National Research FLAGSHIPS
Water for a Healthy Country

CSIRO

www.csiro.au

Surface Water – Groundwater Interactions in the Lower Fitzroy River, Western Australia

Glenn Harrington, Louise Stelfox, Payton Gardner, Phil Davies, Rebecca Doble and Peter Cook

August 2011

Results of a collaborative research initiative 2008–2011

Government of Western Australia
Department of Water

TRaCK
Tropical Rivers and Coastal Knowledge

Water for a Healthy Country Flagship Report series ISSN: 1835-095X

Australia is founding its future on science and innovation. Its national science agency, CSIRO, is a powerhouse of ideas, technologies and skills.

CSIRO initiated the National Research Flagships to address Australia's major research challenges and opportunities. They apply large scale, long term, multidisciplinary science and aim for widespread adoption of solutions. The Flagship Collaboration Fund supports the best and brightest researchers to address these complex challenges through partnerships between CSIRO, universities, research agencies and industry.

The Water for a Healthy Country Flagship aims to provide Australia with solutions for water resource management, creating economic gains of $3 billion per annum by 2030, while protecting or restoring our major water ecosystems. The work contained in this report is collaboration between CSIRO and Western Australia Department of Water.

For more information about Water for a Healthy Country Flagship or the National Research Flagship Initiative visit www.csiro.au/org/HealthyCountry.html.

Citation: Harrington, G.A., Stelfox, L., Gardner, W.P., Davies, P., Doble, R. and Cook, P.G. 2011. Surface water – groundwater interactions in the lower Fitzroy River, Western Australia. CSIRO: Water for a Healthy Country National Research Flagship. 54 pp.

Cover Photograph:

Waterfall on the Fitzroy River, Noonkanbah Station, Western Australia.
Glenn Harrington, May 2010

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

ACKNOWLEDGMENTS

The work presented in this report was conceived and initially funded through the Tropical Rivers and Coastal Knowledge (TRaCK) program with technical assistance and collaboration provided by the WA Department of Water. Later components of the project were funded by the National Water Commission through the Raising National Water Standards project *Fitzroy River integrated ground and surface water hydrology assessment*, managed by the WA Department of Water. Final stages of the project, including sampling, analysis and reporting were funded by CSIRO Water for a Healthy Country National Research Flagship.

The authors sincerely acknowledge the field and technical assistance provided by many staff from the Kununurra regional office of the WA Department of Water, in particular Duncan Palmer, Clare Taylor and Luke Donovan.

Dr Arthur Mory and Dr John Backhouse from the Geological Survey of Western Australia within the Department of Mines and Petroleum are acknowledged for determining the palyntology of the Lightjack Formation from cuttings from water investigation bores drilled on Noonkanbah Station. The assistance of Dr Arthur Mory in providing access to unpublished literature was invaluable in the geological interpretation.

We wish to thank the pastoralists, local Indigenous communities and traditional owners of the lower Fitzroy Valley for their willingness to allow access to their land for the purposes of drilling, sampling and monitoring of bores and the river.

EXECUTIVE SUMMARY

The water resources of the lower Fitzroy River catchment in the Kimberley region of north-west Western Australia are continuing to present both opportunities and impediments for future irrigation development, mining activities and municipal water supply to southern parts of the State. The recent CSIRO Northern Australia Sustainable Yields (NASY) project revealed that the groundwater and surface water resources of this catchment, and many others across northern Australia, lack the historical monitoring data and fundamental technical understanding required to undertake quantitative water assessments and therefore establish sustainable water management policies. In particular, there is a dearth of information and knowledge of groundwater controls on dry season flows in the Fitzroy River. This report presents a synthesis of preliminary research projects that have aimed at starting to address these knowledge gaps. It includes work undertaken by CSIRO as part of the Tropical Rivers and Coastal Knowledge (TRaCK) program, as well as a project in which CSIRO collaborated with WA Department of Water under the Raising National Water Standards program of the National Water Commission, and finally work undertaken by CSIRO as an extension to NASY.

This suite of projects has used contemporary hydrogeological mapping techniques and water bore drilling, in combination with groundwater and river sampling for both routine and novel environmental chemistry analyses. A transect of nine new monitoring bores was installed on Noonkanbah Station in October 2009 to facilitate near-river groundwater sampling and enable monitoring of groundwater level responses to wet season flood flows and recession. Groundwater samples from these shallow bores, and nine other regional bores completed in the different geologies of the Canning Basin, were analysed for major ion chemistry, stable hydrogen and oxygen isotopes of water, radon-222, noble gases (particularly helium-4), chlorofluorocarbons, carbon-14 and stable strontium isotopes. Longitudinal sampling of surface water from different reaches of the Fitzroy River was undertaken on two occasions (May 2008 and May 2010) by helicopter, and samples were analysed for a similar suite of chemical and isotopic constituents.

