely to be water saturated (unless hydrocarbon accumulations are present). Hence at these relatively shallow depths and (1100-1600 m below surface) and structural setting, much of Gidgealpa Group subcrop would be classed as partial aquifers as per Smith et al. (2015).
Data: Hall et al. (2015) Extent of Gidgealpa and Nappamerri groups; Geoscience Australia (2018a) Extent of Cuddapan Formation; Geological and Bioregional Assessment Program (2019e) prospectivity area
Element: GBA-COO-2-168

3.4.3 Hydraulic connectivity within the Eromanga Basin

The hydraulic characteristics of aquifers (in particular the artesian GAB aquifers) in the Eromanga basin vary with the depth and diagenetic history (Green et al., 1989). As outlined in Section 3.2.2, Green et al. (1989) and Dillinger et al. (2016) concluded that porosity and permeability was significantly diminished by burial compaction and pore occlusion, which occur in central parts of the Eromanga Basin. Radke et al. (2000) concluded that, groundwater flow in the Cadna-owie–Hooray aquifer approached near-stagnant conditions. In contrast, lateral throughflow at shallower depths in the aquifer is thought to occur around the periphery of the Cooper GBA region (Section 3.2.2). In summary, the degree of diagenesis and varying depth of burial of artesian GAB aquifers can influence lateral and vertical groundwater flow.

Other formations that are likely to impede vertical flow include the Birkhead and Westbourne formations. Although the Birkhead Formation overall has partial aquifer characteristics (Figure 13), it includes intra-formational shale aquitards and capillary-type diagenetic seals (Boult, 1993), which will affect vertical connectivity. The Westbourne Formation is a leaky aquitard that has comparable but broader extent than the Birkhead Formation. In contrast some groundwater bores have very long screens or multiple casing perforations at different levels, which may allow for some mixing of groundwaters from different aquifers (see Section 2.2.1and Section 3.2.3).

Mapping of fault extents at different intervals within the Cooper and Eromanga basins indicate that some faults that disrupt the Permian sequence are traceable up to the top of the Cadna-owie–Hooray aquifer. Shallower faulting in the Rolling Downs Group Aquitard and Winton–Mackunda partial aquifer appears to be uncoupled with the deeper faults (See Section 3.2.2.3). This is a characteristic of polygonal fault systems that occur in many places throughout the Rolling Downs aquitard (Ransley et al., 2015a; Kulikowski et al., 2018).

From geomechanical modelling, polygonal faults with certain orientations have potential to leak. Specifically, under present-day stress regimes, east-west and northwest to southeast-striking faults of greater than 60° dip are considered to be the most likely to facilitate fluid migration (Kulikowski and Amrouch, 2018a). However, the uncoupled nature of both deeper fault sets and polygonal fault systems is one impediment for direct connectivity pathways to the near-surface unconfined aquifers.

3.5 Surface water – groundwater interactions

3.5.1 Rivers and lakes

Surface water – groundwater conceptualisations around drainage are in part dependent on understanding the surface water (Holland et al., 2020) as well as shallow groundwater systems. Duration and extent of ephemeral surface flows, water quality, high evaporation rates, potential of baseflow after flood events, transmission losses in Cooper Creek catchment, as well as local geomorphology and geology, all contribute to availability of surface water for recharge to shallow groundwater systems and to the functionality of riparian ecosystems.

To date, studies into surface water-groundwater interactions in the Cooper GBA region have focussed on shallow groundwater within about 20 m of surface, with a focus on waterholes and lakes (e.g. Cendón et al., 2010; Costelloe et al., 2009). Cendón et al. (2010) found that episodic flooding of losing streams in the parts of the Cooper Creek floodplain around Goonbabinna Waterhole (see Figure 41 for location) contributes recharge to shallow aquifers. This can result in the development of freshwater lenses in the vicinity of some large near permanent waterholes (Cendón et al., 2010). These freshwater lenses either lay on top of a more saline regional watertable or alternatively are perched above the watertable. In the Cooper Creek flood plain, clay layers lining base of waterholes may limit leakage during periods of no flow. Deep-rooted vegetation may utilise shallow groundwater as a water source during dry periods (Cendón et al., 2010; Evans et al., 2018).

It is important to note that the waterholes studied by Cendón et al. (2010) may only represent one type of waterholes in the Cooper Basin. Many of the permanent waterholes identified within the Cooper Creek catchment (Figure 41) are located near the edge of the alluvial aquifer systems or within catchment constrictions (discussed further in Section 6.1.6). In these marginal positions, perched aquifer systems are unlikely to exist, as confining layers separating shallow and deep systems are typically absent or discontinuous. As a result, there is a higher potential for interaction between the sub-alluvial bedrock, alluvia and surface water features in these areas, as observed in catchments elsewhere (e.g. Raiber et al., 2019) and as discussed further in Section 6.1.6. Furthermore, there is evidence to suggest that a number of conceptual models of how connected are waterholes to groundwater need to be considered for the Cooper Creek floodplain (see Section 5.5).

Studies on the potential for recharge and connectivity with deeper Cenozoic aquifers (i.e. aquifers at greater than 20 m depth) have not been undertaken in the Cooper GBA region and are the subject of knowledge gaps outlined in Section 2.3 and in Section 3.2.3.

Shallow watertable mapping coupled with vegetation mapping and remote sensing (e.g. Enhanced Vegetation Index) has been used to show the potential for surface water–groundwater interactions along many reaches of streams (Ransley and Smerdon, 2012; Ransley et al., 2015a) (Figure 41). Where riparian vegetation remains healthy and vigorous despite drought conditions over several years, as found in the headwaters of the Cooper Creek catchment, it was assumed by Ransley et al., 2015c that deep-rooted vegetation have access to shallow groundwater – this is also associated with a change in the dominant vegetation type (Figure 41).

Ecohydrological studies undertaken subsequent to (Ransley and Smerdon, 2012; Ransley et al., 2015a) in the Western Rivers region (to the west of the Cooper GBA region in the Lake Eyre surface water catchment), found that the relationship between shallow groundwater and vegetation vigour in arid areas was much more complex than the assumptions used in the earlier studies. Using multiple lines of evidence, including hydrochemistry, environmental tracers, tree and soil water potential, and remote sensing, Keppel et al. (2017) found that no riparian ecosystem in this region was entirely dependent on shallow groundwater. Keppel et al. (2017) concluded that riparian vegetation tended to obtain water from a number of stores (e.g. soil water, surface flows, shallow groundwater) and that the mix varies depending on water availability from different sources at the time as well as for different types of vegetation (e.g. water sources for Eucalyptus species versus Acacia species can be different). Shallow perched aquifers, riverbank storage, as well as the regional watertable were considered as sources in this study. The results have implications for how potential water related impacts from developments may (or may not) propagate in an ecological system.

Salt lakes can be the focus of groundwater discharge for near-surface aquifers. Large salt lakes (e.g. Lake Blanche) may also relate to regional diffuse discharge processes from deeper GAB aquifers or have springs discharge in their vicinity. At Coongie Lakes (see Figure 41 for location), Costelloe et al. (2009) noted during dry periods, evaporative groundwater discharge from shallow groundwater can lead to development of salinised soil profiles, particularly under ephemeral lakes. However, during periods of inundation, leakage from lakes may recharge the shallow aquifers and in the process flush some of salts out of the soil profile into the aquifer.

Aside from near surface processes, such as those mentioned for Coongie Lakes, shallow aquifers around Lake Blanche could receive additional groundwater through spring discharge. In addition, on a regional scale, Lake Blanche is situated down hydraulic gradient from the Cooper GBA region, and could potentially be the focus of regional discharge from aquifers in the Lake Eyre Basin and Winton–Mackunda partial aquifers.

The Atlas of Groundwater Dependent Ecosystems (GDE Atlas, Bureau of Meteorology, 2017) identifies areas within the region where aquatic and terrestrial ecosystems may be dependent on groundwater (Figure 42). More detailed wetland data such as Queensland wetland information are available through state agencies. However, in this instance, the GDE Atlas was preferred for this regional scale study as the Cooper GBA region crosses state boundaries. More local scale studies should utilise the higher fidelity data available from state wetland databases.

A comparison of areas considered to have “high riparian vigour” upstream of Windorah along the Thomson and Barcoo rivers (Figure 41), do not appear to be evident as GDE’s on Figure 42. This is an example of how methods behind the data shown on the two figures have highlighted different areas. For key areas, verification using multiple lines of evidence to determine the degree of connection the reliance of GDE or wetland on groundwater may be required to test the GDE classification in remotely sensed datasets.

Anthropogenic discharge is also a key component of the water balance of the GAB, and is primarily sourced from free flowing artesian bores or pumping groundwater bores (Love et al., 2013b; Ransley and Smerdon, 2012). Free-flowing bores discharge into natural drainage or constructed bore drains. Some of these flowing bores are up to 100 years old, and have created long term artificial wetland ecosystems (Phipps, 2008). Some groundwater produced as part of petroleum production is discharged to holding ponds, then eventually released down natural drainage lines. These artificially perennial water flows provide watering points for the pastoral industry as well as support wetlands and riparian vegetation for many kilometres downstream from the discharge point.

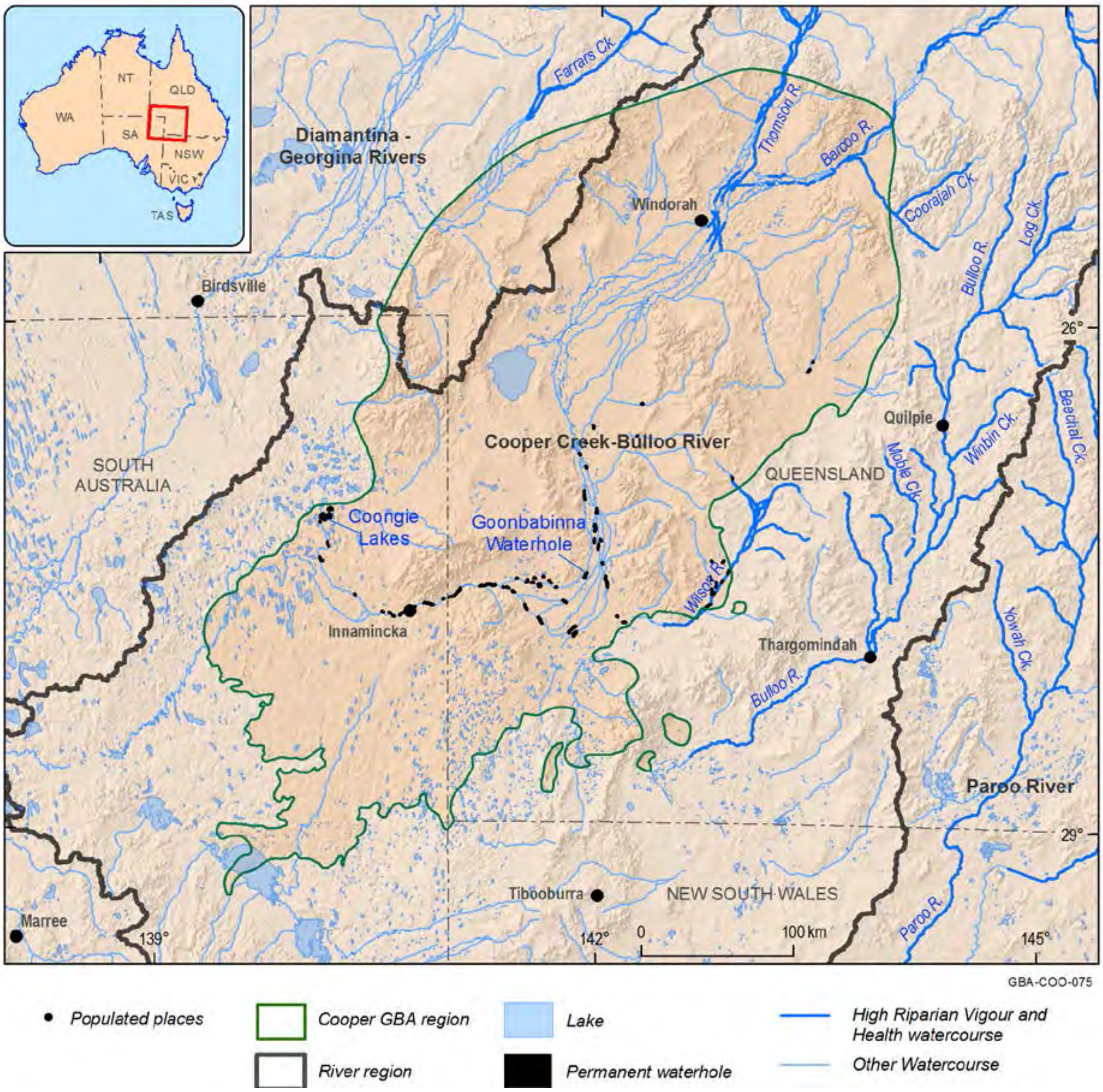


Figure 41 Watercourses coloured based on the Enhanced Vegetation Index (EVI) mapping and permanent waterholes in Cooper Creek

Areas of relatively high EVI outline river reaches where there is higher potential for connectivity between surface water and groundwater (Ransley and Smerdon, 2012).

Data: Geoscience Australia (2018d); Queensland Department of Environment and Resource Management (2009)

Element: GBA-COO-075

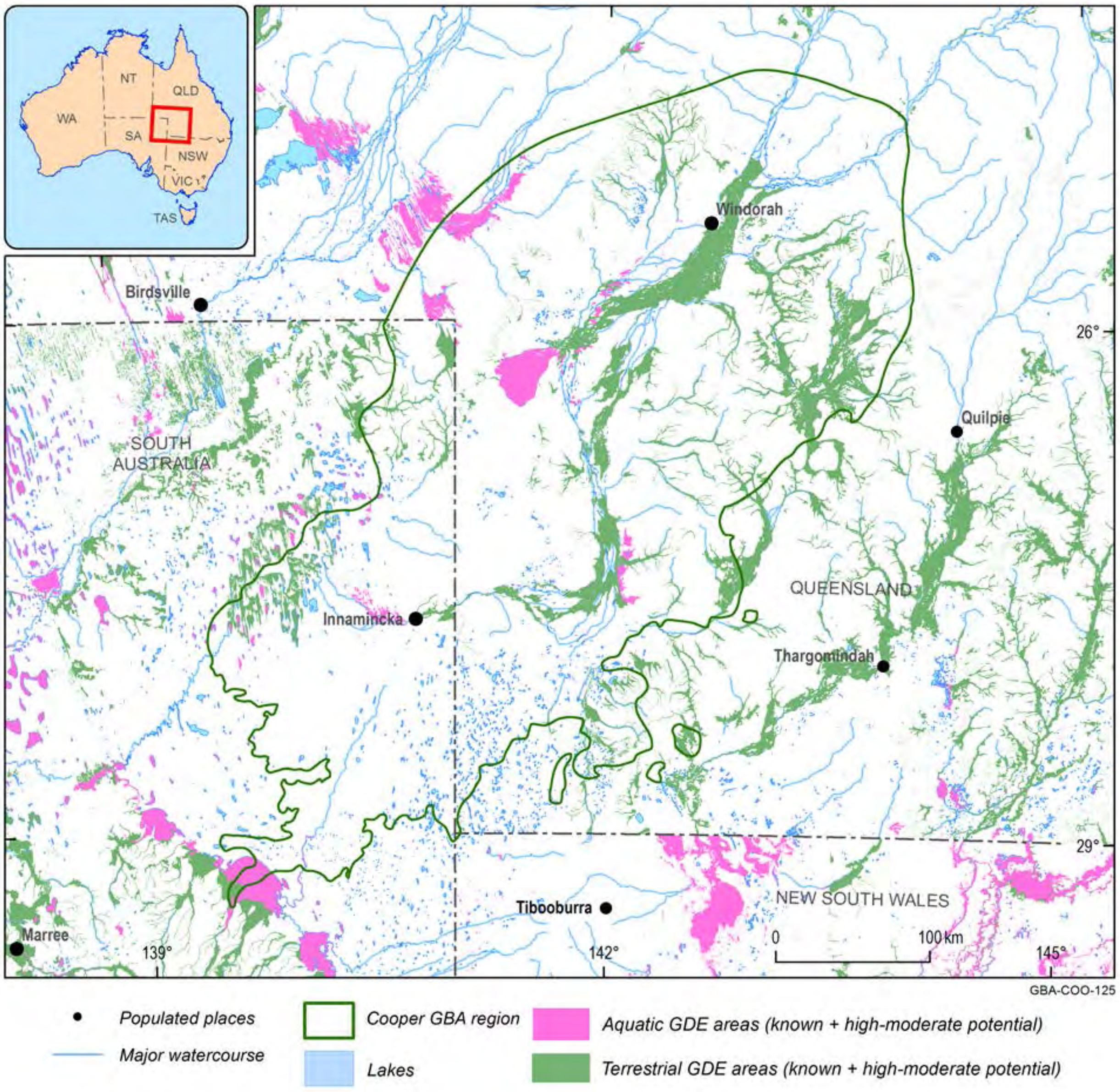


Figure 42 Groundwater-dependent ecosystems in and around the Cooper GBA region

Areas shown are from the GDE Atlas (Bureau of Meteorology, 2017) for either known GDEs or areas of potential GDEs with high to moderate confidence.
Data: Bureau of Meteorology (2017)
Element: GBA-COO-125

3.5.2 Springs

Ecosystems dependent on artesian GAB springs are listed as endangered (Department of the Environment and Energy (Cwlth), 2018) under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act; Australian Government, 1999), so are considered a matter of national environmental significance (see also O'Grady et al., 2020).

The lack of springs that source groundwater from artesian GAB aquifers in the Cooper GBA region (Figure 43) suggests that the Rolling Downs aquitard for the most part impedes connectivity between artesian GAB aquifers and Winton-Mackunda partial aquifer (see Section 3.2.2.3). The closest GAB springs are situated some 20 km the west of the region near the margin of Lake

Blanche in SA (Lake Blanche and Reedy Springs). Key references for GAB springs in South Australia include: Love et al. (2013b); Keppel et al. (2013b); Keppel et al. (2016); and Gotch et al. (2016). The Lake Blanche and Reedy springs are fed through fault conduits (Keppel et al. (2016). The primary source aquifer for Reedy Springs is likely to be the Cadna-owie–Hooray aquifer whereas for the Lake Blanche springs, the source aquifers are the Coorikiana Sandstone and aquifers in the Lake Eyre Basin. From potentiometry, Keppel et al. (2016) inferred that regional groundwater flow in Coorikiana Sandstone was from west to east (so towards the Cooper GBA region). However, in the vicinity of these spring complexes, groundwater flow directions in Cadna-owie–Hooray aquifer appears to be more variable (see figure 2.6.2 in (Keppel et al., 2016) and much poorly constrained due to a lack of information to the east of the springs towards the boundary of the Cooper GBA region.

Tight gas, shale gas and deep coal plays are unlikely to occur near the south-western margin of the Cooper Basin (Lech et al., 2020) in the vicinity of the GAB springs (See Figure 43). However, the potential for future cumulative impacts from multiple play types in the Cooper and Eromanga basins (conventional oil and gas, tight, shale and deep coal gas) should be given consideration particularly once there is clarity in the future around the development pathway for tight, shale and deep coal gas as well as CSG in the Cooper GBA region.

Springs around the eastern and north-eastern margin of the Cooper GBA region (Figure 43) are thought to source groundwater from Lake Eyre Basin (Cenozoic) aquifers (Silcock et al., 2016). However, unlike the artesian GAB springs found to the west of Cooper GBA region, these springs have not been the subject of much study and only very limited information is available (e.g.no comprehensive hydrochemical or isotopic assessment has been conducted on these springs to date).

