Government of **Western Australia**
Department of **Water and Environmental Regulation**

Fitzroy Valley groundwater investigations 2015–18

Kimberley, Western Australia

Hydrogeological record series
Report no. HG 69
October 2023

Department of Water and Environmental Regulation
Prime House, 8 Davidson Terrace
Joondalup Western Australia 6027
Locked Bag 10 Joondalup DC WA 6919

October 2023

FIRST 116006

Acknowledgments

This report was prepared by Steve Clohessy, Scott Macaulay, Sandie McHugh, Josephine Searle and Penny Wallace-Bell. Hisayo Thornton drafted the figures.

Damien Pariman (at the time of being CEO of Walalakoo Corporation) and the Nyikina Mangala Traditional Owners (particularly John Watson and Roger Green) provided guidance for a heritage survey undertaken for the Lower Fitzroy drilling program. The Bunuba Traditional Owners provided support for the drilling and installation of bores around Fitzroy Crossing and Brooking Springs.

Fieldwork was undertaken by Steve Clohessy, Andrew Maughan, Paul Rakich, Hakan Paker, Robyn Loomes, Jacqui Schopf, Simone McCallum, Michael Braccia and Glenn Bathols.

Andrew Taylor (CSIRO) and Glenn Harrington (Innovative Groundwater Solutions – IGS) collaborated in the collection and analysis of data through the Northern Australia Water Resource Assessment program and project agreement with the Department of Water and Environmental Regulation.

Andrew Taylor (CSIRO) and Ryan Vogwill (Hydro Geo Enviro) provided scientific review. Not all of Ryan Vogwill's comments could be addressed due to time and project scope restrictions.

Recommended reference

Department of Water and Environmental Regulation 2023, *Fitzroy Valley groundwater investigations 2015–2018, Kimberley, Western Australia*, Hydrogeological record series, report no. HG69.

For more information about this report, contact:
Water Resource Science Branch, Department of Water and Environmental Regulation.

Cover photograph: Geikie Gorge, June 2017. Photo taken by S Clohessy (15/06/2017).

Disclaimer

Acknowledgement of Country

The Department of Water and Environmental Regulation acknowledges the Traditional Owners and Custodians in the Fitzroy water planning area and their deep and continuing connection to the land and waters of the region.

We pay our respects to Elders past and present, and to all members of the Aboriginal communities in the area and their cultures. We acknowledge the Traditional Owners have been Custodians of Country for countless generations and that water is integral to life.

We recognise that Aboriginal people and their culture across the Fitzroy water planning area are diverse and that continued custodianship of the land and water is fundamental to their health, spirit, culture and community.

We embrace the spirit of reconciliation, and we seek to listen, learn and build strong partnerships with genuine opportunities for Aboriginal people throughout our business.

The Fitzroy River and its tributaries is known by several names across its many nations, including the Martuwarra. To respect these differences in language we have not used dual naming in this report.

Contents

Figures

Tables

Shortened forms

AEM	Airborne electromagnetic
AHD	Australian height datum
AWRC	Australian Water Resources Council
bgl	Below ground level
BoM	Bureau of Meteorology
CFC	Chlorofluorocarbon
CSIRO	Commonwealth Scientific Industrial Research Organisation
DMIRS	Department of Mines and Industry Regulation and Safety
DWER	Department of Water and Environmental Regulation (formerly the Department of Water)
EC	Electrical conductivity
IGS	Integrated Groundwater Solutions
K	Hydraulic conductivity
NAWRA	Northern Australia Water Resource Assessment
TDS	Total dissolved solids
WIR	Water Information Reporting

Summary

The Fitzroy Valley in the Kimberley region of Western Australia is an area of great ecological, social, cultural and economic value.

The Fitzroy River, its tributaries and floodplains are recognised under the West Kimberley National Heritage Place listing and there are numerous registered sites under Western Australian Aboriginal heritage legislation. The Fitzroy is also one of Australia's last remaining wild rivers.

There is a large regional groundwater system underlying the Fitzroy Valley which sits within the Canning Basin, the largest sedimentary basin in the state. There is increasing interest in developing the groundwater resources of the system's principal regional aquifers – the Grant Group and Poole Sandstone (the Grant Poole), the Devonian Reef Complex (Devonian Reef) and the Fitzroy River alluvial aquifers – to expand economic opportunities.

Groundwater use in the Fitzroy Valley has been historically low and, until recently, more was known about the region's resources at a broad, regional scale. The findings of earlier studies (based on the available data) were usually high level or preliminary. Nevertheless they pinpointed where gathering more information would be most useful.

The regional Grant Poole aquifer contains groundwater that is low to moderately saline, with bore yields generally suitable for sustaining large-scale development. The regional and alluvial aquifers are known to be connected to the Fitzroy River in some areas, where they maintain pools with high ecological value. The interactions between these pools, the river and the groundwater systems are often variable and complex.

A more targeted approach to gathering geological and hydrogeological information was needed – not only to understand the potential impacts of future use on cultural and ecological water requirements, but also to help formulate new groundwater management strategies for inclusion in a Fitzroy water allocation plan. To this end, the Western Australian and Australian governments funded a series of groundwater investigations in the Fitzroy Valley between 2015 and 2018.

The Department of Water and Environmental Regulation (the department) completed a series of drilling programs, installed purpose-built monitoring bores, and collected targeted airborne electromagnetic (AEM) data. In addition, several groundwater and surface water sampling campaigns were conducted. From newly installed monitoring bores we collected time-series groundwater-level data for multiple aquifers in the Fitzroy Valley for the first time.

This report presents the findings of the department's groundwater investigation. These findings – combined with a recent analysis of data from surface water gauges and information from previous studies on groundwater–surface water interactions – have updated our understanding of the geology and hydrogeology of key geological units. The findings include new and revised information on groundwater recharge,

inter-aquifer connectivity and groundwater–surface water interactions with the Fitzroy and Margaret rivers. We also evaluate potential groundwater prospectivity and highlight important groundwater management considerations for both the regional and alluvial aquifers.

The investigations confirmed that the Grant Group and overlying Poole Sandstone are regionally extensive, and information from petroleum exploration bores suggests their combined thickness is up to 2,000 m.

Using the AEM information alongside lithological and stratigraphic bore data, we partially reassessed the geometry and extent of the Grant Group and Poole Sandstone and found that outcrop areas in the Camballin region of the Grant Ranges were smaller than previously mapped.

We also found that the mapped outcropping and sub-cropping extent of the Noonkanbah Formation – which overlies the Grant Group and Poole Sandstone and generally acts as an aquitard – outcrops more extensively than previously thought. The revised mapping of the formation also shows it directly underlies the Fitzroy River in an area that was previously mapped as part of the Grant Group and Poole Sandstone. In this area, the formation impedes any flow from the regional aquifer system to the river.

Groundwater chemistry analyses revealed connectivity between the Grant Poole aquifer and the Devonian Reef aquifer on the Lennard Shelf, upstream of Fitzroy Crossing. Groundwater composition in the deeper Grant Group of the Grant Poole aquifer in the Fitzroy Trough also suggests some contribution from either the Fairfield Group or Devonian Reef aquifers. Impacts to both of these aquifers and their water-dependent ecosystems would need to be considered if significant groundwater were to be taken from the Grant Poole aquifer in the future.

Interpretation of environmental tracer composition in groundwater was used to estimate mean residence times, as well as groundwater recharge rates for the Grant Poole aquifer. We adopted multiple approaches not only to estimate groundwater recharge to balance the different assumptions, parameters, limitations and time scales of each method, but also to provide a robust analytical assessment of recharge from the available data. Approaches for recharge estimation included the chloride mass balance method, the use of chlorofluorocarbon and radiocarbon compositions in groundwater.

Groundwater residence times were up to 40,400 years for the deep confined Grant Poole aquifer, reflecting more complex and longer regional groundwater flow paths. Median recharge rates where the aquifer is confined are about 12.6 mm/year.

Groundwater from the Grant Poole aquifer is most prospective and easy to access where it outcrops. Major outcrop areas are around the Grant, Poole and St George ranges and the Lennard Shelf, and groundwater in the Grant Poole aquifer is predominantly of good quality and suitable for irrigation supplies. Generally, bore yields in these areas have the potential to sustain large-scale development. Outside the outcrop areas, the top of the aquifers can be more than 300 m below ground level and are less prospective as drilling costs can be prohibitively expensive.

Where the Grant Poole aquifer is confined, groundwater pressures are high, and hydraulic heads have been recorded as artesian and/or within a few metres of the ground surface.

The Wallal aquifer was not a major focus of these investigations yet preliminary work suggests it is a highly prospective groundwater resource, with an extensive outcropping area in the south-west of the Fitzroy catchment. More work is needed to confirm this prospectivity. The aquifer discharges to the Fitzroy River around Willare, and to springs as vertical discharge.

The Fitzroy River alluvium covers a large area that mirrors the floodplain extent. Drilling investigations have found it to be more heterogeneous (made up of riverbed sand, clay and silt) than previously thought. Interpretation of its groundwater chemistry indicates it is recharged predominantly by rainfall and surface water flows, and by upward leakage from the confined Grant Poole aquifer along fault-induced preferential pathways in the area around Noonkanbah. Hydrochemistry findings suggest the alluvial aquifer may receive recharge from all regional aquifers (depending on geological extent).

Groundwater chemistry confirms that the alluvial and regional aquifers are hydraulically connected to the Fitzroy and Margaret rivers and the findings show that this interaction is complex. Due to multiple hydrogeological controls, it varies spatially and temporally with changes in river and groundwater flow. The investigation significantly improves our understanding and mapping of surface water–groundwater interaction along reaches of both the Fitzroy and Margaret rivers.

New groundwater-level data confirms that the alluvial aquifer seasonally discharges groundwater to the Fitzroy and Margaret rivers. Elevated radon activities observed around Snake Creek, the Noonkanbah reach of the Fitzroy River, Geikie Gorge and the Margaret River from Fitzroy Crossing to Margaret Gorge also support this finding.

Groundwater discharge to the rivers and their tributaries, or the alluvial aquifer, may be critical for supporting river ecology, including aquatic freshwater species and riparian vegetation during the dry season. Groundwater discharge may result in both the persistence of river pools through the dry season (water quantity) and the maintenance of water quality parameters (temperature and salinity, dissolved oxygen) within the critical ranges for supporting various ecological species.

The groundwater residence times range from less than 10 years (indicating areas of highest groundwater recharge) to 40,000 years for the deep Grant Poole aquifer.

Recharge estimates for the alluvial aquifer range from 49 mm/year to 181 mm/year with a median of 89 mm/year. Groundwater quality ranges from fresh (less than 500 mg/L close to the river) to saline (greater than 20,000 mg/L further away). The groundwater supports permanent freshwater pools with significant ecological value and may also be useful for small, localised water supplies, such as for stock and domestic use. However, given our findings reveal a more heterogenous alluvial aquifer, previous storage estimates may be too high.

We also estimated recharge rates for the Liveringa Group aquifer, which is considered a minor aquifer in some areas (median recharge rate of 0.3 mm/year), and the Devonian Reef aquifer (25.2 mm/year).

Unexpectedly we found some possible paleochannels of Grant Group sediments where the channels appear to be incised into the Fairfield Group around Fitzroy Crossing and Gogo Station. This finding is based on 2015 AEM geophysical survey data and needs to be verified by drilling. If verified, these paleochannels could be a prospective water resource.

These investigations, combined with previous studies of the Fitzroy Valley, have contributed to an improved understanding of regional and localised groundwater systems and potential groundwater availability. In addition, it has provided new purpose-built monitoring infrastructure, multiple useable regional-scale datasets and new information to underpin future groundwater management in the region.

1 Introduction

1.1 Context

This report describes a series of groundwater investigations conducted in the Fitzroy Valley between 2015 and 2018. The Department of Water and Environmental Regulation (the department) conducted the investigations under the State Government's Water for Food (WfF) program and the State Groundwater Investigation Program (SGIP). The Australian Government also funded groundwater investigations in the Fitzroy Valley as part of the Northern Australia Water Resource Assessment (NAWRA) project (Taylor et al. 2018). This work was carried out in partnership with the department.

At present only a small amount of groundwater is used in the Fitzroy Valley, about 4.8 gigalitres (GL) per year over an area of more than 37,000 km^2. Thus far it has been appropriate to have broad baseline hydrogeological knowledge, groundwater management through licensing, and regional-scale groundwater monitoring (as per DoW 2011).

However, in response to the projected increase in demand for water in the Fitzroy Valley, and the high social, cultural and environmental values associated with that water, the department will develop a Fitzroy water allocation plan. The plan will be informed by the numerous investigations described in this report.

The department's Fitzroy Valley groundwater investigations began in 2015. The federally funded NAWRA program started its Fitzroy work in 2016, following the Australian Government's 2015 *White paper on developing northern Australia*.

CSIRO was contracted by the Australian Government to complete NAWRA's Fitzroy Valley groundwater investigation work, and a project partnership was developed between the department and CSIRO in 2016. This partnership allowed the combined project resources to be used more effectively and for data to be shared.

The partnership aimed to understand how increased groundwater use might affect the Fitzroy River, as well as the social, cultural and environmental values of the Fitzroy Valley as a whole. It sought to better characterise regional groundwater systems and identify where groundwater might be available for the benefit of water users interested in diversifying their operations to include irrigated agriculture. The partnership collated and reviewed existing hydrogeological data, installed purpose-built groundwater monitoring bores, sampled groundwater throughout the Fitzroy Valley, and sampled surface water along the Fitzroy and Margaret rivers.

NAWRA's Fitzroy Valley groundwater investigation produced two reports: Taylor et al. (2018), which has a catchment-scale focus and contains much of the same groundwater and river sampling data that both organisations collected in 2016 and 2017; and Dawes et al. (2018), which developed an initial water balance between the Grant Group and Poole Sandstone aquifers.

This report details the outcomes of the department's groundwater investigations and builds on much of the same data and analyses described in Taylor et al. (2018).

1.2 Investigation aims and objectives

The objectives of this investigation centred on obtaining new information to underpin future water planning and management in the Fitzroy Valley to meet projected demand, specifically to:

- enable efficient use of groundwater from the Grant Poole Sandstone aquifer while managing potential environmental, social and cultural impacts
- support groundwater planning, policies and management decisions for a Fitzroy water allocation plan with an updated hydrogeological conceptualisation of the groundwater systems.

To support these objectives, we developed a number of technical aims:

- update knowledge of the geometry and extent of the Grant Group and Poole Sandstone outcrop areas
- provide a regional-scale assessment of groundwater recharge to the Fitzroy River alluvial aquifer, as well as to multiple regional aquifers including the Grant Poole and Devonian Reef aquifers
- assess the hydraulic connectivity between the Devonian Reef, Grant Poole and the Fitzroy River alluvial aquifers
- assess groundwater–surface water connectivity between the regional and alluvial aquifers and the Fitzroy and Margaret rivers.

1.3 Fitzroy Valley study area

Figure 1 shows the Fitzroy Valley study area, which includes part of the Fitzroy Trough and Lennard Shelf. It takes in the mouth of the Fitzroy River near Willare in the study area's north-west, and the Margaret River to Margaret Gorge to the south-east. We have not included the Derby region in the investigation: this area is covered by other allocation plans.

Existing hydrogeological data indicates the Grant Poole aquifer has good potential as a water resource (Harrington & Harrington 2015); as such, it was the main target of the groundwater investigations both of the department and NAWRA.

The Grant Poole aquifer is thickest in the Fitzroy Trough and extends further than the study area's boundaries. The Fitzroy River surface water catchment also extends further than the study area, and the catchment area does not follow hydrogeological boundaries.

Multiple pastoral stations are located within the study area, namely Mount Anderson, Liveringa, Myroodah, Noonkanbah, Kimberley Downs, Brooking Springs, Quanbun Downs, Jubilee Downs, Gogo and Fossil Downs – see Figure 2.

The pastoral stations (Figure 2), Aboriginal communities (Figure 3) and the towns of Camballin and Fitzroy Crossing all rely on groundwater for their water supplies and are therefore stakeholders in this study.

1.4 Groundwater use

We looked at groundwater use across the Fitzroy River Catchment and the extent of the Grant Poole aquifer, excluding a small portion around Derby which is managed under the *Derby groundwater allocation plan: draft for public comment* (DWER 2020a)

Annual licensed groundwater use in this area has historically been low and is managed by the department on a case-by-case basis through the licensing process.

As of June 2022, licensed groundwater entitlements totalled 4.2 GL/year. These are spread across aquifers hosted in the Wallal Sandstone, Erskine Sandstone, Grant Group and Poole Sandstone, Liveringa Group and Devonian reef complex.

The aquifer hosted in the Grant Group and Poole Sandstone is mainly used as a source of potable water supply for the towns of Camballin and Fitzroy Crossing, as well as for Aboriginal communities, including Looma and Jarlmadangah.

A preliminary estimate of unlicensed groundwater use at remote communities is 1.7 GL/year. This includes small domestic garden bores in local communities, and unlicensed drinking water for communities. The total volume of stock water which is drawn from shallow bores distributed across this area is approximately 15.2 GL/year.

Groundwater abstraction is metered for larger licences (e.g. town water supply bores), however most production bores within the study area are not metered. This means actual data on groundwater use is generally not available. In these cases, the department uses groundwater licence volumes as a surrogate for abstraction for groundwater planning and management purposes.

More comprehensive data on actual water use will become available in the future, as new metering regulations come into effect.

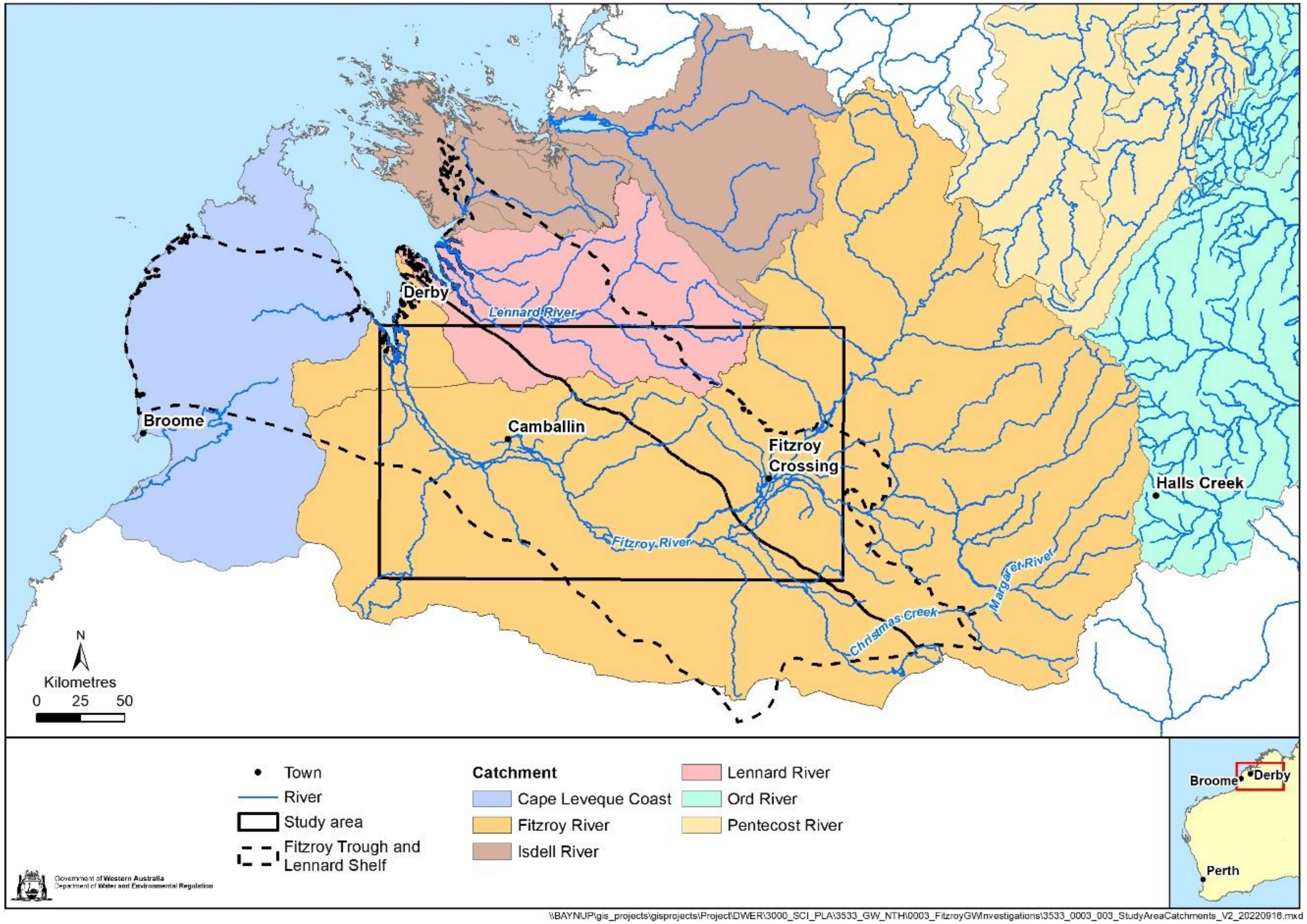


Figure 1 Study area and catchment boundaries

Note: Grant Group thickness and extent from Mory (2010).

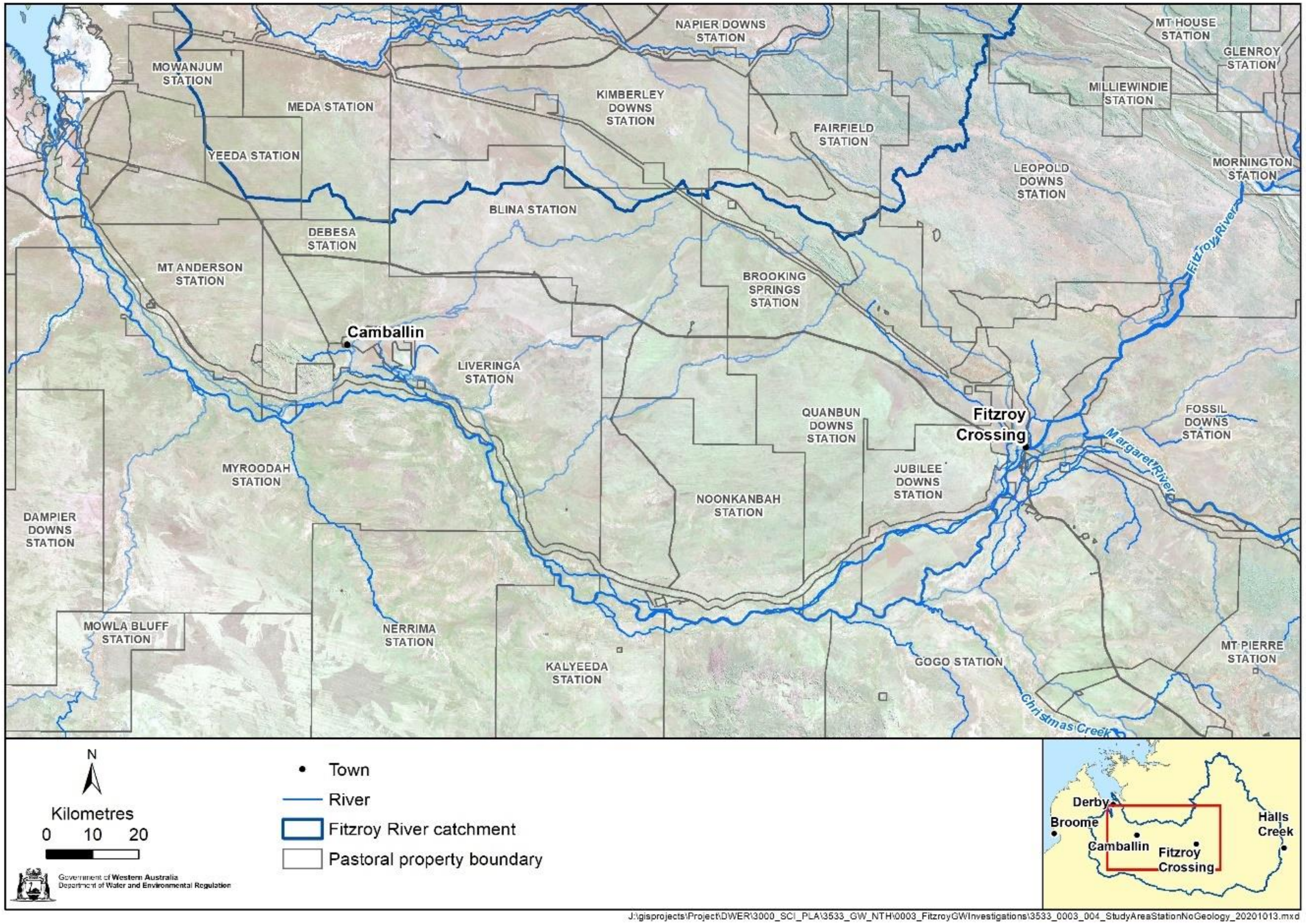


Figure 2 Pastoral stations within the study area

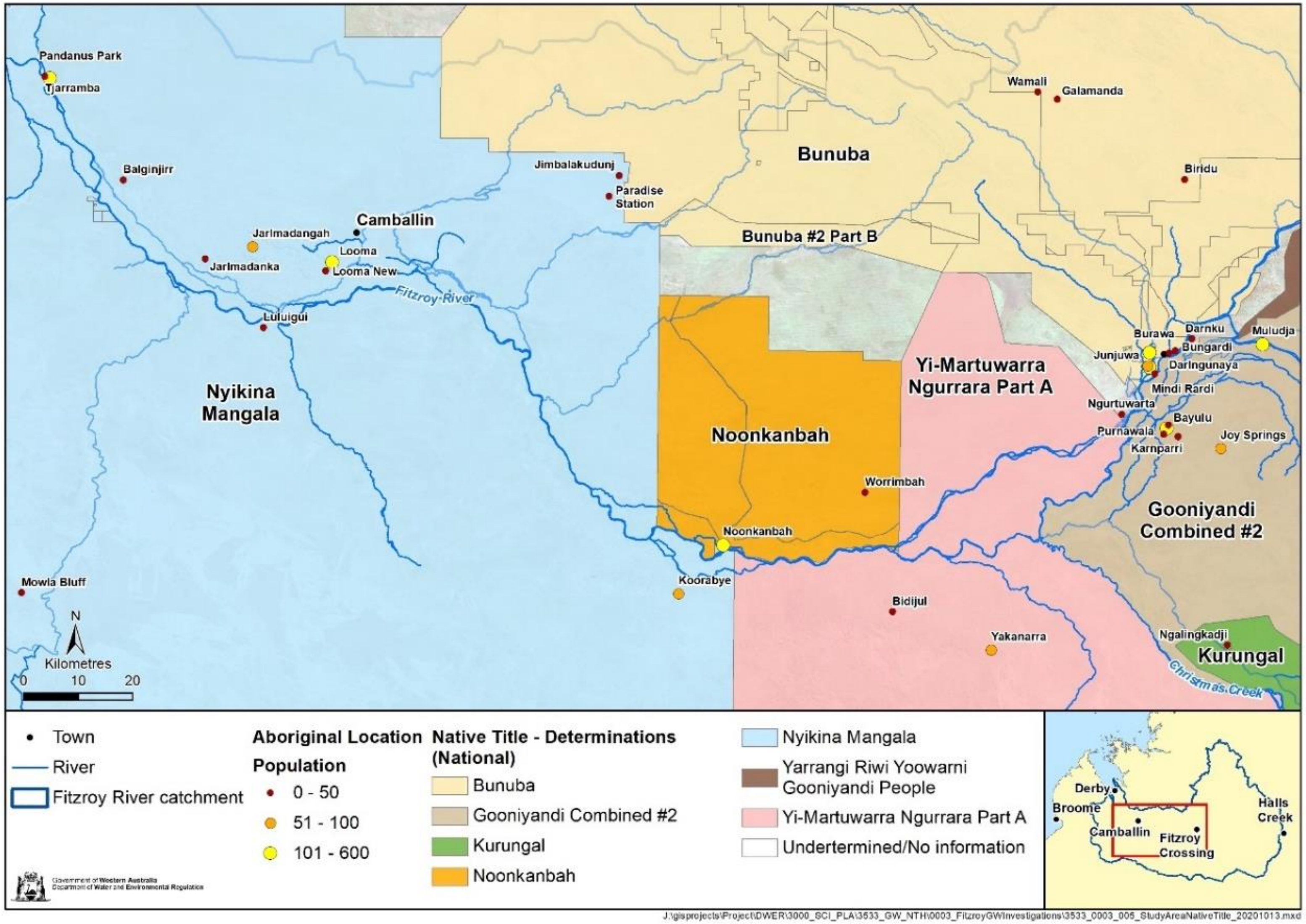


Figure 3 Native title determinations across the Fitzroy study area

2 Setting and background

2.1 Summary of previous work

Several previous studies have investigated the geology and hydrogeology of the Fitzroy Valley. This section summarises the key publications. See the References for a complete list of the publications referred to throughout this study.

Lindsay and Commander (2005) focused on the alluvial aquifer hosted in the Fitzroy River alluvium. This desktop assessment was in response to the idea that water might be transported from the Kimberley to south-west Western Australia.

The assessment found the alluvial aquifer could potentially contain groundwater storage of 13,000 GL, and simple numerical modelling showed that pumping at around 2,000 m^3/day/km of river could be achieved for a drawdown of about 0.5 m at the riverbed.

The assessment was based on limited bore data and assumed that bores located within the area of Willare, Fitzroy Barrage and Gogo Station were representative of the entire Fitzroy River alluvial aquifer. The numerical model simulated pumping from a line of equally spaced production bores along the banks of the Fitzroy River.

Because the study was based on limited data, the derived estimates were viewed as broadly indicative only. The estimated potential storage of 13,000 GL, based on the simplified conceptual model, was unlikely to reflect the actual proportion of sand and gravel that comprise the entire alluvial aquifer. The study recommended an investigation program including an aerial geophysical survey, drilling and pumping tests to define the extent and hydraulic properties of the alluvial aquifer.

Mory (2010) provided a comprehensive geological assessment of the Mid-Carboniferous to Lower Triassic stratigraphy of the Canning Basin, which takes in the Fitzroy Valley study area. It also assessed the potential for hydrocarbon generation and/or CO_2 sequestration.

The study included maps showing the tectonic elements of the Canning Basin, highlighting the Fitzroy Trough and Lennard Shelf. It interpreted data from petroleum wells to constrain the regional geological conceptualisation and provided isopach maps for the Grant Group, Poole Sandstone, Noonkanbah Formation, Liveringa Group and Blina Shale. These maps were used to support the geological interpretations described in this report.

Harrington et al. (2011) provided a synthesis of research projects undertaken by the CSIRO as part of the Tropical Rivers and Coastal Knowledge (TRaCK) program, the Northern Australia Sustainable Yields project and the Raising National Water Standards program (which was a collaboration between CSIRO and the then Department of Water).

The 2011 report also documented the results of a river sampling program and the installation of a series of groundwater monitoring bores near the Fitzroy River at

Noonkanbah Station. This study identified two zones where it was likely that significant groundwater discharge to the river was occurring:

- From the Liveringa Group aquifer: groundwater appeared to discharge to the river through the alluvial aquifer around the confluence of the Fitzroy River and the Cunningham Anabranch.
- From the confined Poole Sandstone aquifer: upward leakage appeared to flow along fault-induced preferential pathways through the alluvial aquifer to recharge the Fitzroy River around Noonkanbah Station.

The study also included simplified numerical modelling of river chemistry profiles. The modelling suggested groundwater was discharging at a total rate of about 102 ML/day along a 100 km stretch of the Fitzroy River around Noonkanbah. This comprised about 3.7 ML/day from the regional aquifers, with the remaining discharge sourced from the Fitzroy River alluvial aquifer.

These results were confirmed by Gardner et al. (2011), which presented findings based on helium-4 (^{4}He) and radon-222 (^{222}Rn) data from the same CSIRO project. While these investigations were only undertaken at a few locations, the findings supported the assessment that groundwater is significant in maintaining dry season flows and pools in parts of the Fitzroy River.

In 2015, Innovative Groundwater Solutions (IGS) undertook a desktop review of the hydrogeology of the Fitzroy Valley from Willare to an area around 100 km north of Fitzroy Crossing. The review by Harrington and Harrington (2015):

- summarised the current hydrogeological understanding of the region
- identified areas with potential for groundwater development
- outlined gaps in knowledge, and
- recommended certain investigations to address those gaps.

See the Department of Primary Industries and Regional Development website for a copy of the review.

2.2 Regional geology

2.2.1 Structural setting

Our Fitzroy Valley groundwater investigation focuses on the north-eastern part of the Canning Basin and includes areas of both the Fitzroy Trough and Lennard Shelf (Figure 4). The Fitzroy Trough is an elongate north-west-trending depocentre containing Quaternary to Ordovician Age sediments up to about 15 km thick (Mory 2010). It is bounded to the north by the Pinnacle Fault System and to the south by the Fenton Fault System (Figure 5).

The Lennard Shelf also trends in a north-westerly direction, and runs adjacent to the Fitzroy Trough, north of the Pinnacle Fault System. The Jurgurra Terrace and

Barbwire Terrace are to the south of the Fitzroy Trough and the Fenton Fault System.

The sediments of the Fitzroy Trough are folded with major anticlinal features trending east-north-east (Figure 6), outcropping in the south-western parts of the trough (Grant Group and Poole Sandstone). The sediments on the Lennard Shelf dip to the south-west.

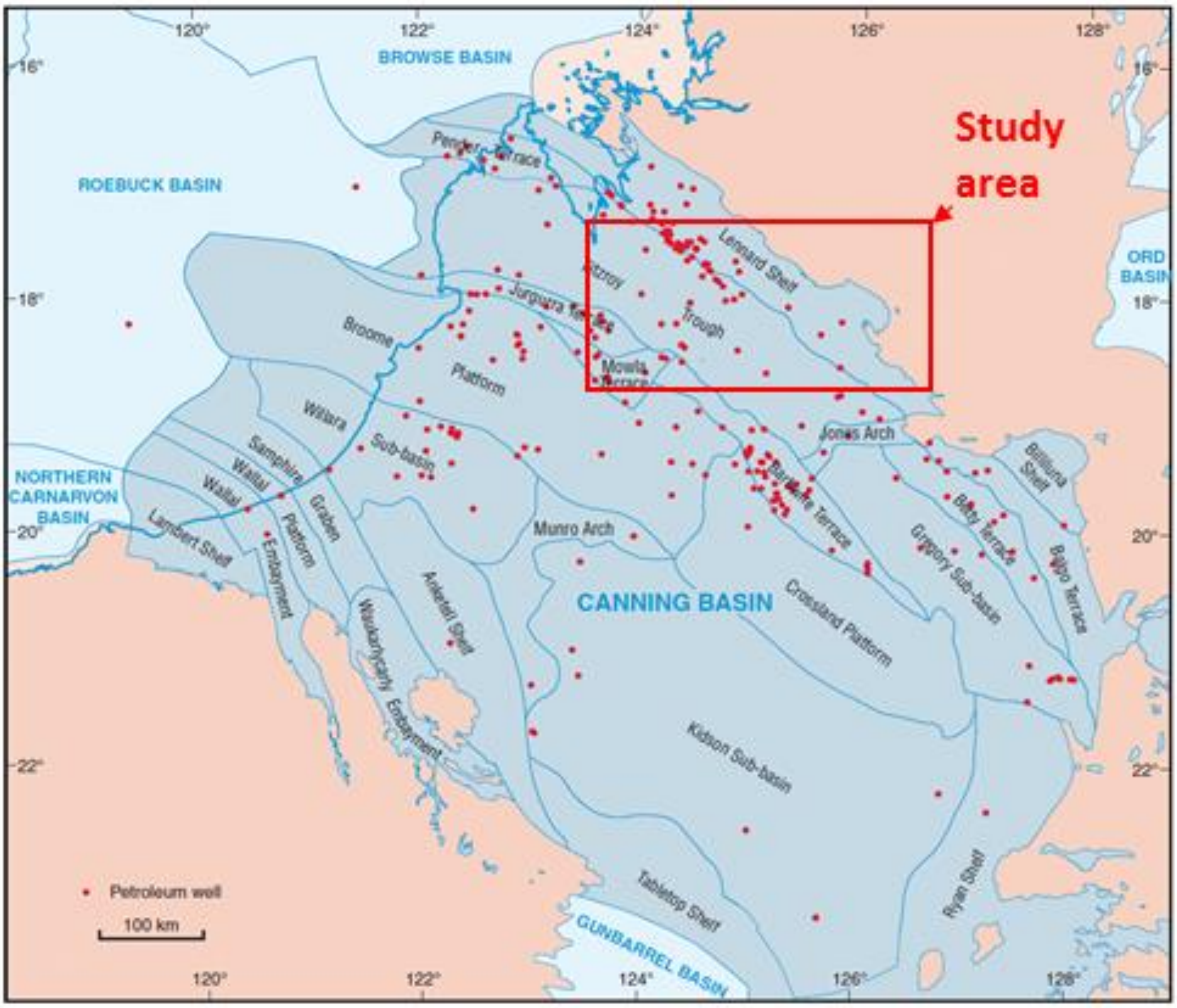


Figure 4 Tectonic elements of the Canning Basin

Note: Adapted from Mory (2010).

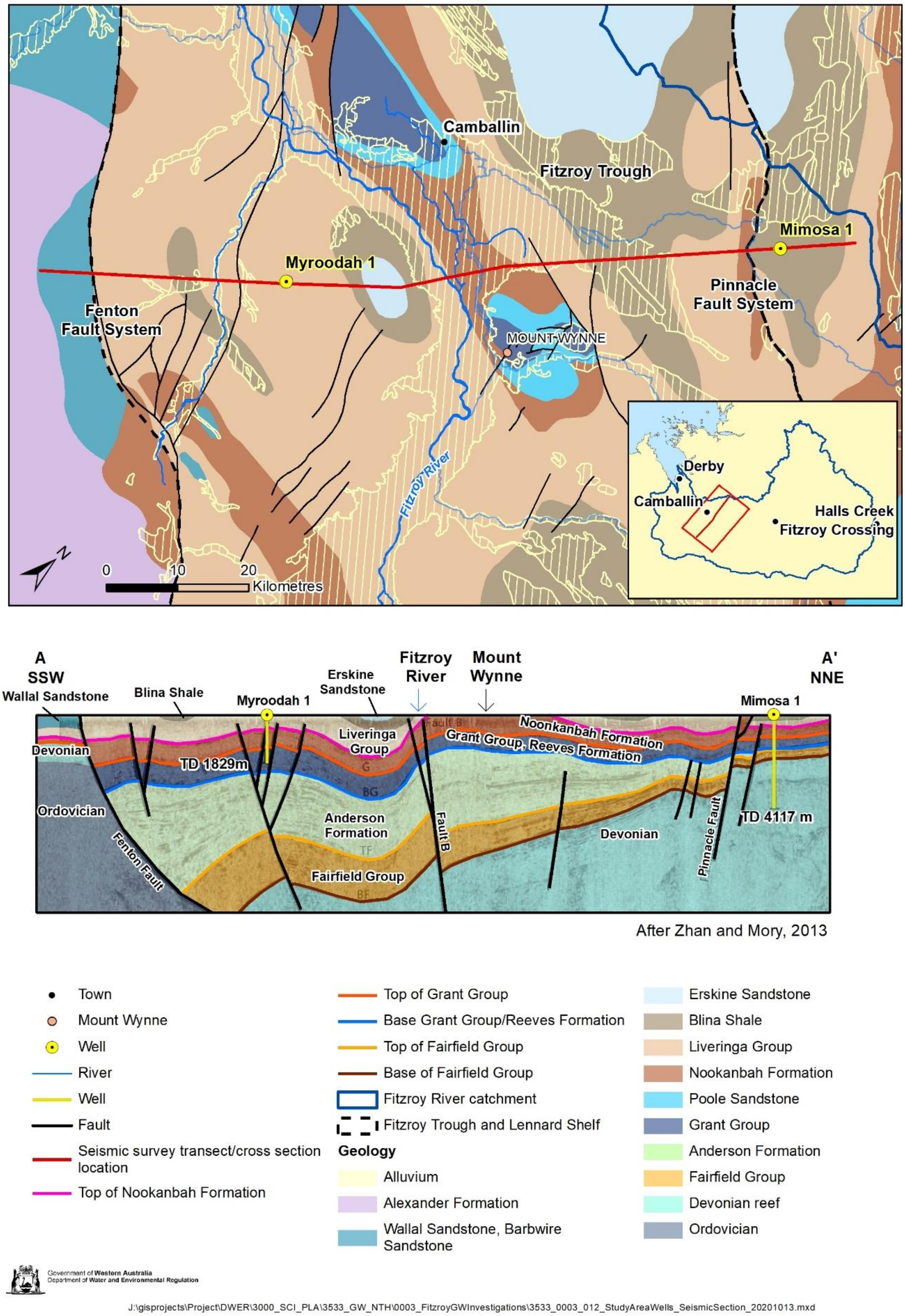


Figure 5   Cross-section across the Fitzroy Trough study area

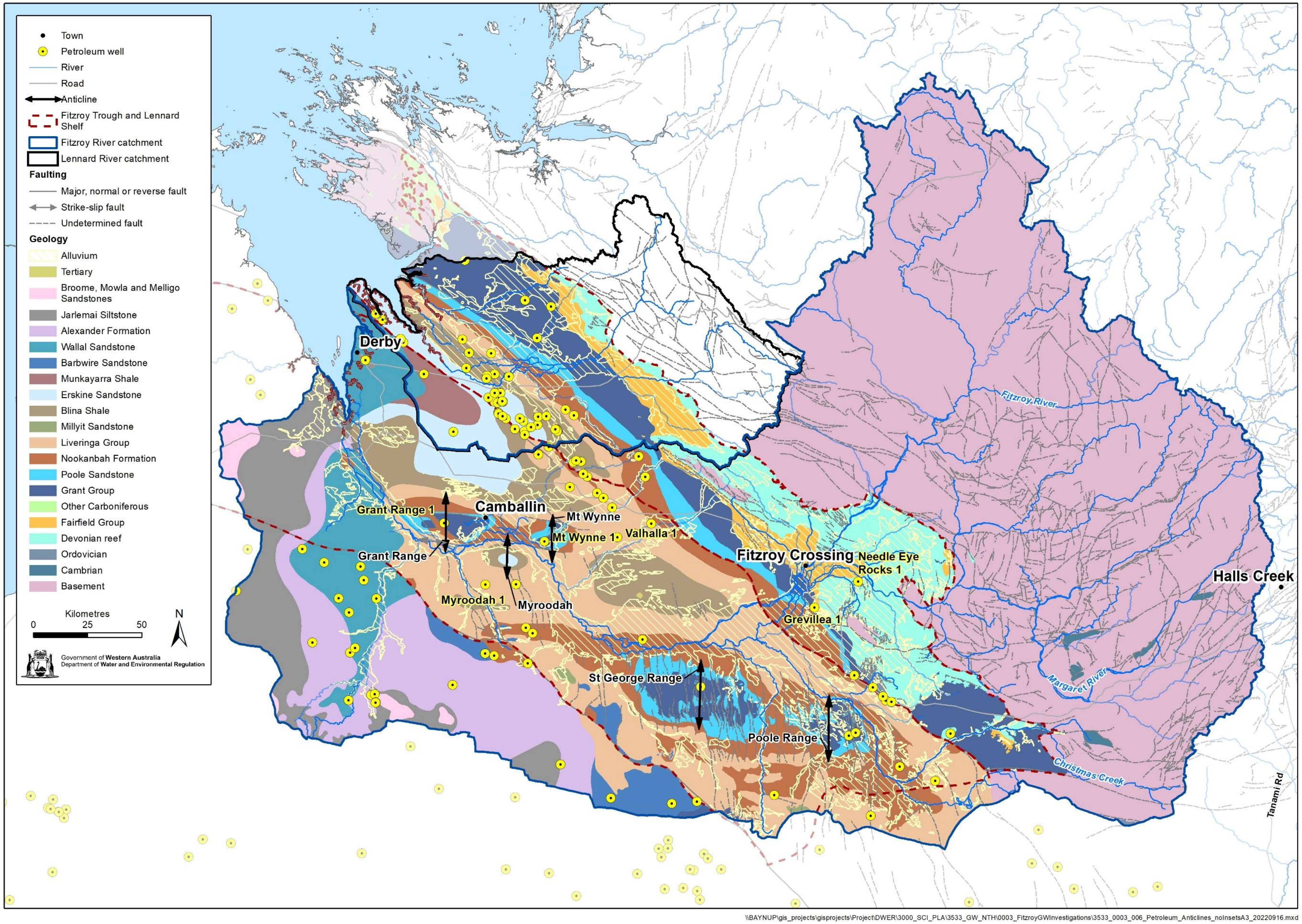


Figure 6 Regional geology, petroleum wells and anticlinal structural features in the Fitzroy Trough

Note: Not all petroleum well names are labelled due to lack of space, but they can be found by referring to Mory (2010).

2.2.2 Stratigraphy

This section briefly describes the following units in their order of deposition (oldest to youngest): the Devonian reef complex, Fairfield Group, Anderson Formation, Grant Group, Poole Sandstone, Noonkanbah Formation, Liveringa Group, Blina Shale, Erskine Sandstone, Munkayarra Shale, Wallal Sandstone and the Fitzroy River alluvium.

Figure 7 shows a simplified stratigraphy for the study area. For more detailed descriptions, see Backhouse and Mory (2020), Mory (2010), Playford et al. (2009) and Zhan and Mory (2013).

Devonian reef complex

The Devonian reef complex of the Canning Basin is present at the surface of a series of outcropping limestone ranges about 350 km long and up to 50 km wide (Figure 8). Sediments of the reef complex are the oldest outcropping rocks in the study area and are up to 2000 m thick, underlying the other units in the Fitzroy Trough. Originally deposited as a series of limestone reefs during the middle to upper Devonian period, they record about 20 million years of barrier reef system development (Playford et al. 2009).

The reef complex is restricted to the Lennard Shelf (Playford et al. 2009) and is bounded on its southern side by the Pinnacle Fault system (Figure 5). It outcrops to the north, south and east of Fitzroy Crossing, with notable outcrops at Geikie Gorge, Windjana Gorge, Tunnel Creek and the Mimbi Caves.

Fairfield Group

The Fairfield Group is Late Carboniferous in age. Within the study area, it overlies the Devonian reef complex and is unconformably overlain by the Anderson Formation (Seyedmehdi 2019).

In the study area the maximum known thickness of the Fairfield Group is more than 2,500 m, based on information from the Grevillea 1 petroleum well (Figure 6). The depth to the top of the Fairfield Group averages around 2,000 m below ground level (Harrington & Harrington 2015). The Fairfield Group outcrops in a north-west-trending strip along the Lennard Shelf (Figure 6).

The Fairfield Group comprises three separate members which, in order of oldest to youngest, are the Gumhole Formation, Yellow Drum Formation and Laurel Formation (Druce & Radke 1979).

Recent re-interpretations of the stratigraphy have proposed a fourth unit at the base of the Fairfield Group. This unit, the May River Shale (Seyedmehdi 2019), has been interpreted by some researchers as being present across both the Fitzroy Trough and Lennard Shelf. However, at the time of writing this report, the May River Shale was not formally recognised as a stratigraphic unit (Geoscience Australia & Australian Stratigraphy Commission 2017) and was not included in this study.

Instead, we have used the three-formation structural interpretation of the Fairfield Group described by Druce and Radke (1979).

Period	Stage*	Age (~Ma) *	Spore-pollen zonation**	Fitzroy Trough and Lennard Shelf
Early Jurassic	Callovian - Oxfordian	157–163		Wallal Sandstone
Early – Middle Triassic	Olenekian – early Asinian	243–247	*T.plafordii, S. quadrifidus*	Erskine Sandstone
Early Triassic	Olenekian	247–250	*T. playfordii, K. saeptatus*	Blina Shale
Mid – Late Permian	Roadian – Wuchiapingian	257–275	*D. villosa, D. granulate, D. ericianus, D. dulhuntyi , D. parvithola*	Liveringa Group
Permian	Artinskian – Kungurian	275–287	*S.fusus, D.byroensis, M. trisina, P. sinuosus*	Noonkanbah Formation
Early Permian	Sakmarian	287–289	*P. pseudoreticulata*	Poole Sandstone
	Asselian – early Sakmarian	290–295	*P.confluens, M.tentula?*	Carolyn Formation (Grant Group)
				Winfred Formation (Grant Group)
				Betty Formation (Grant Group)
Mid – Late Carboniferous	Visean – early Moscovian	330–315	*M. tentula, D.birkheadensis, D tenuistriatus, S.ybertii*	Reeves Formation
Carboniferous	Visean	330–350	*G. frustulentus, G. spiculifera, A. largus, G. maculosa*	Anderson Formation
Late Carboniferous	Tournaisian	350–360	*G. spiculifera, G. frustulentus*	Laurel Formation (Fairfield Group)
				Yellow Drum Formation (Fairfield Group)
				Gumhole Formation (Fairfield Group)
Mid – Late Devonian	Givetian - Famennian	360–390	*Retispora lepidophyta*	Devonian Reef Complex

* Source: Nicoll et al. (2009) Canning Basin Biozonation and Stratigraphy *and* Backhouse & Mory (2020) Mid-Carboniferous – Lower Permian palynozonation and stratigraphy

** Source: Mory (2010) A review of mid-Carboniferous to lower Triassic stratigraphy, Western Australia

Legend: Conformity; Unconformity; Disconformity

Figure 7 Simplified stratigraphy of the study area

The Laurel Formation of the Fairfield Group outcrops in the area around Fitzroy Crossing and along the Lennard Shelf and was the only one of the Fairfield Group's three formations intersected by drilling during this investigation.

The lithology of the Laurel Formation consists of a basal limestone, overlain by a siltstone unit and minor dolomite (Druce & Radke 1979; Seyedmehdi et al. 2016). The formation was deposited during a marine transgression, and the depositional facies range from open marine to lagoonal (Druce & Radke 1979).

Anderson Formation

The Anderson Formation is an early Carboniferous period unit that conformably overlies the Fairfield Group and, in turn, is unconformably overlain by the Grant Group or the Reeves Formation (Figure 7). It comprises thick deltaic deposits of interbedded sandstone, siltstone and shale, with minor amounts of limestone, dolomite and anhydrite (Smith 1992). The unit was deposited during a marine regression.

The unit is found throughout the study area and is known to be up to 1,800 m thick (Mory 2010). The type-section of the Anderson Formation is described in petroleum well Grant Range 1 (Figure 6), where it was found to extend from 2,404 to 3,936 m below ground level (Mory 2010).

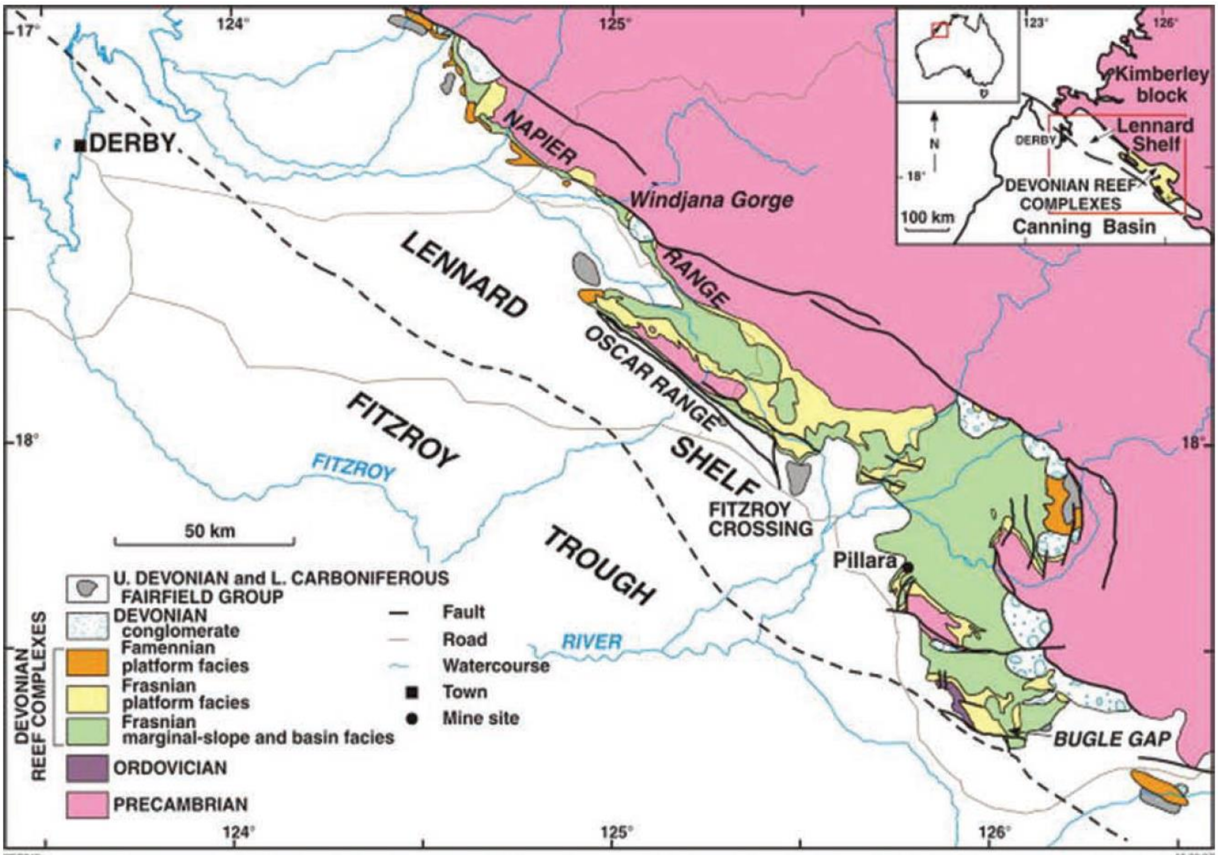


Figure 8 Extent of Devonian reef complex in the study area

Note: Reprinted from Playford et al. 2014

Reeves Formation

The Reeves Formation is a mid- to upper-Carboniferous unit (Backhouse & Mory 2020) and is represented in wells mostly located in the Fitzroy Trough (Mory 2009).

The unit is underlain by either the Anderson or Laurel Formations beneath a regional unconformity at the base of the Reeves Formation (Nicoll & Druce 1979; Zahn & Mory 2013). At the top of the Reeves Formation, palynology indicates a hiatus in deposition, separating the formation from the overlying Grant Group (Backhouse & Mory 2020).

The Reeves Formation consists of siliciclastic facies, which are the result of fluvial and shallow water (possibly marine) depositional environments (Backhouse & Mory 2020). It is dominated by thick, clean sandstones and has a maximum known thickness of up to 715 m (in Grant Range 1 of Backhouse & Mory 2020). It is not known to outcrop anywhere over its extent.

Grant Group

The Grant Group is an Early Permian period unit, with the onset of deposition possibly as early as the Late Carboniferous. It is mostly glacio-fluvial in origin, with minor marine facies mainly evident on the Barbwire Terrace. The Grant Group and its southern lateral equivalent, the Paterson Formation, extend across the entire Canning Basin. The Grant Group is up to 2,000 m thick in the Fitzroy Trough (Backhouse & Mory 2020).

Like the Reeves Formation, the Grant Group comprises siliciclastic facies, but unlike the Reeves Formation, its outcrop and drill core show unambiguous glacial features. Given the similarity in lithologies, the contact between the Grant Group and the Reeves Formation is often difficult to determine using seismic data. Palynology-derived zonation is needed to distinguish between the two units (Backhouse & Mory 2020).

The Grant Group overlies and onlaps many older units and basement, especially at the basin's margins. Within the study area, it is disconformably overlain by the Poole Sandstone and unconformably overlies the Reeves Formation, Anderson Formation or Fairfield Group (Guppy et al. 1958; Mory 2010).

The current stratigraphic interpretation of the Grant Group (Geoscience Australia & Australian Stratigraphy Commission 2017) describes the group as having three component formations: the Betty, Winifred and Carolyn Formations.

This classification of the Grant Group was originally described in Crowe and Turner (1976). Their interpretation has been supported by some authors (Al-Hinaii 2013; Redfern 1990) but others dispute it, pointing out that the three component members cannot be reliably and continuously traced across the Fitzroy Trough and Lennard Shelf area (Backhouse & Mory 2020).

Some authors have proposed abandoning the three-formation stratigraphic interpretation and returning the classification of the Grant Group to a single formation (Backhouse & Mory 2020; Mory & Hocking 2011).

This report has adopted the classification system described in the Australian Stratigraphic Units Database (Geoscience Australia & Australian Stratigraphy Commission 2017). However, we acknowledge that not all authors working in the area agree with this classification, and we may amend it in the future.

Based on this system, the three component formations of the Grant Group are, in order of oldest to youngest, the:

- Betty Formation: up to 417.5 m thick (Al-Hinaii & Redfern 2015) and comprises fine- to coarse-grained, sparsely fossiliferous clastics, deposited during the early stage of a marine transgression (Yeates et al. 1984).
- Winifred Formation: up to 278 m thick and comprises siltstone, minor coal and fossiliferous limestone, deposited during the late stage of a marine transgression (Yeates et al. 1984).
- Carolyn Formation: up to 415 m thick and mainly comprises massive sandstones deposited in a deltaic environment during an early Permian marine regression, although some minor marine units are present (Yeates et al. 1984). The Carolyn Formation is further divided into two members which, from oldest to youngest, are the Wye Worry and Millajidee Members (Mory 2010).

The Grant Group is thickest in the Fitzroy Trough, where the three component formations have a combined thickness of up to 2,000 m (Al Hinaii & Redfern 2015). While the Grant Group thins away from the depocentre of the Fitzroy Trough, all three component formations are still present on both the Lennard Shelf to the north and the Barbwire Terrace to the south (Figure 9).

The Grant Range 1 petroleum well determined that the Grant Group, where it outcrops near Camballin, extends from the natural surface to around 400 m below ground.

The Fitzroy River 1 petroleum well located near the Noonkanbah Homestead intersected around 500 m of the Grant Group, underlying about 100 m of Poole Sandstone from around 400 to 1,000 m below ground.

In the middle of the Fitzroy Trough, petroleum well Valhalla 1 encountered the Grant Group at about 600 m thick from 640 to 1,230 m below ground.

Within the study area, the Grant Group outcrops along the Lennard Shelf as well as at the major anticlinal structural features of the Fitzroy Trough – the Grant Range and Mt Wynne anticlines – in the Camballin region; the St George Range anticline south-east of Noonkanbah; and the Poole Range anticline south-east of the St George Range anticline (Figure 6).

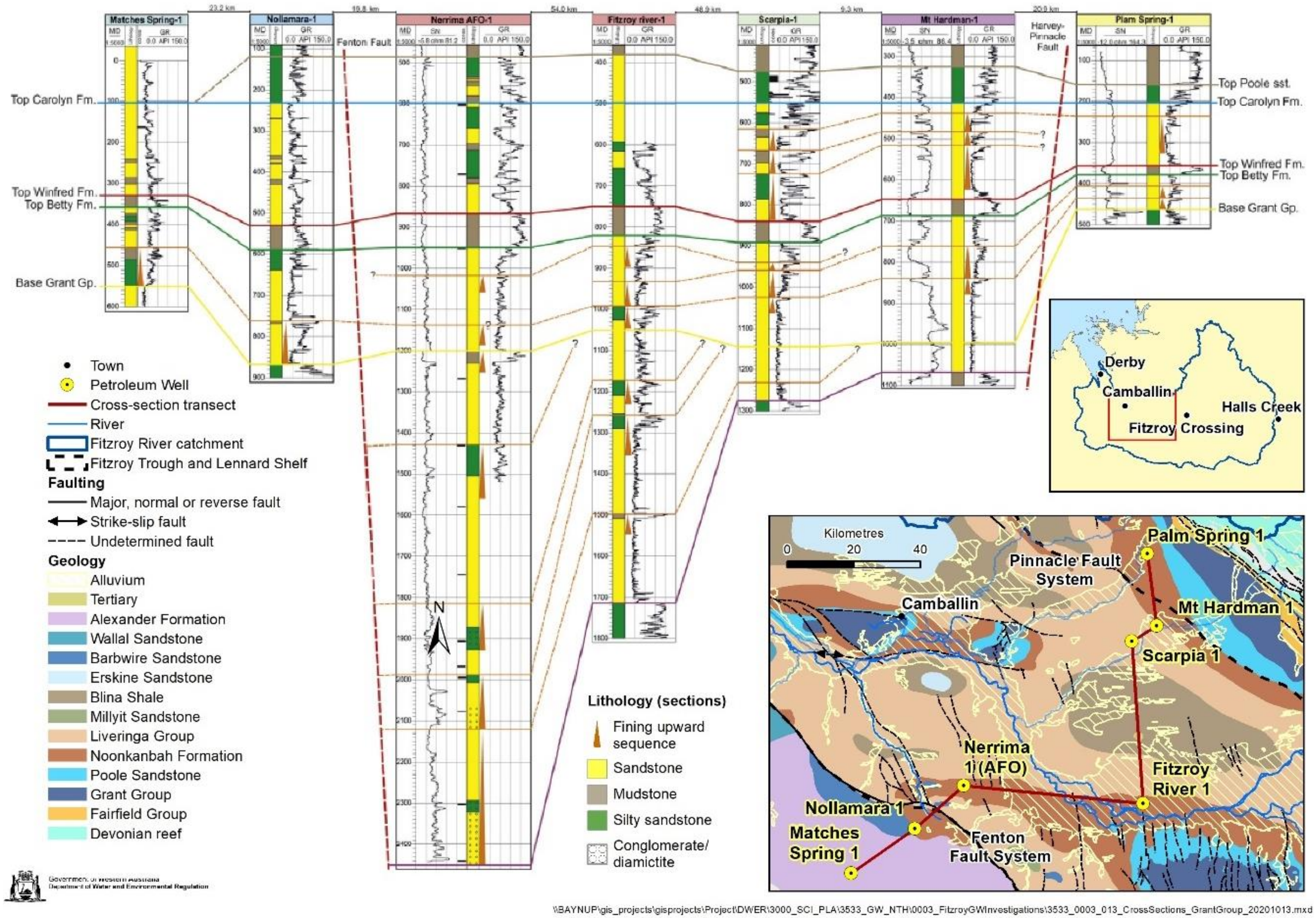


Figure 9 Cross-section showing the Carolyn, Winifred and Betty formations of the Grant Group

Note: Modified from Al Hinaai and Redfern 2015.

Poole Sandstone

The Poole Sandstone is an Early Permian period unit and was deposited in a combination of shallow fluvial and marine depositional environments (Apak 1996). It is conformably overlain by the Noonkanbah Formation and it disconformably overlies the Grant Group (Mory & Hocking 2011).

The unit comprises predominantly sandstone and siltstone (Smith 1992) and is lithologically very similar to the underlying Grant Group.

The Poole Sandstone outcrops along the flanks of Mount Wynne, the anticlines of the St George and Poole Ranges, as well as on the Lennard Shelf (Mory 2010). Its greatest thickness is found in the centre of the Fitzroy Trough, where it can be up to 200 m thick (Mory & Hocking 2011).

There are three recognised members within the Poole Sandstone. In order of deposition, from oldest to youngest, these are the Nura Nura Member, the Tuckfield Member and the Christmas Creek Member (Crowe & Towner 1976).

The Nura Nura Member comprises a fine- to medium-grained fluvio-deltaic sandstone, as well as a basal marine fossiliferous sandy limestone with thin siltstone and coal layers (Crowe & Towner 1976). While this basal limestone unit is a distinctive marker bed for the Nura Nura Member, it is not always present (Mory & Hocking 2011).

The overlying Tuckfield and Christmas Creek Members are described in the Australian Stratigraphic Database (Geoscience Australia & Australian Stratigraphy Commission 2017) as medium to coarse-grained sandstones that are lithologically very similar to each other and to the sandy component of the Nura Nura Member sandstone.

As a result, the different members of the Poole Sandstone are easily confused and can be incorrectly identified, particularly if the limestone marker bed of the Nura Nura Member is missing (Crowe & Towner 1976; Mory 2010).

Noonkanbah Formation

The Noonkanbah Formation is a Permian, shallow marine unit (Mory & Hocking 2011) that conformably overlies the Poole Sandstone and is conformably overlain by the Liveringa Group.

The formation is predominantly a dark grey to black mudstone-siltstone, interbedded with thin sandstone, carbonate beds, and minor conglomerates (Crowe & Towner 1976; Geoscience Australia & Australian Stratigraphy Commission 2017). Fossil fragments are common in both the sandstone and limestone beds and are only occasionally found in the mudstone-siltstone (Crowe & Towner 1976).

The main depocentre for the Noonkanbah Formation is in the Fitzroy Trough, where a thickness of 642 m was recorded at the Myroodah 1 petroleum exploration well (Figure 6).

Significant thickness of the unit was recorded along the southern parts of the Grant Range and in outcrops on both the Mount Anderson and Liveringa stations (Figure 2).

The Noonkanbah Formation thins towards the Lennard Shelf (Mory 2010).

Liveringa Group

The Liveringa Group is a middle to upper Permian period unit that conformably overlies the Noonkanbah Formation. Within the study area, it is unconformably overlain by the Blina Shale.

In order of deposition from oldest to youngest it comprises the Lightjack Formation, Condren Sandstone and Hardman Formation. The Condren Sandstone member is not found in the Fitzroy Trough (Mory 2010).

The Hardman Formation in turn has three separate members. From oldest to youngest, they are the Kirby Range, Hicks Range Sandstone and Cherrabun Members (Crowe & Towner 1976).

The lithology of the Liveringa Group mainly comprises sandstone and mudstone, with minor coal seams and fossiliferous limestones (Mory & Hocking 2011). It can be up to 900 m thick (Harrington & Harrington 2015).

The depositional environment varies from shallow marine to fluvial, with deposition occurring during the early Permian regression of the sea that covered much of the Canning Basin at that time (Dent 2017).

The main depocentre for the Liveringa Group is within the Fitzroy Trough, where it can be up to 620 m thick. At the Myroodah 1 petroleum well it is 435 m thick (Mory 2010). It outcrops over a large part of the study area, including at Mount Anderson, Liveringa and Myroodah stations.

Blina Shale

The Blina Shale is an Early Triassic period, dark-grey fossiliferous mudstone and fine-grained sandstone (Mory 2010; Smith 1992) that is largely confined to the Fitzroy Trough and south-western area of the Lennard Shelf (Mory 2010). It was deposited in a shallow marine environment and is about 200 m thick (Harrington et al. 2011).

It unconformably overlies the Liveringa Group and is disconformably overlain by the Erskine Sandstone. It is known to outcrop at the Blina, Noonkanbah and Myroodah stations (Figure 2) and along a north-west-trending belt to the north of the May and Meda rivers.

Erskine Sandstone

The Erskine Sandstone is a Triassic period unit, deposited in a fluvial environment. It can be up to 200 m thick and comprises both massive and cross-bedded fine-grained sandstone with interbedded conglomerate (Mory 2010).

In the study area the Erskine Sandstone outcrops in the northern part of Liveringa Station and at Myroodah Station, however both are very small occurrences.

Outcrops of the Erskine Sandstone are present mostly outside the study area, mainly around Yeeda and Meda stations (in the *Derby water allocation plan* area).

Munkayarra Shale

The Munkayarra Shale is a middle to late Triassic period unit that is only found in a small part of the study area near Derby.

It consists of multi-coloured, indurated clays and rare coal beds and, where present, the unit separates the Erskine Sandstone from overlying sequences including the Wallal Sandstone (Gallardo 2019).

However, deposition of the Munkayarra Shale is restricted to two east-west-oriented synclines that are located near the town of Derby and extend around 60 km inland (Laws & Smith 1987).

While mapping indicates the Munkayarra Shale is present near Derby (DMIRS 2016), the unit was not encountered in any of the drilling undertaken for this investigation.

Wallal Sandstone

The Wallal Sandstone is a pink and white laminated Jurassic sandstone which is very fine to very coarse grained, with some minor siltstone, conglomerate and lignite (Smith 1992). Within the study area, it unconformably overlies the Liveringa Group. Where it does not outcrop, it is overlain by the Alexander Formation.

The Wallal Sandstone was deposited in a fluvial to shallow marine environment during a marine transgression in the Jurassic period. The unit is known to outcrop around Derby as well as within the study area at locations to the west of the Fitzroy River and south of Willare.

Lithology and downhole geophysical logs taken from bore DHM8 south of Willare indicate that its thickness in the study area is about 100 m.

Alluvium of the Fitzroy and Margaret rivers

Lindsay and Commander (2005) describe a general type-section of the river alluvium as being around 30 m thick, with the upper 10 m dominated by low-permeability silt and clay deposits, and the lower 20 m by higher permeability, more homogenous sand and gravel aquifer material.

Near the mouth of the Fitzroy River, the alluvium is underlain by the Wallal Sandstone and Blina Shale. In the centre of the investigation area, the river is underlain by the Liveringa Group and Noonkanbah Formation. Near Fitzroy Crossing it is underlain by the Poole Sandstone, Grant Group, Fairfield Group and Devonian reef. The Margaret River alluvium, east of Fitzroy Crossing, is mainly underlain by the deposits of the Devonian reef complex.

2.3 Regional hydrogeology

The following sub-section describes the hydrogeology (i.e. aquifers) of the different geological units present within the study area.

2.3.1 Alluvial aquifer

The alluvium of the Fitzroy River, as well as the lower reaches of its tributary the Margaret River, forms an extensive aquifer system comprised of braided alluvial and undifferentiated alluvial deposits that follows the floodplain extents of both rivers. The system has a preliminary estimated storage of 13,000 GL (assuming homogenous sand/gravel lithology of the alluvium) (Lindsay & Commander 2005).

Groundwater recharge to the alluvial aquifer is from a combination of diffuse rainfall recharge and localised bank and/or alluvial aquifer recharge from floods along the Fitzroy and Margaret rivers, and throughflow from regional aquifers. Groundwater in the alluvium is generally fresh near the main river channels, with higher groundwater salinity observed at a distance from the main river channels.

Near the Noonkanbah Aboriginal community, salinity in the Fitzroy River alluvial aquifer close to the Fitzroy River ranges from 398 mg/L (N3B) to 646 mg/L as TDS (N1C) (Harrington et al. 2011). Groundwater salinity near Willare Crossing ranges between 690 mg/L (DHM5A) and 2,910 mg/L as TDS (DHM8C) (Harrington & Harrington 2016).

The primary source of groundwater recharge to the alluvial aquifer is surface water that flows down the Fitzroy River. Surface water flow in the Fitzroy and Margaret rivers is seasonal, with significant flooding during the wet season (December to March), contracting to very low or no flows in the dry season (Lindsay & Commander 2005). Thus, the alluvial aquifer system alternates between riverbank and/or alluvial aquifer recharge and discharge that varies with river stage height.

The Fitzroy River recharges the alluvial aquifer system during wet season flooding (Harrington & Harrington 2015), with higher water levels in the river during the wet season resulting in a water level gradient from the river towards the alluvial aquifer, inducing groundwater recharge. In the dry season, as the river dries, the gradient is reversed, and water stored in the alluvial aquifer flows back into the river (CSIRO 2009).

A secondary source of recharge is groundwater discharge from deeper regional aquifer systems (Lindsay & Commander 2005; Harrington et al. 2011) in areas where there is a hydraulic connection between the systems through direct connectivity or fault conduits.

2.3.2 Erskine aquifer

Within the study area, the Erskine aquifer is limited to a small outcropping area of Erskine Sandstone south of Camballin. A significant outcropping area of Erskine Sandstone occurs to the north of Camballin, however this is entirely within the *Derby water allocation plan* area.

The Erskine aquifer is underlain by the confining Blina Shale and is not in hydraulic connection with the underlying aquifers or the Fitzroy River.

2.3.3 Wallal aquifer

The Wallal aquifer is a regional aquifer found in the north of the Fitzroy catchment. It also occurs both in the south-west of the Fitzroy catchment and within the Derby groundwater area. The department has investigated the irrigation potential of the Wallal aquifer within the Derby groundwater area (Gallardo 2018). The aquifer comprises two units – the Wallal Sandstone and the Alexander Formation (Joseph & Searle 2015). The Alexander Formation directly overlies the Wallal Sandstone, and the two units are likely to have hydraulic continuity.

The maximum known thickness of the Wallal aquifer is more than 500 m, recorded north-west of the Fitzroy River (Harrington & Harrington 2016) and in petroleum exploration bore Yulleroo No. 1 (Searle 2012). Aquifer yields assessed by Taylor et al. (2018) showed a range from 0.5 L/s to 18.4 L/s, with a median yield of 6.9 L/s. The Taylor et al. (2018) study also noted fresh groundwater in the Wallal aquifer, with a median salinity reading of about 460 mg/L. However, salinity in the aquifer is known to increase towards the coast (Taylor et al. 2018).

Groundwater recharge to the Wallal aquifer occurs through rainfall recharge over more than 10,000 km^2 of outcrops within the south-western part of the Fitzroy River catchment (Figure 6). Groundwater discharge from the Wallal aquifer to the Fitzroy River occurs around Willare (Lindsay & Commander 2005) and as upward leakage and discharge to springs (Smith 1992). Regional groundwater flow in the aquifer appears to be generally from south to north-north-west (Petheram et al. 2018; Searle et al. 2012).

2.3.4 Liveringa Group aquifer

The Liveringa Group is present throughout most of the study area. Its quality as an aquifer is variable, and it fluctuates between being an aquiclude and being (less commonly) a minor aquifer. Bores in the Liveringa Group aquifer generally yield small supplies of less than 2 L/sec (Taylor et al. 2018).

Of the three members that make up the Liveringa Group (the Lightjack Formation, Condren Sandstone and Hardman Formation), the Condren Sandstone is the most productive aquifer unit. However, it is not found anywhere in the Fitzroy Trough (Mory 2010).

While the Liveringa Group may be up to 620 m thick in the study area, the unit comprises the Hardman Formation which directly overlies the Lightjack Formation.

Both units are regional aquitard units, with outcrops around Liveringa and Noonkanbah stations (Rey Resources 2014).

Within the study area, the groundwater quality in the Liveringa Group aquifer is generally marginal to brackish, with salinity in the range of 500 to 3,000 mg/L (Lindsay & Commander 2005). Groundwater is generally used for stock or domestic supply, and the Balginjirr community use it as a water supply.

Recharge into the Liveringa Group aquifer is either from vertical infiltration of rainfall recharge – where connected to the surface – during the wet season (Taylor et al. 2018) or leakage from the Fitzroy River through the Le Lievre swamp near Camballin (Lindsay & Commander 2005).

Floodwater recharges the Liveringa Group aquifer where it underlies the Fitzroy River alluvial aquifer. This has been observed along the Noonkanbah reach on the northern side of the Fitzroy River (Harrington & Harrington 2015).

2.3.5 Noonkanbah Formation

The Noonkanbah Formation is generally a regional aquitard, although a few low-yielding, brackish to saline quality bores are completed in the unit (Lindsay & Commander 2005). It is present across most of the study area, although not in the north-east and south-west.

The formation is not generally targeted for groundwater supplies and there is very little groundwater data available. Existing information suggests it has very low hydraulic conductivity and will effectively separate aquifers unless conduits such as faults are evident (Harrington et al. 2011). This study inferred areas of connectivity from the confined Grant Poole aquifer through the Noonkanbah Formation to the Fitzroy River alluvial aquifer and river itself in the areas around Noonkanbah and near the Cunningham Anabranch. It examined the potential that a cluster of faults trending north-south along this stretch of the river acts as a preferential pathway for groundwater to flow from the deep regional aquifer into the alluvium and river.

2.3.6 Grant Poole aquifer

The Poole Sandstone and the two sandstone-rich members of the Grant Group (the Carolyn and Betty formations) are lithologically similar and form a hydraulically connected regional aquifer system (Smith 1992). The department manages the system as a single aquifer for groundwater licensing purposes. We refer to it as the Grant Poole aquifer.

The siltstone-rich Winifred Formation, which underlies the Carolyn Formation, acts as an aquiclude, hydraulically separating the upper Poole Sandstone–Carolyn Formation aquifer from the lower Betty Formation aquifer.

The Grant Poole aquifer is recharged where it outcrops along the Grant, St George and Poole ranges and along the Lennard Shelf (Mory 2010).

Hydraulic head in the confined parts of the Grant Poole aquifer is high, and artesian groundwater pressures have been identified at Noonkanbah station near the Fitzroy River, where the top of the aquifer is around 400 to 500 m below ground level.

Within the study area, the Grant Poole aquifer is overlain either by the Noonkanbah Formation (which acts as a regional aquitard) or, where the Noonkanbah Formation is absent, by the Liveringa Group.

There is generally no flow between the Grant Poole aquifer and the alluvial aquifer, except for an area around Noonkanbah Station, where fault-induced preferential pathways have been identified (Harrington et al. 2011).

Groundwater quality in the Grant Poole is generally fresh and yields range from 0.19 to 34.1 L/sec (Taylor et al. 2018).

2.3.7 Reeves Formation aquifer

In the Fitzroy Trough the Reeves Formation is a sandstone aquifer that conformably underlies the Grant Group (Betty Formation) and Poole Sandstone aquifer, and the two are likely to be hydraulically connected (Mory & Hocking 2011). Because of its depth, the Reeves Formation aquifer is not currently used for water supply, and only limited information is available about its properties (i.e. yields, recharge, discharge) or groundwater quality.

2.3.8 Fairfield Group

Very little is known about the hydrogeology of the Fairfield Group, and even though it is a recognised aquifer it is not considered a prospective water source. The only unit of the Fairfield Group present in the study area is the Laurel Formation, which directly underlies the alluvial aquifer along the northern part of the study area, including around the town of Fitzroy Crossing (Gallardo 2017).

Based on the available lithological information, the Laurel Formation would generally be considered a low-quality aquifer and a poor water supply target. It mainly comprises clays and silts, with only minor isolated sand lenses. The groundwater quality is relatively fresh, with salinity of 520 mg/L as TDS from BU15MB002 (screened across the Fairfield Group). Yields from bore BU15MB002 were less than 0.5 L/s with the bore drying frequently (Gallardo 2017).

2.3.9 Devonian reef aquifer

The Devonian reef complex (Figure 10) forms a significant regional limestone aquifer. It typically contains fresh groundwater, is regionally extensive in the eastern part of the study area and is thought to be more than 2,000 m thick.

Figure 10 Devonian reef outcrop

Relatively little is known about the Devonian reef aquifer, with most of the available groundwater monitoring data coming from the former Pillara lead and zinc mine at Gogo Station, which closed in 2008. Harrington and Harrington (2015) and Taylor et al. (2018) have collated what information is available.

Groundwater recharge to the Devonian reef aquifer likely comes from rainfall where the unit outcrops, as well as from recharge via throughflow from adjacent fractured rock aquifers (CSIRO 2009).

Groundwater discharge mechanisms are uncertain but thought to be a combination of evapotranspiration in areas where shallow water tables occur (Taylor et al. 2018).

Where the aquifer underlies the Fitzroy and Margaret rivers, it may discharge to them in the dry season (CSIRO 2009; Harrington & Harrington 2015).

Because it is a karstic system, the aquifer's hydraulic properties are likely to be highly variable. Rates of groundwater recharge in one area may differ significantly to another. Groundwater quality is variable, with salinity varying from 140 to 500 mg/L as TDS (Taylor et al 2018).

Before this investigation, 22 salinity records across 18 Devonian reef aquifer bores had groundwater TDS ranging from 120 mg/L to 1,230 mg/L (Harrington & Harrington 2015). The results from this study fall within that range.

Elevated groundwater salinity has previously been recorded near the tailings storage facility at the former Pillara mine site. These ranged from around 6,800 mg/L to 15,300 mg/L as TDS in November 2010 and May 2011 (Harrington & Harrington 2015).

No information on aquifer yield is available.

2.4 Current climate and trends in climate

The climate of the Kimberley region is dominated by monsoonal wet seasons that typically extend from December to March, with a pronounced dry season from April to November. Almost all precipitation falls during the monsoonal season. For example, since 1952 an average of 94 per cent of Derby's annual rainfall has fallen from December to March, with the remaining 6 per cent from April to November.