The main reach of the Fitzroy River on which these projects have focussed is between Jubilee Downs Station (i.e. downstream of Fitzroy Crossing) and the eastern boundary of Liveringa Station. We have identified two major zones of groundwater discharge along this reach: the first is around the confluence of the Fitzroy River with Cunningham Anabranch, and the second is between a well-known waterfall and Yungngora Community on Noonkanbah Station. Two complex discharge mechanisms have been invoked to explain chemical and isotopic data in the context of recently revised geology for these areas. In the first zone, old regional groundwater in the Liveringa Group is thought to flow westwards towards the river before being forced upwards into the alluvial aquifer, or directly into the river, as it meets the low permeability mudstones of the Noonkanbah Formation. In the second zone, even older regional groundwater from the deep Poole Sandstone aquifer is thought to discharge into the river, possibly via the alluvial aquifer, through a series of faults that transect the river. Modelling of the river chemistry profiles from May 2010 suggests the total rate of groundwater discharge over the 100 kilometre study reach is about 102 ML/day, comprising about 3.7 ML/day for the regional aquifers. The remaining discharge is sourced from local groundwater flow systems in the alluvial aquifer.

The results demonstrate a high dependence of dry season flows in the Fitzroy River on discharge from both local and regional groundwater flow systems. It is likely that future groundwater pumping adjacent the Fitzroy River will result in a reduction to dry season flows, which in turn will have an impact on the water level of permanent pools. The distance at which future extractive industries should be placed away from the River in order to minimise impacts to dry season flows and permanent pools requires further research; however, it will be site specific—that is, it will depend upon the size and pumping regime of the proposed extraction, the hydrogeological properties of the aquifers between the river and the proposed development, and the proximity of the proposed extraction to the various groundwater discharge mechanisms identified above.

1. INTRODUCTION

Continued stress and in some areas serious over-allocation of water resources in southern Australia is placing increasing pressure on State and Federal Governments to explore alternative water resources in relatively undeveloped parts of Australia. The lower Fitzroy River in the Kimberley region of Western Australia is one such area, where opportunities for major water resource development are being considered. Whilst harvesting the vast quantities of surface water from this valley each wet season is not practical, the underlying aquifers—particularly those of the regional Canning Basin—present real and significant water resource development opportunities.

Because of the very low levels of existing groundwater extraction in the Fitzroy Valley, there is a lack of fundamental data and scientific knowledge on how the groundwater systems are recharged and discharged, including the nature of surface water – groundwater interactions along the Fitzroy River. Unlike many groundwater resources in southern Australia, there is the opportunity to define sustainable extraction levels in the Fitzroy River valley ahead of major development.

The lower Fitzroy River Valley has significant Indigenous heritage value. The traditional owners of the region have many social, food supply and cultural requirements of the water resources, and it will be imperative for any future water policy or plan to acknowledge and accommodate these values.

1.1. History of project development and funding

The work presented in this report was initially conceived in 2007–08 as the CSIRO Northern Australia Sustainable Yields Project was identifying major knowledge gaps in the Fitzroy region. Funding was provided through the Tropical Rivers and Coastal Knowledge (TRaCK) program with technical assistance and collaboration from the WA Department of Water. This work included a helicopter run-of-river sampling program in May 2008, sampling several community water supply bores and the drilling/installation of a transect of nested piezometers on Noonkanbah Station in October 2009.

Subsequent work through until June 2011 was jointly funded by the CSIRO Water for a Healthy Country National Research Flagship and by the National Water Commission through the Raising National Water Standards project *Fitzroy River integrated ground and surface water hydrology assessment*, managed by the WA Department of Water. This work included more strategic helicopter run-of-river sampling in May 2010, sampling piezometers and regional water bores, chemical and isotopic analysis, and reporting.

1.2. Objectives

The overall objective of this research was to develop and apply tools and techniques to understand the key processes of surface water – groundwater interaction in the highly dynamic lower Fitzroy River valley. Specific questions that were posed included:

1. What is the nature of the interactions?
2. What is the spatial and temporal variability of these interactions along the river?
3. What are the sources of groundwater discharging into the river?
4. What is the role of bank storage return flows, floodplain-recharged groundwater, and regional groundwater flow in sustaining dry season flows?