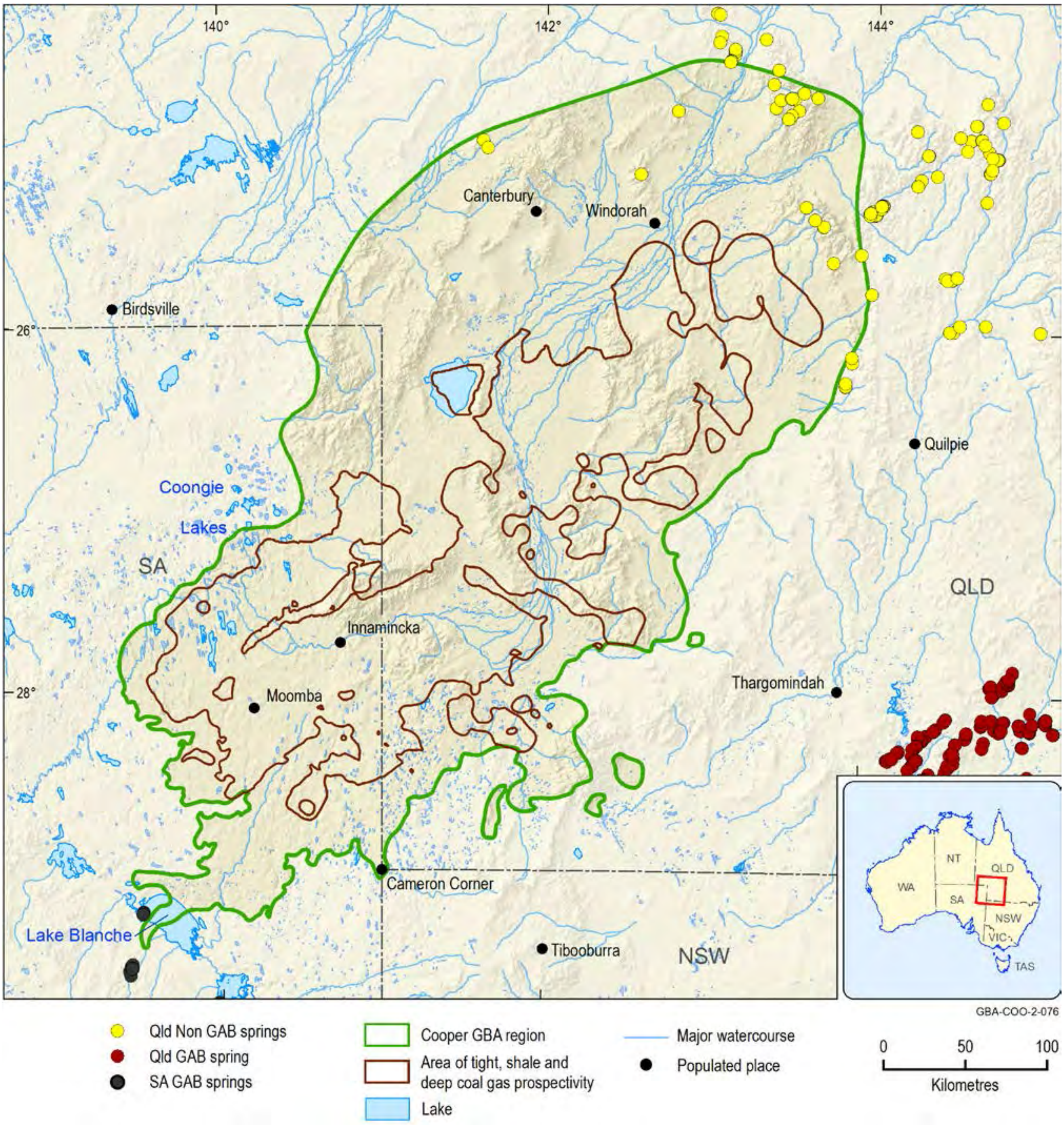


Figure 43 Springs in the Cooper GBA region

None of known springs are located directly within the area defined as prospective for tight, shale, deep coal gas plays.
Data: Queensland Department of Environment and Science (2018); Department of Environment, Water and Natural Resources (SA) (2012); Geological and Bioregional Assessment Program (2019e)
Element: GBA-COO-2-076

3.5.3 Remote sensing water in the landscape

As outlined in Section 2.1, remote sensing data from Digital Earth Australia (DEA) can provide nationally consistent information on spatial and temporal changes in the landscape including changes to water in the landscape and vegetation vigour. As an example for the Cooper GBA region, Water Observations from Space (WOfS) and Tasselled Cap Wetness index (TCW) are utilised to provide a regional overview of water in the landscape.

Water Observations from Space (WOfS) highlights areas of surface water as a percentage of time throughout the 30-year Landsat archive. The WOfS water summary shows for each 25 m pixel, the percentage of clear observations that were detected as wet. The filtered WOfS summary (Figure 45) provides the long-term understanding of the recurrence of water in the landscape, with much of the noise due to misclassification filtered out. WOfS provides insight into the behaviour and distribution of surface water across time. Applications include the degree of perenniality of watercourses, the nature of floods and floodplain extents, the size and nature of wetlands, input into hydrological models, land surface processes and groundwater recharge (Mueller et al., 2016).

The tasselled cap wetness in the landscape summary output is produced using DEA. Landsat surface reflectance data at 25 m resolution with information in the red, green, blue, near infra-red and short-wave infra-red spectral bands are retrieved from the DEA archive using a spatial query for the area of interest. Clouds and areas of terrain shadow are masked from the surface reflectance data. A tasselled cap transformation on each of the surface reflectance bands to produce a per-pixel 'wetness' value. This method is based on the tasselled cap transformation of Crist (1985), but only uses the component of transformed surface reflectance in the 'wetness' direction to identify the presence of water and wet vegetation.

Areas of water and wet vegetation are highlighted on an image where pixels exceed a specified wetness threshold. The time a pixel exceeds the wetness threshold is also counted through image archive, and can represent up to 30 years of observations of how often a pixel was "wet". The wetness in the landscape summary is presented as the percentage of scenes where the pixel has contained water or wet vegetation through time.

The WOfS filtered Water Summary for the Cooper GBA region (Figure 44), highlights the wide floodplains surrounding major watercourses such as the Cooper Creek and Diamantina River in this arid landscape (see Section 3.5.1). The Cooper Creek floodplain contains numerous anastomosing channels, as evident through various diverging and converging paths. For most of its length, the floodplain is in excess of 10 km width, and in places exceeds 60 km. In general, water is confined to certain parts of floodplains, in particular where wetland areas are outlined Figure 42. At a regional scale though it is difficult to discern finer scale features such as permanent in-channel waterholes.

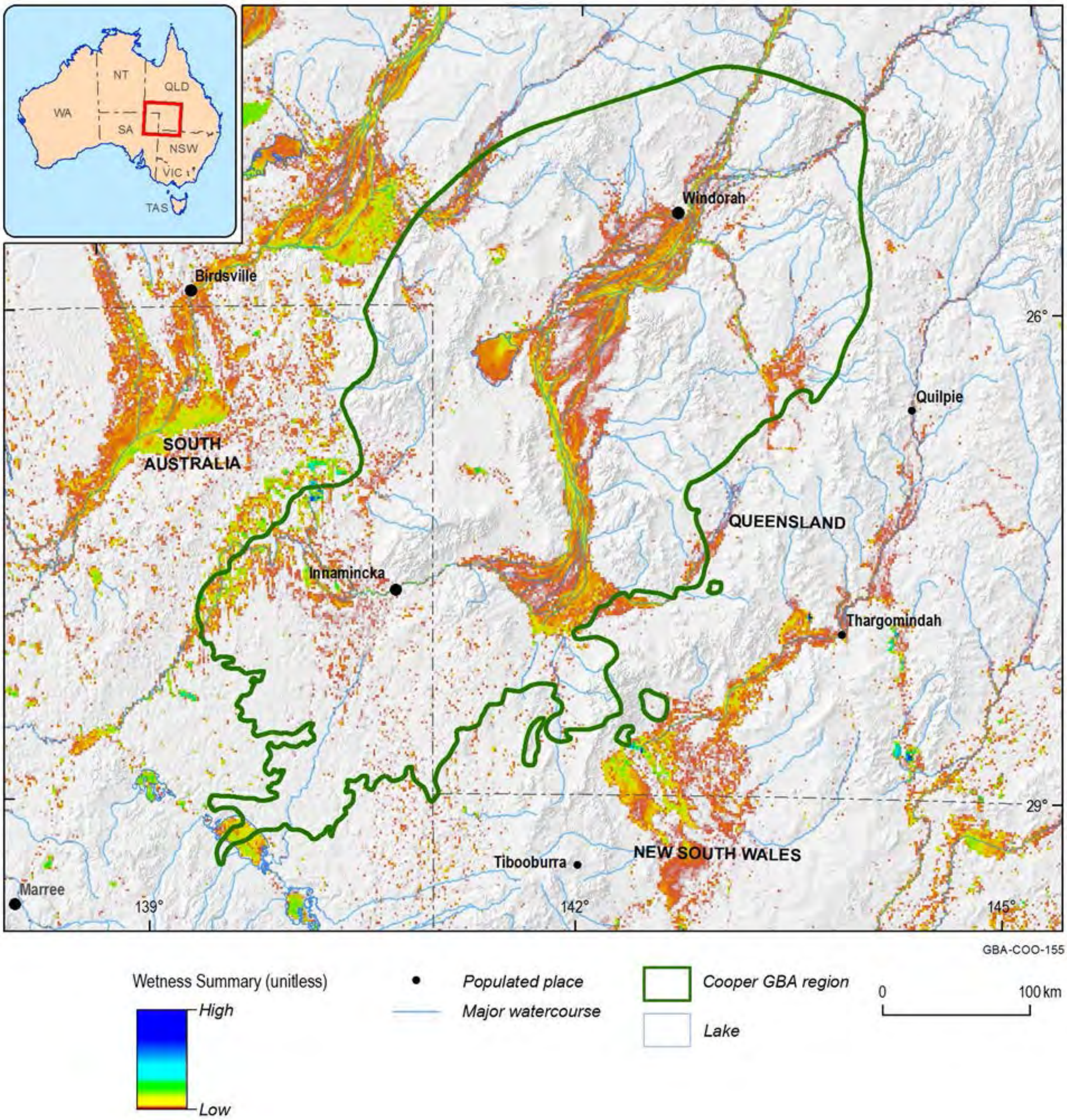


Figure 44 WOfS Water Summary across the Cooper GBA region

Data: Geoscience Australia (2018b)
Element: GBA-COO-155

A selection of maps over a part of the Cooper Creek floodplain near Queensland-South Australian border (Figure 45 and Figure 46) provide examples and highlight some of more detailed aspects. A couple of the waterholes included in these images (Goonbabinna waterhole) were focus of groundwater-surface water investigations undertaken by Cendón et al. (2010).

The WOfS filtered summary shows the location of some small permanent (purple) and semi-permanent (blue) waterbodies located on the Cooper Creek floodplain (Figure 45). These near-permanent waterbodies have been observed to be wet over most of the last 30 years, thus are likely to be areas of groundwater dependency. They are also critical refugia for aquatic species during dry times.

The tasselled cap wetness index (Figure 45) highlights areas likely to contain swampy ground and/or wet vegetation, in addition to the open water that is the focus of WOfS. Figure 45 highlights the more permanent waterholes in the Cooper Creek floodplain, which are important refugia. In contrast, the Sturt Desert Plains and dunes in the Cooper Creek floodplain are essentially dry.

Investigations using spatial and temporal remote sensing data archive would assist in understanding distribution of water in landscape, groundwater-surface water interactions, floodplain and riparian vegetation dynamics and land usage. Such information would be beneficial for the future management of Cooper Creek floodplain.

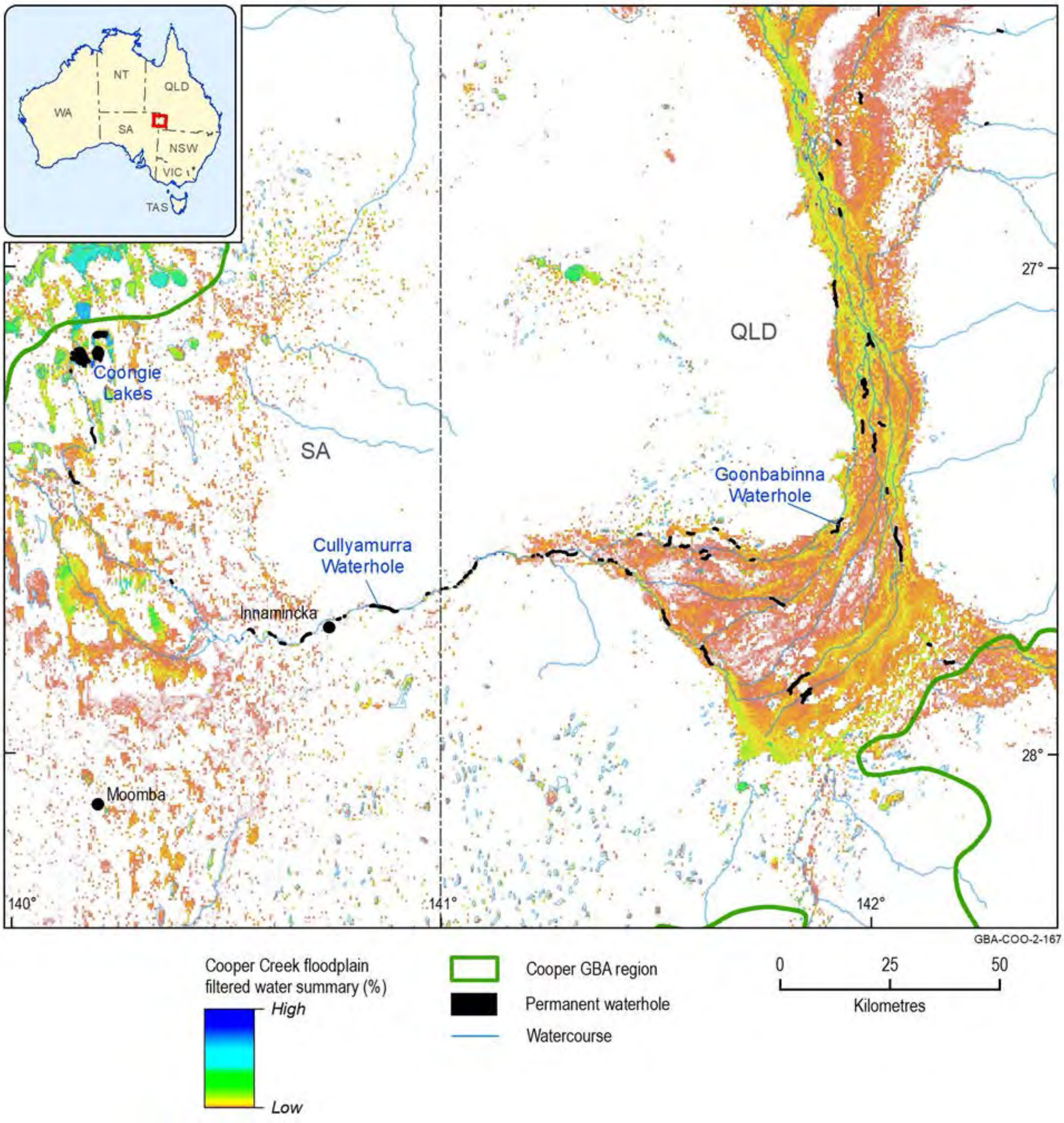


Figure 45 WOfS Filtered Summary for part of the Cooper Creek floodplain and mapped permanent waterholes

Data: Geoscience Australia (2018b); Queensland Department of Environment and Resource Management (2009)
Element: GBA-COO-2-167

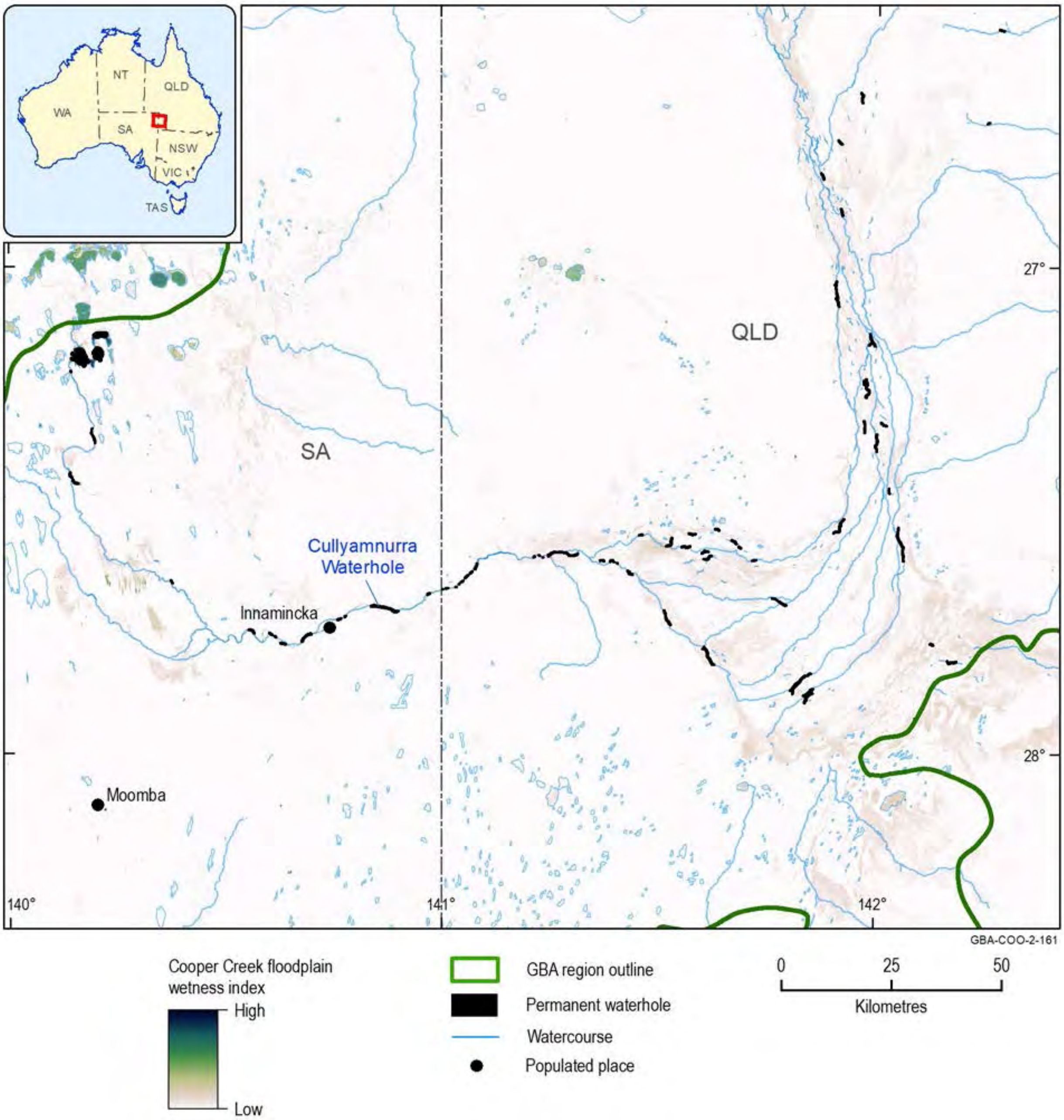


Figure 46 Tasselled cap wetness index for part of the Cooper Creek floodplain and mapped permanent waterholes

Permanent waterholes are highlighted in black.
Data: Geoscience Australia (2018b); Queensland Department of Environment and Resource Management (2009)
Element: GBA-COO-2-161

4 Potential hydrological connections

This section provides an overview on the regional datasets currently available for the Cooper Basin (e.g. hydrochemistry and dissolved methane concentrations) that are relevant for the assessment of hydrogeological connections between stressors (development areas) and environmental assets throughout the various phases of a gas development (including post-decommissioning). The assessment of groundwater and spring hydrochemistry highlighted that deeper GAB aquifers (e.g. Hooray Sandstone) are hydrochemically distinct from shallower GAB aquifers (e.g. Winton-Mackunda Formation). Springs within the Cooper Basin GBA region show a variable picture, where some springs show similarities to the shallower GAB or Cenozoic aquifers, whereas others are more similar to deeper artesian GAB aquifers, indicating that different springs are likely to have shallow and deeper source aquifers.

Dissolved methane concentrations ranging from 150 to 216,500 µg/L (median 32,050 µg/L) were measured within the GAB aquifers in the Cooper Basin GBA region. However, interestingly, the highest measured concentration was encountered in a relatively shallow bore (bore depth of 456 m) screened across the Winton–Mackunda Formation close to the north-eastern margin of the Cooper Basin. Although dissolved methane can also be produced in situ within shallow aquifers, these very high concentrations suggest that gas migration has likely occurred in some areas.