Average annual rainfall is highest in the northern parts of the catchment (around 1,000 to 1,100 mm/year), decreasing southward by around 600 to 700 mm/year to 300 mm/year (Figure 11). Rainfall also decreases towards the western end of the catchment near Derby where the average annual rainfall is 655 mm/year.

Long-term records show that since the 1960s annual rainfall has generally increased (Table 1). However, low rainfall years still occur – as seen in the very dry 2018–19 wet season (Figure 12).

High spatial and seasonal variability in rainfall is seen across the catchment, particularly from October to December (the start of the wet season). Most of the rainfall occurs as thunderstorms, cyclones and cyclonic lows. The annual and average monthly rainfall records from 1998 to 2019 for Kimberley Downs and Fitzroy Crossing rainfall stations illustrate the variability – see Figure 12 and Figure 13.

Using global climate models (GCMs), the Bureau of Meteorology (BoM) has projected future rainfall changes to the end of the century for Australia's monsoonal north, including the Kimberley region (BoM 2022). The rainfall-change projections are given at a 5 km grid scale and are the outputs from two representative concentration pathways (i.e. a medium and high greenhouse-gas-emission scenario) driving four GCM models from the Coupled Model Intercomparison Project Phase 5 (CMIP5).

A regional climate model was used to dynamically downscale the GCM data to produce the data for re-gridding into the 5 km grid cells. These values have been corrected using three bias correction methods to adjust the discrepancies between climate input and observation (one bias correction method used on the dynamically downscaled data and three on the GCM data).

Of the four GCMs, two project a wetting trend for wet season rainfall, while the other two project a decrease in wet season rainfall over northern Australia. While the GCMs cannot represent key climate drivers associated with monsoonal rain, increases and decreases in wet season rainfall are both plausible. Rainfall events are projected to be more intense. Little change to dry season rainfall is projected. Multi-year dry periods are expected to increase. Natural climate variability will remain the main driver of rainfall changes in the next few decades (BoM 2022).

To understand the implications of future changes in rainfall (and other hydroclimate parameters), BoM assessed the changes relative to a reference period (1976 to 2005). The average rainfall over this reference period at Fitzroy Crossing is 618 mm. The 16 low-emission projections show a spread in average rainfall of 548 mm (-10%) to 769 mm (+23%). This spread in rainfall projections is small compared with the variation in observed historic rainfall, where in just the past 25 years totals have varied from 236 mm (-65%) to 1,042 mm (+55%) (Figure 12).

For this investigation we used rainfall information from six BoM rainfall stations located within or near the study area for our assessments: Camballin, Liveringa Station, Fitzroy Crossing, Gogo Station, Brooking Springs and Kimberley Downs. We used the most complete long-term rainfall records from Camballin, Gogo Station and Kimberley Downs to estimate recharge by the chloride mass balance method (Section 6.1). This ensured we captured the conditions that best represented the historical period and the rainfall gradient across the catchment (Crosbie et al. 2018).

Table 1 Overview of selected Bureau of Meteorology rainfall sites in the study area

Location	**Rainfall station**	**Length of record**	**Average over complete record (mm/year)**	**Average rainfall used for CMB calculation (mm/year)**
Liveringa and Mt Anderson	Camballin	1959 – present	589	589
	Liveringa Station	2002 – present	731	
Fitzroy Crossing, Gogo Station and Brooking Springs	Fitzroy Crossing	1998 – present	723	489
	Gogo Station	1911 – present	489	
	Brooking Springs	1902 – 2020	551	
Kimberley Downs	Kimberley Downs	1886 – present	670	670

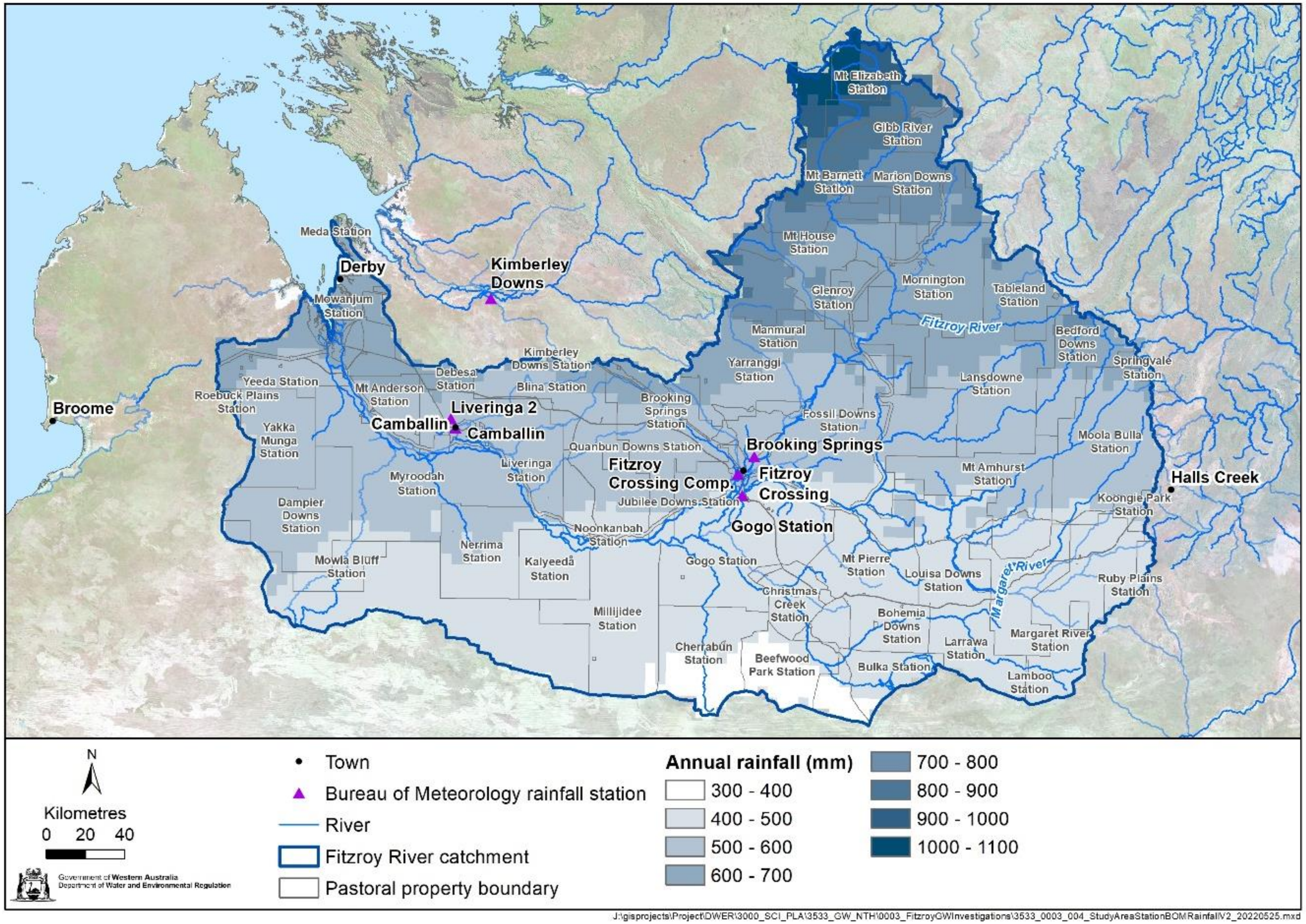
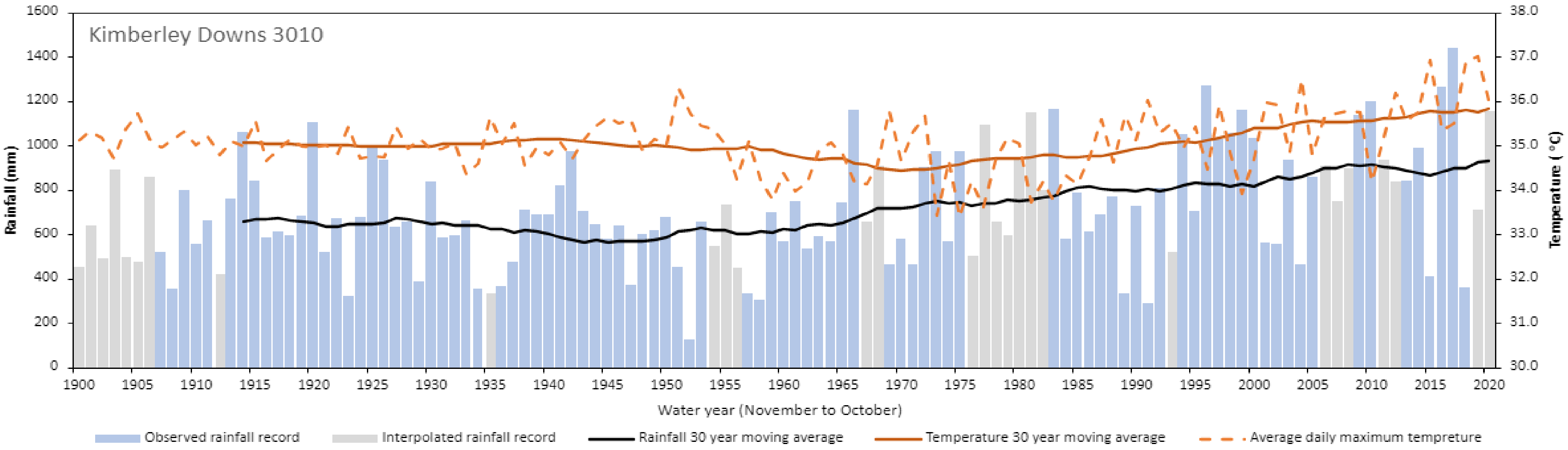


Figure 11 Bureau of Meteorology rainfall monitoring sites and rainfall gradient across the catchment



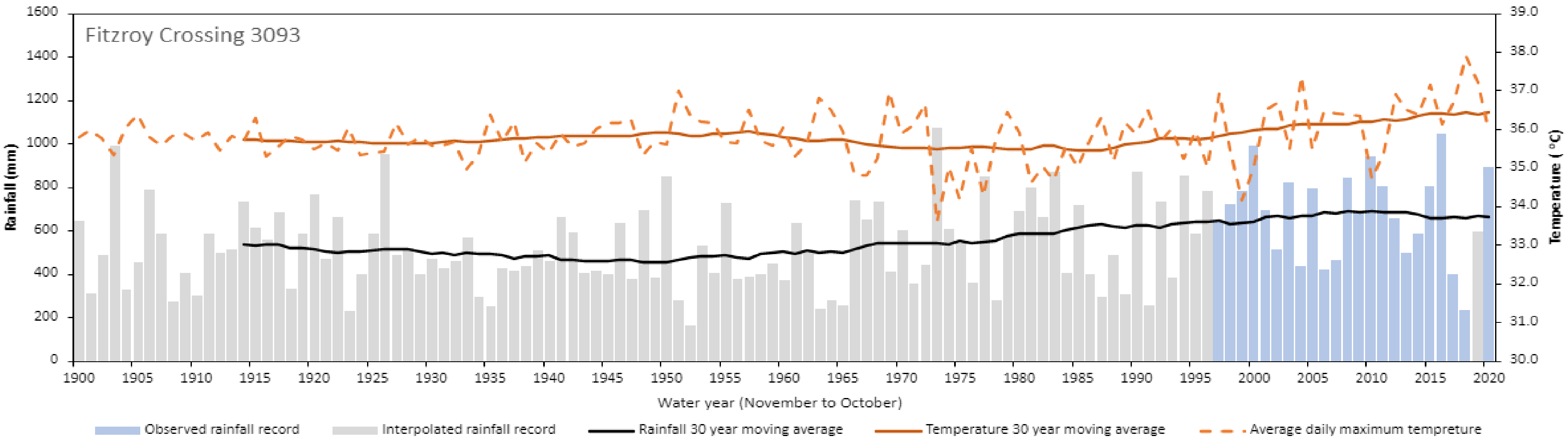


Figure 12 Long-term rainfall trends

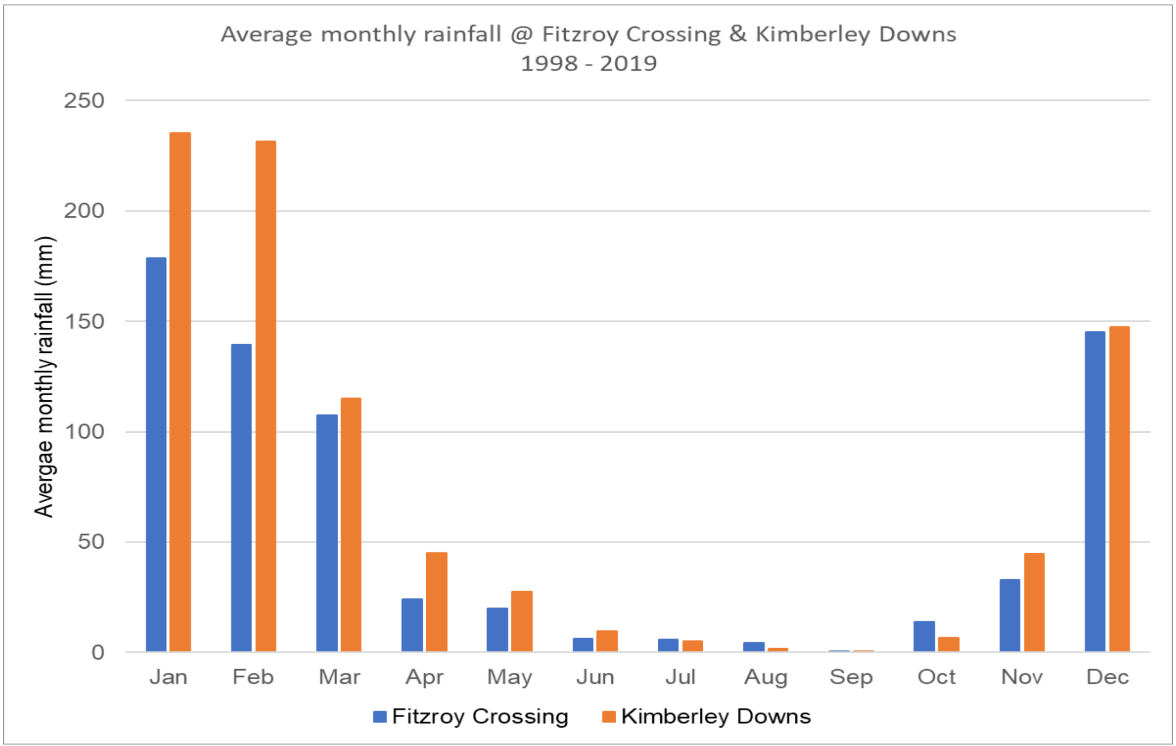


Figure 13 Average monthly rainfall – 1998 to 2019

2.5 River hydrology

The Fitzroy River, one of Australia's largest unregulated rivers, is 730 km long. It flows west from its headwaters in the Wunaamin-Miliwundi (Fitzroy) Ranges in the Central Kimberley, then descends to the low-lying Fitzroy Trough and discharges to the ocean near Derby at King Sound (Figure 14). The system has the largest average annual discharge volume of any river in Western Australia (Petheram et al. 2014). There are 13 operational stream gauges which provide good spatial coverage of streamflow across the catchment.

There are multiple tributaries along the river's length, with the main inflows occurring between gauging stations downstream of Dimond Gorge. The river is also highly braided, with anabranches downstream of Fitzroy Crossing (Cunningham Anabranch) and at Uralla Creek (this leaves the main channel just upstream of Fitzroy Barrage and re-joins the main channel, as Snake Creek, downstream of Looma gauging station). These anabranches are not gauged.

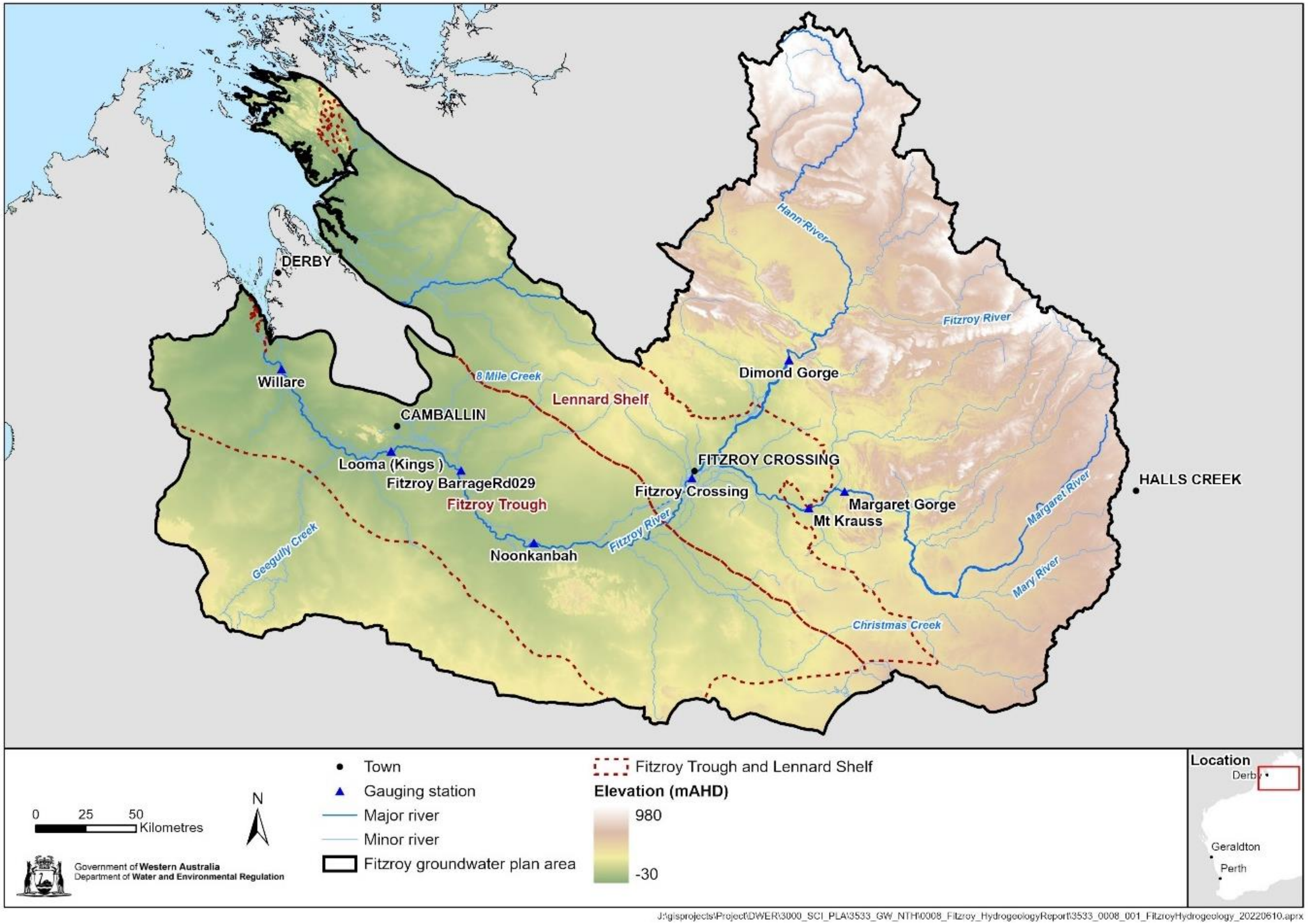


Figure 14 Topography of the Fitzroy River catchment and location of gauging stations

Fitzroy Barrage is the only weir built across the river. It was constructed as part of an irrigation scheme developed from the 1950s to 1960s. The barrier creates a pool that allows the river to flow under gravity into Uralla/Snake Creek as a diversion channel.

River flow in the Fitzroy is strongly seasonal. On average 90 per cent of streamflow is from January to March and inter-annual variability in flow is large. Figure 15 shows the correlation between annual flow (discharge in GL) and rainfall.

Further information on streamflow in the Fitzroy River is available in Hughes et al. (2018) and DWER (2022).

With the onset of the dry season, as rainfall declines significantly, surface flows and river stages decrease. When the elevation of the watertable within the alluvial or regional aquifers is above river level, groundwater and bank storage will discharge along some parts of the river as baseflow. These inflows can maintain streamflow in some areas of the Fitzroy River into the dry season, even in years when little or no rain is recorded.

As the dry season progresses and discharge from the alluvial aquifer continues to decrease, surface flow may cease entirely, reducing the river to a series of disconnected pools – though the pools may still be hydraulically connected to the alluvial aquifer. A high-flow high-rainfall year may result in sufficient recharge to support baseflow to sustain river pools over multiple dry years (Harrington et al. 2011; Doble et al. 2012).

We used remote sensing images to identify the location of pools that persist even in dry years (DWER 2022). The presence of a pool does not in itself indicate a groundwater connection. However, given potential annual evaporation is about 2 m, most pools that persist through the dry season are likely to have some groundwater inflow to sustain them. The catchment also has springs (Figure 17) that may contribute to pool persistence and dry season flows (this could be verified with further study if needed).

Groundwater inflow to the rivers and their tributaries, or the alluvial and other aquifers, may be critical for supporting river ecology during the dry season. The flows may result in both the persistence of river pools through the dry season (water quantity) and maintenance of water quality parameters (e.g. temperature, salinity, dissolved oxygen) within the critical ranges required for supporting river ecology.

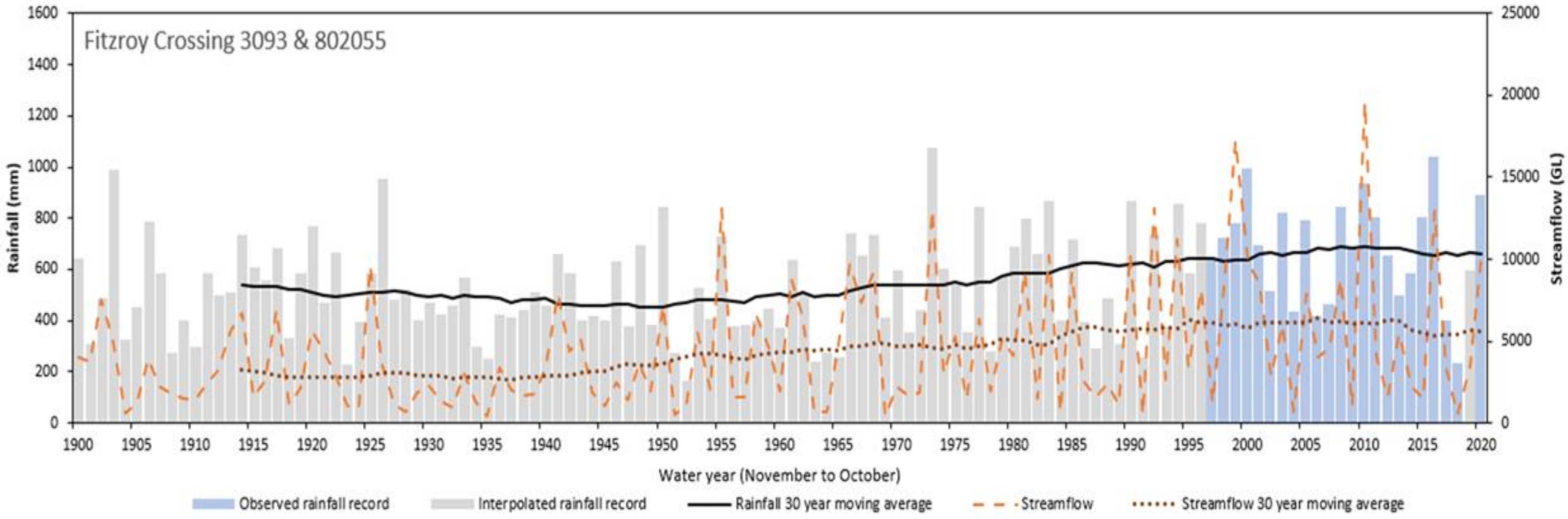


Figure 15 Comparison between rainfall and stream discharge at Fitzroy Crossing

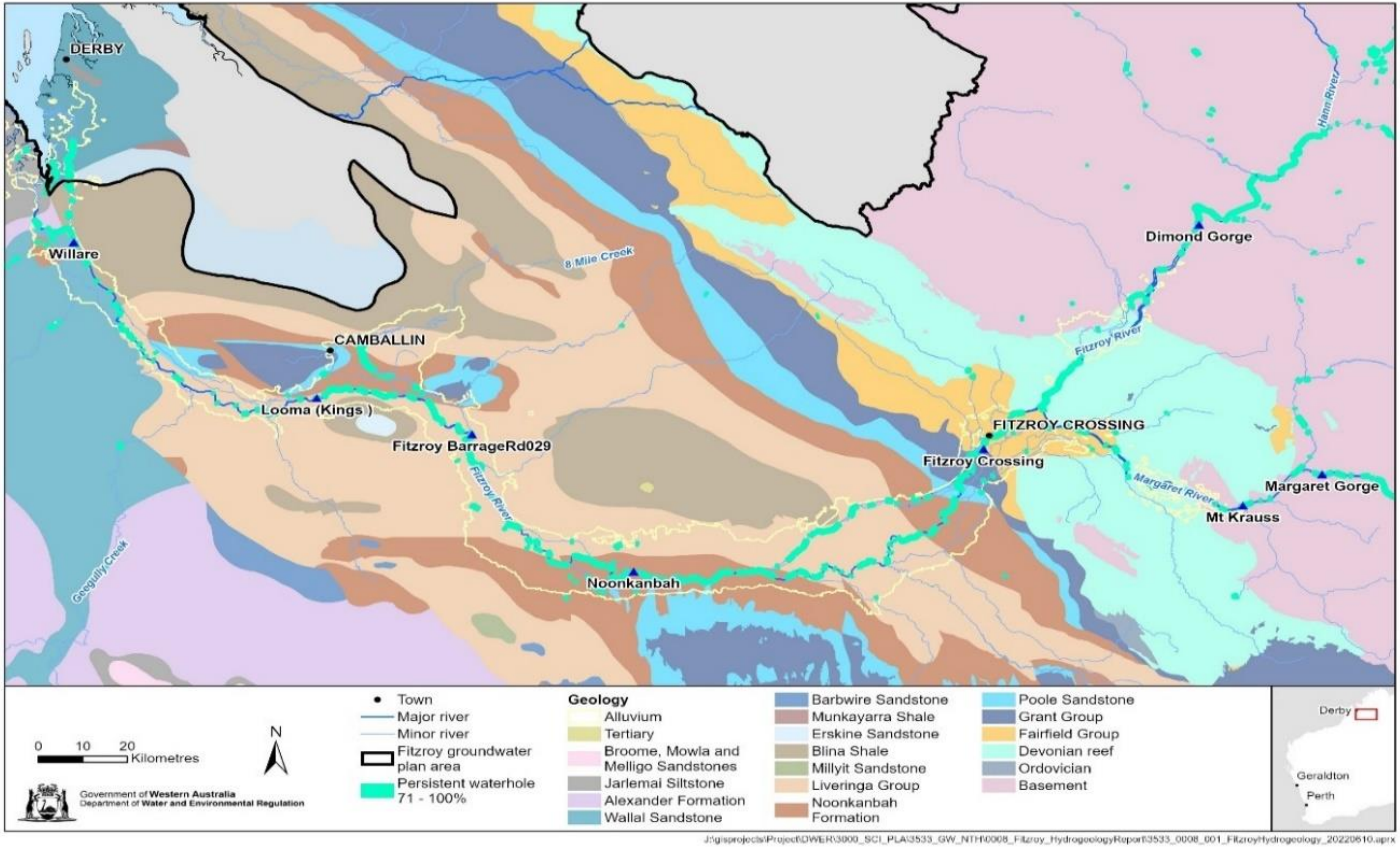


Figure 16 Persistent pools in the Fitzroy catchment (DWER 2022)

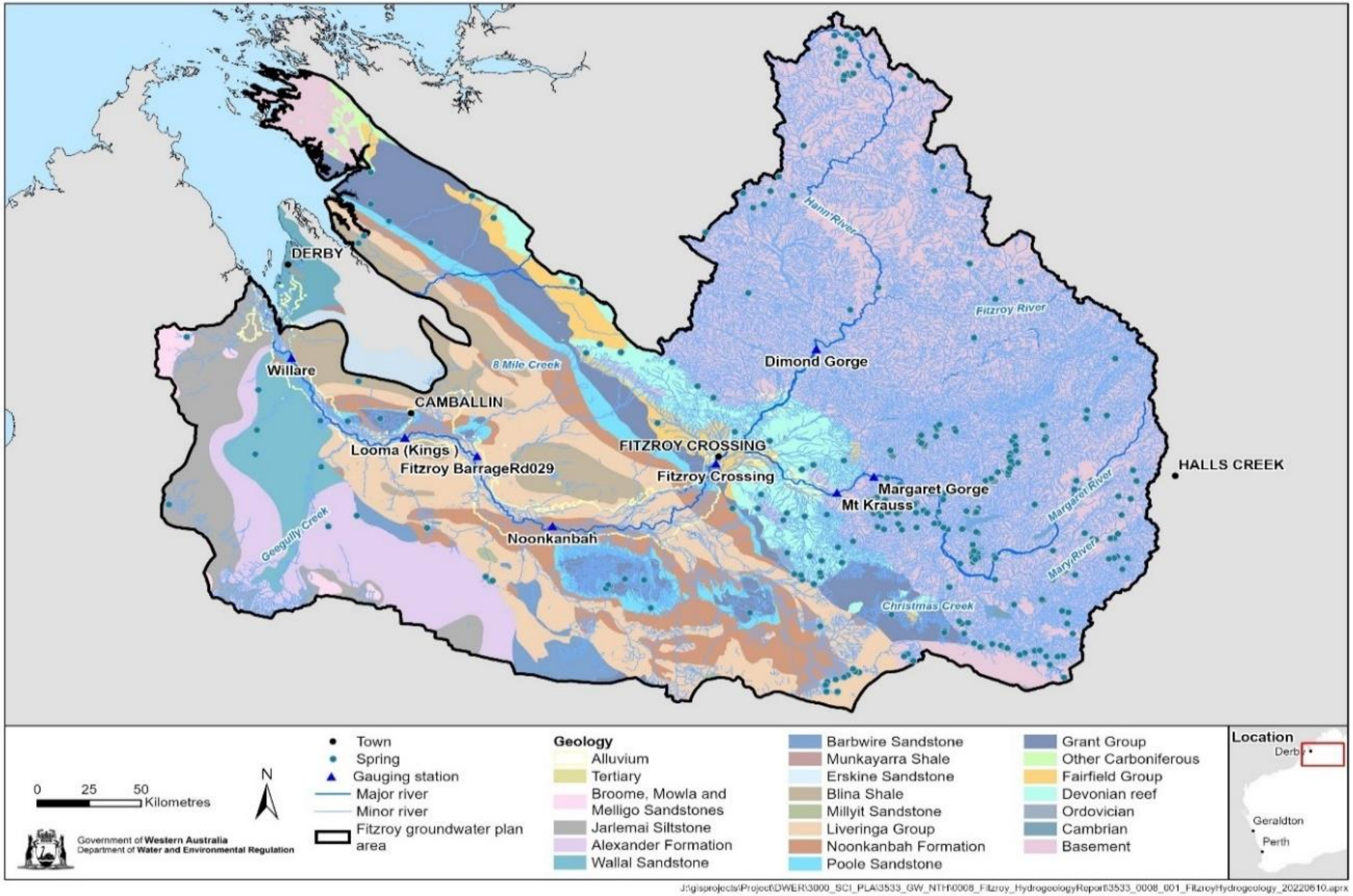


Figure 17 Identified major springs in the Fitzroy catchment

3 Investigation program methodology

Several groundwater investigations were conducted in the Fitzroy Valley through the state-funded Water for Food (WfF) program, the State Groundwater Investigation Program (SGIP) and the groundwater component of the federally funded Northern Australia Water Resource Assessment (NAWRA) program.

Between 2015 and 2018, teams for these investigations:

- collected 5,291 line km of airborne electromagnetic (AEM) data over a 20,000 km^2 area
- drilled 35 investigation holes and installed 26 monitoring bores
- collected and analysed 75 groundwater samples from 61 monitoring bores
- collected and analysed 80 surface water samples along the Fitzroy and Margaret rivers between Willare and Margaret Gorge.

3.1 Airborne electromagnetic survey

An airborne electromagnetic survey (AEM) survey was conducted between 24 September 2015 and 17 October 2015 over about 20,000 km^2 – from Derby in the north-west, along the May and Meda rivers in the north to Fitzroy Crossing, and then along the Fitzroy River to the south (Figure 18).

Undertaken by Geoscience Australia and SkyTEM Australia Pty Ltd, the survey was used to partially define the extent of major aquifer units and assess potential salt stores in the Fitzroy River alluvium. The survey acquired data using the SkyTEM 312 system – this collected useful information down to about 300 m below ground level.

Line spacing of the survey varied from 400 m, where higher density information was collected around Mowanjum station, to 4 km, where lower density information was collected to assess the extent of the regional Canning Basin aquifers. Additional lines were flown along the Fitzroy River. The data, along with the supporting report (Brodie 2016) and metadata, are available from the Geoscience Australia website.

Geoscience Australia completed a second inversion of the West Kimberley data in February 2017 (Christensen 2017), using a slight modification of the original inversion described in Brodie (2016). There is little practical difference between the outputs of the two inversion methods, and both are suitable to underpin a regional geological understanding.

Mira Geoscience (2018) constructed a 3D conceptual geological model in GOCAD, using the Christensen (2017) inversion. It did not include the AEM flight lines around Gogo Station due to the increased complexity of the Devonian reef complex. The Fitzroy River alluvium was not included for similar reasons.

3.2 Drilling

We undertook a series of drilling investigations (Table 2) between 2015 and 2017 to improve our geological knowledge of the Grant Range, Fitzroy Crossing and Lennard Shelf areas. These investigations targeted the Fitzroy River alluvium, Poole Sandstone and Grant Group, and were used to:

- install purpose-built monitoring and sampling infrastructure (bores) required to assess groundwater flow processes, including recharge, throughflow and discharge
- better characterise the lithology and stratigraphy of the Fitzroy alluvium, Poole Sandstone and Grant Group
- support the geological interpretation of the AEM survey
- contribute to the assessment of groundwater–surface water interactions between local and regional aquifers and the Fitzroy River
- collect new information on the bore yield and hydraulic properties of key aquifers
- assess the availability of groundwater.

3.2.1 Fitzroy River alluvium

We conducted two drilling programs to investigate groundwater in the Fitzroy River alluvium. In 2015 we drilled the BU (Bunuba) series of investigation holes near the Daringunaya and Bungardi Aboriginal communities around Fitzroy Crossing (Gallardo 2017). In July 2017 we installed the Lower Fitzroy (LF) series of bores in the Camballin region (Clohessy 2017).

The 2015 Fitzroy Crossing drilling program used reverse circulation drilling, and the 2017 Camballin region program used mud rotary drilling given the presence of more unconsolidated sediments. We drilled a total of 18 exploration holes through the Fitzroy River alluvium as part of both programs.

Of the 18 exploration sites, nine were screened as ongoing groundwater monitoring bores in the Fitzroy River alluvium. Another monitoring bore (BU15MB002) was drilled into and screened in the underlying Fairfield Group aquifer near Fitzroy Crossing, and two more (LF03A and LF04A) were drilled into and screened in the underlying Noonkanbah Formation in the Camballin region.

We constructed all groundwater monitoring bores with 100 mm PN12 PVC casing and screens. For detailed bore construction information, lithological logs and geophysical logs, see the bore completion reports Gallardo (2017) and Clohessy (2017).

3.2.2 Regional geology

Drilling was undertaken to confirm and characterise the outcrop geology of two main areas: the Camballin region of the Grant Ranges in the Fitzroy Trough, and the Lennard Shelf.

We drilled 35 investigation holes across the project area between 2015 and 2017, and then completed 26 of those as groundwater monitoring bores.

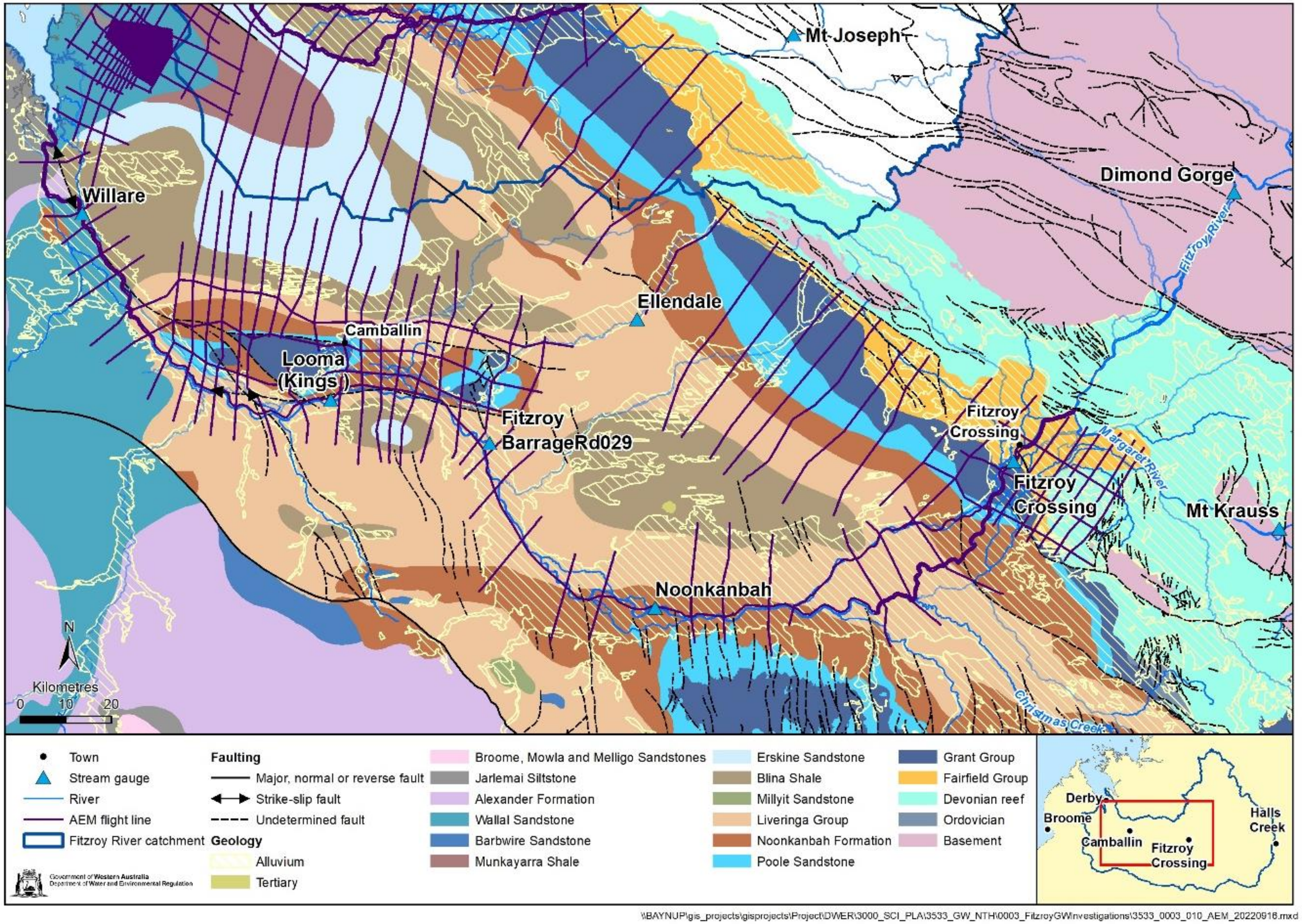


Figure 18 Airborne electromagnetic survey area and flight lines

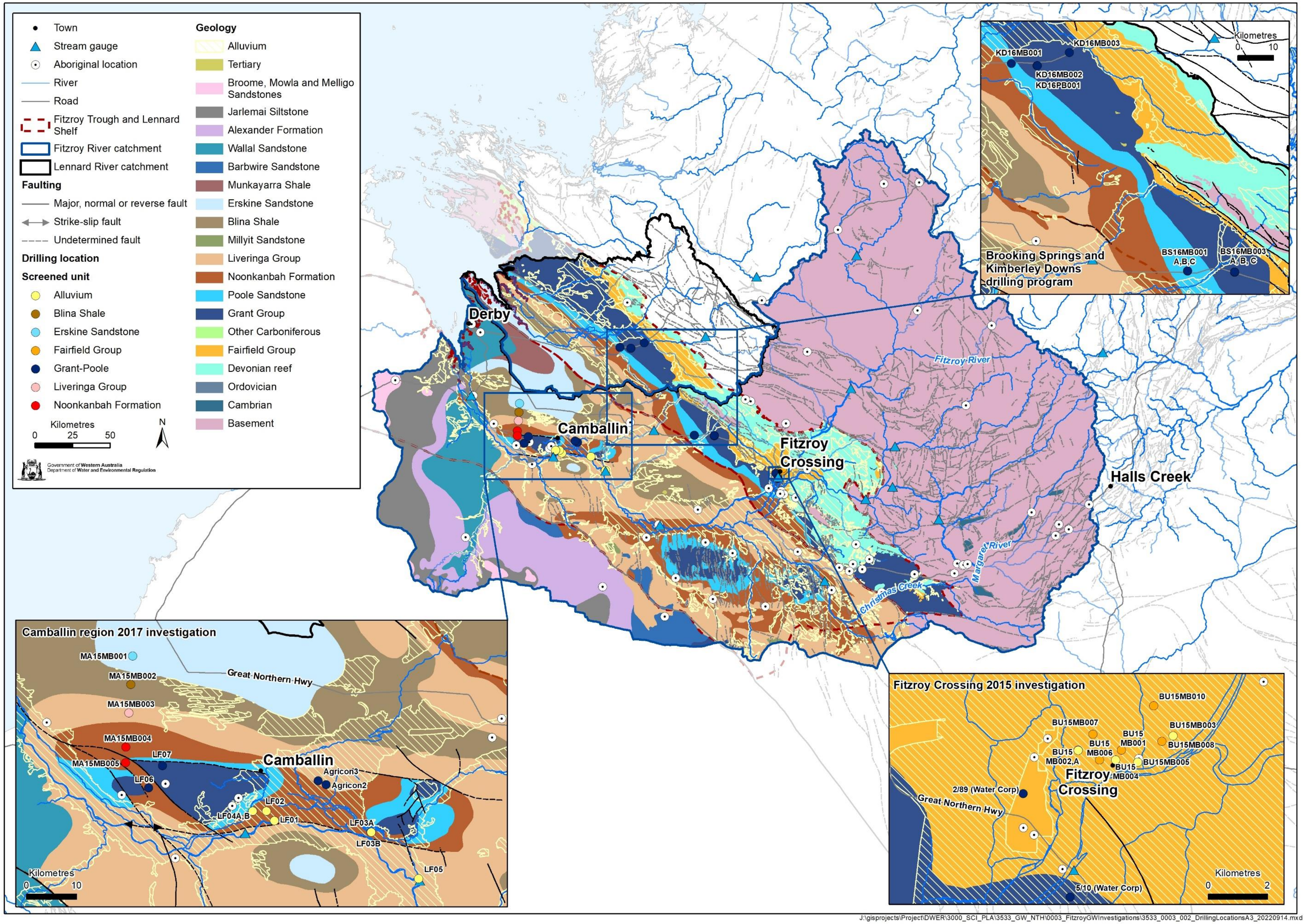


Figure 19 Drilling locations

Table 2 Drilling program

Bore ID	AWRC no.	Investigation program	Purpose	Drilled depth (m bgl)	Bore depth (m bgl)	Screen interval (m bgl)	Screened aquifer
BU15MB001	80200022	Bunuba (Gallardo 2017)	Exp hole	139	-	-	-
BU15MB002	80200023	Bunuba (Gallardo 2017)	Monitoring	139	138	121.0–133.0	Fairfield Group
BU15MB002A	80200045	Bunuba (Gallardo 2017)	Monitoring	31.5	31.5	17.8–23.8	Fitzroy River alluvium
BU15MB003	80200024	Bunuba (Gallardo 2017)	Monitoring	43	28	21.0–27.0	Fitzroy River alluvium
BU15MB004	80200025	Bunuba (Gallardo 2017)	Monitoring	35	30	22.0–28.0	Alluvial
BU15MB005	80200025	Bunuba (Gallardo 2017)	Monitoring	42	29	20.0–26.0	Alluvial
BU15MB006	80200026	Bunuba (Gallardo 2017)	Exp hole	35	-	-	-
BU15MB007	-	Bunuba (Gallardo 2017)	Exp hole	31	-	-	-
BU15MB008	-	Bunuba (Gallardo 2017)	Exp hole	37	-	-	-
BU15MB009	-	Bunuba (Gallardo 2017)	Exp hole	37	-	-	-
BU15MB010	-	Bunuba (Gallardo 2017)	Exp hole	37	-	-	-
LF01	80270063	Lower Fitzroy (Clohessy 2017)	Monitoring	26	20	13.0–18.0	Fitzroy alluvium
LF02	80270064	Lower Fitzroy (Clohessy 2017)	Monitoring	84	32	24.0–30.0	Fitzroy alluvium
LF03A	80270065	Lower Fitzroy (Clohessy 2017)	Monitoring	78	57.5	49.5–55.5	Noonkanbah Formation
LF03B	80270066	Lower Fitzroy (Clohessy 2017)	Monitoring	18	18	10.0–15.0	Fitzroy alluvium
LF04A	80270067	Lower Fitzroy (Clohessy 2017)	Monitoring	84	60	51.0–57.0	Noonkanbah Formation
LF04B	80270068	Lower Fitzroy (Clohessy 2017)	Monitoring	24	22	15.0–20.0	Fitzroy alluvium
LF05	80270069	Lower Fitzroy (Clohessy 2017)	Monitoring	42	27	21.0–25.0	Fitzroy alluvium
MA15MB001	80211439	Mount Anderson (Gallardo 2018b)	Monitoring	102	60	42–54	Erskine
MA15MB002	80211440	Mount Anderson (Gallardo 2018b)	Exp hole	102	-	-	
MA15MB003	80211441	Mount Anderson (Gallardo 2018b)	Exp hole	102	-	-	
MA15MB004	80211442	Mount Anderson (Gallardo 2018b)	Monitoring	102	96	78–90	Noonkanbah Formation
MA15MB005	80211443	Mount Anderson (Gallardo 2018b)	Exp hole	151	-	-	
LF06	80270070	Lower Fitzroy (Clohessy 2017)	Monitoring	120	102	93.0–99.0	Poole Sandstone
LF07	80270071	Lower Fitzroy (Clohessy 2017)	Monitoring	96	71	62.0–68.0	Grant Group
KD16MB001	80300008	Kimberley Downs & Brooking Springs stations (DWER 2017)	Monitoring	120	103	82.0–100.0	Grant Group
KD16MB002	80300009	Kimberley Downs & Brooking Springs stations (DWER 2017)	Monitoring	126	120	100.0–118.0	Grant Group
KD16MB003	80300010	Kimberley Downs & Brooking Springs stations (DWER 2017)	Monitoring	126	52	38.0–50.0	Grant Group
KD16PB001	80300012	Kimberley Downs & Brooking Springs stations (DWER 2017)	Monitoring	120	115	94.0–112.0	Grant Group

Bore ID	AWRC no.	Investigation program	Purpose	Drilled depth (m bgl)	Bore depth (m bgl)	Screen interval (m bgl)	Screened aquifer
BS16MB001A	80200052	Kimberley Downs & Brooking Springs stations (DWER 2017)	Monitoring	96	96	80.0–90.0	Grant Group
BS16MB001B	80270074	Kimberley Downs & Brooking Springs stations (DWER 2017)	Monitoring	58.4	58.4	55.4–58.4	Grant Group
BS16MB001C	80270075	Kimberley Downs & Brooking Springs stations (DWER 2017)	Monitoring	40.5	40.5	37.5–40.5	Grant Group
BS16MB003A	80200054	Kimberley Downs & Brooking Springs stations (DWER 2017)	Monitoring	129	118	96.0–118.0	Grant Group
BS16MB003B	80270076	Kimberley Downs & Brooking Springs stations (DWER 2017)	Monitoring	92	92	86.0–92.0	Grant Group
BS16MB003C	80270077	Kimberley Downs & Brooking Springs stations (DWER 2017)	Monitoring	79	78.3	72.3–78.3	Grant Group

Note: One hole was drilled beyond the Fitzroy River alluvium into the Fairfield Group; exp – exploration geology hole, no groundwater monitoring bore constructed at this location; DWER – Department of Water and Environmental Regulation; m bgl – metres below ground level.

Fitzroy Trough

We drilled seven investigation holes in the Camballin region of the Grant Range, and then constructed 100 mm PVC groundwater monitoring bores at four of these sites, with a single bore screened in each of the Erskine, Noonkanbah Formation and Grant Poole aquifers (Figure 19).

Lennard Shelf

We drilled 10 holes across five separate locations on the Lennard Shelf to investigate the properties of the Grant Group in the Grant Poole aquifer on both Brooking Springs and Kimberley Downs stations. We then constructed groundwater monitoring bores (100 mm PVC) at nine of these sites, and a stainless-steel cased production bore (KD16PB001) at the 10th site near KD16MB02 on Kimberley Downs Station (DWER 2017).

We installed six groundwater monitoring bores across two sites (three bores at each site) on Brooking Springs Station. These bores were all screened in the Grant Group (Figure 19).

Bore construction information, palynology and detailed lithological and geophysical logs from the investigation program are available in Clohessy (2017), DWER (2017) and Gallardo (2018b).

3.3 Pumping test

We carried out a 48-hour constant rate pumping test for production bore KD16PB001 at Kimberley Downs Station in late 2016. This was to evaluate the potential yield from properly constructed production bores in the Grant Group and to derive new information on the aquifer's hydraulic properties. The pumping test method and results are described in Resource Water Group (2016).

3.4 Downhole geophysical logging

We collected downhole geophysical logs from 44 groundwater bores (Appendix A) in the study area from a combination of new holes drilled for this investigation and existing stock bores where these were suitable. This total included 18 bores logged by Geoscience Australia to support interpretation of and provide confidence in the AEM data.

At each site we collected downhole gamma and conductivity logs, and at five bores we collected borehole magnetic resonance (BMR) logs (see Appendix A).

3.5 Monitoring

3.5.1 Groundwater monitoring

We measured groundwater levels through manual dips and continuous data logger measurements from 45 groundwater bores across the study area (Appendix B). We installed loggers in the first group of monitoring bores in November 2015, then installed and removed them from individual bores progressively over the life of the project.

In-Situ Level Troll 400 data loggers were installed in 34 bores throughout the study area. These loggers collect groundwater-level data at hourly intervals from the Fitzroy River alluvial aquifer, Liveringa Group, Grant Poole and Devonian reef aquifers. In-Situ BaroTROLL barometric pressure loggers were also installed at BS16MB003 (Brooking Springs), KD16MB002 (Kimberley Downs), LF06 (Mount Anderson), Homestead Bore 3A (Gogo Station), Liveringa Stock bore (Liveringa Station) and Lightning Bore (Myroodah Station).

We downloaded data from the loggers twice a year in May and October – after the start and before the finish of each dry season – and made it publicly available on the department's Water Information Reporting portal.

We will review the long-term requirement for groundwater monitoring in the study area as part of our allocation planning process.

See the *Lower Fitzroy groundwater monitoring review* (Clohessy 2018) for further information about the monitoring program.

3.5.2 Surface water monitoring

Streamflow gauges were first installed in the Fitzroy River catchment in the 1950s. Currently[1] there are 13 operational stream gauges, which provide good regional spatial coverage over the entire catchment.

Our study uses data from the five streamflow gauging stations located in the south-west of the catchment, downstream of Geike Gorge, focused on the Fitzroy Trough and Lennard Shelf. These streamflow gauges are located at Willare, Looma, Fitzroy Barrage, Noonkanbah and Fitzroy Crossing. We also use data from a sixth streamflow gauge site at Dimond Gorge, upstream of Geike Gorge, as being representative of the streamflow in the upper catchments.

A streamflow gauge measures the height of the water relative to the level of the stream bed. It uses a gas bubbler pressure-sensed water level recorder inside an installation with a pressure line to an orifice within the river (Figure 20). An electronic pressure transducer senses the back pressure and converts it to a water level

[1] Four streamflow gauging stations in the Fitzroy River catchment were damaged during the January 2023 flood event. Two have had temporary repairs made at time of publication of this report.

reading in metres. To overcome issues associated with the river depths and extensive floodplains during floods, many of the water level recorders have been installed on towers near the riverbank (Figure 20).

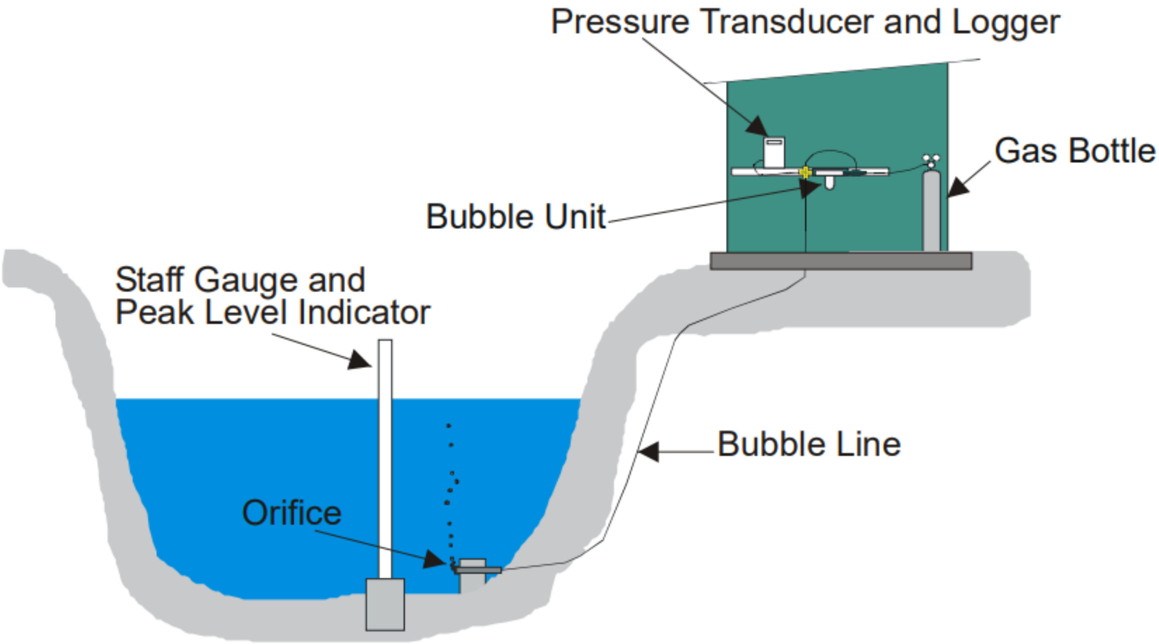


Figure 20 Schematic of streamflow gauge installation for measuring river depths

Ideally, a streamflow gauge should be located on a reach where the channel geometry remains relatively constant over time. Road crossings, weirs and natural rock bars provide stable low-flow controls, which defines a relatively constant river level at which flow stops.

On the Fitzroy River the streamflow gauges at Dimond Gorge, Noonkanbah and Fitzroy Barrage are examples of sites with stable low-flow controls. However, the other streamflow gauges used in this study at Fitzroy Crossing, Looma and Willare are located on reaches without stable low-flow controls. At these sites the riverbed geomorphology can change during each flow event. As a result, the location of pools and the river level at which downstream flow ceases can change from year to year, or in some cases within each season.

For example, riverbed elevation changes at the Fitzroy Crossing streamflow gauge raised the level at which downstream flow stopped by almost 1 m between observations made in 2003 and 2009. This meant that in 2003, despite actual flow of 1 m deep, the water level recorded was the same as that when flow ceased in 2009. Observations made during site visits meant the data could be corrected for the changes in the riverbed. But uncertainty remains about when these riverbed-levels changed and how the river-bed changed between site visits.

Figure 21 Gauging station infrastructure at Noonkanbah on the Fitzroy River

Analyses of flow and other low-flow analyses are affected by how often changes to the cease-to-flow level at the site are observed and the magnitude of these changes.

Water quality sampling is not routinely undertaken at the streamflow gauges. However, basic water quality data – such as conductivity and turbidity – has been collected during site visits at many of the sites.

3.6 Groundwater sampling

Across the study area groundwater samples were collected in 2016 and again in 2017 as part of the collaboration between the CSIRO and the department.

The data has been used to assess regional groundwater quality, groundwater flow processes including recharge, throughflow and discharge, and inter-aquifer connectivity. It has also been used to support an updated assessment of the groundwater interaction of several significant aquifers with the Fitzroy River.

The groundwater sampling program targeted the Fitzroy River alluvial, Liveringa Group, Grant Poole and Devonian reef aquifers.

Groundwater samples were collected from a network of bores that had suitable bore construction, with some bores sampled twice across multiple years to assess seasonal variation. Seven rounds of groundwater sampling took place between 2016 and 2018 (Table 3). See Appendix C for survey and construction data for all bores sampled and Appendix D for the field measured groundwater parameters.

See Taylor et al. (2018) for an interpretation of groundwater chemistry analysed from samples collected before 2017.

Table 3 Groundwater sampling program between 2016 and 2017

Groundwater sampling trips		Bores sampled
June 2016	DWER	10
July 2016	CSIRO	16
September 2016	DWER	8
May 2017	DWER	4
July 2017	CSIRO	8
August–September 2017	DWER	19
August 2018	DWER	10

3.6.2 Site selection for groundwater sampling

The initial set of bores for the groundwater sampling program were selected by desktop analysis. We selected bores with known construction details that were screened in the aquifers targeted for investigation – the Devonian reef, Grant Group and Poole Sandstone, Liveringa and Fitzroy River alluvial aquifers.

After the desktop analysis, we undertook site reconnaissance to confirm the location of the proposed sampling sites. As part of this, we consulted with station managers to locate other bores not registered with the department, to assess suitability for the sampling program.

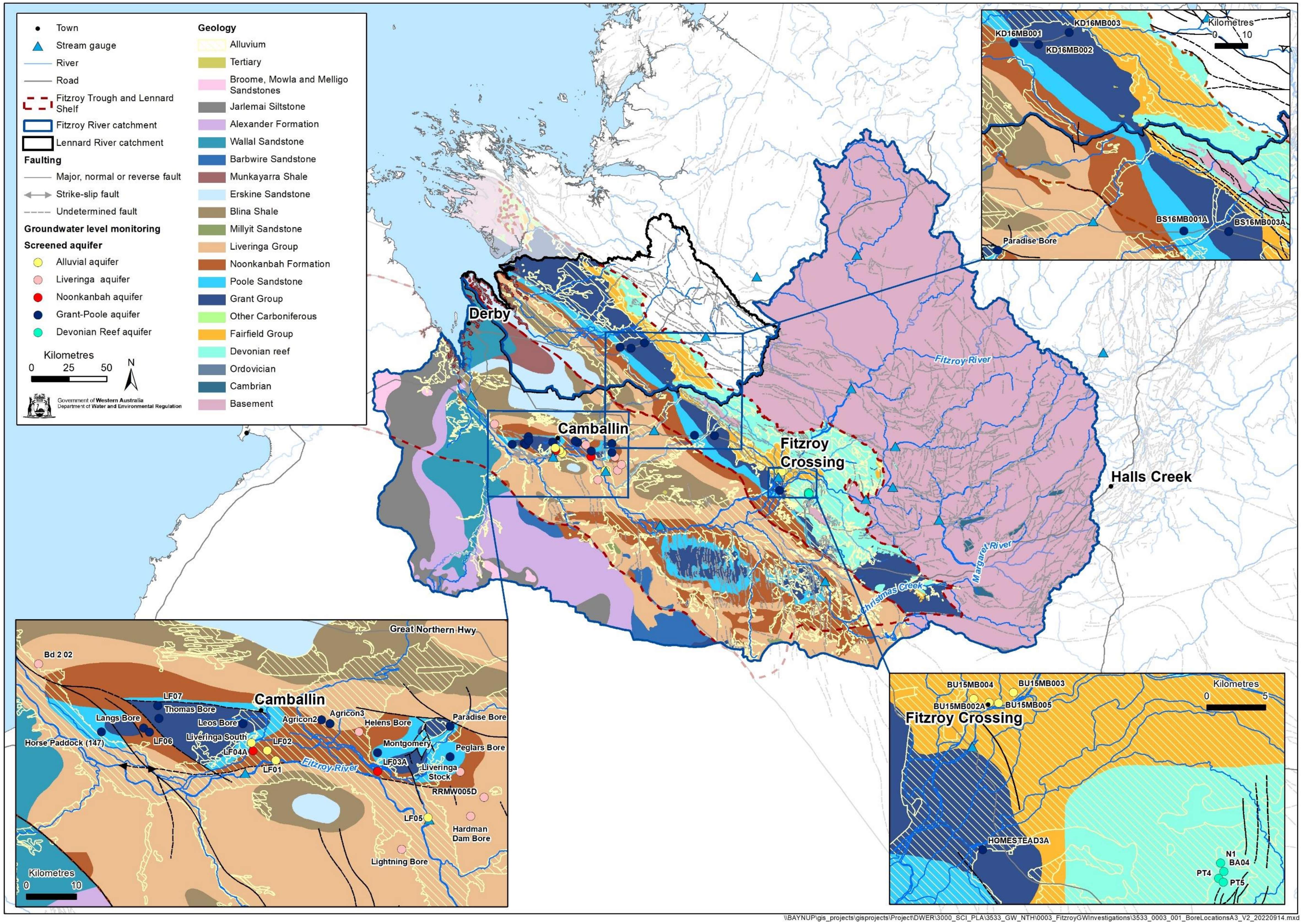


Figure 22 Groundwater monitoring bores, Fitzroy study area

We could only identify a limited number of bores with complete construction details, including screened interval. We conducted down-hole camera surveys at several bores to identify construction details such as screen intervals. For sample bores with unknown inlet depths, we used end-of-hole depth as a surrogate for the collection depth of the sample.

We sampled a total of 61 bores, including 20 bores drilled as part of these investigations and 41 pre-existing bores (Table 4).

3.6.3 Field groundwater sample collection

We sampled groundwater in accordance with Geoscience Australia's *Groundwater sampling and analysis guidelines* (Sundaram et al. 2009). Monitoring bores were purged of a minimum of three casing volumes before the collection of samples. Bores already equipped with pumps and in regular use did not require purging. CFCs were not collected from some shallow operating bores due to the potential for contamination from existing plastic fittings. See Appendix D and Appendix E for summaries of the groundwater sampling data.

Before sampling, we measured field readings – pH, electrical conductivity (EC), temperature, dissolved oxygen (DO) and oxidation reduction potential (ORP) – at five-minute intervals for about 30 minutes, or until field readings had stabilised.

We sampled the bores that were not already equipped with pumps using either a 12V stainless-steel submersible Mega Monsoon pump, or a stainless-steel submersible SQ Grundfos pump.

We used the lower capacity Mega Monsoon pump for sampling shallow bores and to collect CFC samples (given it is made of nylon tubing). We used the higher capacity trailer-mounted SQ pump (Figure 23) to sample deeper bores and/or where CFC analysis was not required.

3.6.4 Groundwater sampling parameters and procedures

Samples were analysed for a variety of laboratory parameters including major ions, nutrients, dissolved metals, stable isotopes, tritium, CFC, radiocarbon and ^{4}He.

CSIRO and the department contract out their sample analyses to a range of different laboratories (Table 5). This is mainly relevant for analysis of CFC data, as the CSIRO and GNS laboratories have different limits of detection; that is:

- CSIRO: CFC 11 < 0.18 p Mol/kg
  CFC 12 < 0.16 p Mol/kg
- GNS Science: CFC 11 < 0.02 p Mol/kg
  CFC 12 < 0.01 p Mol/kg

This difference can sometimes cause discrepancies in calculated residence times and recharge rates if these calculations are based on CFC concentrations.

Table 4 Groundwater bores sampled

Bore ID	AWRC* no.	Project subarea	Station/community	Aquifer	Screen (m bgl)*	Bore depth (m bgl)
LF01	80270063	Fitzroy Trough	Myroodah Crossing	Fitzroy River alluvium	13.0–18.0	20
LF02	80270064	Fitzroy Trough	Myroodah Road	Fitzroy River alluvium	24.0–30.0	32
LF03B	80270066	Fitzroy Trough	Camballin–Noonkanbah Rd	Fitzroy River alluvium	10.0–15.0	17
LF04B	80270068	Fitzroy Trough	South of Looma	Fitzroy River alluvium	15.0–20.0	22
LF05	80270069	Fitzroy Trough	Fitzroy Barrage	Fitzroy River alluvium	21.0–25.0	27
Liveringa South	80270072	Fitzroy Trough	Liveringa	Fitzroy River alluvium	-	36.7
Barefoot Bore	80270073	Fitzroy Trough	Liveringa Station	Erskine Sandstone	74.0–99.0	100
Garden Bore	80210704	Fitzroy Trough	Myroodah	Erskine Sandstone	-	20.4
2-89 Mt Anderson	80210072	Fitzroy Trough	Mount Anderson	Liveringa Group	57.6–66.16	66.2
Helens Bore	80240014	Fitzroy Trough	Liveringa	Liveringa Group	38.0–77.2	77.2
RRMW005D	80212097	Fitzroy Trough	Liveringa	Liveringa Group	94.0–97.0	97
LF03A	80270065	Fitzroy Trough	Camballin–Noonkanbah Rd	Noonkanbah Formation	49.5–55.5	57.5
LF04A	80270067	Fitzroy Trough	South of Looma	Noonkanbah Formation	51.0–57.0	60
1-04 Camballin	80200059	Fitzroy Trough	Camballin	Poole Sandstone	31.5–43.5	44
Langs Bore	80210241	Fitzroy Trough	Mount Anderson	Poole Sandstone	-	54.8
LF06	80270070	Fitzroy Trough	Mount Anderson	Poole Sandstone	93.0–99.0	102
Irrigation Bore	80210620	Fitzroy Trough	Mount Anderson	Poole Sandstone	-	23.77
Montgomery Bore	80210233	Fitzroy Trough	Liveringa	Poole Sandstone	-	42.7
Paradise Bore	80270056	Fitzroy Trough	Liveringa	Poole Sandstone	12.6–13.5	26.5
Peglars Bore	80210841	Fitzroy Trough	Liveringa	Poole Sandstone	-	29
Agricon 1	80210234	Fitzroy Trough	Liveringa	Grant Group	-	600
Agricon 2	80270062	Fitzroy Trough	Liveringa	Grant Group	-	617
Agricon 3	80240013	Fitzroy Trough	Liveringa	Grant Group	-	588
Jarlmadangah 1-02	80200059	Fitzroy Trough	Jarlmadangah	Grant Group	31.7–91.7	92
Leos Bore	80210235	Fitzroy Trough	Liveringa	Grant Group	21.0–24.5	24.5
LF07	80270071	Fitzroy Trough	Mount Anderson	Grant Group	62.0–68.0	71
Shovelton	80210261	Fitzroy Trough	Liveringa	Grant Group	-	549
Thomas Bore	80240012	Fitzroy Trough	Mount Anderson	Grant Group	-	31.3
Looma 1-86	80219133	Fitzroy Trough	Looma	Grant Group	31.7–73.5	73.5
Looma 1-93	80219134	Fitzroy Trough	Looma	Grant Group	38.2–80.2	80.2
Birdwood Bore	80200055	Lennard Shelf	Gogo Station	Fitzroy River alluvium	14.5–17.4	-
BU15MB002A	80200045	Lennard Shelf	Bunuba	Fitzroy River alluvium	19.8–23.8	29.8

Bore ID	AWRC* no.	Project subarea	Station/community	Aquifer	Screen (m bgl)*	Bore depth (m bgl)
BU15MB003	80200024	Lennard Shelf	Bunuba	Fitzroy River alluvium	21.0–27.0	28
BU15MB004	80200025	Lennard Shelf	Bunuba	Fitzroy River alluvium	22.0–28.0	30
Manta Ray Bore	80210901	Lennard Shelf	Gogo Station	Noonkanbah Formation	17.6–35.3	-
Blue Bush	80210973	Lennard Shelf	Quanbun Downs	Poole Sandstone	-	36.6
Chestnut Bore	80210428	Lennard Shelf	Gogo Station	Poole Sandstone	-	182.9
Huttons Bore No.2	80270081	Lennard Shelf	Gogo Station	Poole Sandstone	38.6–56.6	-
No. 8 Bore	80210382	Lennard Shelf	Quanbun Downs	Poole Sandstone	-	76.2
One Tree Bore No.2	80211095	Lennard Shelf	Gogo Station	Poole Sandstone	89–131	-
Pilots Flowing Bore	80270082	Lennard Shelf	Gogo Station	Poole Sandstone	-	-
Tank Bore No.2	80270083	Lennard Shelf	Gogo Station	Poole Sandstone	54–84	-
2/89 – Fitzroy Crossing	80219066	Lennard Shelf	Fitzroy Crossing	Grant Group	27.8–58.3	61.85
5/10 – Fitzroy Crossing	80211372	Lennard Shelf	Fitzroy Crossing	Grant Group	28.7–34.7	39
Acacia Tank Flowing Bore	80270084	Lennard Shelf	Gogo Station	Grant Group	-	-
BS16MB001A	80200052	Lennard Shelf	Brooking Springs	Grant Group	80.0–90.0	96
BS16MB001B	80270074	Lennard Shelf	Brooking Springs	Grant Group	55.4–58.4	58.4
BS16MB001C	80270075	Lennard Shelf	Brooking Springs	Grant Group	37.5–40.5	40.5
BS16MB003A	80200054	Lennard Shelf	Brooking Springs	Grant Group	96.0–118.0	118
BS16MB003B	80270076	Lennard Shelf	Brooking Springs	Grant Group	86.0–92.0	92
BS16MB003C	80270077	Lennard Shelf	Brooking Springs	Grant Group	72.3–78.3	78.3
Donalds Mill No.2	80270085	Lennard Shelf	Gogo Station	Grant Group	-	41.15
Gogo Station Homestead Bore 3A	80211064	Lennard Shelf	Gogo Station	Grant Group	24.8–36.58	38.1
KD16MB002	80300009	Lennard Shelf	Kimberley Downs	Grant Group	100.0–118.0	120
KD16MB003	80300010	Lennard Shelf	Kimberley Downs	Grant Group	38.0–50.0	52
Laurel Homestead Bore	80210371	Lennard Shelf	Laurel Downs	Grant Group	-	61
Bore	80210370	Lennard Shelf	Brooking Springs	Fairfield Group	32.1–35.2	40.3
BA04	80212011	Lennard Shelf	Gogo Station	Devonian reef	11.7–17.98	20
Emanuels Flowing Bore	80270086	Lennard Shelf	Gogo Station	Devonian reef	-	-
PT4	80212103	Lennard Shelf	Gogo Station	Devonian reef	-	107
Sallys Bore	80270087	Lennard Shelf	Gogo Station	Devonian reef	-	-

**AWRC – Australian Water Resources Council; m bgl – metres below ground level.*

Figure 23 Groundwater sampling using pump trailer at LF02

Table 5 Groundwater analytical parameters and laboratories

Groundwater sampling	No. of samples	Laboratory
Major ions, metals, nutrients	75	CSIRO, ALS
Deuterium (^{2}H) and oxygen-18 (^{18}O)	75	University of Western Australia (UWA), University of Queensland (UQ)
Radiocarbon analysis (^{13}C & ^{14}C)	65	Australian National University (ANU), Australian Nuclear Science & Technology Organisation (ANSTO), GNS Science
Tritium analysis	75	GNS Science
CFC analysis	38	CSIRO, GNS Science
Strontium	32	University of Adelaide
Helium-4 (^{4}He)	38	CSIRO
Total samples	**75**	

We collected groundwater samples for analyses of:

- *major ions and bromide* – in a 500 ml plastic container and a 125 ml plastic container respectively
- *cations, dissolved metals and nutrients* – filtered through 0.45 µm filters
- *stable isotopes* – in 100 ml amber glass jars with minimal headspace
- *nutrients (TN, NO_3, NO_2, NH_{3-})* – in 60 ml plastic containers pre-preserved with sulfuric acid
- *dissolved metals* – in 60 ml plastic containers, pre-preserved with nitric acid.

  (All samples analysed for major ions, metals, nutrients and ^{2}H and ^{18}O isotopes were stored at 4°C until they were submitted to the ALS laboratory in Perth or the Analytical Services Unit (ASU) at CSIRO in Adelaide for analysis.)
- *chlorofluorocarbons (CFCs)* – in duplicate (for GNS Science) or triplicate (for CSIRO) in 125 ml clear glass jars, following GNS Science and CSIRO environmental tracer and noble gas laboratory protocols

  (Sampling for CFCs was undertaken using stainless steel pumps and fittings with nylon tubing. They were collected underwater in a stainless-steel bucket to prevent CFC contamination from the atmosphere (Figure 24).

  CFC samples were stored in ambient conditions until they were received by GNS Science in New Zealand or CSIRO in Adelaide.)
- *tritium and radiocarbon* – in 1 L plastic containers, which were stored in ambient conditions until they were submitted to the laboratory.

  (Samples were submitted to the ANU in Canberra, ANSTO in Sydney and GNS Science in New Zealand.)
- *noble gases (He, Ne, Ar, Kr and Xe)* – in duplicate following the CSIRO environmental tracer and noble gas laboratory protocols for the copper tube method (Weiss 1970).

  (Samples were collected using Tygon tubing as the inlet tube to the copper tube, with outlet tubing made from standard nylon attached to a pressure gauge (Figure 25).

  Samples were collected by running water through the copper tube for about two minutes, ensuring no bubbles were present. The pressure gauge was then tightened to ensure back pressure into the tube. The outflow end of the copper tube was clamped shut first, followed by the intake end of the copper tube. The water sample was stored within the copper tube and submitted to the CSIRO for analysis.)

References for laboratory methods are in Table 7, and in Taylor et al. (2018).

Figure 24 Groundwater sampling for CFCs

Figure 25 Groundwater sampling for noble gases, using the copper tube method

3.6.5 Data quality

Before using the water analysis data for any recharge calculations, we checked the charge balances. We did not use data from water samples with large charge balance errors (greater than ± 10%) that could not be accounted for. We also excluded data from samples we suspected were compromised by casing failure and/or potential contamination from land use.

See Table 6 for a summary of the samples we omitted from recharge calculations and Appendix J for a more detailed discussion of our rationale for excluding some water analysis data.

Table 6 Samples removed from analysis

Bore	Not used for chlorofluoro-carbon (CFC) analysis	Not used for chloride mass balance (CMB) analysis	Not used for radiocarbon analysis	Not used for ^{4}He analysis	Rationale (Appendix J)
Leos bore	x	x	x	NA	Bore damaged, elevated nutrient levels
Looma 1-93	x	x	x	NA	Charge balance error > 10%
Blue Bush	x	x	x	NA	Charge balance error > 10%
Garden Bore	x	x	x	NA	Charge balance error > 10%
Helens Bore	x	x	x	NA	Charge balance error > 10%
2-89 Mt Anderson	x	x	x	NA	Charge balance error > 10%
LF03A	x	x	x	NA	Charge balance error > 10%
Birdwood Bore	x	x	x	NA	Charge balance error > 10%
Bore	x	x	x	x	CFCs present but tritium not detected, argon and/or neon detected
PT4	x	NA	NA	NA	CFCs present but tritium not detected
Paradise	x	NA	NA	NA	CFCs present but tritium not detected
Montgomery	NA	NA	x	NA	Anomalous high radiocarbon
Agricon 2	x	x	x	NA	Tritium detected, suggesting cracked casing
Liveringa South	NA	NA	x	NA	Anomalous high radiocarbon; CFCs detected
Chestnut Bore	NA	NA	x	NA	Unknown screen interval
Donalds Mill No. 2	NA	NA	x	NA	Unknown screen interval; elevated nutrients
Emanuels Flowing Bore	NA	NA	NA	x	Argon and/or neon detected suggesting air mixed with sample
Bore	NA	NA	NA	x	Argon and/or neon detected suggesting air mixed with sample

Bore	Not used for chlorofluoro-carbon (CFC) analysis	Not used for chloride mass balance (CMB) analysis	Not used for radiocarbon analysis	Not used for ^{4}He analysis	Rationale (Appendix J)
Acacia Tank Bore	NA	NA	NA	x	Argon and/or neon detected suggesting air mixed with sample
Agricon 3	NA	NA	NA	x	Argon and/or neon detected suggesting air mixed with sample
Shovelton	NA	NA	NA	x	Argon and/or neon detected suggesting air mixed with sample
Peglars	x	x	x	NA	Elevated nutrients
2/89 Fitzroy Crossing	x	x	x	NA	Elevated nutrients
5/10 Fitzroy Crossing	x	x	x	NA	Elevated nutrients

X *Not used because of data quality issues*
NA *Data not collected*

3.7 Fitzroy River and Margaret River sampling

Two separate river sampling programs were undertaken during this investigation: one in 2015 and one in 2017.

3.7.1 River sampling program (2015)

In November 2015, 47 samples were collected at locations along the Fitzroy River between Willare and the Fitzroy Barrage, as well as from selected pools and waterholes off the main river channel (Appendix G). This work is fully documented in Harrington and Harrington (2016) and is available on the Department of Primary Industries and Regional Development website.

We used the results from this sampling program to undertake an initial assessment of groundwater interaction with the Fitzroy River.

3.7.2 River sampling program (2017)

In collaboration with CSIRO, we collected a total of 79 surface water samples from the Fitzroy River (59 sites), Margaret River (six sites) and off-channel pools and creeks (14 sites). Sampling was undertaken on 14 and 15 June 2017 (Figure 26).

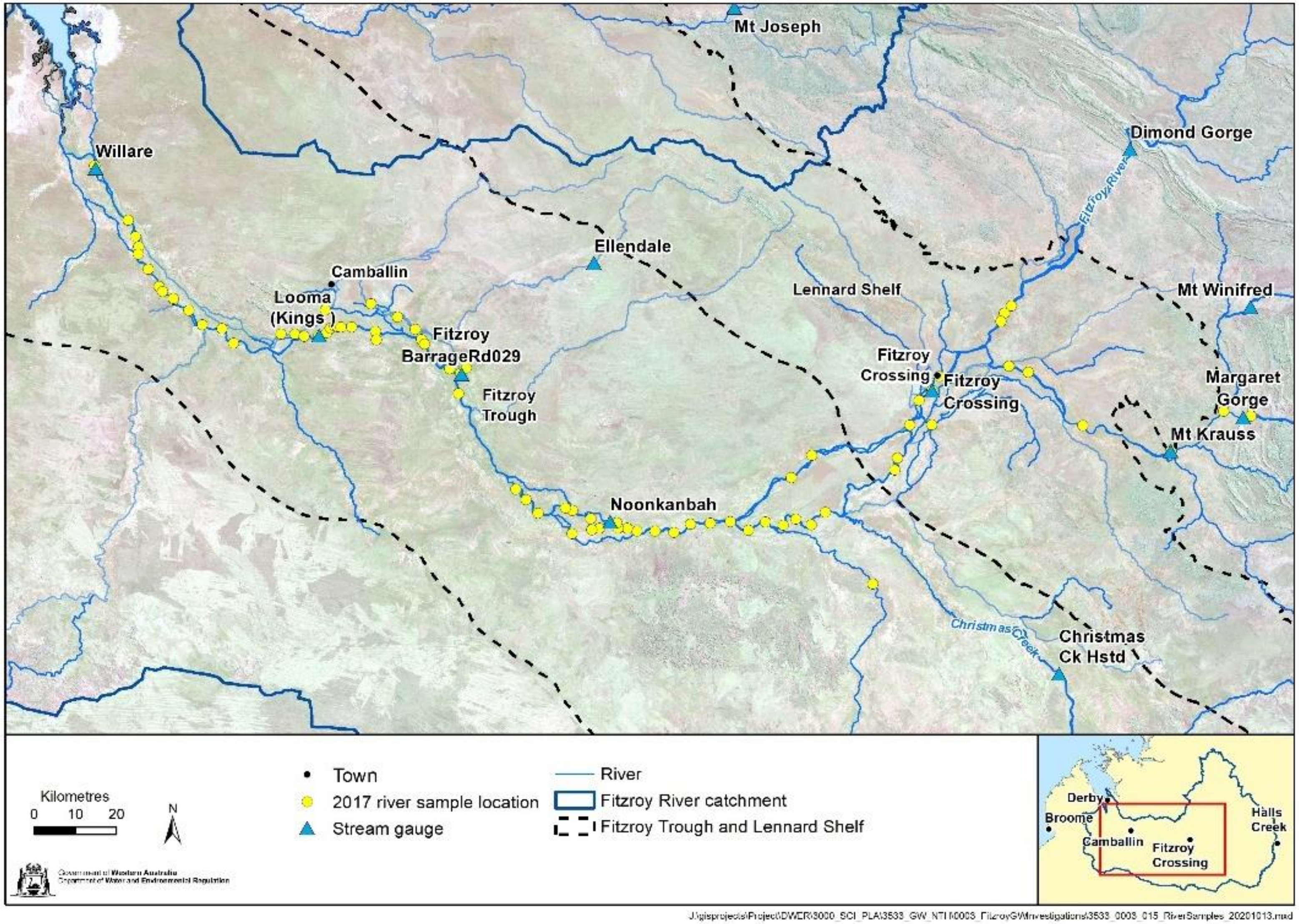


Figure 26 River sample locations, June 2017

3.7.3 Timing of river sampling

We conducted the 2017 river sampling program in June, close to the start of the dry season. The program followed the highest-rainfall wet season in several years (Figure 12). We compared data from the sampling program with that from previous sampling programs – May 2010 at the end of the wet season (Harrington et al. 2011) and November 2015 at the end of the dry season (Harrington & Harrington 2016) – to assess groundwater connectivity with the river seasonally and following wet seasons of different magnitudes.