2. BACKGROUND

2.1. Physiography and climate

The Fitzroy River catchment is located in the Kimberley region of northwest Western Australia and occupies an area of almost 94,000 km^2 in the subtropics between latitudes 16^{o}S and 18^{o}S (Figure 1). The north-eastern half of the catchment is characterised by uplifted and exposed igneous and metamorphic rocks of the rugged King Leopold Range and Mueller Range. In stark contrast, the lower, southern and western parts of the catchment overly the pericratonic Canning Basin and exhibit limited topographic relief. The Fitzroy River flows a total distance of 733 km from its headwaters in the elevated ranges (altitude >450 m) to its mouth at King Sound on the Timor Sea. The lower reaches are tidally influenced with a diurnal range of typically 8–10 m at Derby near the mouth.

The region is arid to semi-arid, with a mean annual rainfall of about 560 mm and mean annual areal potential evapotranspiration of about 1980 mm. There is a strong north–south rainfall gradient across the catchment of about 1.8 mm/km decreasing southwards. On average, more than 90% of the rainfall occurs during the wet season between November and April. Interannual rainfall variability is high, such that the 10th percentile of annual rainfall is 963 mm/a and the 90th percentile is 363 mm/a (CSIRO, 2009).

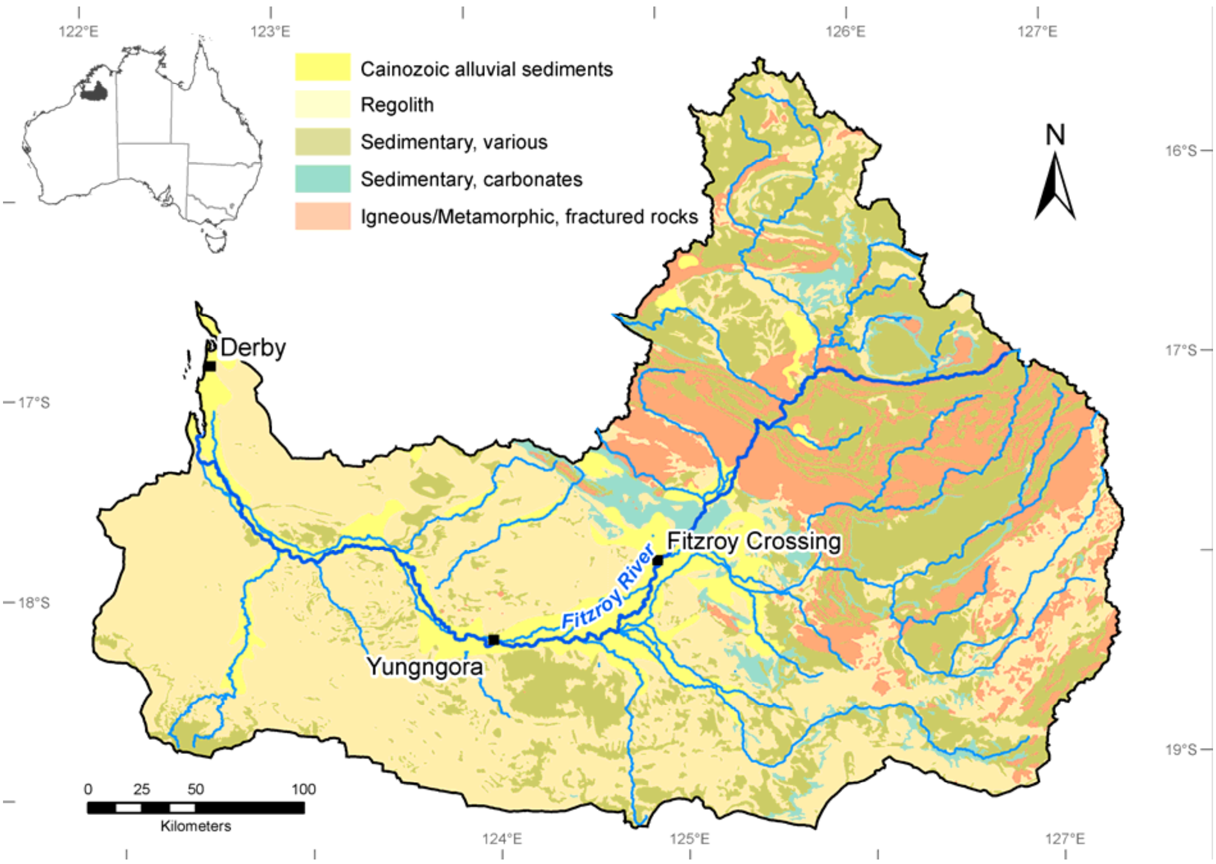


Figure 1. *Location of the Fitzroy River catchment, Western Australia*

2.2. Regional geology

2.2.1. Bedrock

The lower Fitzroy valley is located within the Fitzroy Trough, a major subdivision of the Canning Basin, which contains gently folded Ordovician to Cretaceous sedimentary sequences with a combined thickness of up to 10 km (Laws, 1990). A generalised geological section for the study area is shown in Figure 2, while the published bedrock geology is shown in Figure 3. The latter is based on the 1:500 000 'solid geology' map of the State by the Geological Survey of Western Australia (<www.dmp.wa.gov.au/7113.aspx>).