4.1.1 Introduction

Through construction of conceptual models of the hydrogeological systems encompassing all stratigraphic layers that will be penetrated by gas wells, an investigation of the potential connectivity pathways between adjacent basins, between deep and shallow aquifers, springs, GDE's and streams was conducted. The conceptualisation builds upon existing knowledge of the hydrostratigraphic and geo-structural framework as presented in other sections of this report and in Owens et al. (2020), as well as similar pathway identification work undertaken for coal seam gas basins in Australia (Mallants et al., 2018).

The conceptual models summarise the plausible potential scenarios where these pathways may occur due to a combination of variables, including aquitard thickness, proximity of assets to faults, vertical continuity of the faults and geological heterogeneities near the basin edges. The conceptual models also highlight the data gaps and hypotheses to be tested in future studies to assess the likelihood of identified stressors-assets pathways.

Multiple cross-sections (locations are shown on Figure 47) representing the lateral extent of the regional stratigraphy, position of geological structures in relation to existing datasets and environmental assets were produced to encompass multiple plausible pathways in the Cooper and Eromanga Basin and their connectivity to shallow aquifers and to groundwater dependent ecosystems.

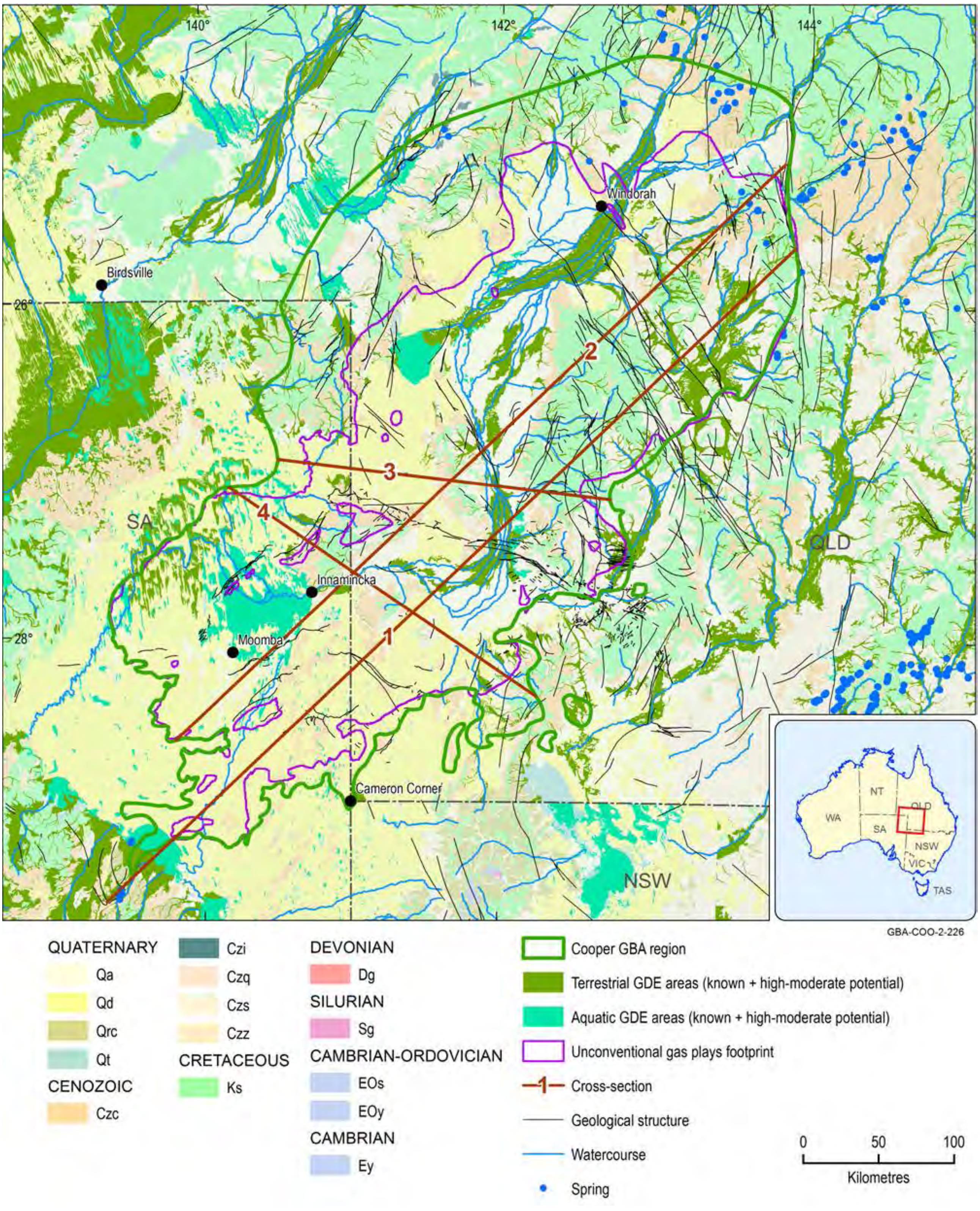


Figure 47 Map of Cooper Basin with geological structures and position of cross-sections discussed in Section 4.1.2

The cross-section lines shown here are illustrated in Figure 48 (cross-section #1), Figure 53 (#2), Figure 54 (#3) and Figure 55 (#4) in Section 4.1.2.

Data: Department for Environment and Water (SA) (2015); Department of Environment and Science (Qld) (2018); Geoscience Australia (2013, 2012); Bureau of Meteorology (2017); Geological and Bioregional Assessment Program (2018b, 2019e, 2018i); Petrosys Pty Ltd (2018)

Element: GBA-COO-2-226

4.1.2 Hydrostratigraphic framework: background

A detailed description of the regional geology supported by a tectonostratigraphic evolution of the Cooper GBA region is presented in Section 3 of Owens et al. (2020). This report revisits and describes the regional and local-scale structural elements identified within the basin domain from the perspective of plausible regional connectivity pathways, beginning in the tight, shale and deep coal gas plays and ending in near surface environmental assets.

Three major hydrostratigraphic sequences occur in the Cooper GBA region, from the oldest to the youngest: the Cooper Basin, the Eromanga Basin and Lake Eyre Basin (Cenozoic) sediments.

The Cooper Basin sequence consists of the Gidgealpa Group (Figure 6), hosting the tight, shale and deep coal gas resources, and the overlying Nappamerri Group, which is considered a regional seal to the Gidgealpa Group. As discussed in Section 3.1.1, increasing gas saturation with depth influences the hydrogeological status of units that comprise the Gidgealpa Group.

The Eromanga Basin sedimentary sequence reaches more than 2000 m in thickness and entirely covers the Cooper Basin sequence. Eromanga hydrostratigraphy is composed of the Winton–Mackunda partial aquifer, under sub-artesian pressures, the confining Rolling Downs Group aquitard (Section 5.2), and several confined and artesian aquifers including but not limited to those within the Cadna-owie–Hooray aquifer system. The major aquifers are in the Hutton, Adori and Cadna-owie–Hooray.

Lake Eyre Basin sediments can be up to 300 m thick in the Callabonna Sub-basin and greater than 100 m under the Cooper Creek floodplain. Due to the sparse and limited data available on lithology and stratigraphy, multiple aquifers comprising the Lake Eyre Basin have not been differentiated. Although a very thick sequence of alluvial sediments is deposited in the wide floodplains (in some areas more than 50-70 km wide) of the Cooper Creek, there are notable catchment constrictions where the width of the alluvial aquifers is considerably smaller (~10-15 km), and where the alluvial sediments are substantially thinner (~20-30 m), as noted in the vicinity of Innamincka Ridge. As described in WetlandInfo (Queensland Government, 2018e), due to the narrowing of the alluvial aquifers, these areas can act as a bottle-neck where the watertable is at a shallow depth. Furthermore, as observed in constrictions in other catchments (e.g. Condamine River catchment constriction near Chinchilla in Queensland), there is often a close connection between sub-alluvial sedimentary bedrock, alluvia and streams in these settings.

The lateral extent of GAB aquifers goes beyond the Cooper Basin footprint (e.g. Figure 48). Lateral migration of fluids or gas through these units may therefore have the capacity to reach assets in communication with this system via geological structures in areas outside of the Cooper Basin.

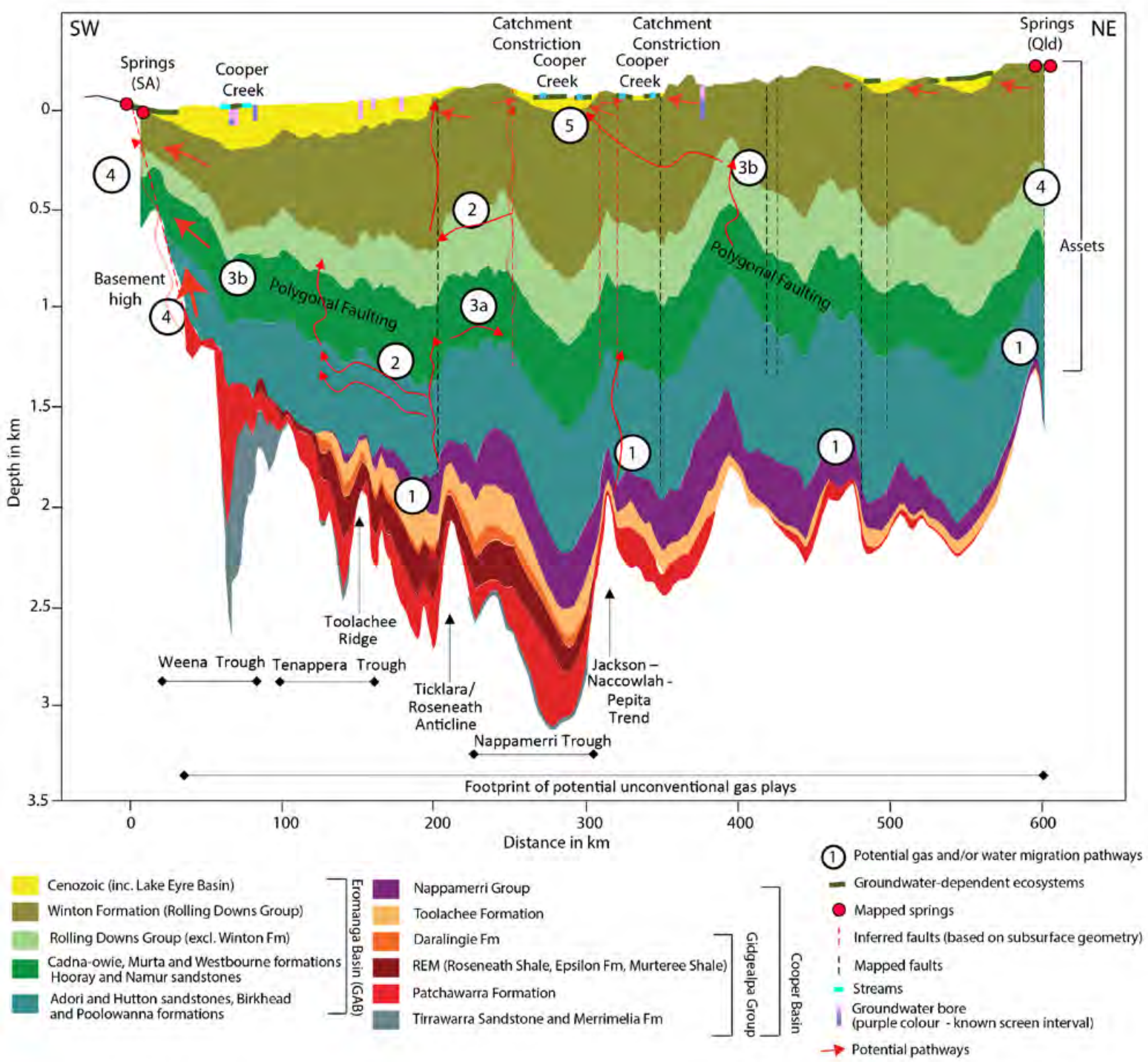


Figure 48 Cross-section 1 with north-east–south-west orientation through Cooper and Eromanga basins, representing north-eastern and south-western basin margins and major geological structures within the Cooper and Eromanga basins and five potential hydrological connections for water or gas migration

The five potential hydrological connections are: 1. vertical migration via dilation faults; 2. migration through porous aquifers; 3. migration through the Rolling Downs Group aquitard via PFS (a – lateral; b – vertical); 4. migration due to contact between gas plays and overlying aquifers near the basin margin; and 5. vertical migration at catchment constrictions where steep hydraulic gradients exist between alluvial aquifers and underlying GAB formations. GAB = Great Artesian Basin.
Data: Geoscience Australia (2008a, 2013, 2018e); Department of Environment and Science (Qld) (2018); Bureau of Meteorology (2017); Department of Environment, Water and Natural Resources (SA) (2012), 3d geological model from Hall and Palu (2016)
Element: GBA-COO-2-097

4.1.3 Methods

This section describes the approach used to investigate existing datasets, including formation pressure, groundwater hydrochemistry and gas concentration measurements in relation to their spatial proximity to the mapped geological faults. In addition, a discussion of the rationale behind the development of multiple conceptual models using a series of 2D cross-sections to represent plausible pathway scenarios expected to be found in the Cooper GBA region is included.

4.1.3.1 Data compilation and quality checks

A series of datasets were extracted from a larger database compiled and revised under the groundwater systems characterisation element. The dataset sources, aquifer attribution process and quality assurance checks described in Section 2.2 were adopted for the data utilised in the current element.

Geological framework

Two datasets representing faults extending through different intervals of the Cooper and Eromanga basins stratigraphic column were used for the combined interpretation with aquifer pressure and physical-chemical properties as potential indicators of preferential flow paths. Mapped faults are sourced from:

- Geoscience Australia (2013): GIS dataset produced for the Great Artesian Basin Water Resource Assessment (GABWRA) at scale 1:6 000 000, previously presented in Figure 2.3 of Ransley and Smerdon (2012) and Figure 3.1 of Smerdon et al. (2012a). Both faults and structural features possibly associated with the Cretaceous Tookoonooka astrobleme are also represented;
- Petrosys Pty Ltd (2018): dataset created from the geological model developed in Petrosys™ by exporting the GIS files representing faults at Cadna-owie level within the NGMA Cooper Eromanga Basins Project, covering following stratigraphic surfaces and intervals:
  - top of Cadna-owie Formation;
  - top of Permian sequence, coinciding with top of Toolachee Formation;
  - Top of Warburton Basin, which coincides with the base of Cooper Basin;
  - Cadna-owie – Permian isopachs; and
  - Permian-Warburton isopachs.

For both datasets, faults are represented as lines on the horizontal plane of the spatial coordinate system, with no associated dip values or vertical changes in orientation at depth along the polyline.

As further discussed in Section 5.3, high angle fault dips (50-90^{o}) were mapped in parts of the Cooper Basin (Kulikowski and Amrouch, 2018a; Mavromatidis, 2008). For the interpretation of physical-chemical datasets aiming to identify possible anomalies that may infer connectivity pathways, all faults were assumed to be vertical.

For better constraining this information gap, the vertical and lateral extent of the faults were compared to the changes in lateral continuity of the surfaces representing the major geological units obtained from 3D geological model with interpretation of the results discussed in Section 5.

Hydrochemistry

Hydrochemical data available from Queensland and South Australia state groundwater databases augmented by hydrochemical records from previous Geoscience Australia sampling were used to determine hydrological processes within the Cooper and Eromanga basins and the Cenozoic strata. Ideally, in order to use hydrochemistry as a tool to detect connectivity between deep and shallow aquifers, data should be collected from a dedicated monitoring network designed to observe such connections (e.g. including nested bores where different aquifers are monitored simultaneously). However, in the Cooper and overlying Eromanga basins, no such monitoring bore network is currently in place and the measurement points where data are available are very sparse and widely spaced, as shown for example on cross-section 1 (Figure 48). This means that connections between different formations or between groundwater and surface water systems may not be captured by the available data.

In order to identify patterns within the dataset, Hierarchical Cluster Analysis (HCA) was used. 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 accurately characterise groundwater chemistry and the processes that control it. The selection of the parameters to be included requires a balance between selecting a wide range of variables, as well as aiming for a large number of complete cases to ensure a good spatial coverage, as HCA considers only cases where a value exists for each variable (e.g. Raiber et al., 2012). In this study, ten variables were selected (Ca, Mg, Na, K, HCO_3, Cl, F, SO_4, pH and electrical conductivity) as they were measured across most sites.

4.1.3.2 Spatial data interpretation

A series of cross-sections was produced within the extent of the Cooper Basin (see Figure 47 for locations). Four representative cross sections are presented in this report, with two lines positioned parallel to the longest basin axis (northeast-southwest) and two orthogonally across (with northwest-southeast and east-west orientations). In addition, a high-resolution cross-section was constructed to highlight specific potential connectivity pathways. All sections were purposely positioned to intercept 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 highest points, respectively and associated faulting zones.

Hydraulic pressures and physical-chemical indicators

An assessment of the spatial patterns of three potential indicators of preferential pathways in the Cooper GBA region was conducted through several cross-sections (Figure 47). These indicators are aquifer pressure, electrical conductivity and temperature measured in groundwater from three GAB units (Cadna-owie-Hooray, Birkhead Formation and Hutton–Poolowanna) and the Nappamerri Group.

This dataset was also used to investigate possible correlations between data points and their distance to the nearest mapped faults, assuming that anomalies or inverse correlations could indicate the presence of potential connectivity pathways or hydraulic barriers associated with these geological structures.

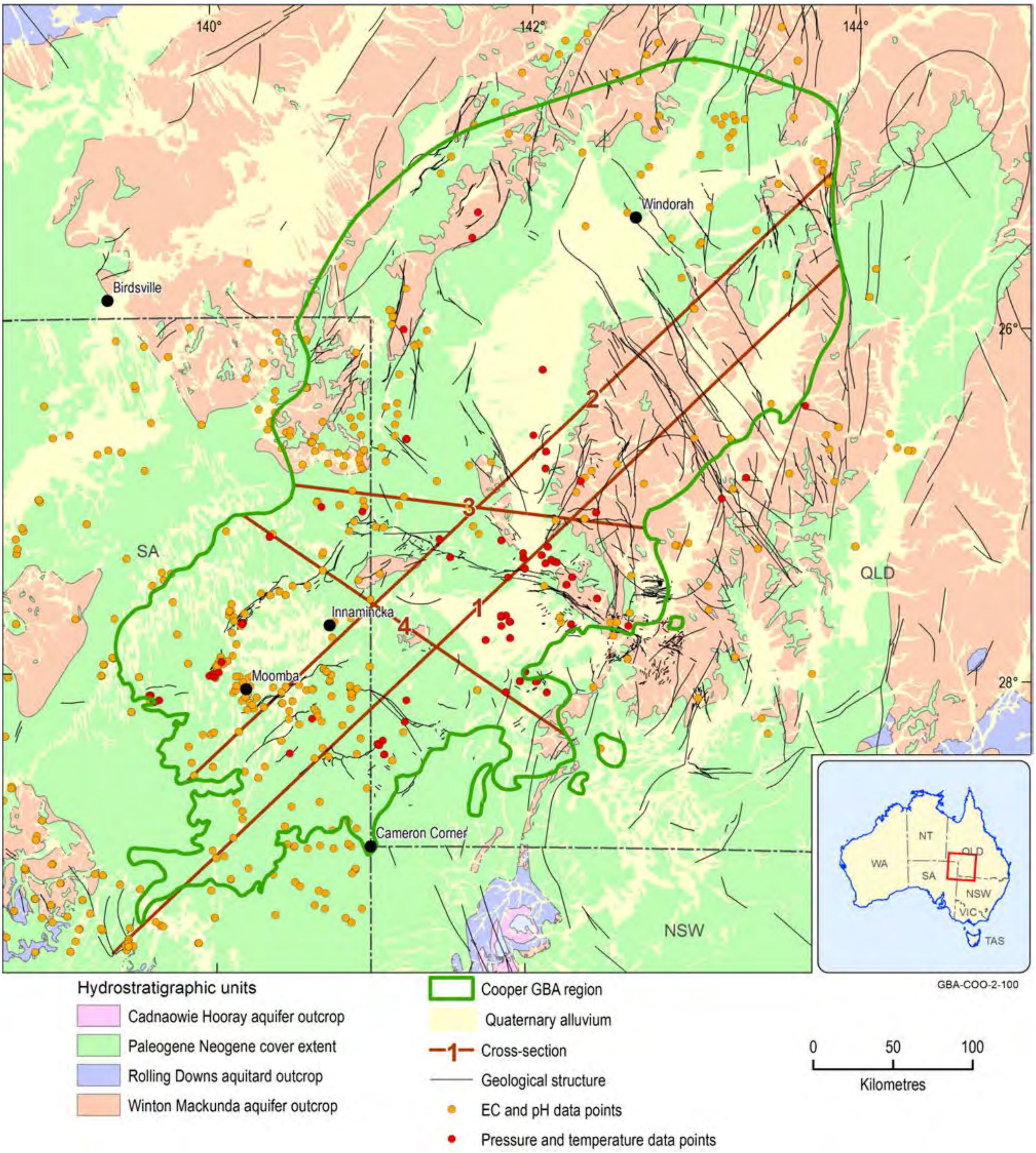


Figure 49 Location of pressure, temperature and salinity indicator (electrical conductivity) data and hydrostratigraphic units for the Cooper Basin

Data: Petrosys Pty Ltd (2018); Geoscience Australia (2015, 2013, 2012); Geological and Bioregional Assessment Program (2018b, 2019d)
Element: GBA-COO-2-100

4.1.4 Data interpretation and findings

The following section presents the findings from the integration of various datasets (Section 4.1.3.1) interpreted within the context of the geological framework with a particular focus on the proximity of the data points to mapped faults.