3.7.4 River sample parameters

Samples were analysed for a similar suite of parameters as for the groundwater analyses: major ions, stable isotopes and ^{222}Rn (Appendix H). Noble gases were also collected and analysed for 22 of the 79 samples (Appendix I). See Table 7 for a summary of the laboratory methods employed for each of the different parameters.

Table 7 Laboratory methods for different parameters

Parameter	Laboratory	Method	Reference
Deuterium (^{2}H) and oxygen-18 (^{18}O)	UWA	Isotope liquid water and continuous water vapour analyser Picarro L1102-I	Skrzpek & Ford 2014
	UQ	Dual inlet isotope ratio mass spectrometer	Stable Isotope Geochemistry Laboratory
Tritium	GNS Science	Tritium measured using electrolytic enrichment and liquid scintillation counting using Quantulus low-level counters	Morgenstern & Taylor 2009
CFC	CSIRO, Adelaide	Gas chromatography	Busenberg & Plummer 1992
	GNS Science	Gas chromatography	GNS Water Dating Laboratory
Radiocarbon	ANU	Single stage accelerator mass spectrometry	Fallon et al. 2010
	ANSTO	Single stage accelerator mass spectrometry	Fink et al. 2004
	GNS Science	Single stage accelerator mass spectrometry	National Isotope Centre, GNS Science
Strontium	University of Adelaide	Isotope Phoenix TIMS instrument	David Bruce, University of Adelaide
Helium-4 (^{4}He)	CSIRO, Adelaide	Quadrupole mass spectrometers	CSIRO Environmental Tracer and Noble Gas Laboratory, Adelaide

3.7.5 Site selection for river sampling

For the 2017 river sampling program we decided to:

- re-sample sites that recorded ^{222}Rn activities > 0.1 Becquerel (Bq) per litre in previous sampling programs, as recommended in Harrington and Harrington (2016), to assess seasonal and annual variation
- re-sample sites around Noonkanbah that previously indicated older, deeper regional groundwater discharge (Harrington et al. 2011)

- align sample sites with streamflow gauging stations
- align sample locations with nearby groundwater bores
- sample locations that appeared to be permanent pools, based on a review of aerial imagery and Water Observations from Space (WOfSpace) data by Taylor et al. (2018).

Figure 27 River sampling, Geikie Gorge (top) and Margaret Gorge (bottom)

Photos taken by S Clohessy, 15 June 2017.

Figure 28 Sampling, Fitzroy River, between Willare and Looma

Photo taken by S Clohessy, 14 June 2017.

4 Geology results

As part of this study we developed several geological cross-sections to illustrate our updated geological and hydrogeological interpretations. The cross-sections are constructed along the airborne electromagnetic (AEM) flight lines shown in Figure 29.

The interpretations shown in these representative cross-sections are based on:

- the 2015 AEM survey (Figure 18)
- surface geology sourced from the 1:500 000 *Interpreted bedrock geology of Western Australia* (DMIRS 2016)
- formation thicknesses sourced from isopach maps in Mory (2010)
- lithology and palynology from drilling in this investigation
- geological information from existing petroleum well data, with geological interpretation from Mory (2010)
- geological information from existing bores, extracted from the department's Water Information and Reporting (WIR) database
- down-hole geophysical information (Appendix A).

An initial interpretation of these datasets (including geological cross-sections) has been published in Taylor et al. (2018).

The geological interpretation used in this study has incorporated strike-slip faulting to the north and south of the Grant Range anticline (Figure 29). The presence of this faulting was inferred in Zhan and Mory (2013), but it was not included in the formal DMIRS (2016) mapping.

4.1 Noonkanbah Formation

Our re-interpreted mapping shows a larger area of Noonkanbah Formation compared with the existing DMIRS (2016) mapping.

Three of the new investigation holes on Mt Anderson (MA) Station – LF06, MA15MB004 and MA15MB005 – intersected shallow Noonkanbah Formation.

The earlier DMIRS (2016) geological mapping indicated that the Poole Sandstone and Grant Group should be present as outcrop.

West of the line of MA bores (Figure 30), five pre-existing shallow (<50 m deep) stock bores with stratigraphic information were identified in the department's WIR database. Of these five bores, two sites (Camballin no. 4 and Camballin no. 5) indicated shallow Noonkanbah Formation, while three (Camballin no. 12, Irrigation Bore and Horse Paddock Bore) showed shallow Grant Group or Poole Sandstone.

The Noonkanbah Formation extent has also been revised between the Grant Range and Mt Wynne anticlines. At sites LF01, LF03 and LF04, the Noonkanbah Formation was encountered near the surface during drilling, which was not anticipated.

Figure 30 shows the updated aerial extent of the Noonkanbah Formation in the Grant Range and Mt Wynne.

This updated interpretation is also shown in Figure 31, which includes two different stratigraphic interpretations transposed along an AEM transect (flight line 550101 and 550102 – Figure 29) flown to the north of the axis of the Grant Range and Mt Wynne anticlines.

The existing interpretation along this flight line (Taylor et al. 2018; DMIRS 2016) shows the faulted area to the west of the Grant Range anticline as predominantly Poole Sandstone, whereas the interpretation developed in this study shows the area as thick Noonkanbah Formation. The presence of the faults is important to note as they could indicate shallow–deep connectivity, but their status as groundwater conduits is unknown.

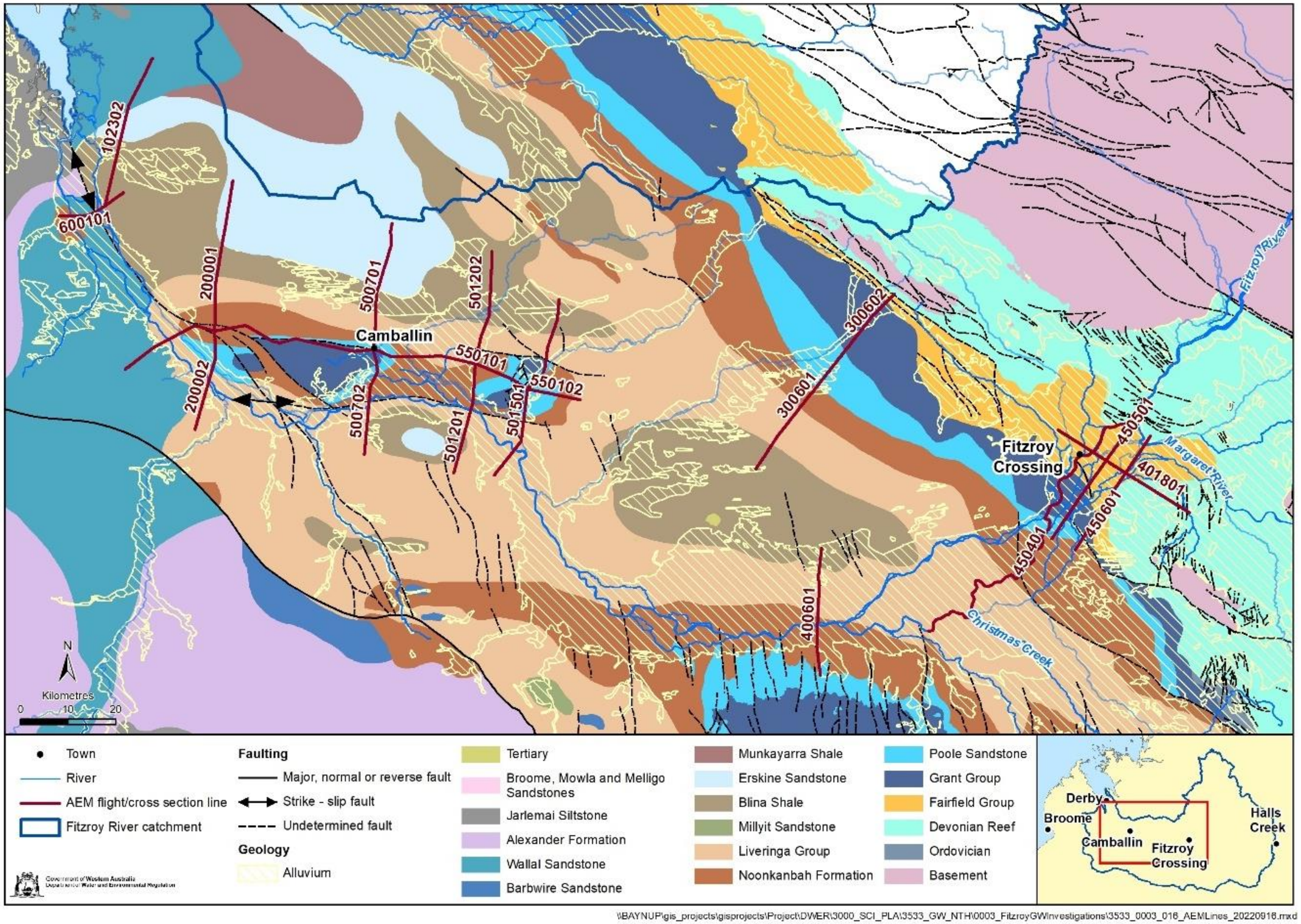
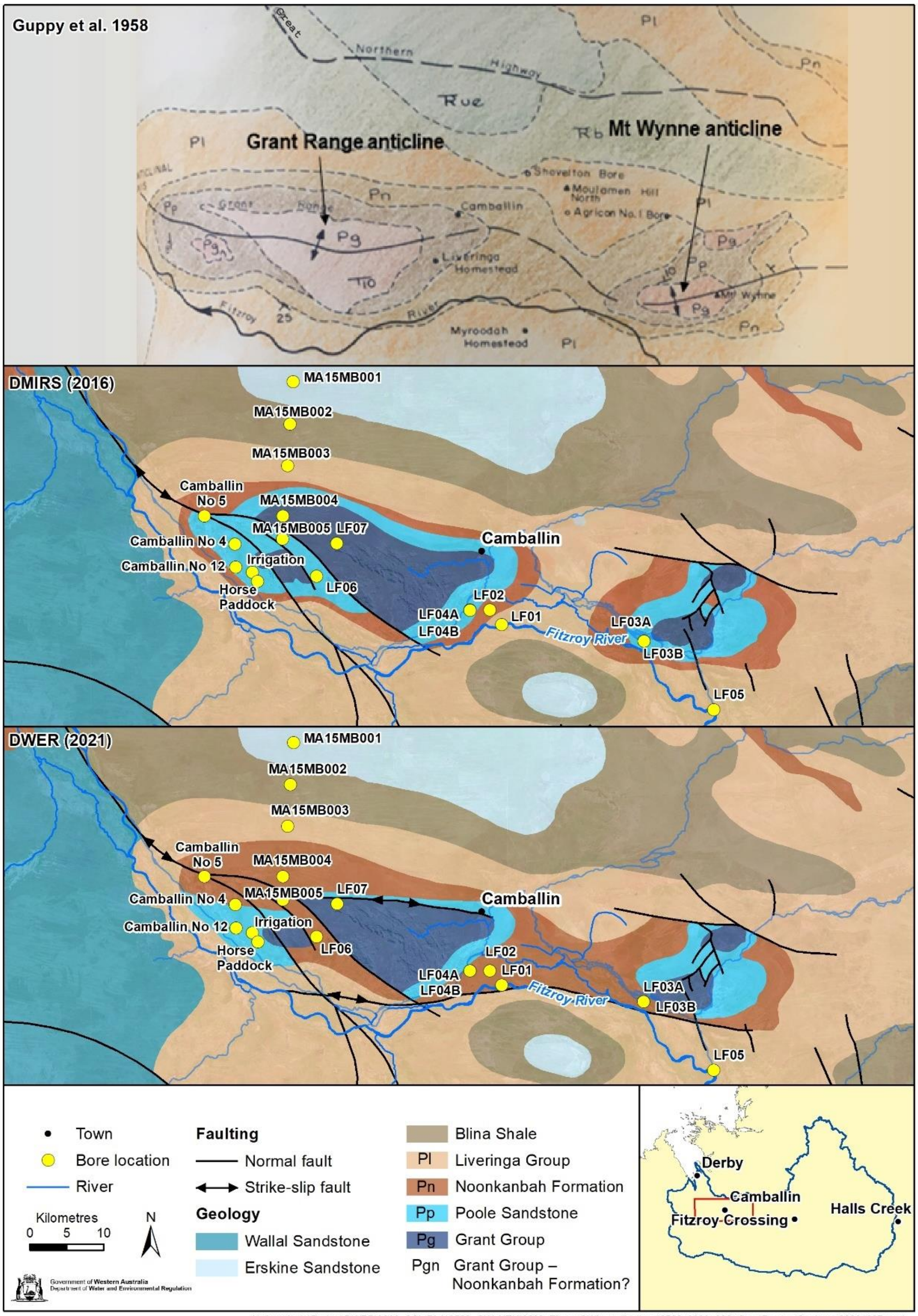


Figure 29 Locations of geological cross-sections from this report and Taylor et al. (2018)



J:\gisprojects\Project\DWER\3000_SCI_PLA\3533_GW_NTH\0003_FitzroyGWInvestigations\3533_0003_020_GrantRangesGeology_20201027.mxd

Figure 30 Evolution of geological interpretation, Camballin region (alluvium not shown)

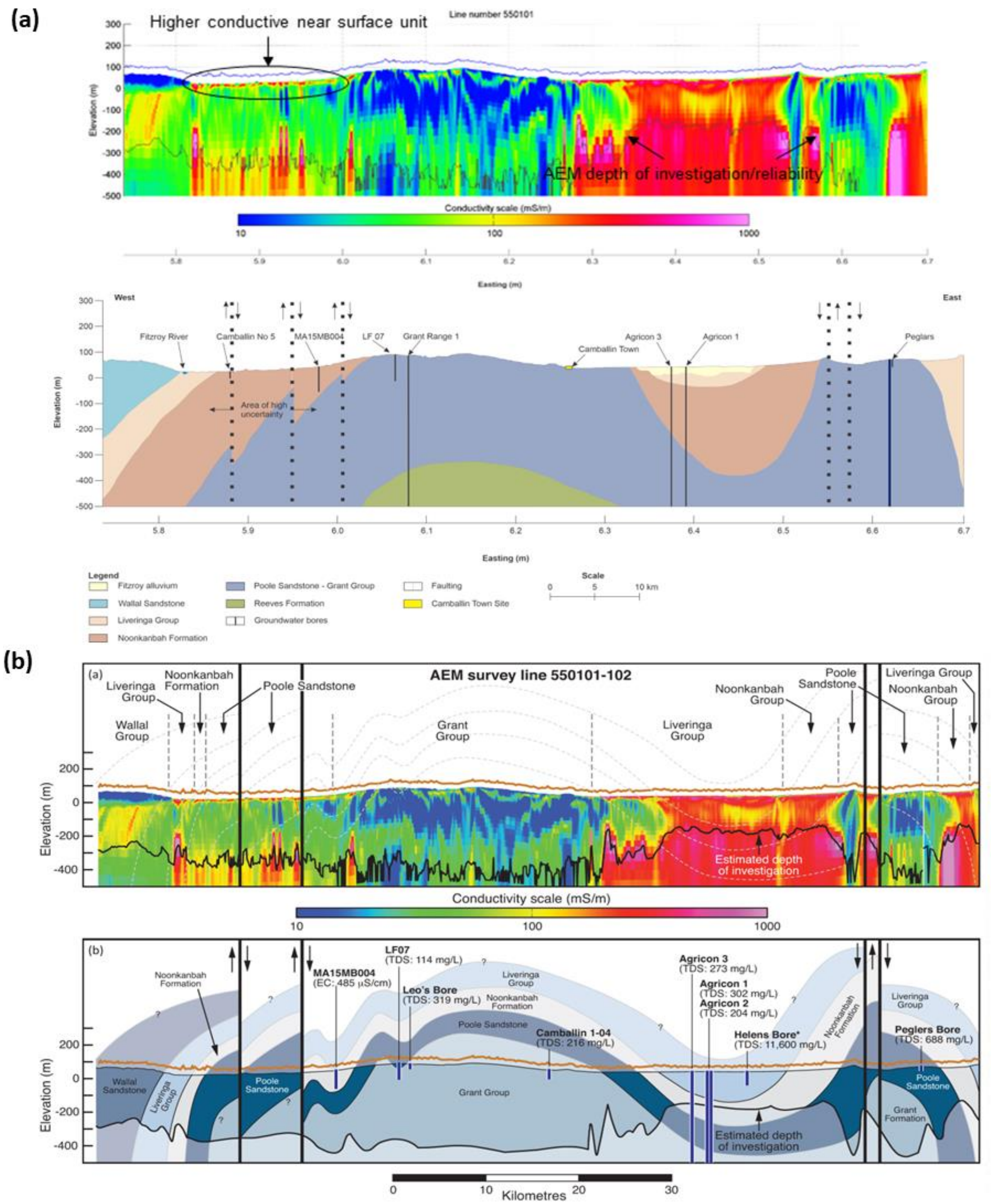


Figure 31 AEM flight line 550101 and 550102

Note: This figure shows (a) DWER (2020) and (b) DMIRS (2016) interpretation – reproduced from Taylor et al. (2018).

While we have included information from these bores in the updated geological mapping, we acknowledge the uncertainty around some of this interpretation. Further work would refine the conceptual geological understanding in this area if required.

4.2 Grant Group and Poole Sandstone

The extent of the Poole Sandstone at the surface has been reduced, based on the increased area of Noonkanbah Formation encountered.

Before this study, the geological interpretation of the area around investigation bores LF03 and LF04 anticipated that the Noonkanbah Formation would be absent (Clohessy 2017; Taylor et al. 2018). Instead, LF03 was found to intersect the Noonkanbah Formation directly underneath the alluvium at 15 m, extending to a depth of at least 78 m at the end of hole (EOH). This stratigraphic interpretation is supported by palynology collected from this bore (Clohessy 2017). At bore LF04, the Noonkanbah Formation (rather than the predicted Poole Sandstone) was encountered near the surface.

The absence of shallow/outcropping Poole Sandstone at bores LF03 and LF04 has resulted in a reduced area of Poole Sandstone south of the Mt Wynne anticline and the eastern end of the Grant Range anticline (Figure 30).

4.3 Wallal Sandstone

Our updated interpretation for the area around Willare has the Wallal Sandstone outcropping to the west of the Fitzroy River, and the Blina Shale to the east (Figure 32) – with both units overlain by the Fitzroy River alluvium.

Our interpretation is consistent with both the DMIRS (2016) mapping and Mory (2010). However, it differs from the Commander and Lindsay (2005) interpretation of the area, which mapped the Liveringa Group beneath the Fitzroy River alluvium throughout the area.

Figure 32 shows a cross-section along AEM line 102302 and the eastern part of AEM line 600101. It indicates that the Blina Shale – which is about 350 to 400 m thick (Mory 2010) – and the Liveringa Group separate the Wallal Sandstone west of the Fitzroy River, from the Wallal Sandstone in the Derby area (on Mowanjum and Yeeda pastoral stations). Bore MW15MB005 (Stocker 2015) was used to support the AEM data and constrain the interpreted thickness of the Wallal Sandstone on AEM line 10232.

The Wallal Sandstone is conformably overlain by the Alexander Formation and is separated from older units, including the Erskine Sandstone, by a major unconformity (Mory & Hocking 2011). The Munkayarra Shale separates the Wallal Sandstone and the Erskine Sandstone in the area around Derby.

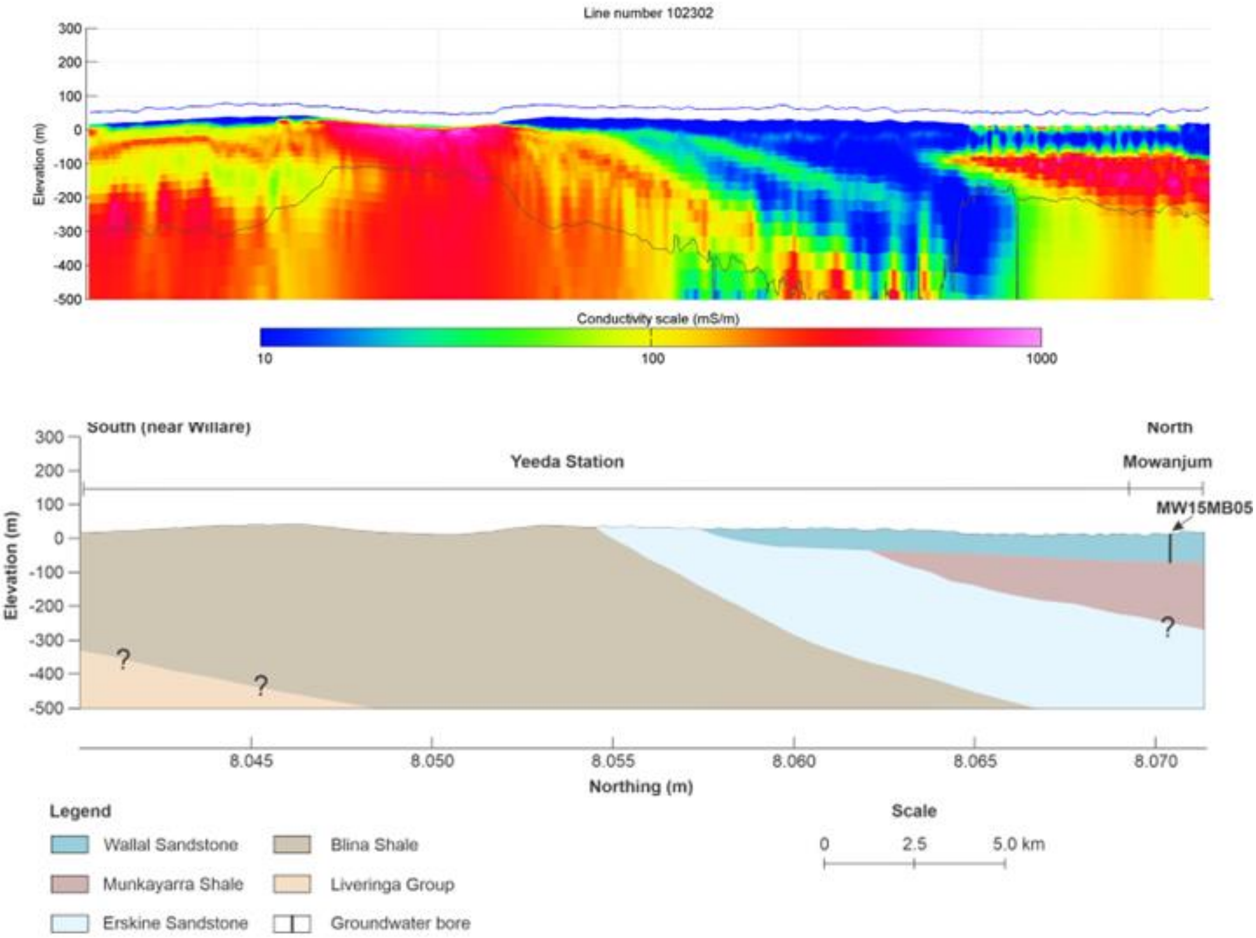


Figure 32 AEM flight line 102302 showing interpreted Wallal Sandstone thickness

4.4 Potential paleochannel

An AEM survey by Geoscience Australia and SkyTEM Australia Pty Ltd identified a linear feature across four separate AEM transect lines. This has been interpreted as a possible paleochannel (Figure 33) – see Appendix N for more information.

The paleochannel feature has low electrical conductivity, is relatively narrow and is restricted in extent. This suggests the feature contains sandier material – possibly equivalent to the Grant Group – that has been incised into the more electrically conductive, clayey Fairfield Group formation (Mira Geoscience 2018).

The feature was identified across four separate AEM transects and may be up to 2 km across and between 100 m and 200 m deep. However, no boreholes intersect this paleochannel feature, and its presence has been inferred solely on the basis of AEM data.

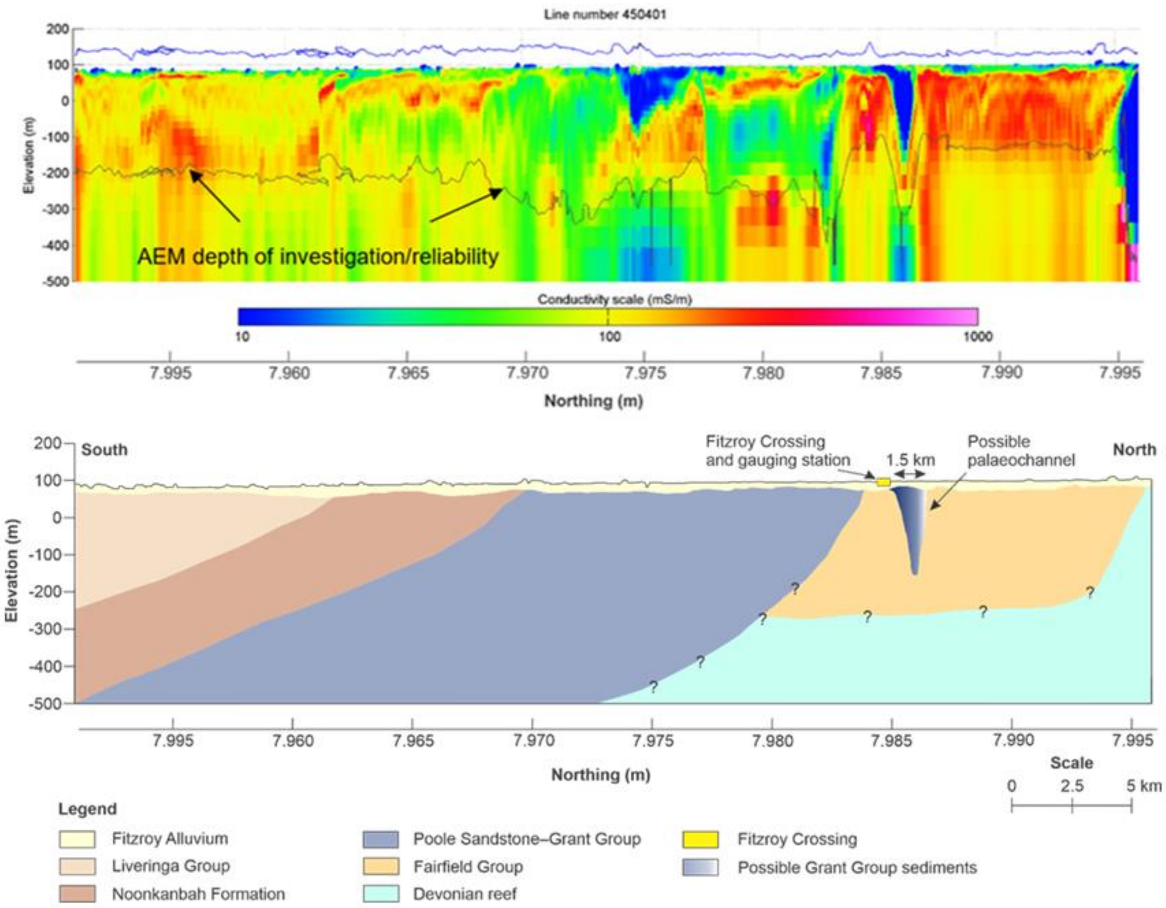


Figure 33 AEM flight line 450401 showing interpreted paleochannel

4.5 Fitzroy River alluvium

Results from this investigation, and from previous drilling undertaken on Noonkanbah Station (Harrington et al. 2011), have further confirmed that the Fitzroy alluvium is highly heterogenous. The alluvium comprises variable interbedded layers of gravel, sand, silt and clay. The AEM (Section 3.1) shows that areas of low electrical conductivity (sand and likely fresh water) are generally within 2 to 3 km of the river, and higher electrical conductivity units (saline water and/or silt/clay) further from the river (Figure 34).

The bores drilled as part of this investigation found the transmissive riverbed sand and gravel layer of the alluvium was discontinuous and variable in thickness, ranging from 2 to 17 m thick, rather than a uniform and regionally extensive 20 m river sand layer (Clohessy 2017; Gallardo 2017). The greatest thickness of alluvium in pre-existing alluvial aquifer bores was observed in Liveringa South (36.7 m thick).

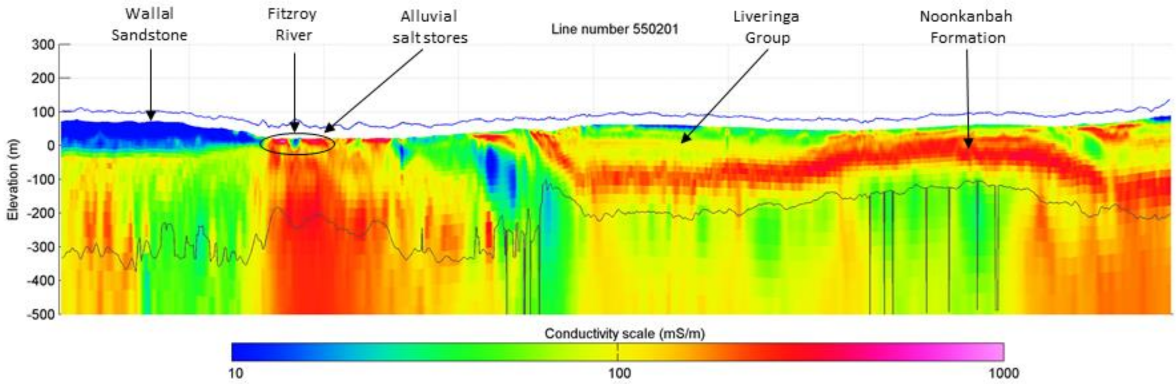
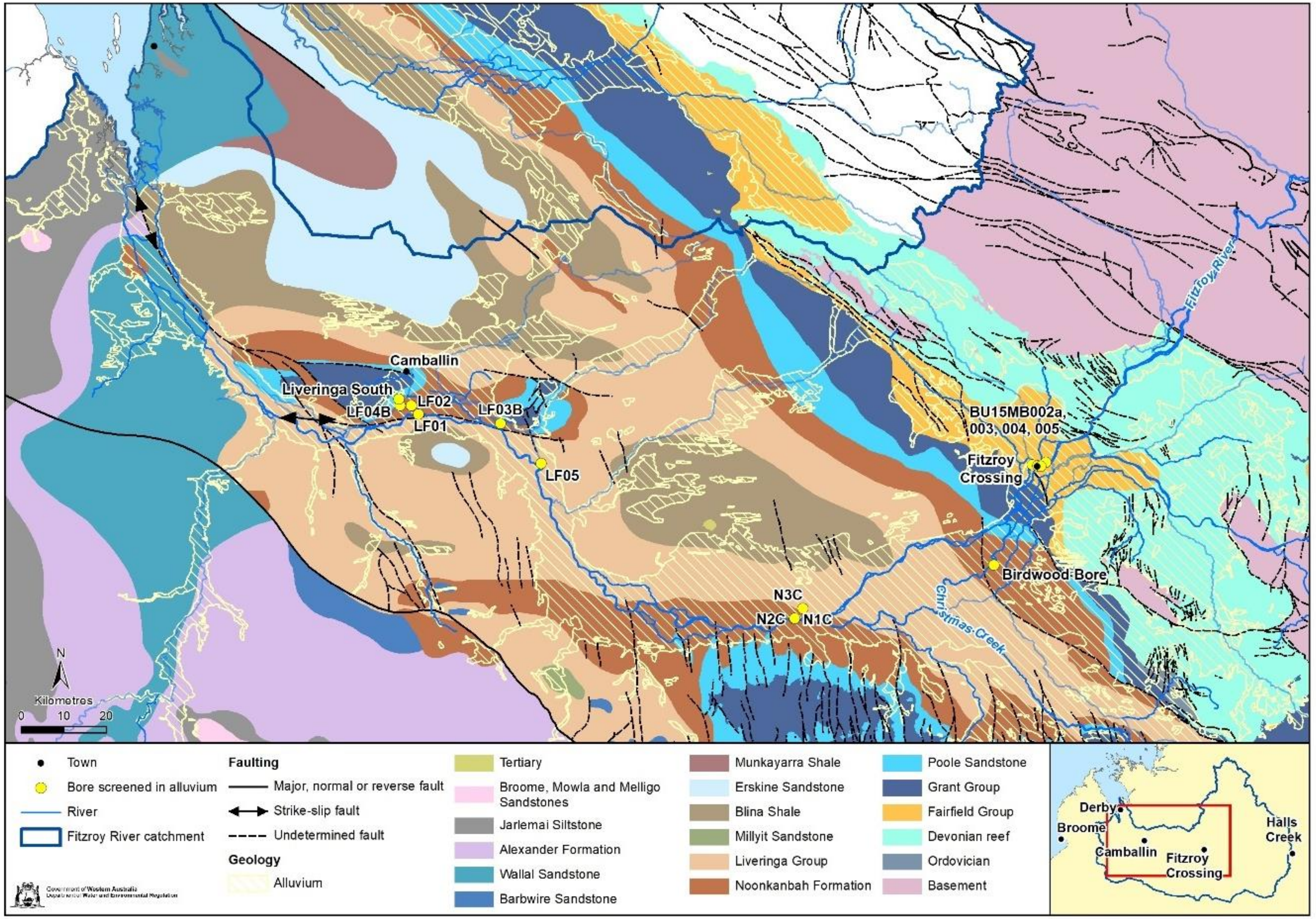


Figure 34 AEM cross-section downstream of Camballin

The Fitzroy River alluvium overlies different geological formations along the length of the river. Around Willare Crossing, it overlies the Wallal Sandstone on the western side of the river, the Blina Shale to the east of the river and the Liveringa Group further south.

In the area between the Looma gauging station and the Lennard Shelf, the Fitzroy River alluvium overlies the Liveringa Group and/or the Noonkanbah Formation. South of Fitzroy Crossing, it overlies the Poole Sandstone and Grant Group, and around Fitzroy Crossing it is underlain by sediments of the Fairfield Group.



\\BAYNUP\gis_projects\gisprojects\Project\DWER\3000_SCI_PLA\3533_GW_NTH\0003_FitzroyGWInvestigations\3533_0003_018_Alluviumextent_noAEM_20220916.mxd

Figure 35 Extent of Fitzroy and Margaret River alluvium

5 Groundwater results

This section presents our analysis of the groundwater-level and chemistry data. We have divided the section into four subsections, bringing together logical groups of data to facilitate interpretation – typically by aquifer.

Groundwater-level data collected from 34 monitoring bores in the Fitzroy Valley's main aquifers from 2015 to 2018 (Table 8) is compared with rainfall and streamflow data collected from gauging stations on the Fitzroy and Margaret rivers to examine connectivity.

We use annual flow-gauging data to infer broadly how groundwater and surface water has interacted along the river during the past 20 years.

We present results from the laboratory analysis of 75 groundwater samples from 61 bores, collected from 2015 to 2018. We assess groundwater salinity, major ion chemistry, environmental tracers, nutrient concentrations and stable isotope ratios for deuterium (^{2}H) and oxygen-18 (^{18}O) across the Fitzroy River alluvium, Liveringa Group, Noonkanbah Formation, Grant Poole and Devonian reef aquifers.

5.1 Groundwater levels and flow gauging

5.1.1 Fitzroy River alluvial aquifer

We collected time-series groundwater-level data from seven alluvial aquifer monitoring bores in the Camballin area. Seasonal groundwater-level fluctuations in the Fitzroy River alluvial aquifer during the 2017–18 period ranged between 0.26 m (Bore LF02) and 2.28 m (Bore LF05) in the Camballin area (Figure 36).

Logger data during the 2015–16 period, collected from Birdwood Bore downstream of Fitzroy Crossing gauging station and at BU15MB004 just upstream of the gauging station, show similar timing but a different magnitude of water-level response to rainfall compared with data from bores in the Camballin region.

There was a hiatus in the monitoring of bore BU15MB004 during the 2017–18 wet season, but this was restarted in July 2018, along with monitoring of BU15MB002A and BU15MB003.

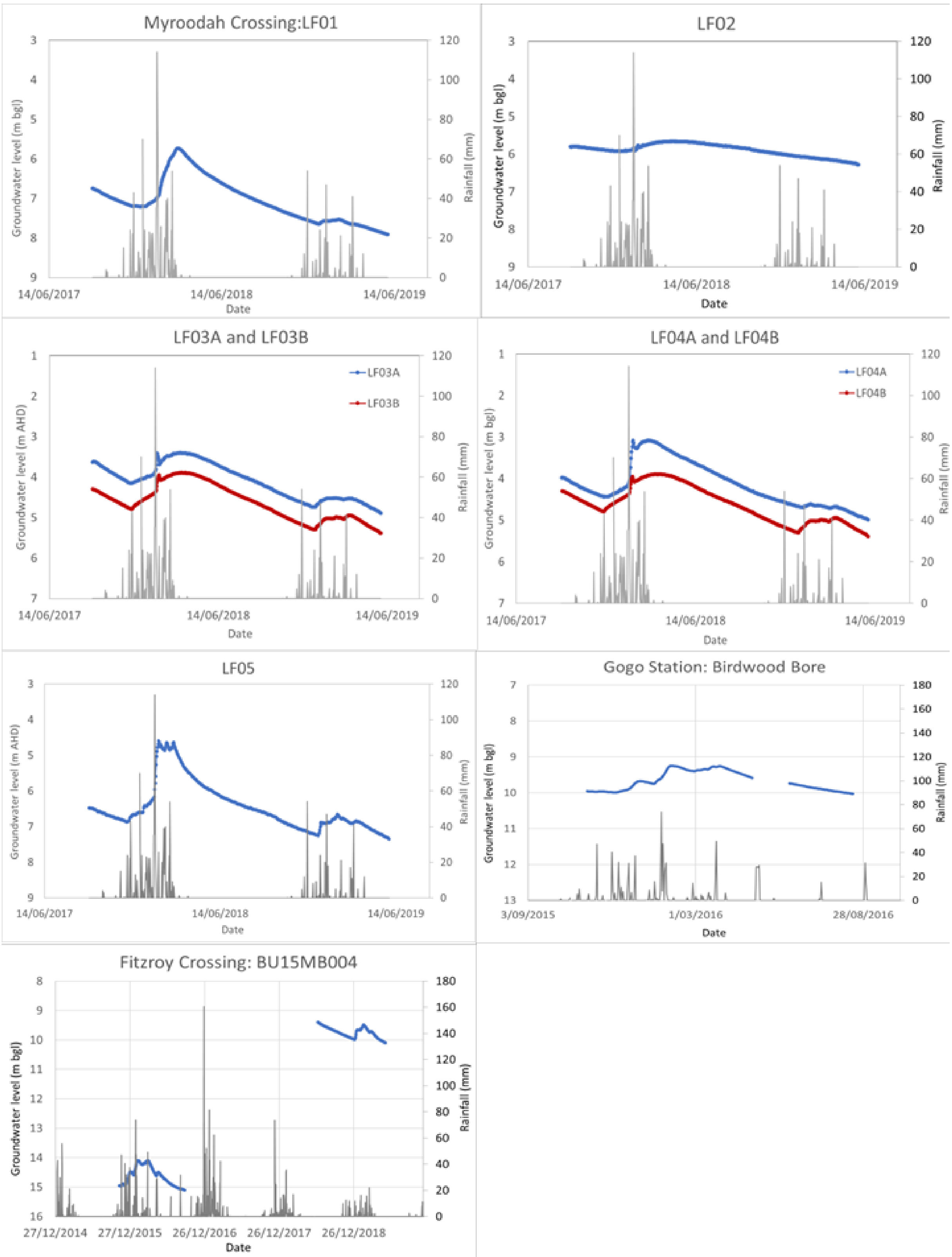


Figure 36 Groundwater levels: alluvial aquifer and Noonkanbah Formation

Note: The hydrographs for the LF series bores show rainfall data from Camballin rainfall station; Birdwood Bore and BU15MB004 hydrographs show rainfall data from Fitzroy Crossing. Note differing time periods.

Table 8 Groundwater-level data

Bore	Subarea	Aquifer	Ground elevation (m AHD)	2015–16		2016–17		2017–18	
				Seasonal change (m)	Average SWL (m bgl)	Seasonal change (m)	Average SWL (m bgl)	Seasonal change (m)	Average SWL (m bgl)
LF01	Fitzroy Trough	Fitzroy River alluvium	41.739	-	-	-	-	1.48	6.63
LF02	Fitzroy Trough	Fitzroy River alluvium	40.456	-	-	-	-	0.26	5.79
LF03B	Fitzroy Trough	Fitzroy River alluvium	46.743	-	-	-	-	0.9	4.27
LF04B	Fitzroy Trough	Fitzroy River alluvium	39.377	-	-	-	-	0.73	4.54
LF05	Fitzroy Trough	Fitzroy River alluvium	51.81	-	-	-	-	2.28	6.02
Birdwood Bore[1]	Lennard Shelf	Fitzroy River alluvium	-	0.78	9.68	-	-	-	-
BU15MB004	Lennard Shelf	Fitzroy River alluvium	108.17	1.01	14.73	-	-	-	-
Lightning Bore	Fitzroy Trough	Liveringa Group	61.581	0.13	15.42	0.18	15.4	0.23	15.34
Hardman Dam Bore	Fitzroy Trough	Liveringa Group	62.038	0.25	11.1	0.35	10.86	-	-
Liveringa Stock Bore	Fitzroy Trough	Liveringa Group	63.143	0.2	7.37	0.59	7.14	0.16	7
RRMW005D	Fitzroy Trough	Liveringa Group	73.333	-	-	0.18	19.33	0.2	19.43
RRMW005S	Fitzroy Trough	Liveringa Group	73.558	-	-	1.36 [2]	22.13	0.29	21.78
Helens Bore	Fitzroy Trough	Liveringa Group	44.076	1.09	6.1	4.14	4.51	1.85	4.23
2-89 Mt Anderson	Fitzroy Trough	Liveringa Group	-	1.67	10.99	-	-	-	-
BD2 02 (BG2)	Fitzroy Trough	Liveringa Group	24.218	0.18	6.92	0.7	6.64	0.63	6.22
Paradise Bore	Fitzroy Trough	Grant Poole	63.437	-	-	1.01	5.71	0.73	6.04
LF06	Fitzroy Trough	Grant Poole	52.449	-	-	-	-	0.67	13.7
Leos Bore	Fitzroy Trough	Grant Poole	63.135	0.19	21.14	10.43	15.45	4.76	11.96
Agricon 3	Fitzroy Trough	Grant Poole	42.817	0.36	0.85	0.73	0.73	0.43	0.63
Thomas Bore	Fitzroy Trough	Grant Poole	65.565	0.64	11.47	5.76	10.02	-	-
LF07	Fitzroy Trough	Grant Poole	92.687	-	-	-	-	0.23	39.13
BS16MB001A	Lennard Shelf	Grant Poole	154.31	-	-	-	-	0.23	27.79
BS16MB001B	Lennard Shelf	Grant Poole	154.32	-	-	-	-	0.21	28.18
BS16MB001C	Lennard Shelf	Grant Poole	154.4	-	-	-	-	0.26	28.32
BS16MB003A	Lennard Shelf	Grant Poole	194.94	-	-	-	-	0.26	60.88
BS16MB003B	Lennard Shelf	Grant Poole	195.06	-	-	-	-	0.33	61.47
BS16MB003C	Lennard Shelf	Grant Poole	194.75	-	-	-	-	0.26	61.63
KD16MB001	Lennard Shelf	Grant Poole	65.02	-	-	-	-	0.43	13.74
KD16MB002	Lennard Shelf	Grant Poole	79.67	-	-	-	-	0.36	19.82

Bore	Subarea	Aquifer	Ground elevation (m AHD)	2015–16		2016–17		2017–18	
				Seasonal change (m)	Average SWL (m bgl)	Seasonal change (m)	Average SWL (m bgl)	Seasonal change (m)	Average SWL (m bgl)
KD16MB003	Lennard Shelf	Grant Poole	88.05	-	-	-	-	0.3	25.99
Gogo Homestead Bore 3A	Lennard Shelf	Grant Poole	107.64	0.14	12.15	1.85	11.25	0.43	11.19
PT4	Lennard Shelf	Devonian reef	151.967	0.22	8.23	1.33	7.42	0.37	6.95
PT5	Lennard Shelf	Devonian reef	151.469	0.8	4.44	3.98	3.24	0.61	4.46
N1	Lennard Shelf	Devonian reef	147.513	0.42	5.21	2.03	4.12	0.61	3.88

[1] Birdwood bore was not surveyed. It has been equipped with a pump by Gogo Station and is no longer monitored for water levels.

[2] Water-level reading was influenced by groundwater sampling so was not considered in the average for 2016–17.

In the sections below we compare alluvial aquifer groundwater levels with data from nearby gauging stations to assess how surface water and groundwater interact.

Looma gauging station (Camballin area)

The Looma gauging station is located about 6 km west of bore LF01, which is screened in the alluvial aquifer.

The hydrograph shows river levels increasing from around November, corresponding with the start of the wet season and significant river flow at the gauging station.

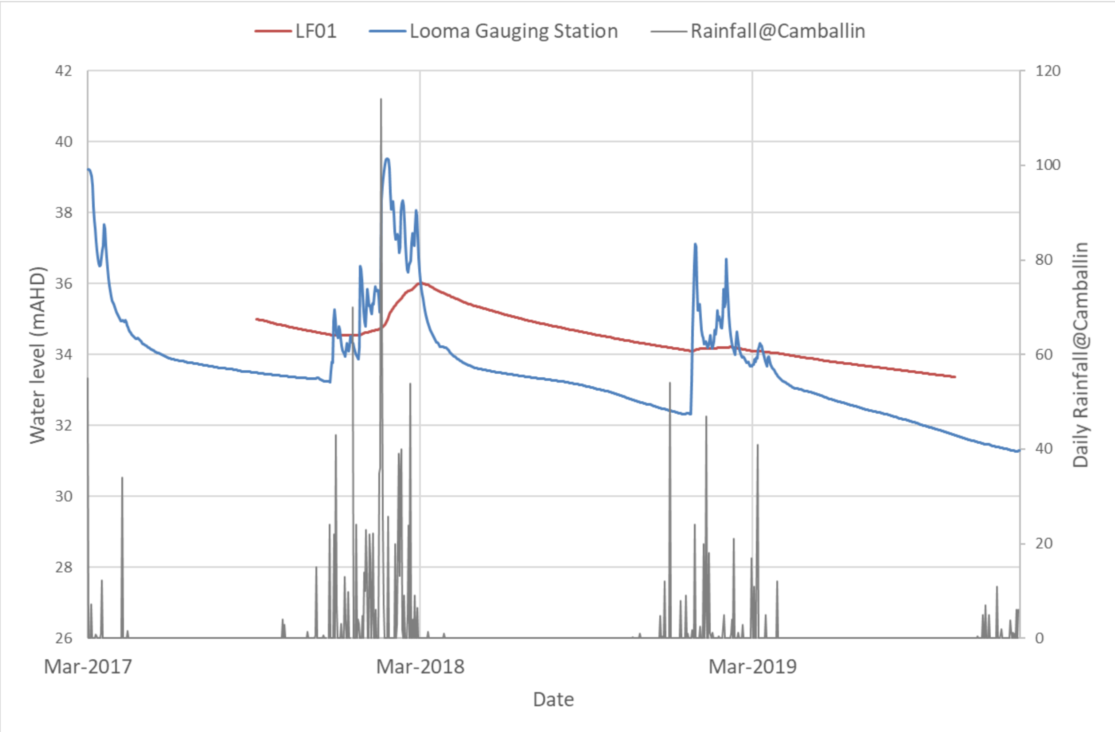


Figure 37 Looma gauging station river levels compared with LF01

Figure 37 suggests that groundwater levels in the alluvial aquifer were generally higher than river water levels during the dry season, and lower than river levels through the wet season, acknowledging the 6 km offset between the gauging station and monitoring bore LF01.

This indicates that while the river is generally gaining flow from the alluvial aquifer, there are cyclic bank and/or alluvial aquifer recharge and discharge processes occurring. The increase in groundwater levels was much more subdued during the 2018–19 wet season when the river stage peaked about 2 m lower than in 2017–18. This indicates that higher volumes of recharge are related to higher river stage.

Both the river levels at the Looma gauging station and groundwater levels at LF01 showed a declining trend over the monitoring period.

Fitzroy Barrage gauging station

The Fitzroy Barrage is a dam-type structure that was built for the Camballin irrigation scheme in the 1960s. The gauging station measures water levels above the barrage, where artificially high surface water levels are maintained. The presence of this water influences the nature of surface water–groundwater connectivity in the immediate area.

Surface water levels measured at the barrage are generally higher than groundwater levels in bore LF05 located about 300 m west of the barrage in the Fitzroy River alluvial aquifer.

Similar to the logger data from LF01 bore, water levels at LF05 show an overall declining trend, despite the recharge events associated with the 2017–18 and 2018–19 wet seasons. It is unclear from the limited datasets whether these are long-term declining trends in groundwater level, or a response to a period of lower rainfall following good wet seasons in 2016 and 2017.

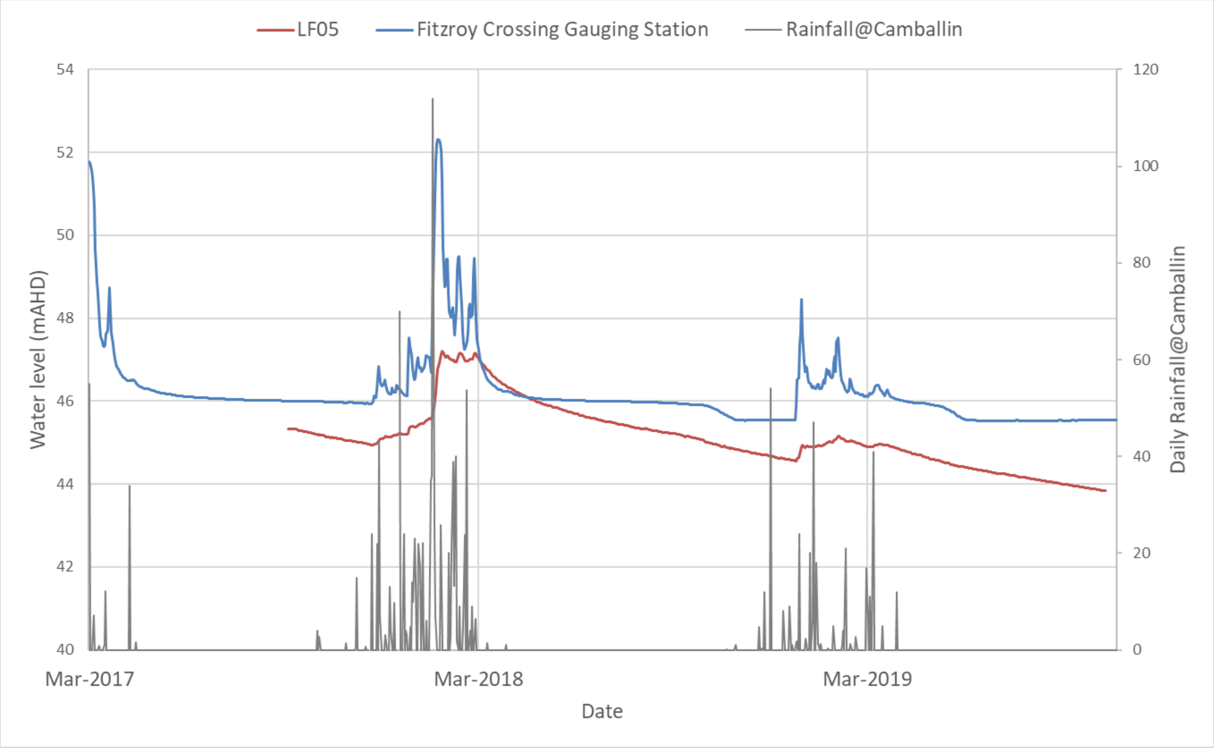


Figure 38 Fitzroy Barrage river levels compared with LF05

Fitzroy Crossing gauging station

Monitoring bore BU15MB004 is located in the Fitzroy River alluvial aquifer about 5 km upstream of the Fitzroy Crossing gauging station, and very close to the river. The groundwater hydrograph for two separate monitoring periods show flatter, more suppressed responses to wet season recharge events, when compared with the hydrographs for LF01 and LF05 located further downstream near Camballin.

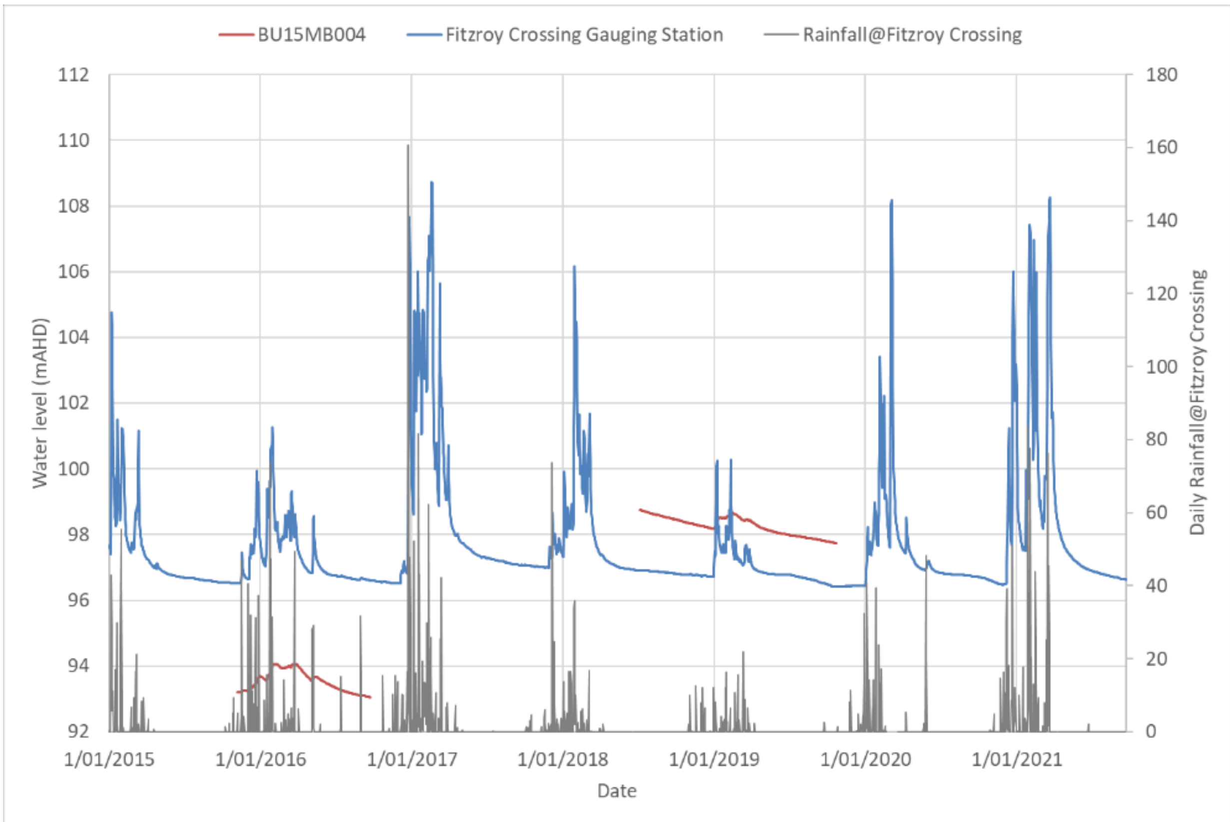


Figure 39 Fitzroy Crossing river levels compared with BU15MB004

Acknowledging the 5 km offset between the Fitzroy Barrage and monitoring bore BU15MB004, the groundwater levels go from being consistently lower than river water levels in the 2015–16 wet season to being consistently higher than river water levels in the 2018–19 wet season.

As with the LF01 and LF05 hydrographs it is possible that the higher, but declining groundwater levels observed in the 2019 wet season were a response to higher recharge in the preceding wet seasons (2016–17 and 2017–18). This may indicate significant bank and/or alluvial aquifer recharge and storage in the alluvial aquifer during periods of high surface-water flow (i.e. periods of sharply rising groundwater level). Groundwater would discharge to the river during drier periods, helping maintain low flows and river pools (i.e. periods of slow decline in groundwater level).

5.1.2 Noonkanbah Formation aquifer

Groundwater levels in the Noonkanbah Formation are monitored at bores LF03A and LF04A (Figure 36). While the formation is generally an aquitard, there are some minor sand lenses.

The lithology and construction logs (Clohessy 2017) show the A bores (screened in the Noonkanbah Formation) and B bores (screened in the alluvium) are monitoring hydrologically distinct units separated by a confining layer. However, the hydrograph data shows the same groundwater-level patterns (timing and magnitude of fluctuations) in both the Fitzroy River alluvial aquifer and deeper confined

Noonkanbah Formation. This may reflect hydraulic connectivity between the two units.

5.1.3 Liveringa Group aquifer

Data loggers were installed across a network of eight monitoring bores in the Liveringa Group aquifer, starting in 2015–16, in the Camballin area (Table 8). The data showed seasonal fluctuations ranging from a minimum of 0.13 m (Lightning Bore: 2015–16) to a maximum of 4.14 m (Helens Bore: 2016–17) (Figure 40). Most bores have only small responses to river flow, suggesting they are situated at the margins of the active groundwater–surface water exchange area. The exceptions are Helens Bore and Mt Anderson 2-89.

Groundwater-level fluctuation in the Liveringa Group aquifer generally appears to have responded to the wet-season rainfall events of 2017 and 2018, with varied lag in response. The largest groundwater-level responses were generally observed during the 2016–17 period, which had the wet season of the monitoring period (Helens Bore, BG2 and 2-89 Mt Anderson) (Section 2.4).

The rapidly fluctuating groundwater levels observed in the hydrograph at Mt Anderson 2-89 were caused by groundwater pumping from the water supply bore in the nearby Balginjirr Aboriginal community.

5.1.4 Grant Poole aquifer

We analysed groundwater levels in the Grant Poole aquifer by considering the Fitzroy Trough and Lennard Shelf separately. The Fitzroy Trough includes the area around Camballin (Liveringa and Mt Anderson stations). The Lennard Shelf includes bores located on Kimberley Downs, Brooking Springs, Fitzroy Crossing and Gogo Station.

Fitzroy Trough

The Grant Poole aquifer in the Fitzroy Trough was monitored by two datalogger-equipped bores during the 2017–18 period. Screened in the Poole Sandstone, the two bores – Paradise Bore (unconfined) and LF06 (confined) – show similar seasonal groundwater-level variations of 0.73 m and 0.67 m respectively (Figure 41).

As the LF06 bore is screened beneath approximately 85 m of confining Noonkanbah Formation, the lagged response to rainfall recharge (similar to the unconfined Paradise Bore) was not anticipated. The response may be due to the proximity of LF06 to the Poole Sandstone outcrop area (about 1.5 km) and the pressure response to increased heads in the outcrop area – which propagates rapidly in a confined aquifer. It could also relate to groundwater pumping impacts at LF06 due to the rapidly oscillating groundwater levels during periods of groundwater-level decline. Heads rise during periods when the rapid groundwater oscillations do not occur, which suggests recovery from pumping.

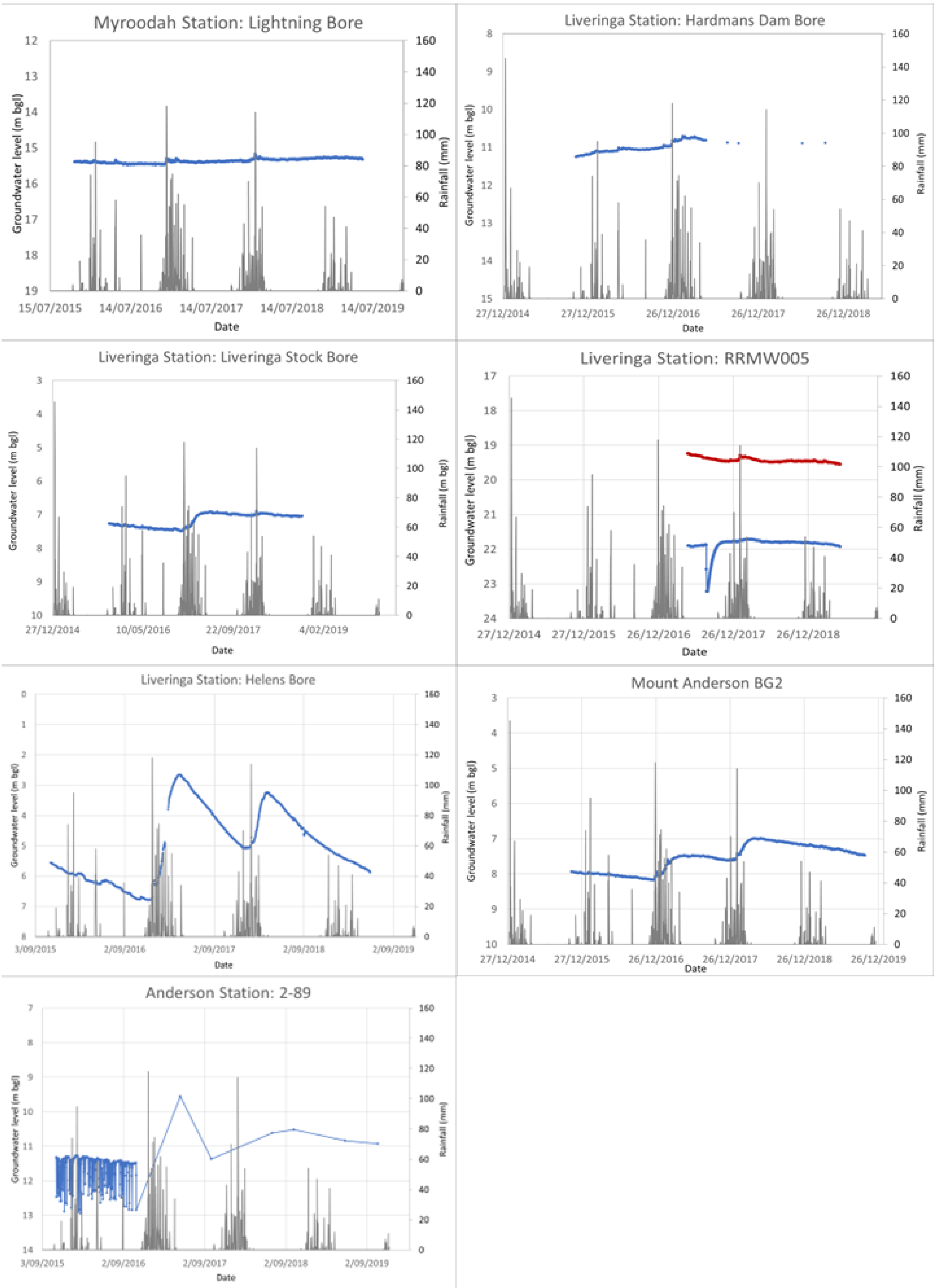


Figure 40 Groundwater levels in the Liveringa Group

Note: The abrupt groundwater-level decline at RRMW005S in August 2017 was caused by groundwater sampling and does not indicate a typical groundwater-level response.

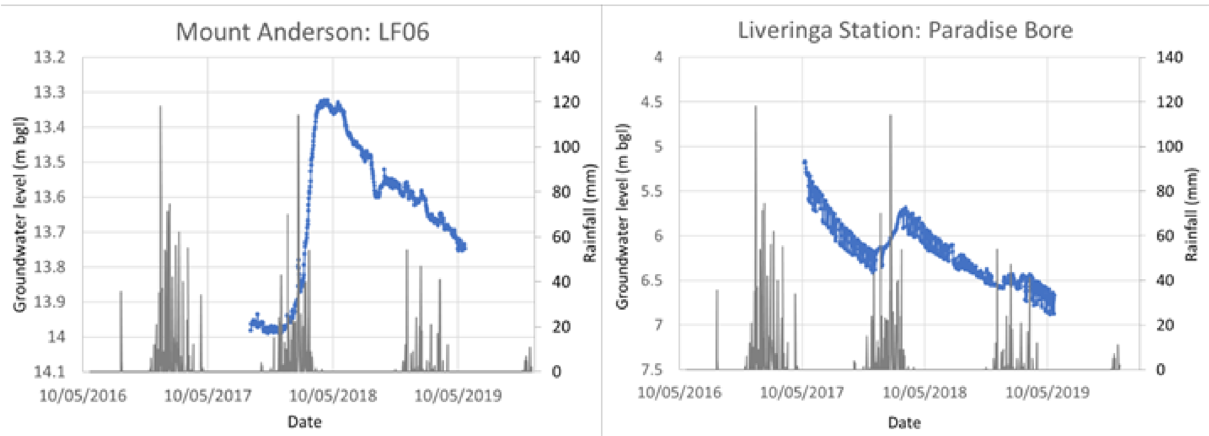


Figure 41 Groundwater levels in the Poole Sandstone aquifer (Fitzroy Trough)

Four datalogger-equipped bores monitoring the Grant Group aquifer in the Fitzroy Trough (Figure 42) show seasonal groundwater-level variations ranging from a minimum of 0.23 m at LF07 to a maximum of 10.43 m at Leos Bore (Table 8). This very large change in water level recorded at Leos Bore does not appear to coincide with the rainfall events, and it is possible this bore has failed (Taylor et al. 2018). We did not use data collected from Leos Bore in this study.

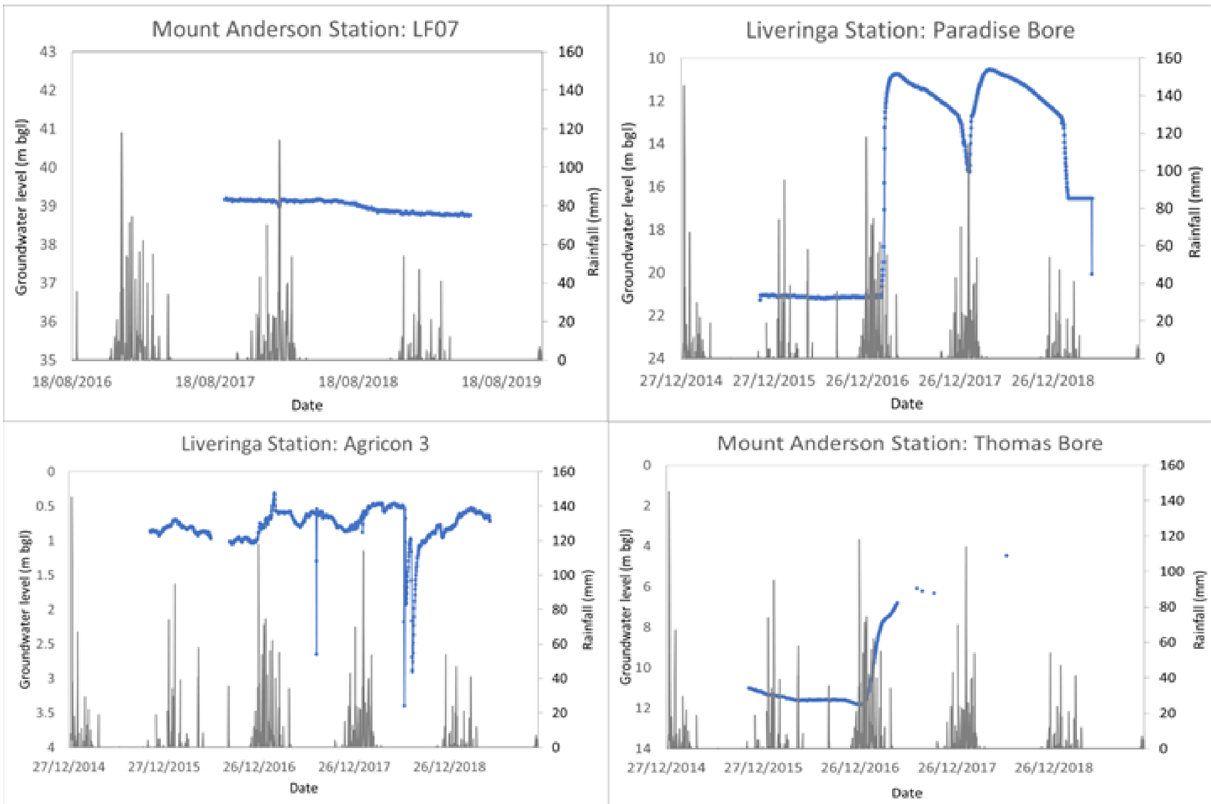


Figure 42 Groundwater levels in the Grant Group aquifer (Fitzroy Trough)

Note: Rainfall data from Camballin BoM weather station.

Figure 42 shows significant seasonal groundwater-level variations between the 2015–16 and 2017–18 monitoring periods in the Grant Group aquifer. There is a large and relatively sharp rise in groundwater level observed in the unconfined Thomas Bore in response to the wet season of 2016–17 – such a rise indicating a relatively permeable aquifer. This compares with smaller but nevertheless significant rises in groundwater level noted from the 2017–18 wet season in the deeper, confined Agricon 3 bore.

The subdued response in LF07 is likely due to the significantly greater depth to groundwater as compared with the three other Grant Group aquifer monitoring bores.

Lennard Shelf

As with bores in the Fitzroy Trough, the largest groundwater-level responses observed in the Grant Poole aquifer were recorded during the 2016–17 wet season. An increase in groundwater level of 1.85 m was recorded at the Gogo Station Homestead Bore 3A following the 2016–17 wet season (Figure 43), while a much smaller response (0.43 m) was observed following the 2017–18 wet season.

At two of the six monitoring sites in the Grant Group aquifer (BS16MB001 and BS16MB003), three nested monitoring bores collected data at different depths to assess vertical hydraulic gradients. At both sites, higher groundwater pressure was recorded in the deeper bores at each location compared with the shallower bores, indicating upward hydraulic heads and possible groundwater discharge where this unit is connected to the alluvium.

The hydrograph responses suggest hydraulic connection throughout the top 100 m of the Grant Group aquifer in this area (Figure 43). This aligns with previous conceptual models (Section 2.3.4).

The greatest depth to groundwater in the unconfined Grant Poole aquifer in the study area was found to be 60 m below ground level in BS16MB003.

Data from bores in the Grant Group at Kimberley Downs (Lennard Shelf) showed a more gradual groundwater-level rise (0.30–0.43 m) than the Grant Group bores in the Fitzroy Trough (Figure 42) after the 2017–18 wet season (Figure 43).

5.1.5 Devonian reef aquifer

We collected time-series groundwater-level data for the Devonian reef aquifer from three bores, all situated on Gogo Station. The groundwater levels recorded similar trends as other aquifers, with the highest seasonal variation measured following the 2016–17 wet season. A relatively subdued water-level response was observed in the other years (Figure 44).

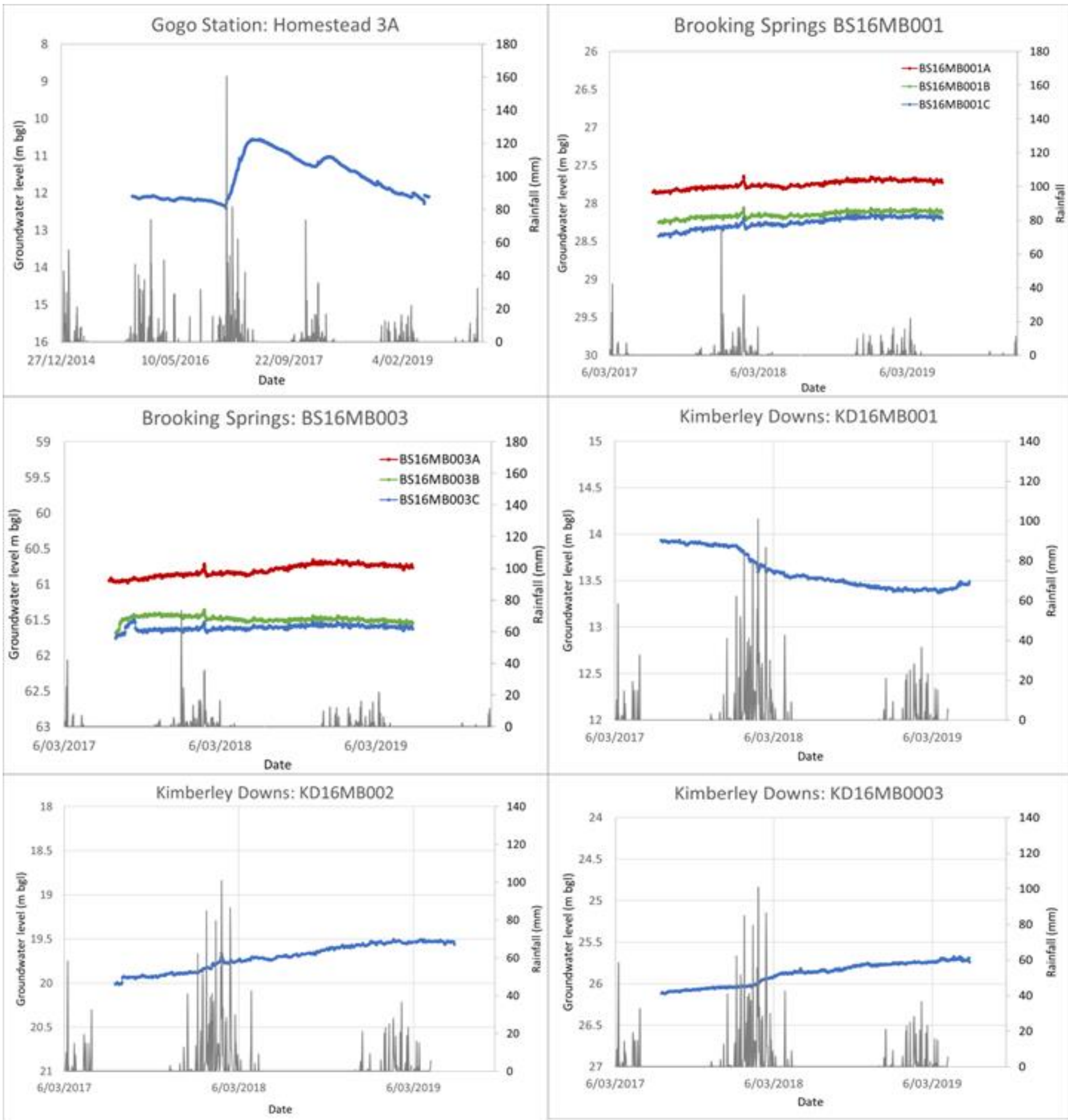


Figure 43 Groundwater levels in the Grant Group aquifer (Lennard Shelf)

Note: Rainfall data for Brooking Springs, Gogo Station from Fitzroy Crossing BoM weather station. Rainfall records for Kimberley Downs from Kimberley Downs BoM weather station. For BS16MB001 and BS16MB003: the blue line represents a shallow bore (C), the green line represents an intermediate bore (B) and the red line represents a deep bore (A).

The three Devonian reef aquifer bores – PT4, PT5 and N1 – are all relatively deep, screened at around 100 m below ground level and over 90 m below the standing water level.

Despite the depths at which they are screened, all three bores show rapid groundwater-level responses to rainfall recharge, indicating the Devonian reef is a highly permeable aquifer. Because of the variability innate to limestone aquifers, it is likely that different groundwater levels may have been observed if groundwater-level data were available from bores screened closer to the watertable.

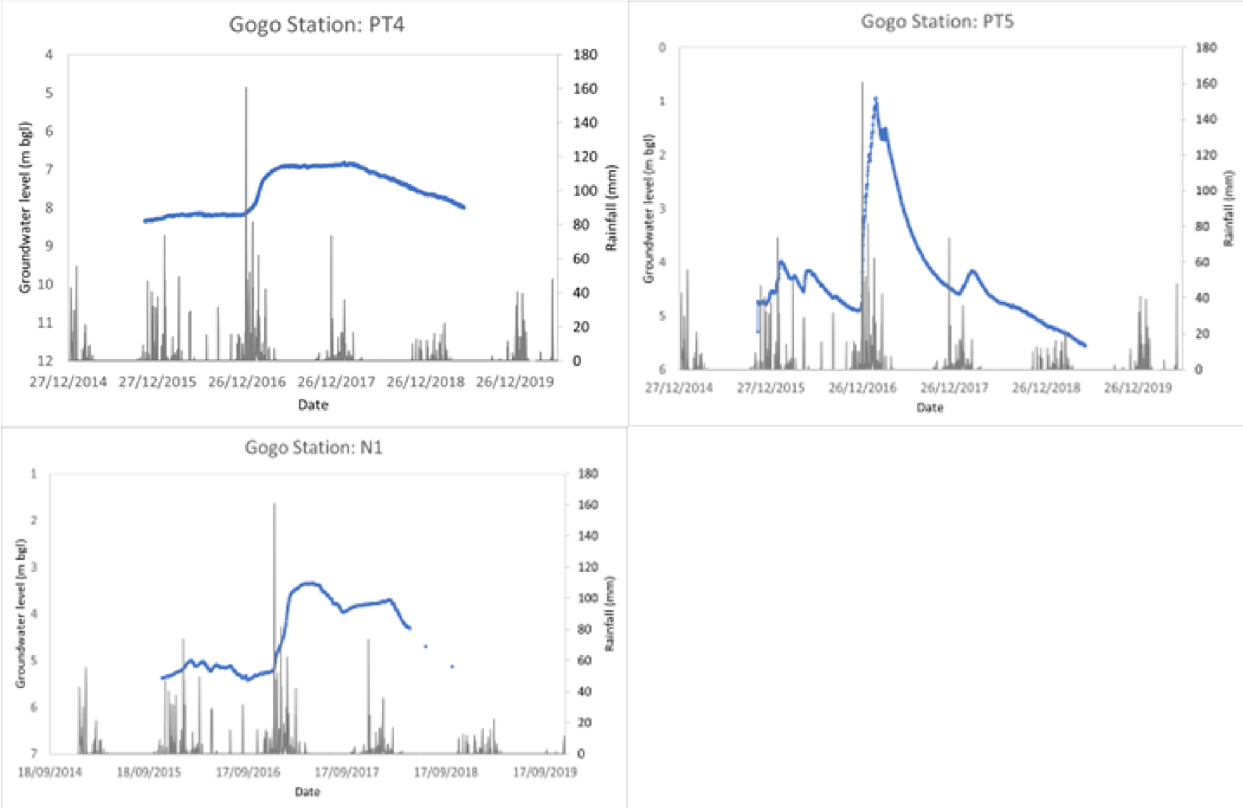


Figure 44 Groundwater levels in the Devonian reef complex

5.1.6 Flow gauging

We analysed time-series gauging station data at six streamflow gauging stations along the Fitzroy River to determine broadly which sections of the river were either gaining or losing flow from groundwater.

Total annual flow (defined as the period from November to October each year) is highly variable due to the episodic and spatially variable (cyclonic and monsoonal) drivers of rainfall in the Fitzroy catchment.

Table 9 shows the large difference between the low, median and high flows at the Looma gauging station. It also shows the very large standard deviation in the annual flow, which is almost as large as the average flow.