The study area contains Devonian to Jurassic strata, intruded by narrow lamprolitic volcanic plugs of Miocene age (Middleton, 1990). Sandstone and shale facies of shallow water marine, deltaic and fluvial origin dominate the succession, with some glacial facies in the mid-Carboniferous to earliest Permian (Mory, 2010).

The oldest rocks in the study area, the **Fairfield Group**, comprise limestones, mudstones, and minor sandstones of late Devonian to early Carboniferous age, but are only exposed to the northeast of the area where they are underlain by the Devonian reef (Limestone) complex. Middle to Upper Carboniferous strata (Reeves Formation) is present at depths beyond the scope of this study.

In outcrop the Fairfield Group is unconformably overlain by the Early Permian **Grant Group**: a unit dominated by sandstone often with fine-grained facies in the middle. The Grant Group is exposed mostly to the southwest of Fitzroy Crossing and in the anticlinal structures that have formed the ranges and prominent hills of Grant Range near Liveringa, St George Ranges south-east of Noonkanbah, and Mount Wynne east of Camballin.

The **Poole Sandstone** (Early Permian) is dominated by thinly bedded, fine-grained sandstone that disconformably overlies the Grant Group, and is exposed south-west of Fitzroy Crossing and in the anticlinal structures of Grant Range, St. George Ranges and Mount Wynne. The basal Nura Nura Limestone Member outcrops only on the northern limb of the Mt Wynne anticline, and has a sporadic distribution in petroleum exploration wells in the region. The remainder of the Poole Sandstone forms rounded hills and is a good aquifer; it has been assigned to the Tuckfield and Christmas Creek Members (Crowe and Towner, 1981) but Mory (2010) indicates the latter is not mappable making distinguishing the former of little use.

The **Noonkanbah Formation** (Early Permian) is dominated by silty shales with thin sandstone and carbonate beds. It underlies the Fitzroy River in the vicinity of Yungngora Community (formerly Noonkanbah station). The formation is poorly exposed and known mostly from coal and petroleum exploration bore drilling. The maximum thickness encountered is 642 m (Mory, 2010).

The **Liveringa Group** (Middle to Late Permian) is composed of sandstone and mudstone with lenses and minor beds of limestone and thin coal seams conformably overlying the Noonkanbah Formation. The Liveringa Group is the most extensive unit underlying the Fitzroy River. The group may be up to 620 m thick in the Fitzroy Trough (Mory, 2010), and comprises the Lightjack Formation, Condren Sandstone[1] and Hardman Formation (in ascending order). Further information on the Liveringa Group, including recent remapping of the boundary between this unit and the Noonkanbah Formation, is provided in Appendix A.

---

[1] The Condren Sandstone is not present or not recognised in part of the 1:250 000 Noonkanbah geological sheet area.