The assessment of hydraulic pressure (n=222) and physical-chemical parameters (n=1444) measured in groundwater at different hydrostratigraphic units versus the distance to the nearest geological fault did not reveal any distinct spatial relationships, anomalies or inverse correlations with fault distance. This is likely due to the sparse nature of the data points and their biased distribution along the structural highs (Figure 49).

4.1.4.1 Hydrochemical and gas measurements

Gas occurrences in groundwater

Gas occurrences within the Eromanga Basin from historic datasets compiled within the Geoscience Australia GAB Atlas (Ransley et al., 2015a) were assessed to understand potential gas migration pathways from deep target formations to assets. An increasing body of literature from studies on conventional and tight, shale and deep coal gas fields in Australia (e.g. Currell et al., 2017) and in North America demonstrate the value of using methane isotopes (δ^2H and δ^{13}C of methane) as tracers. They can be used to determine the origin of methane in aquifers overlying the gas plays, and 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., 2018), particularly when combined with other tracers such as noble gas isotopes and helium or other lines of evidence such as geophysics (Harkness et al., 2017; Mallants et al., 2018).

Together with noble gases (e.g. helium) and trace element concentrations, methane isotopes can help determine the origin of the gas and possible diffusive and advective pathways for gases from gas target units to overlying shallow sedimentary bedrock aquifers. This could be of particular interest to the GAB (e.g. Winton Formation) or alluvial aquifers of the Cooper Creek and associated tributaries. However, no analyses of methane isotopes (δ^2H and δ^{13}C of methane) exist (or are publicly available) within the Cooper GBA region extent.

Furthermore, in the Eromanga Basin within the extent of the Cooper GBA region, dissolved methane concentration measurements are available from only 10 groundwater bores. These measurements were mostly taken from bores screened in the Winton–Mackunda Formation, Hooray Sandstone and Adori Sandstone, with a median bore depth of approximately 1000 m. Although only few measurements are publicly available, the available data show presence of considerable methane concentrations, ranging from 150 to 216,500 µg/L (median 32,050 µg/L). However, interestingly, the highest measured concentration is encountered in a relatively shallow bore (bore depth of 456 m) screened across the Winton–Mackunda Formation close to the north-eastern margin of the Cooper Basin. This is relatively high compared to methane concentrations measured in other sedimentary basins such as the Surat Basin, where the maximum methane concentrations in non-target hydrostratigraphic units such as the Hutton Sandstone is 20,500 µg/L (Mallants et al., 2016).

The presence of such high concentrations in relatively shallow aquifers of the GAB suggests that there are likely to be gas migration pathways that connect the deeper formations with the shallower ones. Given the mobility of dissolved or gaseous methane in aquifers, the presence of methane can be an indicator for the presence of seal bypass systems, and it can be considered a possible precursor of other organic or even inorganic contaminants derived from deep gas reservoirs. Methane migration can occur through seal bypass systems such as faults. However, when there is no pathway between the hydrocarbon resource and a groundwater aquifer (i.e., when no seal bypass systems exist), methane detections in shallow aquifers are more likely due to a shallow source (e.g. near-surface coal seams), which are likely to be present in some shallow formations such as the Winton Formation (Lewis et al., 2014). Alternatively, they could be due to other in situ processes within shallower aquifers, which again would be unrelated to the target tight, shale and deep coal gas plays. In order to improve understanding around potential migration pathways from the Cooper Basin to shallow aquifers or the surface, additional methane concentration measurements are required. To determine if the high methane concentrations in groundwater of the Eromanga Basin (overlying the Cooper Basin) represent the natural background in the GAB aquifers, or are due to migration from underlying formations, it is critical to obtain adequate baseline data (concentrations and isotopes) from alluvial and Cenozoic aquifers, Winton–Mackunda partial aquifer, GAB aquifers and the underlying Cooper Basin. The preferred locations for such additional groundwater sampling would be where high methane concentrations have been detected.

Major and minor ion chemistry and environmental tracers

The results of the Hierarchical Cluster Analysis (HCA) are presented in Table 9, Figure 50 and Figure 51. In total, there were 492 records from bores or springs where all selected variables had a measured value available for the multivariate statistics. Temperature was not included as no field temperature measurement was available for many bores or springs.

The cross-tabulation in Figure 50 confirms that there is a clear relationship between row (hydrostratigraphic unit) and column (cluster). For example, hydrochemical records from the Cadna-owie-Hooray Sandstone are predominantly assigned to clusters 1 and 2. Both of these clusters are characterised by high HCO_3/Cl ratios, low Ca and Mg, high Na (Figure 50), and relatively high F and low SO_4 and are relatively fresh (528 and 2010 µS/cm, respectively). Most samples assigned to these clusters were collected from deep bores (median bore depth of 900 and 1303 m below ground surface for clusters 1 and 2). Only two samples were available from the Hutton Sandstone and the Patchawarra Formation, respectively. For both formations, the hydrochemical records were assigned to Cluster 1.

In contrast, the Winton–Mackunda formations contains only a small number of groundwater samples assigned to clusters 1 and 2, with most Winton–Mackunda formations' hydrochemical records assigned to clusters 3, 4 and 6. These clusters differ from clusters 1 and 2 in that the median bore depth is shallower (Table 1), and that they have a dominance of Cl over HCO_3, higher Ca and Mg, lower F and higher SO_4. Similar characteristics are apparent for samples collected from Cenozoic units, which are mostly assigned to clusters 1-4.

The map of the spatial distribution of the clusters highlights the sparseness of baseline hydrochemical data in many parts of the Cooper Basin. Nevertheless, based on the available data, several inferences can be made. For example, there appears to be a relatively clear distinction between deep and shallow groundwater hydrochemistry. However, as deep and shallow bores are in most instances not sampled from the same area, this does not necessarily provide any evidence that there is no connection.

Springs in South Australia have variable groundwater chemistry and are assigned to clusters 2 to 5. Springs assigned to clusters 3 to 5 could source water from the shallow GAB (Winton–Mackunda Formation). However, it is possible that those springs that are assigned to Cluster 2 (four in total), which as described above, includes predominantly groundwater samples collected from deeper aquifers, could source a contribution from one or several of these deeper aquifers. As shown by Keppel et al. (2016), these springs have low ^{14}C and low ^{36}Cl values, indicative of very old groundwater, and some of them are located near a fault zone. Together, this could suggest that there is a contribution from deeper aquifers, as also proposed by Keppel et al. (2016). The complementary isotopic analysis of noble gases such as helium could further help to test this hypothesis.

Groundwater from the relatively shallow bore (bore depth 456 m below ground surface) in the Winton–Mackunda partial aquifer where the highest methane concentration was observed within the study area is assigned to Cluster 1. As mentioned above, Cluster 1 primarily includes groundwater hydrochemistry records from deep bores, and only 7% of hydrochemistry records within the Winton–Mackunda formations are assigned to this cluster. The combined evidence from methane, hydrochemistry and its location at the edge of the Cooper Basin could also be an indicator for an upwards flux from a deeper hydrostratigraphic unit.

Table 9 Median values of the variables considered in the cluster analysis for each sample group

Cluster	Depth (m)	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	900	528	8.3	260	3.3	0.2	3.6	80.1	4.6	2.41	519
2	1303	2010	8.1	530.1	4.9	0.2	8	130	15.15	3.61	1150
3	112	6000	7.4	1076	115	39.7	11	1744	298	0.5	207
4	65.8	1700	7.7	258	41	25	6.8	344	110	0.5	223
5	47	4693	7.5	1045	11.5	1.2	16.15	615	8.45	1.6	1078
6	128	16065	7.18	3280	375	130	23.7	5432	1886	0.6	118

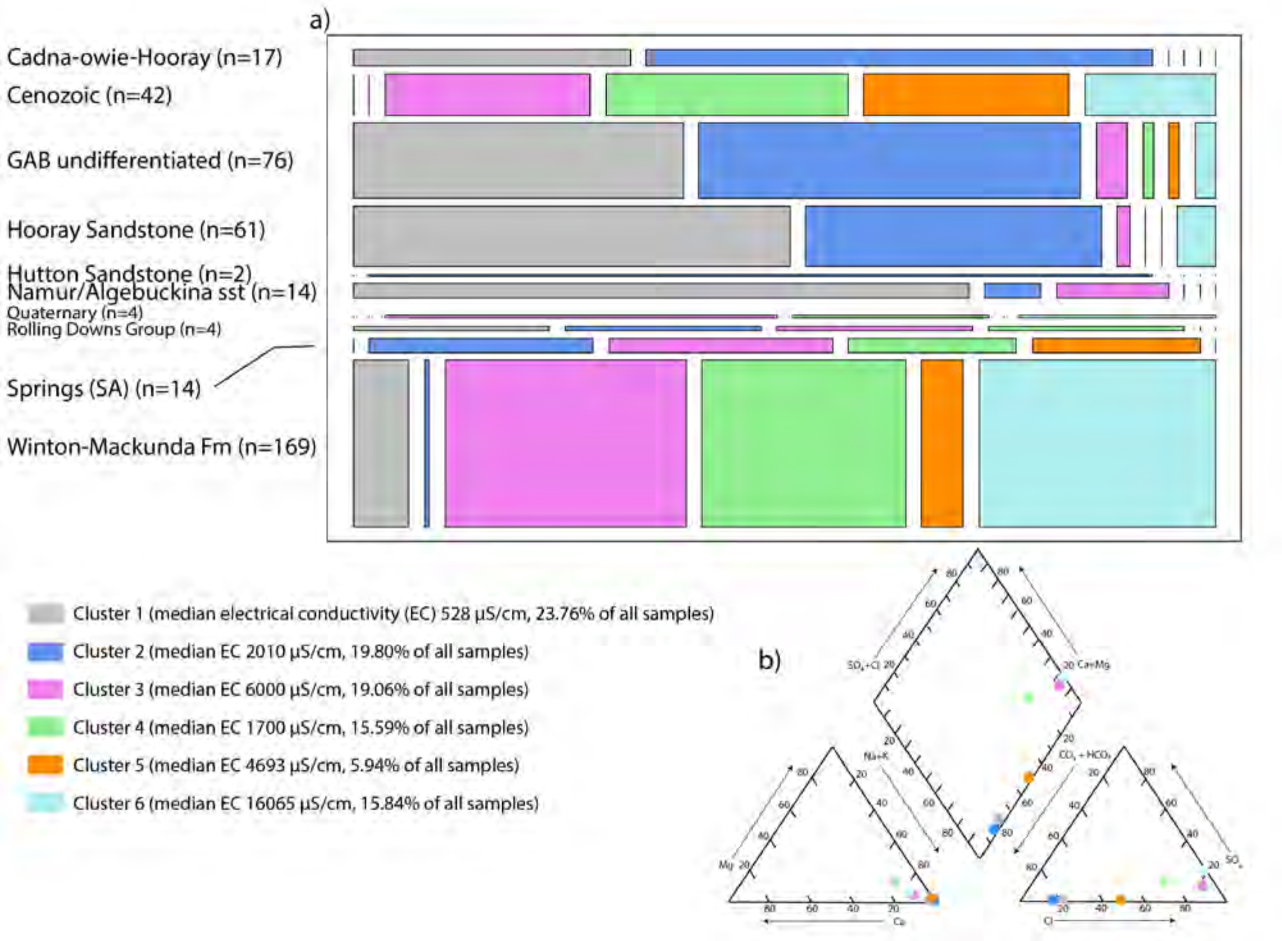


Figure 50 a) Aquifer cluster membership of aquifers b) and Piper plot showing hydrochemical composition of groundwater chemical clusters (based on the median of each cluster) in the Eromanga Basin

(a) The width of the bars represents the relative percentage of groundwater records assigned to each cluster. The numbers in brackets behind the hydrostratigraphic unit correspond to the number of hydrochemical samples for each formation. (b) The Piper plot shows the median concentrations (e.g. Mg + Ca + Na + K) of the different clusters.
EC = electrical conductivity; Fm = formation; GAB = Great Artesian Basin; sst = sandstone
Data: Geological and Bioregional Assessment Program (2019a, 2018h)
Element: GBA-COO-2-099

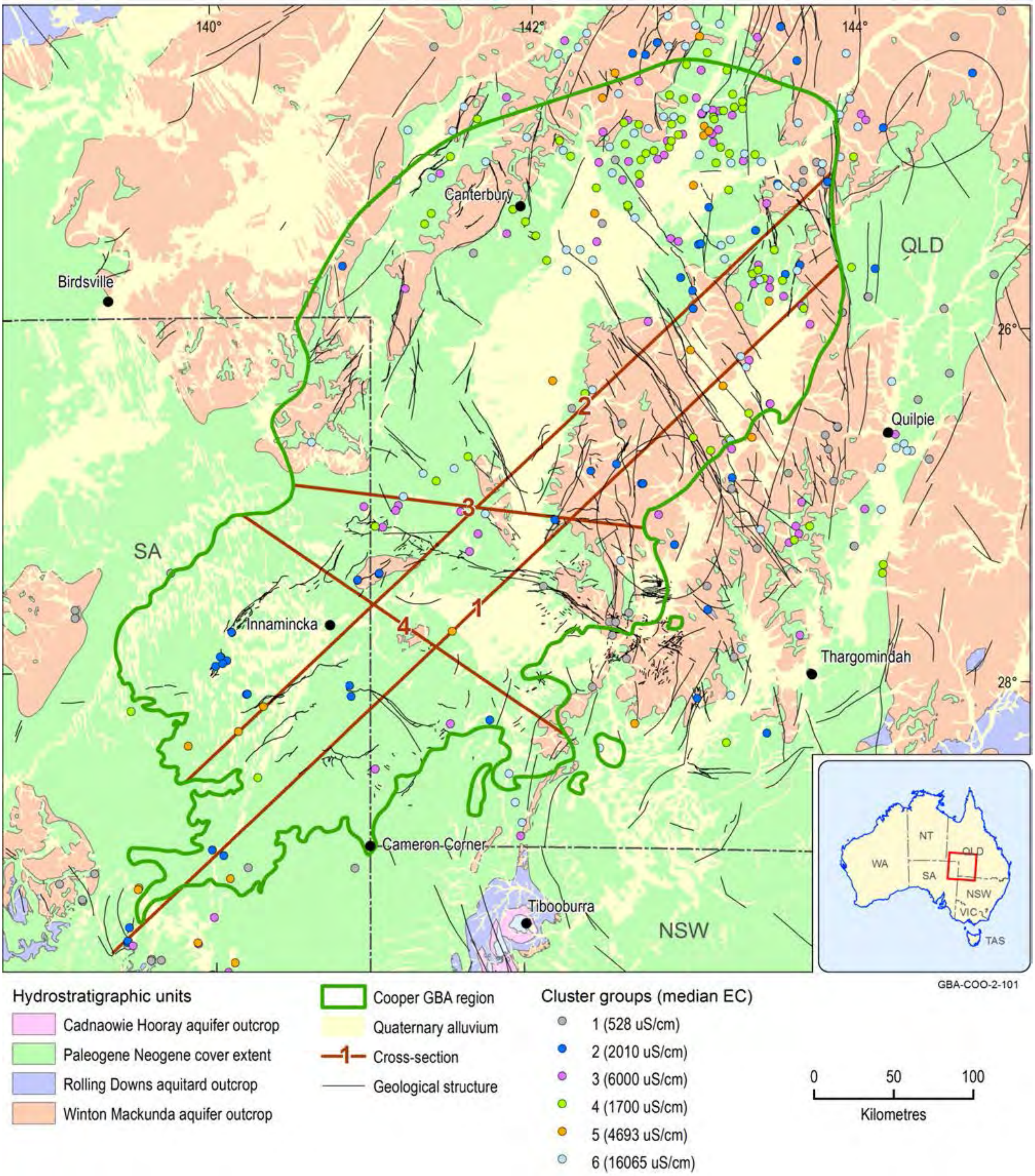


Figure 51 Spatial distribution of groundwater clusters based on hydrochemical variables

Data: Geoscience Australia (2015, 2013, 2012); Geological and Bioregional Assessment Program (2018b, 2019a); Petrosys Pty Ltd (2018)

Element: GBA-COO-2-101

5 Conceptual model of potential connectivity pathways from targets to assets

Five potential hydrological connectivity pathways between unconventional gas reservoirs through aquifers and near surface environmental assets in the Cooper-Eromanga-Lake Eyre basins cannot be ruled out based on the developed conceptual models. In addition, extraction of groundwater to support gas development from Cenozoic aquifers or from aquifers of the Eromanga Basin is also considered potential stressors. Multiple potential hydrological connection pathways are considered plausible, including connections associated with aquifer and aquitard architecture, proximity of assets to faults, vertical continuity of faults and geological heterogeneities near the basin margins.

The five potential hydrological connectivity pathways that were identified are: 1. vertical migration via dilation faults; 2. migration through porous aquifers; 3. migration through partial aquifers/aquitards; 4. migration due to contact between gas plays and overlying aquifers near the basin margin and 5. Vertical migration at catchment constrictions where steep hydraulic gradients exist between alluvial aquifers and underlying GAB formations.

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

Investigation of plausible pathways for fluid migration from stressors (tight, shale and deep coal gas plays and prospective aquifers to supply development activities) to near-surface environmental assets was undertaken via the development of conceptual models built on interpretation of a series of cross-sections produced within the Cooper GBA region spatial extent and its immediate vicinity.

The cross-sections (Figure 48, Figure 53, Figure 54, Figure 55) were spatially positioned to intercept the relevant geological structural elements mapped in the GAB aquifer units (Geoscience Australia, 2013) and within Cooper-Eromanga basins hydrostratigraphic sequences (Petrosys Pty Ltd, 2018).

Conceptual models were produced by combining the stratigraphic architecture obtained from the 3D geological model prepared by Hall and Palu (2016) with sets of geological structures as described in Section 4. They are supported by a 1-second digital elevation model (DEM, Geoscience Australia, 2011) representing the present day topography and datasets of physical-chemical parameters that could indirectly help to identify potential pathways.

Ideally, for testing the hypotheses suggested by the conceptual models, multiple lines of evidence should be integrated to provide a more robust understanding. Often, multiple factors are required to increase confidence in the assessment of the likelihood whether identified potential pathways eventually connect stressors and the environmental assets.