We ranked annual totals at each of the gauging stations for the period from 1999 to 2020 as either high-, median- or low-flow years (based on the 0–33rd, 33–66th and 66–100th percentiles). We used the rankings and differences in flow between gauging stations to derive information about groundwater–surface water interaction. Table 10 shows the difference in flow between the gauging stations from May to October, with loss of surface water to groundwater highlighted in red and gains from groundwater to surface water in green.

Table 9 Looma gauging station – annual flow statistics

Statistic	Annual flow (GL/year)
Maximum	27,821
Minimum	570
Average	8,887
Median	5,895
Standard deviation	7,721
Low-flow threshold (0–33rd percentile)	0–4,697
Medium-flow threshold (33rd–66th percentile)	4,697–9,932
High-flow threshold (>66th percentile)	9,932–27,821

Table 10 Difference in flow between gauging stations, May to October (1999–2020)

Legend	
Low flow year	Gaining flow
Medium flow year	Losing flow
High flow year	

Annual Flow @ Looma (GL)	Year	Looma to Willare	Fitzroy Barrage to Looma	Noonkanbah to Fitzroy Barrage	Fitzroy Crossing to Noonkanbah	Dimond Gorge to Fitzroy Crossing
11,824	1999	107	33	-92	-90	227
24,231	2000	587	73	-488	453	468
15,243	2001	172	22	-190	210	179
10,134	2002	147	-16	-102	98	-12
3,703	2003	21	11	-3	-7	53
7,273	2004	100	-2	24	-30	158
695	2005	7	-3	-4	8	2
9,711	2006	132	-6	11	14	32
4,727	2007	35	8	6	11	39
5,895	2008	-12	3	-9	32	3
12,824	2009	23	9	-12	31	10
1,033	2010	14	-20	16	32	5
27,821	2011	464	47	-473	23	676
5,237	2012	52	2	-43	63	38
1,784	2013	19	-15	-5	38	-9
7,742	2014	19	6	-65	91	-3
3,638	2015	4	-6	-2	18	-4
1,906	2016	30	-66	36	20	37
22,217	2017	230	72	-102	4	182
5,572	2018	53	30	-4	8	8
570	2019	-1	1	-1	0	1
4,686	2020	34	-6	7	8	3
Mean flow		102	8	-68	47	95
Median flow		35	2	-4	19	21

The system shows considerable variability, however clear trends can be observed. For example, the reach from Noonkanbah to the Fitzroy Barrage gauging stations show a relatively consistent loss of flows between the two gauges, even during years of high flow. Conversely, Looma to Willare and Fitzroy Crossing to Noonkanbah appear generally to be gaining reaches.

The extents of the designated gaining and losing reaches are defined by the locations of the gauging stations, which may not reflect the true extent to which parts of the river are gaining or losing flows to groundwater. There are also uncertainties associated with deriving information from surface water gauging, such as accounting for tributary inflows, the lack of permanent measurement structures, geomorphology changes at the gauging sites, and the highly braided nature of the river (particularly in lower reaches, making accurate low-flow measurements difficult).

5.2 Water chemistry

See Appendix D for the field-measured groundwater parameters for all bores sampled and Appendix D for their laboratory-measured chemistry.

5.2.1 Groundwater total dissolved solids (TDS)

Groundwater quality can vary significantly across a water resource and can range from fresh to saline (Table 11). Groundwater salinity is a key parameter for considering the suitability of groundwater for irrigation and domestic, town or stock water supply. Salinity < 2,000 mg/L as TDS is generally suitable for most stock and irrigation uses, while town water supplies require lower salinity levels (< 500 mg/L as TDS).

Table 11 Water quality and salinity

Water quality	Salinity in mg/L as TDS
Fresh	0–500
Marginal	500–1,000
Brackish	1,000–3,000
Saline	3,000–35,000
Hypersaline	> 35,000

Groundwater salinity can also help determine a range of groundwater flow processes including recharge, throughflow and discharge, as well as inter-aquifer connectivity. We discuss these in the following sections. See Table 12 for groundwater salinity results, and appendices D and E for additional information.

Fitzroy River alluvial aquifer

Groundwater salinity in the Fitzroy River alluvial aquifer was highly variable, ranging from fresh to saline (Appendix E). The results, which corresponded with those of previous sampling programs, were:

- (< 500 mg/L as TDS) at LF01 near the Fitzroy River at Looma gauging station, and at Fitzroy Crossing (BU15MB003, BU15MB004)
- (> 20,000 mg/L as TDS) further from the river at bore LF02 (23,700 mg/L as TDS).

This reflects the findings of the AEM survey, where lower bulk conductivity within the alluvial aquifer was generally identified close to the river and conductivity increased with distance from the river (Section 4.5).

Erskine aquifer

Only limited reliable groundwater quality data was collected for the Erskine aquifer as part of this study. Groundwater investigations around Meda and Yeeda stations in the Derby groundwater area (Gallardo 2018a; Gallardo 2018b) recorded extensive fresh groundwater resources in the Erskine Sandstone, with salinity less than 500 mg/L as TDS.

Liveringa Group aquifer

Groundwater salinity measured from two bores in the Liveringa Group were saline, ranging from > 5,000 mg/L as TDS at RRMW005D up to a maximum of 11,600 mg/L at Helens Bore on Liveringa Station (Appendix E).

Noonkanbah Formation

Groundwater from bore LF04A, screened in a thin sandy lens in the Noonkanbah Formation, recorded a field TDS of 1,080 mg/L at the Manta Ray Bore (Appendix D).

Grant Poole aquifer

Data collected for this study showed that groundwater in the Grant Poole aquifer is predominantly fresh.

Groundwater in the Poole Sandstone section of the aquifer is also predominantly fresh in both unconfined and confined samples (Appendix E), with groundwater samples generally recording values of TDS < 1,000 mg/L.

Bores in both the unconfined and confined Grant Group section of the aquifer recorded lower TDS than those in the Poole Sandstone part of the aquifer, with TDS generally less than 500 mg/L (Appendix E).

Devonian reef aquifer

We sampled three Devonian reef aquifer monitoring bores for water quality analysis, and all returned a charge balance error of > 10% (Appendix J). None of these samples have either field- or laboratory-measured TDS concentrations and given the charge balance error, calculated salinities (from summed anions and cations) should be considered as having a margin of error. Their calculated groundwater TDS values were all < 1,000 mg/L.

Table 12 Groundwater salinity

Bore ID	AWRC no.	Sample date	Aquifer	Confined / unconfined	Screen from (m bgl)	Screen to (m bgl)	Bore depth (m bgl)	pH	EC (µS/cm)	TDS (calculated) mg/L	TDS (measured) mg/L	Cl mg/L
Liveringa South	80270072	30/07/2017	Alluvium	Unconfined	-	-	36.7	7.14	2,025	-	951	477
LF01	80270063	13/09/2017	Alluvium	Unconfined	13.0	18.0	20	7.08	679	-	335	43
LF01	80270063	20/08/2018	Alluvium	Unconfined	13.0	18.0	20	7.15	513	-	312	43
LF02	80270064	13/09/2017	Alluvium	Unconfined	24.0	30.0	32	6.52	38,912	-	23,700	12,200
LF02	80270064	20/08/2018	Alluvium	Unconfined	24.0	30.0	32	6.66	30,355	-	23,000	12,300
LF03B	80270066	14/09/2017	Alluvium	Unconfined	10.0	15.0	17	7	21,837	-	10,200	6,470
LF03B	80270066	21/08/2018	Alluvium	Unconfined	10.0	15.0	17	7.03	17,818	-	10,700	6,150
LF04B	80270068	13/09/2017	Alluvium	Unconfined	10.0	15.0	22	6.59	21,583	-	11,000	6,440
LF04B	80270068	20/08/2018	Alluvium	Unconfined	15.0	20.0	22	6.7	16,050	-	10,700	5,870
LF05	80270069	14/09/2017	Alluvium	Unconfined	21.0	25.0	27	7.62	3,148	-	1,430	438
LF05	80270069	21/08/2018	Alluvium	Unconfined	231.0	25.0	27	7.68	2,572	-	1,450	421
Birdwood Bore*	80200055	7/07/2016	Alluvium	Unconfined	14.5	17.4	-	7.39	304	-	-	9.5
BU15MB002	80200045	23/08/2018	Alluvium	Unconfined	17.8	23.8	31.5	7.19	1,485	-	892	370
BU15MB003	80200024	23/08/2018	Alluvium	Unconfined	21.0	27.0	28	6.93	401	-	263	34
BU15MB004	80200025	23/08/2018	Alluvium	Unconfined	22.0	28.0	30	7.22	456	-	340	59
Garden Bore*	80210704	24/06/2016	Erskine Sandstone	Unconfined	-	-	20.4	5.48	92	-	-	10
Barefoot Bore	80270073	15/09/2017	Erskine Sandstone	Unconfined	-	-	-	6.12	535	-	292	92
Helens Bore	80240014	4/09/2016	Liveringa Group	Unconfined	38	72	77.2	6.56	14,616	-	11,600	3,760
2-89 Mt Anderson*	80210072	7/09/2016	Liveringa Group	Unconfined	57.6	66.2	66.2	5.9	577	-	342	133
RRMW005D	80212097	17/08/2017	Liveringa Group	Unconfined	94.0	87.0	97	7.04	8,650	-	5,190	1,460
LF03A*	80270065	14/09/2017	Noonkanbah Formation	Unconfined	49.5	55.5	57.5	7.69	2,047	-	897	410
LF04A	80270067	12/09/2017	Noonkanbah Formation	Unconfined	51.0	57.0	60	7.34	2,496	-	1,080	509
Manta Ray Bore	80210901	6/07/2016	Noonkanbah Formation	Unconfined	17.6	35.3	-	7.08	5,610	-	-	1,215
Peglars Bore*	80210841	21/06/2016	Poole Sandstone	Unconfined	-	-	29	5.95	1,260	819	-	268
Peglars Bore*	80210841	18/05/2017	Poole Sandstone	Unconfined	-	-	29	6.39	2,407	1,565	688	293
Paradise Bore	80270056	22/06/2016	Poole Sandstone	Unconfined	12.6	13.5	26.5	7	1,016	660	-	116
Paradise Bore	80270056	15/08/2017	Poole Sandstone	Unconfined	12.6	13.5	26.5	6.95	1,210	787	681	117
Montgomery Bore	80210233	23/06/2016	Poole Sandstone	Unconfined	-	-	42.7	6.44	452	294	-	61
Langs Bore	80210241	26/06/2016	Poole Sandstone	Unconfined	-	-	54.8	6.73	851	553	-	131
Langs Bore	80210241	16/05/2017	Poole Sandstone	Unconfined	-	-	54.8	6.81	821	534	456	144
Langs Bore	80210241	8/09/2016	Poole Sandstone	Unconfined	-	-	54.8	6.68	829	539	-	-

Bore ID	AWRC no.	Sample date	Aquifer	Confined / unconfined	Screen from (m bgl)	Screen to (m bgl)	Bore depth (m bgl)	pH	EC (µS/cm)	TDS (calculated) mg/L	TDS (measured) mg/L	Cl mg/L
Blue Bush*	80210973	5/09/2016	Poole Sandstone	Unconfined	-	-	36.6	6.67	538	350	298	22
1-04 Camballin	80200059	30/08/2016	Poole Sandstone	Unconfined	31.5	43.5	44.0	6.12	321	209	192	38
1-04 Camballin	80200059	16/05/2017	Poole Sandstone	Unconfined	31.5	43.5	44.0	6.65	367	239	216	49
1-04 Camballin	80200059	21/08/2018	Poole Sandstone	Unconfined	31.5	43.5	44.0	6.1	321	-	187	43
Irrigation Bore*	80210620	22/08/2018	Poole Sandstone	Unconfined	-	-	23.77	6.9	1,269	-	747	126
No. 8 Bore	80210382	30/06/2016	Poole Sandstone	Unconfined	-	-	76.2	6.55	474	308	-	44
LF06	80270070	12/09/2017	Poole Sandstone	Confined	93.0	99.0	102.0	6.44	12,072	7,847	7,100	2,390
Huttons Bore No.2	80270081	2/07/2016	Poole Sandstone	Confined	38.6	56.6	-	6.81	3,083	2,004	-	555
Pilots Flowing Bore	80270082	2/07/2016	Poole Sandstone	Confined	-	-	-	7.44	1,127	733	-	185
Tank Bore No.2	80270083	3/07/2016	Poole Sandstone	Confined	54.0	84.0	-	7.81	2,636	1,713	-	683
One Tree Bore No.2	80211095	3/07/2016	Poole Sandstone	Confined	89.0	131.0	-	7.86	1,593	1,035	-	371
Chestnut Bore	80210428	6/07/2016	Poole Sandstone	Confined	-	-	182.9	8.27	1,706	1,109	-	379
Looma 1-86	80219133	22/06/2016	Grant Group	Unconfined	31.7	73.5	73.5	5.31	111	72	-	18
Looma 1-86	80219133	18/05/2017	Grant Group	Unconfined	31.7	73.5	73.5	5.74	216	140	56	17
Jarlmadangah 1-02	80200059	26/06/2016	Grant Group	Unconfined	31.7	91.7	92.0	7.42	377	245	-	17
Leos Bore*	80210235	27/06/2016	Grant Group	Unconfined	21.0	24.5	24.5	6.22	171	111	-	13
Leos Bore*	80210235	31/07/2017	Grant Group	Unconfined	21.0	24.5	24.5	5.71	182	118	319	23
Looma 1-93*	80219134	30/08/2016	Grant Group	Unconfined	38.2	80.2	80.2	4.26	46	30	24	8
Thomas Bore*	80240012	2/09/2016	Grant Group	Unconfined	26.3	31.3	31.3	6.94	503	327	304	66
Thomas Bore*	80240012	29/07/2017	Grant Group	Unconfined	26.3	31.3	31.3	6.87	3,684	2,395	2,230	916
Shovelton	80210261	3/08/2017	Grant Group	Confined	515.0	545.0	549.0	7.15	1372	892	521	105
Acacia Tank Flowing Bore	80270084	4/07/2016	Grant Group	Confined	-	-	-	7.28	1,518	987	-	287
Agricon 1	80210234	3/08/2017	Grant Group	Confined	537.0	545.0	600.0	7.11	708	460	302	29
Agricon 2*	80270062	3/08/2017	Grant Group	Confined	-	-		7.15	559	363	204	21
Agricon 3	80240013	2/08/2017	Grant Group	Confined	400.0	588.0	588.0	7.16	683	444	273	28
LF07	80270071	12/09/2017	Grant Group	Unconfined	62.0	68.0	71.0	6.19	213	138	114	17
Laurel Homestead Bore*	80210371	30/06/2016	Grant Group	Unconfined	-	-	61.0	6.71	755	491	-	34
2/89 – Fitzroy Crossing*	80219066	29/06/2016	Grant Group	Unconfined	27.8	58.3	61.85	8.02	501	326	-	45
5/10 – Fitzroy Crossing*	80211372	29/06/2016	Grant Group	Unconfined	28.7	34.7	39.0	6.88	568	369	-	43
Donalds Mill No.2*	80270085	4/07/2016	Grant Group	Unconfined	-	-	41.15	7.08	1,245	809	-	184

Bore ID	AWRC no.	Sample date	Aquifer	Confined / unconfined	Screen from (m bgl)	Screen to (m bgl)	Bore depth (m bgl)	pH	EC (µS/cm)	TDS (calculated) mg/L	TDS (measured) mg/L	Cl mg/L
Gogo Station Homestead Bore 3A	80211064	4/07/2016	Grant Group	Unconfined	24.8	36.58	38.1	7.45	1,526	92	-	328
BS16MB001A	80200052	3/07/2017	Grant Group	Unconfined	80.0	90.0	96.0	6.52	438	285	-	29
BS16MB001B	80270074	2/07/2017	Grant Group	Unconfined	55.4	58.4	58.4	6.53	449	292	-	30
BS16MB001C	80270075	2/07/2017	Grant Group	Unconfined	37.5	40.5	40.5	6.55	445	289	-	29
BS16MB003A	80200054	4/07/2017	Grant Group	Unconfined	96.0	118.0	118.0	6.8	656	426	-	17
BS16MB003B	80270076	4/07/2017	Grant Group	Unconfined	86.0	92.0	92.0	6.73	629	409	-	16
BS16MB003C	80270077	4/07/2017	Grant Group	Unconfined	72.3	78.3	78.3	6.82	653	424	-	17
KD16MB002	80300009	5/07/2017	Grant Group	Unconfined	100.0	118.0	120.0	6.45	424	276	-	23
KD16MB003	80300010	5/07/2017	Grant Group	Unconfined	38.0	50.0	52.0	6.36	277	180	-	29
Bore	80210370	6/09/2016	Fairfield Group	Unconfined	32.1	35.2	40.3	6.66	878	571	-	76
BA04	80212011	1/07/2016	Devonian reef	Unconfined	11.7	18.0	20.0	6.75	605	393	-	6
PT4	80212103	1/07/2016	Devonian reef	Unconfined	-	-	107.0	6.8	629	409	-	7.7
Sallys Bore*	80270087	5/07/2016	Devonian reef	Unconfined	-	-	-	7.07	565	367	-	8.9
Emanuels Flowing Bore	80270086	5/07/2016	Devonian reef	Confined	-	-	-	8.39	1,310	852	-	79

* Data not included in calculations for data quality reasons (see Appendix J).

5.2.2 Major ions

We used major ion chemistry to characterise groundwater type and assess the hydrochemical similarity between aquifers (this can help determine aquifer connectivity and interaction with surface water). We also used groundwater hydrochemistry to indicate the geochemical processes active within the groundwater systems.

The Piper diagrams in Figure 45, Figure 46 and Figure 47 visually describe the proportions of dissolved major ions and group water samples into ‘water types’. Devonian Reef aquifer samples were mainly calcium-bicarbonate ($Ca\text{-}HCO_3$) water type (Figure 45). Carbonate minerals such as calcite ($CaCO_3$) were present in many geological units in the area and comprised a major component of the Devonian Reef (limestone) aquifer. Groundwater samples with dominant $Ca\text{-}HCO_3$ water type were also found in samples from the Grant Group unit of the Grant Poole aquifer on the Lennard Shelf (Figure 45), the Fairfield Group aquifer, and in one alluvial aquifer sample (Figure 47).

Groundwater samples from the Poole Sandstone unit of the Grant Poole aquifer on the Lennard Shelf and in the Fitzroy Trough plot were predominantly sodium-chloride (Na-Cl) water type; that is, closer to sea water and coastal rainfall (Figure 46).

We also plotted rainfall composition given it is generally the major source of aquifer recharge (Figure 47). Rainfall composition on the Pilbara coast plotted near sea water (from the Learmonth station) reflects the influence of seawater aerosols on rainfall (Hingston & Gailitis 1976). In contrast, the rainfall at Halls Creek, inland and just to the east of the Fitzroy River catchment, is dominated by $Ca\text{-}Na\text{-}HCO_3$. The chemical composition of Halls Creek rainfall was derived from a series of monthly sampling over several years (Crosbie et al. 2012; Crosbie et al. 2018) and we consider it the more suitable dataset to compare with groundwater samples in recharge areas.

Figure 48 plots water type by aquifer spatially across the catchment with symbol size indicating water type, and colour indicating aquifer. Except for groundwater sampled from bore LF01, all samples with a $Ca\text{-}HCO_3$ water type lie on the Lennard Shelf, either within or adjacent to the Devonian Reef or Fairfield Group aquifers. Groundwater in the alluvial aquifer primarily originates from surface water recharge, which was $Ca\text{-}HCO_3$ type water when sampled in June 2017 (see Section 5.2.6).

Spatially, Na-Cl water type was found in samples from all bores in the catchment’s south-east (except the Devonian Reef aquifer samples), including those from the Poole Sandstone unit of the Grant Poole, Noonkanbah Formation (Manta Ray bore) and the Lennard Shelf samples from the Grant Group unit of the Grant Poole aquifer (Gogo Homestead and Acacia Tank flowing bore). Groundwater samples near Camballin, including from the Fitzroy River alluvial, Liveringa Group, Erskine Sandstone, Noonkanbah Formation and Grant Poole aquifers were also Na-Cl type.

By contrast, most groundwater samples from the Grant Group unit of the Grant Poole aquifer in the Fitzroy Trough near Camballin, along with some from bores in the

Poole Sandstone unit, were sodium-bicarbonate (Na-HCO_3) water type. This was particularly true for the deeper bores (e.g. Agricon 1 to 3 > 400 m depth). Groundwater from the deeper bores also exhibited the highest observed temperatures, ranging from 43 to 52°C, compared with 31 to 37°C for other samples. This likely indicates evolution of water type with depth and increasing residence time in the aquifer.

The source of Na-HCO_3 as major ions may come from either dissolution of Na and K-rich aluminosilicate minerals, or an ion exchange process known as ‘freshening’, where Ca-HCO_3 type recharging water displaces Na sorbed to aquifer materials (Appelo 1994). Bicarbonate (HCO_3) ions may also originate from mineralisation of organic carbon.

Groundwater from Emanuels Flowing Bore, although located in the outcrop of the Devonian Reef aquifer, also had Na-HCO_3 composition – suggesting this bore may not be screened in the Devonian Reef complex.

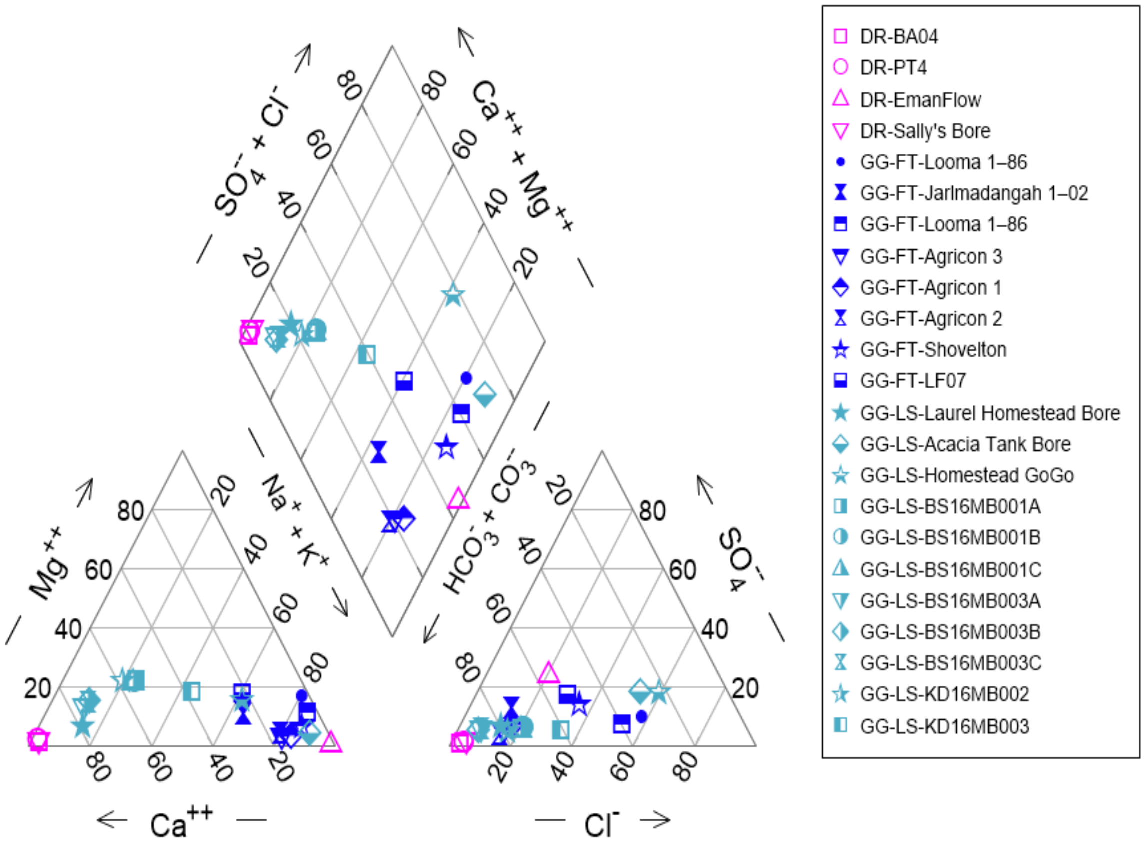


Figure 45 Piper plots of major ions in meq/L (Devonian Reef and Grant Group aquifers)

DR: Devonian Reef aquifer; GG-FT: Grant Group aquifer (Fitzroy Trough); GG-LS: Grant Group aquifer (Lennard Shelf).

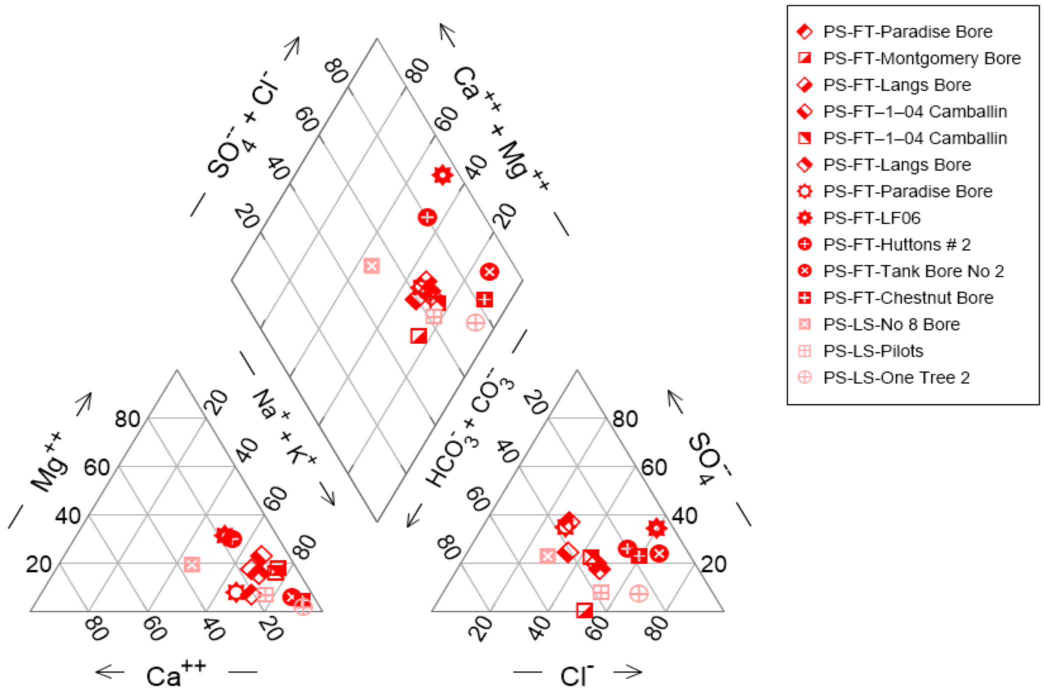


Figure 46 Piper plots of major ions in meq/L (Poole Sandstone aquifer)

PS-FT: Poole Sandstone aquifer (Fitzroy Trough); PS-FS: Poole Sandstone aquifer (Lennard Trough).

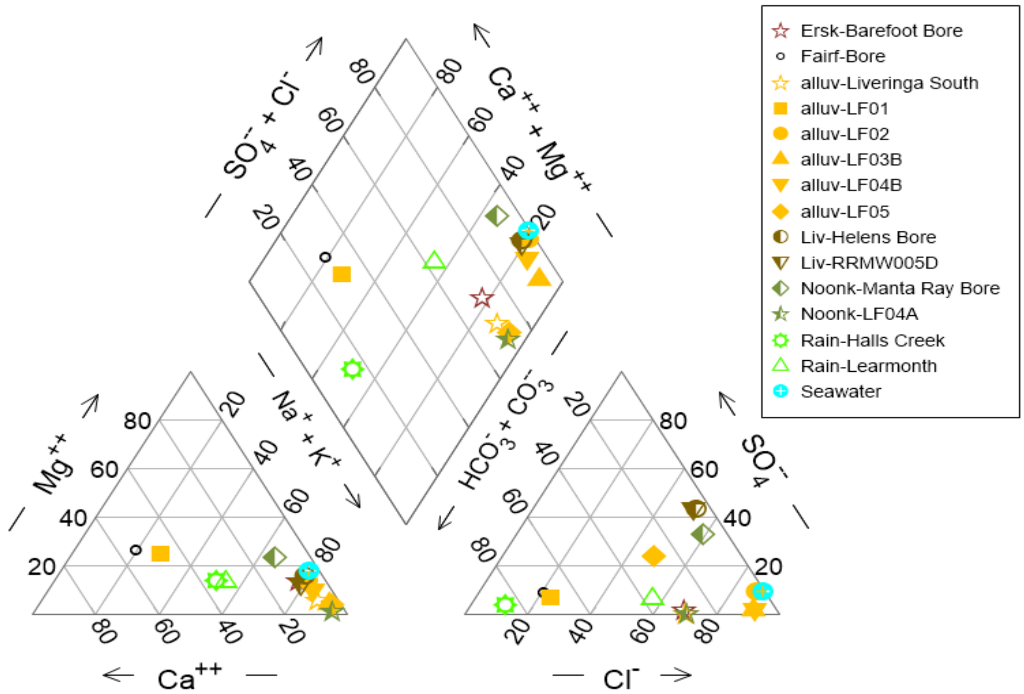


Figure 47 Piper plots of major ions in meq/L (other aquifers)

Ersk: Erskine Sandstone aquifer; Fair: Fairfield Group aquifer; alluv: alluvial aquifer; Liv: Liveringa Group aquifer; Noonk: Noonkanbah Formation.

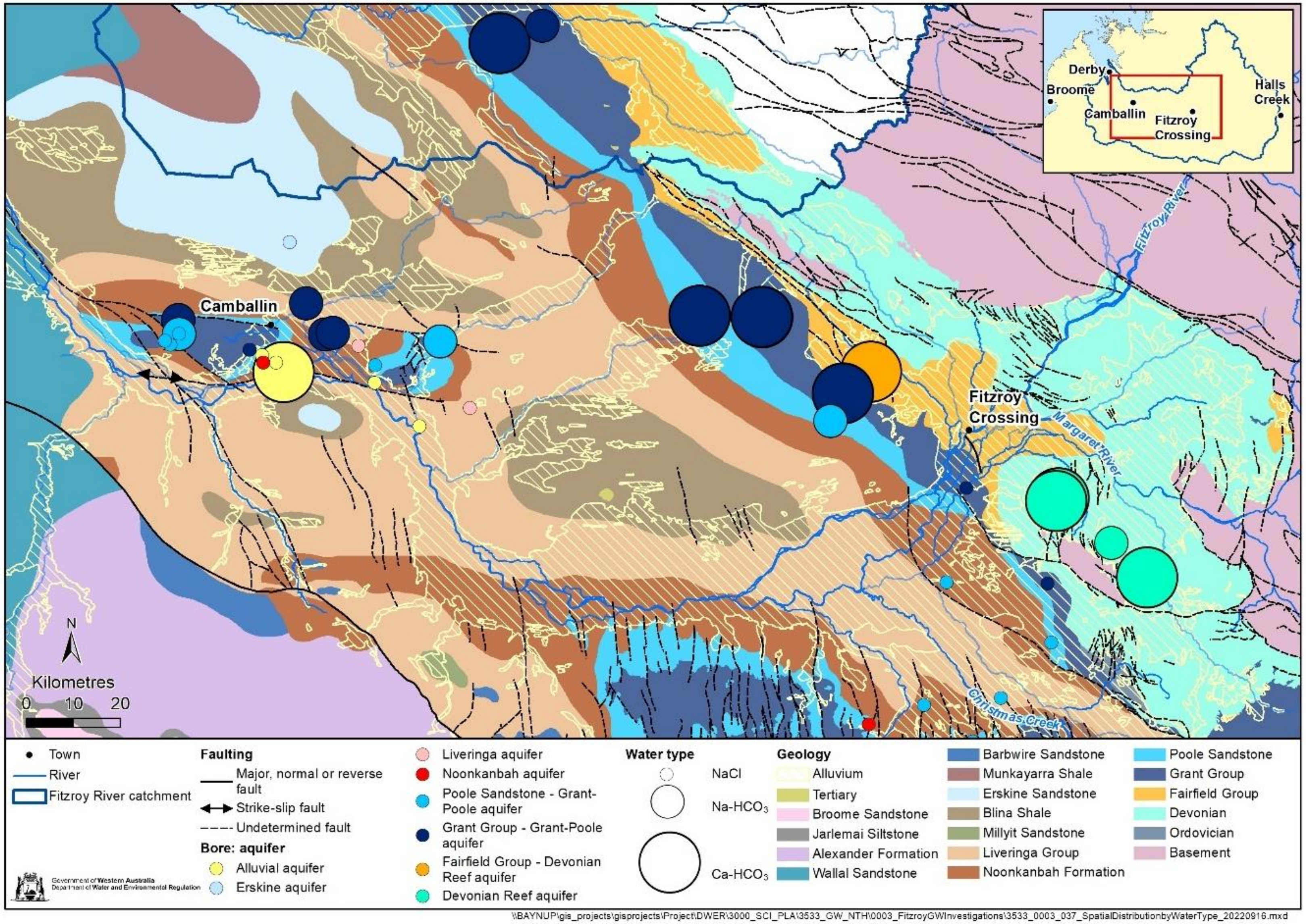


Figure 48 Spatial water type plot by aquifer

5.2.3 Ionic ratios

Bromide (Br) to chloride (Cl) ratios derived for groundwater samples from the Fitzroy River alluvial and regional aquifers largely follow seawater dilution (Figure 49). This indicates that a mineral source of chloride (such as halite dissolution) is unlikely, suggesting chloride is behaving conservatively. This means that ionic ratios with chloride can be used to assess hydrogeochemical evolution, and meets the assumption for using the chloride mass balance method for recharge estimation.

Where samples plotted away from the seawater dilution line, chloride concentrations were very low and/or bromide was below the laboratory detection limit. Because of this, significant uncertainty in these ratios arose.

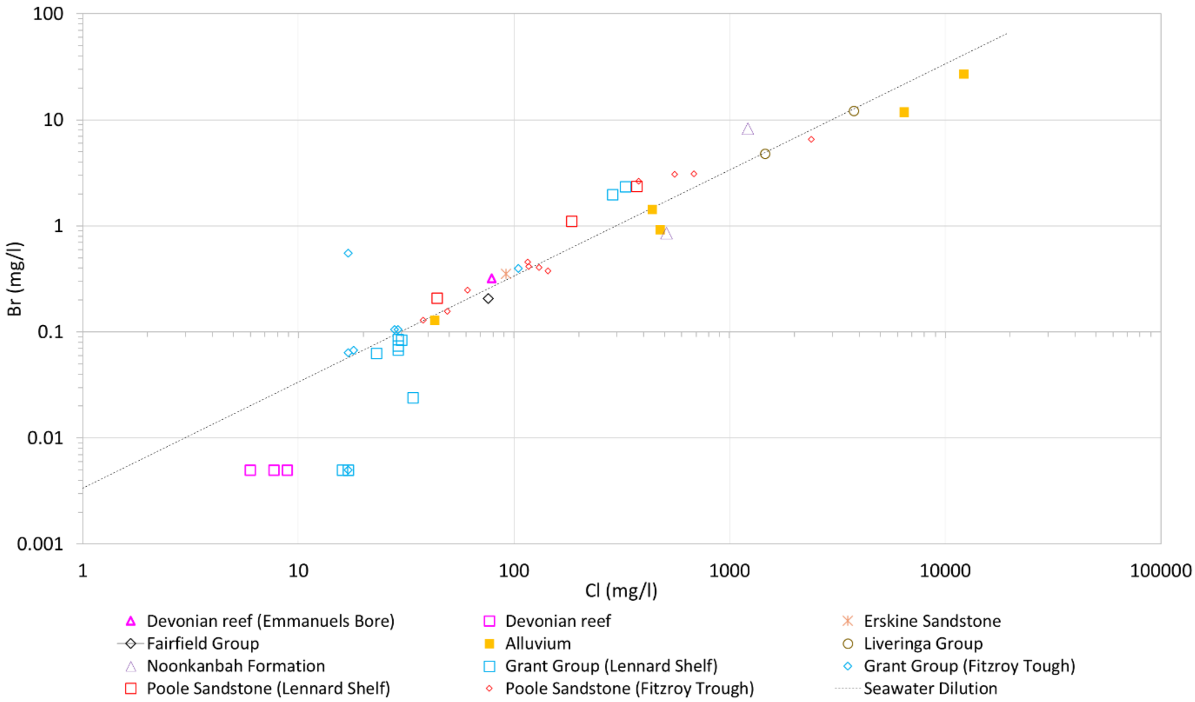


Figure 49 Bromide versus chloride

Dotted line = seawater dilution. Bromide detection limit 0.005 mg/L

We plotted major ion ratios (cation/Cl) with chloride to infer geochemical processes and to guide sampled selection of an appropriate radiocarbon correction model for calculating radiocarbon residence times (Figure 50). For example, radiocarbon may be diluted by ‘dead’ carbon from carbonate mineral dissolution and could skew results and create uncertainty in estimating groundwater residence times (see Appendix R).

Figure 50 also shows lines for seawater and rainfall ratios (volume-weighted average) from Halls Creek and Learmonth. The rainfall chemistry data has been sourced from Crosbie et al. (2012).

The Na/Cl and SO_4/Cl ratios of both rainfall and groundwater lie fairly close to the seawater and rainfall ratios, indicating that evapo-concentration and dilution are major drivers of their concentrations. The exceptions were the Na/Cl ratios of samples from bores screened in the Grant Group unit of the Grant Poole aquifer near Camballin, and those from Emanuels flowing bore, which were Na-HCO_3-type waters. Those samples plotted well above the rainfall ratio lines, indicating that an additional source of Na is present in the groundwater, likely due to ion exchange during aquifer freshening (Giménez-Forcada 2010). Effectively the original more-saline pore water is being flushed out, with mildly elevated Na levels being produced thereafter. This is a useful geochemical indicator of groundwater discharge from the Grant Group unit of the Grant Poole aquifer to either shallow aquifers or the river.

Ratio plots of chloride with Ca, Mg and HCO_3 (alkalinity) show that many groundwater samples lie above the seawater and rainwater ratios: this indicates the addition of these ions through dissolution of Ca/Mg carbonate minerals, such as from the Devonian reef complex and other calcrete units throughout the catchment. As mildly acidic rainfall infiltrates and flows through a carbonate-rich aquifer, carbonate minerals are dissolved and Ca, Mg and CO_3/HCO_3 all become free ions. Most of the elevated cations in the project area are alkalinity (HCO_3) and Ca, suggesting that the aquifer minerals being dissolved are Ca carbonates as opposed to Mg carbonates.

The relatively neutral groundwater pH causes the dissolved alkalinity to be present as HCO_3. This is a useful indicator of aquifer groundwater discharge, particularly for the Devonian reef aquifer. If the water pH were higher (i.e. more alkaline), CO_3 would appear in increasing concentrations, with these being significant with pH above 9.

SO_4/Cl values lie above and below the seawater and rainfall ratios. Lower SO_4/Cl ratios (below the seawater/rainfall lines) typically indicate reducing conditions are precipitating sulfur minerals. Higher SO_4/Cl ratios typically indicate weathering/ dissolution of sulfide minerals – a relatively minor geochemical process based on the SO_4/Cl data.

In geological units such as shale, mudstone and siltstone, the sulfide mineral present will typically be pyrite (FeS). In sediments deposited in saline to hypersaline conditions, the sulfur mineral present will typically be gypsum ($CaSO_4$). Given the high Ca/Cl samples do not have elevated SO_4 concentrations, it is likely that pyrite dissolution is the major source of dissolved SO_4 in all aquifers.

Acid sulfate soils (ASS) which contain iron sulfides are likely present in floodplain wetlands. When ASS are exposed to oxygen as the floodplain dries, they oxidise and produce Fe and SO_4 as free ions accompanied by a drop in pH (increase in acidity). This decreasing pH/increasing acidity can be buffered by CO_3/HCO_3. Some Fitzroy River alluvial aquifer water samples have mildly elevated SO_4 concentrations and relatively low alkalinity concentrations, so any acidity produced is being buffered by dissolved alkalinity. Prolonged exposure and ASS oxidation of floodplain wetlands could cause water quality impacts. Some of the SO_4/Cl ratios are below the seawater dilution line, which indicates SO_4 reduction as well as oxidation. Essentially some areas are forming ASS while others are oxidising – as would be expected in this type of wetland environment. Appendix E presents all major ion chemistry data collected for the investigation.

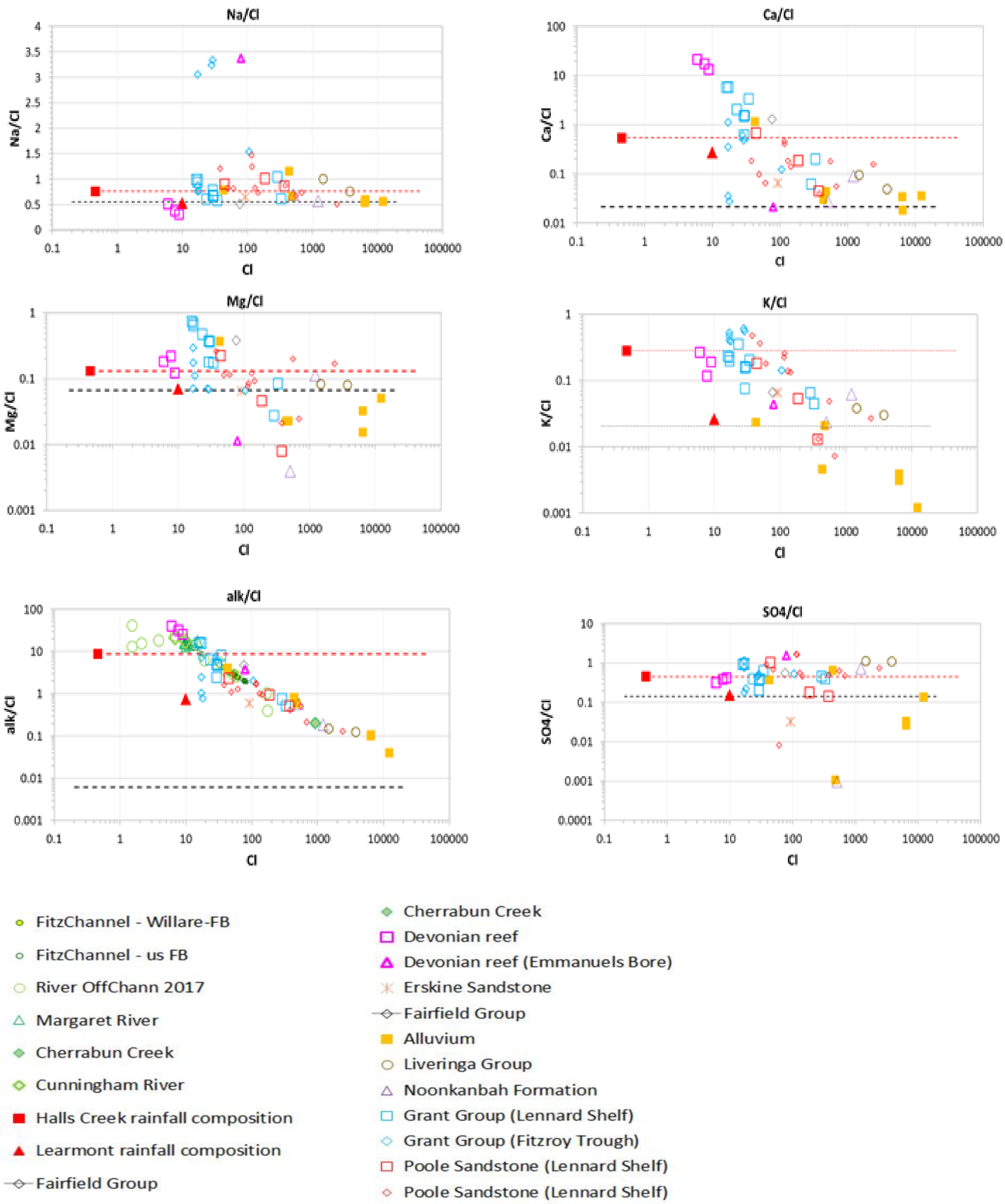


Figure 50 Major ion ratios (based on concentration in mg/L)

Black dashed line = seawater dilution; red dashed line = evaporation of Halls Creek rainfall

Note: Precipitation of minerals as concentrations increase has not been taken into account (given the low concentrations this is unlikely to be a major factor); log scale used on y-axis for all plots except Na.

5.2.4 Nutrients

Nutrient concentrations in groundwater ranged from <0.1 mg/L to 9.2 mg/L total nitrogen (TN) (Appendix E).

Naturally high concentrations of nitrate have been reported at some arid zone locations in Australia and elsewhere (Barnes et al. 1992; Stone & Edmunds 2014). At these sites, aerobic (oxidising) conditions and low organic carbon in soils and aquifers are thought to limit nitrate loss by denitrification. The breakdown of nitrogen-fixing vegetation can also cause significant nitrogen concentrations in shallow groundwater.

In this study, groundwater samples with the highest TN also generally had high oxidation reduction potential (ORP) and high nitrate (NO_3) concentrations, suggesting the nitrogen has originated from surface processes (as described above). However, some samples exhibited low ORP, and nitrogen was predominantly present as ammonium (total NH_3 and NH_4) (Figure 51), which is often formed during the process of denitrification. This suggests that a range of processes are affecting nitrogen concentrations in this system, potentially including denitrification.

Natural sources of nitrogen have been reported to include fixation by microbes or biomass associated with certain types of vegetation (particularly Acacia species), termite mounds if present, and/or microbial soil crusts. Atmospheric deposition of nitrogen may also be a factor in some areas (Barnes et al. 1992; Gates et al. 2008; Stone & Edmunds 2014). Groundwater sampled from Jarlmadangah 1-02 bore had a TN concentration of 4.2 mg/L, with the bore being located near an area with a high concentration of acacias and termite mounds.

Anthropogenic sources of nutrients in the study area include livestock, fertiliser, landfills and wastewater. In some cases, we attributed elevated nutrient concentrations (including the highest concentration measured) to land use at the bore site. We considered that these instances did not reflect the native regional aquifer conditions and they are not discussed here. These samples are reported in Appendix J.

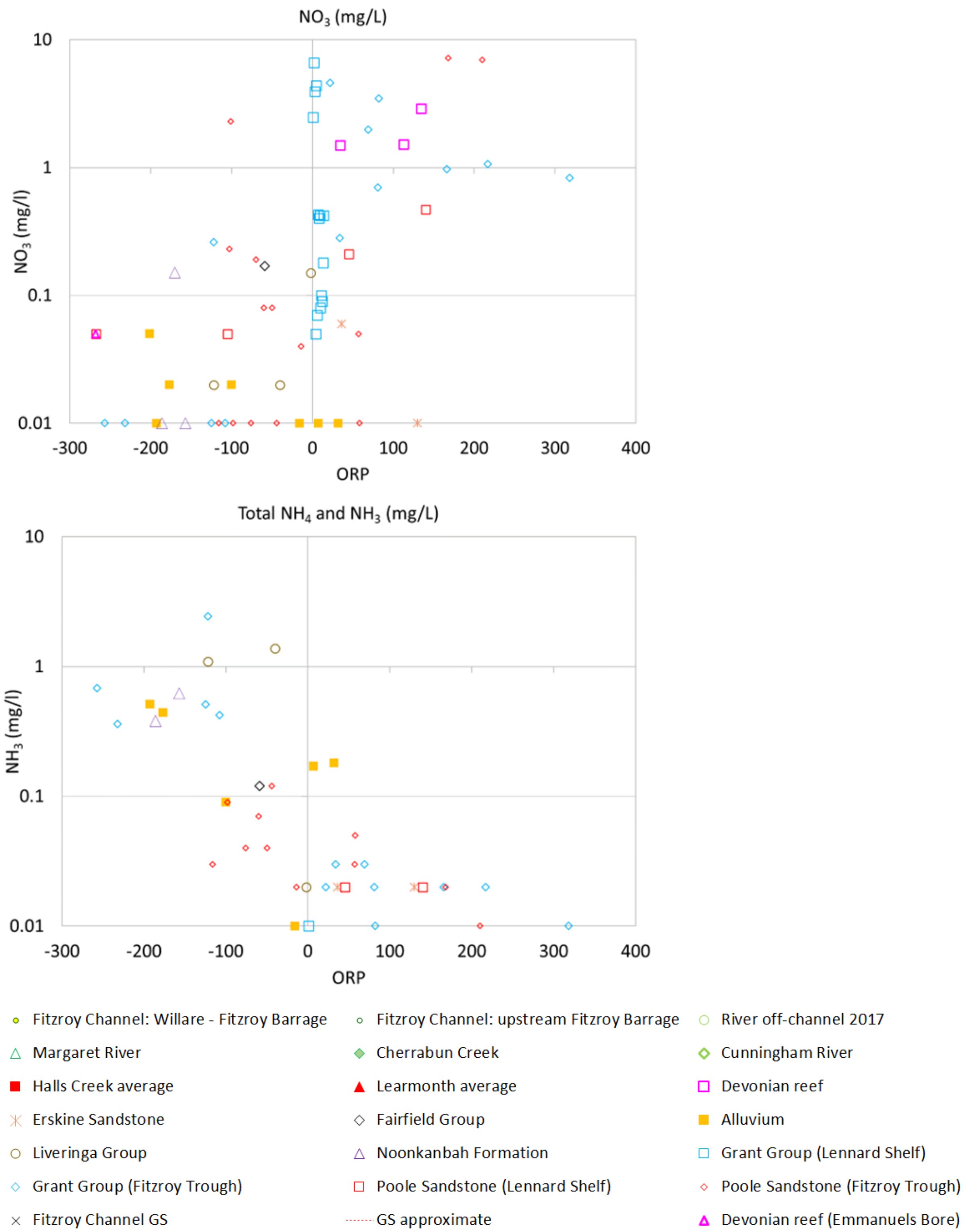


Figure 51 Nitrate (top) and ammonia (bottom) concentrations vs oxidation-reduction potential (ORP)

5.2.5 Deuterium and oxygen-18

We used deuterium (^{2}H) and oxygen-18 (^{18}O) (Figure 52) stable isotope data to support the assessment of recharge processes, evapo-concentration, aquifer connectivity and groundwater interaction with the Fitzroy River. Both ^{2}H and ^{18}O can be interpreted by plotting local rainfall data to produce a local meteoric water line (LMWL) and the volume-weighted average, which will plot along the LMWL.

We can then interpret data points and groups of data points which deviate from the LMWL. Usually this deviation from the LMWL originates from the volume-weighted average and occurs due to stable isotope fractionation. In most groundwater–surface water interaction studies, the dominant isotopic fractionation mechanism is water evaporation. This results in a relative depletion of ^{2}H, which plots below the LMWL, and often creates an obvious trend line – as in Figure 52.

Other processes that affect stable isotope concentrations include CO_2 exchange, silicate hydration, H_2S exchange, condensation and water–rock interactions. Figure 52 indicates the dominant stable isotope fractionation process is evaporation, although the deviations of individual data points around the LMWL and evaporation trendlines suggest other processes as well.

The stable isotope results for most groundwater samples plot close to the LMWL and plot closer to the Learmonth average. This suggests groundwater has mostly been recharged by rainfall with an isotopic signature from closer to the coast (Learmonth) than the Halls Creek rainfall samples (inland). The Devonian Reef and Grant Group (Lennard Shelf) plot between the data from the two rainfall sites, suggesting a more mixed rainfall recharge source.

The proximity of groundwater samples to the LMWL indicates relatively rapid rainfall recharge that is largely unaffected by evaporation. Most groundwater samples also exhibit a more depleted signature than the volume-weighted average rainfall for either Halls Creek or Learmonth (but closer to Learmonth), indicating that groundwater is mostly recharged by intense rain events in the wet season when the isotopic signature of rainfall is most depleted.

River and off-channel samples are affected by evaporative fractionation to varying degrees, with potential fractionation trendlines shown as dashed lines in Figure 52. These can be interpreted as follows: note the sample groups aligning with each trendline are listed in order of increasing fractionation (evaporation) effects.

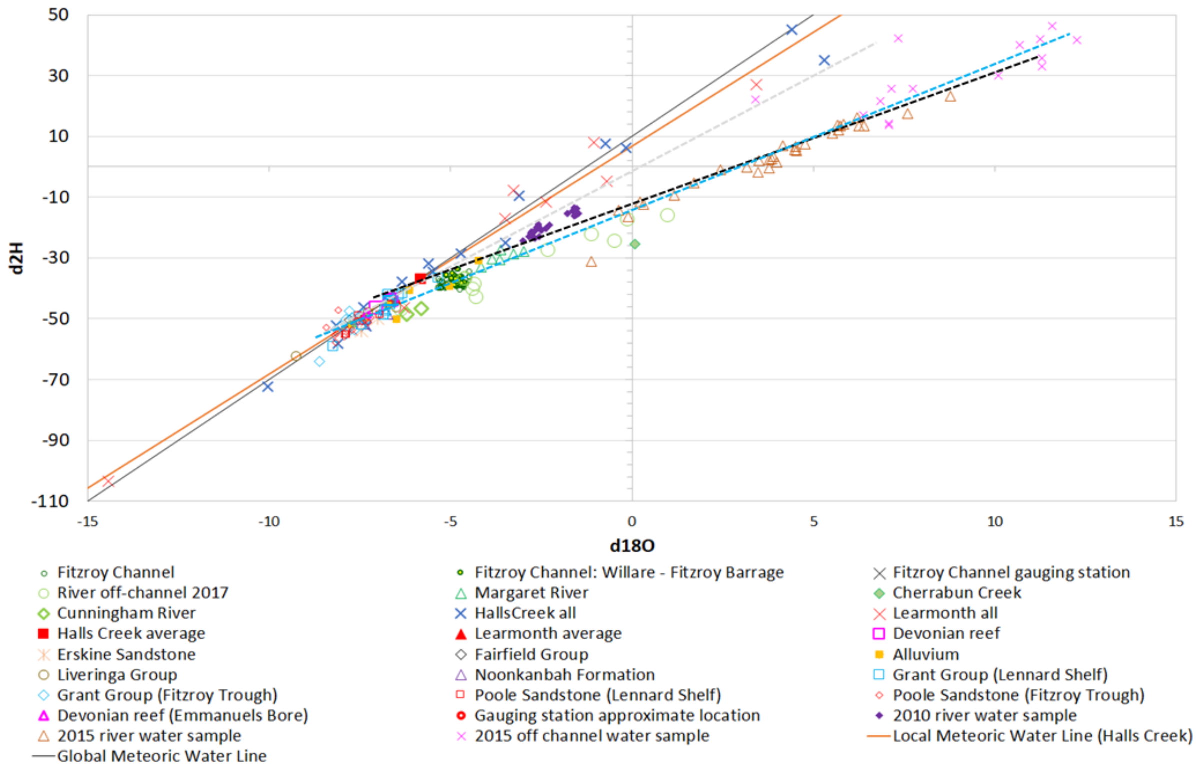


Figure 52 Stable isotopes of water in groundwater, rainfall and surface water

Surface water samples from main river channel (2010, 2015 and 2017) and off-channel (2017 and 2015). Rainfall raw data from Learmonth and Halls Creek (Crosbie et al. 2012).

- The grey dashed line originates from the Learmonth volume-weighted average and aligns with the data from the Fitzroy channel, is close to the Margaret River samples, and aligns well with the longitudinal river transects from 2010 and two of the samples from the 2015 off-channel sampling program.
- The black dashed line originates from the Halls Creek volume-weighted average, plots close to the Fitzroy channel samples, is close to the Margaret River samples, and aligns well with the 2010 longitudinal river samples, the 2015 longitudinal river samples and the 2015 off-channel samples.
- The blue dashed line originates from the Learmonth volume-weighted average, plots close to the Cunningham River samples, and aligns well with the Fitzroy channel samples, the Margaret River samples, the off-channel samples from 2017, the 2015 longitudinal river samples and the 2015 off-channel samples.

Given the complex nature of groundwater–surface water interaction and the varying isotopic signatures of rainfall sources, the fact that three trendlines can explain different portions of the data is expected. The blue dashed line offers the best explanation of the data: it suggests that most of the surface water is from rainfall isotopically similar to the Learmonth data. In reality, surface water will originate from a mixture of rainfall across the catchment combined with local groundwater inputs, which are then affected by fractionation processes. This explains why all samples do not closely follow any particular trendline. It is also important to note that we do not have an abundance of local rainfall stable isotope data, which is why Learmonth has been used even though it is 1,200 km west-south-west of Fitzroy Crossing. Hence these interpretations need to be taken as preliminary until more data is collected, although they do provide some useful insights.

5.2.6 River water quality sampling

In this section we present a series of figures showing water quality and chemical composition results for river sampling undertaken in June 2017. We plot these spatially along the x-axis (as eastings) from near the river mouth (low eastings) to the upper reaches (high eastings). We also display groundwater data on each plot to compare the water quality and chemical composition of groundwater with that of surface water. See Figure 53 for river sampling locations.

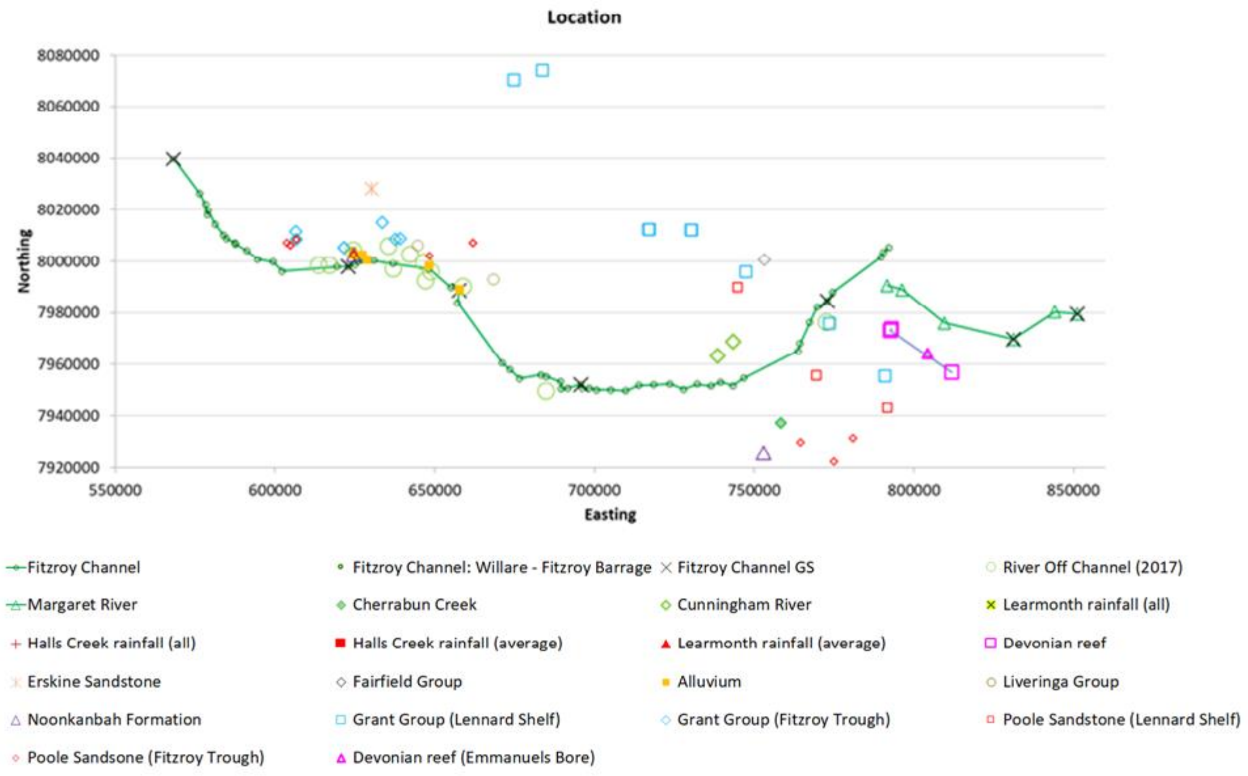


Figure 53 Surface water and groundwater sampling locations

Approximate eastings are used for samples in the far eastern side as these are in Zone 52 and the remainder of the samples are in Zone 51. FitzChannel GS = river gauging stations which are from east to west; that is, Margaret Gorge, Mt Krauss, Fitzroy Crossing, Noonkanbah, Fitzroy Barrage, Looma (Kings) and Willare.

Field measurements

The pH values measured in the field in June 2017 were between 7.5 and 9 (Figure 54) – considerably higher than most groundwater samples but not unusual for surface water. The pH increased downstream to Noonkanbah, then decreased towards Willare. The June 2017 river temperature was relatively constant (Figure 55) and at least 10°C cooler than the reported groundwater temperatures.

Conductivity and major ions

Sampling in June 2017 showed that surface water with the lowest electrical conductivity (EC) – 343 µS/cm – was the furthest upstream sampling site on the Margaret River (Figure 56). The next sampling point downstream, at the confluence of the Margaret and Leopold rivers, showed a much higher EC (646 µS/cm). After that the EC continued to decrease downstream.

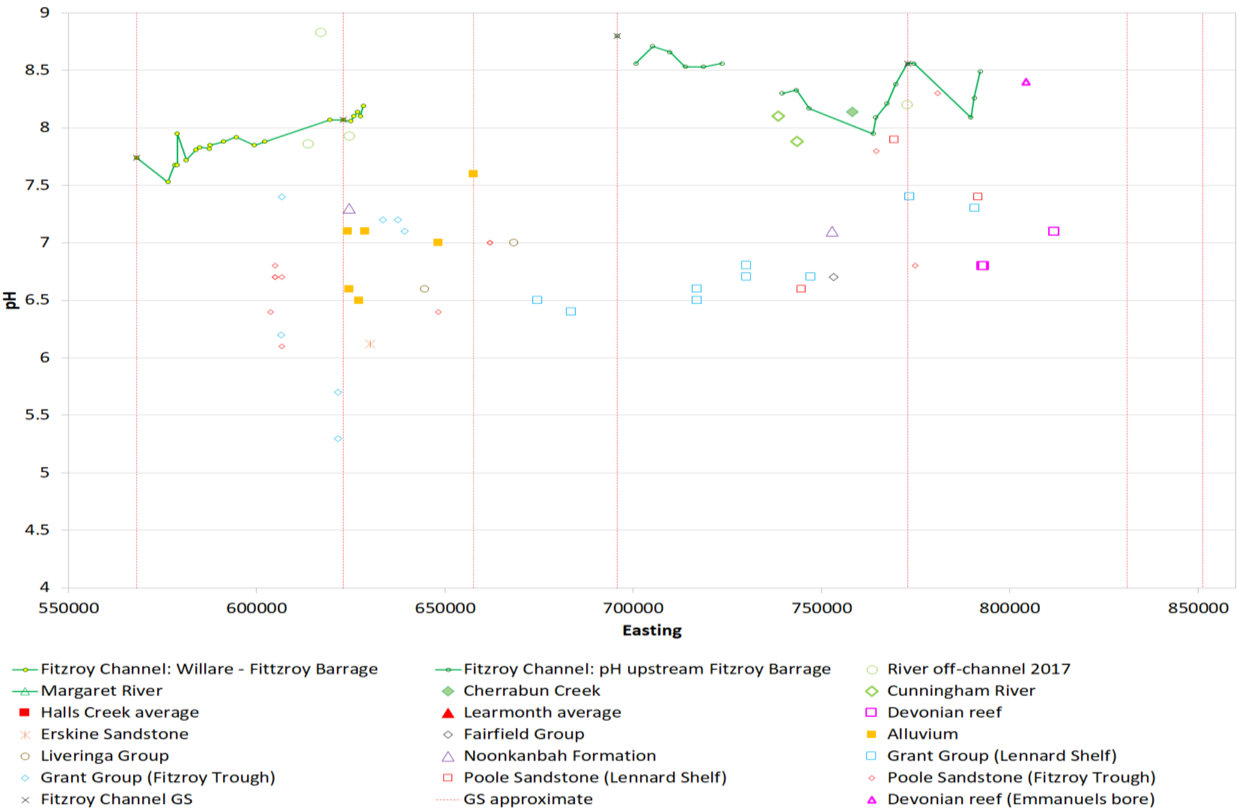


Figure 54 pH – river and groundwater samples (2017)

Figure 55 Temperature – river and groundwater samples (2017)

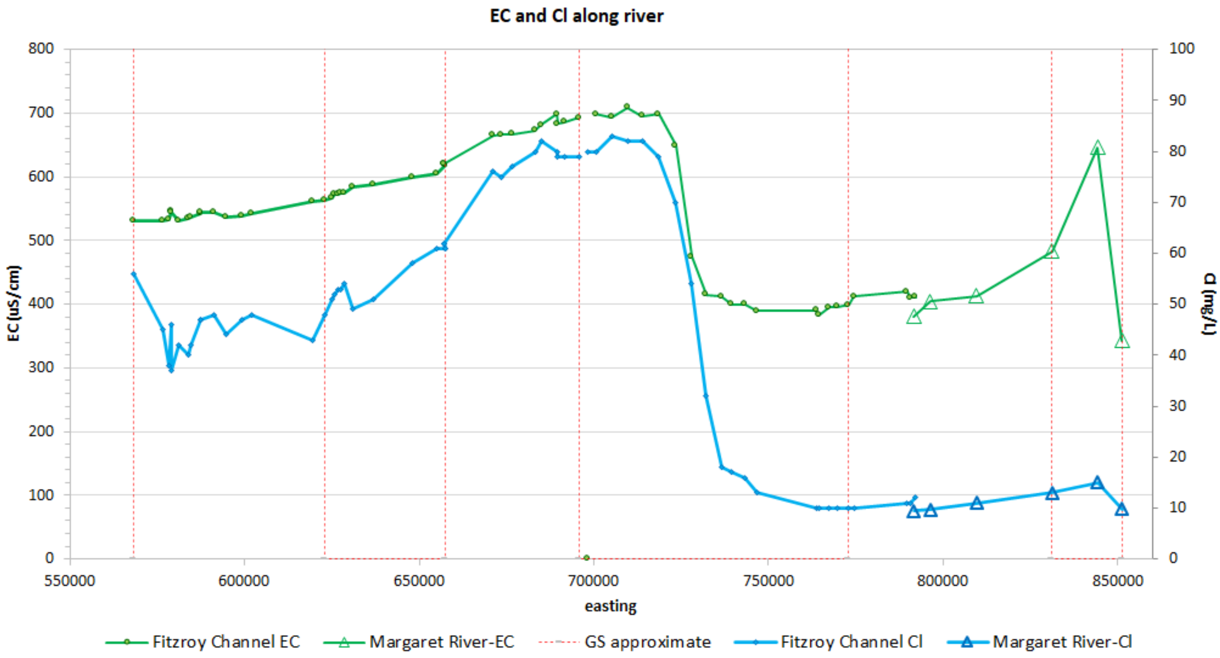


Figure 56 Electrical conductivity (EC) and chloride (Cl) in Fitzroy River (2017)

Gauging stations from east to west: Margaret Gorge, Mt Krauss, Fitzroy Crossing, Noonkanbah, Fitzroy Barrage, Looma (Kings) and Willare.

Similarly low EC values were measured in the main channel, both upstream at Geikie Gorge and downstream towards Fitzroy Crossing. However, between Fitzroy Crossing and Noonkanbah gauging station, the EC increased again markedly over a distance of more than 100 km by almost a factor of two. At sample sites LF63 and LF64, at or just downstream of where the Cunningham Anabranch re-joins the main channel, the EC levelled off and then gradually decreased again towards Willare.

Major ion composition indicates the increase in EC between Fitzroy Crossing and Noonkanbah was primarily a result of higher concentrations of Cl, SO_4 and Na, as well as Br and Sr (Figure 58 and Figure 59). To further emphasise the different relative changes in species along the channel, the concentration of each ion is also plotted as a ratio with its concentration at Fitzroy Crossing (Figure 59). Piper diagrams and major ion ratios with Cl, compared with seawater and rainfall ratios, are also presented in Appendix L. At the same point along the channel, there is only a minor increase in Ca, Mg, alkalinity and Si.

Despite the increase in Cl and SO_4, all river channel samples in June 2017 were predominantly bicarbonate-type water, however the composition varied along the channel. Magnesium was the dominant cation in samples upstream of Fitzroy Crossing, and in some samples on the Margaret River. At and below Fitzroy Crossing, Ca-HCO_3 was replaced with Na-HCO_3 water type at the point of increase in EC. Below Looma, Ca-HCO_3 was again the main water type for some distance, then mixed Na- and Ca-HCO_3 type towards Willare.

Ionic composition of surface water showed very low Br (below detection) in all samples upstream of the zone with increased EC (Figure 58). A jump in concentration occurred in several ions in the final sample downstream at Willare, indicating possible seawater influence (Figure 57 to Figure 59). The highest potassium (K) concentrations were observed in the Margaret River samples. Potassium was also the only major ion to increase consistently in the Fitzroy River between Fitzroy Crossing and the coast (Figure 57 and Figure 59).

Data from the longitudinal water quality sampling in June 2017 (after a high rainfall wet season) is plotted with data collected in November 2015 and May 2010 (both relatively dry years) (Harrington et al. 2011; Harrington & Harrington 2016). See Appendix K for the differences in flow and rainfall for the preceding wet season years. Earlier grab samples collected at gauging stations in wet and dry seasons from 2006 to 2011 are also presented.

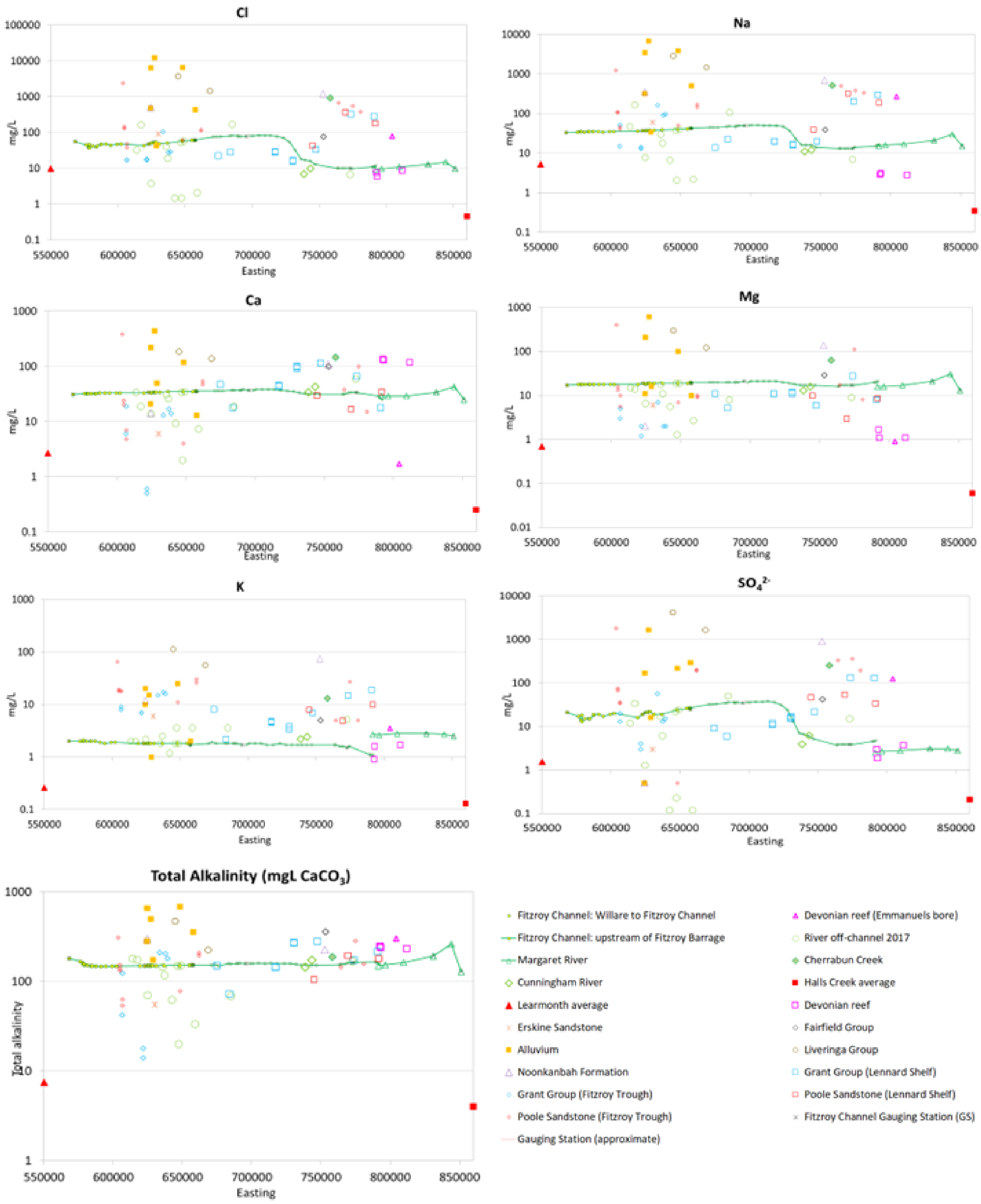


Figure 57 Surface water, groundwater and rainwater composition

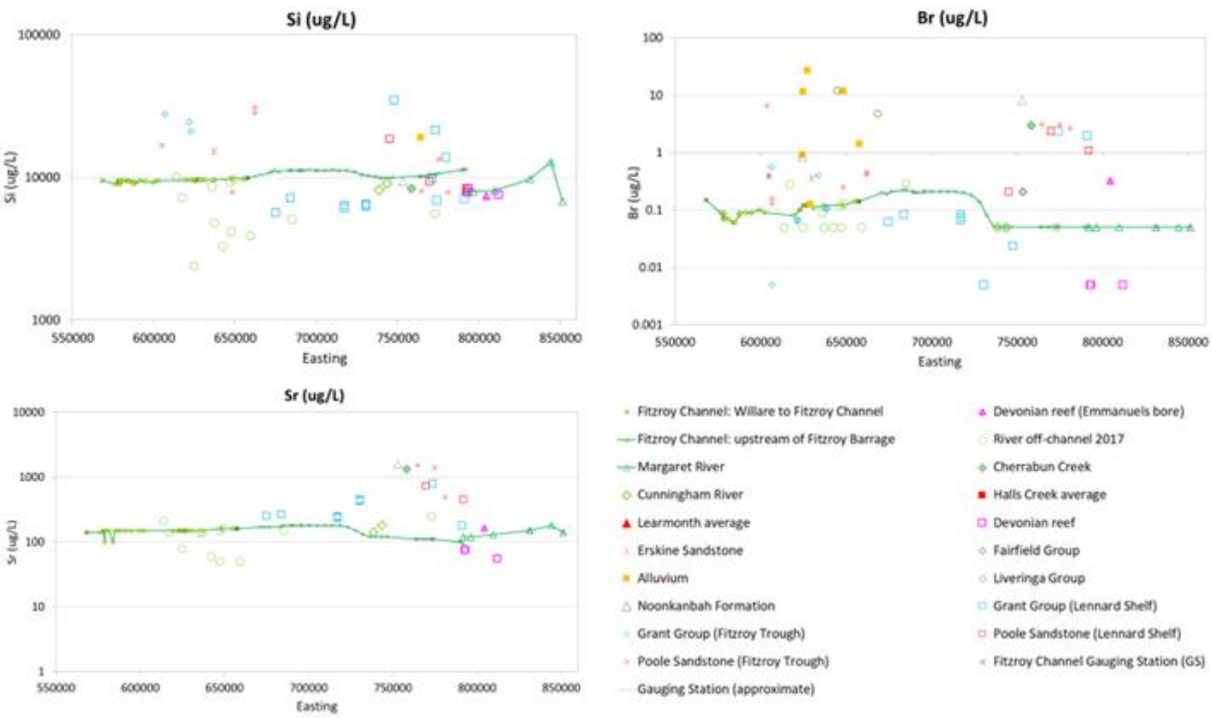


Figure 58 Concentration of Si, Br and Sr in surface water, groundwater and rainwater, plotted by easting

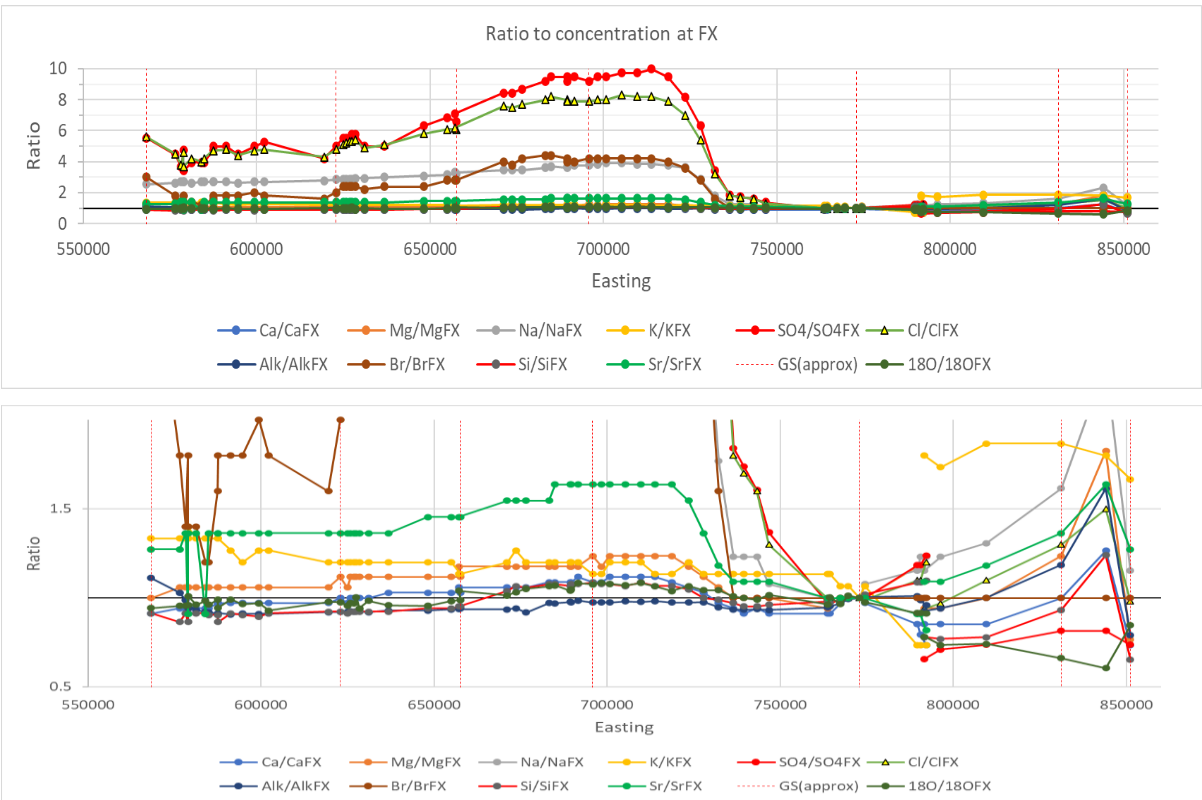


Figure 59 Major ions species and Br, Si and Sr in river samples from east to west

Top plot: all data; bottom plot: zoomed in to lower range ratios. All data plotted as a ratio with its concentration at Fitzroy Crossing. River samples were taken from both the Fitzroy and Margaret rivers. Note overlapping samples (by easting) at both the lower end of the Margaret River and at the Geike Gorge samples upstream of Fitzroy Crossing (Fx) approx. easting 790,000.

Surface water samples collected in November 2015 – late in the dry season and after a wet season that was very dry – showed Cl concentrations in the lower reaches were much higher and more variable along the channel than in 2017 (Figure 60). The variability could be because the pools became disconnected, depending on how the local conditions influenced different rates of evaporation and/or groundwater inflow.

The May 2010 sampling (Harrington et al. 2011) extended above Noonkanbah, and a similar increase in Cl to that of 2017 was observed in the middle of the reach. Yet the concentrations upstream and downstream were much lower in 2010 than in 2017 or 2015. Earlier grab sample data from 2006 to 2011 confirms that the EC measured at the gauging stations; that is, up and downstream of the zone with increased EC, was anomalously low in 2010 (Figure 61).