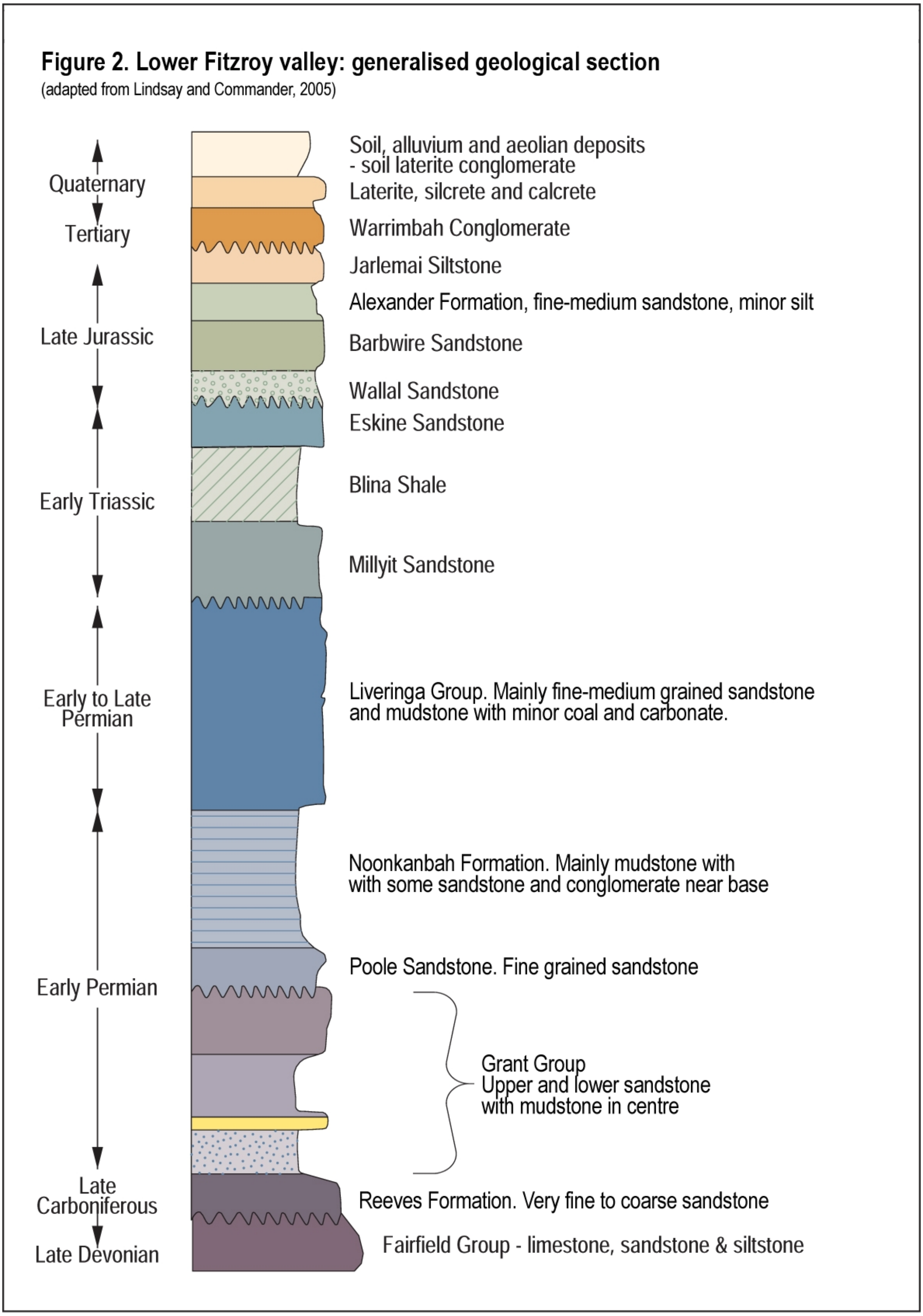


Figure 2. *Generalised geological section for the study area (modified from Lindsay and Commander, 2005)*