The factors considered in the conceptualisation of potential connectivity pathways from stressors to assets include:

- Footprint and thickness of the tight, shale and deep coal gas play intervals and their linear distance (predominantly vertical) to GAB aquifers and near surface assets;
- Same parameters applied to aquifers with potential to supply the development activities and near surface assets;
- Upward formation pore pressure (or hydraulic) gradient potentials between the unconventional plays and the overlying hydrostratigraphic units more likely to be immediately affected by depressurisation of the gas fields;
- General stress regime associated with the geological structures conducive to fault reactivation and dilation;
- Spatial distribution of thickness and hydraulic properties of the aquitard/seals positioned between the unconventional plays and the identified assets, including shallow aquifers;
- Anomalies identified in physical-chemical, hydrochemical (including gas) and tracers measured in reservoir fluids, aquifers, springs and surface waters (if applicable);
- Spatial location and extent of environmental assets, including shallow groundwater bores used for water supply, waterholes, groundwater dependent ecosystems (GDEs) such as springs or reaches where baseflow to streams occurs.

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

5.1 Tight, shale and deep coal gas plays and associated activities – stressors

The potential stressors identified in the Cooper Basin are the late-Carboniferous/Permian shale gas, tight gas and deep coal plays of the Gidgealpa Group (cross-section 1, Figure 48). In addition, extraction of groundwater to support gas development from Cenozoic aquifers or from aquifers of the Eromanga Basin may also be a potential stressor.

The principal shale gas plays of the Roseneath and Murteree shales, separated by tight sands of the Epsilon Formation, also known as Roseneath-Epsilon-Murteree (REM) play, occur predominantly in the southern section of the Cooper Basin.

The most extensive basin-centred tight gas play with a thickness of more than 1300 m is found in the Nappamerri Trough (Figure 48). The separation distance between overlying aquifers and this depositional centre in the Cooper Basin is variable, ranging from several hundred meters in the central part of the depositional centres to areas where they are potentially in direct contact at the basin margins. These early Permian successions are also present in multiple depocentres across the basin, including the Patchawarra, Woolloo, Allunga and Windorah troughs. Such plays are characterised by thermally mature gas-prone source rocks interbedded by sand deposits (Department for Energy and Mining (SA), 2018).

Deep coal plays are the gas-saturated Permian sedimentary rocks of the Toolachee, Epsilon and Patchawarra formations, which occur predominantly in the following depocentres: Patchawarra, Nappamerri and Arrabury Troughs (Senex Energy Ltd, 2013; Beach Energy, 2018, 2015b, 2015a).

The composite footprint of the tight, shale and deep coal gas plays is shown in Figure 47. It occupies approximately 72% of the Cooper Basin area, and this extent was considered as the footprint of the potential stressors for the investigation of possible occurrence of fluid pathways to assets.

The depth to the uppermost tight, shale and deep coal gas play (Toolachee Formation) ranges between 1090 m and 3280 m below ground surface, with a mean of 2320 m. The region where the top of Toolachee Formation is closest to the surface corresponds to a continuous strip along the eastern border of the basin (Figure 11).

Furthermore, extraction of groundwater from shallow aquifers (e.g. alluvial aquifers or the Winton Formation) to support gas development activities (e.g. hydraulic fracturing or infrastructure development) may also have an influence on near-surface environmental assets.

5.2 Aquitards hydraulic sealing performance - potential barriers

The purpose of this section is to highlight the properties of the regional seals or barriers to hydrocarbon migration from the deep tight, shale and deep coal gas plays to the near-surface environmental assets.

For the investigation of potential connectivity pathways, an understanding of the distribution, continuity and heterogeneity of the low permeability units located between the assets and the stressors and their hydraulic performance (including their spatial continuity and integrity) to act as aquitards is crucial (Underschultz et al., 2016).

Seals/aquitards identified in the Cooper Basin are predominantly of intra-formational nature, which indicates that there is some degree of lateral and vertical heterogeneity and anisotropy (Deighton et al., 2003; Gravestock et al., 1998).

Sediments of the Cenozoic Namba Formation may be considered mostly as an aquitard. However, the presence of enclosed channels within this sequence means that the lateral continuity of its sealing capacity is likely compromised, leading to leaky conditions. The consideration of the Cenozoic as a continuous hydraulic seal is therefore discarded and not discussed further in this section.

5.2.1 Rolling Downs Group

The basal interval of the Rolling Downs Group, consisting of the Wallumbilla and Toolebuc formations, Allaru Mudstone, Bulldog Shale, Coorikiana Sandstone and Oodnadatta Formation, is identified as the uppermost thick aquitard unit in the hydrostratigraphic column of the Cooper –

Eromanga - Eyre basin system. The characterisation of the hydraulic properties and lateral continuity of this system is extremely important for the assessment of potential regional connectivity between shale and tight gas systems (stressors) and surficial groundwater and groundwater dependent ecosystems).

Also known as the Rolling Downs aquitard (Ransley et al., 2015a), this sequence presents a lateral continuity across the basin's domain, with average thickness of 310 m and hydraulic conductivity values as low as 0.4 $x10^{-13}$ m/sec (Smerdon et al., 2012b). In the central-western part of the basin (Figure 52), this low permeability sequence reaches over 970 m in thickness. Due to these properties, particularly its relatively homogenous thickness distribution over the basin footprint, this unit has been classified as a regional aquitard, with low permeability relative to the overlying Mackunda Formation. In parts of the Cooper GBA region where this unit is not compromised by seal-by pass structures (i.e., where no faults are present; Figure 48); it likely represents an effective sealing sequence; which limits vertical fluid flow from deeper hydrocarbon reservoirs in both Cooper and Eromanga basins.

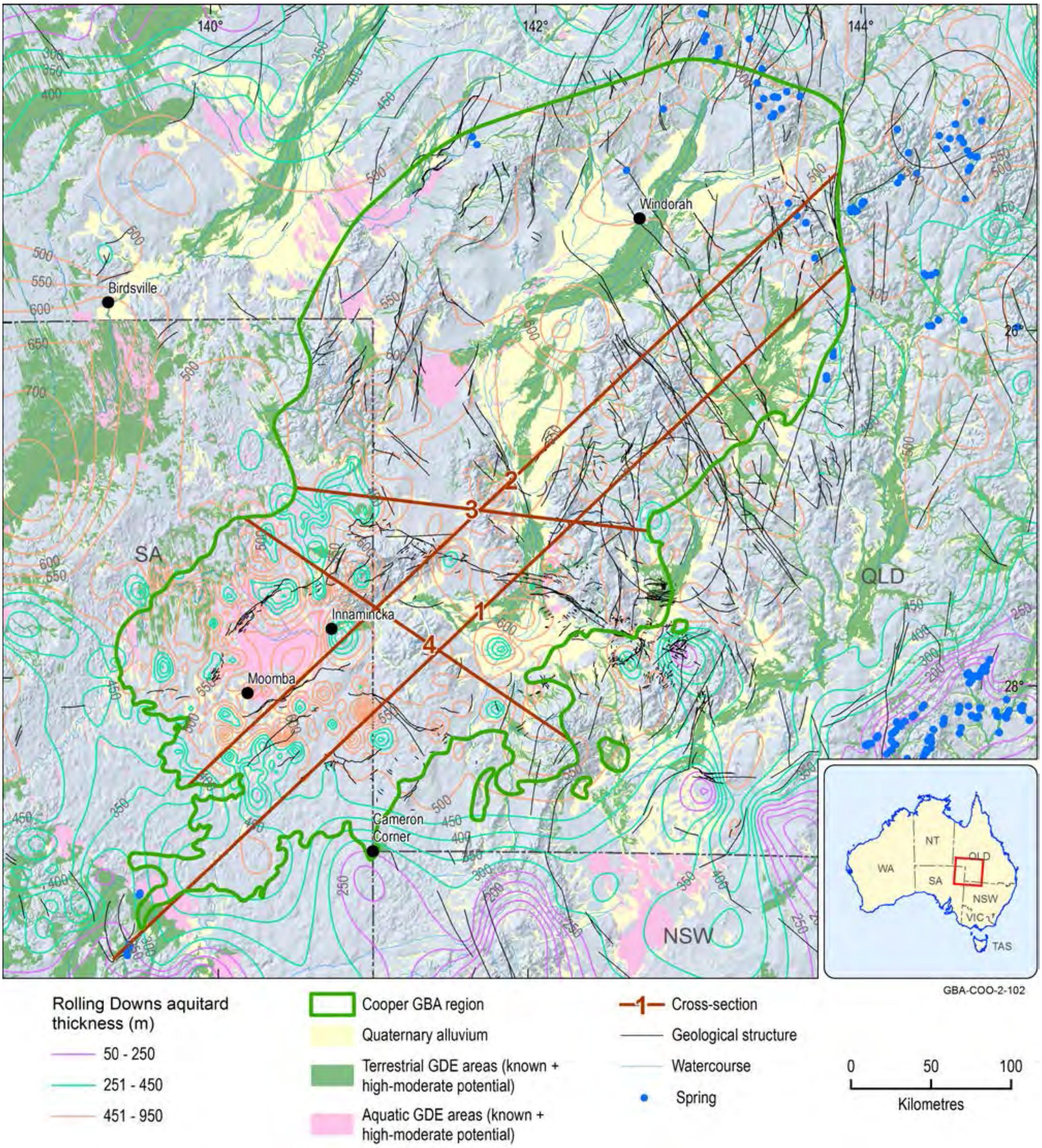


Figure 52 Rolling Downs Group isopach map (Ransley et al., 2014) with identification of geological structures and environmental assets (GDE's, water courses and springs) and orientation of cross-sections

Data: Department for Environment and Water (SA) (2015); Department of Environment and Science (Qld) (2018); Petrosys Pty Ltd (2018); Geoscience Australia (2015, 2013, 2012, 2008b); Geological and Bioregional Assessment Program (2018b); Bureau of Meteorology (2017)
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The lateral extent of the Rolling Downs aquitard is represented by the interval between 'Top Toolebuc or equivalent' and 'Top of Cadna-owie' shown in cross-section 1 (Figure 47 and Figure 48). Although fault-induced displacements are not explicitly incorporated into the 3D geological model of the Cooper and Eromanga basins, the sub-surface geometry shown in the cross-sections highlights that geological structures (faults) are likely to juxtapose formations considerably in some depocentres, affecting the lateral continuity of aquitards and adjacent aquifers. This means that it is likely that aquifers may be juxtaposed against aquitards, as observed in other basins such as the adjacent Galilee-Eromanga basins (e.g. Moya et al., 2014). There is no data on the permeability of the faults striking the GAB and Cooper geological units, which increases the uncertainty in quantitatively classifying this unit as a regionally continuous aquitard.

Furthermore, an intra-formational and pervasive faulting system identified as polygonal fault system (PFS) has been described as providing potential pathways for fluid migration in the Rolling Downs aquitard (Ransley and Smerdon, 2012; Ransley et al., 2015a; Ransley et al., 2015b).

No quantification of fluid leakage through the PFS is available in the literature for the whole of the cooper GBA region (Section 5.2), with only a conceptual description of the likelihood of the faults disrupting the continuity of aquifers and acting as conduits of aquifer leakage into shallow aquifers and into gaining streams, as illustrated Figure 23.

The above described conceptualisation is supported by the findings of a recent 3D seismic analysis carried out in the Swan Lake field, located to the east of the Gidgealpa-Merrimelia-Innamincka ridge (Kulikowski and Amrouch, 2018b). The referred study presented the occurrence of a primary NE-SW striking polygonal fault set with high dip angle (60°) that extends from Cretaceous sediments, including Cadna-owie–Hooray and Winton–Mackunda units into the Paleogene to Quaternary, possibly associated with the reactivation of faults by tectonic events occurred between 33 to 23Ma.

Finally, Kulikowski et al. (2018) geomechanically modelled the randomly oriented polygonal faults and found that a set of near vertical dip NE-SW and NW-SE striking faults could be open to fluid flow. Even though the focus of the study by Kulikowski et al. (2018) was conducted to assess the migration of hydrocarbons from the Lower Cretaceous sediments into shallow Cretaceous sequences, this provides an example of a relatively well-characterised fault system and the same pathways could also allow groundwater and gas flow under upward pressure gradient conditions, as discussed in Section 6.1.6.

Areas this may be prevalent may be where the Rolling Downs aquitard thins and coincides with PFS structures. As identified in the southern portion of the Cooper GBA region (Figure 52) with an estimated thickness of 250 m, these conditions may be prone to vertical fluid migration from deeper hydrocarbon bearing units of the Cooper-Eromanga basins to surficial aquifer systems of the Eromanga and Lake Eyre basins.

5.2.2 Nappamerri Group

The thick siltstones of the Nappamerri Group (Section 3.1.1) have been regarded as a regional seal to pervasive vertical gas migration from the Gidgealpa Group. However, the Nappamerri Group is heterogeneous and composed of various lithofacies and consequently contains both leaky aquitards and some aquifers. In addition, this unit abuts against basement highs, which in combination with faults could possibly create preferential pathways for vertical fluid migration (e.g. Figure 48; Section 4.1.2).

Secondarily, the Roseneath Shale acts as a seal to the Epsilon Formation, and the Murteree Shale may act as a seal to the underlying Patchawarra Formation (Gravestock et al., 1998; Gray and Draper, 2002).

5.2.3 Gidgealpa Group

As referred to in Section 3.1.1, only the lacustrine sequence of Murteree and Roseneath shales in the lower Gidgealpa Group can be characterised as regional aquitards. However, these are restricted to the Allunga, Nappamerri and Patchawarra troughs, Milpera Depression and Mettika Embayment (syn-sedimentary depressions).

As noted in cross-section 1 (Figure 48), deep-seated faults may affect this sequence by juxtaposing the unit's source rock against the higher permeability sequences of the overlying Nappamerri Group. This combination could result in preferential flowpaths to fluids from the source rocks into the overlying permeable intervals of the GAB aquifers. In addition, where this group sub-crops against basement along the south-eastern, southern and south-western margins of the Cooper Basin, connectivity between this group and the overlying aquifers and aquitards of the Eromanga Basin has been previously reported (Ransley et al., 2015a), and this mechanism is therefore included as potential connectivity pathway (Section 6.1.6).

5.3 Structural geology framework

Fault zones may create conditions prone to vertical hydraulic connectivity between different hydrostratigraphic intervals and/or compartmentalise strata horizontally, requiring a range of complementary assessment methods for a comprehensive and reliable fault zone analysis (Underschultz et al., 2018).

The structurally complex sequences of the Cooper and Eromanga basins have been affected by at least six tectonic events between 450Ma and 23Ma. In addition, the likelihood for fault reactivation and fault dilation (or the likelihood for open fractures/faults) following a Paleogene (33-23Ma) compressional event was recently demonstrated via geomechanical modelling and calcite twin stress inversion (Kulikowski and Amrouch, 2018a). This indicates that the two most recent tectonic events that affected the Cooper-Eromanga-Eyre basins, despite being of compressional nature, may have resulted in the reactivation of NE-SW striking faults and most importantly potential dilation of N-S and E-W striking faults, all with dip angles ranging from 50 to 70^{o}.

The numerous high-angle faults striking the geological units of the Cooper–Eromanga basins coincide with vertical shifts in the lateral distribution of geological units produced by the 3D geological model from Hall and Palu (2016), as clearly indicated in cross-sections 1, 2, 3 and 4 (Figure 48, Figure 53, Figure 54, and Figure 55, respectively).

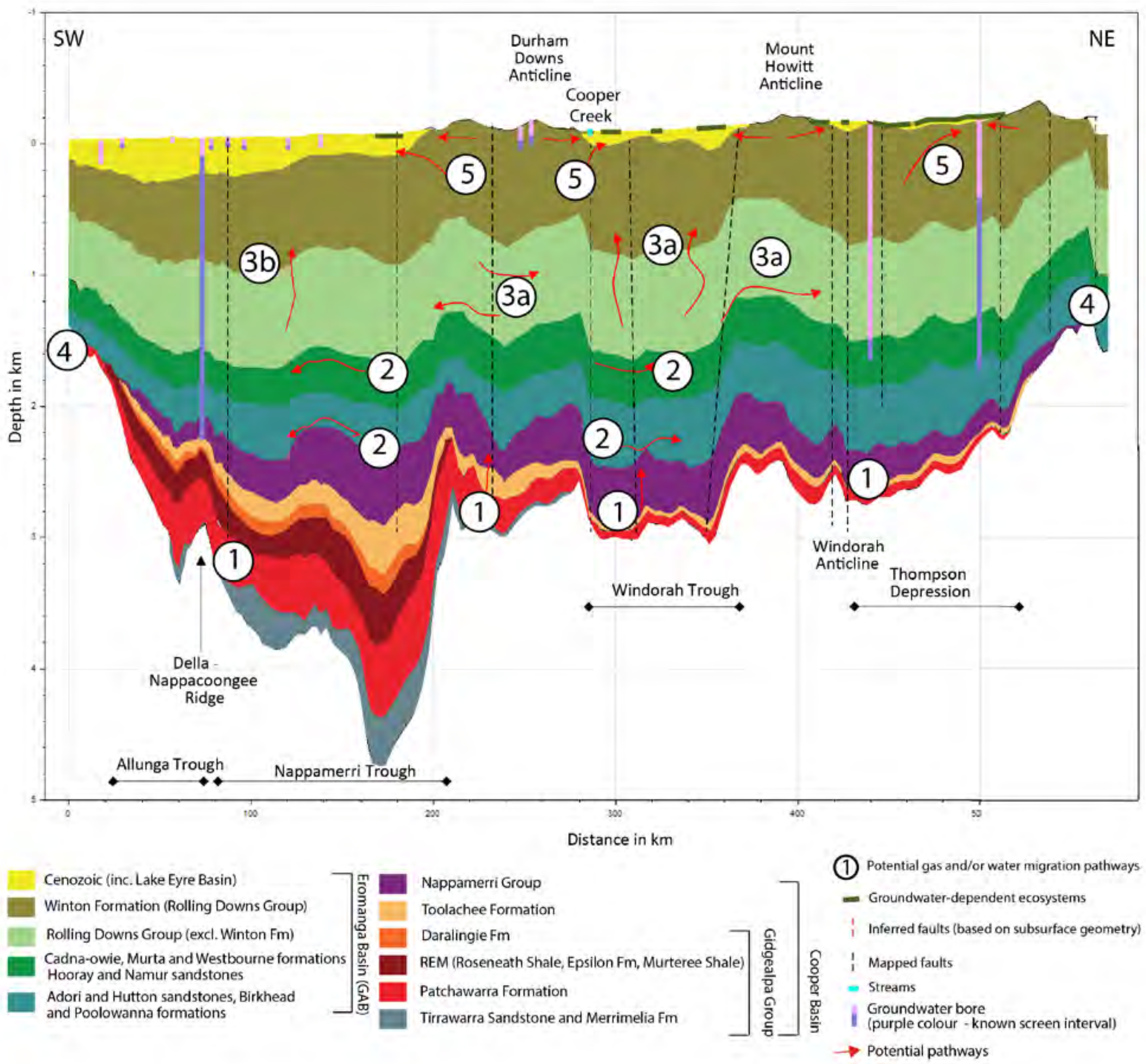

Figure 53 Cross-section 2, semi-parallel to cross-section 1, striking through Nappamerri and Windorah troughs