The gauging station data also shows that concentrations in the river are dynamic, most clearly seen with Cl concentrations in 2006 (Figure 62): as the rains began and flow discharge increased in September 2006, the water with high Cl was pushed downstream (e.g. compare Cl at Noonkanbah and Looma in September and October/November of 2006). Note also that in the wet season sampling from 2007 to 2010, the EC at all gauging stations converged on a lower value (closer to rainwater).

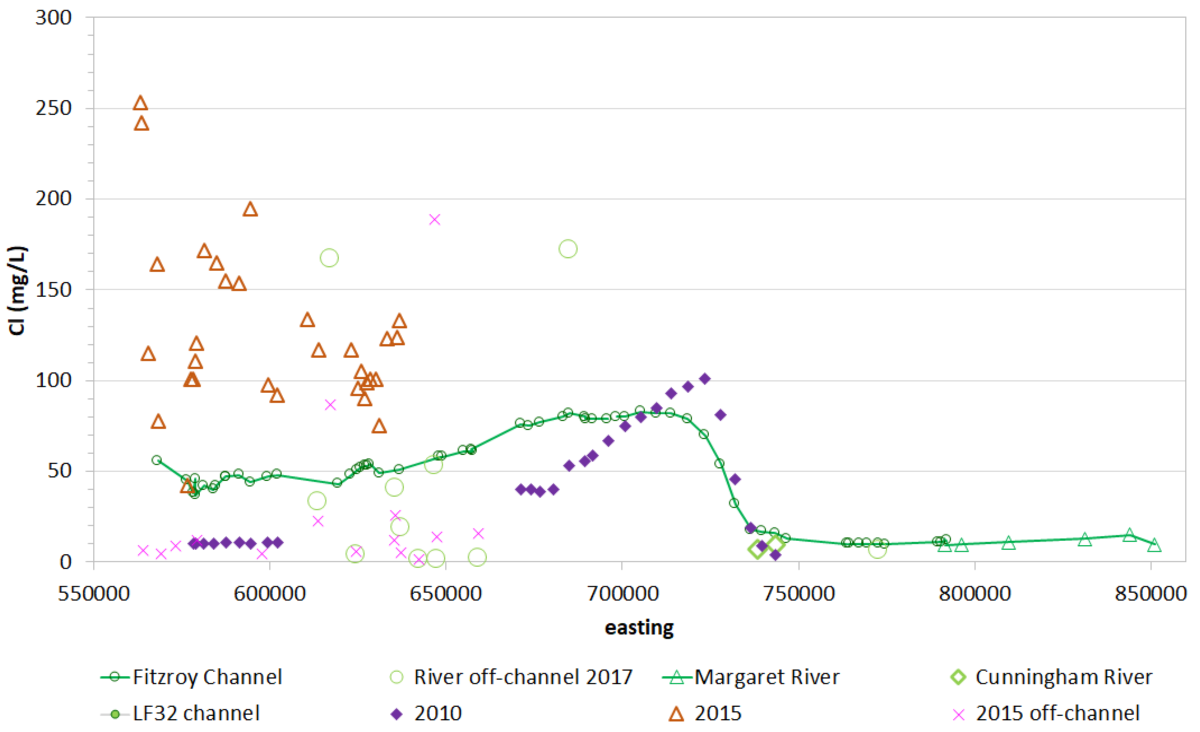


Figure 60 Cl concentration in 2017, 2015 and 2010 in main channel and off-channel samples

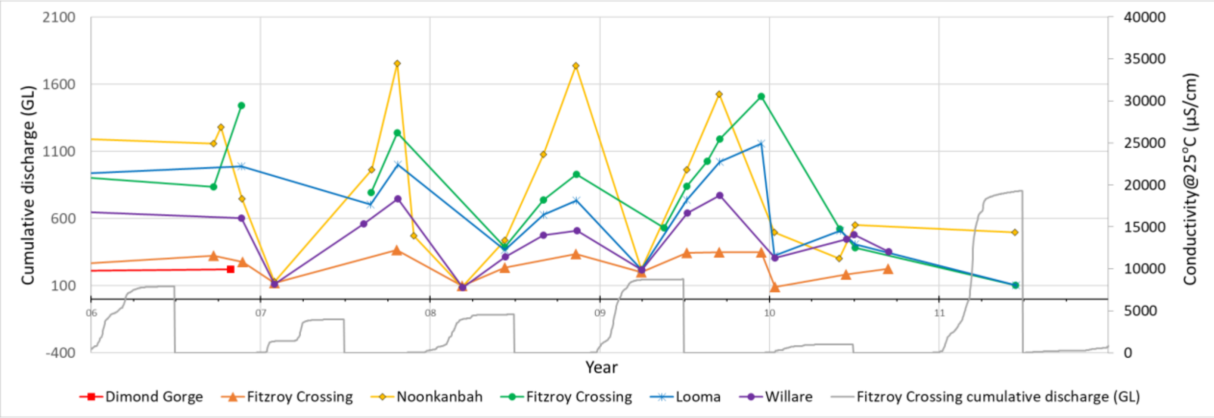


Figure 61 Conductivity and cumulative annual discharge measured at gauging stations between 2006 and 2011

Figure 62 Cl concentration measured at gauging stations between 2006 and 2007 (top) and annual cumulative flow (bottom) from July at Fitzroy Crossing

The major ion composition varied considerably in these different datasets; for example, in contrast to the 2017 Na- and Ca-HCO_3 water types in the lower reaches, the river water in 2015 was predominantly Na-Cl type (see Piper plots in Appendix L).

Saturation indices

Saturation index calculations indicate that river water is slightly oversaturated with respect to calcite in the upper reaches and remains very close to solubility equilibrium towards the coast (Figure 63). This means an influx of Ca- or HCO_3-bearing water would not result in a further increase in Ca or alkalinity, as the concentration of these species would be limited by calcite precipitation.

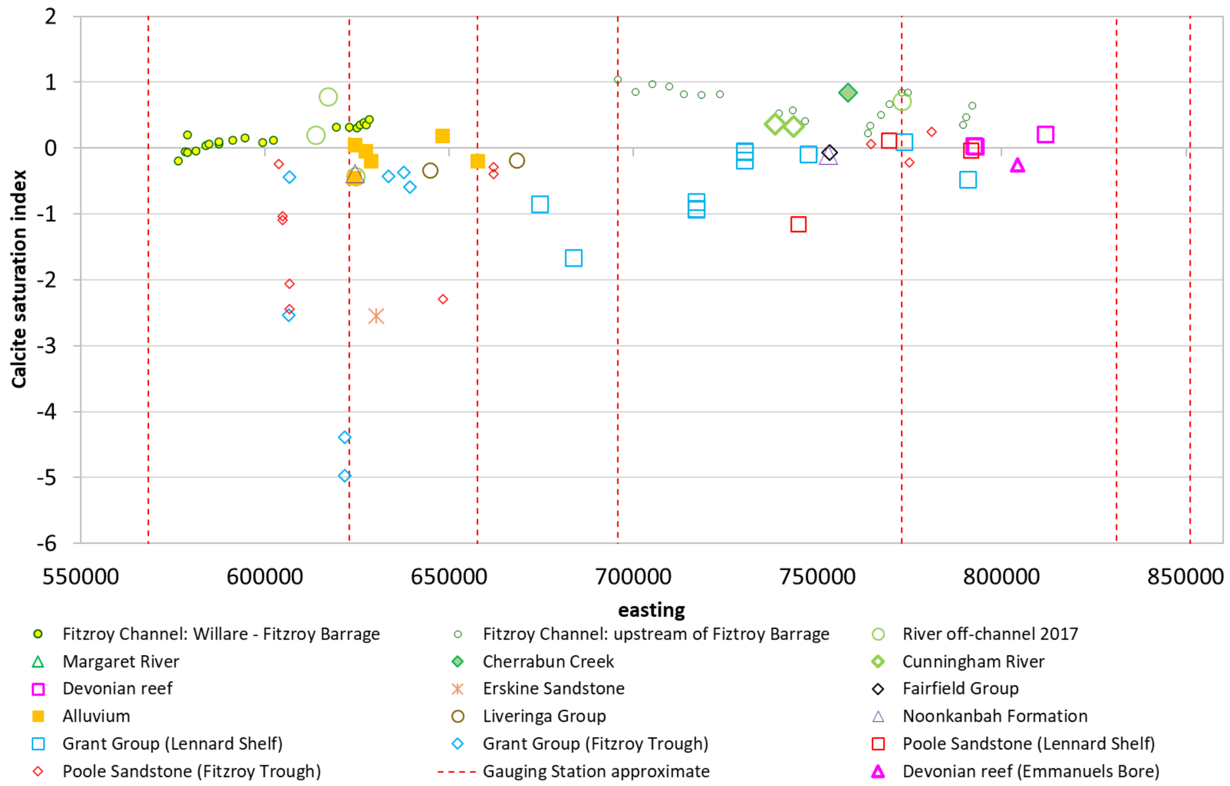


Figure 63 Saturation index for calcite in river and groundwater samples

Samples exhibited a similar degree of saturation with respect to dolomite as for calcite, although as mentioned above, a more likely control on Mg concentrations would be incorporation into Mg-calcite.

All river and groundwater samples were undersaturated with respect to gypsum, halite and strontianite ($SrCO_3$), but had close to solubility equilibrium with respect to a Si mineral (chalcedony, SiO_2).

See Appendix F for the saturation indices for all minerals.

Stable isotopes

As for the major ions, the stable isotope concentrations presented here are a snapshot of the 2017 dry season isotopic signature. The samples from the main channel in June 2017 plot off the LMWL to the right, indicating an evaporated signal compared with rainfall and most groundwater samples (Figure 64). Main channel samples were also relatively homogenous compared with the spread among groundwater samples. The Margaret River samples showed a further enriched and evaporated signal than the Fitzroy River main channel samples. Several off-channel samples, including Cherrabun Creek, were more enriched – suggesting a stronger signal of evaporation.

River water sampled in 2017 has a similar signature to alluvial groundwater in two locations: LF05 near Fitzroy Barrage and LF02 near Camballin and Uralla/Snake Creek (but with a more depleted signal).

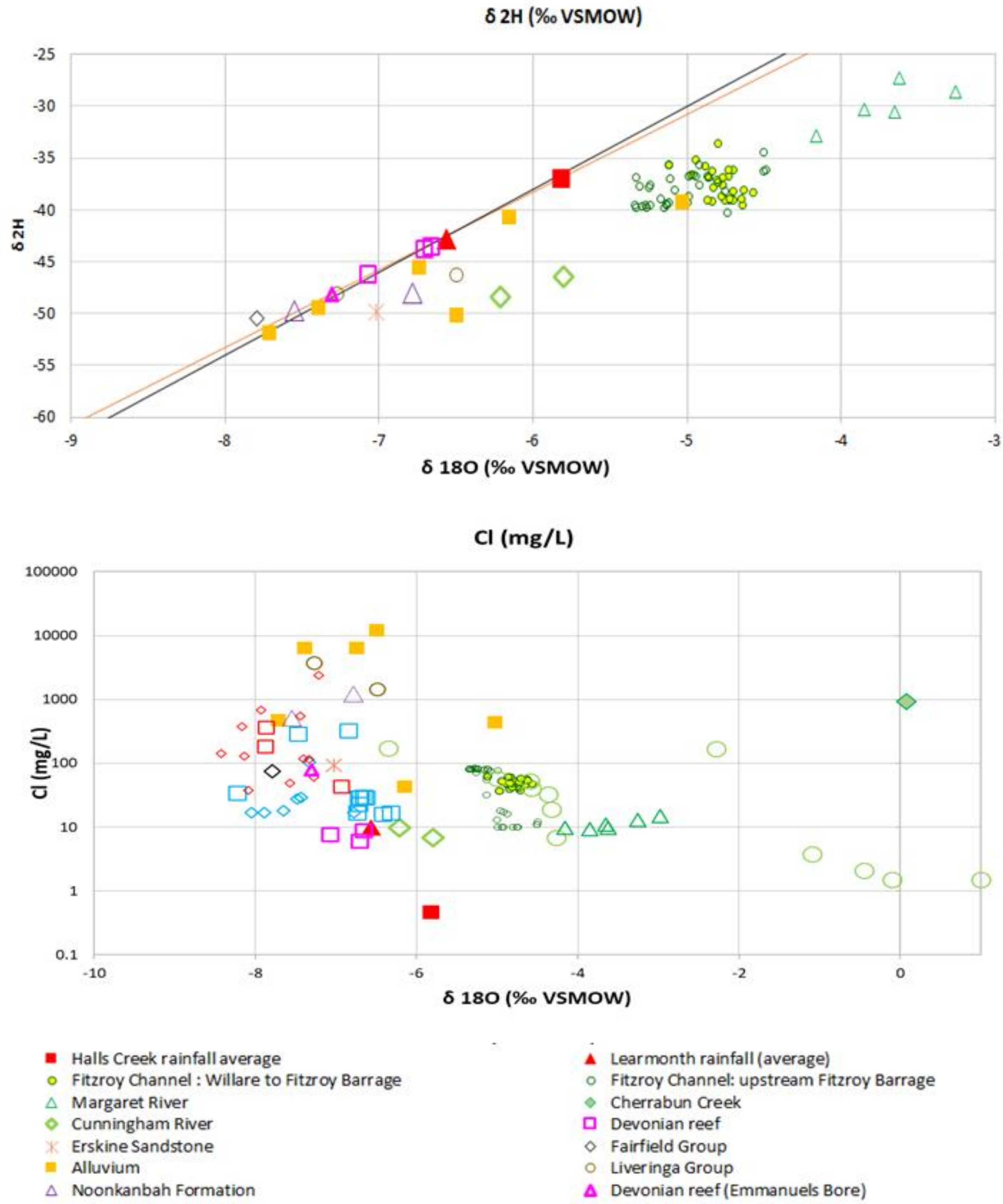


Figure 64 δ^{2}H vs δ^{18}O (top plot) and Cl vs δ^{18}0 (bottom plot)

Note the stable isotopes in the river vary considerably over time, with rainfall events and interannually. The presence of an evaporated stable isotope signature does not necessarily imply higher Cl concentrations, as the lower panel in Figure 64 shows. The Margaret River and some of the off-channel wetland samples, which exhibit the evaporated stable isotope signature, have lower Cl concentrations than other samples along the river (and indeed in some cases, lower Cl concentrations than the volume-weighted average Cl concentration in coastal rainfall).

Figure 65 shows the δ^{18}O and Cl along the river in 2017 by eastings. There is a clear decreasing trend in δ^{18}O values in samples downstream of Fitzroy Crossing to Noonkanbah, and an increasing trend from Noonkanbah to Fitzroy Barrage. The pattern of lower ^{18}O between Fitzroy Crossing and Fitzroy Barrage was also seen when the river was sampled in 2010, albeit with a more enriched ^{18}O and ^{2}H signal overall (see also Figure 66). This is consistent with the 2010 sampling coming after a drier wet season than that of 2017.

River and off-channel samples from 2015 (from the lower reaches, downstream of Noonkanbah) exhibited an even stronger evaporative signal than the off-channel samples in 2017 and 2010 (Figure 66). 2010 was a lower discharge year than 2015, although the sampling was earlier in the dry season (May) and the river was flowing. In contrast, sampling in November 2015 was at the end of the dry season. This was a low rainfall year when the river ceased to flow at Fitzroy Crossing (Appendix K).

In 2015, off-channel samples were similar to the Margaret River samples taken in 2017. Both sampling periods showed a stable isotope signature that was more evaporated, with a lower Cl concentration (Figure 65). This suggests evapo-concentration of water with a much lower Cl concentration, closer in composition to dilute rainfall, or river floodwater during the peak.

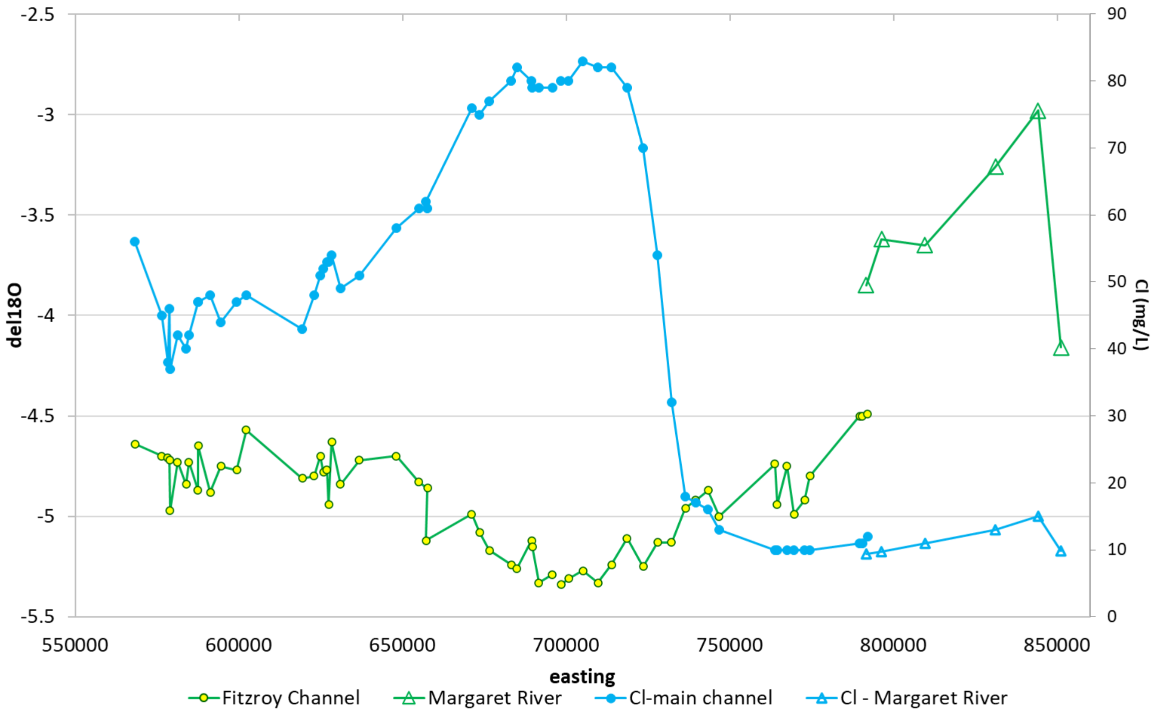


Figure 65 2017 δ^{18}O and Cl in river samples plotted by easting

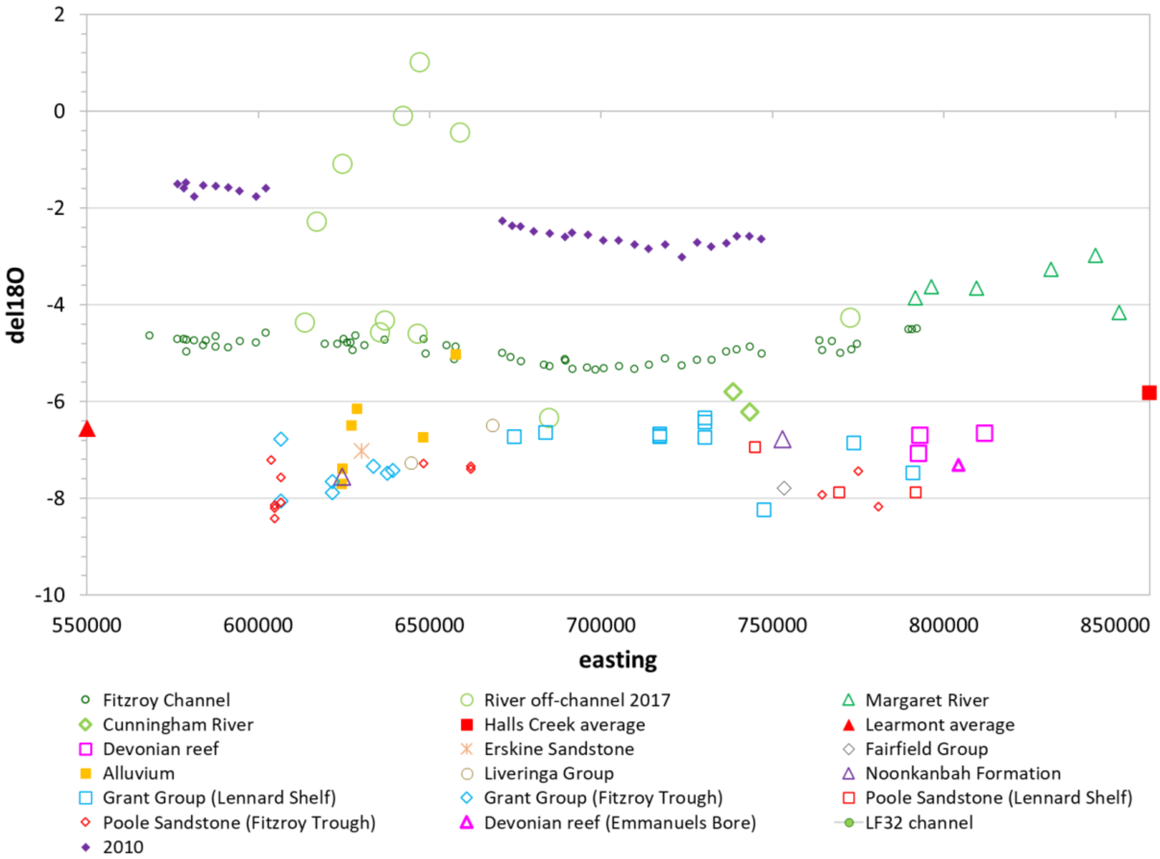


Figure 66 δ18O in river and groundwater samples in June 2017 and May 2010

Rainfall samples (Crosbie et al. 2012) are plotted at the edge of the figure and do not represent sampling locations).

Radon

Radon (^{222}Rn) was detected at every sampling location. Margaret River samples from June 2017 showed the highest ^{222}Rn concentrations. This could suggest either a higher proportion of groundwater input, or a naturally higher radon concentration in the source aquifer. Increased concentrations were also observed in the Fitzroy River's main channel above Fitzroy Crossing, and in a zone around Noonkanbah (Figure 67), also suggesting these are important groundwater inflow areas.

^{222}Rn concentrations measured downstream of Fitzroy Barrage were similar in 2017, 2015 and 2010 (Figure 67) and were about 0.2 Bq/L in 2008. The 2010 samples upstream of Noonkanbah showed a similar pattern to the high concentrations observed around Noonkanbah in 2017, which were also reported in 2008 (Doble et al. 2010).

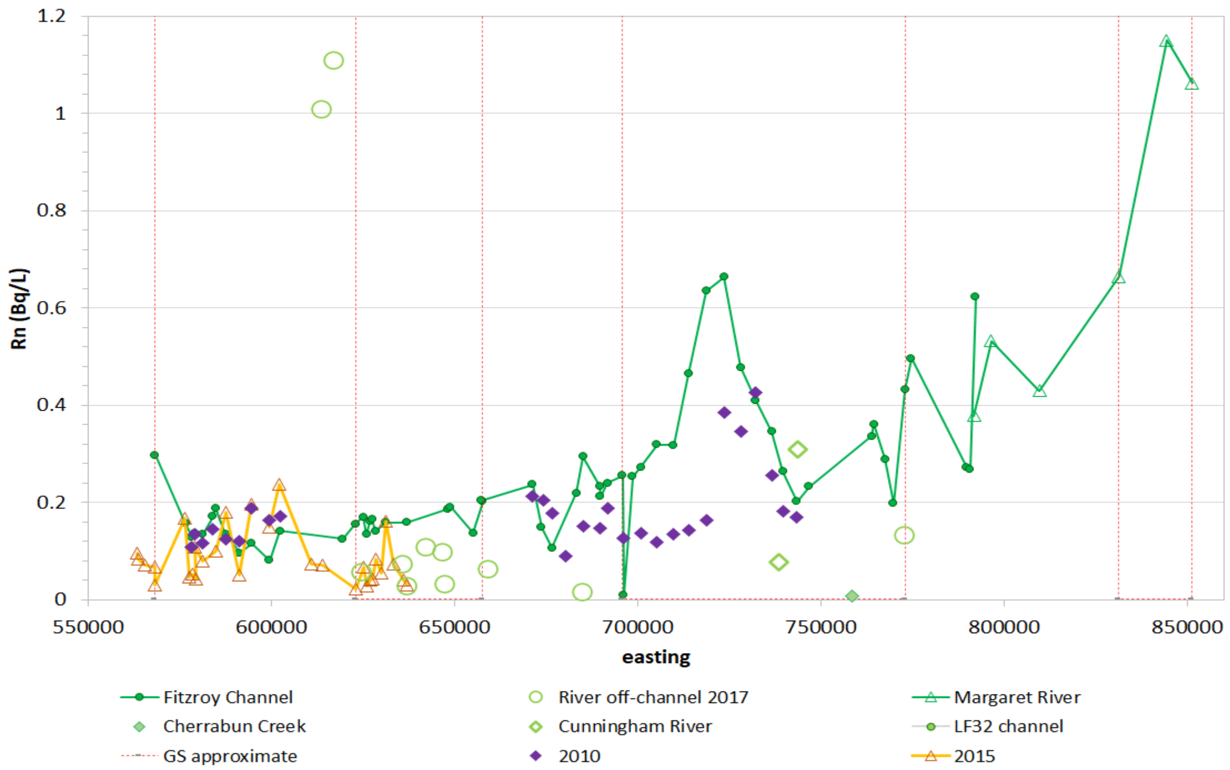


Figure 67 ^{222}Rn concentrations in 2017, 2015 and 2010

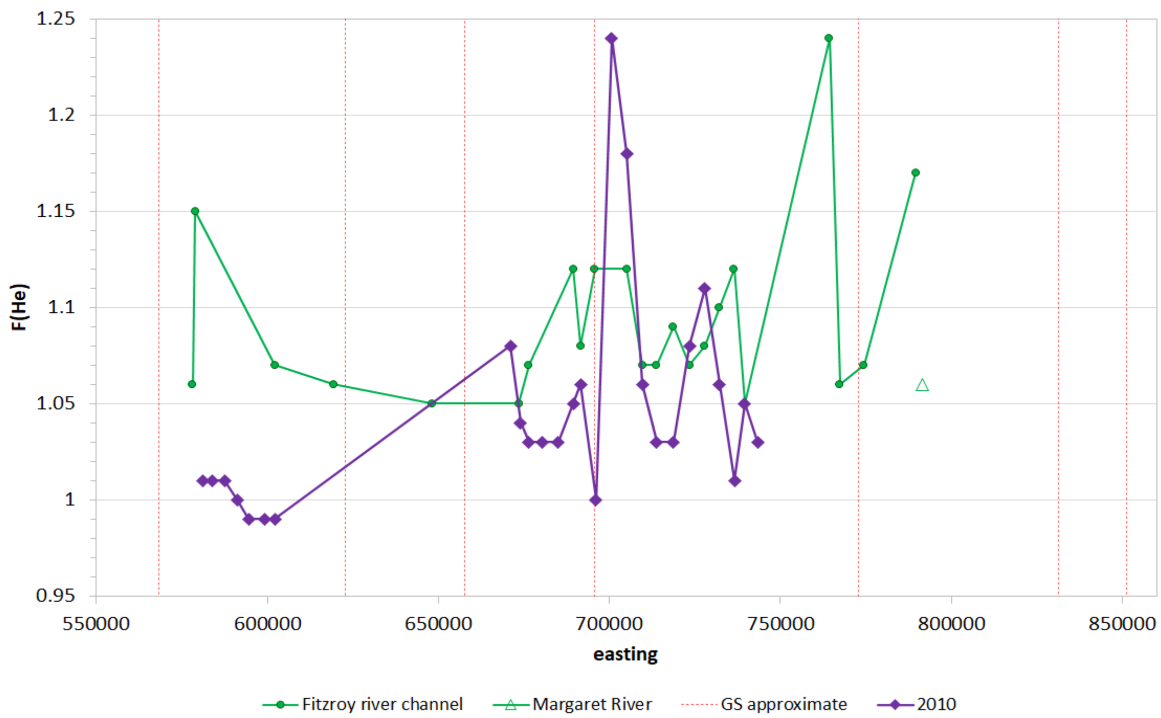


Figure 68 ^{4}He in 2017 and 2010 plotted by easting

Helium (^{4}He)

Figure 68 shows the fractionation factor of the ratio of ^{4}He/^{40}Ar in a water sample versus ^{4}He/^{40}Ar in air (^{4}He) in river samples in 2017 and 2010. Figure 69 shows ^{4}He in the groundwater and river samples plotted by easting. Despite different sampling methods and different flow rates at the time of sampling, all samples had elevated ^{4}He between Fitzroy Crossing and Noonkanbah gauging stations, and Noonkanbah and Fitzroy Barrage.

This supports the ^{222}Rn interpretation that these are significant groundwater input zones and suggests the source water is an older regional aquifer. In 2017, elevated ^{4}He above atmospheric was also observed upstream of Fitzroy Crossing near Geikie Gorge, and near Willare (sampling location LF05). This is where geological mapping suggests the Liveringa formation meets the Wallal Sandstone from the west and Blina Shale from the north-east.

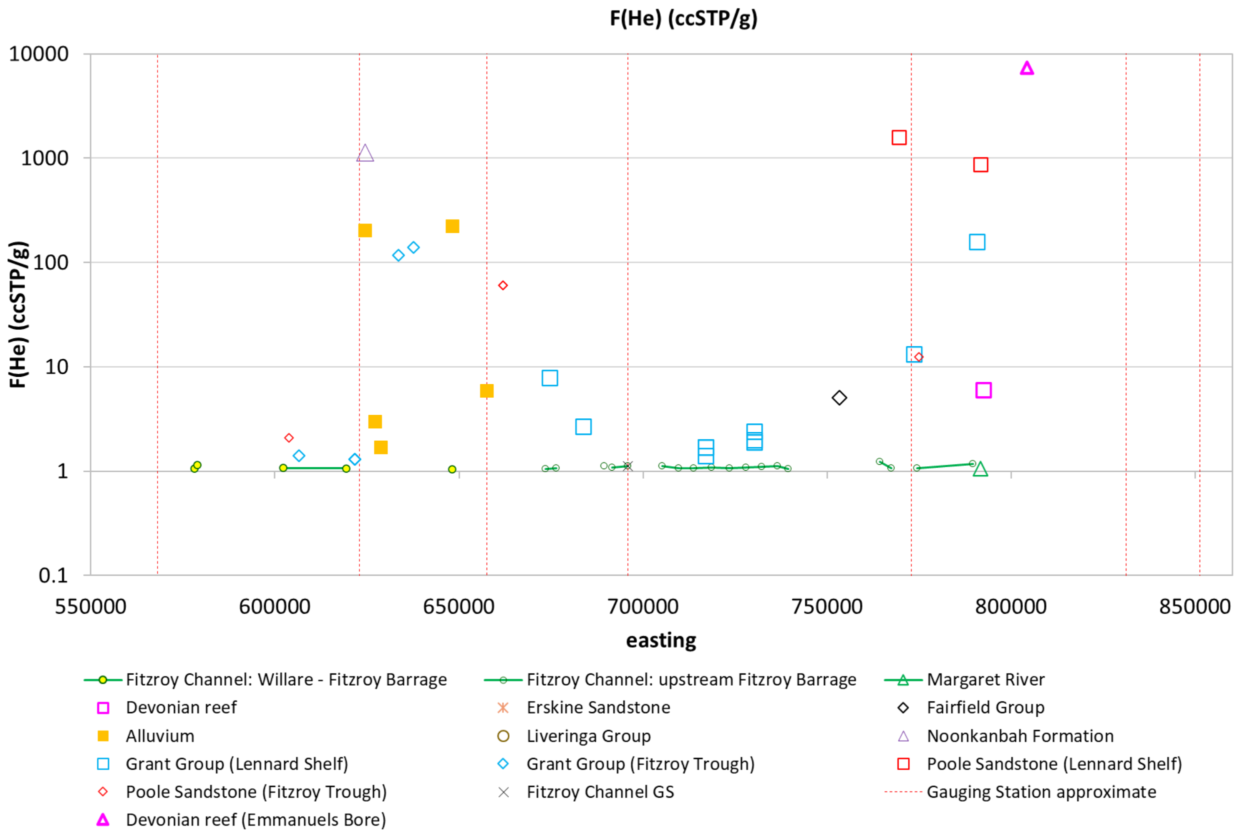


Figure 69 ^{4}He in groundwater and river samples plotted by easting

Nutrients and dissolved organic carbon

Dissolved organic carbon concentrations, measured as non-particulate organic carbon (NPOC), were highest in river samples between Fitzroy Crossing and Noonkanbah, co-incident with the zone of elevated Cl (Figure 70). TN and nitrate concentrations were orders of magnitude higher in groundwater than in river channel samples (Figure 70).

Ammonia, total kjeldahl nitrogen (TKN) and total phosphorus (TP) were measured in groundwater but not in surface water samples.

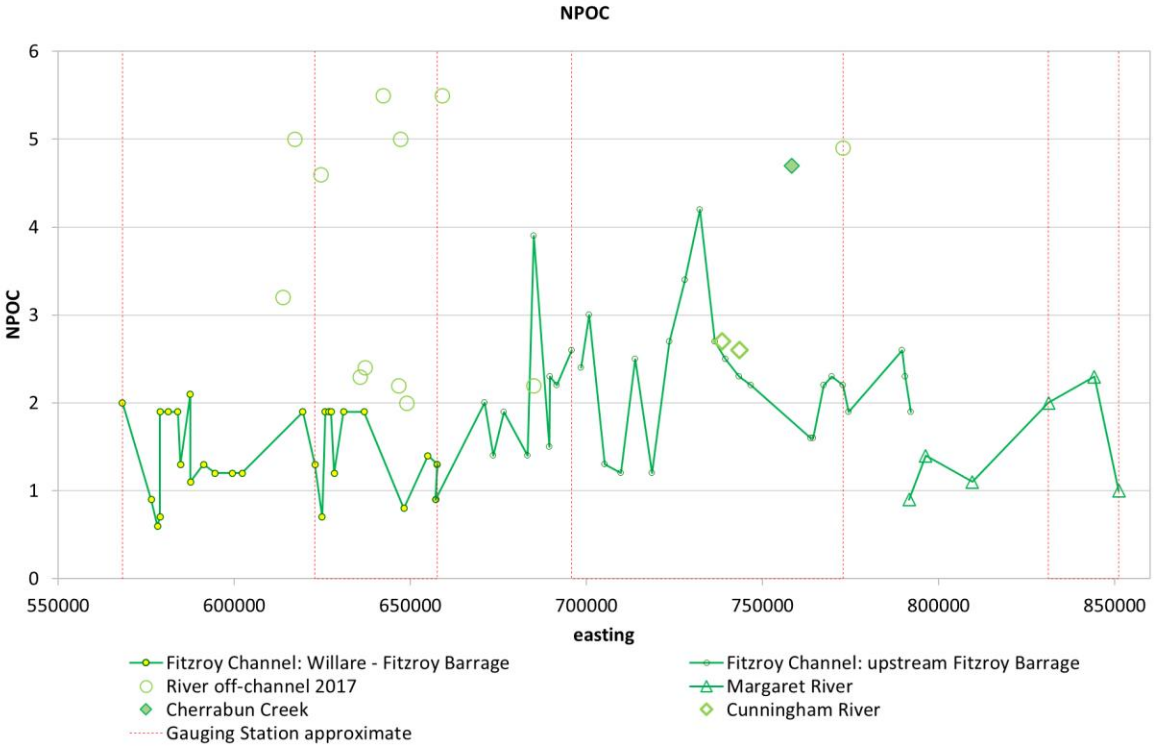


Figure 70 Non-particulate organic matter (June 2017) from main channel and off-channel samples

Concentrations of major ions and ^{222}Rn in off-channel samples were more variable than those in the main channel (Figure 57 and Figure 58). Water types from the off-channel samples differed from the main channel. For example, around Camballin some off-channel samples were $Ca\text{-}HCO_3$ or $Mg\text{-}HCO_3$ type, when the main channel was $Na\text{-}HCO_3$ (see Appendix L). In 2015 the stable isotopic signatures in many of the off-channel samples were more evaporated than the main channel (Figure 52), but their Cl was often lower (Figure 60). In many cases the organic carbon (Figure 70) and nitrogen species (Figure 71) concentrations were above those measured in the main channel.

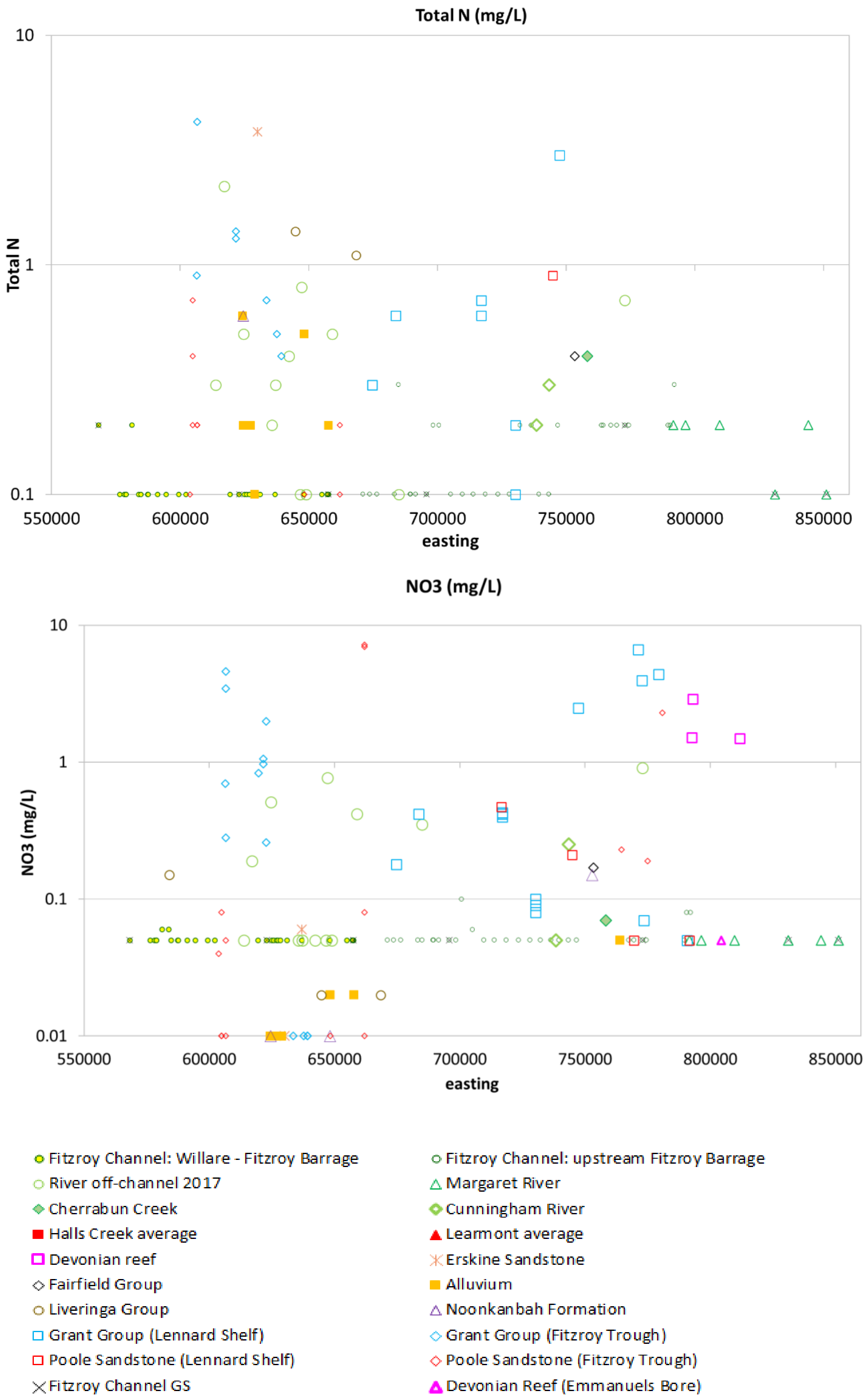


Figure 71 Total nitrogen and nitrate in river and groundwater samples

Samples below the detection limit are plotted as the detection limit.

5.3 Groundwater residence times

Groundwater residence times are fundamental to understanding groundwater flow paths and estimating recharge rates. For this study we calculated groundwater residence times for the Fitzroy River alluvial, Liveringa Group, Grant Poole and the Devonian reef aquifers, using different methods to account for the range of potential times. We used measured concentrations of chlorofluorocarbon (CFC) and tritium to determine short residence times (i.e. tens of years), and radiocarbon for longer residence times (i.e. thousands of years).

Specific yield – sometimes referred to as effective porosity – is required for determining groundwater residence times. We based the specific yield values for this study on the literature (rather than on measured values) and so these are the greatest source of uncertainty in our recharge estimates. We determined the following values using both Harrington and Harrington (2015) and Fetter (2001):

- Fitzroy River alluvium: 0.20
- Liveringa Group: 0.05
- Noonkanbah Formation: 0.02
- Grant Group and Poole Sandstone: 0.20
- Devonian reef: 0.20

5.3.1 Chlorofluorocarbon (CFC)

Table 13 presents groundwater residence times calculated using analysed CFC concentrations and validated using tritium. See Appendix R for more details on the methods used for the calculations.

We took CFC-derived groundwater residence times from measured concentrations of CFC-11 and CFC-12, following the methodology and equations taken from Chapter 3 of International Atomic Energy Agency (2016), *Use of chlorofluorocarbons in hydrology*.

We then calculated groundwater residence times using CFC-12 rather than CFC-11, consistent with the approach taken in Taylor et al. (2018). CFCs are stable under aerobic conditions, but they may degrade under anaerobic conditions. CFC-11 is more susceptible to this degradation than CFC-12.

Anoxic groundwater conditions and/or microbial decomposition may also consume CFCs, reducing their concentration and making the sample date seem older than it is. This appears to have occurred at sites LF01, 5/10 Fitzroy Crossing and Looma 1-93.

The tritium level in rainfall in the Fitzroy region is about 1.4 tritium units (TU), based on an Australian regional map of tritium in rainfall (Tadros et al. 2014). This compares with the highest groundwater tritium values, measured at bore LF01 (0.992 TU) and Birdwood Bore (0.943 TU). These high tritium concentrations show minimal degradation below the rainfall level has occurred, indicating relatively short residence times for groundwater in these aquifers.

The CFC-derived residence times reported in Taylor et al. (2018) were similar to this study.

No CFCs were detected in any confined aquifer samples; however, tritium was detected at One Tree Bore, which is screened in the confined Poole Sandstone.

Table 13 CFC-derived groundwater residence times

Bore ID	Sample date	Aquifer	Confined/unconfined	Depth (m bgl)	CFC-12 (pmol/kg)	+/-	CFC-12 residence time Years	Tritium (TU)	Tritium (+/-)
LF01	13/09/2017	Fitzroy River alluvium	Unconfined	15.5	0.04	0.07	59.5	0.992	0.031
LF01	20/08/2018	Fitzroy River alluvium	Unconfined	15.5	0.11	0.01	53.5	0.971	0.029
Birdwood Bore*	7/07/2016	Fitzroy River alluvium	Unconfined	16	1.31	0.05	10.0	0.943	0.023
BU15MB003	23/08/2018	Fitzroy River alluvium	Unconfined	24	1.05	0.04	26.5	0.556	0.023
BU15MB004	23/08/2018	Fitzroy River alluvium	Unconfined	25	0.19	0.01	49.5	0.547	0.023
Liveringa South	30/07/2017	Fitzroy River alluvium	Unconfined	33.7	0.09	0.06	53.5	0.268	0.016
LF05	21/08/2018	Fitzroy River alluvium	Unconfined	23	0.19	0.01	49.5	0.224	0.02
LF05	14/09/2017	Fitzroy River alluvium	Unconfined	23	0.04	0.02	60	0.061	0.019
LF03B	21/08/2018	Fitzroy River alluvium	Unconfined	12.5	-	-		0.058	0.018
LF04B	20/08/2018	Fitzroy River alluvium	Unconfined	17.5	-	-	-	0.054	0.017
LF02	20/08/2018	Fitzroy River alluvium	Unconfined	27	0.23	0.01	46.5	0.052	0.017
LF02	13/09/2017	Fitzroy River alluvium	Unconfined	27	0.29	0.02	43.5	0.035	0.024
BU15MB002A	23/08/2018	Fitzroy River alluvium	Unconfined	21.8	0.16	0.01	51.5	0.033	0.016
LF04B	13/09/2017	Fitzroy River alluvium	Unconfined	17.5	0.09	0.02	53	0.028	0.018
LF03B	14/09/2017	Fitzroy River alluvium	Unconfined	12.5	0.11	0.01	51.5	0.014	0.018
2-89 Mt Anderson*	7/09/2016	Liveringa Group	Unconfined	61.9	0.33	0.01	42.5	0.55	0.021
Irrigation Bore*	22/08/2018	Poole Sandstone	Unconfined	-	-	-	-	0.036	0.016
1-04 Camballin	16/05/2017	Poole Sandstone	Unconfined	33.5	0.04	0.01	59.5	0.028	0.015
Paradise Bore	22/06/2016	Poole Sandstone	Unconfined	13.1	< 0.16	NA	> 50	0.015	0.017
1-04 Camballin	30/08/2016	Poole Sandstone	Unconfined	33.5	< 0.16	NA	> 50	0.013	0.015
1-04 Camballin	21/08/2018	Poole Sandstone	Unconfined	33.5	0	NA	> 50	0.012	0.017
Paradise Bore	15/08/2017	Poole Sandstone	Unconfined	13.1	0.09	0.01	53.5	-0.004	0.016
Leos Bore*	31/07/2017	Grant Group	Unconfined	22.5	1.12	0.04	< 10	1.281	0.027
Thomas Bore*	29/07/2017	Grant Group	Unconfined	29.3	0.54	0.03	38	0.563	0.02
5/10 – Fitzroy Crossing*	29/06/2016	Grant Group	Unconfined	32	< 0.16	NA	> 50	0.349	0.02
Looma 1-93*	30/08/2016	Grant Group	Unconfined	59.2	< 0.16	NA	> 50	0.324	0.018
Looma 1-86	18/05/2017	Grant Group	Unconfined	52.6	0.06	0.01	57	0.132	0.016
Looma 1-86	22/06/2016	Grant Group	Unconfined	52.6	< 0.16	NA	> 50	0.129	0.018

Bore ID	Sample date	Aquifer	Confined/unconfined	Depth (m bgl)	CFC-12 (pmol/kg)	+/-	CFC-12 residence time Years	Tritium (TU)	Tritium (+/-)
2/89 – Fitzroy Crossing*	29/06/2016	Grant Group	Unconfined	43	0.21	0.01	47	0.122	0.018
Thomas Bore*	2/09/2016	Grant Group	Unconfined	29.3	< 0.16	NA	> 50	0.098	0.016
Gogo Station Homestead Bore 3A	4/07/2016	Grant Group	Unconfined	33	< 0.16	NA	> 50	0.003	0.014
Donalds Mill No.2*	4/07/2016	Grant Group	Unconfined	31	< 0.16	NA	NA	-0.001	0.013
BA04	1/07/2016	Devonian reef	Unconfined	14.7	< 0.16	NA	> 50	0.111	0.018
Bore	6/09/2016	Fairfield Group	Unconfined	33.1	0.2	0.01	47	-0.006	0.015
One Tree Bore No.2	3/07/2016	Poole Sandstone	Confined	110	< 0.16	NA	> 50	0.013	0.014
Huttons Bore No.2	2/07/2016	Poole Sandstone	Confined	47.5	< 0.16	NA	> 50	-0.004	0.018
Pilots Flowing Bore	2/07/2016	Poole Sandstone	Confined	36	< 0.16	NA	> 50	-0.011	0.013
Tank Bore No.2	3/07/2016	Poole Sandstone	Confined	69	< 0.16	NA	> 50	-0.014	0.013
Emanuels Flowing Bore	5/07/2016	Devonian reef	Confined	20.5	< 0.16	NA	> 50	-0.015	0.013
Acacia Tank Flowing Bore	4/07/2016	Grant Group	Confined	69	< 0.16	NA	> 50	-0.003	0.013

Note: * Bores not included in calculations for data quality reasons.

pmol/kg = picomole per kilogram

TU = tritium units

Depth of bore denotes middle of screen interval.

Grey highlights limits of reporting (CSIRO samples, lower LORs for samples analysed by GNS Science).

CFC-12 value for LF01 is unreliable, as the error +/- is greater than the apparent measured value. Also, CFC-12 likely degraded for LF01, biasing an older CFC-12 residence time. This is supported by the tritium data.

5.3.3 Radiocarbon

When applying radiocarbon age-dating to the groundwater, a correction model must be used to account for the addition of 'dead' carbon to the dissolved inorganic carbon pool. Understanding the groundwater system and the geochemical processes is necessary to select the right correction model. See Appendix R for further information on how we selected the most suitable correction model.

Table 14 compares various radiocarbon correction models. Two of them – the Tamers and Pearson models – correct for calcite dissolution, as well as for soil gas CO_2 dissolution. Information derived from major ion ratios (Section 5.2.2), saturation indices and carbon-13 indicate that carbonate weathering processes are occurring across all aquifers containing carbonate minerals that were sampled, and that calcite dissolution needs to be corrected for.

Both the Tamers and Pearson models produced similar residence times, and either model is likely suitable for interpretation of the data. While soil gas dissolution was not specifically identified as a process requiring correction, it is a common process and should be accounted for in most investigation areas, particularly if there is a range in thickness of unsaturated zones. For example, the unsaturated zone of the Liveringa Group aquifer ranges in thickness from around 3 m to more than 20 m (Figure 40).

Table 14 Radiocarbon correction models (IAEA 2013)

Chemical process	Vogel	Tamers	Pearson	Mook	Fontes and Garnier
Carbonate dissolution		✓	✓	✓	✓
Soil gas CO_2 dissolution		✓	✓	✓	✓
CO_2 gas: aqueous exchange				✓	✓
Calcite: HCO_3 exchange					✓
Gypsum dissolution					✓
Ca/Na cation exchange					✓

The Vogel method is based on data from north-western Europe and does not consider carbonate dissolution. The Mook model is more appropriate in systems where reactions with carbonate minerals are not dominant (IAEA 2013), which is *not* the case for this groundwater investigation. We did not select the Fontes and Garnier model because it considers additional geochemical processes that are not occurring in this system, such as gypsum dissolution. Neither did we choose the Tamers model because even though it might have been suitable, it does not include measured $\delta^{13}C$.

We selected the Pearson model (Ingerson & Pearson 1964) as the most appropriate correction model to calculate groundwater residence times for all samples collected in this study.

See Table 15 for the groundwater ages determined from radiocarbon data for all samples: both uncorrected and corrected using each of the five analytical correction models. The results show the range in residence times across the different correction models along with the conventional radiocarbon age (CRA).

The oldest residence times are reflected in the uncorrected residence times and the Vogel correction model. Residence times for the remaining analytical correction models are reasonably similar. This is because carbonate dissolution is the main chemical process requiring correction for each of these models, and the influence of other processes are not significant, not occurring or do not require correction.

Note that the Pearson model calculation includes measured $\delta^{13}C$ in the collected groundwater sample, which the Tamers model does not. The Pearson model was also used in Taylor et al. (2018), which includes the 2016 and 2017 samples collected as part of the CSIRO–Department of Water and Environmental Regulation project partnership discussed previously in this report.

Table 15 Radiocarbon-derived groundwater residence times and ages

Bore ID	Date	Aquifer	Project subarea	Confined/ unconfined	Screen	Bore depth	Conventional radiocarbon age (CRA)	Vogel	Tamers	Pearson	Fontes and Garner	Mook	Estimated residence time (yrs)	For recharge calculation (yrs)
Liveringa South+	30/07/2017	Fitzroy River alluvium	Fitzroy Trough	Unconfined	-	36.7	25,800	24,100	21,000	21,200	21,100	21,100	54	54
LF01	13/09/2017	Fitzroy River alluvium	Fitzroy Trough	Unconfined	13.0–18.0	20	1,500	Modern	Modern	Modern	Modern	Modern	59	59
LF02	13/09/2017	Fitzroy River alluvium	Fitzroy Trough	Unconfined	24.0–30.0	32	600	Modern	Modern	Modern	Modern	Modern	44	44
LF03B	14/09/2017	Fitzroy River alluvium	Fitzroy Trough	Unconfined	10.0–15.0	17	1,800	100	Modern	Modern	Modern	Modern	52	52
LF04B	13/09/2017	Fitzroy River alluvium	Fitzroy Trough	Unconfined	15.0–20.0	22	2,600	900	Modern	Modern	Modern	Modern	53	53
LF05	14/09/2017	Fitzroy River alluvium	Fitzroy Trough	Unconfined	21.0–25.0	27	5,300	3600	Modern	1200	900	700	60	60
Birdwood Bore*	7/07/2016	Fitzroy River alluvium	Fitzroy Trough	Unconfined	14.5–17.4	-	200	Modern	Modern	Modern	Modern	Modern	10	10
Garden Bore*	24/06/2016	Erskine Sandstone	Fitzroy Trough	Unconfined	-	20.4	5,400	3,700	4,900	3,500	3,500	4,100	3,500	3,500
Barefoot Bore	15/09/2017	Erskine Sandstone	Fitzroy Trough	Unconfined	-	-	2,000	300	100	Modern	Modern	Modern	50–300	150
Helens Bore*	4/09/2016	Liveringa Group	Fitzroy Trough	Unconfined	38.0–77.2	77.2	8,400	6,700	4,800	500	800	2,500	500	500
2-89 Mt Anderson*	7/09/2016	Liveringa Group	Fitzroy Trough	Unconfined	57.6–66.2	66.2	4,300	2,600	3,000	Modern	Modern	1,200	43	43
RRMW005D	17/08/2017	Liveringa Group	Fitzroy Trough	Unconfined	94.0–97.0	97	20,300	18,600	15,600	16,500	16,300	16,100	16,500	16,500
LF03A*	14/09/2017	Noonkanbah Formation	Fitzroy Trough	Unconfined	49.5–55.5	57.5	34,300	32,700	28,900	29,600	29,500	29,300	29,600	29,600
LF04A	12/09/2017	Noonkanbah Formation	Fitzroy Trough	Unconfined	51.0–57.0	60	42,900	41,300	37,800	38,200	38,100	38,100	38,200	38,200
Manta Ray Bore	6/07/2016	Noonkanbah Formation	Fitzroy Trough	Unconfined	17.6–35.3	-	7,300	5,600	2,500	3,400	3,200	3,000	3,400	3,400
Peglars Bore*	21/06/2016	Poole Sandstone	Fitzroy Trough	Unconfined	-	29	1,400	Modern	Modern	Modern	Modern	Modern	50–300	150
Peglars Bore*	18/05/2017	Poole Sandstone	Fitzroy Trough	Unconfined	-	29	1,800	100	Modern	Modern	Modern	Modern	50–300	150
Paradise Bore	15/08/2017	Poole Sandstone	Fitzroy Trough	Unconfined	12.6–13.5	26.5	11,800	10,100	7,300	6,800	6,800	7,000	5,600	5,600
Paradise Bore	22/06/2016	Poole Sandstone	Fitzroy Trough	Unconfined	12.6–13.5	26.5	10,800	9,100	6,400	5,600	5,600	5,900	6,800	6,800
Langs Bore*	16/05/2017	Poole Sandstone	Fitzroy Trough	Unconfined	-	54.8	9,000	7,300	5,200	4,900	4,900	5,000	3,400	3,400
Langs Bore*	26/06/2016	Poole Sandstone	Fitzroy Trough	Unconfined	-	54.8	8,800	7,100	4,700	3,400	3,400	3,900	4,900	4,900
1-04 Camballin	16/05/2017	Poole Sandstone	Fitzroy Trough	Unconfined	31.5–43.5	44	7,800	6,100	5,900	5,400	5,400	5,600	2,700	2,700
1-04 Camballin	30/08/2016	Poole Sandstone	Fitzroy Trough	Unconfined	31.5–43.5	44	7,000	5,300	3,400	2,700	2,700	3,000	5,400	5,400
Looma 1-86	18/05//2017	Grant Group	Fitzroy Trough	Unconfined	31.7–73.5	73.5	800	Modern	400	Modern	Modern	Modern	57	57
Looma 1-86	22/06/2016	Grant Group	Fitzroy Trough	Unconfined	31.7–73.5	73.5	1,200	Modern	300	Modern	Modern	Modern	50-300	150
Looma 1-93*	30/08/2016	Grant Group	Fitzroy Trough	Unconfined	38.2–80.2	80.2	0	Modern	Modern	Modern	Modern	Modern	50–300	150
Jarlmadangah 1-02	26/06/2016	Grant Group	Fitzroy Trough	Unconfined	31.7–91.7	92	6,500	4,800	1,300	2,600	2,300	2,100	2,600	2,600
Leos Bore*	31/07/2017	Grant Group	Fitzroy Trough	Unconfined	21.0–24.5	24.5	200	Modern	Modern	Modern	Modern	Modern	10	10
Leos Bore*	27/06/2016	Grant Group	Fitzroy Trough	Unconfined	21.0–24.5	24.5	100	Modern	Modern	Modern	Modern	Modern	50–300	150

Bore ID	Date	Aquifer	Project subarea	Confined/ unconfined	Screen	Bore depth	Conventional radiocarbon age (CRA)	Vogel	Tamers	Pearson	Fontes and Garner	Mook	Estimated residence time (yrs)	For recharge calculation (yrs)
Thomas Bore*	29/07/2017	Grant Group	Fitzroy Trough	Unconfined	-	31.3	5,200	3,500	800	1,400	1,200	1,200	38	38
Thomas Bore*	2/09/2017	Grant Group	Fitzroy Trough	Unconfined	-	31.3	600	Modern	Modern	Modern	Modern	Modern	1,400	1,400
LF07	12/09/2017	Grant Group	Fitzroy Trough	Unconfined	62.0–68.0	71	2,900	1,200	900	700	700	700	700	700
Blue Bush*	5/09/2016	Poole Sandstone	Lennard Shelf	Unconfined	-	36.6	2,900	1,200	1800	Modern	Modern	Modern	50–300	150
No. 8 Bore	30/06/2016	Poole Sandstone	Lennard Shelf	Unconfined	-	76.2	6,600	4,900	3,400	1,700	1,800	2,400	1700	1,700
Laurel Homestead Bore	30/06/2016	Grant Group	Lennard Shelf	Unconfined	-	61	1,600	Modern	Modern	Modern	Modern	Modern	50-1000	150
2/89–Fitzroy Crossing*	29/06/2016	Grant Group	Lennard Shelf	Unconfined	27.8–58.3	61.85	600	Modern	Modern	Modern	Modern	Modern	47	47
5/10–Fitzroy Crossing*	29/06/2016	Grant Group	Lennard Shelf	Unconfined	28.7–34.7	39	900	Modern	Modern	Modern	Modern	Modern	50–300	150
Donalds Mill No.2*	04/07/2016	Grant Group	Lennard Shelf	Unconfined	-	41.15	3,200	1500	Modern	Modern	Modern	Modern	300–1,000	150
Gogo Station Homestead Bore 3A	04/07/2016	Grant Group	Lennard Shelf	Unconfined	24.8–36.58	38.1	13,800	12,100	8,500	8,100	8,100	8,300	8,100	8,100
BS16MB001A	03/07/2017	Grant Group	Lennard Shelf	Unconfined	80.0–90.0	96	4,400	2,700	1,300	800	900	1,000	800	800
BS16MB001B	02/07/2017	Grant Group	Lennard Shelf	Unconfined	55.4–58.4	58.4	4,300	2,600	1,100	1,100	1,100	1,100	1,100	1,100
BS16MB001C	02/07/2017	Grant Group	Lennard Shelf	Unconfined	37.5–40.5	40.5	3,900	2,200	700	400	400	500	400	400
BS16MB003A	04/07/2017	Grant Group	Lennard Shelf	Unconfined	96.0–118.0	118	3,600	1,900	Modern	Modern	Modern	Modern	50–300	150
BS16MB003B	04/07/2017	Grant Group	Lennard Shelf	Unconfined	86.0–92.0	92	3,300	1,600	Modern	Modern	Modern	Modern	50–300	150
BS16MB003C	04/07/2017	Grant Group	Lennard Shelf	Unconfined	72.3–78.3	78.3	3,300	1,600	Modern	Modern	Modern	Modern	50–300	150
KD16MB002	05/07/2017	Grant Group	Lennard Shelf	Unconfined	100.0–118.0	120	8,700	7,000	5,800	5,400	5,400	5,600	5,400	5,400
KD16MB003	05/07/2017	Grant Group	Lennard Shelf	Unconfined	38.0–50.0	52	3,900	2,200	1,300	1,700	1,600	1,500	1,700	1,700
Bore	06/09/2016	Fairfield Group	Lennard Shelf	Unconfined	32.1–35.2	40.3	2,800	11,00	Modern	Modern	Modern	Modern	300–1,000	500
BA04	01/07/2016	Devonian reef	Lennard Shelf	Unconfined	11.7–18.0	20	1,300	Modern	Modern	Modern	Modern	Modern	50–300	150
PT4	01/07/2016	Devonian reef	Lennard Shelf	Unconfined	-	107	2,400	700	Modern	Modern	Modern	Modern	300–1,000	500
Sallys Bore	05/07/2016	Devonian reef	Lennard Shelf	Unconfined	-	-	900	Modern	Modern	Modern	Modern	Modern	10	10
LF06	12/09/2016	Poole Sandstone	Fitzroy Trough	Confined	93.0–99.0	102	8,200	6,500	5,000	4,700	4,700	4,800	4,700	4,700
Huttons Bore No.2	02/07/2016	Poole Sandstone	Lennard Shelf	Confined	38.6–56.6	-	17,100	15,400	12,900	13,700	13,500	13,400	13,700	13,700
One Tree Bore No.2	03/07/2016	Poole Sandstone	Lennard Shelf	Confined	89.0–131.0	-	21,000	19,400	15,500	18,100	17,500	17,100	18,100	18,100
Tank Bore No.2	03/07/2016	Poole Sandstone	Lennard Shelf	Confined	54.0–84.0	-	32,500	30,800	27,000	28,800	28,400	28,100	28,800	28,800
Chestnut Bore	06/07/2016	Poole Sandstone	Lennard Shelf	Confined	-	182.9	32,800	31,100	27,200	28,900	28,500	28,200	28,900	28,900
Pilots Flowing Bore	02/07/2016	Poole Sandstone	Lennard Shelf	Confined	-	-	39,300	37,700	34,100	35,500	35,200	35,000	35,500	35,500
Acacia Tank Flowing Bore	04/07/2016	Grant Group	Lennard Shelf	Confined	-	-	392,00	37,500	34,200	33,600	33,600	33,800	33,600	33,600

Bore ID	Date	Aquifer	Project subarea	Confined/ unconfined	Screen	Bore depth	Conventional radiocarbon age (CRA)	Vogel	Tamers	Pearson	Fontes and Garner	Mook	Estimated residence time (yrs)	For recharge calculation (yrs)
Shovelton	03/08/2017	Grant Group	Fitzroy Trough	Confined	515.0–545.0	549	33,600	31,900	28,800	28,600	28,600	28,700	28,600	28,600
Agricon 1**	03/08/2017	Grant Group	Fitzroy Trough	Confined	537.0–545.0	600	46,700	45,000	41,900	40,400	40,500	41,100	40,400	40,400
Agricon 3**	02/08/2017	Grant Group	Fitzroy Trough	Confined	400.0–588.0	588	39,300	37,600	34,500	33,700	33,700	34,000	33,700	33,700
Emanuels Flowing Bore	05/07/2016	Devonian reef	Lennard Shelf	Confined	-	-	38,900	37,200	33,400	21,600	22,700	28,500	21,600	21,600

+ Liveringa South not included in radiocarbon dating calculations because screen interval is unknown.

* Bores excluded from calculations for data quality reasons.

** Long open holes, former irrigation bores, installed in 1971.

300 years has been selected as the conservative value for estimated residence times with a range from 50–300 years.

1,000 years has been selected as the conservative estimated residence time for those samples with a range from 300–1,000 years.

5.3.4 Helium (^4He)

We used ^4He data to support the radiocarbon-derived groundwater residence times and to indicate any older regional sources of potential groundwater leakage.

As ^4He is a noble gas, it is not typically subject to interference from geochemical conditions. If sampling protocols are followed, and the water samples do not contain elevated levels of carbon dioxide or other gases, it provides a robust guide to support interpreting residence times.

Taylor et al. (2018) documents the data in more detail. The key points are:

- The radiocarbon residence times for the Fitzroy River alluvial aquifer were all generally modern, and below the limits of certainty for the radiocarbon dating technique. However, the data from the Fitzroy River alluvial aquifer groundwater samples taken from LF03B and LF04B has ^4He concentrations that indicate a component of older groundwater. This older recharge water is likely sourced through the underlying Noonkanbah Formation via fault conduits.
- The results of the ^4He data align with the radiocarbon residence times for older groundwater, where samples with higher ^4He concentrations correlated with higher radiocarbon residence times. This is particularly evident for the confined aquifer groundwater samples.
- Low ^4He concentrations were detected for unconfined groundwater samples, with minor exceptions, confirming younger, rainfall-recharged groundwater with little to no older groundwater input.
- As expected, the ^4He concentrations in groundwater in the deeper aquifers (Figure 69) are orders of magnitude higher than in the river. Considerable concentrations were also found in some alluvial bores, but whether this indicates connection to regional groundwater systems or long residence times in low-conductivity layers in the alluvial aquifer itself, requires further investigation.

5.3.5 Estimates of groundwater residence times

Table 15 lists the groundwater residence times estimated from radiocarbon for all the groundwater samples collected for this study. By aquifer the times are:

- Fitzroy River alluvial aquifer: 10 to 60 years
- Grant Group aquifer: 10 to > 30,000 years
- Poole Sandstone aquifer: 150 to > 35,000 years
- Fairfield Group: 500 years
- Devonian reef aquifer: > 3,500 years
- Liveringa Group aquifer: > 16,000 years

Some samples were considered compromised, re-flagged in Table 15 and excluded from recharge calculations. These estimates are provided as a range where appropriate, and are based on the following principles and assumptions:

- Where CFC is detected (and has not been removed due to data quality issues), the CFC residence time is used.
- Where CFC is not detected (or was not sampled) and tritium is detected and radiocarbon residence time is modern, an estimated residence time of 50 to 300 years is estimated, based on approximate dating ranges of CFC and tritium.
- Where CFC and tritium are not detected, and radiocarbon residence time is modern, a range of 300 to 1,000 years is estimated, based on approximate dating ranges of CFC, tritium and radiocarbon.
- Where CFC and tritium are not detected, and radiocarbon residence time is not modern, the Pearson-corrected residence time is used.
- At LF07 and the Laurel Homestead Bore, CFCs were not sampled, and both samples recorded higher levels of tritium. On the basis that it is unknown if CFCs are present, the estimated residence time range was extended to 50 to 1,000 years for these samples.

Table 15 includes a column entitled '*For recharge calculation*', where 300 years has been selected as the conservative value for estimated residence times with a range from 50 to 300 years, and 1,000 years has been selected as the conservative estimated residence time for those samples with a range from 300 to 1,000 years.

These numbers were used to calculate the recharge rates in Chapter 6.

Fitzroy River alluvial aquifer

Results for groundwater residence times for most radiocarbon samples taken from the Fitzroy River alluvial aquifer determined the groundwater was modern and aligned with direct rainfall and flood water recharge. Exceptions were samples from Liveringa South bore, where a long residence time of 21,200 years was recorded (Table 15), and LF05, where a residence time of 1,200 years was recorded (note this is below the general limits of reliability for the radiocarbon residence time, which is about 2,000 years).

Both CFCs and radiocarbon were detected in groundwater from Liveringa South bore, suggesting a mixture of waters with different residence times. Older groundwater at this bore could be the result of restricted flow rates caused by the alluvium being more clay-rich in this area, which is supported by the high gamma readings from the downhole log for the Liveringa South bore (Appendix A). Older groundwater may be present where faulting occurs and acts as a conduit for groundwater flow from deeper, older regional aquifers; however, there are no known faults near this bore.

Erskine Sandstone, Liveringa Group and Noonkanbah Formation aquifers

Samples taken from the recharge area of the Erskine Sandstone aquifer where it outcrops on the northern part of Liveringa Station (Barefoot Bore) and Myroodah Station (Garden Bore) recorded short residence times (Table 15). Longer residence times were recorded for samples taken from the aquitard units of both the Noonkanbah Formation (38,200 years at LF04A) and the Liveringa Group (16,500 years at RRMW005D). A shorter residence time was recorded in the shallower part of the Noonkanbah Formation at Manta Ray Bore.

In the Liveringa Group a shorter residence time was also observed at the 2-89 Mt Anderson bore. In this instance it is unclear whether this result indicates recharge into the Liveringa Group, or whether frequent pumping from the nearby Balginjirr Aboriginal community water supply bore is drawing in more modern groundwater from other sources.

Grant Poole aquifer – Fitzroy Trough

Modern groundwater residence times were recorded where the Grant Group and Poole Sandstone outcrop in the Camballin region (Looma 1-86, Looma 1-93 and Peglars Bore).

However, another sample taken from this outcrop area (Paradise Bore) returned a significantly longer groundwater residence time of about 6,800 years. Paradise Bore is situated in the north-eastern part of the Grant Group and Poole Sandstone outcrop area.

Repeat sampling for radiocarbon identified at least some degree of modern groundwater recharge following the 2016–17 wet season at a number of bores – Paradise Bore, Langs Bore, 1-04 Camballin and Thomas Bore. These bores were all sampled in both 2016 and 2017, and all recorded shorter residence times in 2017.

Grant Poole and Devonian reef aquifers – Lennard Shelf

Groundwater residence times in the unconfined Grant Group, Poole Sandstone and Devonian reef aquifers on the Lennard Shelf were typically short, indicating a recharge area for these aquifers.

However, longer groundwater residence times were recorded at two sites in the Grant Group: Gogo Station Homestead Bore 3A (8,100 years) and KD16MB002 (5,400 years). The longer residence time at KD16MB002 is consistent with the greater depth of these bores, screened 100 m below ground level.

The explanation for the older water in the Gogo Station Homestead Bore 3A is less apparent. It is screened at a relatively shallow depth so, unlike KD16MB002, the older age of the groundwater cannot necessarily be attributed to the depth of the bore. Unfortunately, no logging information for the bore is available, so it cannot be determined whether this longer groundwater residence time is related to lithology. There is a possibility that upward discharge of deeper, older water is mixing with younger water. No CFCs were detected in the bore, but very low levels of tritium were recorded, indicating the presence of at least some modern recharge water.

Groundwater residence times for the confined aquifer bores in the Poole Sandstone and Devonian reef aquifers were generally much higher than those for the unconfined bores.

The shortest groundwater residence time for the confined aquifer bores was from the Poole Sandstone LF06 (4,700 years), which is situated very close to the unconfined Grant Group and Poole Sandstone aquifer. The longest residence time in this study was recorded at Agricon 1 (Table 15), which is also the deepest bore in the study.

6 Groundwater recharge discussion

In this chapter we present regional groundwater recharge estimates for the Fitzroy River alluvial aquifer, and the Liveringa, Noonkanbah Formation, Grant Group and Poole Sandstone aquifers.

These recharge estimates are based on chloride mass balance and groundwater residence times derived from CFC, tritium and radiocarbon analysis (see Section 5.3).

We present and discuss the results of each method. Note that because a different number of samples was available for each method, we used the median groundwater recharge across all samples from all applicable methods as a way to arrive at a regional recharge estimate for an aquifer. Where multiple samples were taken from the same bore, we took an average of those samples to avoid biasing the overall median to bores with multiple samples. Also, because the Grant Group and Poole Sandstone aquifers are managed as a single aquifer, we have combined their estimates in the overall recharge assessment.

The methods balance different assumptions, parameters, limitations and timescales to provide the most robust analytical assessment of recharge based on available data. However, there are some limitations in applying each of these different methods (see Appendix R).

6.1 Chloride mass balance

We calculated chloride mass balance (CMB)-derived recharge rates for the unconfined areas of the Liveringa Group, Noonkanbah Formation, Grant Group and Poole Sandstone and the Devonian reef aquifers (Table 16). Appendix R details the equations and assumptions of this method.

We did not use CMB for the Fitzroy River alluvial aquifer or for the confined aquifers. A key component of the Fitzroy River alluvial aquifer's recharge originates from flooding of the river. It is also an intermittent discharge zone. This means an underlying assumption of this method (that chloride in groundwater is only sourced from rainfall) is not valid.

Similarly, for the confined aquifers, the assumption that chloride is only sourced from rainfall may not be true, as additional chloride may be input through groundwater leakage and diffusion from confining units (such as the Liveringa Group and Noonkanbah Formation). For this reason, neither Taylor et al. (2018) nor this study used CMB to estimate recharge for the confined aquifers.

We calculated steady-state CMB recharge estimates using a chloride-in-rainfall level of 0.46 mg/L, equivalent to the concentration of chloride in rainfall at Halls Creek from Crosbie et al. (2012). The chloride-in-groundwater values for this study were all derived from sampling undertaken from 2016 to 2018.

We used annual average rainfall calculated from long-term records from multiple rainfall stations (see Table 1, Section 2.4) to reflect the south-to-north rainfall gradient across the catchment.

In general, the Liveringa Group and the Noonkanbah Formation aquifers had the lowest recharge rates according to the CMB method, and the unconfined Grant Group and Devonian reef aquifers had the highest.

Groundwater samples from the Grant Group unit of the Grant Poole aquifer were collected across two of these rainfall zones: the Mt Anderson and Liveringa stations and the Fitzroy Crossing, Gogo and Brooking Springs stations.

Calculated average recharge rates were significantly lower in the Mt Anderson and Liveringa rainfall zone (6.9 mm/year) than in the Fitzroy Crossing, Gogo and Brooking Springs rainfall zone, which averaged about 12.3 mm/year.

The results of the CMB recharge analysis undertaken for this study are broadly consistent with those of Taylor et al. (2018), which used an average annual spatial chloride deposition (kg/ha/year) map (Davies & Crosbie 2014; Crosbie et al. 2018) instead of an estimate of chloride in rainfall.

This study estimated that CMB recharge ranged from 1.88 mm to 7.13 mm/year for the unconfined Poole Sandstone unit of the Grant Poole aquifer; from 2.07 to 7.13 mm/year for the unconfined Grant Group unit of the Grant Poole aquifer; and from 25.21 to 37.72 mm/year for the Devonian reef aquifer.

Table 16 Chloride mass balance (CMB) recharge

Bore ID	Date	Aquifer	Rainfall recharge zone	Average annual rainfall (mm/year)	Groundwater level (m btoc)	Screen (m bgl)	Bore depth (m btoc)	Chloride (mg/l)	Recharge (mm/year)
Helens Bore*	4/09/2016	Liveringa Group	Mount Anderson and Liveringa Station	660	6.97	38.0–77.2	77.2	3760	0.07
2/89 Fitzroy Crossing*	7/09/2016	Liveringa Group	Mount Anderson and Liveringa Station	660	11.55	57.6–66.16	66.2	133	4.99
RRMW005D	17/08/2017	Liveringa Group	Mount Anderson and Liveringa Station	660	20.04	94.0–97.0	97	1460	0.19
LF03A*	14/09/2017	Noonkanbah Formation	Mount Anderson and Liveringa Station	660	7.69	49.5–55.5	57.5	410	0.66
LF04A	12/09/2017	Noonkanbah Formation	Mount Anderson and Liveringa Station	660	5.25	51.0–57.0	60	509	0.53
Manta Ray Bore	6/07/2016	Noonkanbah Formation	Fitzroy Crossing, Gogo, Brooking Springs	590	17.6	17.6–35.3	-	1215	0.19
Peglars Bore*	21/06/2016	Poole Sandstone	Mount Anderson and Liveringa Station	660	17.1	-	29	268	1.01
Peglars Bore*	18/05/2017	Poole Sandstone	Mount Anderson and Liveringa Station	660	16.51	-	29	293	0.92
Paradise Bore	22/06/2016	Poole Sandstone	Mount Anderson and Liveringa Station	660	7.67	12.6–13.5	26.5	116	2.34
Paradise Bore	15/08/2017	Poole Sandstone	Mount Anderson and Liveringa Station	660	6.44	12.6–13.5	26.5	117	2.32
Montgomery Bore	23/06/2016	Poole Sandstone	Mount Anderson and Liveringa Station	660	9.97	-	42.7	61	4.44
Langs Bore	26/06/2016	Poole Sandstone	Mount Anderson and Liveringa Station	660	11.1	-	54.8	131	2.07
Langs Bore	16/05/2017	Poole Sandstone	Mount Anderson and Liveringa Station	660	-	-	54.8	144	1.88
1-04 Camballin	30/08/2016	Poole Sandstone	Mount Anderson and Liveringa Station	660	5.95*	31.5–43.5	44	38	7.13
1-04 Camballin	16/05/2017	Poole Sandstone	Mount Anderson and Liveringa Station	660	5.95*	31.5–43.5	44	49	5.53
Blue Bush*	5/09/2016	Poole Sandstone	Fitzroy Crossing, Gogo, Brooking Springs	590	-	-	36.6	22	10.22
Looma 1-86	22/06/2016	Grant Group	Mount Anderson and Liveringa Station	660	14.45*	31.7–73.5	73.5	18	15.05
Looma 1-86	18/05/2017	Grant Group	Mount Anderson and Liveringa Station	660	14.45*	31.7–73.5	73.5	17	15.94
Looma 1-93*	30/08/2016	Grant Group	Mount Anderson and Liveringa Station	660	8.59*	38.2–80.2	80.2	8	33.87
Leos Bore*	27/06/2016	Grant Group	Mount Anderson and Liveringa Station	660	21.42	21.0–24.5	24.5	13	20.84
Leos Bore*	31/07/2017	Grant Group	Mount Anderson and Liveringa Station	660	11.7	21.0–24.5	24.7	23	11.78

Bore ID	Date	Aquifer	Rainfall recharge zone	Average annual rainfall (mm/year)	Groundwater level (m btoc)	Screen (m bgl)	Bore depth (m btoc)	Chloride (mg/l)	Recharge (mm/year)
Jarlmadangah 1-02	26/06/2016	Grant Group	Mount Anderson and Liveringa Station	660	20.5*	31.7–91.7	92	17	15.94
Thomas Bore*	2/09/2016	Grant Group	Mount Anderson and Liveringa Station	660	12.3	-	31.3	66	4.11
Thomas Bore*	29/07/2017	Grant Group	Mount Anderson and Liveringa Station	660	6.77	-	31.3	916	0.30
LF07	12/09/2017	Grant Group	Mount Anderson and Liveringa Station	660	40.27	62.0–68.0	71	17	15.94
Laurel Homestead Bore	30/06/2016	Grant Group	Fitzroy Crossing, Gogo, Brooking Springs	590	-	-	61	34	6.62
2/89–Fitzroy Crossing*	29/06/2016	Grant Group	Fitzroy Crossing, Gogo, Brooking Springs	590	24.9	27.8–58.3	61.85	45	4.99
5/10–Fitzroy Crossing*	29/06/2016	Grant Group	Fitzroy Crossing, Gogo, Brooking Springs	590	11.16	28.7–34.7	39	43	5.23
No. 8 Bore	30/06/2016	Poole Sandstone	Fitzroy Crossing, Gogo, Brooking Springs	590	-	-	76.2	44	5.11
Donalds Mill No.2*	4/07/2016	Grant Group	Fitzroy Crossing, Gogo, Brooking Springs	590	-	-	41.15	184	1.22
Gogo Station Homestead Bore 3A	4/07/2016	Grant Group	Fitzroy Crossing, Gogo, Brooking Springs	590	12.68	24.8–36.58	38.1	328	0.69
BS16MB001A	3/07/2017	Grant Group	Fitzroy Crossing, Gogo, Brooking Springs	590	27.87	80.0–90.0	96	29	7.72
BS16MB001B	2/07/2017	Grant Group	Fitzroy Crossing, Gogo, Brooking Springs	590	28.27	55.4–58.4	58.4	30	7.56
BS16MB001C	2/07/2017	Grant Group	Fitzroy Crossing, Gogo, Brooking Springs	590	28.44	37.5–40.5	40.5	29	7.64
BS16MB003A	4/07/2017	Grant Group	Fitzroy Crossing, Gogo, Brooking Springs	590	-	96.0–118.0	118	17	13.55
BS16MB003B	4/07/2017	Grant Group	Fitzroy Crossing, Gogo, Brooking Springs	590	62.49	86.0–92.0	92	16	14.44
BS16MB003C	4/07/2017	Grant Group	Fitzroy Crossing, Gogo, Brooking Springs	590	62.55	72.3–78.3	78.3	17	13.36
KD16MB002	5/07/2017	Grant Group	Kimberley Downs	670	20.05	100.0–118.0	120	23	13.59
KD16MB003	5/07/2017	Grant Group	Kimberley Downs	670	26.14	38.0–50.0	52	29	10.5
Bore	6/09/2016	Fairfield Group	Fitzroy Crossing, Gogo, Brooking Springs	590	16.57	32.1–35.2	40.3	76	2.96
BA04	1/07/2016	Devonian reef complex	Fitzroy Crossing, Gogo, Brooking Springs	590	6.09	11.7–17.98	20	6	37.72
PT4	1/07/2016	Devonian reef complex	Fitzroy Crossing, Gogo, Brooking Springs	590	8.62	-	107	7.7	29.22
Sallys Bore	5/07/2016	Devonian reef complex	Fitzroy Crossing, Gogo, Brooking Springs	590	flowing spring	-	-	8.9	25.21

* Data not included in calculations for data quality reasons.