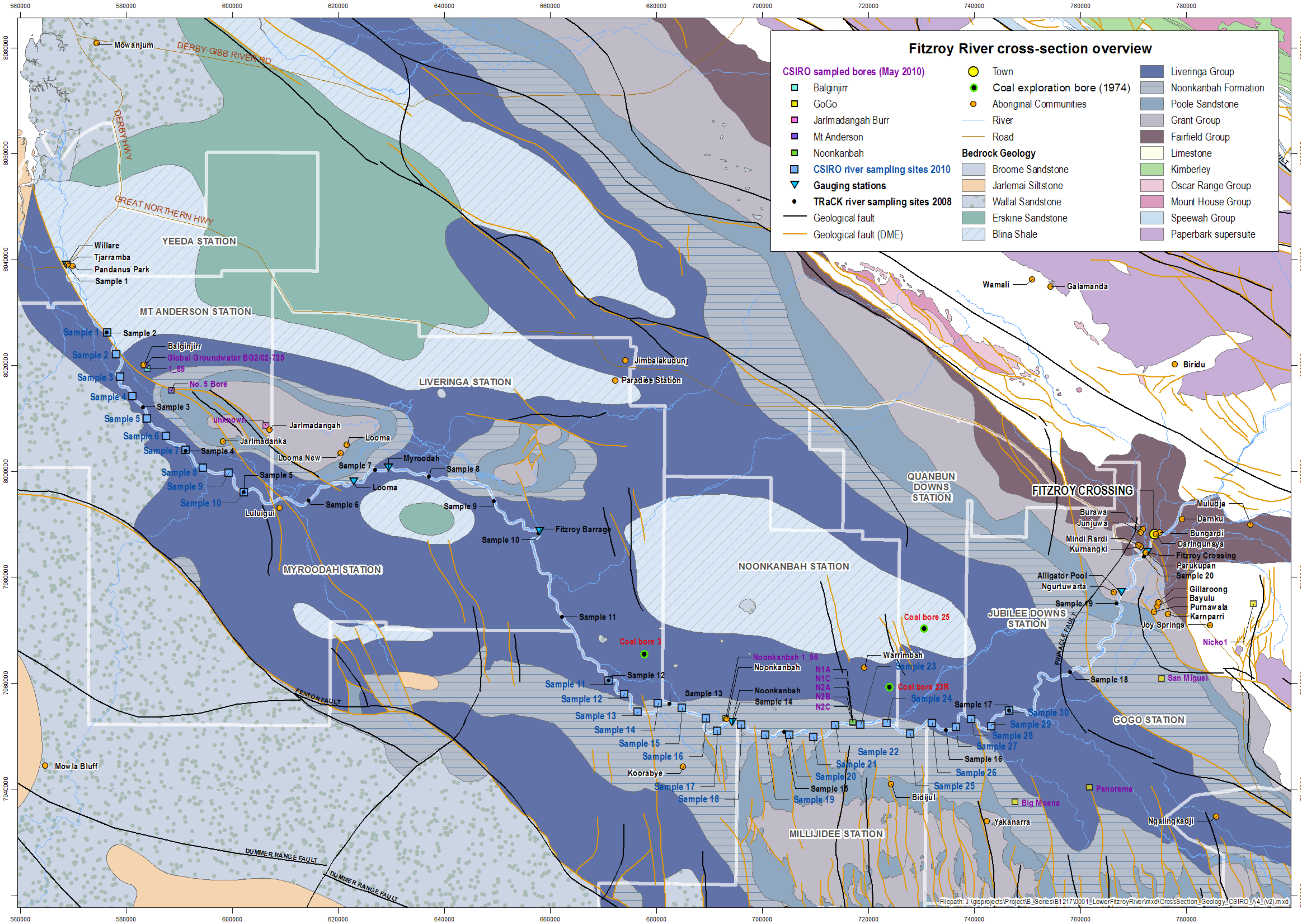


Figure 3. *Published basement geology of the Fitzroy Trough in the Canning Basin, WA, and locations of 2008 and 2010 river sampling sites, Noonkanbah piezometers and regional groundwater bores sampled May 2010*

The Lower Triassic **Blina Shale** overlies the Liveringa Group and is about 200 m thick. It is a siltstone deposited in a marine environment, and is similar in appearance to the Noonkanbah Formation, but with less sandstone. Fractures are common throughout the lower 60–90 m (Galloway and Howell, 1975). It is poorly exposed, but subcrops in the Noonkanbah–Quanbun syncline west of Fitzroy Crossing, in the Myroodah syncline south of Camballin, and in the Erskine syncline east of Derby (Figure 3).

The **Erskine Sandstone** (Triassic) disconformably overlies the Blina Shale. It covers a wide area to the east of Willare where it forms low scarps within the Erskine syncline. The formation varies in thickness from 30 m in the Erskine Ranges to 269 m at Myalls Bore near Derby (Lindsay and Commander, 2005).

A major unconformity separates the Erskine Sandstone (middle Triassic) and the overlying **Wallal Sandstone** (late Jurassic). The Wallal Sandstone consists of laminated pink and white, very fine to very coarse grained sandstone with minor siltstone, conglomerate and lignite. It crops out extensively to the south of the Fitzroy River and east of Derby and is 335 m thick in WAPET Fraser River No.1 well (a petroleum exploration bore, drilled on Yeeda station, NW of Willare). The overlying Barbwire and Alexander Formations are similar in lithology and of variable thickness, with a maximum combined thickness of approximately 95 m (Lindsay and Commander, 2005).

The **Jarlemai Siltstone** conformably overlies the Alexander Formation and is predominantly a mudstone with scattered coarse sand grains and granules. It forms the Edgar Ranges in the south west of the study area and typically forms mesas and breakaways with steep sides and slopes.

2.2.2. Superficial deposits

The western two-thirds of the Fitzroy region are covered by superficial deposits of variable thickness (Figure 1). Tertiary and Quaternary sediments are thickest in the Fitzroy River valley. **Alluvial deposits** beneath the Fitzroy River floodplain are up to 40 m thick, consisting of a basal sand/gravel representing the river bed-load deposits, overlain by up to 10 m of silt/clay over-bank deposits (Lindsay and Commander, 2005). The **Warrimbah Conglomerate**, a thin (approximately 10 m thick) cobble and pebble conglomerate that unconformably overlies older Permian and Triassic rocks, was deposited along an ancestral course of the Fitzroy River (Crowe and Towner, 1981). It lies within 15 km north of the present course of the river, and is less than 20 m above the bed of the present river. (Refer to Appendix 3.) The Warrimbah Conglomerate forms beds of scattered gravel between Myroodah Homestead and Noonkanbah.

2.2.3. Structure

The Fitzroy Trough and the lower Fitzroy valley are bounded to the north and east by the Pinnacle Fault system, and to the south and west by the parallel Fenton Fault System (Crowe and Towner, 1981). The Pinnacle Fault system, with a throw of approximately 1 km (Crowe and Towner, 1981), juxtaposes Permian, Triassic and Jurassic rocks to the south against Devonian limestones to the north.