Note that Cooper Creek alluvium deposits are bounded by highs created by Durham Downs and Mount Howitt anticlines.
Data: Geoscience Australia (2008a, 2013, 2018e); Department of Environment and Science (Qld) (2018); Bureau of Meteorology (2017); Department of Environment, Water and Natural Resources (SA) (2012), 3D geological model from Hall and Palu (2016); Geological and Bioregional Assessment Program (2018b)
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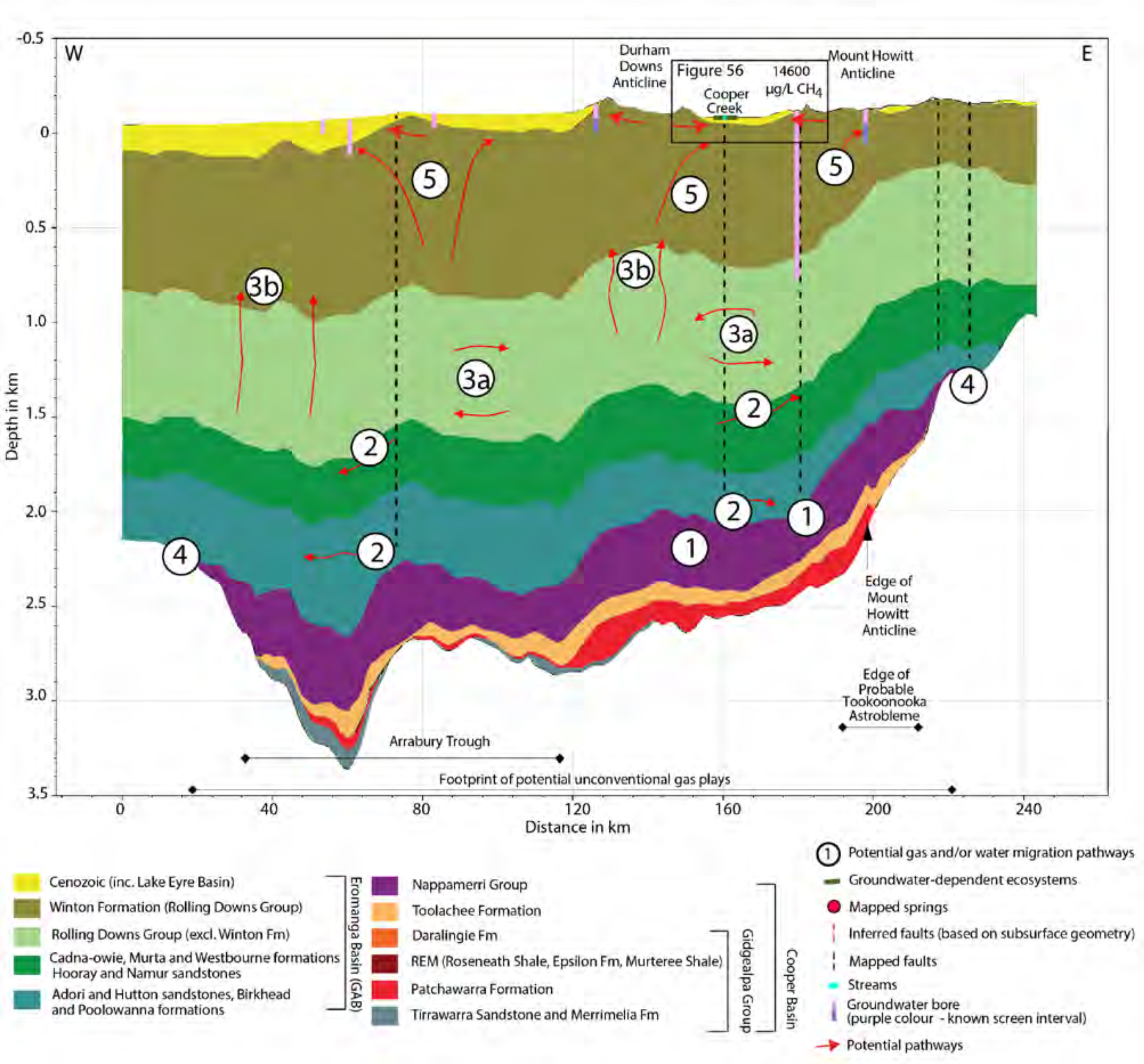

Figure 54 Cross-section 3, with north-west–south-east orientation, representing likely geological structural control of Cooper Creek alluvium, very high concentration of methane in a groundwater bore at the centre of Packsaddle Ridge and five potential hydrological connections for water or gas migration

The five potential hydrological connections are: 1. vertical migration via dilation faults; 2. migration through porous aquifers; 3. migration through the Rolling Downs Group aquitard via PFS (a – lateral; b – vertical); 4. migration due to contact between gas plays and overlying aquifers near the basin margin; and 5. vertical migration at catchment constrictions where steep hydraulic gradients exist between alluvial aquifers and underlying Great Artesian Basin formations. Refer to Figure 56 for detailed view of cross-section.

Data: Geoscience Australia (2008a, 2013, 2018e); Department of Environment and Science (Qld) (2018); Bureau of Meteorology (2017); Department of Environment, Water and Natural Resources (SA) (2012), 3D geological model from Hall and Palu (2016); Geological and Bioregional Assessment Program (2018b)

Element: GBA-COO-2-103

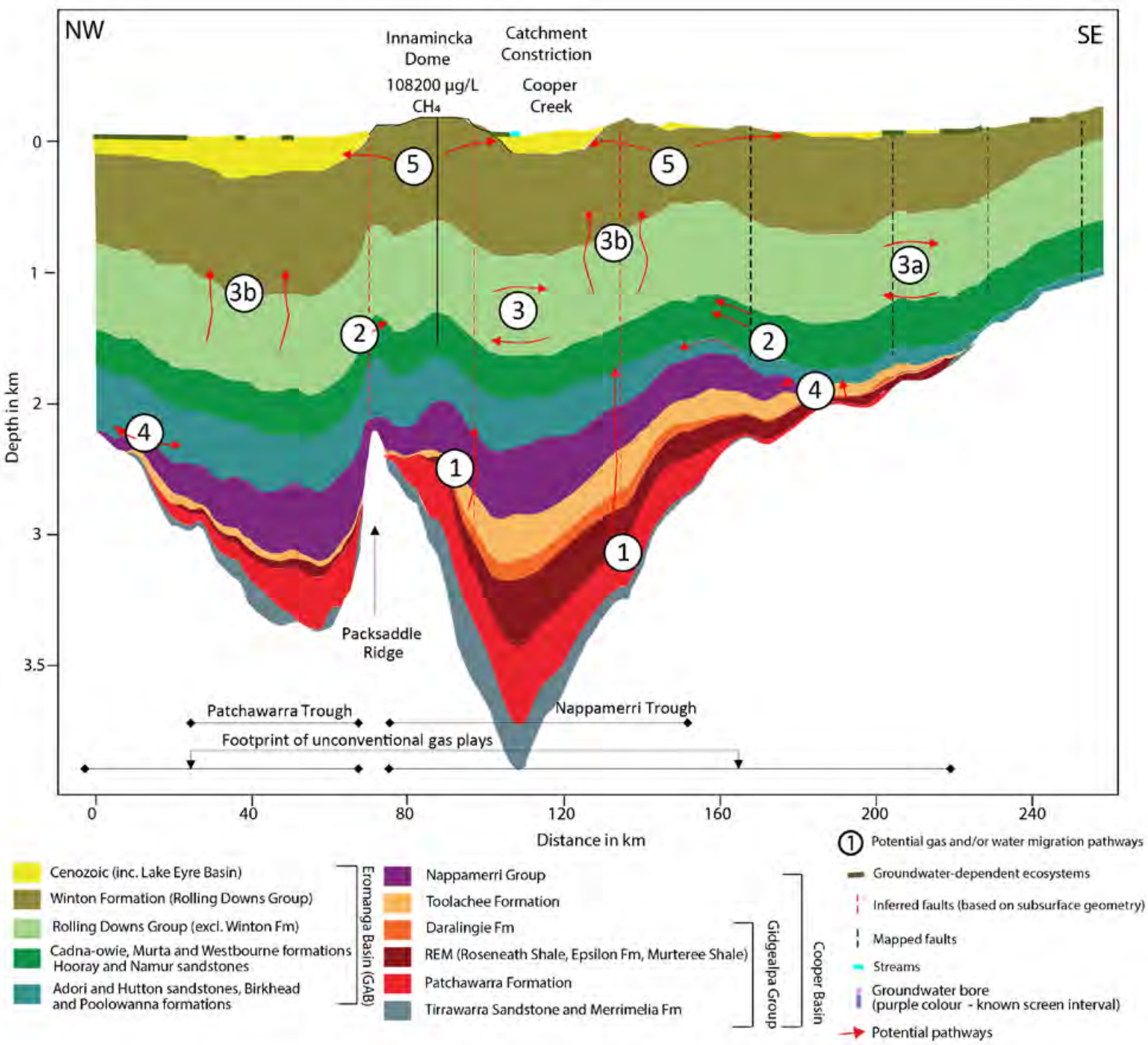

Figure 55 Cross-section 4, representing likely geological structural control of Cooper Creek and high concentration of methane at the centre of Packsaddle Ridge

Data: Geoscience Australia (2008a, 2013, 2018e); Department of Environment and Science (Qld) (2018); Bureau of Meteorology (2017); Department of Environment, Water and Natural Resources (SA) (2012), 3d geological model from Hall and Palu (2016)
Element: GBA-COO-2-098

Although the 3D geological model of the Cooper and Eromanga basins does not represent faulting directly (i.e. fault displacements/juxtaposition of stratigraphic units are not modelled), the observed changes in the thickness variation of geological layers allow inferring where significant fault displacements occur. Such fault-controlled displacements are more pronounced at the edges of the Weena and Nappamerri troughs as seen in cross-section 1 (Figure 48) or the Windorah trough (Figure 53), which form graben-like features controlled by the reactivation of basement structures. Importantly, catchment constrictions identified in several regions in the mid-catchment of Cooper Creek, as for instance near the Durham Downs Anticline (Figure 53), also appear to be structurally controlled, as documented by the presence of faults on both margins of the alluvial aquifers. These are often areas where sub-alluvial bedrock, alluvia and streams are in proximity, as the alluvial systems become considerably thinner and narrower. In the Cooper Creek mid-catchment, the floodplain narrows significantly from approximately 60 km width upstream to less than 15 km, and the thickness of the alluvium decreases from more than 100 m in the wider alluvial floodplain to 20-30 m. These conditions suggest that could be a high likelihood of connectivity and potential groundwater and/or gas migration pathways between sub-alluvial bedrock, alluvia and streams, as observed in many other catchment constrictions elsewhere (e.g. Condamine River alluvium constriction near Chinchilla). Due to the limited thickness and width, the alluvial aquifers (and associated GDEs) in the vicinity of the constrictions are more sensitive to any changes than those in the wider parts of the alluvial plains.

The inferred fault zone represented by high angle faults with red dashed lines in cross-section 1 (Figure 48) and the mapped faults at the edge of the alluvium overlying the Windorah trough fits in the conceptualisation of a 'horst-graben' system, where Cooper Creek and its alluvial system would be currently installed along a structural zone of weakness (Figure 53). This inference coincides with inflections noted in the top of all geological units underlying the Winton Formation.

If confirmed that the presence of deeper geological structures has an effect on the creek constrictions, they may also form potential fluid pathways connecting the Winton–Mackunda partial aquifer with lower intervals via polygonal faults in Rolling Downs aquitard (Section 5.2) and near surface assets, including possible GDEs associated with the creek. Furthermore, in this central catchment constriction, the course of Cooper Creek closely coincides with the orientation of a mapped fault over approximately 10-15 km, which could be an additional indicator of the potential influence of faulting on the architecture and potentially connectivity of alluvial systems with sub-alluvial bedrock.

5.4 Environmental and economic assets

Among the identified assets subject to possible interaction with groundwater and fluids migrated from deeper O&G plays associated with the Cooper Basin, the following were considered of relevance (Figure 52):

- Springs
- GDEs
- Water courses, shallow freshwater lenses, waterholes and lakes
- Waterholes
- Shallow groundwater bores used for domestic and stock water supply.

The vertical position of the environmental assets in relation to the identified stressors is represented in conceptual models presented in Figure 48, Figure 53, Figure 54, and Figure 55.

5.4.1.1 Springs

Two sets of springs were identified in the immediate vicinity of the Cooper Basin (Figure 47, Figure 43) concentrated predominantly near the northeast and southwest corners of the basin in Queensland and South Australia, respectively.

The springs located within the precise footprints of the Cooper Basin (n=18) and the unconventional O&G plays (n=6) in Queensland are all classified as permanently saturated springs and as not associated with the Great Artesian Basin (Queensland Department of Environment and

Science, 2018). However, this classification is not based on a comprehensive assessment, as for example no environmental tracer or detailed hydrochemical data exist for these springs. It is valid to note that at least 12 more springs are also mapped within a 10 km radius from the basin footprint in the north-eastern part of the Cooper Basin.

Several springs in Queensland are semi-parallel to NW-SE striking faults (Figure 47) and appear to be located at the projected extent at ground surface of deep-seated GAB faults, as illustrated in cross-section 1 (Figure 48).

Silcock et al. (2016) proposed a conceptual model representing the water source of the springs located near the confluence of Thomson River and Barcoo River in Queensland, where rainfall percolates through Cenozoic sediments and discharges at ground surface along the contact between a porous zone in the Cenozoic sandstone and the underlying Cretaceous sediments of the Winton Formation. These authors further state that none of these springs have connection to GAB aquifers, a proposition initially presented by Habermehl (1982).

However, no deep faults and potential upward pressure gradients were taken into account for the conceptual model developed by Silcock et al. (2016). In addition, only field parameters such as pH and EC were measured, and no hydrochemical or environmental tracer datasets exist to support this proposition.

This suggests that there is a considerable degree of uncertainty related to the potential source aquifers of the springs within the Cooper Basin in Queensland. This represents a significant knowledge/data gap to be addressed as springs are sensitive environmental assets (see also Section 6.2).

Two clusters of spring complexes have also been identified at a distance range of 5 -15 km from the southwest corner of the Cooper Basin (Figure 47) and inferred to be potentially sourcing GAB groundwaters. These complexes were investigated by Keppel et al. (2016) and identified as 'Lake Blanche Springs (QLB001)' and 'Reedy Springs (ORE)' complexes, respectively. The springs mapped in the northeastern corner of the Cooper GBA region are positioned at approximately 1650 m vertical distance from the top of the shallowest unconventional O&G plays.

The first springs' complex, composed of ten springs located closer to the western boundary of the Cooper Basin and the Weena Trough (~5 km) coincide with mapped GDE wetlands associated with the Lake Blanche and may correspond to potentially sensitive assets.

The second complex, comprising 386 springs, is located at approximately 20 km southwest of the Cooper basin and the unconventional plays boundaries (See Figure 47 and Section 3.5.2). This complex of springs is in close proximity to a set of geological structures, classified as faults associated with the GAB hydrostratigraphic units.

Through a combination of geophysical investigations, hydrochemistry and environmental tracers, Keppel et al. (2016) hypothesised that 'Lake Blanche Springs' are most likely supplied by shallow aquifer systems (Coorikiana Sandstone and Cenozoic aquifers) and 'Reedy Springs' are fed predominantly by the Cadna-owie-Hooray aquifer. The above authors also indicate that there is insufficient evidence in the collected hydrochemical datasets to suggest a potential connection of the springs to the Patchawarra Formation (Cooper Basin). However, they also highlight that the hydrochemical differences of Cadna-owie-Hooray aquifer and the Patchawarra Formation are small. It should be noted that Patchawarra Formation is not present in the spring area, as it is confined to the Cooper Basin, and occurs up to 15 km to the east.

Despite the fact that none of the springs have been attributed to source water from aquifers of the Eromanga Basin within the Cooper Basin boundary (Section 3.5.2), the lack of sufficient evidence to characterise the source aquifer of springs in Queensland and the relatively close proximity of the GAB sourced springs in South Australia highlights that these springs should be included as potential environmental assets in the conceptual models. They should also be the focus of any subsequent environmental baseline analysis whereby environmental tracers give more definitive answers about the origin of their source waters.

5.4.1.2 GDEs

Aquatic and terrestrial ecosystems that potentially depend on groundwater were regionally mapped by the Bureau of Meteorology (Bureau of Meteorology, 2012) and reproduced within the Cooper Basin region in Figure 52, indicating that such areas are generally associated with the dendritic water course routes.

In the Queensland section of the basin, GDEs are classified into terrestrial and surface expression GDEs, with five major conceptual models associated with them (Queensland Government, 2018e):

- Alluvia – mid (moderate alluvial development) and lower (extensive alluvial development) catchment;
- Catchment constrictions – identified during the current study even though this type is not listed in the WetlandInfo 2014 (Queensland Government, 2018e);
- Permeable rocks (rocks with predominantly primary porosity), which can contain one or more unconfined, permeable rock aquifers; and
- Sedimentary rocks (Great Artesian Basin) - identified during the current study even though this type is not listed in the WetlandInfo 2014 (Queensland Government, 2018e);
- Wind-blown inland sand dunefields, which are composed greatly of unconsolidated sand deposited by wind (aeolian processes).

The degree of confidence in GDE mapping varies from low to high, and the assessments are all based on expert elicitation.

Notably, terrestrial GDEs are frequently present throughout the wider parts of the Cooper Creek floodplain, but only cover a small portion of the floodplain near the creek. In contrast, around the catchment constriction in the central Cooper Creek, nearly the entire width of the alluvial extent is covered by mapped terrestrial GDEs, highlighting the significance of these constrictions.

5.4.1.3 Groundwater users

As described in Section 2.3, the groundwater users that can be considered potential environmental receptors include bores sustaining supplies for stock, domestic, town water supplies, petroleum, mining, power generation, industrial, tourism, and road maintenance. The Great Artesian Basin aquifers are the major target for the larger users. However, the Cenozoic permeable sequences are hydraulically connected to the Winton–Mackunda partial aquifer. These aquifers (Section 3.2.2.4, Section 3.2.3), are currently some of the most utilised aquifers in the Cooper GBA region, considering their relatively shallow depths.

5.5 Potential connectivity pathways

From the interpretation of cross-sections, which integrate currently available fault zone architecture information into the context of the regional stratigraphic, hydrogeological and hydrological framework, simplified conceptual models were developed to highlight potential areas where interconnectivity pathways between the tight, shale, and deep gas plays through aquifers and the near surface assets may occur. The models were also used to assist in the proposition of further work to test the knowledge gap hypotheses discussed in Section 6.2. It is important to highlight that these are potential connectivity pathways. For many of these pathways, it is at present unknown if there is actual flow of groundwater as this has not been quantified by past work. Likewise, it is not assessed as part of this section on potential connectivity pathways if activities associated with gas development or groundwater extraction (stressors) are likely to lead to impacts on assets. This will be examined further during Stage 3 of the assessment.

The thickness of the Eromanga Basin sequence ranges between 2000 and 2600 m, which is over than an order of magnitude greater than depths reached by most groundwater user bores (90% of groundwater bores are less than 300 m, see Section 2.1.1). However, the possible combination of the factors discussed above (Section 5), the likelihood for lateral gas migration and seals pinching out or abutting against impermeable basement near the basin margins may result in scenarios, which allow vertical fluid, and/or gas migration from the stressors to identified assets in these areas.

The potential pathways inferred from the interpretation of four representative cross-sections through the Cooper Basin, as shown in Figure 48, Figure 53, Figure 54 and Figure 55, include:

① **Vertical migration** of water or gas via deep-seated dilation faults connecting tight, shale and deep coal gas plays to overlying GAB aquifers (Hutton Sandstone, Adori or Cadna-owie-Hooray), Winton-Mackunda partial aquifer, shallower Cenozoic and alluvial aquifers or surficial assets such as perched water tables, GDEs and springs. Whether the presence of faults and the fault-induced displacement of seals results in any actual upwards flow of groundwater is unknown and will be examined further during Stage 3 of this assessment.

② **Lateral migration** through porous GAB aquifers, such as the Winton-Mackunda partial aquifer, and Cenozoic sequence;

③ **Lateral (a) and vertical (b) migration** through the Rolling Downs Group partial aquitard via PFS, potentially connecting GAB aquifers with permeable sections of the Winton-Mackunda partial aquifer;

④ **Migration due to contact between gas plays and overlying aquifers near the basin margin** where gas play strata abutting against basement highs or directly adjacent to the overlying GAB Aquifers; faults may also form pathways for groundwater or gas migration in these areas.

⑤ **Vertical migration** from Winton-Mackunda partial aquifer and/or Cenozoic aquifer (bedrock) to alluvial aquifers at the edge of the alluvium and/or within catchment constrictions, where the alluvium pinches out against the hydraulically connected part of the bedrock and where upward pressure gradients may occur. A pressure reduction in the sub-alluvial bedrock or conversely a drop of waterlevels in the alluvial aquifers can result in a rapid response of waterlevels and water quality (at time scales of years to decades) within shallow aquifers or streams, as observed in catchments elsewhere (e.g. Cui et al., 2018; Raiber et al., 2019).