6.2 CFC and tritium

We used CFC-12 to assess groundwater recharge rates for 15 unconfined aquifer samples (Table 17), located predominantly in the Fitzroy River alluvium. We calculated the groundwater recharge rates according to the International Atomic Energy Agency (IAEA) (2006) method for an unconfined aquifer of constant thickness, as detailed in Appendix Q.

Calculated groundwater recharge rates for the Fitzroy River alluvial aquifer ranged between 49 mm/year (LF03B) and 181 mm/year (BU15MB003). Higher recharge rates, resulting from more modern recharge water in the sample, are consistent with higher tritium levels. These results could indicate significant bank recharge and/or overbank flooding.

Interestingly, we did not observe this relationship at bore LF01, which had one of the lowest recharge rates calculated, despite high levels of tritium suggesting a high proportion of modern recharge water. LF01 was re-sampled in August 2018. This gave equivalent results to the data obtained in 2017. The results may indicate some CFC-12 degradation is taking place.

Table 17 CFC groundwater recharge rates

Bore ID	Sample date	Aquifer	GW level (m bgl)	Screen (m bgl)	Recharge rate derived from CFC-12 (mm/year)	Tritium (TU)	Tritium +/-
LF01	13/09/2017	Fitzroy River alluvium	8.2	13.0–18.0	52	0.992	0.031
LF01	20/08/2018	Fitzroy River alluvium	8.5	13.0–18.0	58	0.971	0.029
Birdwood Bore*	7/07/2016	Fitzroy River alluvium	10.12	14.5–17.4	320	0.943	0.023
BU15MB003	23/08/2018	Fitzroy River alluvium	11.76	21.0–27.0	181	0.556	0.023
BU15MB004	23/08/2018	Fitzroy River alluvium	10.36	22.0–28.0	101	0.547	0.023
Liveringa South	30/07/2017	Fitzroy River alluvium	2.14	30.7–36.7	126	0.268	0.016
LF05	14/09/2017	Fitzroy River alluvium	7.73	21.0–25.0	77	0.061	0.019
LF05	21/08/2018	Fitzroy River alluvium	7.85	21.0–25.0	93	0.224	0.02
LF02	13/09/2017	Fitzroy River alluvium	7.04	24.0–30.0	124	0.035	0.024
LF02	20/08/2018	Fitzroy River alluvium	7.03	24.0–30.0	116	0.052	0.017
BU15MB002A	23/08/2018	Fitzroy River alluvium	8.82	19.8–23.8	85	0.033	0.016
LF04B	13/09/2017	Fitzroy River alluvium	5.88	15.0–20.0	66	0.028	0.018
LF03B	14/09/2017	Fitzroy River alluvium	5.48	10.0–15.0	49	0.014	0.018
2-89 Mt Anderson*	7/09/2016	Liveringa Group	11.55	57.6–66.2	73	0.55	0.021
1-04 Camballin	16/05/2017	Poole Sandstone	5.95	31.5–43.5	84	0.013	0.015
1-04 Camballin	21/08/2018	Poole Sandstone	5.95	31.5–43.5	-	0.012	0.017
Leos Bore*	31/07/2017	Grant Group	11.7	21.0–24.5	338	1.281	0.027
Looma 1-86	18/05/2017	Grant Group	14.45	31.7–73.5	138	0.129	0.018
2/89 – Fitzroy Crossing*	29/06/2016	Grant Group	24.9	27.8–58.3	137	0.122	0.018
Thomas Bore*	29/07/2017	Grant Group	6.77	26.3–31.3	116	0.098	0.016

* Bores not included in calculations for data quality reasons

6.3 Radiocarbon

6.3.1 Unconfined Grant Poole and Devonian reef aquifers

We calculated recharge estimates for the unconfined aquifers using radiocarbon-derived groundwater residence times, following the exponential flow model documented in Cook and Bohlke (2000).

We determined recharge rates across both aquifer and aquitard units within the study area, but did not use radiocarbon-derived residence times for the Fitzroy River alluvial aquifer because they were too low (< 2,000 years) to be within the reliability range for radiocarbon dating.

See Table 18 and Table 19 for the recharge rates derived from radiocarbon dating. The highest calculated groundwater recharge rates were greater than 50 mm/year, observed at three co-located bores near Fitzroy Crossing (BS16MB003A, BS16MB003B and BS16MB003C). However, there is some uncertainty in the calculated recharge rates for these bores, as the residence times were all below the reliable dating range for radiocarbon. We have presented the results in the table below, but have excluded these bores when calculating the median recharge rate for the Grant Group.

While the depth to groundwater level in these bores is about 60 m below ground level, the lithology is entirely sand, with no silt or clay (DWER 2017). Therefore, the rate of infiltration, particularly for heavier monsoonal rainfall, is expected to be rapid.

In addition, the uniformly high recharge rates across these three nested bores and the similarity in water level responses suggests strong vertical connectivity across the aquifer at this location.

Future studies could apply a method of determining residence times for these bores which represent a shorter timescale, such as CFCs, to confirm recharge rates.

The radiocarbon-derived estimates for this study are broadly consistent with those reported in Taylor et al. (2018). Variations between the two studies relate to the slightly different approaches to estimating modern residence times, as detailed in Appendix R.

Table 18 Radiocarbon recharge for unconfined aquifer samples

Sample ID	Date	Aquifer	Subarea	Residence time	Recharge rate (mm/year)
Barefoot Bore	15/09/2017	Erskine Sandstone	Fitzroy Trough	300	50.7
Garden Bore*	24/06/2016	Erskine Sandstone	Fitzroy Trough	3,500	0.9
Helens Bore*	4/09/2016	Liveringa Group	Fitzroy Trough	1,000	2.9
RRMW005D	17/08/2017	Liveringa Group	Fitzroy Trough	16,500	0.3
Manta Ray Bore	6/07/2016	Noonkanbah Formation	Lennard Shelf	3,400	0.4
LF03A*	14/09/2017	Noonkanbah Formation	Fitzroy Trough	29,600	0.1
LF04A	12/09/2017	Noonkanbah Formation	Fitzroy Trough	38,200	0.1
Blue Bush*	5/09/2016	Poole Sandstone	Lennard Shelf	300	18.0
No. 8 Bore	30/06/2016	Poole Sandstone	Lennard Shelf	1,700	7.8
Peglars Bore*	21/06/2016	Poole Sandstone	Fitzroy Trough	300	12.7
Peglars Bore*	18/05/2017	Poole Sandstone	Fitzroy Trough	300	12.7
Langs Bore*	16/05/2017	Poole Sandstone	Fitzroy Trough	3,400	2.6
Langs Bore*	26/06/2016	Poole Sandstone	Fitzroy Trough	4,900	1.8
1-04 Camballin	30/08/2016	Poole Sandstone	Fitzroy Trough	5,400	1.4
Paradise Bore	15/08/2017	Poole Sandstone	Fitzroy Trough	5,600	0.5
Paradise Bore	22/06/2016	Poole Sandstone	Fitzroy Trough	6,800	0.4
Looma 1-86	18/05/2017	Grant Group	Fitzroy Trough	300	34.7
Leos Bore*	27/06/2016	Grant Group	Fitzroy Trough	300	15.0
Looma 1-93*	30/08/2016	Grant Group	Fitzroy Trough	300	39.3
Thomas Bore*	2/09/2016	Grant Group	Fitzroy Trough	1,400	3.0
LF07	12/09/2017	Grant Group	Fitzroy Trough	700	18.6
Laurel Homestead Bore	30/06/2016	Grant Group	Lennard Shelf	300	34.0
5/10 – Fitzroy Crossing*	29/06/2016	Grant Group	Lennard Shelf	300	42.7
BS16MB001C	2/07/2017	Grant Group	Lennard Shelf	400	21.3
BS16MB003A*	4/07/2017	Grant Group	Lennard Shelf	300	71.3
BS16MB003B*	4/07/2017	Grant Group	Lennard Shelf	300	59.3
BS16MB003C*	4/07/2017	Grant Group	Lennard Shelf	300	50.0
BS16MB001A	3/07/2017	Grant Group	Lennard Shelf	800	21.3

Sample ID	Date	Aquifer	Subarea	Residence time	Recharge rate (mm/year)
BS16MB001B	2/07/2017	Grant Group	Lennard Shelf	1,100	10.4
KD16MB003	5/07/2017	Grant Group	Lennard Shelf	1,700	5.2
Donalds Mill No.2*	4/07/2016	Grant Group	Lennard Shelf	1,000	6.2
Jarlmadangah 1-02	26/06/2016	Grant Group	Fitzroy Trough	2,600	4.8
KD16MB002	5/07/2017	Grant Group	Lennard Shelf	5,400	4.0
Gogo Station Homestead Bore 3A	4/07/2016	Grant Group	Lennard Shelf	8,100	0.8
BA04	1/07/2016	Devonian reef complex	Lennard Shelf	300	9.8
PT4	1/07/2016	Devonian reef complex	Lennard Shelf	1,000	16.0

* Bores not included in calculations for data quality reasons.

Table 19 Radiocarbon recharge for confined aquifer samples

Sample ID	Date	Aquifer	Subarea	Screen (m bgl)	Aquifer thickness (m)	Width (x)(m)	Distance (x*)(m)	Pearson (years)	Recharge rate (mm/year)
Agricon 1	3/08/2017	Grant Group	Fitzroy Trough	537.0–545.0	916	5,000	11,400	40,430	14.4
Agricon 3	2/08/2017	Grant Group	Fitzroy Trough	400.0–588.0	916	5,000	11,400	33,700	16.6
Shovelton	03/08/2017	Grant Group	Fitzroy Trough	515.0–545.0	916	5,000	8,300	28,600	16.2
LF06	12/09/2017	Poole Sandstone	Fitzroy Trough	93.0–99.0	877	4,500	1,500	4,700	16.9
Huttons Bore No.2	02/07/2016	Poole Sandstone	Lennard Shelf	38.6–56.6	619	4,000	3,000	13,700	7.5
Tank Bore No.2	03/07/2016	Poole Sandstone	Lennard Shelf	54.0–84.0	556	6,800	6,400	28,800	4.1
One Tree Bore No.2	03/07/2016	Poole Sandstone	Lennard Shelf	89.0–131.0	275	4,800	14,400	18,100	10.7
Pilots Flowing Bore	02/07/2016	Poole Sandstone	Lennard Shelf	21.0–52.0	10	500	2,600	35,500	0

Note: Estimated aquifer thickness from Taylor et al. (2018).

6.3.2 Confined Grant Poole Sandstone aquifers

We estimated confined aquifer groundwater recharge using residence times (derived from the Pearson correction model) applied to the exponential piston-flow model described in Appendix R (Cook & Bohlke 2000).

Groundwater recharge rates within the Fitzroy Trough in the confined Grant Group and Poole Sandstone aquifers ranged from 14.4 to 16.2 mm/year.

On the Lennard Shelf, four bores intersect the confined Poole Sandstone aquifer: their recharge rates were lower than those calculated for the Fitzroy Trough, ranging from 0 to 16.9 mm/year. The very low recharge rate at Pilots Flowing Bore (0 mm/year) is attributed to the thinness of the Poole Sandstone aquifer (10 m) south of Fitzroy Crossing.

Taylor et al. (2018) estimated recharge rates in a range between 1 and 15 mm/year for the confined Poole Sandstone aquifer. This is consistent with the findings in this study.

For the confined Grant Group bores (Agricon 1, Agricon 3 and Shovelton) we estimated a recharge range between 14.4 and 16.6 mm/year. This is consistent with the Taylor et al. (2018) finding of 23 mm/year for Agricon 1.

We did not use the recharge estimates from Agricon 2 because tritium was detected and it had a very low Pearson residence time compared with Agricon 1 and Agricon 3. These factors suggest the casing on Agricon 2 has failed (Section 3.8.3).

6.4 Groundwater recharge estimates

In total, we found that 73 groundwater recharge estimates could be used (Table 20). These estimates were calculated using a combination of chloride mass balance and groundwater residence times (CFC and radiocarbon) across the different aquifers investigated.

We did not calculate CMB recharge for the Fitzroy River alluvial aquifer, as the assumptions that underpin the application of this method do not apply. Neither did we estimate recharge using radiocarbon for the Fitzroy River alluvial aquifer nor provide recharge estimates using CFCs for the confined aquifers, as these units fall outside the reliable dating range for these methods.

We typically excluded samples with a charge balance error (CBE) greater than 10% from recharge calculations. However, because only a limited number of samples were available for recharge calculations for the Devonian Reef aquifer, we included those with CBEs greater than 10% (BA04, PT4 and Sallys Bore) (Table 20).

Table 20   All recharge estimates by method

Bore ID	Date	Aquifer	Subarea	Recharge from chloride mass balance (mm/year)	Recharge from radiocarbon (mm/year)	Recharge from CFC (mm/year)
BA04	1/07/2016	Devonian reef complex	Lennard Shelf	37.72	9.8	-
PT4	1/07/2016	Devonian reef complex	Lennard Shelf	29.22	16	-
Sallys Bore	5/07/2016	Devonian reef complex	Lennard Shelf	25.21	-	-
Garden Bore*	24/06/2016	Erskine Sandstone	Fitzroy Trough	-	0.9	-
Barefoot Bore	15/09/2017	Erskine Sandstone	Fitzroy Trough	-	50.7	-
Bore	6/09/2016	Fairfield Group	Lennard Shelf	2.96	-	-
Birdwood Bore*	7/07/2016	Fitzroy River alluvium	Lennard Shelf	-	-	320
Liveringa South	30/07/2017	Fitzroy River alluvium	Fitzroy Trough	-	-	126
LF01	13/09/2017	Fitzroy River alluvium	Fitzroy Trough	-	-	52
LF02	13/09/2017	Fitzroy River alluvium	Fitzroy Trough	-	-	124
LF04B	13/09/2017	Fitzroy River alluvium	Fitzroy Trough	-	-	66
LF03B	14/09/2017	Fitzroy River alluvium	Fitzroy Trough	-	-	49
LF05	14/09/2017	Fitzroy River alluvium	Fitzroy Trough	-	-	77
LF01	20/08/2018	Fitzroy River alluvium	Fitzroy Trough	-	-	58
LF02	20/08/2018	Fitzroy River alluvium	Fitzroy Trough	-	-	116
LF05	21/08/2018	Fitzroy River alluvium	Fitzroy Trough	-	-	93
BU15MB002A	23/08/2018	Fitzroy River alluvium	Lennard Shelf	-	-	85
BU15MB003	23/08/2018	Fitzroy River alluvium	Lennard Shelf	-	-	181
BU15MB004	23/08/2018	Fitzroy River alluvium	Lennard Shelf	-	-	101
Looma 1-86	22/06/2016	Grant Group	Fitzroy Trough		-	-
Jarlmadangah 1-02	26/06/2016	Grant Group	Fitzroy Trough	15.94	4.8	-
Leos Bore*	27/06/2016	Grant Group	Fitzroy Trough	20.84	15	-
2/89 – Fitzroy Crossing*	29/06/2016	Grant Group	Lennard Shelf	4.99	-	137
5/10 – Fitzroy Crossing*	29/06/2016	Grant Group	Lennard Shelf	5.23	42.7	-
Laurel Homestead Bore	30/06/2016	Grant Group	Lennard Shelf	6.62	34	-
Donalds Mill No.2*	4/07/2016	Grant Group	Lennard Shelf	1.22	6.2	-
Gogo Station Homestead Bore 3A	4/07/2016	Grant Group	Lennard Shelf	0.69	0.8	-
Looma 1-93*	30/08/2016	Grant Group	Fitzroy Trough	33.87	39.3	-
Thomas Bore*	2/09/2016	Grant Group	Fitzroy Trough	4.11	3	-
Looma 1-86	18/05/2017	Grant Group	Fitzroy Trough	15.05	34.7	138
BS16MB001B	2/07/2017	Grant Group	Lennard Shelf	7.56	10.4	-
BS16MB001C	2/07/2017	Grant Group	Lennard Shelf	7.64	21.3	-
BS16MB001A	3/07/2017	Grant Group	Lennard Shelf	7.72	21.3	-

Bore ID	Date	Aquifer	Subarea	Recharge from chloride mass balance (mm/year)	Recharge from radiocarbon (mm/year)	Recharge from CFC (mm/year)
BS16MB003A*	4/07/2017	Grant Group	Lennard Shelf	13.55	71.3	-
BS16MB003B*	4/07/2017	Grant Group	Lennard Shelf	14.44	59.3	-
BS16MB003C*	4/07/2017	Grant Group	Lennard Shelf	13.36	50	-
KD16MB002	5/07/2017	Grant Group	Lennard Shelf	13.59	4	-
KD16MB003	5/07/2017	Grant Group	Lennard Shelf	10.5	5.2	-
Thomas Bore*	29/07/2017	Grant Group	Fitzroy Trough	0.3	-	116
Leos Bore*	31/07/2017	Grant Group	Fitzroy Trough	11.78	-	338
LF07	12/09/2017	Grant Group	Fitzroy Trough	15.94	18.6	-
Helens Bore*	4/09/2016	Liveringa Group	Fitzroy Trough	0.07	2.9	-
2-89 Mt Anderson*	7/09/2016	Liveringa Group	Fitzroy Trough	2.04	-	73
RRMW005D	17/08/2017	Liveringa Group	Fitzroy Trough	0.19	0.3	-
Manta Ray Bore	6/07/2016	Noonkanbah Formation	Lennard Shelf	0.19	0.4	-
LF04A	12/09/2017	Noonkanbah Formation	Fitzroy Trough	0.53	0.1	-
LF03A*	14/09/2017	Noonkanbah Formation	Fitzroy Trough	0.66	0.1	-
Peglars Bore*	21/06/2016	Poole Sandstone	Fitzroy Trough	1.01	12.7	-
Paradise Bore	22/06/2016	Poole Sandstone	Fitzroy Trough	2.34	0.4	-
Montgomery Bore	23/06/2016	Poole Sandstone	Fitzroy Trough	4.44	-	-
Langs Bore*	26/06/2016	Poole Sandstone	Fitzroy Trough	1.88	1.8	-
1-04 Camballin	30/08/2016	Poole Sandstone	Fitzroy Trough	7.13	1.4	-
Blue Bush*	5/09/2016	Poole Sandstone	Lennard Shelf	10.22	18	-
No 8 Bore	30/06/2016	Poole Sandstone	Lennard Shelf	5.11	7.8	-
1-04 Camballin	16/05/2017	Poole Sandstone	Fitzroy Trough	5.53	-	84
Langs Bore	16/05/2017	Poole Sandstone	Fitzroy Trough	2.07	2.6	-
Peglars Bore*	18/05/2017	Poole Sandstone	Fitzroy Trough	0.92	12.7	-
Paradise Bore	15/08/2017	Poole Sandstone	Fitzroy Trough	2.32	0.5	-
Agricon 1	3/08/2017	Grant Group (confined)	Fitzroy Trough	-	14.4	-
Agricon 3	2/08/2017	Grant Group (confined)	Fitzroy Trough	-	16.6	-
Shovelton	3/08/2017	Grant Group (confined)	Fitzroy Trough	-	16.2	-
LF06	12/09/2017	Poole Sandstone (confined)	Fitzroy Trough	-	16.9	-
Huttons Bore No.2	2/07/2016	Poole Sandstone (confined)	Lennard Shelf	-	7.5	-
Tank Bore No.2	3/07/2016	Poole Sandstone (confined)	Lennard Shelf	-	4.1	-
One Tree Bore No.2	3/07/2016	Poole Sandstone (confined)	Lennard Shelf	-	10.7	-
Pilots Flowing Bore	2/07/2016	Poole Sandstone (confined)	Lennard Shelf	-	0	-

* Bores not included in calculations for data quality reasons (Appendix J).

Table 21 and Table 22 provide the range and median recharge estimates across the different methods for each aquifer. Median recharge rates for the Grant Group and Poole Sandstone aquifer have been calculated separately, as there are significant lithological differences which impact on recharge. Where more than one sample exists (and therefore recharge estimate) for a bore, we used the average value. Where there are nested bores with likely high vertical connectivity, we used an average value for these sites.

Groundwater recharge rates vary within each aquifer due to a combination of factors that include:

- different methods of estimation that consider different timescales and parameters with different limitations and assumptions
- large variations in annual rainfall across different wet seasons, and across geological time
- spatial variation in rainfall across the large study area
- timescales of measurement (that is, measuring one wet season compared with 30 wet seasons)
- lithological variation, presence or absence of confining layers
- flood extent of the Fitzroy River and variation therein
- distance from recharge zone, depth to groundwater and groundwater flow patterns
- groundwater head direction
- depth of the screen/bore.

Table 21 Summary of groundwater recharge estimates

	Range	Fitzroy River alluvium (mm/yr)	Liveringa Group (mm/yr)	Unconfined Grant Group (mm/yr)	Unconfined Poole Sandstone (mm/yr)	Confined Grant Group & Poole Sandstone (mm/yr)	Devon ian reef (mm/yr)
Cl mass balance (CMB)	From	-	-	0.69	1.88	-	25.21
	Median	-	0.21	12.05	4.44	-	29.22
	To	-	-	15.94	7.13	-	37.72
CFC-12	From	49	-	-	-	-	-
	Median	89	-	-	-	-	-
	To	181	-	-	-	-	-
Radio carbon	From	-	-	0.8	0.4	0	9.8
	Median	-	0.3	5.2	1.8	12.6	12.9
	To	-	-	21.3	7.8	16.9	16

Table 22 Median recharge rate for each aquifer

Aquifer	(mm/year)	(% rain)	Method used
Fitzroy River alluvium	85.0	12.1%	CFC-12
Liveringa Group	0.3	0.04%	CMB, radiocarbon
Unconfined Grant Group	10.5	1.5%	CMB, radiocarbon
Unconfined Poole Sandstone	2.33	0.3%	CMB, radiocarbon
Confined Grant Group and Poole Sandstone	12.6	1.8%	Radiocarbon
Devonian reef complex	25.2	3.6%	-

Note: Information on % rain is provided for context and is based on the assumption of 700 mm/year. Rainfall is highly variable over time and area in the Kimberley, and 700 mm/year was adopted as representative of the average rainfall used across the Camballin region, Fitzroy Crossing, Gogo Station, Brooking Springs and Kimberley Downs.

Median values provide equal weighting for each measurement and eliminate the very high and very low estimates that may bias the result, particularly when viewed on a regional scale.

The CFC-12 and radiocarbon-derived recharge rates are sensitive to the different age ranges of groundwater – between 10 and 50 years for CFC-12 and between 2,000 and 40,000 years for radiocarbon.

Low CMB estimates may either be the result of groundwater recharge following preferential recharge flow paths (e.g., preferential flow through cracking surface clays) or arise from intense monsoonal rainfall (Crosbie et al. 2010).

Low CMB recharge estimates may also be attributed to low and/or uncertain estimates of chloride in the rainfall used in the recharge calculation. Chloride concentrations in rainfall are proportional to the recharge estimate using the CMB approach. We used the Cl concentration in rainfall of 0.46 mg/L from Halls Creek (Crosbie et al. 2012), about 400 km east of Fitzroy Crossing (Section 5.2.2).

The recharge values for the unconfined Grant Poole aquifer across all samples and different analytical methods ranged from a maximum of 71.3 mm/year to a minimum of 0.4 mm/year, with a median recharge of 9.0 mm/year. This is consistent with the findings of Taylor et al. (2018), which estimated median recharge rates for the Grant Poole in a range from 13 to 70 mm/year.

7 Hydraulic connectivity discussion

In this section we synthesise the multiple sources of information presented in previous chapters to interpret the hydraulic connectivity between aquifers and determine where groundwater and surface water interacts. We use:

- distribution of geological formations
- hydrogeological properties of different geological units
- groundwater and surface water hydrographs
- streamflow-gauging data (i.e. gaining verses losing reaches)
- the location and persistence of baseflow and river pools, and
- water chemistry and isotopic tracers, most notably ^{4}He and ^{222}Rn.

7.1 Fitzroy River alluvial aquifer

The Fitzroy River alluvial aquifer covers a large area and is in hydraulic connection with regional aquifers where they underlie the alluvium, and with the river and its tributaries.

Around Willare, it is likely that the alluvial aquifer and the Fitzroy River are connected to and receive recharge from the Wallal Sandstone aquifer where the sandstone unit sub-crops beneath the alluvium. This is indicated by high ^{4}He concentrations measured in river samples downstream of the Looma gauging station (Section 5.2.6).

Stream-gauging data between Looma and Willare gauging stations, while not highly accurate for low flow, consistently indicates the river gains flow from groundwater along this reach in most years (Section 5.1.6).

Groundwater residence times from the alluvial aquifer sampled from bores in the Camballin area (LF03B, LF04B and LF05) were between 50 and 60 years. These bores recorded lower tritium concentrations than groundwater sampled from LF01 and Birdwood Bore (south of Fitzroy Crossing), suggesting longer residence times.

South of the Noonkanbah reach of the Fitzroy River, the Grant Poole aquifer discharges to the Fitzroy River alluvial aquifer as indicated by high ^{222}Rn concentrations, elevated ^{4}He and a decrease in $^{87}Sr/^{86}Sr$ in surface water (Gardner et al. 2011; Harrington et al. 2011; Taylor et al. 2018).

Major ion chemistry around Fitzroy Crossing suggests that the alluvial aquifer is recharged by either the Devonian reef or Fairfield Group aquifer, or both. The chemical composition of the alluvial aquifer, as measured at Birdwood bore, downstream of Fitzroy Crossing, is Ca-HCO_3 type. This differs from most alluvial aquifer groundwater samples which have Na-Cl chemistry. While Na-Cl water type is indicative of modern, rainfall-sourced recharge, Ca-HCO_3 water type in the river and in the alluvial aquifer indicates the aquifer is connected to and is recharged by Ca-HCO_3 water type (Section 5.2.6). Ca-HCO_3 water type in the river suggests it is being recharged by discharge from limestone aquifers such as the Devonian reef or Fairfield Group.

While there are indications that the alluvial aquifer is being recharged by the Devonian reef and other regional aquifers, its primary source of recharge appears to be the Fitzroy River streamflow and flooding.

Paired hydrograph data from three alluvial aquifer bores and three gauging stations indicates that the connection between the river and the alluvial aquifer varies spatially, seasonally and inter-annually (Figure 72). The gradient from the aquifer towards the river around Looma during the dry season is fairly consistent, and reverses during the wet season. Around the Fitzroy Barrage and bore LF05, groundwater-level monitoring between September 2017 and October 2019 shows only a brief interval at the end of the 2017–18 wet season when water from the alluvial aquifer may have discharged to the river. Therefore, over this two-year period, the alluvial aquifer was consistently recharged by streamflow.

River-flow data between Noonkanbah and the Fitzroy Barrage gauging stations shows consistent loss of streamflow along this reach of the river over 20 years (Section 5.1.6). However, within the same river reach ^{4}He and ^{222}Rn concentrations in river samples measured over several years suggest groundwater input. This is because the spatial extent of this losing reach is defined by the locations of the gauging stations and may not reflect the actual location(s) where surface water is lost to groundwater or vice versa (i.e. groundwater could inflow to the river upstream of the river reach). It does appear that surface water is consistently being lost to groundwater at some point or points along the reach of the river between the Noonkanbah and Fitzroy Barrage gauging stations.

Noting those uncertainties, the surface water gauging data shows the Fitzroy River can generally be characterised as a gaining system over most of its length (Section 5.1.6).

Paired groundwater – surface water information also suggests significant bank and/or alluvial aquifer storage associated with large flood events around Fitzroy Crossing (Figure 72). While there is a gap in the groundwater data for alluvial aquifer bore BU15MB004 for the 2017–18 period, the groundwater level in the alluvial aquifer shows an increase of 4 m, most likely caused by large flood events in the preceding two years. This supports a general conceptual model of the Fitzroy River recharging the alluvial aquifer system during wet season flooding. In the dry season, as the river levels decline, the gradient is reversed, and water stored in the alluvial aquifer flows back into the river (Harrington & Harrington 2015; CSIRO 2009).

Long-term groundwater discharge to the river maintains baseflow and persistent river pools, often for multiple years after flooding. The presence of year-round river flows and river pools that persist into the dry season, despite characteristically low rainfall during these months, are indicators of regional groundwater connectivity (and discharge) to the alluvial aquifer and the river (Section 2.5). While baseflow is supported by groundwater discharge, the question of whether this flow to the river is sourced from the alluvial aquifer or one of the major regional aquifers is a more complicated one.

Even though persistent pools suggest groundwater is discharging to the river, their presence is not by itself definitive evidence. For example, if pools are deeper than the annual evaporation rate of about 2 m, they may persist through a dry year without additional inflows. In addition, the presence of persistent pools does not provide any further insight into whether groundwater inflows are restricted to the alluvial aquifer or are also supported by input from regional aquifers.

The available data does not fully resolve the amount or source of groundwater inflow (i.e. alluvial versus regional aquifers) to particular sections of the river using current information. Further investigation to determine recharge source, flow directions and seasonal variability of groundwater discharge along much of the river’s length would help refine our understanding.

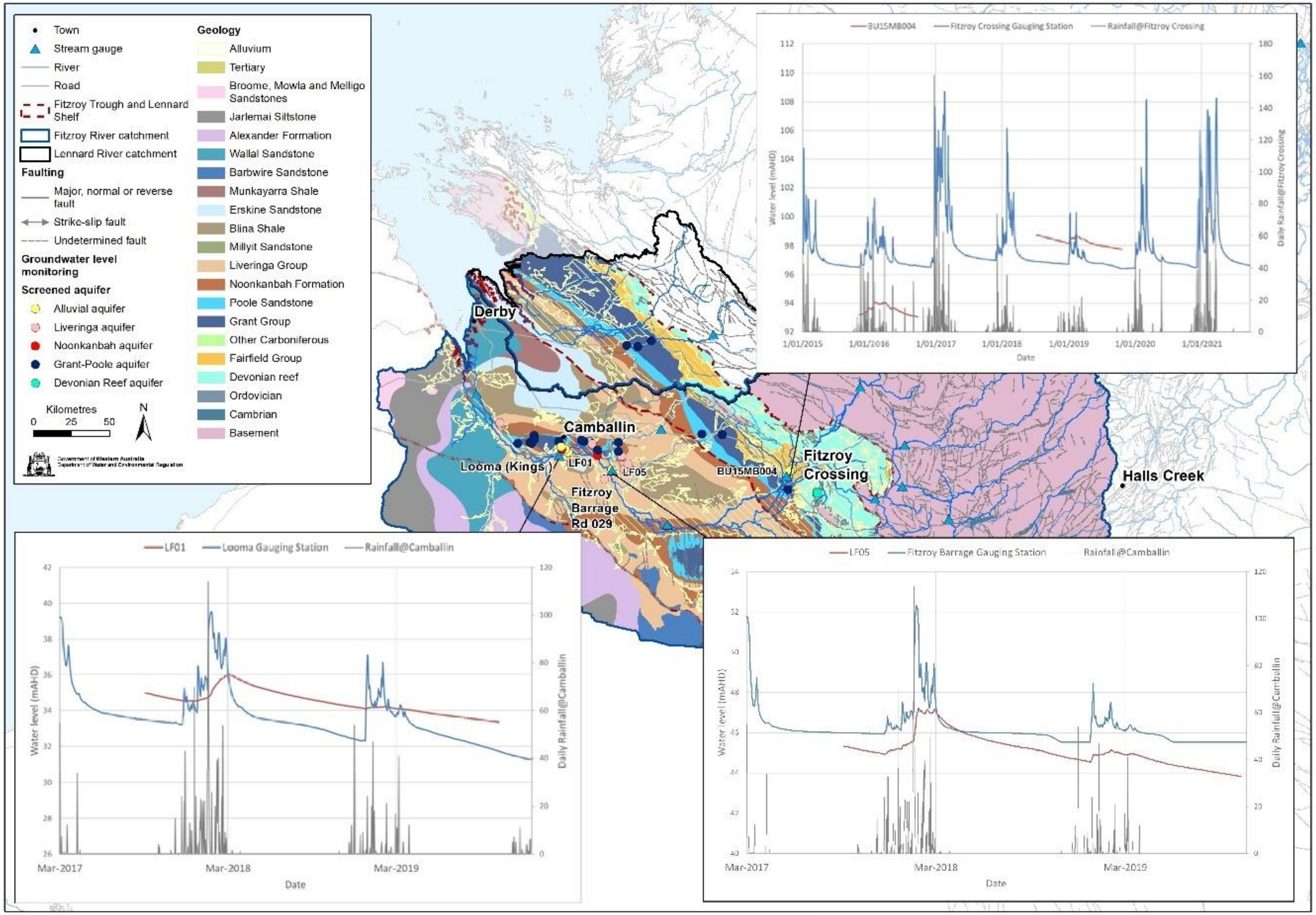


Figure 72 Alluvial aquifer – surface water interactions along the Fitzroy River

7.2 Erskine Sandstone

Within the Fitzroy study area, the Erskine Sandstone is limited to a small outcropping area south of Camballin. A significant outcropping area of Erskine Sandstone occurs to the north of Camballin, however this is entirely within the Derby management plan area (DWER 2020).

The Erskine Sandstone is underlain by the confining Jarlemai Siltstone and is not in hydraulic connection with underlying aquifers or the Fitzroy River.

7.3 Wallal aquifer

There are two separate occurrences of the Wallal aquifer within the Fitzroy catchment. The aquifer's northern extent was investigated as part of the *Groundwater exploration for irrigation supply to the Knowsley area, West Kimberley* (Gallardo 2018). It is separated from the Wallal Sandstone in the west of the catchment by the Blina Shale and the Liveringa Group. The western extent outcrops south-west of the Fitzroy River and is overlain by and hydraulically connected with the Alexander Formation. The two units are managed as a single groundwater resource.

A large spike in ^{4}He measured in the river downstream of the Looma gauging station (Section 5.2.6) indicates discharge of older groundwater sourced from a regional rather than alluvial aquifer. Given where the high river ^{4}He was measured, it is likely the Fitzroy River is connected with and being recharged by the Wallal Sandstone aquifer where it meets the lower section of the river and alluvial aquifer (Section 7.1).

7.4 Noonkanbah Formation

The Noonkanbah Formation is generally a regional aquitard, although there are a few low-yielding brackish to saline bores completed in the unit (Lindsay & Commander 2005). Harrington and Harrington (2015) described the TDS range for the Noonkanbah Formation as typically > 1,000 mg/L.

The presence of the Noonkanbah Formation is an indicator of poor or no connection between the underlying regional aquifers and the river, except in situations where preferred flow pathways through the aquitard exist.

7.5 Liveringa Group aquifer

The Liveringa Group aquifer is spatially extensive. At best, it is a low-quality aquifer, used primarily for stock and domestic supplies, although it can provide useful water supplies in some areas (e.g. the Balginjirr community water supply is sourced from the Liveringa aquifer).

Groundwater samples collected from the Liveringa aquifer during this study recorded salinity within the same range as Harrington and Harrington (2015).

The Liveringa Group aquifer is probably recharged by river floodwaters in areas where there is a good connection between the river, alluvial aquifer and sandier areas of the Liveringa Group (Taylor et al. 2018). However, except for the Le Lievre swamp near Camballin, where there is known recharge from the river to the Liveringa Group (Lindsay & Commander 2005), little work has been done to identify other specific areas of connection. Earlier work noted evidence of recharge of the alluvial aquifer from the Liveringa Group aquifer in this area downstream of the Looma gauging station (Lindsay & Commander 2006).

The 2-89 Mt Anderson bore in the Liveringa aquifer is known to be impacted by pumping from the nearby Balginjirr Aboriginal community (Section 5.1.3), and this should be taken into account when evaluating the reliability of residence time and recharge results from this bore. Taylor et al. (2018) and this study both determined significantly higher recharge at this bore than either of the other two Liveringa aquifer bores (Table 20), and it is possible routine pumping has drawn in younger water from other sources. As such, analysis of water sampled from this bore may not be representative of recharge rates into the Liveringa aquifer generally. This bore has not been included in recharge calculations.

Previous studies have identified areas where groundwater from the Liveringa Group aquifer appears to be discharging to the Fitzroy River.

Between Fitzroy Crossing and the Noonkanbah gauging station (Harrington et al. 2011), groundwater sourced from the Liveringa Group was inferred from the presence of ^{222}Rn and ^{4}He, along with a decrease in $^{87}Sr/^{86}Sr$. Outcropping strata, believed to be Liveringa Group sandstones – or possibly older consolidated alluvium – was also observed along this reach of the river (Harrington et al. 2011).

Lindsay and Commander (2006) noted evidence of recharge of the alluvial aquifer from the Liveringa Group downstream of the Looma gauging station.

A relatively high groundwater discharge area was also identified near the Grant Range. Snake Creek, a tributary of the Fitzroy River, recorded surface water ^{222}Rn levels up to 1.108 Bq/L (Section 5.2.6). These were the highest ^{222}Rn levels recorded anywhere in the study area. This water likely comes from the alluvial aquifer, although there may be some input from the underlying Liveringa Group.

7.6 Grant Poole aquifer

The Grant Group and Poole Sandstone units are generally well connected to each other across the study area and the combined aquifer system is recharged by direct vertical recharge from rainfall:

- in outcrop areas around Camballin (Grant Range)
- to the south of Noonkanbah and Fitzroy Crossing
- in places where it either subcrops beneath or outcrops adjacent to the alluvial aquifer.

Over much of the study area, the Grant Poole aquifer is separated from direct connection with the river, and from vertical rainfall recharge, by the Liveringa Group and Noonkanbah Formation – both of which typically act as aquitards.

Groundwater is known to discharge from the confined Grant Poole aquifer to the alluvial aquifer and the river along the reach of the river between Fitzroy Crossing and Noonkanbah (Section 7.1). This is indicated by high ^{222}Rn concentrations, elevated ^{4}He, and a decrease in $^{87}Sr/^{86}Sr$ in surface water – described in detail in Gardner et al. (2011), Harrington et al. (2011) and Taylor et al. (2018). Immediately south of this reach of the river is a large outcrop of Grant Group and Poole Sandstone with extensive north–south trending faults. Groundwater discharge to the river is controlled by this faulting, which appears to be acting as a conduit for flow from the confined aquifer, through the overlying Noonkanbah Formation and into the river.

Although the Grant Group and Poole Sandstone units of the Grant Pool aquifer are thought to be hydraulically connected and are managed as a single groundwater resource, there are differences in their water chemistry. These suggest multiple recharge pathways and/or different residence times. The overlying Poole Sandstone shows uniform Na-Cl type chemistry for all samples, while the Grant Group samples vary from $Na\text{-}HCO_3$ type in the Fitzroy Trough to $Ca\text{-}HCO_3$ type on the Lennard Shelf. Sodium-bicarbonate composition in the Fitzroy Trough may indicate groundwater freshening from an inflow of calcium-carbonate-rich groundwater, possibly sourced from the underlying limestone-bearing Fairfield or Devonian reef aquifers. Alternatively, this may indicate that the limestone-bearing Nura Nura Member at the base of the Poole Sandstone is freshening the underlying Grant Group (Section 5.2.2).

7.7 Fairfield Group

Investigations into the Fairfield Group aquifer and its connection with the river and other aquifers have been limited to date.

For this study we could only identify a single bore that was screened in the Fairfield group for sampling and testing. The water sampled showed carbonate chemistry characteristic of a limestone-bearing formation such as the Fairfield Group.

Surface water interaction with the Fairfield Group aquifer is likely around the town of Fitzroy Crossing, where the Fitzroy River and alluvial aquifer intersect the unit. Shallow tributaries crossing the Fairfield Group outcrop and draining into the river may also be groundwater-fed. The presence of springs in the area around Fitzroy Crossing indicate that groundwater is discharging to the surface (Section 5.2.6).

7.8 Devonian reef aquifer

Outcropping of the Devonian reef aquifer is restricted to the Lennard Shelf upstream of Fitzroy Crossing. Some connection between the Devonian reef aquifer and the Grant Group in this area is inferred from the $CaCO_3$ type water chemistry observed in

Grant Group bores (Figure 45 – Figure 47). ^{222}Rn data collected from the river upstream of Fitzroy Crossing at Geikie Gorge also suggests connectivity between the Devonian reef aquifer and the river (no alluvial aquifer is present through the gorge). Significant faulting is known to be present around Geikie Gorge, which may be acting as a preferred flow pathway between the confined aquifers and the river.

This connection is also supported by elevated concentrations of ^{4}He measured in the river upstream of Fitzroy Crossing (Appendix I), which suggest that older, regional groundwater is discharging into the river (Taylor et al. 2018). Additionally, the absence of bromide in both the Devonian reef aquifer groundwater samples and surface water (Margaret River) samples is unusual and may indicate a connection between the two (Section 5.2.2). It is possible that bromide is being adsorbed within the limestone aquifer.

Several of the BU series of alluvial aquifer bores drilled immediately upstream of Fitzroy Crossing (Gallardo 2017) recorded the presence of CFCs and tritium (Table 20) in the groundwater samples collected. These are indicators of modern recharge (i.e. rainfall) rather than older recharge sourced from the underlying regional aquifers. However, the presence of recently recharged groundwater in the alluvial aquifer samples does not preclude the presence of older groundwater sourced from the underlying regional aquifers recharging the alluvium.

7.9 Groundwater–surface water interaction

Figure 73 presents the possible interaction between groundwater and surface water in different zones along the Fitzroy River. During flooding associated with the wet season, we assume that recharge to the alluvial aquifer and the underlying regional aquifers will occur across the catchment. Below describes the possible dry season interactions from east to west.

Devonian Reef zone: Likely interactions between Devonian reef aquifer and the river, with recharge and discharge being equally likely and probably varying within and between years.

Fairfield Group zone: Possible groundwater discharge – source aquifer not determined but likely Fairfield Group.

Grant Group and Poole Sandstone zone: Likely groundwater discharge from the Grant Poole and alluvial aquifers.

Noonkanbah zone 2: No evidence to suggest significant interaction between surface water and groundwater.

Liveringa zone 3: Likely groundwater discharge from the Liveringa Group aquifer.

Noonkanbah zone: Likely groundwater discharge from the Grant Poole and alluvial aquifers.

Liveringa zone 2: Likely recharge to the alluvial aquifer from the river. Possible groundwater discharge, likely from the alluvial aquifer.

Noonkanbah-Liveringa zone: Possible groundwater discharge – source aquifer not determined.

Liveringa zone 1: Possible groundwater discharge – source aquifer not determined.

Wallal Zone: Likely groundwater discharge from the Wallal and alluvial aquifers.

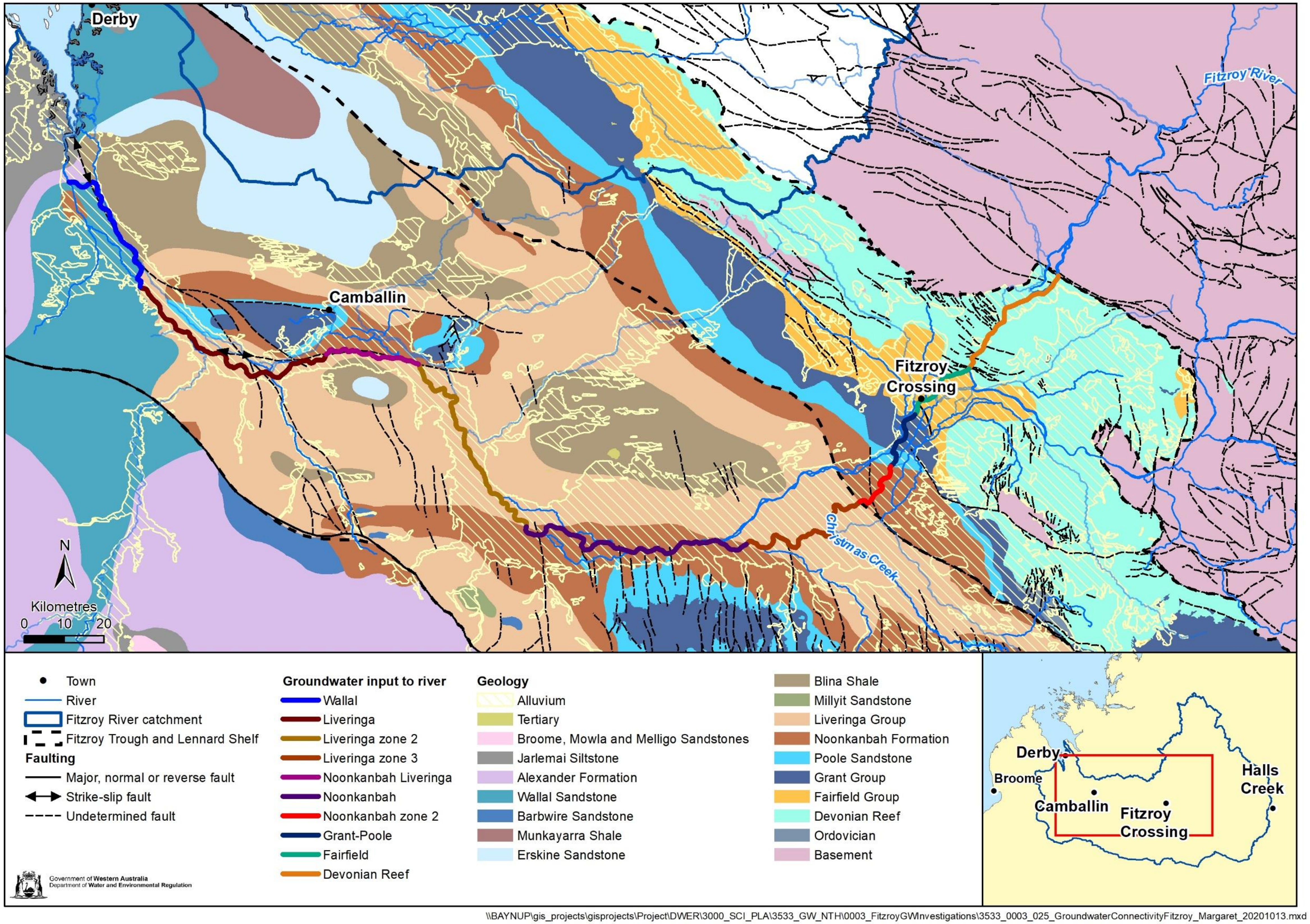


Figure 73 Zones of groundwater–surface water interaction

8 Summary of findings

This investigation and the collaborative project described in Taylor et al. (2018) have provided us with new information derived from drilling, geophysics and water chemistry. These have led to a new understanding of the geology and hydrogeology of the Fitzroy Valley, as well as revised estimates of groundwater recharge for major aquifers. We also have new information on the inter-connectivity of the different major aquifers of the study area, and on how they connect with the Fitzroy and Margaret rivers. We have used our findings to comment on the prospectivity of the major aquifers (below).

8.1 Updated geometry and extent of Grant Group and Poole Sandstone outcrop areas

This study updated the extent of the Grant Group and Poole Sandstone outcrop in the Camballin region. The main changes are:

- The Noonkanbah Formation outcrop is more extensive and closer to a previous conceptualisation in Guppy et al. (1958). It outcrops between the western and eastern outcrops of the Grant Group and Poole Sandstone. It also outcrops adjacent to the Liveringa Group, near the Fitzroy River.
- The Grant Group and Poole Sandstone outcrop extent has been reduced in two places near Camballin: the eastern end of the Grant Range anticline, and south of the Mt Wynne anticline, where the Noonkanbah Formation now underlies the Fitzroy River rather than the Grant Group and Poole Sandstone.

8.2 Regional-scale assessment of groundwater recharge

This study has produced updated groundwater recharge estimates for several aquifers in the study area. To arrive at these estimates, we used various methods of analysis, which we selected based on the likely timescales for groundwater to recharge different aquifers. For example, CFC-12 recharge rates reflect the past 10 to 50 years, while radiocarbon-derived recharge rates reflect long-term average net recharge rates.

Groundwater and surface water hydrographic and hydrochemical information suggests variable recharge to the alluvial aquifer, depending on location, lithology and connectivity with the river.

Recharge to the Grant Poole is by vertical recharge from rainfall:

- in outcrop areas around Camballin (Grant Range)
- to the south of Noonkanbah and Fitzroy Crossing
- in places where it either sub-crops beneath or outcrops adjacent to the alluvial aquifer.

Table 22 shows the median recharge estimates for each aquifer, along with the methods used to make the calculations in each case.

8.3 Potential paleochannel(s) at Fitzroy Crossing and Gogo stations

The AEM survey data (Section 3.1) indicated that paleochannel sediments of the Grant Group may be incised into the Fairfield Group around Fitzroy Crossing and Gogo Station (Section 4.5).

This interpretation is inferred from geophysical data: there are no bores in the area to confirm this. The AEM signature could also indicate different mineralogy. The inferred geometry of the channel appears to be up to 180 m thick and about 1.5 to 2 km wide.

If verified, this paleochannel system could provide an additional water resource for irrigation at Gogo Station, or water supplies for the town of Fitzroy Crossing and nearby Aboriginal communities. The paleochannel also appears to underlie the Fitzroy River at Fitzroy Crossing, hence potential connectivity with the river would need to be further investigated.

8.4 Groundwater prospectivity

The Fitzroy Valley hosts several aquifers that are prospective as regional groundwater resources, including the Wallal, Liveringa Group, Grant Poole, Devonian reef and the Fitzroy River alluvial aquifers. Of these, this study has concentrated on the Grant Poole which, along with the Wallal Sandstone, is the major prospective groundwater resource within the management area. Other minor resources are also discussed below.

An assessment of prospectivity in any given location would need to consider that changes to groundwater use could potentially impact:

- the Fitzroy and Margaret rivers, particularly permanent groundwater-fed pools
- off-stream permanent pools, springs and other water-dependent places of cultural significance
- the town water supplies of Camballin and Fitzroy Crossing
- the water supplies of Aboriginal communities
- stock bores that supply water for cattle throughout the pastoral stations
- existing licensed groundwater users, such as Gogo Station
- stygofauna and troglofauna.

8.4.1 Alluvial aquifer

The Fitzroy River alluvial aquifer is lithologically heterogeneous and shows a wide range of salinity, generally increasing with distance from the river. Investigation results suggest that groundwater prospectivity will be constrained by the connectivity between the aquifer and the Fitzroy and Margaret rivers. The river floodplain is also subject to seasonal flooding, which can damage groundwater pumping infrastructure.

Previous storage estimates are probably over-estimated and any groundwater use from the alluvial aquifer would likely only be useful in small volumes at isolated locations and where water quality allows. This is consistent with the findings of Taylor et al. (2018).

8.4.2 Wallal Sandstone and Alexander Formation

The Wallal aquifer is a highly prospective groundwater resource with an extensive outcropping area in the south-west of the Fitzroy catchment.

The Wallal Sandstone and Alexander Formation are in hydraulic connection and are considered to be a single aquifer (referred to as the Wallal aquifer). The aquifer outcrops over a considerable area south of Camballin and there is evidence of it being in hydraulic connection with and contributing flow to the Fitzroy River.

While not the focus of this study, the Wallal aquifer represents a major potential groundwater resource. However, it is poorly parameterised within the Fitzroy management area, and its hydrogeological properties and connectivity with the other regional aquifers is generally not well understood.

8.4.3 Grant Poole aquifer

The Grant Poole aquifer is highly prospective. There are extensive outcrop areas and it contains large volumes of fresh water, suitable for irrigation, stock and town water supplies.

The depth to the aquifer is shallow in outcrop areas and deep (> 300 m) outside of them. Where the aquifer is confined by either the Noonkanbah or Liveringa Group, groundwater pressures are high, and levels have been recorded within a few metres of the ground surface (Taylor et al. 2018).

Groundwater use from the Grant Poole aquifer in the central part of the study area is less prospective than in other areas, due to the greater depths to the aquifer (> 400 m) (Figure 74).There is also evidence that the aquifer discharges to the Fitzroy River along the Noonkanbah reach (Figure 73), meaning groundwater use has the potential to affect surface water flows.

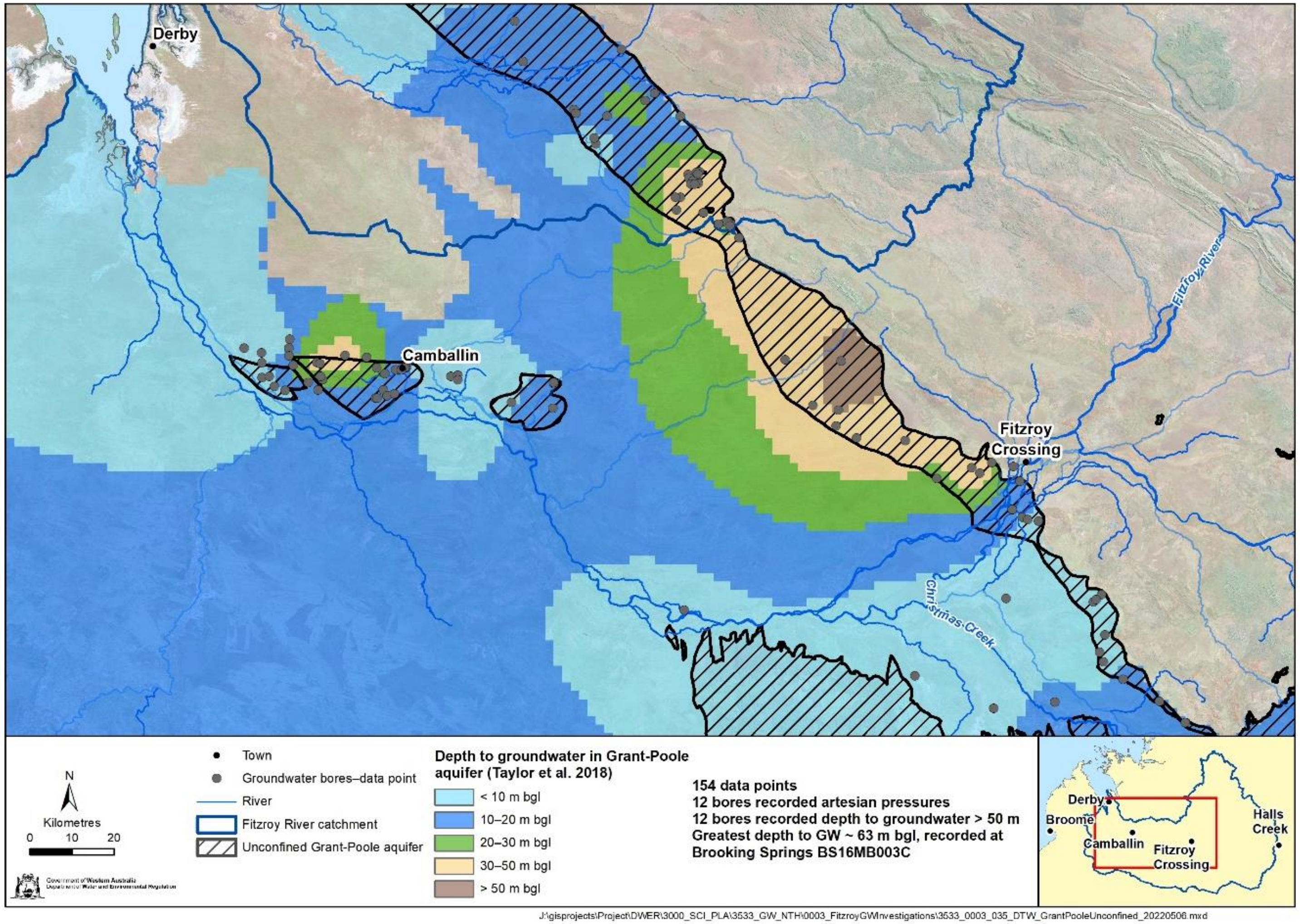


Figure 74 Hydraulic heads in the Grant Group and Poole Sandstone aquifers (modified from Taylor et al. 2018)

Note: m bgl is metres below ground level. Where the Grant Poole aquifer is confined, depth to the top of the aquifer can be > 300 m bgl; however, as pressure in the aquifer is high, groundwater levels can rise to a few metres below the surface.

The area where the Grant Poole outcrops along the Lennard Shelf is also prospective for groundwater supplies. While the Poole Sandstone aquifer is thin and mostly unsaturated in this area, the Grant Group aquifer is thick – storing high-yielding fresh water. Pumping tests at Kimberley Downs station gave yields of about 40 L/second.

8.4.4 Devonian reef and Fairfield Group aquifers

The Devonian reef and Fairfield Group aquifers outcrop extensively on the Lennard Shelf and contain significant volumes of fresh groundwater. Groundwater flows from these aquifers appear to be strongly connected with both the Fitzroy and Margaret rivers, as well as the Grant Poole and alluvial aquifers.

The Devonian reef complex in particular contains karstic features, so aquifer characteristics are likely to be highly variable. It is also possible that significant pumping from this aquifer would impact on environmental and ecological receptors such as the Fitzroy and Margaret rivers, Geikie Gorge, Tunnel Creek, Mimbi Caves and Windjana Gorge.

Within the project area, outcropping areas of the Fairfield Group are restricted to the Lennard Shelf. While the unit is an aquifer, exploration drilling investigated the Fairfield Group as a potential water supply and was unable to identify any suitable aquifer material to screen across (Gallardo 2017).

8.4.5 Minor aquifers

Several geological units across the catchment host minor groundwater resources and could be targeted for small-scale localised use.

Although spatially limited across the catchment, groundwater investigations around Meda and Yeeda stations (Gallardo 2018a) recorded extensive fresh groundwater resources in the Erskine Sandstone, with salinity less than 500 mg/L as TDS.

The Noonkanbah Formation is generally a major regional aquitard, yet some areas have sandy units that make up a minor aquifer hosting a few low-yielding, brackish bores.

Although the Liveringa Group is spatially extensive, it is a low-quality aquifer used primarily for stock and domestic supplies. This unit can provide useful water supplies in some areas, such as water supply for the Balginjirr community.

8.5 Options for future work

As and when groundwater use in the Fitzroy Valley increases, more targeted information and baseline data would help define groundwater resources more precisely. At this time, and based on the location of future development, consideration should be given to the following work:

- obtaining more time-series groundwater-level data
- sampling surface water quality at gauging stations

- installing additional bores (e.g. nested bores to define vertical gradients; bores close to gauging stations to compare with surface water; and at the potential palaeochannel near Fitzroy Crossing, bores to enable throughflow assessment across the Pinnacle Fault system)
- updating the 3D geological model
- developing a coupled groundwater–surface water model
- improving understanding of the extent of the alluvium covered by low-, medium- and high-flow events.

Appendices

Appendix A Geophysical logs

** Agricon bores were constructed as an open hole beneath a steel surface casing. Resistivity logs were run in the open hole interval.*

Bore ID	Easting	Northing	Casing material	Drill depth	Resistivity	Conductivity	Gamma	BMR
KD16MB001	667316	8070900	PVC	103	✕	✓	✓	✓
KD16MB002	674610	8070294	PVC	120	✕	✓	✓	✓
KD16MB003	683785	8073937	PVC	120	✕	✓	✓	✓
Helens Bore	644703	8006082	PVC	75	✕	✓	✓	✓
Liveringa Stock Bore	663858	7997987	PVC	160	✕	✓	✓	✕
A1 GoGo	792663	7974029	PVC	137	✕	✓	✓	✕
N1 GoGo	792762	7974480	PVC	130	✕	✓	✓	✕
PT5 GoGo	792957	7972849	PVC	93	✕	✓	✓	✕
PD791 GoGo	792598	7972820	PVC	150	✕	✓	✓	✕
EW1 Ellendale	705120	8045933	PVC	131	✕	✓	✓	✕
EW5 Ellendale	703258	8047865	PVC	34	✕	✓	✓	✕
EW6 Ellendale	701109	8044752	PVC	234	✕	✓	✓	✕
LR12 Ellendale	694496	8054166	PVC	177	✕	✓	✓	✕
GM1 Ellendale	688645	8050802	PVC	175	✕	✓	✓	✕
GM2 Ellendale	697269	8044752	PVC	116	✕	✓	✓	✕
SLK90	664107	8071151	PVC	34	✕	✓	✓	✕
Homestead Bore 3A Gogo Station	773554	7975889	PVC	37	✕	✓	✓	✕
Lightning Bore	652629	7982720	PVC	88	✕	✓	✓	✓
Agricon 2*	639197	8007777	steel/open hole	617	✓*	✕	✓*	✕
Agricon 3*	637591	8008533	steel/open hole	588	✓*	✕	✓*	✕
Thomas Bore	606663	8009001	PVC	31	✕	✕	✓	✕
Liveringa South	624252	8004072	PVC	37	✕	✕	✓	✕
LF01	628833	8000538	PVC	26	✓	✕	✓	✕
LF02	627241	8002497	PVC	84	✓	✕	✓	✕
LF03A	648157	7998262	PVC	78	✓	✕	✓	✕
LF04A	624528	8002485	PVC	84	✓	✕	✓	✕
LF05	657653	7988973	PVC	42	✓	✕	✓	✕
LF06	603728	8007103	PVC	42	✓	✕	✓	✕
LF07	606484	8011567	PVC	95	✓	✕	✓	✕
BS16MB001A	716961	8012492	PVC	96	✕	✕	✓	✕
BS16MB003A	730196	8012174	PVC	118	✕	✕	✓	✕
BU15MB001	774428	7988697	PVC	151	✕	✕	✓	✕

Bore ID	Easting	Northing	Casing material	Drill depth	Resistivity	Conductivity	Gamma	BMR
BU15MB002	772957	7988697	PVC	139	✓	✕	✓	✕
BU15MB003	776180	7989177	PVC	43	✓	✕	✓	✕
BU15MB004	774230	7988364	PVC	35	✓	✕	✓	✕
BU15MB007	773458	7989235	PVC	31	✓	✕	✓	✕
BU15MB008	775799	7988990	PVC	37	✕	✕	✓	✕
BU15MB009	775524	7989413	PVC	37	✕	✕	✓	✕
BU15MB010	775518	7990203	PVC	37	✕	✕	✓	✕
MA15MB001	600561	8033484	PVC	102	✓	✕	✓	✕
MA15MB002	600139	8027773	PVC	102	✓	✕	✓	✕
MA15MB003	599789	8022111	PVC	102	✓	✕	✓	✕
MA15MB004	599150	8015281	PVC	102	✓	✕	✓	✕
MA15MB005	599117	8012134	PVC	151	✓	✕	✓	✕

Appendix B Groundwater-level monitoring, Fitzroy Trough

Bore ID	Station/community	Project subarea	Confined/ unconfined	AWRC number	Easting	Northing	Aquifer	Logger (2018)
LF01	Myroodah Crossing	Fitzroy Trough	Unconfined	80270063	628833	8000538	Fitzroy alluvium	✓
LF02	Myroodah Road	Fitzroy Trough	Unconfined	80270064	627241	8002497	Fitzroy alluvium	✓
LF03B	Camballin – Noonkanbah	Fitzroy Trough	Unconfined	80270066	648162	7998260	Fitzroy alluvium	✓
LF04B	South of Looma	Fitzroy Trough	Unconfined	80270068	624527	8002477	Fitzroy alluvium	✓
LF05	Fitzroy Barrage	Fitzroy Trough	Unconfined	80270069	657653	7988973	Fitzroy alluvium	✓
Liveringa South	Liveringa	Fitzroy Trough	Unconfined	80270072	624252	8004072	Fitzroy alluvium	✕
Homestead	Myroodah	Fitzroy Trough	Unconfined	80210699	634476	7995826	Blina Shale	✕
Hardman Dam Bore	Liveringa	Fitzroy Trough	Unconfined	80210323	665785	7989159	Liveringa Group	✕
Helens Bore	Liveringa	Fitzroy Trough	Unconfined	80240014	644701	8006086	Liveringa Group	✓
RRMW005S	Liveringa	Fitzroy Trough	Unconfined	80212098	668340	7992905	Liveringa Group	✓
RRMW005D	Liveringa	Fitzroy Trough	Unconfined	80212097	668340	7992905	Liveringa Group	✓
Liveringa Stock Bore	Liveringa	Fitzroy Trough	Unconfined	80211311	663856	7997995	Liveringa Group	✕
2-89 Mt Anderson	Mount Anderson	Fitzroy Trough	Unconfined	80210072	583953	8019507	Liveringa Group	✕
BD2 02 (BG2)	Mount Anderson	Fitzroy Trough	Unconfined	80211413	583877	8019640	Liveringa Group	✓
Lightning Bore	Myroodah	Fitzroy Trough	Unconfined	80240015	652625	7982722	Liveringa Group	✓
LF03A	Camballin – Noonkanbah	Fitzroy Trough	Unconfined	80270065	648162	7998260	Noonkanbah Formation	✓
LF04A	South of Looma	Fitzroy Trough	Unconfined	80270067	624528	8002485	Fitzroy alluvium	✓
Peglars Bore	Liveringa	Fitzroy Trough	Unconfined	80210841	661984	8001004	Poole Sandstone	✓
Paradise Bore	Liveringa	Fitzroy Trough	Unconfined	80270056	662011	8007073	Poole Sandstone	✓
Montgomery Bore	Liveringa	Fitzroy Trough	Unconfined	80210233	648215	8001942	Poole Sandstone	✕
Langs Bore	Mount Anderson	Fitzroy Trough	Unconfined	80210241	604844	8006315	Poole Sandstone	✕
LF07	Mount Anderson	Fitzroy Trough	Unconfined	80270071	606484	8011567	Grant Group	✓
Leos Bore	Liveringa	Fitzroy Trough	Unconfined	80210235	622636	8007884	Grant Group	✓
Thomas Bore	Mount Anderson	Fitzroy Trough	Unconfined	80240012	606663	8009001	Grant Group	✕
LF06	Mount Anderson	Fitzroy Trough	Confined	80270070	603728	8007103	Poole Sandstone	✓
Shovelton	Liveringa	Fitzroy Trough	Confined	80210261	633583	8015072	Grant group	✕
Agricon 1	Liveringa	Fitzroy Trough	Confined	80210234	639229	8008812	Grant Group	✕
Agricon 2	Liveringa	Fitzroy Trough	Confined	80270062	639197	8007777	Grant Group	✕
Agricon 3	Liveringa	Fitzroy Trough	Confined	80240013	637591	8008533	Grant Group	✓

Bore ID	Station/community	Project subarea	Confined/ unconfined	AWRC number	Easting	Northing	Aquifer	Logger (2018)
BU15MB002A	Fitzroy Crossing	Lennard Shelf	Unconfined	80200045	772954	7988692	Fitzroy alluvium	✓
BU15MB003	Fitzroy Crossing	Lennard Shelf	Unconfined	80200024	776180	7989177	Fitzroy alluvium	✓
BU15MB004	Fitzroy Crossing	Lennard Shelf	Unconfined	80200025	774229	7988364	Fitzroy alluvium	✓
BS16MB001A	Brooking Springs	Lennard Shelf	Unconfined	80200052	716963	8012492	Grant Group	✓
BS16MB001B	Brooking Springs	Lennard Shelf	Unconfined	80270074	716975	8012513	Grant Group	✓
BS16MB001C	Brooking Springs	Lennard Shelf	Unconfined	80270075	716948	8012513	Grant Group	✓
BS16MB003A	Brooking Springs	Lennard Shelf	Unconfined	80200054	730196	8012174	Grant Group	✓
BS16MB003B	Brooking Springs	Lennard Shelf	Unconfined	80270076	730216	8012190	Grant Group	✓
BS16MB003C	Brooking Springs	Lennard Shelf	Unconfined	80270077	730192	8012199	Grant Group	✓
Gogo Station Homestead Bore 3A	Gogo Station	Lennard Shelf	Unconfined	80211064	773517	7975901	Grant Group	✓
KD16MB001	Kimberley Downs	Lennard Shelf	Unconfined	80300008	667312	8070903	Grant Group	✓
KD16MB002	Kimberley Downs	Lennard Shelf	Unconfined	80300009	674610	8070294	Grant Group	✓
KD16MB003	Kimberley Downs	Lennard Shelf	Unconfined	80300010	683658	8073981	Grant Group	✓
BA04	Gogo Station	Lennard Shelf	Unconfined	80212011	793011	7973754	Devonian reef complex	✓
PT4	Gogo Station	Lennard Shelf	Unconfined	80212103	792592	7973184	Devonian reef complex	✓
PT5	Gogo Station	Lennard Shelf	Unconfined	80212104	792957	7972850	Devonian reef complex	✓
N1 GoGo	Gogo Station	Lennard Shelf	Unconfined	80240017	792759	792759.5	Devonian reef complex	✕

Note: Loggers not installed in the following bores due to use for stock and/or domestic water supply: Montgomery Bore, Agricon 1, Shovelton, Langs Bore, Thomas Bore.