The prominent Grant Range and St George Ranges are west-northwest striking anticlines defined by resistant sandstone outcrops of the Poole Sandstone and Grant Group. These ranges control, to some extent, the path of the Fitzroy River. Both anticlinal structures, as well as other smaller associated folds, are cross cut by numerous north-northwest trending transverse faults creating a trellised drainage system (Figure 1) (Crowe and Towner 1981; Gibson and Crowe 1982).

2.3. Previous hydrogeology investigations

2.3.1. Government of Western Australia

The only significant body of work on the hydrogeology of the Fitzroy valley is that reported by Lindsay and Commander (2005). The purpose of the desktop study was to assess the groundwater resources of the Fitzroy River alluvial deposits given increasing water shortages in the southwest of Western Australia. Previous exploratory and investigation drilling across the floodplain at Willare, Fitzroy Barrage and Fitzroy Crossing had confirmed the presence of an alluvial aquifer of 20–30 m of sands and gravels overlain by approximately 10 m of silts and clays. If representative of the entire Fitzroy valley alluvium, the aquifer was estimated to contain approximately 13,000 GL.

Lindsay and Commander described river water recharging the alluvium through the river bed during the wet season. During the dry season the river flow is reported as initially being maintained by groundwater discharge, until declining levels drop beneath the river bed. Permanent pools in the river bed are reported as being maintained by groundwater from the alluvium. The dry season river flows were interpreted as indicating that the groundwater salinity is generally less than 500 mg/L. Higher salinities were identified in a reach of the Fitzroy River centred on Noonkanbah Station. The alluvium was reported to receive groundwater discharge from the regional Canning Basin aquifers, which have varying salinities. Based on limited historical data from regional bores, Lindsay and Commander (2005) infer the groundwater flow direction to be generally westward, converging locally towards the Fitzroy River and other significant surface drainage features.

Management of drawdown in the river bed is identified as being required in order to maintain dry season flows and permanent pools. Due to the absence of any hydrogeological data for the alluvial aquifer, Varma (in Lindsay and Commander, 2005) constructed a simple numerical model based on assumptions for the Fitzroy River alluvial aquifer. A preliminary average yield of 200 GL per annum was estimated for the 275 km stretch of alluvium between Fitzroy Crossing and Willare.

Lindsay and Commander (2005) recommended that an investigation program be developed to gain further knowledge of the hydrogeological properties of the Fitzroy valley. An aerial geophysics survey, investigation drilling and pumping tests were recommended to define the spatial extent and properties of the alluvial aquifer. Following this work, the 3-year Raising National Water Standards project was funded by the National Water Commission and the Department of Water, with work commencing in July 2008.

The Raising National Water Standards work (in progress) has identified over 300 bores in the lower Fitzroy valley, drilled primarily for stock and Indigenous Community water supplies. Several consultants' reports have been written for government departments managing Indigenous Communities' water supplies. The recent work indicates that aquifers in the lower Fitzroy have been targeted for local water supplies. The groundwater quality is variable and localised piezometric heads indicate the potential for surface water – groundwater interaction.

Routine surface water monitoring

The Department of Water routinely carries out surface water gauging in the Fitzroy River catchment. There are currently 6 open (i.e. actively monitored) gauging stations in the Upper Fitzroy (upstream of Fitzroy Crossing), and 7 open gauging stations in the lower Fitzroy. Within the lower catchment, there are 5 gauging stations on the main river. The locations of open gauging stations are shown in Figure 4. The length and reliability of records from all gauging stations (open and closed) are detailed in Table 1.

The reliability of flow rating curves for gauges in the Kimberley region has historically been limited. Between 2008 and 2010 a number of river reaches in the Fitzroy catchment were surveyed and the flow modelled to develop new rating curves. Further information on this modelling will soon be available via a Raising National Water Standards project technical report.

The rating curves at low flows for all gauging stations on the lower Fitzroy River (except Fitzroy Barrage) are susceptible to annual change due to sand bar migration during the high flows of the wet season. Low flow discharge measurements and a cease to flow measurement are required over the course of every dry season to revalidate the curve to ensure reliable low flow data is produced.