Importantly, Figure 45 highlights that most of the permanent waterholes mapped within the Cooper Creek catchment are located within catchment constrictions and/or close to the edge of the alluvial aquifers, where the alluvium is in close contact with the underlying sub-alluvial bedrock. In contrast, only few of the permanent waterholes are located within the wide alluvial plains where these are > 30 km wide. As shown in Figure 56, in some of these catchment constrictions, reactivated basement faults likely have a significant control on not only the extent and geometry of the major depocentres within the Cooper and Eromanga basins, but also the geomorphology and the association between the positions of the Cooper River channels in relation to geological contacts. More importantly, the location of the faults here infers the presence of hydrogeological pathways connecting the shallow aquifers (i.e., alluvial aquifer) and the sub-alluvial bedrock units. In this specific section of the Cooper Creek catchment, the geological cross-section suggests the presence of a fault-controlled geological ‘graben’, bound by normal faults, which appear to place the strata of the Cretaceous Winton Formation partial aquifer against alluvial sediments deposited by Cooper Creek.

The detailed representation of the shallower aquifer systems (Figure 56) also indicates that there is more than one possible conceptual representation for connectivity between waterholes and underlying aquifers. As well as for the potential sources of water, that feed the waterholes throughout during cycles of droughts and floods.

Durham Waterhole is associated with the western branch of Cooper Creek. It is positioned near the geological contact between the Glendower Formation – Winton Formation and the alluvium, and it is possibly fed by groundwater from the regional alluvial aquifer and it may receive some contribution from the Winton Formation partial aquifer. Although based on sparse spatial data, the regional watertable elevation map for the Winton-Mackunda partial aquifer (Figure 26) suggests possible interaction between this system and the overlying alluvial aquifer. The western branch of Cooper Creek is incised into the bedrock units (Glendower Formation and Winton Formation). This indicates that the western Cooper Creek channel is potentially controlled by faulting, as inferred in Figure 56.

The Galina Waterhole, on the other hand, associated with eastern Branch of the Cooper Creek, is located closer to the central parts of a flat but relatively narrow alluvial plain (~20 km wide) within a catchment constriction, as previously described. As shown by the inferred shallow water table, Galina Waterhole may be hydraulically connected to a shallow perched water table within the alluvium and potentially primarily fed by surface water, similar to the waterholes described by Cendón et al. (2010) located approximately 50 km south within the Cooper Creek catchment.

Alternative conceptual models representing waterhole hydraulic gradients based on geomorphology, geology and hydrogeology should be considered to support further scientific investigations and determine whether waterholes are fed by groundwater sources at different times. In addition, this demonstrates that where groundwater is extracted from the shallow alluvial aquifer system or the underlying sub-alluvial bedrock aquifers (Winton Formation) to support gas development activities that pressure changes could be transferred to the overlying waterholes, confirming that this potential pathway cannot be ruled out at this stage of the assessment.

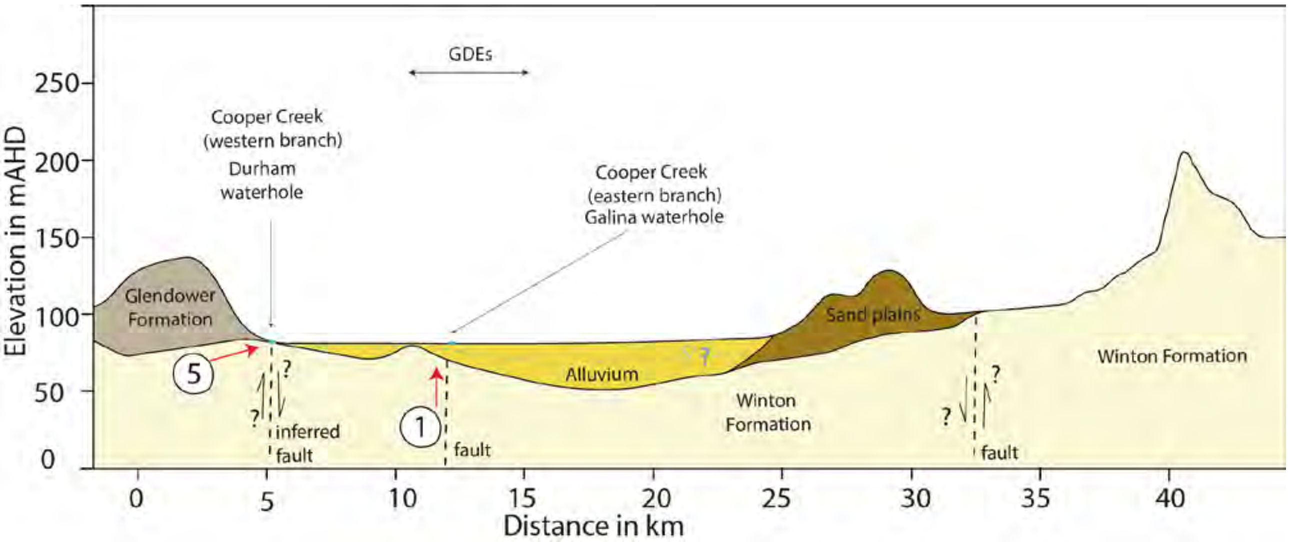

Figure 56 Detailed representation of potential hydrological connection 5 – vertical migration at catchment constrictions in a segment of cross-section 2 (see inset of Figure 54)

Geomorphological and geological frameworks suggest an alternative conceptual representation of surface water – groundwater interactions at waterholes near catchment constrictions. Pathways 1 and 5 are described in Figure 54. The blue dashed line represents inferred watertable.
The fault at point “1” was identified using geological mapping. The other faults are inferred to exist.
The topographic surface is based on the 1-second digital elevation model (DEM, Geoscience Australia, 2011).
Data: Geoscience Australia (2008a, 2012, 2013, 2018e)
Element: GBA-COO-2-312

Hydrocarbons are not only associated with the tight, shale and deep coal gas plays described above, but also within conventional oil and gas reservoirs in both Cooper and Eromanga basins. Simultaneously, some of the Jurassic-Cretaceous sediments of the Eromanga Basin also comprise the principal GAB aquifers, composed of sandstone reservoirs with structural traps and pinch out plays on basin margins (see Section 3.2.2 and (O'Neil, 1998).

This is relevant because in the unlikely event that hydrocarbon tracers are detected in surficial aquifers (Winton-Mackunda, Cenozoic or alluvial) or even near environmental assets (e.g. springs, waterholes, creeks and GDEs), the potential source of such hydrocarbons would more likely be associated with the conventional oil and gas plays rather than the unconventional ones. This assumption is based on the vertical distance between the stressors and the assets and the occurrence of a regional potential seal between the two basins, composed of sediments of the Nappamerri Group, as above described (Section 5.2). However, more data are required to determine if the conventional oil and gas resources have a different chemical and isotopic signature than the tight, shale and deep coal gas.

6 Conclusions

6.1 Key findings

Some key findings in the Cooper GBA region are as follows:

6.1.1 Groundwater data

- There are 2137 groundwater bores registered in the Cooper GBA region of which 1520 are in operation (Table 1). These numbers do not include plugged and abandoned petroleum exploration wells that were included in the state groundwater bore databases.
- Groundwater bore data can be incomplete, with a majority of bores missing information such as the depth from which groundwater obtained in a bore (i.e. missing screened/open intervals depths) or salinity data.
- No groundwater monitoring is undertaken for shallow aquifers, i.e. the Winton–Mackunda partial aquifer and aquifers in the Lake Eyre Basin (Cenozoic). The vast majority of groundwater bores (approximately 90%) in the Cooper GBA region are less than 300 m deep and would draw water from these aquifers.
- For the Cooper Basin and deeper aquifers in the Eromanga Basin (e.g. the Hutton Sandstone), groundwater-related information is derived primarily from petroleum exploration and production wells targeting petroleum resources. Information such as formation pressure data collected as part of petroleum drilling activities is useful for understanding deep hydrogeology in the Cooper Basin and artesian GAB aquifers in the Eromanga Basin.
- Little hydrochemistry or salinity data are available for groundwater produced from the Cooper Basin.

6.1.2 Hydrostratigraphy

- There are three major hydrostratigraphic sequences in the Cooper GBA region: the Cooper Basin, Eromanga Basin and Lake Eyre Basin.
- The Cooper Basin sequence consists of the Gidgealpa Group and the Nappamerri Group. Conventional petroleum resources occur in both Gidgealpa and Nappamerri groups, whilst tight, shale, deep coal gas plays only occur in the Gidgealpa Group. Furthermore, the lithology can vary considerably within individual formations, thus making a simplified lithological based categorisation of hydraulic properties (as undertaken for this project) problematic. These aspects have a bearing on hydrogeological status of a formation.
- Within the Gidgealpa Group, variable over-pressuring in source rocks and adjoining sandstones has expelled much of the free water to render them gas-charged units. With little to no water saturation, assigning a hydrogeologic categorisation is less applicable. Therefore, a category “Hydrogeological status uncertain due to predominant gas over-pressures (low water saturation in sandstones)” is assigned to some of the formations that comprise the Gidgealpa Group.

- Eromanga Basin hydrostratigraphy includes the sub-artesian Winton–Mackunda partial aquifer, the confining units that comprise the Rolling Downs aquitard, and a number of confined artesian aquifers including but not limited to those within the Cadna-owie–Hooray aquifer. The Eromanga Basin sequence is generally greater than 2000 m thick and completely covers the Cooper Basin sequence.
- Significant thicknesses of Lake Eyre Basin (Cenozoic) sediments occur in the Callabonna Sub-basin or the Cooper Creek floodplain. Whilst several aquifers exist in the Lake Eyre Basin, it is difficult to differentiate them in the subsurface from available groundwater data.

6.1.3 Hydrodynamics, hydrochemistry and groundwater resources

- Pressures in artesian GAB aquifers in the Eromanga Basin and the Nappamerri Group of the Cooper Basin follow similar pressure patterns, which suggest that they operate under the same pressure regime.
- In the Cooper Basin, pressures in the underlying Gidgealpa Group show considerably more variation with depth. Over-pressuring becomes increasing evident, which is likely to be due to increasing presence of hydrocarbons, in particular gas.
- Depleted formation pressures (under-pressure) in Eromanga and Cooper basins is likely to attributable to either pressure depletion from past or on-going petroleum production, hydrocarbons or slow pressure recovery during the pressure test because of low permeability.
- It is difficult to pick clear trends in equivalent hydraulic heads at a regional scale in the Cooper Basin. Relatively low equivalent hydraulic heads (i.e. less than 100 m above sea-level) tend to occur around the margins of Nappamerri and Patchawarra troughs, intermingled with some values that are much greater than 100 m. The highly variable hydraulic head distribution may be a result of historical production from petroleum reservoirs and reservoir compartmentalisation. Potential for flow is towards zones of lower hydraulic head. Such flow could potentially occur both horizontally and vertically, which complicates predicting the potential for fluid movement within the Cooper basin.
- Across the Eromanga Basin, groundwater from artesian GAB aquifers are managed primarily to maintain aquifer pressure and are not necessarily based on volumetric withdrawals. Aside from being a groundwater supply, GAB aquifers such as the Cadna-owie–Hooray aquifer system, are also under specific geological circumstances conventional petroleum reservoirs (primarily for oil).
- Potentiometric mapping for the Cadna-owie–Hooray aquifer suggests that a groundwater sink occurs in the south-western portion of Cooper GBA region. Here, inferred groundwater flow rates are inferred to be very low to stagnant. The occurrence of the groundwater sink in deeper parts of the Eromanga Basin may be in part be related to greater degree of diagenesis and compaction, which has significantly modified original porosity and permeability at depth. Groundwater flow is thought to preferentially skirt around the margins of the Cooper GBA region (e.g. the Birdsville Track Ridge) where the Cadna-owie–Hooray aquifer is at shallower levels and overall have higher porosities and permeability.

- Relatively few groundwater bores (around 50) draw water from artesian GAB aquifers due to depth. However, these aquifers can sustain higher flow rates, can be artesian and have more consistent water quality.
- A few hundred bores draw groundwater from the Winton–Mackunda partial aquifer. This is particularly the case in Queensland where outcrop of the Winton Formation is more prevalent than outcrop of the Lake Eyre Basin. However, water quality is more variable and yields are lower than artesian GAB aquifers. The Winton-Mackunda partial aquifer is a sub-artesian, unconfined to semi-confined aquifer system. Conceptually sandstone aquifers in these formations could be confined where the overlying Lake Eyre Basin cover sequence is very relatively thick or by thick layers of finer grained sediments that comprise a part of the Winton Formation.
- The occurrence of at least two distinct water types (Na-HCO_3 and Na-Cl) suggest that it may oversimplification to consider the Winton–Mackunda partial aquifer as a single aquifer system. There could well be a number of discrete aquifer systems within the Winton–Mackunda partial aquifer, with varying rates of recharge, hydraulic conductivity and water-rock interactions. Potentially Na-HCO_3 dominated water types could represent points of enhanced recharge or areas where their carbonate dissolution is occurring within the aquifer. The degree of lithological variation in the aquifer is also likely to be an influence. More work is required to unravel the groundwater pathways and hydrochemistry in this aquifer system.
- Aquifers in the Lake Eyre Basin are also utilised by hundreds of bores in the Cooper GBA region. Although salinity data are very patchy, the available data suggest that overall there are at least two aquifer systems in the Lake Eyre Basin: a shallow system above 60-80 m with highly variable salinity, and a deeper system below 60-80 m with relatively fresher (lower salinity) water. High salinity tend to occur where depth to groundwater is shallow (i.e. generally less than 20 m).

Inter- and intra-basin connectivity:

- There is potential for upwards leakage, from artesian GAB aquifers to the sub-artesian Winton–Mackunda partial aquifer through the Rolling Downs aquitard. Faulting, including polygonal fault networks may contribute to such a pathway. Limited available hydrochemistry suggests that whilst these two systems are distinct, some samples in Winton–Mackunda partial aquifer are similar to artesian GAB aquifers. Whether these points represent areas, where leakage is actually occurring across the aquitard is unknown, but may be a possibility.
- Sub-artesian groundwater systems in the Winton–Mackunda partial aquifer and Cenozoic aquifers are often similar in their hydrodynamics and hydrochemical patterns. It is likely that these two systems are strongly linked. However, there is a lack of quality pump test or waterlevel data to prove this.
- Separation between artesian GAB aquifers and the tight, shale and deep coal gas resource plays is generally in the order of 600 m or greater. Separation between shallower aquifers, such as Winton-Mackunda partial aquifer and tight, shale and deep coal gas resources is much greater, in excess of 2000 m.

- Where hydraulic head in the Cadna-owie–Hooray aquifer is higher than hydraulic heads in adjacent formations would be areas where there is potential for upward or downward groundwater flow. However, it is difficult to pinpoint these areas with data at hand. Conceptually, where the pressures in aquifers are higher than pressures in underlying formations could induce downward potential flow gradients. These conditions could essentially act as a 'pressure barrier to upward flow from even deeper aquifers such as in the Gidgealpa Group.

6.1.4 Surface water – groundwater interactions

- The closest springs with an artesian GAB aquifer source are located some 20 km west of Cooper GBA region, near Lake Blanche in South Australia. Although these springs are mostly located outside the footprint of the Cooper Basin GBA region, the sub-surface geometry as represented by the cross-sections developed during this project highlights that some of the springs may be dependent on groundwater flowing out of the Cooper Basin GBA region. Historic spring water chemistry and tracer data also do not rule out that possibility.
- Waterholes: the distribution of permanent waterholes relative to Winton Formation outcrop and within the floodplain and previous studies suggests that some of them are likely to be primarily fed by surface water (i.e., those waterholes that are located further away from the edge of the alluvium-bedrock boundary are more likely to be influenced by the presence of perched watertables). However, many waterholes are located at the margin of the alluvial aquifer systems close to the alluvium-bedrock interface or within narrow catchment constrictions, where perched watertables are unlikely to exist and where the waterholes may represent a 'window' into the watertable of the sub-alluvial bedrock. As observed in other alluvium-bedrock aquifer systems throughout Australia, there is likely to be a component of groundwater dependency for ecosystems at the edge of the alluvial aquifer systems. Importantly, the relative proportion of surface and groundwater contained within the waterholes at the margins of the alluvium and within catchment constrictions is likely to vary throughout flood-drought cycles.
- Springs in the north-eastern part of the Cooper Basin in Qld: these are commonly described as non-GAB or recharge springs. However, this is based on limited evidence, and the position of some of these springs located on fault zones means that further verification is required to characterise and identify the source of these springs.
- Streams: similar to the waterholes, there may be a contribution of groundwater to streams in some reaches, particularly where the stream courses run close to the edge of the alluvial aquifers (and are therefore in close proximity to the sub-alluvial bedrock). Furthermore, in some reaches, the stream course coincides with mapped faults, suggesting that there may be potential for some contribution from deeper formations here.

6.1.5 Potential groundwater sources for drilling

- Potential groundwater sources include produced water from conventional petroleum production, shallow aquifers (Cenozoic and Winton–Mackunda partial aquifers) and Cadna-owie–Hooray aquifers. Artesian GAB aquifers will be more expensive to access due to the depth of drilling required to reach them. However, the artesian GAB aquifers generally sustain higher flow rates with more consistent water quality than shallower aquifers such as the Winton-Mackunda partial aquifer or aquifers in the Lake Eyre Basin. It is likely that the volumes that could be extracted from one artesian GAB bore will be greater than what could be obtained from several bores into shallow aquifers.

6.1.6 Potential hydrological connections

From the interpretation of cross-sections that integrate available fault zone architecture information into the context of a regional stratigraphic, hydrogeological and hydrological framework, simplified conceptual models were developed. These highlight potential areas where interconnectivity between stressors (deep plays and prospective aquifers) and shallow assets may occur. The models also assist in the proposition of further work to test the knowledge gap hypotheses discussed in Section 6.2.3.

Five potential hydrological connectivity pathways occurring between unconventional reservoirs and aquifers, surface water systems and environmental assets in the Cooper-Eromanga-Lake Eyre basins cannot be ruled out based on existing conceptual models. Multiple potential hydrological connections are considered to be plausible, including connections associated with aquifer and aquitard architecture, proximity of assets to faults, vertical continuity of faults and geological heterogeneities near the basin margins.

The five potential hydrological connections that were identified are 1. vertical migration via dilation faults; 2. migration through porous aquifers; 3. migration through partial aquifers/aquitards; 4. migration due to contact between gas plays and overlying aquifers near the basin margin and 5. vertical migration at catchment constrictions where steep hydraulic gradients exist between alluvial aquifers and underlying GAB formations. Hydrochemistry and dissolved gas concentrations provide some evidence of potential connectivity between deep and shallow system components. Importantly, this assessment also highlights that considerable data and knowledge gaps exist, and outlines hypotheses that can be tested in future studies to determine the likelihood of potential hydrological connections between stressors and assets.

6.2 Data gaps, limitations and future directions

Knowledge gaps exist for all aquifer systems outlined in this section. Shallow aquifers are likely to be a primary target for groundwater as development of unconventional resources expands into new areas across the Cooper GBA region. The current lack of knowledge around shallow aquifers and utilisation of these shallow could be pertinent over next 5 -10 years (which is the timeframe set for the GBA program), so potentially building knowledge and baseline data on shallow aquifers may be beneficial for future management. However, there are also pertinent knowledge gaps with artesian GAB aquifers and groundwater in the Cooper Basin including understanding fluxes between the two basins. These may assist in answering questions for long-term management of artesian GAB aquifers.

The list of future investigations outlined in Section 6.2.1to Section 6.2.3 are divided into two parts. 1. Investigations that will be undertaken as part of stage 3 of the Cooper GBA project and 2. Future investigations.

6.2.1 Shallow aquifers

Key knowledge gaps that may affect management and utilisation of Lake Eyre Basin (Cenozoic) and Winton-Mackunda partial aquifers include:

- Extent of "deep" Cenozoic aquifer (below 60-80 m). Does it consist of discrete aquifer units or is it a more connected regional system? Better understanding here would define the extent of any potential groundwater resource, potential for lateral connectivity and in determining extent of future usage and management options.
- Source of recharge for deeper Cenozoic aquifer system, e.g. is it palaeo-recharge or recharge due to episodic flooding? Recharge is a key component of the water balance and understanding recharge sources is a key input to aquifer management
- Nature of boundary between shallow Cenozoic aquifer system and 'deeper" Cenozoic system. This has implications for understanding near surface impacts from future groundwater developments
- The boundary between Lake Eyre Basin (Cenozoic) sequence and top of Winton Formation is poorly defined. This boundary determines the vertical extent of Cenozoic aquifers system and is an input potential for leakage between Winton Formation
- Potential for salinisation from future development. Understanding controls on salinity will assist in determining its suitability as a long-term water resource.
- Information on water usage.
- Better understanding of groundwater-surface water interactions in Cooper Creek floodplain area including degree of recharge, eco-hydrological water use will improve any future water balance for the floodplain region.