Appendix C Bore survey data

** = Reference point used for water level readings.*

Bore ID	AWRC number	Easting	Northing	Subarea	RL PVC (m AHD)	RL steel casing (m AHD)	GL (m AHD)
LF01	80270063	628832.7	8000538	Fitzroy Trough	43.213*	43.152	41.739
LF02	80270064	627240.6	8002497	Fitzroy Trough	41.692*	41.716	40.456
LF03A	80270065	648157.5	7998262	Fitzroy Trough	48.015*	48.152	46.802
LF03B	80270066	648162	7998260	Fitzroy Trough	47.94*	47.75	46.743
LF04A	80270067	624528.3	8002485	Fitzroy Trough	40.691*	40.677	39.377
LF04B	80270068	624527.2	8002477	Fitzroy Trough	40.665*	40.617	39.377
LF05	80270069	657652.9	7988973	Fitzroy Trough	53.147*	53.324	51.81
LF06	80270070	603728.5	8007103	Fitzroy Trough	53.382*	53.234	52.449
LF07	80270071	606483.9	8011567	Fitzroy Trough	93.775*	93.932	92.687
Agricon 1	80210234	639228.8	8008812	Fitzroy Trough	N/A	44.086*	43.421
Agricon 2	80270062	639197.3	8007777	Fitzroy Trough	N/A	43.974*	43.274
Agricon 3	80240013	637590.8	8008533	Fitzroy Trough	N/A	44.017*	42.817
Shovelton	80210261	633583.5	8015072	Fitzroy Trough	N/A	54.011	53.641
Lightning Bore	80240015	652625.5	7982722	Fitzroy Trough	62.201*	N/A	61.581
Liveringa Stock Bore	80211311	663856.4	7997995	Fitzroy Trough	63.418*	63.381	63.143
Liveringa South	80270072	624252.2	8004072	Fitzroy Trough	N/A	39.368*	39.084
Montgomery	80210233	648214.8	8001942	Fitzroy Trough	51.858*	N/A	51.358
Paradise Bore	80270056	662011	8007073	Fitzroy Trough	N/A	64.122*	63.437
Peglars Bore	80210841	661984.1	8001004	Fitzroy Trough	N/A	71.535*	71.133
RRMW005S	80212098	668340.2	7992909	Fitzroy Trough	74.143*	74.223	73.558
RRMW005D	80212097	668339.9	7992905	Fitzroy Trough	74.033*	74.083	73.333
Hardman Dam Bore	80210323	665785.2	7989159	Fitzroy Trough	N/A	62.288*	62.038
Helens Bore	80240014	644701.5	8006086	Fitzroy Trough	44.514*	N/A	44.076
Leos Bore	80210235	622635.9	8007884	Fitzroy Trough	N/A	63.355*	63.135
Thomas Bore	80240012	606663.4	8009001	Fitzroy Trough	66.245*	65.965	65.565
BD2 02 (BG2)	80211413	583877.2	8019640	Fitzroy Trough	24.543	24.543	24.218
Langs Bore	80210241	604844.1	8006315	Fitzroy Trough	50.924*	50.929	50.444
Homestead – Myroodah	80210699	634475.9	7995826	Fitzroy Trough	54.306*	N/A	53.786
BS16MB001A	80200052	716961	8012492	Lennard Shelf	155.013*	155.008	154.31

Bore ID	AWRC number	Easting	Northing	Subarea	RL PVC (m AHD)	RL steel casing (m AHD)	GL (m AHD)
BS16MB001B	80270074	716974	8012513	Lennard Shelf	155.107*	155.069	154.32
BS16MB001C	80270075	716946.4	8012511	Lennard Shelf	155.258*	155.23	154.4
BS16MB003A	80200054	730196.1	8012174	Lennard Shelf	195.822*	195.763	194.94
BS16MB003B	80270076	730215.7	8012188	Lennard Shelf	195.843*	195.93	195.06
BS16MB003C	80270077	730188.2	8012197	Lennard Shelf	195.537*	195.577	194.75
KD16MB001	80300008	667312.4	8070903	Lennard Shelf	65.701*	65.841	65.02
KD16MB002	80300009	674609.1	8070297	Lennard Shelf	80.546*	80.508	79.67
KD16PB001	80300012	674635.2	8070275	Lennard Shelf	80.75*	80.867	79.96
KD16MB003	80300010	683658.4	8073982	Lennard Shelf	88.67*	88.786	88.05
Homestead 3A – Gogo	80211064	773516.9	7975901	Lennard Shelf	108.153*	N/A	107.64
Homestead 3B – Gogo	NR	773515.3	7975898	Lennard Shelf	108.424*	N/A	107.64
Homestead 3C – Gogo	NR	773437	7975894	Lennard Shelf	109.015*	108.709	N/A
N1 GoGo	80240017	792759.5	7974477	Lennard Shelf	148.003*	N/A	147.513
PT4	80212103	792587.7	7973180	Lennard Shelf	152.432*	N/A	151.967
PT5	80212104	792957.5	7972850	Lennard Shelf	152.049*	N/A	151.469

Note: RL= Reduced level

GL= Ground level

NR = Not recorded

Appendix D Field-measured groundwater parameters

Bore ID	AWRC no.	Date	Easting	Northing	Aquifer	Temp (°C)	pH	EC (µS/cm)	DO (mg/L)	ORP (mV)	Total alkalinity (mg/L CaCO3-)
Peglars Bore	80210841	21/06/2016	661984	8001004	Grant - Poole	32.54	6	1260	3.37	210	69
1-04 Camballin	80200059	30/08/2016	626037	8010432	Grant - Poole	34.64	6.1	321	0.1	57	63
1-04 Camballin	80200059	16/05/2017	626037	8010432	Grant - Poole	35.49	6.7	367	0.74	58	54
2/89 – Fitzroy Crossing	80219066	29/06/2016	771092	7987221	Grant Group	32.39	8.02	501	3.94	93.3	-
2-89 Mount Anderson	80210072	7/09/2016	583953	8019507	Liveringa Group	34.37	5.90	577	0.06	-2	78
5/10 – Fitzroy Crossing	80211372	29/06/2016	772692	7983710	Grant Group	31.62	6.88	568	0.3	-8.5	-
Acacia Tank Flowing Bore	80270084	4/07/2016	790752	7955651	Grant Group	33.00	7.28	1518	0.62	-39.3	217
Agricon 1	80210234	3/08/2017	639229	8008812	Grant - Poole	44.20	7.1	708	0.00	-232	180
Agricon 2	80270062	3/08/2017	639197	8007777	Grant - Poole	47.00	7.2	559	0.01	-257	162
Agricon 3	80240013	2/08/2017	637591	8008533	Grant - Poole	43.10	7.2	683	0.49	-108	204
BA04	80212011	1/07/2016	793011	7973754	Devonian Reef	33.40	6.75	605	1.91	134.9	240
Birdwood Bore	80200055	7/07/2016	763928	7965117	Fitzroy Alluvium	31.00	7.39	304	0.11	-201.2	113
Blue Bush	80210973	5/09/2016	716581	8009451	Grant - Poole	31.64	6.7	538	2.61	140	234
Bore	80210370	6/09/2016	753283	8000596	Fairfield Group	33.67	6.7	878	0.68	-59	> 300
BS16MB001A	80200052	3/07/2017	716963	8012492	Grant - Poole	33.00	6.52	438	3.16		145
BS16MB001B	80270074	2/07/2017	716975	8012513	Grant - Poole	32.60	6.53	449	3.31		145
BS16MB001C	80270075	2/07/2017	716948	8012513	Grant - Poole	32.80	6.55	445	3.11		146
BS16MB003A	80200054	4/07/2017	730196	8012174	Grant - Poole	33.50	6.80	656	3.57		274
BS16MB003B	80270076	4/07/2017	730216	8012190	Grant - Poole	33.40	6.73	629	3.66		271
BS16MB003C	80270077	4/07/2017	730192	8012199	Grant - Poole	33.10	6.82	653	4.25		269
Chestnut Bore	80210428	6/07/2016	780904	7931392	Poole Sandstone	32.70	8.27	1706	5.66	-101.3	156
Donalds Mill No.2	80270085	4/07/2016	779347	7967997	Grant Group	32.90	7.08	1245	3.91	44.3	291
Emanuels Flowing Bore	80270086	5/07/2016	804273	7964344	Devonian Reef	36.50	8.39	1310	0.31	-268.4	301

Bore ID	AWRC no.	Date	Easting	Northing	Aquifer	Temp (°C)	pH	EC (µS/cm)	DO (mg/L)	ORP (mV)	Total alkalinity (mg/L CaCO3-)
Garden Bore	80210704	24/06/2016	636873	7992702	Erskine Sst	35.70	5.5	92	0.11	36	29
Helens Bore	80240014	4/09/2016	644701	8006086	Liveringa Group	33.25	6.6	14616	1.11	-40	> 300
Gogo Station Homestead Bore 3A	80211064	4/07/2016	773517	7975901	Grant - Poole	33.70	7.45	1526	0.06	-170.7	174
Huttons Bore No. 2	80270081	2/07/2016	774907	7922197	Poole Sandstone	34.50	6.81	3083	0.07	-69.8	283
Jarlmadangah 1-02	80200059	26/06/2016	606635	8008606	Grant - Poole	33.63	7.4	377	5.72	82	123
KD16MB002	80300009	5/07/2017	674610	8070294	Grant - Poole	34.60	6.45	424	1.34		151
KD16MB003	80300010	5/07/2017	683658	8073981	Grant - Poole	33.40	6.36	277	3.68		73
Langs Bore	80210241	26/06/2016	604844	8006315	Grant - Poole	33.13	6.7	851	0.27	-76	132
Langs Bore	80210241	8/09/2016	604844	8006315	Grant - Poole	33.47	6.7	829	0.06	-60	153
Langs Bore	80210241	16/05/2017	604844	8006315	Grant - Poole	33.58	6.8	821	0.48	-44	-
Laurel Homestead Bore	80210371	30/06/2016	747341	7996004	Grant - Poole	33.03	6.7	755	2.01	103	282
Leos Bore	80210235	27/06/2016	622636	8007884	Grant - Poole	34.82	6.2	171	0.93	-122	-
Leos Bore	80210235	31/07/2017	622636	8007884	Grant - Poole	34.10	5.7	182	0.93	69	45
LF01	80270063	13/09/2017	628833	8000538	Alluvium	34.30	7.1	679	0.01	-16	174
LF02	80270064	13/09/2017	627241	8002497	Alluvium	32.30	6.5	38912	0.01	32	> 300
LF03A	80270065	14/09/2017	648157	7998262	Noonkanbah Frm	33.80	7.7	2047	0.01	-186	282
LF03B	80270066	14/09/2017	648162	7998260	Alluvium	33.70	7.00	21837	0.01	-177	> 300
LF04A	80270067	12/09/2017	624528	8002485	Noonkanbah Frm	36.40	7.3	2496	0.01	-157	297
LF04B	80270068	13/09/2017	624527	8002477	Alluvium	34.50	6.6	21583	0.02	7	> 300
LF05	80270069	14/09/2017	657653	7988973	Alluvium	32.70	7.6	3148	0.03	-100	> 300
LF06	80270070	12/09/2017	603728	8007103	Grant - Poole	35.80	6.4	12072	0.03	-14	> 300
LF07	80270071	12/09/2017	606484	8011567	Grant - Poole	34.50	6.2	213	3.64	81	42
Liveringa South	80270072	30/07/2017	624252	8004072	Alluvium	34.10	7.1	2025	0.02	-193	282
Looma 1-86	80219133	22/06/2016	621617	8005246	Grant - Poole	32.51	5.3	111	5.35	217	-

Bore ID	AWRC no.	Date	Easting	Northing	Aquifer	Temp (°C)	pH	EC (µS/cm)	DO (mg/L)	ORP (mV)	Total alkalinity (mg/L CaCO3-)
Looma 1-86	80219133	18/05/2017	621617	8005246	Grant - Poole	32.81	5.7	216	5.17	166	18
Looma 1-93	80219134	30/08/2016	619652	8003441	Grant - Poole	33.05	4.3	46	4.42	318	20
Manta Ray Bore	80210901	6/07/2016	752883	7925788	Noonkanbah	33.40	7.08	5610	0.05	-170	226
Montgomery Bore	80210233	23/06/2016	648215	8001942	Grant - Poole	33.00	6.4	452	-	-116	78
No 8 Bore	80210382	30/06/2016	744752	7990143	Grant - Poole	32.80	6.6	474	2.62	45	105
One Tree Bore No.2	80211095	3/07/2016	769371	7955898	Poole Sandstone	37.30	7.86	1593	0.05	-267.5	195
Paradise Bore	80270056	22/06/2016	662011	8007073	Grant - Poole	34.25	7.00	1016	0.07	-98	195
Paradise Bore	80270056	15/08/2017	662011	8007073	Grant - Poole	34.60	7	1210	0.03	-50	210
Peglars Bore	80270056	18/05/2017	661984	8001004	Grant - Poole	33.04	6.4	2407	3.25	168	72
Pilot's Flowing Bore	80270082	2/07/2016	791585	7943193	Grant - Poole	38.50	7.44	1127	0.9	-105.1	181
PT4	80212103	1/07/2016	792592	7973184	Devonian Reef	33.00	6.80	629	1.19	113.1	248
RRMW005D	80212097	17/08/2017	668340	7992905	Liveringa Group	35.60	7	8650	0.01	-122	225
Sallys Bore	80270087	5/07/2016	811799	7956989	Devonian Reef	28.90	7.07	565	3.74	34.5	233
Shovelton	80210261	3/08/2017	633583	8015072	Grant - Poole	51.80	7.2	1372	0.16	-125	210
Tank Bore No.2	80270083	3/07/2016	764532	7929895	Poole Sandstone	32.90	7.81	2636	1.43	-102.6	145
Thomas Bore	80240012	2/09/2016	606663	8009001	Grant - Poole	33.37	6.9	503	0.04	34	126
Thomas Bore	80240012	29/07/2017	606663	8009001	Grant - Poole	34.10	6.9	3684	0.10	22	273

Appendix E Groundwater chemistry

Results of major ion analysis in groundwater (units in mg/L)

Bore ID	Date	Aquifer	TDS	Ca	Mg	Na	K	$SO4^{2-}$	Cl	Tot Alk	Br	NH_3 (mg/L)	NO_2 (mg/L)	NO_3 (mg/L)	TKN (mg/L)	Total N (mg/L)	Total P (mg/L)
Liveringa South	30/07/2017	Alluvium	951	21	11	319	10	0.5	477	234	0.923	0.51	< 0.01	< 0.01	0.6	0.6	< 0.01
LF01	13/09/2017	Alluvium	335	50	16	34	1	16	43	144	0.128	0.01	< 0.01	0.01	< 0.1	< 0.1	0.02
LF02	13/09/2017	Alluvium	23,700	439	610	6,840	15	1,660	12,200	496	27	0.18	< 0.01	< 0.01	0.2	0.2	0.13
LF03B	14/09/2017	Alluvium	10,200	118	100	3,880	25	217	6,470	682	11.9	0.44	< 0.01	0.02	0.5	0.5	0.08
LF04B	13/09/2017	Alluvium	11,000	219	209	3,480	20	169	6,440	657	11.8	0.17	< 0.01	< 0.01	0.2	0.2	0.19
LF05	14/09/2017	Alluvium	1,430	13	10	505	2	292	438	356	1.43	0.09	< 0.01	0.02	0.2	0.2	0.06
Birdwood Bore*	7/07/2016	Alluvium		33	12	11	1.7	2.3	9.5	137	0.099			<0.05			
Garden Bore*	24/06/2016	Erskine Sandstone	60	1	2	9	5	5	10	22	0.043	0.02	< 0.01	0.06	0.1	0.2	0.02
Barefoot Bore	15/09/2017	Erskine Sandstone	292	6	6	60	6	3	92	55	0.355	0.02	< 0.01	3.31	0.5	3.8	< 0.02
Helens Bore*	4/09/2016	Liveringa Group	11,600	187	304	2,870	114	4,200	3,760	472	12.2	1.37	< 0.01	0.02	1.4	1.4	0.08
2-89 Mt Anderson*	7/09/2016	Liveringa Group	342	8	18	72	7	60	133	89	0.384	0.02	0.02	0.15	< 0.1	0.2	< 0.01
RRMW005D	17/08/2017	Liveringa Group	5,190	139	123	1,480	56	1,670	1,460	208	4.82	1.09	< 0.01	0.02	1.1	1.1	0.03
LF03A*	14/09/2017	Noonkanbah Formation	897	11	2	292	8	1	410	227	0.762	0.38	< 0.01	0.01	0.4	0.4	0.02
LF04A	12/09/2017	Noonkanbah Formation	1,080	14	2	357	12	0.5	509	248	0.859	0.62	< 0.01	< 0.01	0.6	0.6	0.08
Manta Ray Bore	6/07/2016	Noonkanbah Formation		109	138	696	75	908	1,215	264	8.26			0.15			
Peglars Bore*	21/06/2016	Poole Sandstone	819	22	23	161	29	106	268	57	1.01	0.01	< 0.01	6.97	2.2	9.2	< 0.01
Peglars Bore*	18/05/2017	Poole Sandstone	688	20.7	20.4	164	33.1	108	293	56	0.984	0.02	< 0.01	7.19	1.1	8.3	0.02
Paradise Bore	22/06/2016	Poole Sandstone	660	47	9	171	26	198	116	179	0.457	0.09	< 0.01	< 0.01	0.2	0.2	< 0.01
Paradise Bore	15/08/2017	Poole Sandstone	681	54	10	146	30	192	117	158	0.417	0.04	< 0.01	0.08	< 0.1	< 0.1	0.02
Montgomery Bore	23/06/2016	Poole Sandstone	294	4	7	50	11	0.5	61	67	0.249	0.03	< 0.01	< 0.01	< 0.1	< 0.1	< 0.01
Langs Bore*	26/06/2016	Poole Sandstone	553	24	16	109	18	75	131	164	0.408	0.04	< 0.01	< 0.01	0.4	0.4	0.02
Langs Bore*	8/09/2016	Poole Sandstone										0.07	0.01	0.08	0.6	0.7	0.02
Langs Bore*	16/05/2017	Poole Sandstone	456	20.2	13.3	106	19.1	67	144	140	0.379	0.12	< 0.01	0.01	0.2	0.2	0.03
Blue Bush*	5/09/2016	Poole Sandstone	298	54	24	24	12	4,200	22	240	0.104	0.02	< 0.01	0.47	0.2	0.7	< 0.01
1-04 Camballin*	30/08/2016	Poole Sandstone	192	7	10	46	18	36	38	61	0.13	0.03	< 0.01	0.05	0.2	0.2	0.1
1-04 Camballin*	16/05/2017	Poole Sandstone	216	4.8	5.6	40.6	17.8	34	49	55	0.157	0.05	< 0.01	< 0.01	0.2	0.2	0.07

Bore ID	Date	Aquifer	TDS	Ca	Mg	Na	K	$SO4^{2-}$	Cl	Tot Alk	Br	NH_3 (mg/L)	NO_2 (mg/L)	NO_3 (mg/L)	TKN (mg/L)	Total N (mg/L)	Total P (mg/L)
LF06	12/09/2017	Poole Sandstone	7,100	381	404	1,220	65	1,820	2,390	308	6.57	0.02	< 0.01	0.04	< 0.1	< 0.1	0.01
Huttons Bore No.2*	2/07/2016	Poole Sandstone		100	112	378	27	357	555	320	3.072			0.19			
Pilots Flowing Bore	2/07/2016	Poole Sandstone		35	8.7	189	10	34	185	225	1.106			<0.05			
Tank Bore No.2	3/07/2016	Poole Sandstone		38	17	500	5	330	683	173	3.096			0.23			
One Tree Bore No.2	3/07/2016	Poole Sandstone		17	3	323	4.9	54	371	200	2.384			<0.05			
Chestnut Bore	6/07/2016	Poole Sandstone		15	8.1	334	5	194	379	178	2.648			2.3			
No. 8 Bore	30/06/2016	Poole Sandstone	308	30	10	40	8	47	44	97	0.21	0.02	< 0.01	0.21	0.7	0.9	0.01
Shovelton*	3/08/2017	Grant Group	521	13	7	162	15	57	105	220	0.398	0.51	< 0.01	< 0.01	0.7	0.7	< 0.01
Looma 1-86	22/06/2016	Grant Group	72	0.5	2	14	7	4	18	14	0.067	0.02	< 0.01	1.06	0.3	1.4	< 0.01
Acacia Tank Flowing Bore	4/07/2016	Grant Group		18	8	301	19	132	287	267	1.983			<0.05			
Looma 1-86	18/05/2017	Grant Group	56	0.6	1.2	13	6.9	3	17	13	0.064	0.02	< 0.01	0.97	0.3	1.3	0.01
Jarlmadangah 1-02	26/06/2016	Grant Group	245	19	5	52	9	20	17	143	0.005	< 0.01	< 0.01	3.46	0.7	4.2	0.02
Leos Bore*	27/06/2016	Grant Group	111	3	2	9	3	0.5	13	23	0.063	2.43	0.02	0.26	3.2	3.5	0.04
Leos Bore*	31/07/2017	Grant Group	319	0.5	3	27	7	0.5	23	40	0.064	0.03	< 0.01	1.98	0.5	2.5	< 0.01
Laurel Homestead Bore	30/06/2016	Grant Group	491	116	6	20	7	22	34	266	0.024	< 0.01	< 0.01	2.48	0.5	3	0.03
Looma 1-93*	30/08/2016	Grant Group	24	0.5	0.5	4	1	1	8	3	0.028	< 0.01	< 0.01	0.83	0.3	1.1	0.01
Thomas Bore*	2/09/2016	Grant Group	304	48	13	31	16	32	66	134	0.247	0.03	< 0.01	0.28	0.2	0.5	0.02
Thomas Bore*	29/07/2017	Grant Group	2,230	137	74	365	81	57	916	244	3.72	0.02	< 0.01	4.59	0.7	5.3	< 0.01
Agricon 1	3/08/2017	Grant Group	302	14	2	97	16	15	29	205	0.105	0.36	< 0.01	< 0.01	0.4	0.4	< 0.01
Agricon 2*	3/08/2017	Grant Group	204	12	2	64	12	7	21	186	0.072	0.68	< 0.01	< 0.01	0.8	0.8	< 0.01
Agricon 3	2/08/2017	Grant Group	273	17	2	91	17	13	28	174	0.106	0.42	< 0.01	< 0.01	0.5	0.5	< 0.01
LF07	12/09/2017	Grant Group	114	6	3	15	8	13	17	34	0.557	0.02	< 0.01	0.7	0.2	0.9	0.02
2/89 – Fitzroy Crossing*	29/06/2016	Grant Group		52	12	35	4	9.8	45	190	0.272			6.61			
5/10 – Fitzroy Crossing*	29/06/2016	Grant Group		70	23	14	2.2	27	43	211	0.29			3.94			
Donald's Mill No. 2*	4/07/2016	Grant Group		84	29	138	9.9	47	184	353	1.152			4.37			

Bore ID	Date	Aquifer	TDS	Ca	Mg	Na	K	$SO4^{2-}$	Cl	Tot Alk	Br	NH_3 (mg/L)	NO_2 (mg/L)	NO_3 (mg/L)	TKN (mg/L)	Total N (mg/L)	Total P (mg/L)
Gogo Station Homestead Bore 3A	4/07/2016	Grant Group		67	28	204	15	134	328	211	2.362			0.07			
BS16MB001A	3/07/2017	Grant Group	281.16	44	11	20	4.7	11	29	160	0.068			0.43		0.7	
BS16MB001B	2/07/2017	Grant Group	285.12	46	11	20	4.8	12	30	180	0.084			0.4		0.6	
BS16MB001C	2/07/2017	Grant Group	280.5	46	11	20	4.6	11	29	193	0.074			0.42		0.7	
BS16MB003A	4/07/2017	Grant Group	417.78	102	11	16	3.4	17	17	294	0.005			0.08		0.1	
BS16MB003B	4/07/2017	Grant Group	400.62	93	12	16	3.8	15	16	286	0.005			0.1		0.2	
BS16MB003C	4/07/2017	Grant Group	411.18	100	12	17	3.8	16	17	293	0.005			0.09		0.2	
KD16MB002	5/07/2017	Grant Group	268.62	48	11	14	8.2	9.2	23	163	0.063			0.18		0.3	
KD16MB003	5/07/2017	Grant Group	175.56	18	5.3	23	2.2	6	29	83	0.085			0.42		0.6	
Bore	6/09/2016	Fairfield Group	510	100	29	39	5	42	76	360	0.208	0.12	< 0.01	0.17	0.2	0.4	< 0.01
BA04	1/07/2016	Devonian reef		130	1.1	3.1	1.6	1.9	6	297	0.005			2.89			
PT4	1/07/2016	Devonian reef		135	1.7	2.9	0.9	3	7.7	309	0.005			1.51			
Emanuels Flowing Bore	5/07/2016	Devonian reef		1.7	0.9	267	3.5	125	79	353	0.32			<0.05			
Sallys Bore	5/07/2016	Devonian reef		118	1.1	2.8	1.7	3.7	8.9	283	0.005			1.49			

Note: TDS not measured for CSIRO collected samples.

* Data not included in calculations for data quality reasons.

Appendix F Saturation Indices

Bore ID	Sample date	Structural setting	Aquifer	Calcite	Dolomite	Gypsum	Halite
Liveringa South	30/07/2017	Fitzroy Trough	Alluvium	-0.42	-0.68	-4.51	-5.42
LF01	13/09/2017	Fitzroy Trough	Alluvium	-0.22	-0.5	-2.5	-7.4
LF02	13/09/2017	Fitzroy Trough	Alluvium	-0.03	0.52	-0.68	-2.88
LF03B	14/09/2017	Fitzroy Trough	Alluvium	0.19	0.76	-1.81	-3.36
LF04B	13/09/2017	Fitzroy Trough	Alluvium	0.03	0.51	-1.69	-3.41
LF05	14/09/2017	Fitzroy Trough	Alluvium	-0.18	-0.07	-2.08	-5.28
Birdwood Bore*	7/07/2016	Lennard Shelf	Alluvium	-0.27	-0.57	-3.44	-8.53
BU15MB002A	23/08/2018	Lennard Shelf	Alluvium	-0.26	-0.49	-1.79	-5.77
BU15MB003	23/08/2018	Lennard Shelf	Alluvium	-0.56	-1.26	-2.53	-7.74
BU15MB004	23/08/2018	Lennard Shelf	Alluvium	-0.44	-1.11	-2.63	-7.46
Garden Bore*	24/06/2016	Fitzroy Trough	Erskine Sandstone	-4.14	-7.53	-4.44	-8.57
Barefoot Bore	15/09/2017	Fitzroy Trough	Erskine Sandstone	-2.5	-4.56	-4.02	-6.81
Bore	6/09/2016	Lennard Shelf	Fairfield Group	-0.11	-0.32	-1.92	-7.12
Helens Bore*	4/09/2016	Fitzroy Trough	Liveringa Group	-0.37	-0.16	-0.48	-3.74
2-89 Mt Anderson*	7/09/2016	Fitzroy Trough	Liveringa Group	-2.55	-4.31	-2.7	-6.59
RRMW005D	17/08/2017	Fitzroy Trough	Liveringa Group	-0.14	0.07	-0.73	-4.38
LF03A*	14/09/2017	Fitzroy Trough	Noonkanbah Formation	-0.15	-0.59	-4.44	-5.52
LF04A	12/09/2017	Fitzroy Trough	Noonkanbah Formation	-0.35	-1.08	-4.67	-5.35
Manta Ray Bore	6/07/2016	Lennard Shelf	Noonkanbah Formation	-0.13	0.24	-0.97	-4.75
Peglars Bore*	21/06/2016	Fitzroy Trough	Poole Sandstone	-2.2	-3.69	-2.13	-5.95
Peglars Bore*	18/05/2017	Fitzroy Trough	Poole Sandstone	-1.76	-3.12	-2.14	-5.91
Paradise Bore	22/06/2016	Fitzroy Trough	Poole Sandstone	-0.39	-1.08	-1.56	-6.3
Paradise Bore	15/08/2017	Fitzroy Trough	Poole Sandstone	-0.34	-0.99	-1.52	-6.36
Montgomery	23/06/2016	Fitzroy Trough	Poole Sandstone	-2.26	-3.84	-4.96	-7.06
Langs Bore*	26/06/2016	Fitzroy Trough	Poole Sandstone	-1.06	-1.88	-2.18	-6.42
Langs Bore*	16/05/2017	Fitzroy Trough	Poole Sandstone	-1.02	-1.79	-2.29	-6.39
LF06	12/09/2017	Fitzroy Trough	Poole Sandstone	-0.2	0.05	-0.4	-4.27
1-04 Camballin	30/08/2016	Fitzroy Trough	Poole Sandstone	-2.43	-4.26	-2.9	-7.31
1-04 Camballin	16/05/2017	Fitzroy Trough	Poole Sandstone	-2.11	-3.7	-3.06	-7.25
Irrigation Bore*	21/08/2018	Fitzroy Trough	Poole Sandstone	-0.3	-0.36	-1.73	-6.15
Blue Bush*	5/09/2016	Lennard Shelf	Poole Sandstone	1.98	3.83	0.01	-8.01

Bore ID	Sample date	Structural setting	Aquifer	Calcite	Dolomite	Gypsum	Halite
Huttons Bore No.2	2/07/2016	Lennard Shelf	Poole Sandstone	-0.21	0.05	-1.26	-5.32
Pilots Flowing Bore	2/07/2016	Lennard Shelf	Poole Sandstone	0	-0.13	-2.38	-6.05
Tank Bore No.2	3/07/2016	Lennard Shelf	Poole Sandstone	0.08	0.21	-1.59	-5.1
One Tree Bore No.2	3/07/2016	Lennard Shelf	Poole Sandstone	0.08	-0.13	-2.54	-5.53
Chestnut Bore	6/07/2016	Lennard Shelf	Poole Sandstone	0.22	0.58	-2.11	-5.51
No. 8 Bore	30/06/2016	Lennard Shelf	Poole Sandstone	-1.2	-2.45	-2.21	-7.31
Shovelton	3/08/2017	Fitzroy Trough	Grant Group	-0.48	-0.71	-2.53	-6.36
Looma 1-86	22/06/2016	Fitzroy Trough	Grant Group	-4.97	-8.91	-4.84	-8.12
Jarlmadangah 1-02	26/06/2016	Fitzroy Trough	Grant Group	-0.42	-0.99	-2.72	-7.6
Leos Bore*	27/06/2016	Fitzroy Trough	Grant Group	-3.04	-5.8	-4.96	-8.45
Looma 1-93*	30/08/2016	Fitzroy Trough	Grant Group	-5.78	-11.14	-5.4	-9.01
Thomas Bore*	2/09/2016	Fitzroy Trough	Grant Group	-0.53	-1.2	-2.21	-7.25
Looma 1-86	18/05/2017	Fitzroy Trough	Grant Group	-4.35	-7.97	-4.88	-8.17
Thomas Bore*	29/07/2017	Fitzroy Trough	Grant Group	0	0.18	-1.88	-5.12
Leos Bore*	31/07/2017	Fitzroy Trough	Grant Group	-4.07	-6.92	-5.78	-7.74
Agricon 3	2/08/2017	Fitzroy Trough	Grant Group	-0.41	-1.26	-2.98	-7.16
Agricon 1	3/08/2017	Fitzroy Trough	Grant Group	-0.58	-1.51	-2.99	-7.12
Agricon 2*	3/08/2017	Fitzroy Trough	Grant Group	-0.6	-1.46	-3.35	-7.43
LF07	12/09/2017	Fitzroy Trough	Grant Group	-2.54	-4.95	-3.3	-8.12
Acacia Tank Flowing Bore	4/07/2016	Lennard Shelf	Grant Group	-0.5	-0.93	-2.16	-5.67
Laurel Homestead Bore	30/06/2016	Lennard Shelf	Grant Group	-0.08	-1.01	-2.08	-7.75
2/89 (Water Corp)	29/06/2016	Lennard Shelf	Grant Group	0.73	1.25	-2.7	-7.37
5/10 (Water Corp)	29/06/2016	Lennard Shelf	Grant Group	-0.25	-0.57	-2.18	-7.79
Donalds Mill No.2	4/07/2016	Lennard Shelf	Grant Group	0.12	0.2	-1.97	-6.19
Gogo Station Homestead Bore 3A	4/07/2016	Lennard Shelf	Grant Group	0.15	0.34	-1.64	-5.78
BS16MB001A	3/07/2017	Lennard Shelf	Grant Group	-0.91	-1.99	-2.67	-7.79
BS16MB001B	2/07/2017	Lennard Shelf	Grant Group	-0.89	-1.97	-2.62	-7.78
BS16MB001C	2/07/2017	Lennard Shelf	Grant Group	-0.86	-1.91	-2.66	-7.79
BS16MB003A	4/07/2017	Lennard Shelf	Grant Group	-0.04	-0.61	-2.23	-8.14
BS16MB003B	4/07/2017	Lennard Shelf	Grant Group	-0.15	-0.75	-2.32	-8.17
BS16MB003C	4/07/2017	Lennard Shelf	Grant Group	-0.04	-0.57	-2.27	-8.12
KD16MB002	5/07/2017	Lennard Shelf	Grant Group	-0.9	-2	-2.72	-8.05
KD16MB003	5/07/2017	Lennard Shelf	Grant Group	-1.7	-3.5	-3.22	-7.72
BA04	1/07/2016	Lennard Shelf	Devonian reef	-0.03	-1.7	-3.07	-9.31

Bore ID	Sample date	Structural setting	Aquifer	Calcite	Dolomite	Gypsum	Halite
PT4	1/07/2016	Lennard Shelf	Devonian reef	0.04	-1.39	-2.86	-9.23
Emanuels Flowing Bore	5/07/2016	Lennard Shelf	Devonian reef	-0.26	-0.33	-3.18	-6.27
Sallys Bore	5/07/2016	Lennard Shelf	Devonian reef	0.18	-1.28	-2.8	-9.17

Appendix G River sample locations

Samples collected between Willare and Looma gauging stations, Fitzroy River.

Site ID	AWRC	Easting	Northing	Sample location
LF1	8021031	568205	8039551	Fitzroy River
LF2	8021032	576426	8026250	Fitzroy River
LF3	8021033	578204	8022107	Fitzroy River
LF4	8021034	578906	8019686	Fitzroy River
LF5	8021035	578884	8017934	Fitzroy River
LF6	8021036	581261	8014222	Fitzroy River
LF7	8021037	583928	8010025	Fitzroy River
LF8	8021038	584749	8008773	Fitzroy River
LF9	8021039	587415	8007096	Fitzroy River
LF10	8021040	587539	8006747	Fitzroy River
LF11	8021041	591221	8004129	Fitzroy River
LF12	8021042	594528	8000680	Fitzroy River
LF13	8021043	599359	7999733	Fitzroy River
LF14	8021044	602184	7996103	Fitzroy River
LF15	8021045	613746	7998388	Off-channel pool
LF16	8021046	617097	7998413	Off-channel pool
LF17	8021047	619395	7997832	Fitzroy River

Samples collected between Looma and Fitzroy Barrage gauging stations, Fitzroy River.

Site ID	AWRC	Easting	Northing	Sample location
LF18	8021048	622911	7997887	Fitzroy River
LF19	8021049	624907	7998688	Fitzroy River
LF20	8021050	625818	7999830	Fitzroy River
LF21	8021051	626868	8000412	Fitzroy River
LF22	8021052	627475	8000155	Fitzroy River
LF23	8021053	628344	8000109	Fitzroy River
LF24	8021054	624594	8004239	Off-channel pool – Liveringa Pool
LF25	8021055	631007	8000131	Fitzroy River
LF26	8021056	636836	7999043	Fitzroy River
LF27	8021057	637027	7997007	Off-channel pool
LF28	8021058	635682	8005748	Off-channel pool – Uralla Creek
LF29	8021059	642241	8002520	Off-channel pool
LF30	8021060	646570	7999507	Off-channel pool – Uralla Creek
LF31	8021061	648112	7997020	Fitzroy River
LF32	8021062	648839	7995896	Fitzroy River
LF33	8021063	647215	7992459	Off-channel pool
LF34	8021064	654959	7989940	Fitzroy River
LF35	8021065	657578	7988795	Fitzroy River
LF36	8021066	657153	7983900	Fitzroy River
LF37	8021067	658997	7990102	Off-channel pool – Troys Lagoon

Samples collected between Margaret Gorge and Fitzroy Crossing, Margaret River.

Site ID	AWRC	Easting	Northing	Sample location
LF38	8021068	216277	7979478	Margaret River
LF39	8021069	209519	7980365	Margaret River
LF40	8021070	831159	7969779	Margaret River
LF41	8021071	809583	7976072	Margaret River
LF42	8021072	796306	7989025	Margaret River
LF43	8021073	791612	7990555	Margaret River

Samples collected between Fitzroy Crossing and Noonkanbah gauging stations, Fitzroy River.

Site ID	AWRC	Easting	Northing	Sample location
LF44	8021074	792130	8005261	Fitzroy River
LF45	8021075	790511	8003488	Fitzroy River
LF46	8021076	789653	8001525	Fitzroy River
LF47	8021077	774495	7987980	Fitzroy River
LF48	8021078	772881	7984630	Fitzroy River
LF49	8021079	769636	7982121	Fitzroy River
LF50	8021080	772780	7976247	Off-channel pool
LF51	8021081	767375	7976134	Fitzroy River – Alligator Pool
LF52	8021082	764390	7968094	Fitzroy River
LF53	8021083	763689	7965233	Fitzroy River
LF54	8021084	743416	7968759	Cunningham River
LF55	8021085	738447	7963270	Cunningham River
LF56	8021086	746701	7954776	Fitzroy River
LF57	8021087	758275	7937343	Cherrabun Creek
LF58	8021088	743306	7951845	Fitzroy River
LF59	8021089	739514	7953211	Fitzroy River
LF60	8021090	736465	7951685	Fitzroy River
LF61	8021091	732138	7952431	Fitzroy River
LF62	8021092	727942	7950477	Fitzroy River
LF63	8021093	723517	7952516	Fitzroy River
LF64	8021094	718628	7952192	Fitzroy River
LF65	8021095	713819	7952019	Fitzroy River
LF66	8021096	709723	7949870	Fitzroy River
LF67	8021097	705141	7950289	Fitzroy River
LF68	8021098	700670	7950278	Fitzroy River
LF69	8021099	698384	7950925	Fitzroy River
LF70	8021100	696080	7950956	Fitzroy River

Samples collected between Noonkanbah and Fitzroy Barrage gauging stations, Fitzroy River.

Site ID	AWRC	Easting	Northing	Sample location
LF71	8021101	695773	7952258	Fitzroy River
LF72	8021102	691573	7950956	Fitzroy River
LF73	8021103	689629	7950608	Fitzroy River
LF74	8021104	689445	7953339	Fitzroy River
LF75	8021105	684865	7949668	Off-channel pool
LF76	8021106	684947	7955332	Fitzroy River
LF77	8021107	683226	7955948	Fitzroy River
LF78	8021108	676520	7954608	Fitzroy River
LF79	8021109	673584	7957945	Fitzroy River
LF80	8021110	671116	7960468	Fitzroy River

Appendix H River chemistry

ID	AWRC	Sample date	Sample time	Temp (°C)	Field pH	Lab pH	Field EC (µS/cm)	Lab EC (µS/cm)	Total alk (mg/L $CaCO_3$)	Cl^- mg/L	Br^- mg/L	$SO_4^{=}$ mg/L	Ca mg/L	K mg/L	Mg mg/L	Na mg/L	NPOC mg/L	TN mg/L	NO_3^- mg/L
LF1	8021031	14/06/2017	8:14:00 AM	19.5	7.74	8.92	531	457	180.6	56	0.15	21	31	2	17	33	2	0.2	<0.05
LF2	8021032	14/06/2017	8:20:00 AM	18.6	7.53	8.75	531	469	167.2	45	0.09	17	32	2	18	34	0.9	0.1	<0.05
LF3	8021033	14/06/2017	8:25:00 AM	18.7	7.68	8.69	534	471	160.2	38	0.07	14	32	2	18	35	0.6	0.1	<0.05
LF4	8021034	14/06/2017	8:30:00 AM	19.3	7.95	8.6	545	467	156	37	0.07	13	32	2.1	18	35	1.9	0.1	<0.05
LF5	8021035	14/06/2017	8:35:00 AM	19.3	7.68	8.49	546	472	153	46	0.09	18	32	2	18	35	0.7	0.1	<0.05
LF6	8021036	14/06/2017	8:40:00 AM	18.1	7.72	8.46	531	475	151.4	42	0.07	15	32	2	18	34	1.9	0.2	0.06
LF7	8021037	14/06/2017	8:45:00 AM	18.3	7.81	8.44	535	473	149.5	40	0.06	15	32	2	18	35	1.9	0.1	0.06
LF8	8021038	14/06/2017	8:50:00 AM	18.5	7.83	8.46	536	475	149.1	42	0.06	15	32	2	18	35	1.3	0.1	<0.05
LF9	8021039	14/06/2017	9:00:00 AM	19	7.82	8.44	543	475	148.3	47	0.08	18	33	2	18	35	2.1	0.1	<0.05
LF10	8021040	14/06/2017	9:05:00 AM	19.1	7.85	8.43	544	473	148.3	47	0.09	19	33	2	18	35	1.1	0.1	<0.05
LF11	8021041	14/06/2017	9:15:00 AM	19.1	7.88	8.44	545	474	147.3	48	0.09	19	33	1.9	18	35	1.3	0.1	<0.05
LF12	8021042	14/06/2017	9:20:00 AM	18.4	7.92	8.41	536	476	148.1	44	0.09	17	33	1.8	18	34	1.2	0.1	<0.05
LF13	8021043	14/06/2017	9:30:00 AM	18.6	7.85	8.41	538	477	147.9	47	0.1	19	33	1.9	18	35	1.2	0.1	<0.05
LF14	8021044	14/06/2017	9:35:00 AM	18.6	7.88	8.39	542	477	148.1	48	0.09	20	33	1.9	18	35	1.2	0.1	<0.05
LF15	8021045	14/06/2017	9:40:00 AM	18.8	7.86	8.17	547	481	180.4	33	<0.05	12	34	2	15	47	3.2	0.3	<0.05
LF16	8021046	14/06/2017	9:50:00 AM	18.7	8.83	7.73	1066	964	175.4	167	0.28	34	19	2	14	167	5	2.2	0.19
LF17	8021047	14/06/2017	10:00:00 AM	19.2	8.07	8.35	562	490	149.3	43	0.08	16	33	1.8	18	36	1.9	0.1	<0.05
LF18	8021048	14/06/2017	10:10:00 AM	19.1	8.07	8.36	564	492	149.5	48	0.1	19	34	1.8	19	37	1.3	0.1	<0.05
LF19	8021049	14/06/2017	10:15:00 AM	19.2	8.06	8.33	568	490	149.9	51	0.12	21	33	1.8	18	37	0.7	0.1	<0.05
LF20	8021050	14/06/2017	10:20:00 AM	19.4	8.1	8.34	573	498	150.2	52	0.12	21	34	1.8	19	37	1.9	0.1	<0.05
LF21	8021051	14/06/2017	10:30:00 AM	19.5	8.14	8.32	573	497	149.7	53	0.12	21	34	1.8	19	37	1.9	0.1	<0.05
LF22	8021052	14/06/2017	10:40:00 AM	19.4	8.1	8.33	575	501	150.4	53	0.12	22	34	1.8	19	37	1.9	0.2	<0.05
LF23	8021053	14/06/2017	10:50:00 AM	19.3	8.19	8.35	575	501	150.2	54	0.12	22	34	1.8	19	38	1.2	0.1	<0.05
LF24	8021054	14/06/2017	11:00:00 AM	19.7	7.93	7.77	182	159	70.5	3.8	<0.05	1.3	14	2.2	6.6	7.8	4.6	0.5	0.51
LF25	8021055	14/06/2017	11:05:00 AM	19.9		8.32	584	502	149.3	49	0.11	19	34	1.8	19	38	1.9	0.1	<0.05
LF26	8021056	14/06/2017	11:10:00 AM	19.4		8.32	588	508	150.8	51	0.12	19	35	1.8	19	39	1.9	0.1	<0.05
LF27	8021057	14/06/2017	11:15:00 AM	19.1		8.18	349	307	118.1	19	<0.05	6.1	26	2.5	11	18	2.4	0.3	<0.05
LF28	8021058	14/06/2017	11:20:00 AM	18.6		8.29	500	442	145.9	41	0.09	17	31	1.8	18	30	2.3	0.2	<0.05

ID	AWRC	Sample date	Sample time	Temp (°C)	Field pH	Lab pH	Field EC (µS/cm)	Lab EC (µS/cm)	Total alk (mg/L $CaCO_3$)	Cl^- mg/L	Br^- mg/L	$SO_4^=$ mg/L	Ca mg/L	K mg/L	Mg mg/L	Na mg/L	NPOC mg/L	TN mg/L	NO_3^- mg/L
LF29	8021059	14/06/2017	11:25:00 AM	18.3		8.73	137	123	62.5	1.5	<0.05	0.12	9.3	1.2	5.6	6.6	5.5	0.4	<0.05
LF30	8021060	14/06/2017	11:30:00 AM	18.1		8.31	558	497	150.8	53	0.12	22	34	1.8	19	37	2.2	0.1	<0.05
LF31	8021061	14/06/2017	11:35:00 AM	19.6		8.34	600	514	150.8	58	0.12	24	35	1.8	19	40	0.8	0.1	<0.05
LF32	8021062	14/06/2017	11:43:00 AM	20.4		8.36	612	519	151	58	0.13	24	35	1.8	19	40	2	0.1	<0.05
LF33	8021063	14/06/2017	11:55:00 AM	18.1		7.24	48	45	20	1.5	<0.05	0.23	2	3.6	1.3	2.1	5	0.8	0.77
LF34	8021064	14/06/2017	12:00:00 PM	19.1		8.34	605	532	151.8	61	0.14	26	35	1.8	19	41	1.4	0.1	<0.05
LF35	8021065	14/06/2017	12:05:00 PM	19.6		8.32	619	534	152.6	61	0.14	25	35	1.7	19	42	1.3	0.1	<0.05
LF36	8021066	14/06/2017	12:12:00 PM	19.2		8.35	621	540	152.2	62	0.14	27	36	1.7	20	43	0.9	0.1	<0.05
LF37	8021067	14/06/2017	12:26:00 PM	18.6		7.49	82	78	33.6	2.1	<0.05	0.12	7.4	3.6	2.7	2.2	5.5	0.5	0.42
LF38	8021068	14/06/2017	2:58:00 PM	20		8.22	343	292	128.5	9.8	<0.05	2.8	25	2.5	13	15	1	0.1	<0.05
LF39	8021069	14/06/2017	3:05:00 PM	20.4		8.41	646	538	261.9	15	<0.05	3.1	43	2.7	31	30	2.3	0.2	<0.05
LF40	8021070	14/06/2017	3:12:00 PM	20.4		8.38	483	410	192.4	13	<0.05	3.1	34	2.8	21	21	2	0.1	<0.05
LF41	8021071	14/06/2017	3:27:00 PM	20.7		8.38	413	346	162.6	11	<0.05	2.8	29	2.8	17	17	1.1	0.2	<0.05
LF42	8021072	14/06/2017	3:37:00 PM	20.5		8.35	405	328	152.8	9.7	<0.05	2.7	29	2.6	16	16	1.4	0.2	<0.05
LF43	8021073	14/06/2017	3:45:00 PM	20.3		8.36	381	323	150.4	9.4	<0.05	2.5	29	2.7	16	15	0.9	0.2	<0.05
LF44	8021074	14/06/2017	3:57:00 PM	20.6	8.49	8.18	411	344	156	12	<0.05	4.7	25	1.1	21	16	1.9	0.3	0.08
LF45	8021075	14/06/2017	4:02:00 PM	20	8.26	8.2	410	347	160.2	11	<0.05	4.5	27	1.1	20	16	2.3	0.2	0.08
LF46	8021076	14/06/2017	4:05:00 PM	20.5	8.09	8.24	420	354	164.2	11	<0.05	4.5	29	1.1	20	15	2.6	0.2	<0.05
LF47	8021077	14/06/2017	4:21:00 PM	20.4	8.56	8.34	412	344	163	9.9	<0.05	3.8	33	1.6	17	14	1.9	0.2	<0.05
LF48	8021078	15/06/2017	7:48:00 AM	18.8	8.56	8.29	399	349	162.4	10	<0.05	3.8	34	1.5	17	13	2.2	0.2	<0.05
LF49	8021079	15/06/2017	7:52:00 AM	18.9	8.38	8.33	396	346	161.4	10	<0.05	3.8	34	1.6	17	13	2.3	0.2	<0.05
LF50	8021080	15/06/2017	7:58:00 AM	17.2	8.2	8.17	411	377	167.6	6.8	<0.05	15	59	5.2	9	7	4.9	0.7	0.91
LF51	8021081	15/06/2017	8:03:00 AM	19.6	8.21	8.32	395	338	157.4	10	<0.05	3.8	33	1.6	17	13	2.2	0.2	<0.05
LF52	8021082	15/06/2017	8:14:00 AM	19.1	8.09	8.31	383	332	154.6	10	<0.05	3.8	31	1.7	17	13	1.6	0.2	<0.05
LF53	8021083	15/06/2017	8:25:00 AM	20.1	7.95	8.32	390	329	153.6	10	<0.05	3.7	31	1.7	16	13	1.6	0.2	<0.05
LF54	8021084	15/06/2017	8:36:00 AM	19.7	7.88	8.28	439	376	174	9.9	<0.05	6.2	43	2.4	16	12	2.6	0.3	0.25
LF55	8021085	15/06/2017	8:41:00 AM	19.1	8.1	8.3	353	308	144.5	6.9	<0.05	3.9	34	2.2	13	11	2.7	0.2	<0.05
LF56	8021086	15/06/2017	8:49:00 AM	19	8.17	8.28	389	341	151.4	13	<0.05	5.2	31	1.7	17	14	2.2	0.2	<0.05
LF57	8021087	15/06/2017	9:02:00 AM	15.9	8.14	8.23	3901	3626	188.2	925	2.98	251	147	13	63	511	4.7	0.4	0.07
LF58	8021088	15/06/2017	9:12:00 AM	19.2	8.33	8.36	400	352	152.2	16	<0.05	6.1	32	1.7	17	16	2.3	0.1	<0.05

ID	AWRC	Sample date	Sample time	Temp (°C)	Field pH	Lab pH	Field EC (µS/cm)	Lab EC (µS/cm)	Total alk (mg/L $CaCO_3$)	Cl^- mg/L	Br^- mg/L	$SO_4^=$ mg/L	Ca mg/L	K mg/L	Mg mg/L	Na mg/L	NPOC mg/L	TN mg/L	NO_3^- mg/L
LF59	8021089	15/06/2017	9:16:00 AM	18.6	8.3	8.3	400	355	151.6	17	<0.05	6.6	31	1.7	17	16	2.5	0.1	<0.05
LF60	8021090	15/06/2017	10:42:00 AM	19		8.32	412	359	151.8	18	<0.05	7	32	1.7	17	16	2.7	0.2	<0.05
LF61	8021091	15/06/2017	10:52:00 AM	19.3		8.28	415	412	154	32	0.08	13	33	1.7	18	23	4.2	0.2	<0.05
LF62	8021092	15/06/2017	11:01:00 AM	20.2		8.31	475	505	158.4	54	0.14	24	35	1.7	19	37	3.4	0.1	<0.05
LF63	8021093	15/06/2017	11:10:00 AM	18.9	8.56	8.28	649	561	158.2	70	0.18	31	36	1.8	20	47	2.7	0.1	<0.05
LF64	8021094	15/06/2017	11:19:00 AM	20.3	8.53	8.27	699	586	158.2	79	0.2	36	37	1.7	21	49	1.2	0.1	<0.05
LF65	8021095	15/06/2017	11:30:00 AM	19.4	8.53	8.28	696	596	159.4	82	0.21	38	38	1.7	21	50	2.5	0.1	<0.05
LF66	8021096	15/06/2017	11:42:00 AM	20.5	8.66	8.3	709	596	158.8	82	0.21	37	38	1.8	21	50	1.2	0.1	<0.05
LF67	8021097	15/06/2017	11:52:00 AM	19.6	8.71	8.32	694	601	159.2	83	0.21	37	38	1.8	21	51	1.3	0.1	0.06
LF68	8021098	15/06/2017	12:02:00 PM	20.3	8.56	8.28	699	598	158.2	80	0.21	36	38	1.8	21	51	3	0.2	0.1
LF69	8021099	15/06/2017	12:07:00 PM			8.25		598	158.6	80	0.21	36	37	1.7	20	50	2.4	0.2	<0.05
LF70	8021100	15/06/2017	12:12:00 PM	No sample collected															
LF71	8021101	15/06/2017	12:17:00 PM	20.1	8.8	8.31	693	586	158.2	79	0.21	35	37	1.7	21	49	2.6	0.1	<0.05
LF72	8021102	15/06/2017	2:01:00 PM	20.1		8.29	686	594	160	79	0.2	36	38	1.8	20	49	2.2	0.1	<0.05
LF73	8021103	15/06/2017	2:10:00 PM	20		8.32	683	586	158.2	79	0.2	35	37	1.8	20	48	2.3	0.1	<0.05
LF74	8021104	15/06/2017	2:14:00 PM	21.1		8.27	699	586	158.8	80	0.21	36	37	1.8	20	47	1.5	0.1	<0.05
LF75	8021105	15/06/2017	2:24:00 PM	20.2		7.86	827	711	68.7	172	0.29	51	19	3.6	8	107	2.2	0.1	0.35
LF76	8021106	15/06/2017	2:29:00 PM	20		8.33	681	586	157.6	82	0.22	36	37	1.8	20	48	3.9	0.3	<0.05
LF77	8021107	15/06/2017	2:33:00 PM	20		8.3	673	581	157.8	80	0.22	35	37	1.8	20	47	1.4	0.1	<0.05
LF78	8021108	15/06/2017	2:38:00 PM	20.6		8.12	667	558	149.1	77	0.21	33	36	1.8	20	45	1.9	0.1	<0.05
LF79	8021109	15/06/2017	2:49:00 PM	20.8		8.25	666	557	152.8	75	0.19	32	36	1.9	20	45	1.4	0.1	<0.05
LF80	8021110	15/06/2017	3:00:00 PM	20.5		8.25	665	548	151.8	76	0.2	32	36	1.8	20	45	2	0.1	<0.05

Appendix I River ^{4}He data – F (He) – along the Fitzroy River in 2010 and 2017

2010 ID	2017 ID	2010 F (He)	2017 F (He)
3	LF5	1.01	1.12
10	LF14	0.99	1.07
28	LF59	1.05	1.05
27	LF60	1.01	1.12
26	LF61	1.06	1.1
25	LF62	1.11	1.08
24	LF63	1.08	1.07
23	LF64	1.03	1.09
22	LF65	1.03	1.07
20	LF67	1.18	1.13
17	LF72	1.06	1.08
16	LF74	1.05	1.12
13	LF78	1.03	1.07
12	LF79	1.04	1.05

Appendix J Samples not used for data quality reasons

Data removed because of charge balance errors

Electrical balances were calculated for all water samples analysed with the United States Geological Survey (USGS) PHREEQC software, using calcium, magnesium, sodium, potassium, sulfate, chloride and alkalinity.

Field alkalinity was used to calculate electrical balances in preference to laboratory alkalinity data, but where field alkalinity concentrations exceeded the methods limit of reporting (> 300 mg/L as $CaCO_3$), the laboratory measurement was used as a surrogate.

Of the 75 samples analysed, 10 recorded electrical charge balance errors greater than ±10%. Six of these 10 samples were biased towards the negative (that is, anions > cations), while the other four samples were biased towards cations. The reasons for these imbalances are unclear. Some may be due to the presence of dissolved metals and/or nutrients that were not considered in the calculation of the electrical balance.

As a general rule only samples with electrical balance errors within ±10% were retained for analysis. An exception to this rule was made for the only three Devonian Reef aquifer bores that were sampled – Sallys Bore, PT4 and BA04 – which all had a charge balance error greater than 10% but which were retained so that a recharge estimate could be determined. It is acknowledged that this causes some increased uncertainty with the calculated recharge values for the Devonian Reef aquifer.

The following seven samples with a charge balance error greater than ±10% were removed from all recharge calculations: Garden Bore, 2-89 Mt Anderson, Helens Bore, LF03A, Looma 1-93, Birdwood Bore and Blue Bush.

Table 23 Charge balance errors

Bore ID	Date	Aquifer	Electrical balance (%) ((PHREEQC)[1]
Liveringa South	30/07/2017	Alluvium	-8.61
LF01	13/09/2017	Alluvium	2.91
LF02	13/09/2017	Alluvium	-2.54
LF03B	14/09/2017	Alluvium	-4.5
LF04B	13/09/2017	Alluvium	-4.89
LF05	14/09/2017	Alluvium	-4.29
Birdwood Bore	7/07/2016	Alluvium	10.32
BU15MB002A	23/08/2018	Alluvium	-6.17
BU15MB003	23/08/2018	Alluvium	5.87
BU15MB004	23/08/2018	Alluvium	3.55
Garden Bore	24/06/2016	Erskine Sandstone	-13.64

Bore ID	Date	Aquifer	Electrical balance (%) ((PHREEQC)[1]
Barefoot Bore	15/09/2017	Erskine Sandstone	-4.83
Helens Bore	4/09/2016	Liveringa Group	-12.61
2-89 Mt Anderson	7/09/2016	Liveringa Group	-11.95
RRMW005D	17/08/2017	Liveringa Group	1.63
LF03A	14/09/2017	Noonkanbah Formation	-11.72
LF04A	12/09/2017	Noonkanbah Formation	-9.77
Manta Ray Bore	6/07/2016	Noonkanbah Formation	-8.98
Peglars Bore	21/06/2016	Poole Sandstone	-1.93
Paradise Bore	22/06/2016	Poole Sandstone	-0.47
Montgomery Bore	23/06/2016	Poole Sandstone	-0.89
Langs Bore	26/06/2016	Poole Sandstone	-1.18
Blue Bush	5/09/2016	Poole Sandstone	-27.24
1-04 Camballin	30/08/2016	Poole Sandstone	8.41
1-04 Camballin	16/05/2017	Poole Sandstone	-4.12
Langs Bore	16/05/2017	Poole Sandstone	-6.97
Peglars Bore	18/05/2017	Poole Sandstone	-5.71
Shovelton	3/08/2017	Grant Group	1.86
Paradise Bore	15/08/2017	Poole Sandstone	-4.08
LF06	12/09/2017	Poole Sandstone	-2.39
Irrigation Bore	21/08/2018	Poole Sandstone	-2.63
Huttons Bore No.2	2/07/2016	Poole Sandstone	4.69
Pilots Flowing Bore	2/07/2016	Poole Sandstone	6.92
Tank Bore No.2	3/07/2016	Poole Sandstone	-7.33
One Tree Bore No.2	3/07/2016	Poole Sandstone	-0.71
Chestnut Bore	6/07/2016	Poole Sandstone	-5.34
No.8 Bore	30/06/2016	Poole Sandstone	-0.64
Looma 1-86	22/06/2016	Grant Group	5.76
Jarlmadangah 1-02	26/06/2016	Grant Group	7.02
Leos Bore	27/06/2016	Grant Group	-3.35
Acacia Tank Flowing Bore	4/07/2016	Grant Group	-0.15
Laurel Homestead Bore	30/06/2016	Grant Group	2.01
Looma 1-93	30/08/2016	Grant Group	-37.16
Thomas Bore	2/09/2016	Grant Group	1.77
Looma 1-86	18/05/2017	Grant Group	-1.75
Thomas Bore	29/07/2017	Grant Group	-2.58

Bore ID	Date	Aquifer	Electrical balance (%) ((PHREEQC)[1]
Leos Bore	31/07/2017	Grant Group	2.1
Agricon 3	2/08/2017	Grant Group	2.58
Agricon 1	3/08/2017	Grant Group	7.55
Agricon 2	3/08/2017	Grant Group	-1.56
LF07	12/09/2017	Grant Group	-6.28
2/89 – Fitzroy Crossing	29/06/2016	Grant Group	-0.62
5/10 – Fitzroy Crossing	29/06/2016	Grant Group	0.51
Donalds Mill No.2	4/07/2016	Grant Group	3.53
Gogo Station Homestead Bore 3A	4/07/2016	Grant Group	-2.1
BS16MB001A	3/07/2017	Grant Group	1.86
BS16MB001B	2/07/2017	Grant Group	2.49
BS16MB001C	2/07/2017	Grant Group	2.8
BS16MB003A	4/07/2017	Grant Group	3.71
BS16MB003B	4/07/2017	Grant Group	1.99
BS16MB003C	4/07/2017	Grant Group	4.98
KD16MB002	5/07/2017	Grant Group	3.34
KD16MB003	5/07/2017	Grant Group	-0.22
Bore	6/09/2016	Fairfield Group	-5.45
BA04	1/07/2016	Devonian reef	15.29
PT4	1/07/2016	Devonian reef	15.04
Emanuels Flowing Bore	5/07/2016	Devonian reef	4.53
Sallys Bore	5/07/2016	Devonian reef	10.72

PHREEQC stands for PH REdox EQuilibirum (in C computer language) and is public domain geochemical modelling software developed by the United States Geological Survey (USGS).

Data removed from CFC analysis

Three samples were removed from CFC analysis because, while CFCs were present, tritium was not detected. This suggested the CFCs were likely present as contamination. CFC contamination may be sourced from atmospheric input or remnant sunscreen on hands when sampling, while CFC degradation can occur under anoxic conditions.

The three samples removed were from the following bores: Bore, PT4 and Paradise Bore – sample collected in 2017.

Data removed for radiocarbon analysis

The following samples were removed from radiocarbon analysis:

- Montgomery Bore recorded unusually high radiocarbon groundwater residence times, which could be an anomaly. It was equipped as a windmill bore when sampled in 2016, but in 2018 it was equipped with a solar submersible pump. Re-sampling of this bore, for comparison with the original sample, would help to assess the reliability of the data.
- Agricon 2 recorded a much lower groundwater residence time than the nearby Agricon 1, Agricon 3 and Shovelton bores, all of which intersect similar depths of the same aquifer. Agricon 2 also detected tritium, indicating a component of modern water, perhaps from a cracked upper part of the casing, or remnant floodwater.
- Liveringa South recorded a much higher than expected radiocarbon groundwater residence time, as well as tritium and CFCs, indicating the radiocarbon data was unreliable.
- For Chestnut Bore, a residence time was calculated, but a recharge estimate could not be provided because the uncertainties regarding screen interval were too great. Because the screen interval was not known, this bore was not used for any further interpretation or calculation of recharge rates.
- For Donalds Mill No. 2, a recharge estimate could not be provided because screen interval and bore depth were not known. As with the Chestnut Bore, Donalds Mill No. 2 was not used for any further interpretation or calculation of recharge rates because of the unknown screen interval.

Data removed from ^{4}He analysis

Elevated levels of argon and neon in groundwater samples can be an indication that excess air may be present and may have compromised the ^{4}He data. Therefore, argon and neon were included in the laboratory assessment of samples to support the ^{4}He analysis (results in Taylor et al. 2018).

Based on the data in Taylor et al. (2018), a number of samples appeared to have been contaminated and were disregarded. These were from:

- Emanuels Flowing Bore
- Bore
- Acacia Tank Bore
- Agricon 3
- Shovelton.

Data with elevated nutrient concentrations

Elevated levels of nutrients in water samples indicates the presence of organic material. Several samples showed high nutrient concentrations associated with land uses such as cattle grazing, fertiliser runoff, landfills or wastewater treatment ponds (Section 5.2.4).

The following samples had high nutrient levels that might be linked to anthropogenic sources and thus we omitted them from the recharge calculations.

- Peglars Bore: recorded the highest total nitrogen (TN) levels – up to 9.2 mg/L as TN (mostly in the form of nitrate 6.97 mg/L, indicating an oxidising environment).
- Donald Mill No 2: recorded nitrate at 4.37 mg/L, also indicating an oxidising environment.
- 2/89 Fitzroy Crossing: recorded nitrate at 6.61 mg/L. It is located in the town of Fitzroy Crossing, with nitrate likely to be sourced from urban runoff.
- 5/10 Fitzroy Crossing: had nitrate of 3.94 mg/L. It is located in close proximity (approximately 80 m) to wastewater treatment ponds.
- Thomas Bore: had TN of 5.3 mg/L (mostly nitrate 4.59 mg/L) in July 2017, following the previous measure of 0.5 mg/L TN in September 2016. Shows a very large change in water-level, water quality and age between the two samples.
- Leos Bore: had TN of 3.5 mg/L in June 2016 (mostly comprising ammonia 2.43 mg/L) and 2.5 mg/L in July 2017 (mostly comprising nitrate 1.98 mg/L). As discussed previously, this bore appears to be damaged and is not considered a useable data point.

Appendix K River flows

Rainfall and discharge at Fitzroy Crossing in the year before the three longitudinal sampling events in May 2010, November 2015 and June 2017. Both daily and cumulative quantities are shown. The timing of water quality sampling is indicated by vertical red line.

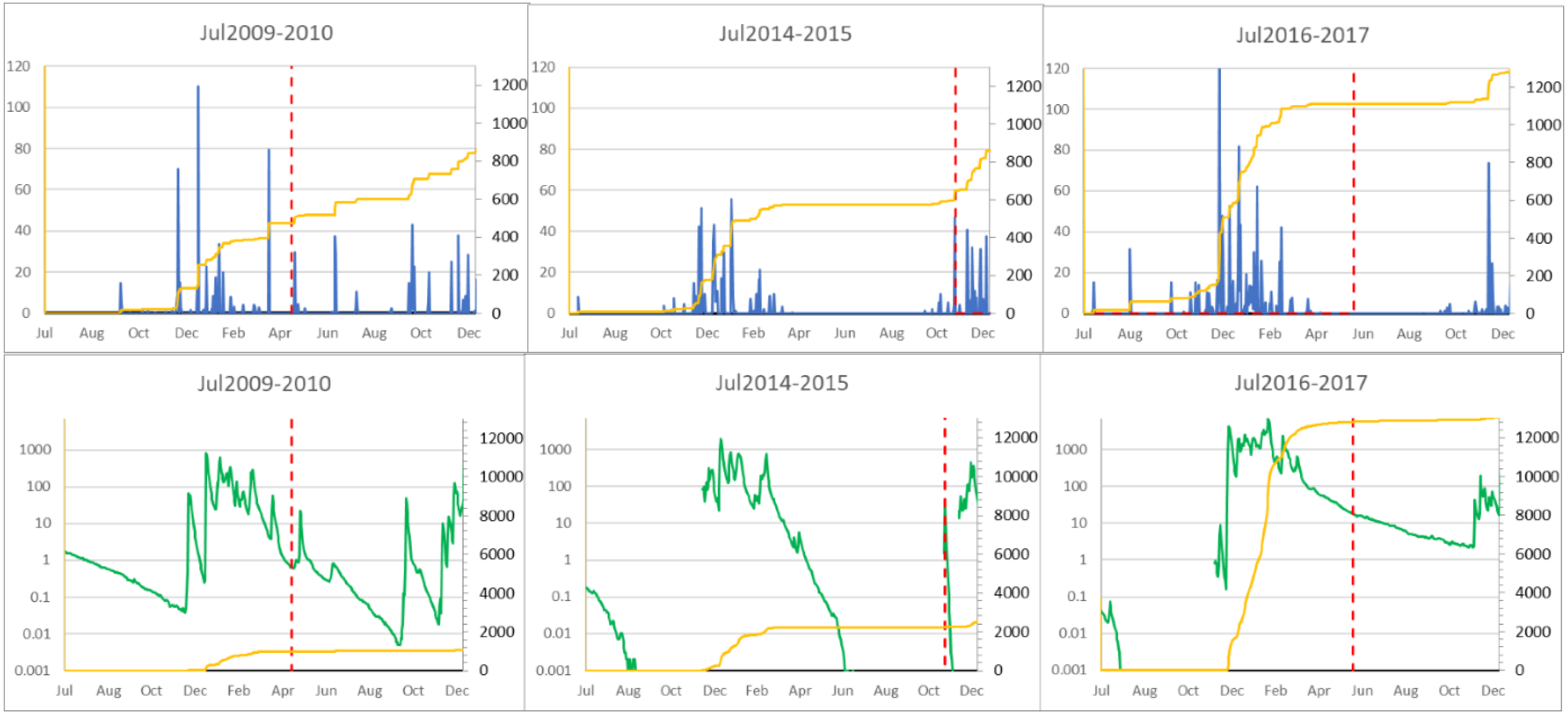


Figure 75 Rainfall and discharge at Fitzroy Crossing

Appendix L River water quality

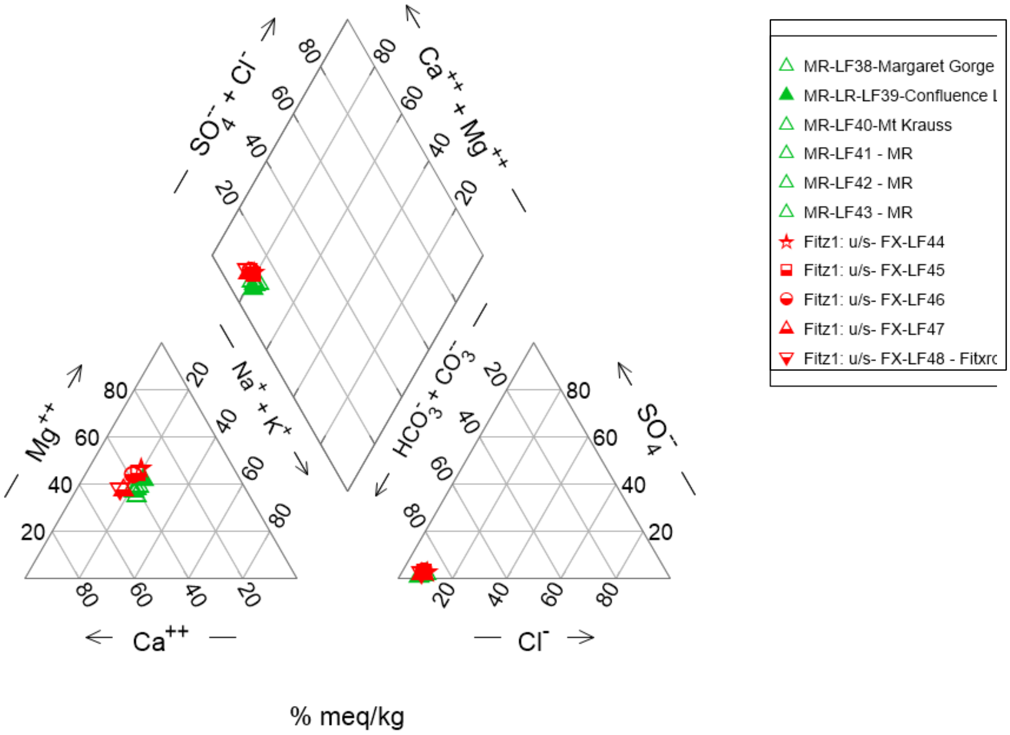


Figure 76 River water quality samples 2017: Margaret Gorge to Fitzroy Crossing (green); Geike Gorge to Fitzroy Crossing (red)

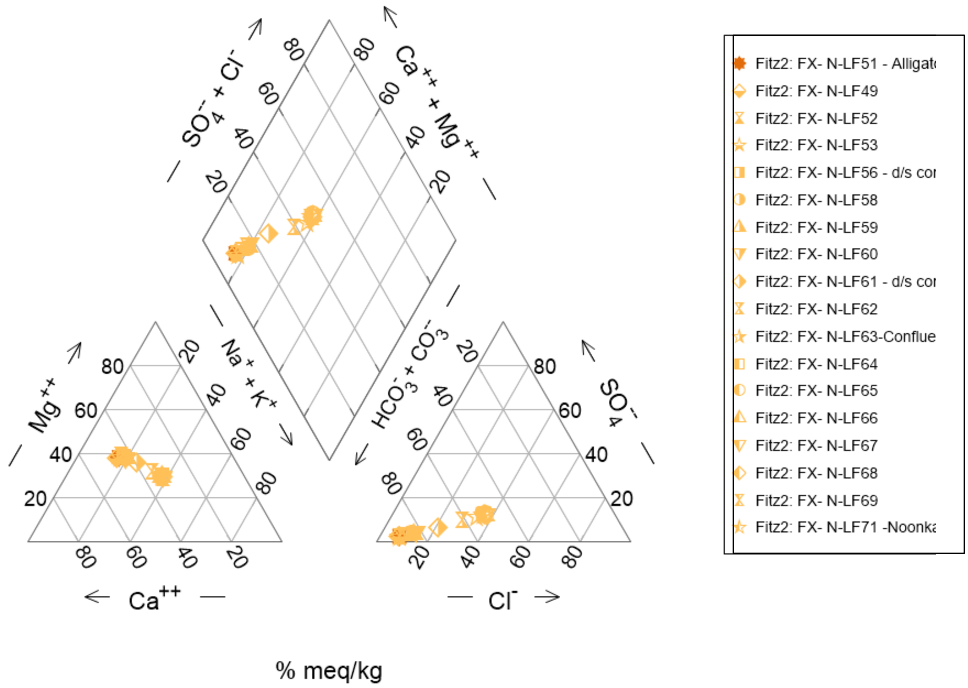


Figure 77 River water quality samples 2017: Fitzroy Crossing to Noonkanbah

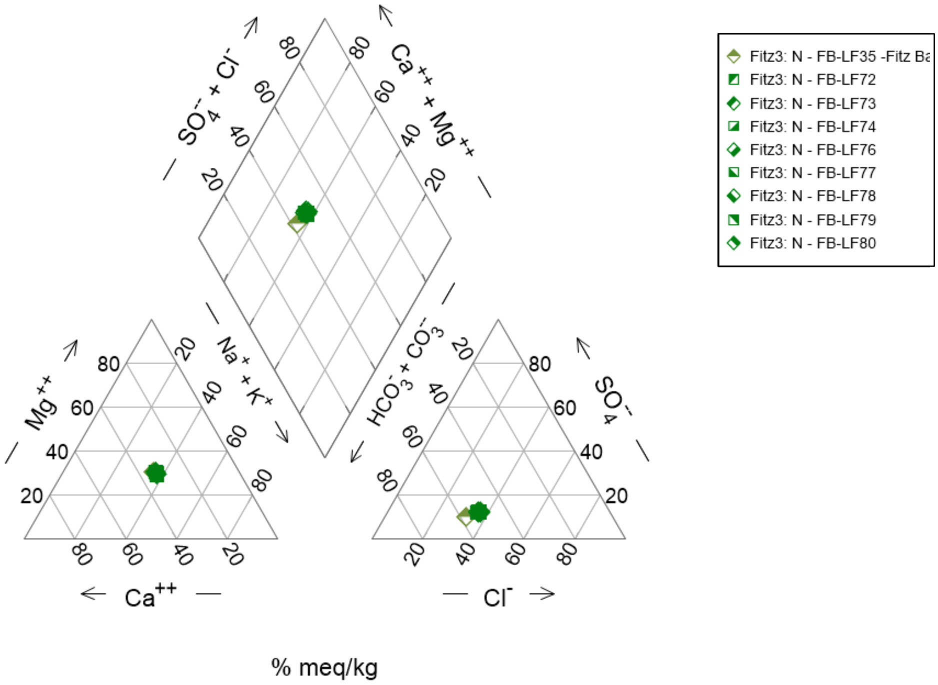


Figure 78 River water quality samples 2017: Noonkanbah to Fitzroy Barrage

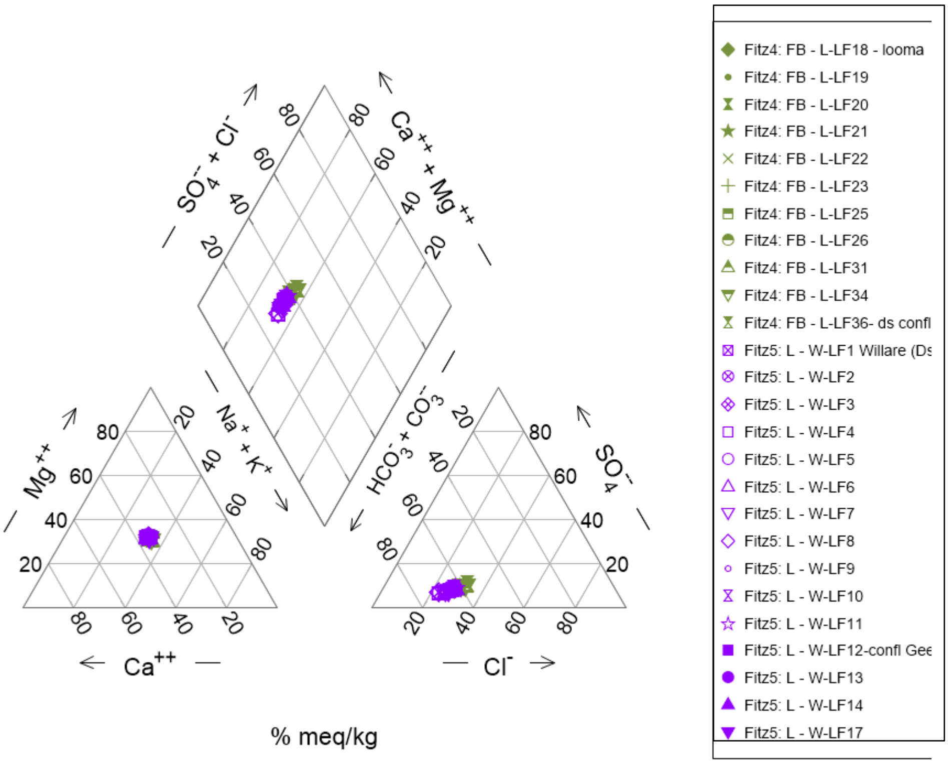


Figure 79 River water quality samples 2017: FB = Looma (green); Looma to Willare (purple)

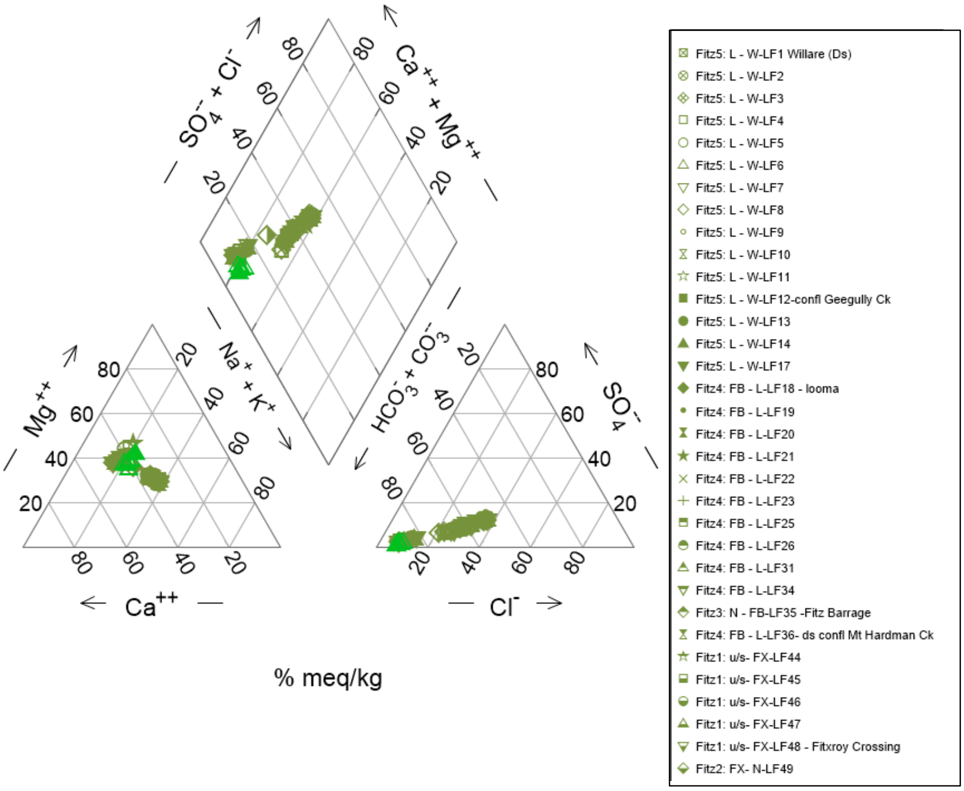


Figure 80 Piper plot showing all main channel samples from 2017 (Margaret River in paler green)

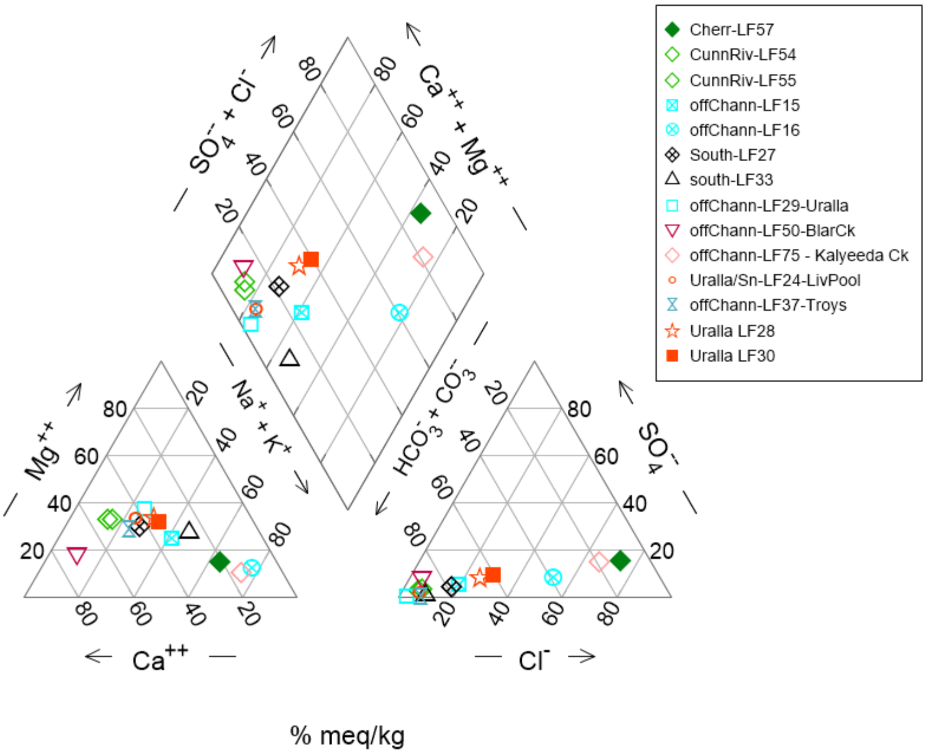


Figure 81 Piper plot showing off-channel samples from 2017

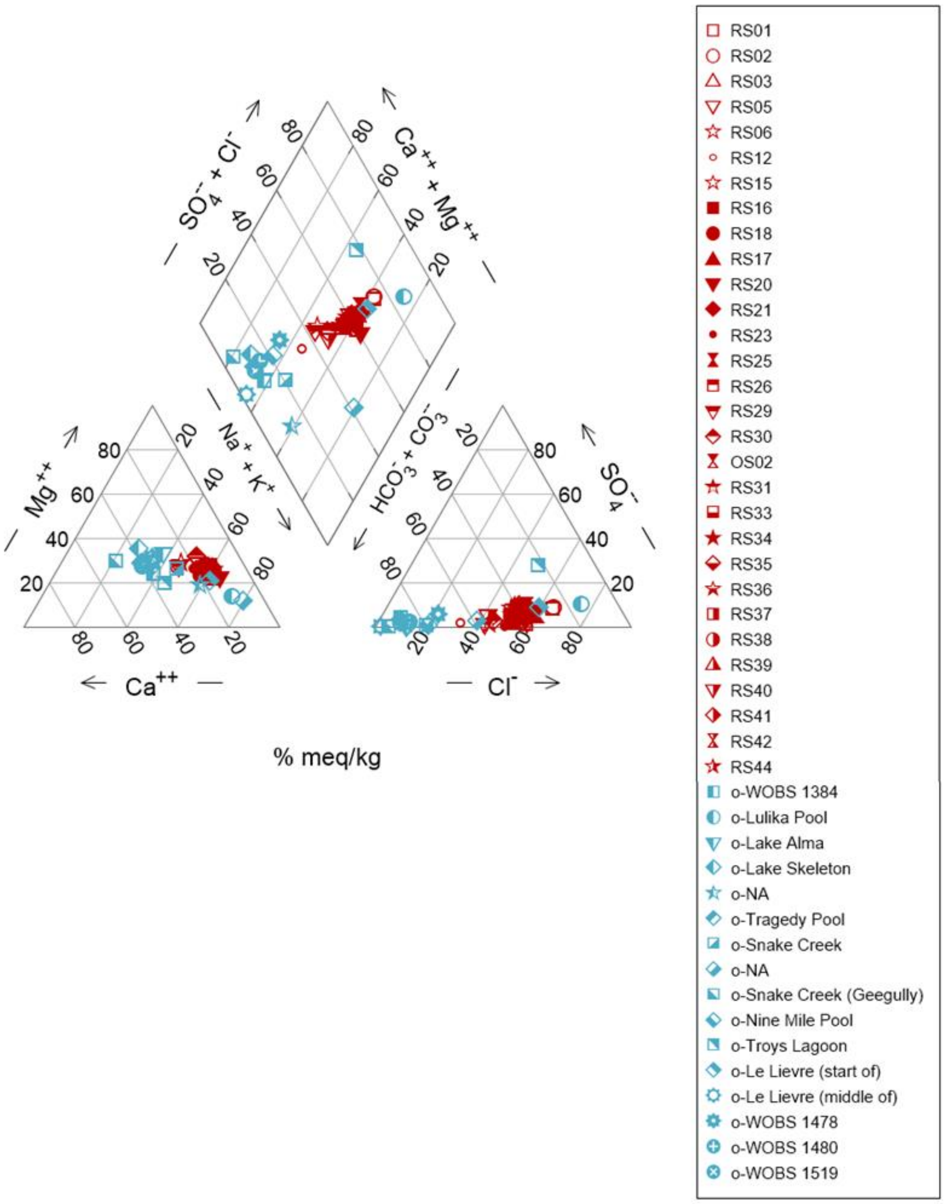


Figure 82 Piper diagram with major ion chemistry reported for river sampling in November 2015 (Harrington & Harrington 2016). Red = main channel samples. Blue = off-channel samples.

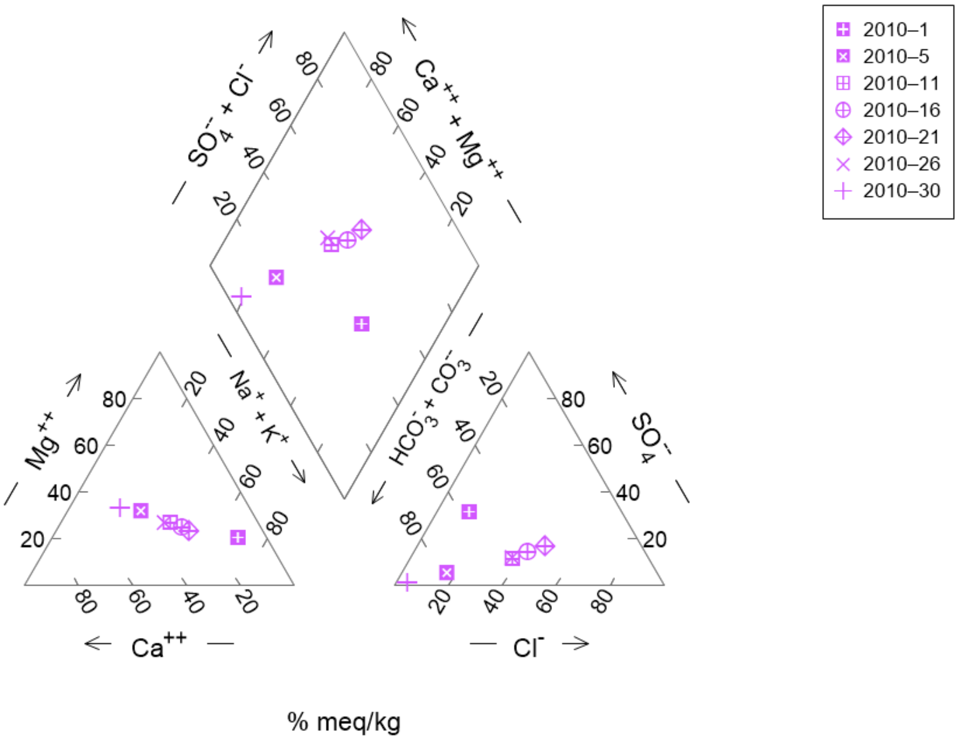


Figure 83 Piper diagram with major ion chemistry reported from river sampling in May 2010 (Harrington et al. 2011)

Note that samples 2010-1 and 010-0 have excessive charge balance errors, and other samples have charge balance errors above 5%.

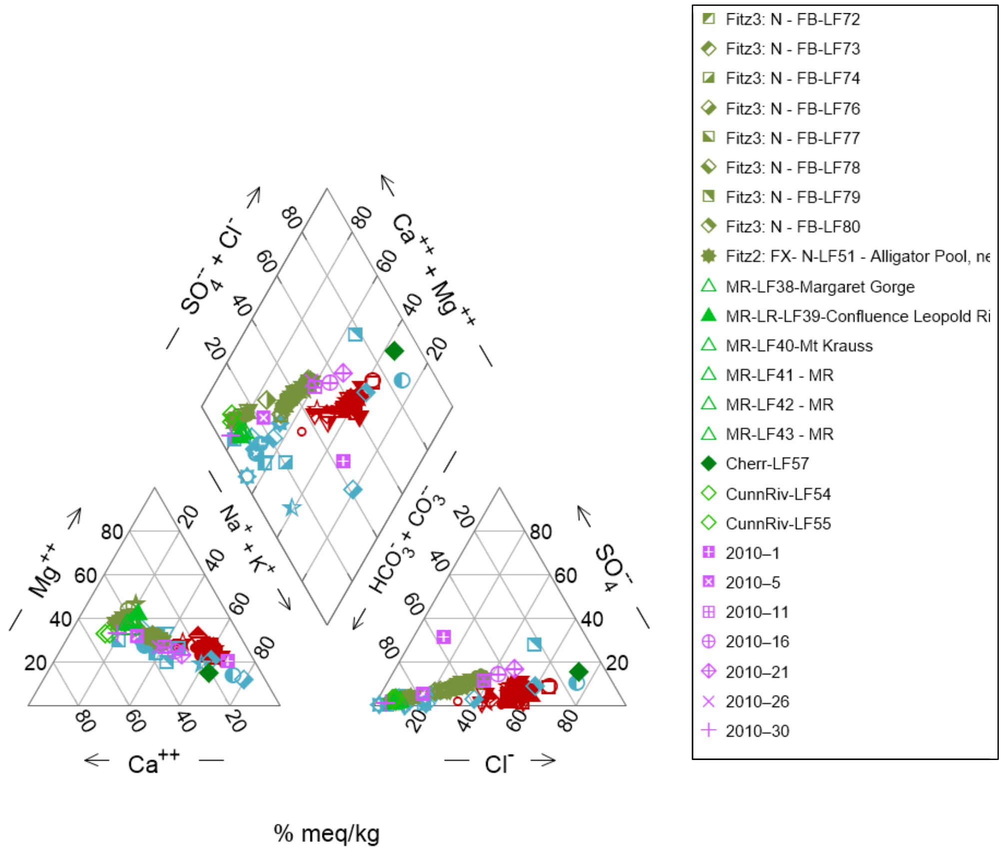


Figure 84 Piper diagram compiling river samples from July 2017 (green), November 2015 main channel (red), November 2015 off-channel (blue) and May 2010 (purple) – see figure and figure text above for details of the different datasets.