New information and work that would assist in answering these questions include:

GBA Stage 3

- Model scenarios to determine timeframes and potential for drawdown in shallow aquifers
- A small sampling programme with be undertaken to collect hydrochemistry data and environmental groundwater tracers to provide baseline water quality data for parts of the artesian GAB aquifers. This information can be used to characterise aquifer processes and groundwater residence times and improve understanding around connectivity between different hydrostratigraphic units.
- Interrogation of existing non-groundwater data (e.g. petroleum exploration data) may provide extra information that will improve geological understanding and framework of Cenozoic and Winton-Mackunda aquifer

Future Investigations

- Installation of new monitoring bores in areas where there is potential for developments to impact key assets. Survey the locations and elevations of key existing bores.

- Time-series waterlevel data for Cenozoic or Winton-Mackunda aquifers. Reliable time-series waterlevel data will assist in determining the status of the aquifer, and if there are longer term trends that are important for future management. For instance, the reduction in pressure from 100 years of artesian aquifer extractions has decreased upwards leakage to shallow aquifers. This in turn may have longer-term implications for shallower sub-artesian aquifers. However, there is currently no monitoring data against which to determine trends or provide a baseline to monitor for future impacts.
- Water balance for aquifers in the Cenozoic and Winton-Mackunda partial aquifer in areas of interest. Anecdotal evidence suggests that the water quality and flow rates can vary considerably over short distances, which may limit availability of groundwater in a particular area. This would need to be factored into any future water balance assessment.
- Ground and airborne geophysical surveys, such as airborne or ground electromagnetics or other geophysical methods targeting aquifers in Cenozoic or Winton-Mackunda partial aquifer, would provide information between sparse bore data on the geological framework (including structures), recharge pathways, aquifer properties, water salinity and depth to groundwater.
- Investigation using spatial and temporal remote sensing data archive would assist in understanding distribution of past inundation patterns and water in landscape, groundwater-surface water interactions, floodplain and riparian vegetation dynamics and land usage. Such information would be beneficial for the future management of Cooper Creek floodplain.

6.2.2 Artesian GAB aquifers

Far fewer bores obtain groundwater from artesian GAB aquifers than shallower sub-artesian aquifers. However, artesian GAB aquifers generally have more consistent water quality, as well as higher and more sustainable flow rates than what could be obtained from shallow aquifers (see Table 3 for summary of flow rates from different aquifers).

Data gaps that may be resolved within the GBA timeframe include:

GBA Stage 3

- Improved understanding of water quality of produced waters from artesian GAB aquifers in the Cooper Basin.
- Model scenarios to determine timeframes and potential for drawdown to migrate vertically through Nappamerri Group and Rolling Downs aquitard.
- A small hydrochemical sampling programme including environmental groundwater tracers, will be undertaken to characterise aquifer processes and groundwater residence times as well as provide quality baseline data.

Future Investigations

- Artesian GAB aquifers are managed by state agencies for pressure and not volume. Improved understanding of distribution of pressures in GAB aquifers and factors that influence pressure change will assist in longer-term management of GAB aquifers. For instance, deep pressure studies could include: effect of compartmentalisation on pressure distribution, further compilation of existing pressure data (to fill data-gaps outlined in Section 2.2), potential of production related pressure drawdowns in the Cooper Basin to affect pressures in deep Eromanga Basin, and more detailed investigations of pressure gradients to elucidate potential vertical and horizontal flow paths.

- Improved understanding of water saturation and distribution of groundwater will greatly build on the conceptual understanding of how petroleum accumulations influence regional groundwater regime in the Cooper Basin.
- Understanding contributions and rate of leakage between Cadna-owie–Hooray aquifer and Winton-Mackunda partial aquifer will refine groundwater balance for both systems. It will improve understanding if pressure declines in Cadna-owie–Hooray aquifer will influence groundwater systems in Winton-Mackunda partial aquifer and Lake Eyre Basin.
- Understanding whether pressure changes due to hydrocarbon production in the Cooper Basin (or Eromanga Basin) can influence regional pressure distributions in artesian GAB aquifers would assist with long term management of pressures regime in the artesian GAB aquifers. In addition, using pressure data to investigate if variations in hydraulic head and pressure occur vertically within a formation, would improve understanding of the degree of compartmentalisation within artesian GAB aquifers. Improved understanding of pressure distribution with the aquifers, barriers and compartments will assist with future management artesian GAB aquifers, as they are managed for pressure and not volumes.

Any work towards filling these gaps will be beneficial for future management of groundwater systems in the Cooper GBA region. Work focussed on shallow sub-artesian aquifers may also assist with longer-term management of Cooper Creek floodplain.

6.2.3 Potential hydrological connections

From the analysis of existing datasets and an integrated assessment of the structural geology and hydrogeological characterisation of the Cooper-Eromanga- Lake Eyre basin system, a set of knowledge and data gaps were identified. Further investigations would be required to assist in testing questions around the preliminary potential impact pathways from stressors to the assets, as summarised in Table 10.

Table 10 Summary of potential hydrological connections, potential impacts on water and the environment, evidence base, questions and recommended investigations in the Cooper GBA region

Potential hydrological connections	Potential impacts on water and the environment	Evidence base	Questions	Possible avenues for future investigations
① Vertical migration via deep-seated dilational faults connecting unconventional gas plays to overlying aquifers	Water bores and springs that access artesian GAB aquifers	• North-south and east-west striking faults along Gidgealpa-Merrimelia-Innamincka ridges have been modelled to have some dilation tendency (Kulikowski and Amrouch, 2018a). • Hydrochemistry and pressure data indicate potential connectivity between Nappamerri Group and the lower GAB aquifer	• What is the likelihood for vertical fluid or gas migration through deep-seated faults from unconventional gas plays to overlying aquifers and near-surface assets?	**GBA Stage 3** • Model scenarios to determine timeframes and potential for drawdown to migrate vertically through Nappamerri Group and Rolling Downs Group aquitard **Future** • Collate and assess borehole image logs from oil and gas wells to analyse in-situ stress orientations • Update the three-dimensional geological model to incorporate faults • Determine areas where aquifers are displaced against aquitards
② Lateral migration through porous GAB aquifers and Winton-Mackunda partial aquifer	Water bores tapping the GAB aquifers and Winton-Mackunda partial aquifer	• Hydrocarbon shows are reported to occur in certain Eromanga Basin units that host GAB aquifers	• To what extent and at which velocity can water and/or gas migrate laterally through GAB aquifers?	**GBA Stage 3** • Hydrochemical and isotopic fingerprinting of groundwater and dissolved gases at representative bores in different hydrostratigraphic units for inter-aquifer connectivity assessment and surface water-groundwater interaction, including helium, methane and tracers such as $^{87}Sr/^{86}Sr$
③a) Lateral migration through the Rolling Downs Group aquitard via PFS	Not directly	• Not available	• Can this correspond to an actual hydrological connection between deeper and shallower aquifer systems via faults? • How effective is the Rolling Downs aquitard as a barrier to fluid movement?	**Future** • Targeted sampling for environmental tracers in Rolling Downs Group to better understand lateral connectivity.
③b) Vertical migration through the Rolling Downs Group aquitard via PFS reaching permeable intervals of the Winton-Mackunda partial aquifer	Water bores in the Winton-Mackunda partial aquifer	• Hydraulic upward flow from underlying GAB aquifer (Smerdon et al., 2012a))	• Is there evidence to confirm that fluids or gases migrate vertically and horizontally through the Rolling Downs Group aquitard due to the influence of the polygonal faulting?	**GBA Stage 3** • Model scenarios to determine timeframes and potential for drawdown to migrate through the aquitard • Targeted sampling for environmental tracers in Winton-Mackunda partial aquifer; Lake Eyre Basin, surface water and trees to better understand the hydraulic connections at shallow depths as well as with artesian GAB aquifers, which underlie the Rolling Downs Group aquitard **Future** • Carry out a sampling campaign to constrain the sources of springs in the Queensland part of the Cooper Basin, in proximity to mapped faults

Potential hydrological connections	Potential impacts on water and the environment	Evidence base	Questions	Possible avenues for future investigations
④ Migration due to contact between gas plays and overlying aquifers near the basin margin (due to the top of the Nappamerri Group pinching out and/or through inferred fault zones associated with basement highs)	Springs fed by GAB aquifers in the south (Lake Blanche Springs) and GDEs associated with lakes in the south (e.g. Lake Blanche). Impacts from shale, tight and deep coal developments would be quite indirect, as these types of plays occur in the Copper Basin, and not the Eromanga Basin.	• Hydrological connections inferred from subsurface geometry as shown in cross-sections 1 (Figure 48) and 2 (Figure 53) • Potential contributions from deep GAB aquifers to springs in SA inferred from hydrochemistry data (Section 3.5.2) • Migration due to contact between gas plays and overlying aquifers near the basin margin	• How can hydrocarbon compounds associated with GAB aquifers be distinguished from hydrocarbons associated with unconventional gas plays if detected in an asset (e.g. springs)? • Can GAB groundwater that feed spring complexes found near the south-west margin of the Cooper GBA region be differentiated from groundwater from the Patchawarra Formation (Cooper Basin)? • Is there any contribution of GAB groundwater to springs in Queensland?	**GBA Stage 3** • Model scenarios to determine timeframes and potential for fluids to migrate through the aquifer **Future** • Use oil and gas production well chemistry data to update the multi-variate statistical analysis to identify connections between deep reservoirs and shallower aquifers • Targeted sampling for environmental tracers at springs to better understand the hydraulic connection and define groundwater flow paths GAB aquifers in the vicinity of the springs. • Environment tracers, including noble gases such as helium, could detect contributions to springs in Queensland from deeper aquifers. These springs are not a priority as they are located outside the prospective areas.
⑤ Vertical migration at catchment constrictions where steep hydraulic gradients exist between alluvial aquifers and underlying GAB formations	Impacts due to extracting water, particularly from Winton-Mackunda partial aquifer and Lake Eyre Basin.	• GAB discharges into Cenozoic along fault-controlled drainage in the north-east Cooper Basin (Kellett et al., 2012a) • Potential contributions from deep GAB aquifers to springs in SA inferred from hydrochemistry data (Section 3.5.2)	• Is there sufficient evidence to confirm that mapped springs in Queensland are not supplied by GAB aquifers despite their close proximity to faulting zones mapped near the basin margins? • Are the faults mapped in the GAB and underlying hydrostratigraphic units potentially extending to permeable zones near the surface including the Winton-Mackunda, Cenozoic, alluvial aquifers and streams? • Is it proposed that the mapped GDEs will rely on perched watertables integrating the alluvial aquifer system or are they connected to more regional watertable? • Is there evidence to eliminate a potential hydraulic connectivity between the permeable intervals of the Winton-Mackunda partial aquifer with the overlying alluvial aquifer?	**GBA Stage 3** • Conduct a synoptic surface water chemistry and tracer survey along Cooper Creek to assess surface water – groundwater interaction and alluvium and bedrock connectivity • Carry out targeted sampling for environmental tracers in Winton-Mackunda partial aquifer, Lake Eyre Basin, surface water and trees to better understand the hydraulic connection. **Future** • Carry out shallow geophysical survey (e.g. transient electromagnetics (TEM)) to locate and characterise structural elements in the top 100 m near sensitive environmental assets. • Reassess two- and three-dimensional seismic lines and refine the fault zone architecture, offsets and juxtaposition analysis • Carry out hydrochemical and isotopic fingerprinting of springs in Queensland. Note that springs in Queensland occur outside the prospective area.

GAB = Great Artesian Basin; GDE = groundwater-dependent ecosystem; PFS = polygonal fault system

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Glossary

The register of terms and definitions used in the Geological and Bioregional Assessment Program is available online at http://registry.it.csiro.au/def/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.

accumulation: in petroleum geosciences, an ‘accumulation’ is referred to as an individual body of moveable petroleum

aeolian: relating to or arising from the action of wind

anticline: an arch-shaped fold in rock in which rock layers are upwardly convex. The oldest rock layers form the core of the fold and, outward from the core, progressively younger rocks occur.

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

aquitard: a saturated geological unit that is less permeable than an aquifer, and incapable of transmitting useful quantities of water. Aquitards commonly form a confining layer over an artesian aquifer.

artesian aquifer: an aquifer that has enough natural pressure to allow water in a bore to rise to the ground surface

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

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

basement: the oldest rocks in an area; commonly igneous or metamorphic rocks of Precambrian or Paleozoic age that underlie other sedimentary formations. Basement generally does not contain significant oil or gas, unless it is fractured and in a position to receive these materials from sedimentary strata.

basin-centred gas: a type of tight gas that occurs in distributed basin-centred gas accumulations, where gas is hosted in low permeability reservoirs which are commonly abnormally overpressured, lack a down dip water contact and are continuously saturated with gas. This is also sometimes referred to as 'continuous' and 'pervasive' gas.

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

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.

burial history: the depth of a sedimentary layer versus time, usually corrected for compaction

casing: a pipe placed in a well to prevent the wall of the hole from caving in and to prevent movement of fluids from one formation to another

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

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

coal seam gas: coal seam gas (CSG) is a form of natural gas (generally 95% to 97% pure methane, CH_4) extracted from coal seams, typically at depths of 300 to 1000 m. Also called coal seam methane (CSM) or coalbed methane (CBM).

compression: lateral force or stress (e.g. tectonic) that tends to decrease the volume of, or shorten, a substance

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

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

Cooper Basin: the Cooper Basin geological province is an Upper Carboniferous – Middle Triassic geological sedimentary basin that is up to 2500 m thick and occurs at depths between 1000 and 4400 m. It is overlain completely by the Eromanga and Lake Eyre basins. Most of the Cooper Basin is in south-west Queensland and north-east SA, and includes a small area of NSW at Cameron Corner. It occupies a total area of approximately 130,000 km^2, including 95,740 km^2 in Queensland, 34,310 km^2 in SA and 8 km^2 in NSW.

crust: the outer part of the Earth, from the surface to the Mohorovicic discontinuity (Moho) cumulative impact: for the purposes of geological and bioregional assessments, the total environmental change resulting from the development of selected unconventional hydrocarbon resources when all past, present and reasonably foreseeable actions are considered

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

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

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

drill stem test: an operation on a well designed to demonstrate the existence of moveable petroleum in a reservoir by establishing flow to the surface and/or to provide an indication of the potential productivity of that reservoir. Drill stem tests (DSTs) are performed in the open hole to obtain reservoir fluid samples, static bottomhole pressure measurements, indications of productivity and short-term flow and pressure buildup tests to estimate permeability and damage extent.

drilling fluid: circulating fluid that lifts rock cuttings from the wellbore to the surface during the drilling operation. Also functions to cool down the drill bit, and is a component of well control.

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

expulsion: the process of primary migration, whereby oil or gas escapes from the source rock due to increased pressure and temperature. Generally involves short distances (metres to tens of metres).

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

fluvial: sediments or other geologic features formed by streams

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.

gas saturation: the relative amount of gas in the pores of a rock, usually as a percentage of volume

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

granite: an intrusive igneous rock with high silica (SiO_2) content typical of continental regions

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) hydrostatic pressure: equal pressure in all direction, equivalent to the pressure which is exerted on a portion of a column of water as a result of the weight of the fluid above it

impact: the difference between what could happen as a result of activities and processes associated with extractive industries, such as shale, tight and deep coal gas development, and what would happen without them. Impacts may be changes that occur to the natural environment, community or economy. Impacts can be a direct or indirect result of activities, or a cumulative result of multiple activities or processes.

injection: the forcing or pumping of substances into a porous and permeable subsurface rock formation. Examples of injected substances can include either gases or liquids.

isopach: a contour that connects points of equal thickness. Commonly, the isopachs, or contours that make up an isopach map, display the stratigraphic thickness of a rock unit as opposed to the true vertical thickness. Isopachs are true stratigraphic thicknesses (i.e. perpendicular to bedding surfaces).

Lake Eyre Basin: a geologic province containing Cenozoic terrestrial sedimentary rocks within the Lake Eyre surface water catchment. It covers parts of northern and eastern SA, south-eastern NT, western Queensland and north-western NSW. In the Cooper GBA region, the basin sedimentary package is less than 300 m thick.

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

mantle: the region of the Earth composed mainly of solid silicate rock that extends from the base of the crust (Moho) to the core–mantle boundary at a depth of approximately 2900 km

material: pertinent or relevant

methane: a colourless, odourless gas, the simplest parafin hydrocarbon, formula CH_4. It is the principal constituent of natural gas and is also found associated with crude oil. Methane is a greenhouse gas in the atmosphere because it absorbs long-wavelength radiation from the Earth's surface.

migration: the process whereby fluids and gases move through rocks. In petroleum geoscience, 'migration' refers to when petroleum moves from source rocks toward reservoirs or seep sites. Primary migration consists of movement of petroleum to exit the source rock. Secondary migration occurs when oil and gas move along a carrier bed from the source to the reservoir or seep. Tertiary migration is where oil and gas move from one trap to another or to a seep.

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

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

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

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

percentile: a specific type of quantile where the range of a distribution or set of runs is divided into 100 contiguous intervals, each with probability 0.01. An individual percentile may be used to indicate the value below which a given percentage or proportion of observations in a group of observations fall. For example, the 95th percentile is the value below which 95% of the observations may be found.

perforation: a channel created through the casing and cement in a well to allow fluid to flow between the well and the reservoir (hydraulic fracturing fluids into the reservoir, or gas and oil into the well). The most common method uses perforating guns equipped with shaped explosive charges that produce a jet.

permeability: the measure of the ability of a rock, soil or sediment to yield or transmit a fluid. The magnitude of permeability depends largely on the porosity and the interconnectivity of pores and spaces in the ground.

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

petroleum system: the genetic relationship between a pod of source rock that is actively producing hydrocarbon, and the resulting oil and gas accumulations. It includes all the essential elements and processes needed for oil and gas accumulations to exist. These include the source, reservoir, seal, and overburden rocks, the trap formation, and the hydrocarbon generation, migration and accumulation processes. All essential elements and processes must occur in the appropriate time and space in order for petroleum to accumulate.

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

plug: a mechanical device or material (such as cement) placed within a well to prevent vertical movement of fluids

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

recharge: see groundwater recharge

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)

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

risk: the effect of uncertainty on objectives (ASNZ ISO 3100). This involves assessing the potential consequences and likelihood of impacts to environmental and human values that may stem from an action, under the uncertainty caused by variability and incomplete knowledge of the system of interest.

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)

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.

subsidence: the sudden sinking or gradual downward settling of the Earth's surface with little or no horizontal motion. The movement is not restricted in rate, magnitude, or area involved.

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

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.

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

total organic carbon: the quantity of organic matter (kerogen and bitumen) is expressed in terms of the total organic carbon (TOC) content in mass per cent. The TOC value is the most basic measurement for determining the ability of sedimentary rocks to generate and expel hydrocarbons.

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

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

unconformity: a surface of erosion between rock bodies that represents a significant hiatus or gap in the stratigraphic succession. Some kinds of unconformities are (a) angular unconformity – an unconformity in which the bedding planes above and below the unconformity are at an angle to each other; and (b) disconformity – an unconformity in which the bedding planes above and below the stratigraphic break are essentially parallel.

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 saturation: the fraction of water in a given pore space. It is expressed in volume/volume, percent or saturation units. Unless otherwise stated, water saturation is the fraction of formation water in the undisturbed zone. The saturation is known as the total water saturation if the pore space is the total porosity, but is known as effective water saturation if the pore space is the effective porosity. If used without qualification, the term usually refers to the effective water saturation.

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

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

watertable: the upper surface of a body of groundwater occurring in an unconfined aquifer. At the watertable, pore water pressure equals atmospheric pressure.

weathering: the breakdown of rocks and other materials at the Earth's surface caused by mechanical action and reactions with air, water and organisms. Weathering of seep oils or improperly sealed oil samples by exposure to air results in evaporative loss of light hydrocarbons.

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

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

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