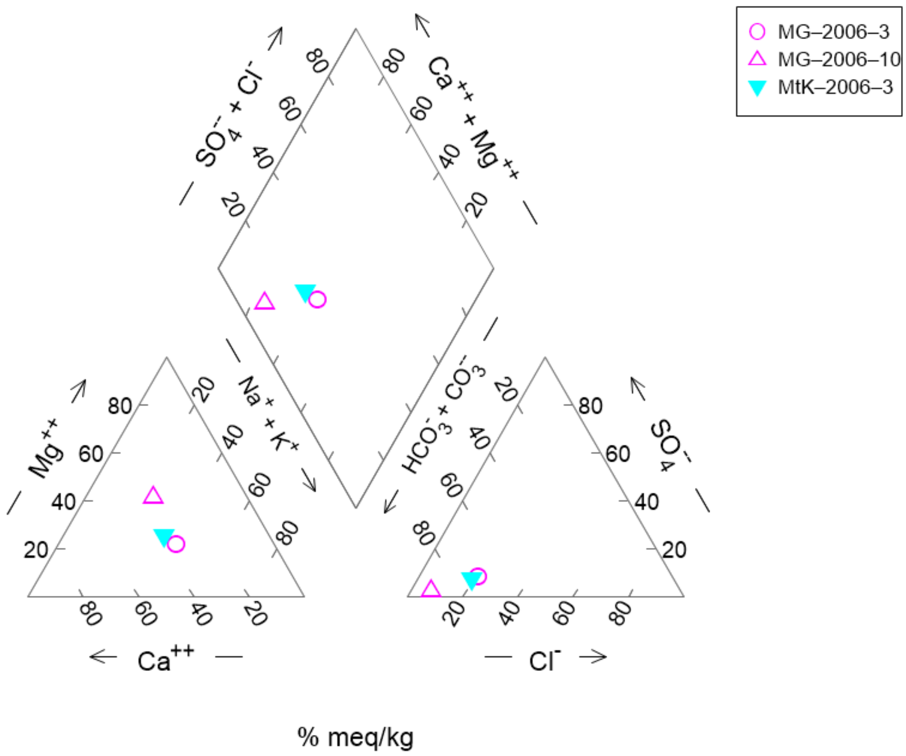


Figure 85 Water quality samples collected from gauging stations, available in the department's online database. MG = Margaret Gorge; MtK = Mt Krauss. Legend indicates year and month of sampling.

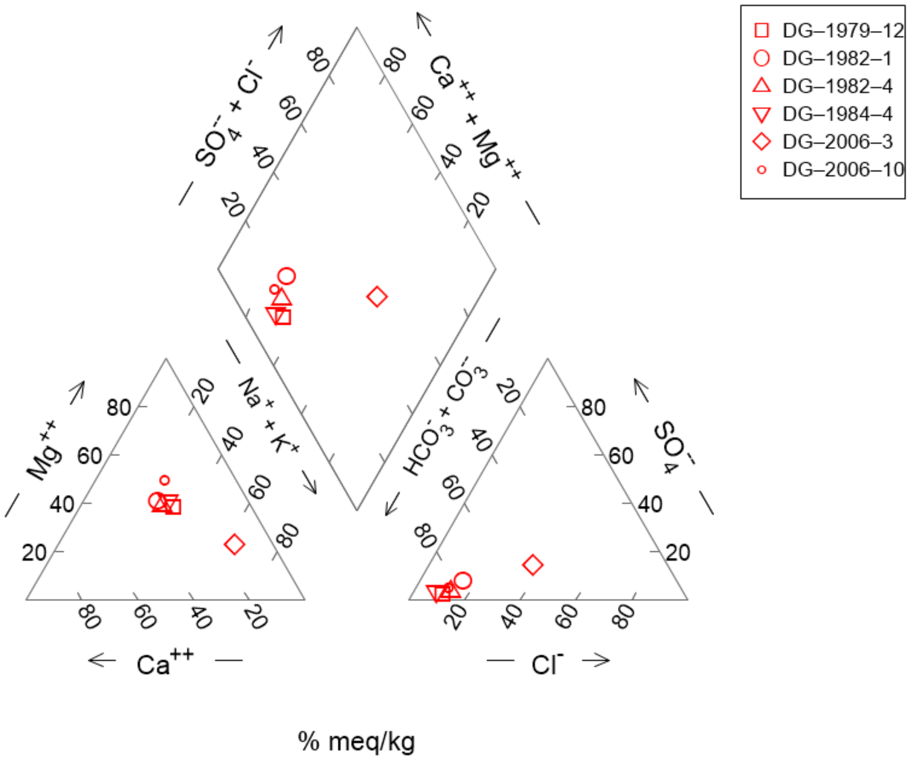


Figure 86 Water quality samples collected from gauging stations, available in the department's online database. DG = Dimond Gorge. Legend indicates year and month of sampling.

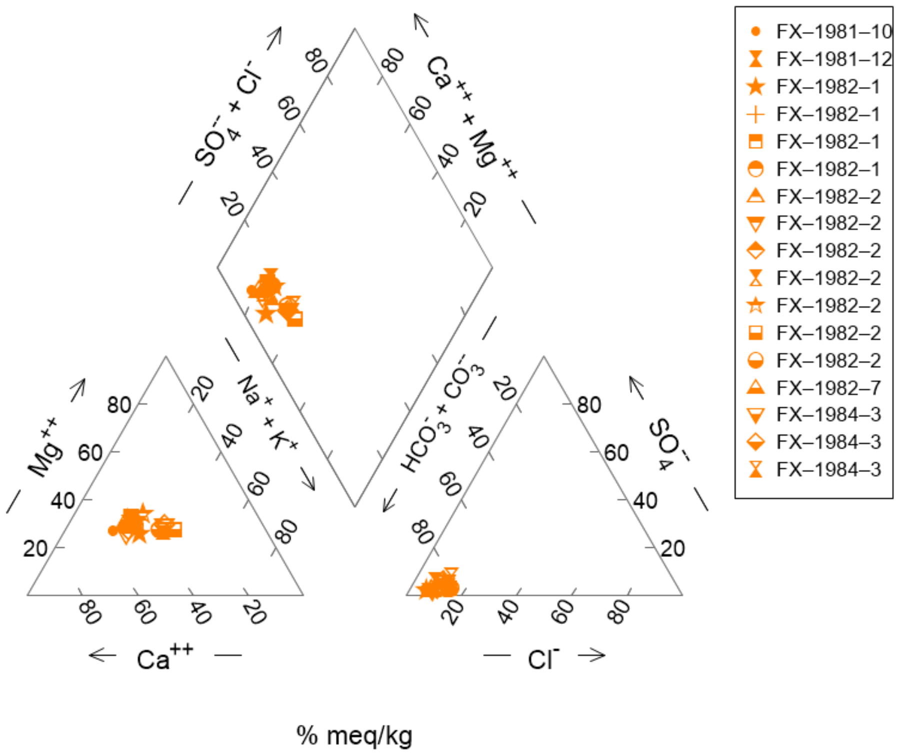


Figure 87 Water quality samples collected from gauging stations, available in the department's online database. FX = Fitzroy Crossing, 1981–1984. Legend indicates year and month of sampling.

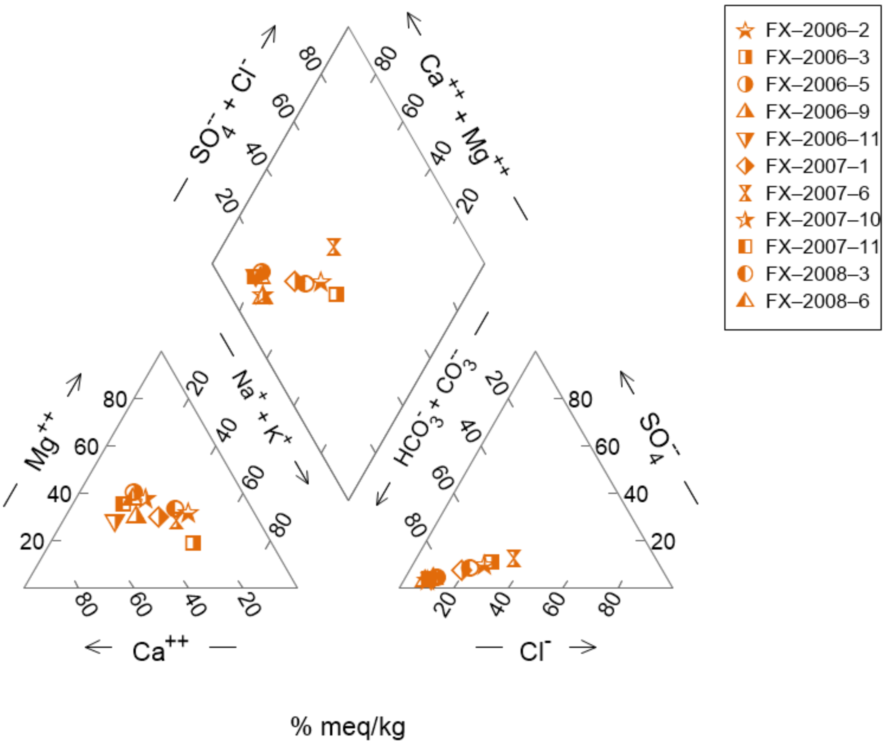


Figure 88 Water quality samples collected from gauging stations, available in the department's online database. FX = Fitzroy Crossing, 2006–2008. Legend indicates year and month of sampling.

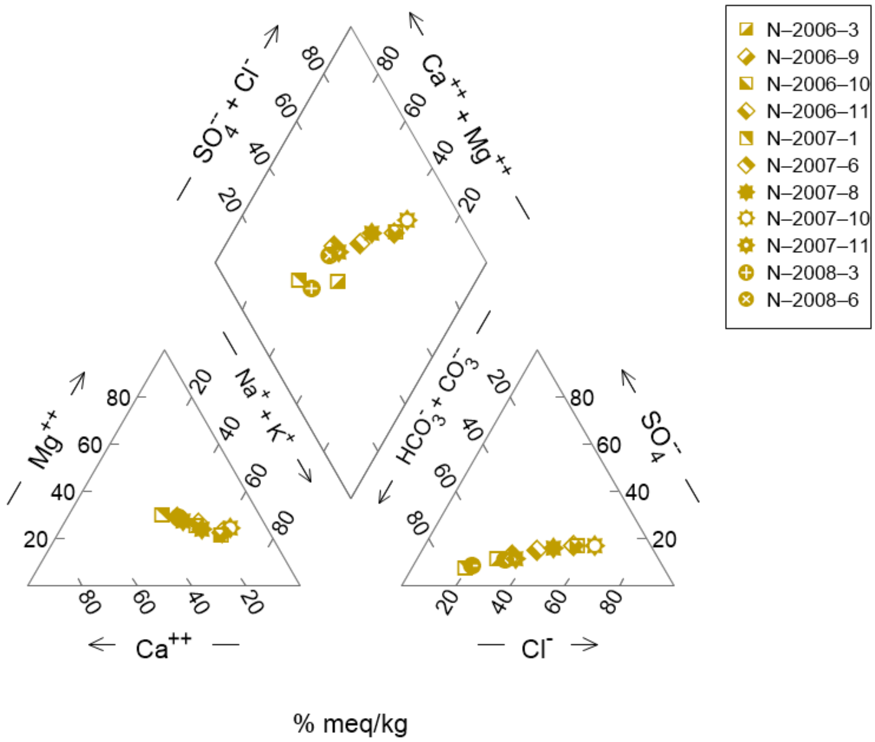


Figure 89 Water quality samples collected from gauging stations, available in the department's online database. N = Noonkanbah. Legend indicates year and month of sampling.

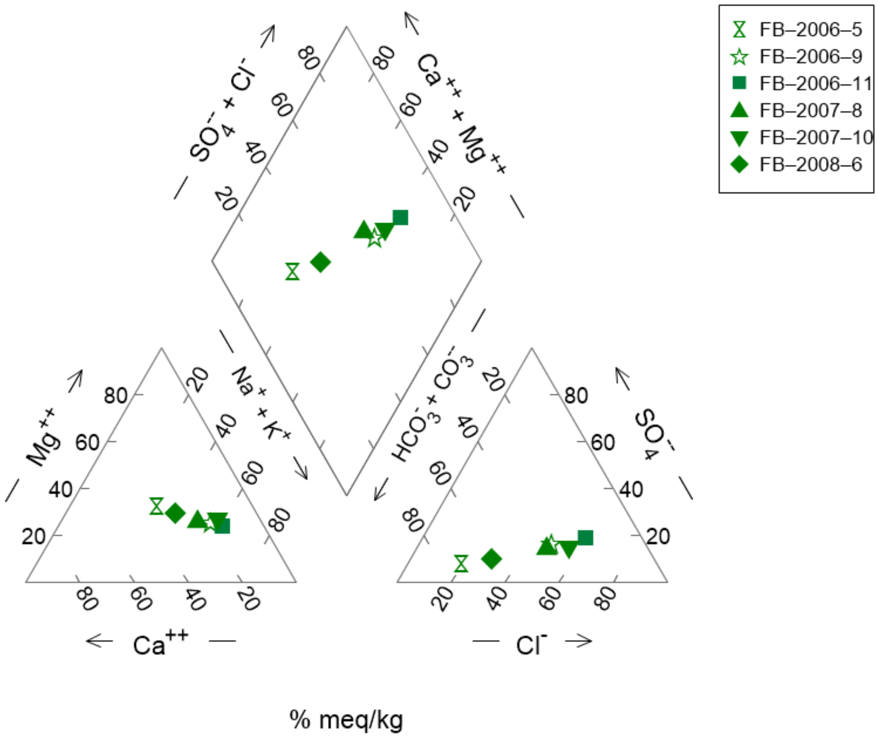


Figure 90 Water quality samples collected from gauging stations, available in the department's online database. FB = Fitzroy Barrage. Legend indicates year and month of sampling.

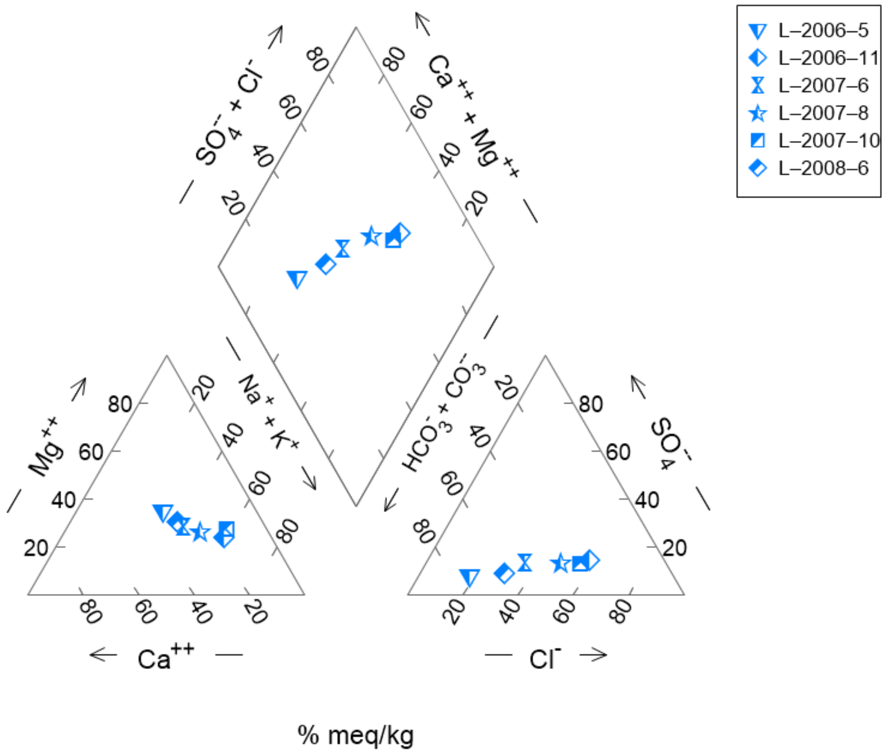


Figure 91 Water quality samples collected from gauging stations, available in the department's online database. L = Looma (Kings). Legend indicates year and month of sampling.

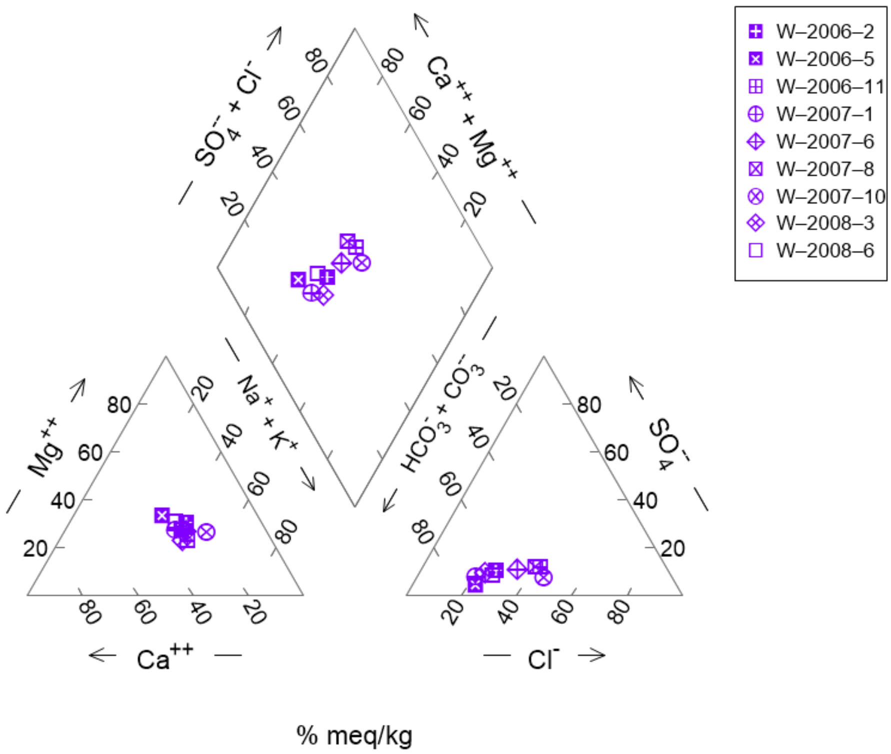


Figure 92 Water quality samples collected from gauging stations, available in the department's online database. W = Willare. Legend indicates year and month of sampling.

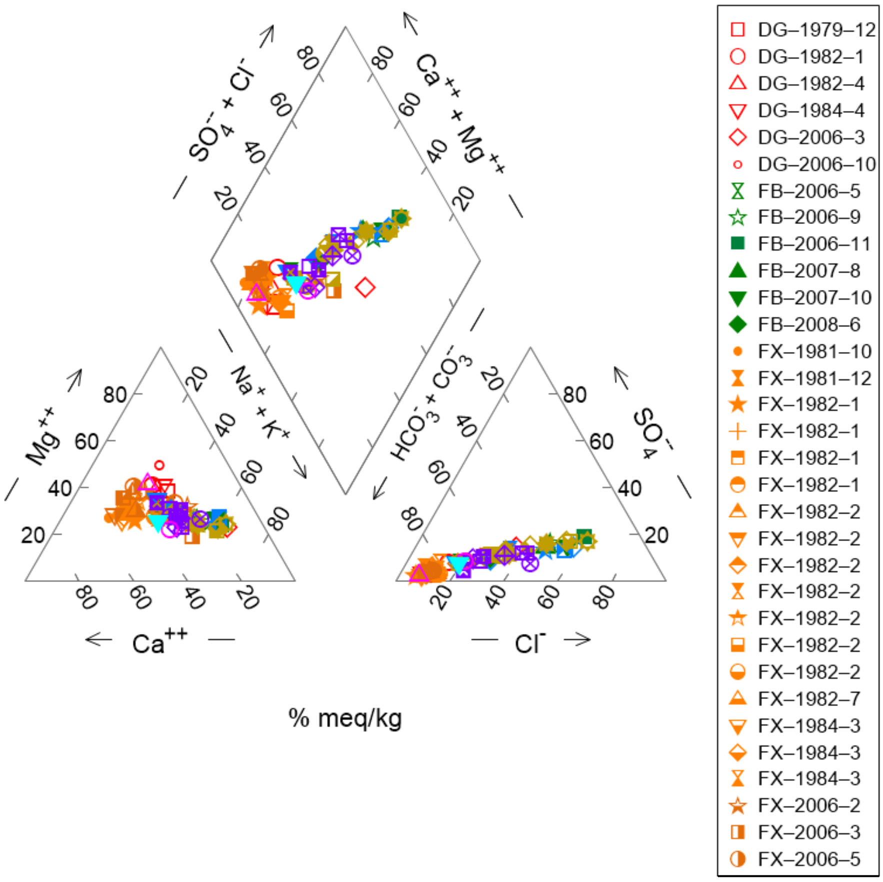


Figure 93 Piper diagram showing major ion composition from all samples collected from gauging stations, as available in the department's database. (Details for each gauging station in figures above, same symbols.)

Appendix M Lithology and geology logs

The following lithology and geology logs are from new and existing bores registered in the department's database and are used to support the geological conceptualisation in Section 4. Other sources of information can be found by referring to DMIRS (2016) mapping, interpretation of petroleum bores and isopach maps in Mory (2010):

Bore ID: Camballin no. 4

AWRC no: 80210068

From (mbgl)	To (mbgl)	Lithology	Stratigraphy
0	2.4	Red sandy soil	Quaternary
2.4	9.14	Light brown clay	
9.14	20.12	Hard black shale	Noonkanbah Formation/Poole Sandstone
20.12	21.34	Dark grey sand	

Bore ID: Camballin no. 5

AWRC no: 80210069

From (mbgl)	To (mbgl)	Lithology	Stratigraphy
0	6.1	Hard sandstone	Quaternary
6.1	8.23	Coarse sand and shingle	
8.23	10.97	River sand	
10.97	15.24	Light brown sandy clay	
15.24	16.15	Cement	
16.15	16.76	River sand and wash	
16.76	19.81	Grey sandy shale	Noonkanbah Formation
19.81	23.77	Hard black shale	
23.77	25.3	Grey shale	
25.3	26.21	Hard grey sandstone	

Bore ID: Camballin no. 12

AWRC no: 80210621

From (mbgl)	To (mbgl)	Lithology	Stratigraphy
0	1.83	Sandy soil	Quaternary
1.83	6.1	Brown sandy clay	Poole Sandstone
6.1	14.6	Brown sandstone	
14.6	21.34	Grey sandstone	

Bore ID: **Irrigation**

AWRC no: **80210620**

From (mbgl)	To (mbgl)	Lithology	Stratigraphy
0	0.3	Soil	Quaternary
0.3	6.1	Sandstone with bands of clay	Poole Sandstone
6.1	13.72	Brown sandy clay	
13.72	15.24	Grey sandy shale	
15.24	20.42	Grey sandstone	
20.42	21.03	Sandy shale	
21.03	23.77	Grey sandstone	

Bore ID: **Camballin – Horse Paddock**

AWRC no: **80210044**

From (mbgl)	To (mbgl)	Lithology	Stratigraphy
0	3.66	Red sandstone	Quaternary
3.66	14.63	Grey, brown sandstone	Poole Sandstone
14.63	15.85	Black sandy shale	
15.85	17.37	Dark grey sandstone	
17.37	18.9	Light grey sandstone	
18.9	22.25	Dark grey sandstone	
22.25	24.08	Light grey sandstone	

Bore ID: **DHM5A**

AWRC no: **80210089**

From (mbgl)	To (mbgl)	Lithology	Stratigraphy
0	9	Clay	Quaternary alluvium
9	12	Sand	
12	18	Gravel	
18	21	Gravel	
21	30	Gravel	
30	39	Not logged	

Bore ID: DHM6A

AWRC no: 80210096

From (mbgl)	To (mbgl)	Lithology	Stratigraphy
0	12	Clay	Quaternary alluvium
12	40	Gravel	

Bore ID: DHM7A

AWRC no: 80210097

From (mbgl)	To (mbgl)	Lithology	Stratigraphy
0	6	Clay	Quaternary alluvium
6	15	Sand	Wallal Sandstone
15	18	Clay	
18	21	Gravel	
21	26	Clay	Liveringa Group or Noonkanbah Formation

Bore ID: DHM8A

AWRC no: 80210098

From (mbgl)	To (mbgl)	Lithology	Stratigraphy
0	3	Clay	Quaternary (0–3 m)
3	9	Sandstone	Wallal Sandstone (3–57 m)
9	12	Unknown	
12	18	Sandstone	
18	24	Sand	
24	42	Sand	
42	48	Sand	
48	63	Sand	
63	72	Clay	Liveringa Group (57–182 m)
72	102	Sand	
102	105	Sand	
105	129	Clay	
129	132	Claystone	
132	180	Clay	
180	288	Clay	Noonkanbah Formation (182 m–EOH)

EOH = End of hole

Bore ID: MA15MB04

AWRC no: 802114426

From (mbgl)	To (mbgl)	Lithology	Stratigraphy
0	16		Quaternary
16	102		Noonkanbah Formation

Bore ID: LF04A

AWRC no: 80270067

From (mbgl)	To (mbgl)	Lithology	Stratigraphy
0	22		Alluvium
15	84		Noonkanbah Formation

Bore ID: LF05

AWRC no: 80270069

From (mbgl)	To (mbgl)	Lithology	Stratigraphy
0	24		Alluvium
24	42		Liveringa Group

Bore ID: Looma 1-93

AWRC no: 80219134

From (mbgl)	To (mbgl)	Lithology	Stratigraphy
0	6	Sandstone, grey, firm	Poole Sandstone
6	11	Sandstone, grey, with brown sand layers	
11	31	Sandstone, grey and brown, firm	
31	60	Sandstone, grey and brown, with fractured bands	

Bore ID: **Agricon 2**

AWRC no: **80270062**

Note: stratigraphic picks based on downhole geophysics

From (mbgl)	To (mbgl)	Lithology	Stratigraphy
0	25		Alluvium
25	70		Liveringa Group
70	437		Noonkanbah Formation
437	553		Poole Sandstone
553	EOH		Grant Group

EOH = End of hole

Bore ID: **Agricon 3**

AWRC no: **80240013**

Note: stratigraphic picks based on downhole geophysics

From (mbgl)	To (mbgl)	Lithology	Stratigraphy
0	21		Alluvium
21	35		Liveringa Group
35	409		Noonkanbah Formation
415	526		Poole Sandstone
526	EOH		Grant Group

EOH = End of hole

Appendix N Potential paleochannel

The thickness of the Fairfield Group and Devonian reef complex is not known based on the results of Grevillea 1 and Needle Eye Rocks petroleum bores (Mory 2010). It likely extends beyond the depth of airborne electromagnetic (AEM) investigation/reliability. The thickness of the Devonian reef complex is thought to be more than 2,000 m.

As the thickness of the Fairfield Group is unknown, question marks are annotated onto each geological section to reflect this high level of uncertainty. It could range from around 100 to 600 m, with thicker sections of Fairfield Group in the Fitzroy Trough than the Lennard Shelf.

The thickness of the Fairfield Group that lies between the Devonian reef complex and the Grant Group on the Lennard Shelf is a significant factor in assessing possible connectivity between the Devonian reef complex and Grant Group aquifers.

The Devonian reef complex underlies the Fairfield Group and outcrops to the east (Figure 94). The contact between the Devonian reef complex and the adjacent Fairfield Group varies in its angle and nature, which may be associated with the three main facies that make up the Devonian reef complexes: platform, marginal slope and basin facies.

The platform deposits and basin facies were laid down horizontally, while the marginal slope deposits were laid in front of the platforms up to several hundred metres in depth (Playford et al. 2009). Reef slope deposits also show depositional dips ranging from vertical to about 40° (Playford et al. 2014).

The AEM data highlights a clear higher conductive unit in the combined Grant Group and Poole Sandstone units (Figure 94 to Figure 96). This may represent the Winifred Formation, known to be a siltstone unit in the middle of the Grant Group, or just a high conductive clay unit within other members of the Grant Group and Poole Sandstone.

These high conductive units likely act as a screen, preventing any reliable conductivity interpretation beneath these units. For this reason, the shape of the high conductive units within the Grant Group and Poole Sandstone is not known.

Due to uncertainties in the geometry of the high conductive unit, its shape may conform to the general orientation of the Grant group and Poole Sandstone, or alternatively may be influenced by some faulting and/or folding that is not represented on the regional DMIRS (2016) mapping.

Adding further uncertainty to the geometry of the Winifred Formation is the large distance between type sections of the Betty, Winifred and Carolyn formations, which casts significant doubt over how they correlate with each other (Mory 2010).

Guidance as to the geometry of the Winifred Formation is also unclear, as the depositional history of the Grant Group is complex. The Grant Group is a fluvial to marine glaciogenic succession, as indicated in Section 2 of this report (Mory 2010).

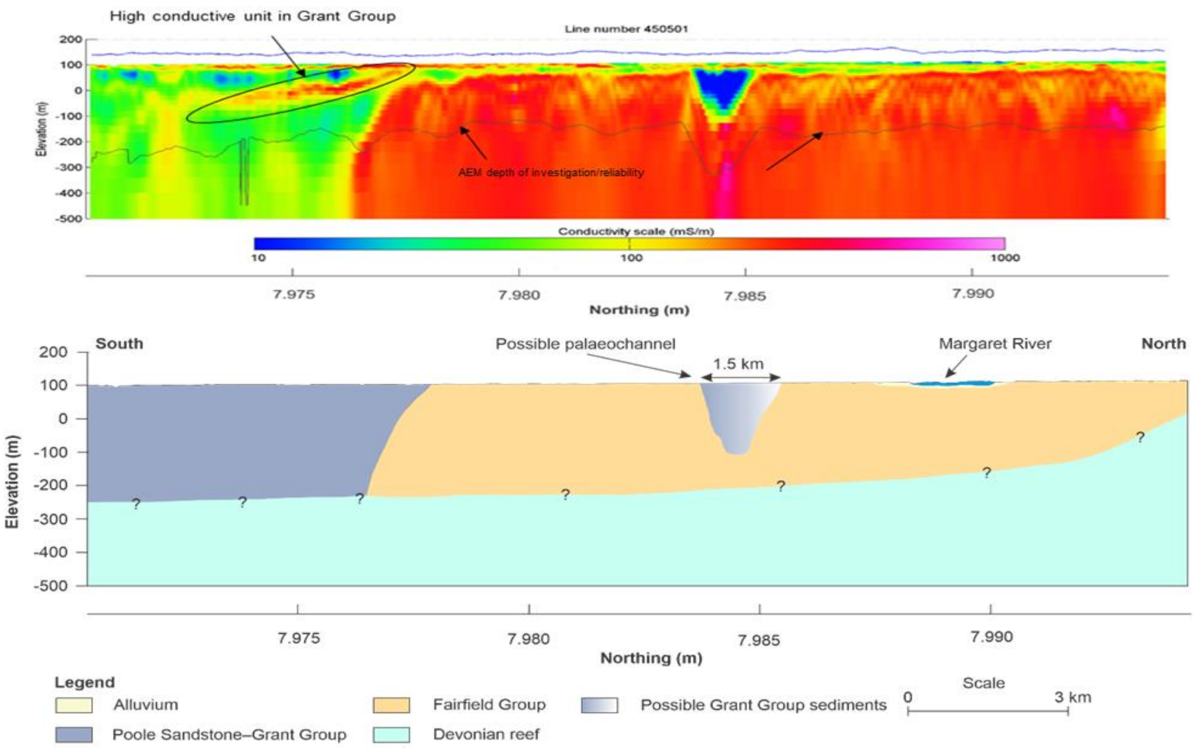


Figure 94 Geological cross-section, AEM line 450501

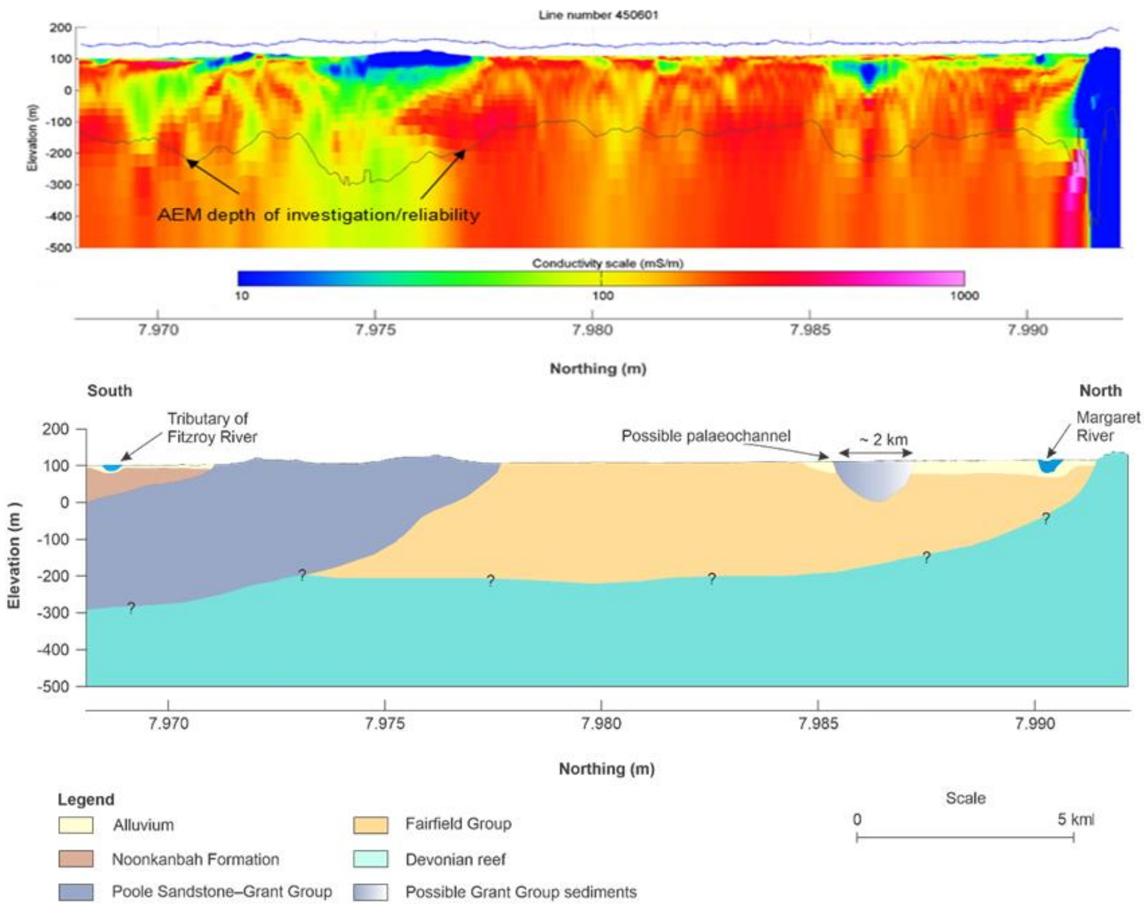


Figure 95 Geological cross-section, AEM line 450601

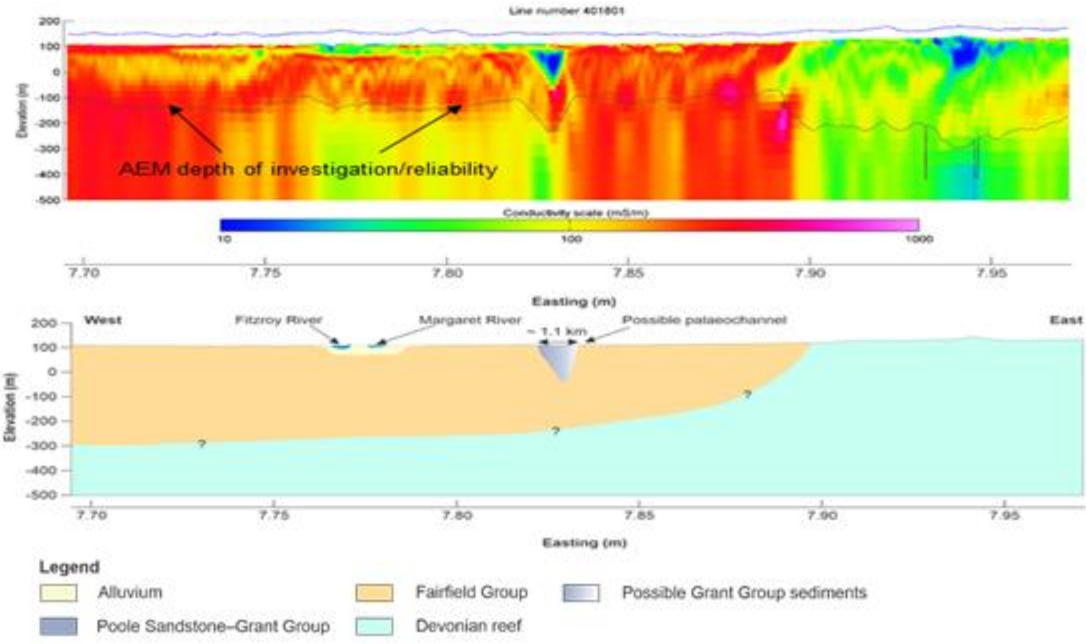


Figure 96 Geological cross-section, AEM line 401801

Appendix O River chloride (mg/L) values for sampling programs in 2017, 2015 and 2010

2017 Site ID	2017 Cl (mg/L)
LF1	56
LF2	45
LF3	38
LF5	46
LF6	42
LF7	40
LF8	42
LF9	47
LF10	47
LF11	48
LF12	44
LF13	47
LF14	48
LF15	33
LF16	167
LF17	43
LF19	51
LF20	52
LF21	53
LF22	53
LF23	54
LF25	49
LF26	51
LF27	19
LF33	1
LF36	62
LF56	13

2015 Site ID	2015 Cl (mg/L)
RS06	78
RS12	42
RS16	101
RS18	111
RS20	172
RS21	165
RS23	155
RS25	154
RS26	195
RS29	98
RS30	92
RS32	23
OS03	87
RS33	117
RS34	96
RS35	105
RS36	90
RS37	99
RS38	101
RS40	75
RS44	133
RS46	5
RS49	14
OS04	193

2010 Site ID	2010 Cl (mg/L)
1	11
2	10
3	10
4	10
5	10
6	11
7	11
8	10
9	11
10	11
30	4

2017 Site ID	2017 Cl (mg/L)
LF58	16
LF59	17
LF60	18
LF61	32
LF62	54
LF63	70
LF64	79
LF65	82
LF66	82
LF67	83
LF68	80
LF72	79
LF74	80
LF76	82
LF78	77
LF79	75
LF80	76

2015 Site ID	2015 Cl (mg/L)

2010 Site ID	2010 Cl (mg/L)
29	4
28	9
27	19
26	46
25	81
24	101
23	97
22	93
21	85
20	80
19	75
17	59
16	56
15	53
13	39
12	40
11	40

Appendix P River ^{222}Rn activities along the Fitzroy River in 2010, 2015 and 2017

2017 Sample ID	2017 ^{222}Rn		2015 Sample ID	2015 ^{222}Rn		2010 Sample ID	2010 ^{222}Rn
LF1	0.297		RS06	0.03		1	0.123
LF2	0.157		RS12	0.168		2	0.108
LF3	0.129		RS16	0.052		3	0.134
LF5	0.136		RS18	0.109		4	0.116
LF6	0.135		RS20	0.08		5	0.145
LF7	0.171						
LF8	0.189		RS21	0.101			
LF9	0.133		RS23	0.179		6	0.125
LF10	0.134					7	0.12
LF11	0.096		RS25	0.051		8	0.188
LF12	0.116		RS26	0.197		9	0.163
LF13	0.081		RS29	0.149		10	0.172
LF14	0.142		RS30	0.237			
LF15	1.007		RS32	0.173			
LF16	1.108		OS03	0.14			
LF17	0.125		RS33	0.023			
LF19	0.17		RS34	0.067			
LF20	0.134		RS35	0.067			
LF21	0.161		RS36	0.067			
LF22	0.166		RS37	0.067			
LF23	0.141		RS38	0.067			
LF25	0.159		RS40	0.161			
LF26	0.159		RS44	0.03			
LF27	0.027		RS46	0.141			
LF33	0.031		RS49	0.136			
LF36	0.204		OS04	0.044		30	0.14
LF56	0.233					29	0.169

2017 Sample ID	2017 ^{222}Rn		2015 Sample ID	2015 ^{222}Rn		2010 Sample ID	2010 ^{222}Rn
LF58	0.202					28	0.182
LF59	0.264					27	0.255
LF60	0.346					26	0.426
LF61	0.409					25	0.347
LF62	0.478					24	0.385
LF63	0.664					23	0.164
LF64	0.635					22	0.143
LF65	0.465					21	0.135
LF66	0.318					20	0.118
LF67	0.319					19	0.136
LF68	0.273					17	0.188
LF72	0.24					16	0.148
LF74	0.234					15	0.152
LF76	0.294					13	0.178
LF78	0.107					12	0.205
LF79	0.149					11	0.212
LF80	0.237						

Appendix Q ^{4}He in groundwater

Bore ID	Aquifer	Confined/unconfined	^{4}He (ccSTP/g)	F(He)	He detects (old water)	Pearson radiocarbon age (years)
Birdwood Bore	Alluvium	Unconfined	8.50E-08	1.6	×	Modern
LF01	Alluvium	Unconfined	1.00E-07	1.7	×	Modern
LF02	Alluvium	Unconfined	1.40E-07	3	✓	Modern
LF03B	Alluvium	Unconfined	1.10E-05	222.2	✓	Modern
LF04B	Alluvium	Unconfined	9.60E-06	202.9	✓	Modern
LF05	Alluvium	Unconfined	3.20E-07	5.9	✓	Modern
2-89 Mt Anderson	Liveringa Group	Unconfined	4.70E-07	8.8	✓	Modern
LF03A	Noonkanbah Formation	Aquitard	4.70E-05	995.4	✓	29,600
LF04A	Noonkanbah Formation	Aquitard	5.30E-05	1,130.10	✓	38,200
Peglars Bore	Poole Sandstone	Unconfined	1.40E-07	3.1	✓	Modern
Paradise Bore	Poole Sandstone	Unconfined	3.30E-06	60.1	✓	6,800
Huttons Bore No.2	Poole Sandstone	Confined	1.10E-06	12.5	✓	13,700
Pilots Flowing Bore	Poole Sandstone	Confined	3.20E-05	873.3	✓	35,500
Tank Bore No.2	Poole Sandstone	Confined	9.90E-05	NA	✓	28,800
One Tree Bore No.2	Poole Sandstone	Confined	7.60E-05	1,584.40	✓	18,100
LF06	Poole Sandstone	Confined	1.00E-07	2.1	✓	4,700
Looma 1-86	Grant Group	Unconfined	5.70E-08	1.3	×	Modern
Looma 1-93	Grant Group	Unconfined	6.40E-08	1.3	×	Modern
Thomas Bore	Grant Group	Unconfined	7.40E-08	1.5	×	Modern
LF07	Grant Group	Unconfined	6.10E-08	1.4	×	Modern
BS16MB001A	Grant Group	Unconfined	8.40E-08	1.7	×	Modern
BS16MB001B	Grant Group	Unconfined	7.70E-08	1.7	×	Modern
BS16MB001C	Grant Group	Unconfined	6.30E-08	1.4	×	Modern
BS16MB003A	Grant Group	Unconfined	1.20E-07	2.4	✓	Modern
BS16MB003B	Grant Group	Unconfined	9.90E-08	1.9	×	Modern
BS16MB003C	Grant Group	Unconfined	1.00E-07	2	✓	Modern
KD16MB002	Grant Group	Unconfined	4.20E-07	7.9	✓	5,400
KD16MB003	Grant Group	Unconfined	1.50E-07	2.7	✓	1,700
Laurel Homestead Bore	Grant Group	Unconfined	6.10E-08	1.2	×	Modern
Donalds Mill No.2	Grant Group	Unconfined	2.50E-06	48.4	✓	Modern
Gogo Homestead Bore 3A	Grant Group	Unconfined	7.10E-07	13.2	✓	8,100
Agricon 2	Grant Group	Confined	5.90E-06	109.5	✓	NR

Bore ID	Aquifer	Confined/unconfined	^{4}He (ccSTP/g)	F(He)	He detects (old water)	Pearson radiocarbon age (years)
PT4	Devonian reef	Unconfined	3.30E-07	6	✓	Modern
Birdwood Bore	Alluvium	Unconfined	8.50E-08	1.6	×	Modern
LF01	Alluvium	Unconfined	1.00E-07	1.7	×	Modern
LF02	Alluvium	Unconfined	1.40E-07	3	✓	Modern
LF03B	Alluvium	Unconfined	1.10E-05	222.2	✓	Modern
LF04B	Alluvium	Unconfined	9.60E-06	202.9	✓	Modern
LF05	Alluvium	Unconfined	3.20E-07	5.9	✓	Modern
2-89 Mt Anderson	Liveringa Group	Unconfined	4.70E-07	8.8	✓	Modern
LF03A	Noonkanbah Formation	Aquitard	4.70E-05	995.4	✓	29,600
LF04A	Noonkanbah Formation	Aquitard	5.30E-05	1,130.10	✓	38,200
Peglars Bore	Poole Sandstone	Unconfined	1.40E-07	3.1	✓	Modern

Appendix R Calculating groundwater residence times and recharge rates

CFC and tritium analysis

Tritium is a more robust indicator of groundwater residence time than CFCs, because it is less subject to contamination and/or degradation. In samples where it is suspected that CFC concentrations have been impacted by factors such as anoxic groundwater conditions, microbial decomposition or sampling errors caused by atmospheric equilibration, tritium may be used as a check, as higher tritium levels should correspond to younger CFC residence times.

Tritium in rainfall in the Fitzroy region is about 1.4 tritium units (TU) – equivalent to 1.4 tritium atoms per 1x108 hydrogen atoms. This is based on a regional tritium in Australia rainfall map (Tadros et al. 2014).

CFC-derived groundwater residence times were calculated following methodology and equations taken from Chapter 3 of International Atomic Energy Agency (IAEA) (2006), *Use of chlorofluorocarbons in hydrology*.

To calculate total atmospheric pressure (P):

$$\ln P = -{}^{H}\!/_{8300} \qquad (1)$$

Where: P = atmospheric pressure

H = the elevation where recharge took place (in metres).

- To calculate Henrys Law constants (K_H) for CFC-11 and CFC-12:

$$lnK_H = a_1 + a_2\left[\frac{100}{T}\right] + a_3 ln\left[\frac{T}{100}\right] + S\left[b_1 + b_2\left(\frac{T}{100}\right) + b_{30}\left(\frac{T}{100}\right)^2\right] \qquad (2)$$

Where : $a_1, a_2, a_3, b_{1,} b_2, b_3$ are constants (Table 3.1, page 19, IAEA (2006))

T = temperature in degrees kelvin, and

S = salinity in parts per thousand (by weight).

- To calculate the partial pressure of water (P_{H2O}):

$$\ln p_{H_2O} = 24.4543 - 6.4509\left[\frac{100}{T}\right] - 4.8489 ln\left[\frac{T}{100}\right] - 0.000544S \qquad (3)$$

Where: T = temperature of the groundwater sample in degrees kelvin

S = salinity in parts per thousand (by weight).

- To calculate the concentration (*x*) of CFC-11 (pptv) and CFC-12 (pptv) in the sample:

$$x = \frac{C}{K_H}\left(P - p_{H_2O}\right) \qquad (4)$$

Where: P = atmospheric pressure (equation 1)

K_H = Henrys Law constant (equation 2)

p_{H_2O} = partial pressure of water (equation 3)

C = molar concentration of either CFC-11 or CFC-12 (mol/kg).

The partial pressure (pptv) is then aligned with a recharge year as per the atmospheric mixing ratios for the southern hemisphere in Appendix II: ‘Input Functions’ in IAEA (2006).

Radiocarbon analysis

Conventional radiocarbon age (CRA) is based on the rate of radioactive decay, with no correction for any groundwater chemical processes. This produces the highest estimated residence time.

- The following methodology and calculations to estimate CRA were taken from Chapter 4: IAEA (2013), *Isotope methods for dating old groundwater*.

$$t = \frac{5730}{ln2} ln\left(\frac{A_{nd}}{A}\right) \quad (5)$$

Where:

t = time elapsed since recharge

5730 = is the half-life of ^{14}C in years

A_{nd} = is the initial ^{14}C content, highest measured percent modern carbon (pMC) of 104.45 used

A = the measured ^{14}C content (pMC) of each sample.

The conventional radiocarbon age (CRA) for each sample is presented in Section 5 – Groundwater residence times, along with the residence times calculated from analytical correction models for comparison. Selection of a correction model is required to account for water-rock interactions as indicated from the major ion ratio analysis, mineral saturation index analysis and the δ13C analysis.

The following assumed values were used in the calculation of the Tamers, Pearson, Fontes, and Garnier and Mook analytical correction models.

End member	Value
Soil gas ^{14}C	104.45 pMC
Soil gas $\delta^{13}C$	-20 per mille
Carbonate ^{14}C	0 pMC
Carbonate $\delta^{13}C$	0 per mille
Egb (CO_2g to HCO_3aq)	7 per mille
Ecb (HCO_3 and solid)	0.9 per mille

The rationale behind selection of an appropriate radiocarbon correction model is discussed in Section 6.3. The Pearson model (Ingerson & Pearson 1964) was selected as the most appropriate correction model to evaluate groundwater residence times based on radiocarbon analysis for this study.

The Pearson correction model was calculated as follows, according to IAEA (2013):

$$A_{o\ Pearson} = \frac{(A_g - A_c)(\delta_T - \delta_c)}{(\delta_g - \delta_c)} + A_c \qquad (6)$$

Where: $A_{o\ Pearson}$ = the initial ^{14}C specific activity

A_g = soil gas ^{14}C

δ_g = soil gas $\delta^{13}C$

A_c = carbonate ^{14}C

δ_c = carbonate $\delta^{13}C$.

$$Pearson\ residence\ time\ (years) = \frac{ln\left(\frac{A_{o\ Pearson}}{A}\right)}{k} \qquad (7)$$

Where: $A_{o\ Pearson}$ = the initial ^{14}C specific activity

A = the measured ^{14}C content in the sample

k = ^{14}C decay constant = 0.0001209 per year.

Recharge estimates for unconfined aquifers were calculated using radiocarbon-derived groundwater residence times. Calculations used the following exponential flow model:

$$R = \frac{z\varepsilon}{t} \qquad (8)$$

Where:

R: recharge rate in mm/year

z: groundwater sample depth (mid-section of screen interval)

t: corrected radiocarbon residence time (Pearson correction model)

ε: porosity (same estimates used as in CFC analysis).

Confined aquifer groundwater recharge estimates were calculated using the following exponential piston-flow model (Cook & Bohlke 2000):

$$R = \left(\frac{H\varepsilon}{t}\right) ln\left(\frac{H}{H-z}\right) + \left(\frac{x^{*}H\varepsilon}{xt}\right) \qquad (9)$$

Where:

R: groundwater recharge rate (mm/year)

H: aquifer thickness (m)

z: groundwater sample depth, mid-section of screen interval (m)

t: corrected radiocarbon residence time (the Pearson correction model is discussed in Section 7.2)

ε: porosity

x*: distance between bore sampled and aquifer outcrop area (m)

x: width of outcrop area (m).

Chloride mass balance

The chloride mass balance (CMB) method was also used to provide a recharge estimate. The CMB method assumes the following (Wood & Sanford 1995):

- Chloride is highly soluble.
- Chloride is a conservative tracer.
- Chloride in groundwater is only sourced from rainfall.
- Chloride concentration in rainfall has been constant over thousands of years (or the age of the sample).
- The groundwater system is in steady state.
- Surface runoff is known or can be estimated, but ponded water (that is, floodwater) is not a significant source of groundwater recharge.

- When surface runoff is negligible, the CMB method can be expressed as:

$$R = \frac{PC_p}{C_{gw}} \qquad (10)$$

Where:

R: groundwater recharge rate (mm/year)

P: annual rainfall (mm/year)

C_p: chloride concentration in rainfall (mg/L)

C_{gw}: chloride concentration in groundwater (mg/L).

CFC analysis

- Groundwater recharge rates can be determined for an unconfined aquifer of constant thickness according to the following equation (IAEA 2006):

$$R = \frac{z\theta}{t} \qquad (11)$$

Where:

R: recharge rate (mm/year)

θ: porosity (estimated for each aquifer)

T: residence time in years

z: depth of sample below unconfined watertable (mm).

Appendix S Determining correction model for radiocarbon dating

This study used the ratio of carbon-13 to carbon-12 (δ13C), reported in parts per thousand (‰), for dissolved inorganic carbon to select the most suitable correction model for calculating groundwater residence times using the radiocarbon method. These were also used to help better understand geochemical processes such as carbonate dissolution.

The range of δ13C values for each of the different aquifers was:

- Fitzroy River alluvial aquifer: from -8.60 ‰ (LF04B) to -14.5 ‰ (LF01)
- Liveringa Group aquifer: one useable sample -12.6 ‰ (RRMW005D)
- Noonkanbah Formation: from -11.3 ‰ (LF03A) to -12.46 ‰ (Manta Ray Bore)
- Poole Sandstone aquifer: from -8.9 ‰ (Montgomery Bore) to -13.94 ‰ (One Tree Bore No. 2)
- Grant Group aquifer: from -9.4 ‰ (2/89 – Fitzroy Crossing) to -16.2 ‰ (Looma 1-86)
- Devonian reef aquifer: from -2.47 ‰ (Emanuels Flowing Bore) to -12.32 ‰ (Sallys Bore).

The highest δ13C composition recorded by this study was -2.47 ‰ at Emanuels Flowing Bore in the Devonian reef aquifer system. It is unclear why this value is higher than all other δ13C values. The next highest value (-7.33 ‰) was recorded in the Grant Group at 2/89 – Fitzroy Crossing.

Excluding the result from Emanuels Flowing Bore, the largest range in δ13C values was observed in the Fitzroy River alluvial aquifer, which is consistent with its lithological heterogeneity and wide range in salinity levels.

A larger range in δ13C values indicates a range of geochemical processes, which will affect groundwater residence times calculated using the radiocarbon method. Therefore, a suitable correction model must be applied (IAEA 2013).

Carbonate dissolution

An increasing trend in δ13C is also linked with carbonate mineral dissolution. Lower bicarbonate values are connected with unconfined, younger groundwater directly recharged by rainfall, while higher bicarbonate levels are correlated with longer residence times and increased mineral dissolution.

Groundwater from the Fitzroy River alluvial aquifer at Camballin (LF02, LF03B and LF04B) indicates carbonate dissolution. Samples with < 2 mmol/L of bicarbonate are associated with direct rainfall recharge.

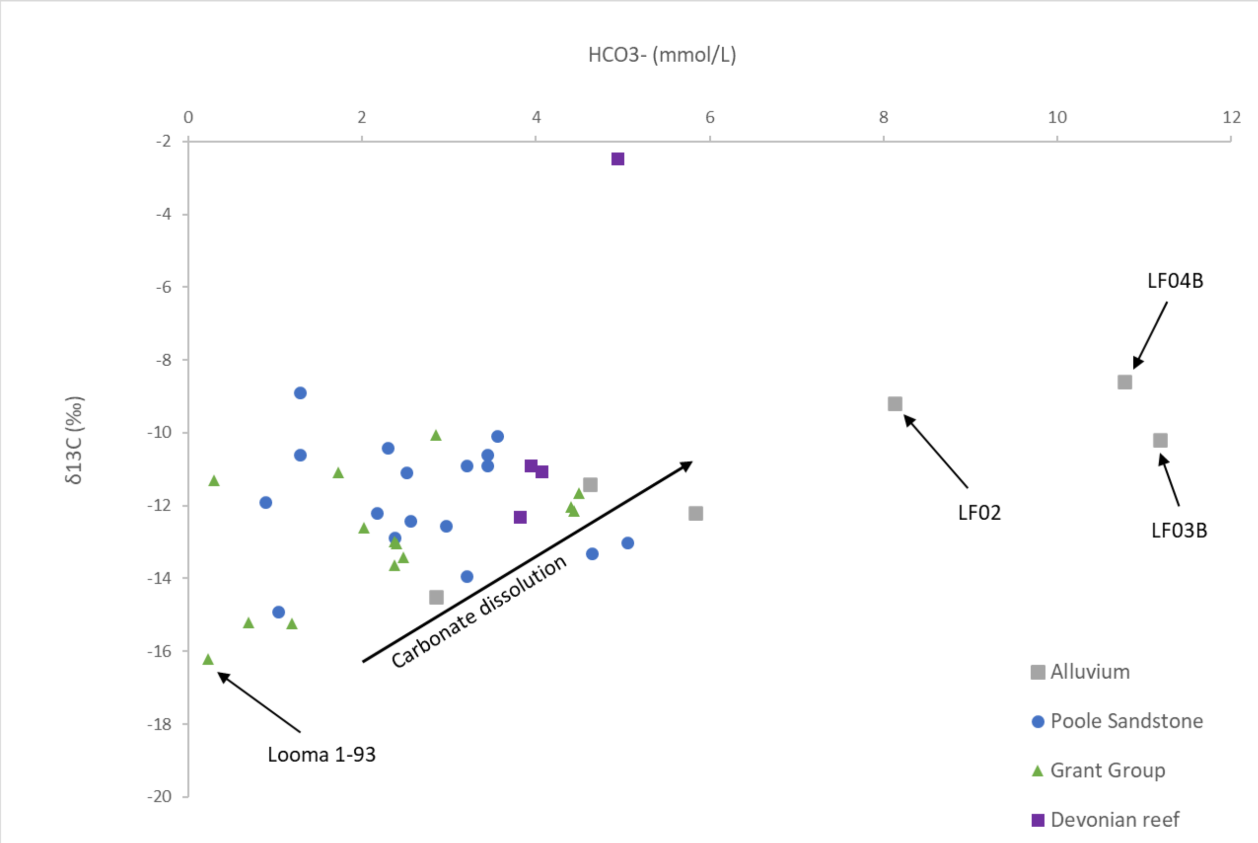


Figure 97 δ13C versus field bicarbonate concentrations

Groundwater samples from the Grant Poole aquifer that indicate carbonate dissolution are either older, confined, deeper samples in the Fitzroy Trough flow paths or are from the Lennard Shelf, where groundwater chemistry may be influenced by the up-gradient Fairfield Group and Devonian reef aquifers.

More samples were collected from the unconfined Grant Poole aquifer in the Fitzroy Trough than were collected on the Lennard Shelf.

The Grant Poole aquifer bores in the Fitzroy Trough all plot within the rainfall recharge box. Other Fitzroy Trough bores along the carbonate dissolution line have longer residence times and are located further along their respective groundwater flow paths.

Of the groundwater samples collected on the Lennard Shelf, the low bicarbonate levels observed in No. 8 bore and KD16MB003 indicate they are located in areas of higher recharge. These samples do not appear to be subject to changes in chemical composition due to inflow from, or connectivity with, the Devonian reef aquifer.

References

Al-Hinaai J 2013, *Constraining the structural evolution of the Canning Basin, NW Australia, and controls on Carboniferous-Permian ice sheets development*, a thesis submitted to the University of Manchester for the degree of Doctor of Philosophy in the faculty of Engineering and Physical Sciences, p. 228.

Al-Hinaai J & Redfern J 2015, 'Tectonic and climatic controls on the deposition of the Permo-Carboniferous Grant Group and Reeves Formation in the Fitzroy Trough, Canning Basin, Western Australia', *Marine and Petroleum Geology,* vol. 59, pp. 217–231.

ANZECC & ARMCANZ 2000*, Australian and New Zealand guidelines for fresh and marine water quality, 2000*, Australian and New Zealand Environment and Conservation Council (ANZECC) & Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ), Canberra.

Apak SN 1996, *Depositional history of the Lower Permian Carolyn Formation and Poole Sandstone in the Northern Canning Basin: Implications for hydrocarbon potential*, Geological Survey of Western Australia, Record 1996/8.

Apak SN & Backhouse J 1998, *Stratigraphy and petroleum exploration objectives of the Permian-Carboniferous of the Barbwire Terrace and adjacent areas, Northeast Canning Basin*, Geological Survey of Western Australia, Report 68, p. 30.

Appelo CAJ 1994, 'Cation and proton exchange, pH variations and carbonate reactions in a freshening aquifer'*, Water Resources Research,* vol. 30, pp. 2793–2805.

Backhouse J & Mory AJ 2020, *Mid-Carboniferous – Lower Permian palynology and stratigraphy, Canning Basin, Western Australia*, Geological Survey of Western Australia, Report 207, p. 133.

Barnes CJ, Jacobson G & Smith GD 1992, 'The origin of high-nitrate ground waters in the Australian arid zone', *Journal of Hydrology*, vol. 137(1): pp. 181–97.

Bureau of Meteorology (BoM) 2022, *Monsoonal North – National Hydrological Projections Assessment report,* Bureau of Meteorology, Australia.

Brodie RC 2016, *West Kimberley Airborne Electromagnetic Survey, WA, 2015 – Contractors supplied data and conductivity models*, Geoscience Australia and the Western Australia Department of Water through the WA Water for Food Initiative, Geoscience Australia.

Busenberg E & Plummer LN 1992, 'Use of chlorofluorocarbons (CCl_3F and CCl_2F_2) as hydrologic tracers and age-dating tools: The alluvium and terrace system of central Oklahoma', *Water Resources Research*, vol. 28(9), pp. 2257–2283.

Charles S, Petheram C, Berthet A, Browning G, Hodgson G, Wheeler M, Yang A, Gallant S, Vaze J, Wang B, Marshall A, Hendon H, Kuleshov Y, Dowdy A, Reid P, Read A, Feikema P, Hapuarachchi P, Smith T, Gregory P & Shi L 2016, *Climate data and their characterisation for hydrological and agricultural scenario modelling across the Fitzroy, Darwin and Mitchell catchments*, a technical report to the Australian Government from the CSIRO Northern Australia Water

Resource Assessment, part of the National Water Infrastructure Development Fund: Water Resource Assessments. CSIRO, Australia. p. 182

Christensen NB 2017, *Inversion of the West Kimberley Fitzroy SkyTEM 312 survey*, short report prepared for Geoscience Australia.

Clohessy S 2017, *Bore completion report, Lower Fitzroy drilling program 2017*, Hydrogeological record series HR393, Department of Water and Environmental Regulation.

Clohessy S 2018, *Fitzroy groundwater monitoring review, Kimberley, WA*, Hydrogeological record series HR398, Department of Water and Environmental Regulation.

Cook PG 2013, 'Estimating groundwater discharge to rivers from river chemistry surveys', *Hydrological Processes,* vol. 27 3694, 14 p.

Cook PG 2015, 'Quantifying river gain and loss at regional scales', *Journal of Hydrology*, vol. 531, pp. 749–758.

Cook PG & Bohlke JK 2000, 'Determining timescales for groundwater flow and solute transport', in: O Cook & AL Herczeg (eds), *Environmental tracers in subsurface hydrology*, pp. 1–30.

Copp IA 2000, *Subsurface facies analysis of Devonian reef complexes, Lennard Shelf, Canning Basin, Western Australia*, Western Australia Geological Survey, Report 58, p. 127.

Crosbie RS, Jolly I, Leaney F, Petheram C & Wohling D 2010, *Review of Australian groundwater recharge studies*, CSIRO: Water for a Healthy Country National Research Flagship, pp. 81.

Crosbie RS, Morrow D, Cresswell RG, Leaney FW, Lamontagne S & Lefournour M 2012, *New insights into the chemical and isotopic composition of rainfall across Australia*, CSIRO: Water for a Healthy Country Flagship, Australia, pp. 86.

Crosbie RS, Peeters LJM, Herron N, McVicar TR & Herr A 2018, 'Estimating groundwater recharge and its associated uncertainty: Use of regression kriging and the chloride mass balance method', *Journal of Hydrology,* vol. 561, pp. 1063–1080.

Crowe RWA & Towner RR 1976, *Definition of some new and revised rock units in the Canning Basin*, Geological Survey of Western Australia, Record no. 1976/24.

CSIRO 2009, *Water in the Timor Sea Drainage Division*, a report to the Australian Government from the CSIRO Northern Australia Sustainable Yields Project, CSIRO: Water for a Healthy Country Flagship, Australia.

Davies PJ & Crosbie R 2014, *Australian chloride deposition rate v4*, CSIRO Data Collection 10.4225/08/545BEE54CD4FC.

Davies PJ & Crosbie RS 2018, 'Mapping the spatial distribution of chloride deposition across Australia', *Journal of Hydrology*, vol. 561, pp 76–88.

Dawes WR, Taylor AR, Harrington GA & Davies PJ 2018, *Groundwater flow modelling of the Grant Group and Poole Sandstone aquifer – Fitzroy Trough*, Western Australia, a technical report to the Australian Government from the CSIRO Northern Australia Water Resource Assessment (part of the National

Water Infrastructure Development Fund: Water Resource Assessments, CSIRO, Australia) doi.org/10.25919/5b86ed8ebc095

Dent LM 2017, *The Liveringa Group, Canning Basin: correlating outcrop to subsurface*, Geological Survey of Western Australia, Report 173, p. 73.

Dentith MC, Dent L, George AD, Langhi L, Sanchez G, Seyedmehdi Z, Strand J, Vaslin A & Zaheer R 2015, *Geosequestration potential of the Carboniferous–Permian Grant Group and Permian Poole Sandstone, northwest Canning Basin, Western Australia*, Geological Survey of Western Australia, Report 139, p. 101.

Department of Health 2011, *Guidelines for the non-potable uses of recycled water in Western Australia*, Water Unit Environmental Health Directorate, Department of Health, Perth, p. 100.

Department of Mines, Industry, Regulation and Safety (DMIRS) 2016, *1:500,000 state interpreted bedrock geology of Western Australia,* (DMIRS-016).

Department of Water 2011*, Water allocation planning in Western Australia – A guide to our process*, Water resource allocation planning series, Government of Western Australia. ISBN 978-1-921789-96-0.

Department of Water and Environmental Regulation (DWER) 2017, *Bore completion report, Water for Food: Fitzroy Valley drilling, Kimberley Downs and Brooking Springs stations*, Hydrogeological record series HR388, Department of Water and Environmental Regulation.

Department of Water and Environmental Regulation (DWER) 2020, Derby groundwater allocation plan, for public comment, Water resource allocation planning, report no. 69, Department of Water and Environmental Regulation, Joondalup.

Department of Water and Environmental Regulation (DWER) 2022, *Hydrology and surface water modelling in the Fitzroy River,* Surface water hydrology series, Department of Water and Environmental Regulation, Joondalup.

Department of Water and Environmental Regulation (DWER) 2022, *Heritage and environmental values and the importance of water in the Fitzroy,* Environmental water report series, report no. 24, Department of Water and Environmental Regulation, Joondalup.

Doble RC, Palmer D, Cook P & McCallum J 2010, *Sampling for stream-aquifer connections by helicopter in a remote, inaccessible area*, in: Groundwater 2010, 31 October – 4 November 2010, Canberra, International Association of Hydrogeologist and Geological Society of Australia.

Doble R, Brunner P, McCallum J & Cook PG 2012, ‘An analysis of river bank slope and unsaturated flow effects on bank storage’, *Groundwater*, vol. 50(1), pp 77–86

Druce EC & Radke BM 1979, *The geology of the Fairfield Group, Canning Basin, Western Australia*, Department of National Development, Bureau of Mineral Resources, Geology and Geophysics, Bulletin 200, Canberra 1979.

Fallon SJ, Fifield LK & Chappell JM 2010, ‘The next chapter in radiocarbon dating at the Australian National University: status report on the single stage AMS’, *Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms*, vol. 268 (7–8): pp 898– 901.

Fetter CW 2001, *Applied hydrogeology*, 4th edition, Prentice Hall, p. 598.

Fink D, Hotchkis M, Hua Q, Jacobsen G, Smith AM, Zoppi U, Child D, Mifsud C, van der Gaast H, Williams A & Williams M 2004, 'The Antares AMS facility at ANSTO', *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 223, pp 109–115.

Gallardo A, Paker H & Stocker C 2015, *Water for Food – Mowanjum irrigation trial: technical report*, Hydrogeological record series, HR 354, Department of Water.

Gallardo A 2017, *Fitzroy Valley hydrogeological investigation – Bunuba bore completion report*, Hydrogeological record series, HR 356, Department of Water and Environmental Regulation.

Gallardo A 2018a, *Groundwater exploration for irrigation supply to the Knowsley area, West Kimberley*, Hydrogeological record series, HR 371, Department of Water and Environmental Regulation.

Gallardo A 2018b, *Bore completion report, Water for Food: Fitzroy Valley drilling, Mount Anderson Station*, Hydrogeological record series, HR386, Department of Water and Environmental Regulation.

Gallardo A 2019, 'Hydrogeological characterisation and groundwater exploration for the development of irrigated agriculture in the West Kimberley region, Western Australia', *Groundwater for Sustainable Development*, vol. 8, pp. 187–197.

Gardner WP, Harrington GA, Solomon DK & Cook PG 2011, 'Using terrigenic ^{4}He to identify and quantify regional groundwater discharge to streams', *Water Resources Research*, vol. 47, doi: 10.1029/2010WR010276.

Gates JB, Böhlke JK & Edmunds WM 2008, 'Ecohydrological factors affecting nitrate concentrations in a phreatic desert aquifer in northwestern China', *Environmental Science & Technology*, vol. 42(10), pp 3531–3537.

Geoscience Australia and Australian Stratigraphy Commission 2017, Australian Stratigraphic Units Database, available from Australian Stratigraphic Units Database, Geoscience Australia (ga.gov.au), viewed 21 July 2020.

Giménez-Forcada E 2010, 'Dynamic of sea water interface using hydrochemical facies evolution diagram,' *Groundwater*, vol. 48: 212–216. doi.org/10.1111/j.1745-6584.2009.00649.x

Guppy DJ, Lindner AW, Rattigan JH & Casey JN 1958, *The geology of the Fitzroy Basin, Western Australia*, Bureau of Mineral Resources, Geology and Geophysics Bulletin no. 36, Department of National Development, Commonwealth of Australia.

Harbaugh AW 2005, *MODFLOW-2005, the US Geological Survey modular ground-water model – the ground-water flow process*, US Geological Survey Techniques and Methods 6-A16.

Harrington GA, Stelfox L, Gardner WP, Davies P, Doble R & Cook PG 2011, *Surface water – groundwater interactions in the lower Fitzroy River, Western Australia,* CSIRO: Water for a Healthy Country National Research Flagship, pp. 54.

Harrington GA & Harrington NM 2015, *Lower Fitzroy River groundwater review*, a report prepared for Department of Water by Innovative Groundwater Solutions.

Harrington GA & Harrington NM 2016, *A preliminary assessment of groundwater contribution to wetlands in the lower reaches of Fitzroy River catchment*, a report prepared for Department of Water, Western Australia, by Innovative Groundwater Solutions.

Harrington GA, Payton GW & Munday TJ 2014, 'Tracking groundwater discharge to a large river using tracers and geophysics'*, Groundwater,* vol. 52, no. 6, November – December 2014, pp. 837–852.

Hingston FJ & Gailitis V 1976, 'The geographic variation of salt precipitated over Western Australia', *Australian Journal of Soil Research*, 1976, vol. 14, pp 319–335

Hounslow AW 1995, *Water quality data; analysis and interpretation*, Lewis Publishers, Washington DC, p. 381.

Hughes J, Yang A, Wang B, Marvanek S, Carlin L, Lynn S, Petheram C & Jai V 2017, *Calibration of river system and landscape models for the Fitzroy, Darwin and Mitchell catchments*, a technical report to the Australian Government from the CSIRO Northern Australia Water Resource Assessment, part of the National Water Infrastructure Development Fund: Water Resource Assessments doi.org/10.25919/5b86ed6c5dfdd

Ingerson E & Pearson FJ Jr. 1964, 'Estimation of age and rate of motion of groundwater by the ^{14}C method', *Recent research in the fields of hydrosphere, atmosphere, and nuclear geochemistry*, Tokyo: Maruzen. p 263–83.

International Atomic Energy Agency 2016, *Use of chlorofluorocarbons in hydrology: a guidebook*, International Atomic Energy Agency, Vienna, p. 291

International Atomic Energy Agency 2013, *Isotope methods for dating old groundwater*, International Atomic Energy Agency, Vienna, p. 376.

Joseph J & Searle J 2015, *An investigation of the hidden precious water resources of Dampier Peninsula using airborne electromagnetic method*, ASEG Extended Abstracts 2015, 1–4.

Laws AT & Smith RA 1987, *The Derby regional groundwater investigation 1987*, Geological Survey of Western Australia, Record 1989/12, p. 46.

Lindsay RP & Commander DP 2005, *Hydrogeological assessment of the Fitzroy alluvium, Western Australia*, Department of Water, Hydrogeological record series HG16.

Mira Geoscience 2018, *Fitzroy Valley SkyTEM Survey: Interpretation and geological modelling*, a report to the Department of Water and Environmental Regulation, Western Australia, Mira Geoscience Project #4675, p. 97.

Morgenstern U & Taylor CB 2009, 'Ultra low-level tritium measurement using electrolytic enrichment and LSC', *Isotopes in Environmental and Health Studies,* vol. 45(2), pp 96–117.

Mory 2010, *A review of mid-Carboniferous to Triassic stratigraphy, Canning Basin, Western Australia,* Geological Survey of Western Australia, Report 107, p. 130.

Mory AJ & Hocking RM (compilers) 2011, *Permian, Carboniferous and Upper Devonian geology the northern Canning Basin, Western Australia – a field guide*, Geological Survey of Western Australia, Record 2011/16, p. 36.

Nicoll RS & Druce EC 1979, *Conodonts from the Fairfield Group, Canning Basin, Western Australia*, Bulletin of the Bureau of Mineral Resources, Geology and Geophysics Australia, vol. 190, p. 134.

Nicoll RS, Laurie JR, Kelman AP, Mantle DJ, Haines PW, Mory AJ & Hocking RM 2009, *Canning Basin biozonation and stratigraphy*, Geoscience Australia, Chart 31.

Petheram C, Bruce C, Chilcott C & Waton I (eds) 2018, *Water resource assessment for the Fitzroy catchment*, a report to the Australian Government from the CSIRO Northern Australia Water Resource Assessment, part of the National Water Infrastructure Development Fund: Water Resource Assessments. CSIRO, Australia.

Playford, PE, Hocking, RM & Cockbain, AE 2009*, Devonian reef complexes of the Canning Basin, Western Australia*, Geological Survey of Western Australia, Bulletin 145, p. 444.

Playford PE, Hocking RM & Cockbain AE 2014*,* 'Devonian Great Barrier Reef of the Canning Basin, Western Australia: the evolution of our understanding', *Journal of the Royal Society of Western Australia*, vol. 97, pp. 153–172.

Redfern J 1990, *The sedimentology and stratigraphy of the Permo-Carboniferous Grant Group, Barbwire Terrace, Canning Basin, Western Australia*, University of Bristol PhD thesis, p. 197.

Resource Water Group 2016, *Test pumping report: production bore KD16PB001 Fitzroy Phase 2 – Greenfields for Department of Water, WA, Water for Food*.

Rey Resources 2014, *Duchess Paradise Project, public environmental review*, EPA Assessment no. 1899; EPBC Assessment no. 2011/6033, p. 368.

Searle JA 2012, *Groundwater resource review, Dampier Peninsula*, Hydrogeological record series, report no. HG57, Department of Water, Perth.

Seyedmehdi Z 2019, 'Sequence stratigraphy influenced by tectonics and implications for reservoir development, latest Devonian–Early Carboniferous ramp, Canning Basin, Australia', *Marine and Petroleum Geology,* vol. 99, pp. 252–264.

Seyedmehdi Z, George AD & Tucker ME 2016, 'Sequence development of a latest Devonian–Tournaisian distally-steepened mixed carbonate–siliciclastic ramp, Canning Basin, Australia', *Sedimentary Geology,* vol. 333, pp. 164–183.

Sims N, Anstee J, Barron O, Botha E, Lehmann E, Li L, McVicar T, Paget M, Ticehurst C, Van Niel T & Warren G 2016, *Earth observation remote sensing*, a technical report to the Australian Government from the CSIRO Northern Australia Water Resource Assessment, part of the National Water Infrastructure Development Fund: Water Resource Assessments. CSIRO, Australia.

Skrzypek G & Ford D 2014, ‘Stable isotope analysis of saline water samples on a cavity ring-down spectroscopy instrument’, *Environmental Science & Technology*, vol. 48(5), pp. 2827–2834.

Smith RA 1992, *Explanatory notes on the Derby 1:250 000 hydrogeological sheet*, Geological Survey of Western Australia, p. 52.

Stocker C 2015, *Bore completion report – Mowanjum irrigation trial*, Hydrogeological record series, report no. HR355, Department of Water, Government of Western Australia.

Stone AEC & Edmunds WM 2014, ‘Naturally-high nitrate in unsaturated zone sand dunes above the Stampriet Basin, Namibia’, *Journal of Arid Environments*, vol. 105, June 2014, pp 41-51

Sundaram B, Feitz AJ, de Caritat P, Plazinska A, Brodie RS, Coram J & Ransley T 2009, *Groundwater sampling and analysis – a field guide*, Geoscience Australia Record 2009/27, pp. 95.

Tadros CV, Hughes CE, Crawford K, Hollins SE & Chisari R 2014, ‘Tritium in Australian precipitation: a 50-year record’, *Journal of Hydrology*, vol. 513, pp. 262–273.

Taylor AR, Harrington GA, Clohessy SG, Dawes WR, Crosbie RS, Doble RC, Wohling DL, Batlle-Aguilar J, Davies PJ, Thomas M & Suckow A 2018, *Hydrogeological assessment of the Grant Group and Poole Sandstone – Fitzroy Catchment, Western Australia*, a technical report to the Australian Government from the CSIRO Northern Australia Water Resource Assessment (part of the National Water Infrastructure Development Fund: Water Resource Assessments, CSIRO, Australia). doi.org/10.25919/5b86ed7e26b48

Thorpe PM 1993, *Radon-222 content of groundwater in Western Australia*, Geological Survey of Western Australia annual review (1993–1994), pp 77–81.

Weiss RF 1970, ‘Helium isotope effect in solution in water and seawater’, *Science*, vol. 168, issue 3928, pp. 247–248. doi.org/10.1126/science.168.3928.247

Wood W & Sanford W 1995, ‘Chemical and isotopic methods for quantifying ground-water recharge in a regional, semiarid environment’, *Groundwater*, vol. 33, no. 3, May–June 1995.

Yeates AN, Gibson DL, Towner RR & Crowe RWA 1984, ‘Regional geology of the onshore Canning Basin, WA’, in PG Purcell (ed), The Canning Basin, WA: *Proceedings Geological Society of Australia and Petroleum Exploration Society of Australia Symposium*, Perth, Western Australia, pp. 24–55.

Zhan Y & Mory AJ 2013, *Structural interpretation of the Northern Canning Basin, Western Australia*, Geological Survey of Western Australia, West Australian Basins Symposium 2013.

Department of Water and Environmental Regulation
8 Davidson Terrace JOONDALUP WA 6027
Locked Bag 10 Joondalup DC JOONDALUP WA 6919
p: 08 6364 7000
w: www.dwer.wa.gov.au
e: fitzroywaterplanning@dwer.wa.gov.au
22230356