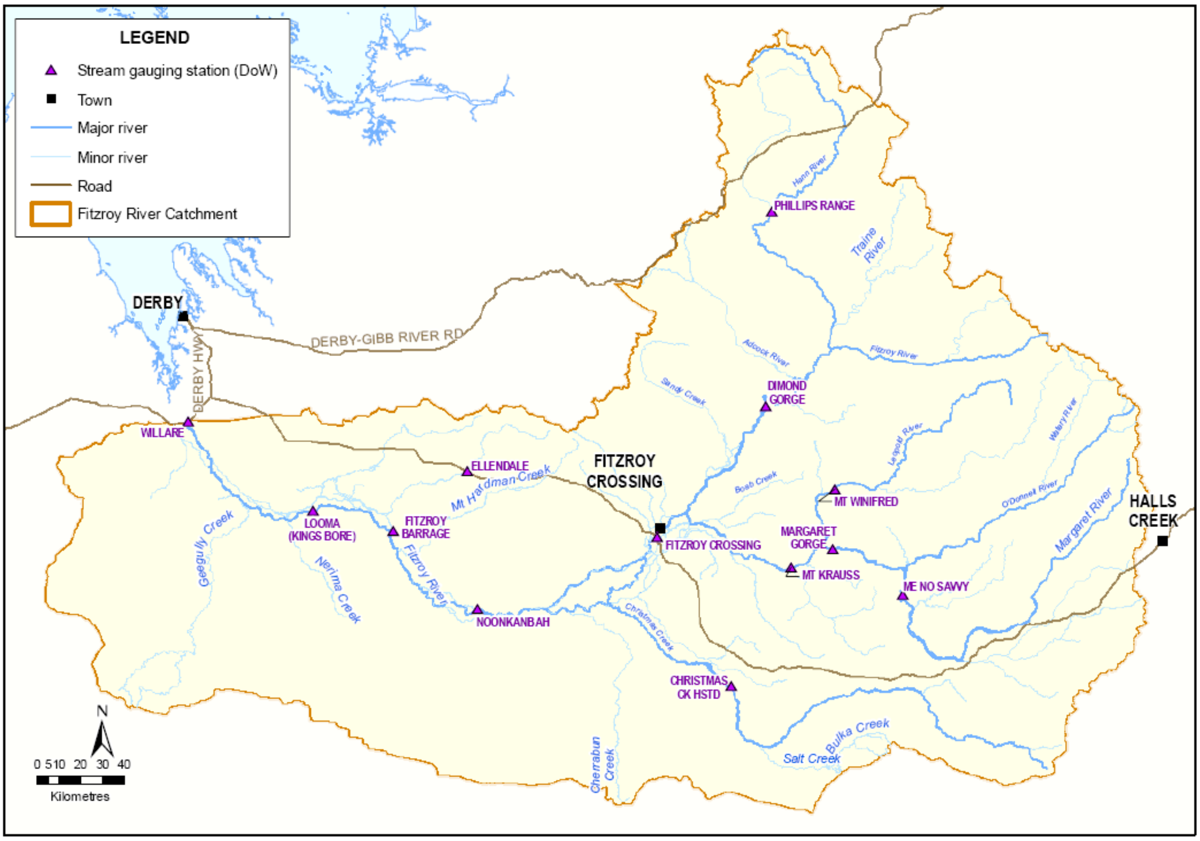


Figure 4. *Locations of river flow gauging stations in the Fitzroy catchment*

Table 1. *Details of current and historical river flow gauging stations in the upper (grey) and lower (white) Fitzroy River catchment*

Name	WIN ref no.	River	Date open	Date close	Recording freq	Telem Y/N	W/Q freq	Reliability
Fossil Downs	802054	Margaret	1956	1972	n/a	n	n	Very poor data set (level and flow).
Margaret Gorge	802156	Margaret	1997	open	10min	y	irreg/ infreq	Rating curve developed by theoretical modelling in 2009. To be confirmed by measurements.
Me No Savvy	802198	Margaret	1965	open	10min	y	irreg/ infreq	Rating curve reasonable based on measurements from 1968 to mid flow only.
Mt Krauss	802203	Margaret	1965 1996	1979	10min	y	irreg/ infreq	Rating curve refined by theoretical modelling in 2009. Limited measurements from 1974.
Mt Winifred	802202	Leopold	1964	open	10min	y	irreg/ infreq	Rating curve refined by theoretical modelling in 2009, calibrated for all except very high flows using measurements from 1985.
Phillips Range	802213	Hann	1966	open	5min	y	irreg/ infreq	Rating curve revised by theoretical modelling in 2009. Needs calibrating for medium and high flows.
Mt Pierre Gorge	802002	Mt Pierre Creek		1998				Rating curve is poor, defined by low flow measurements only.
Mt Amhurst	802001	Watery River	1967	1979				Rating curve is poor based on 3 discharge measurements in the low flow range.
Dimond Gorge	802137	Fitzroy	1961	open	10min	y	irreg/ infreq	Rating curve refined by theoretical modelling in 2009. Calibrated to mid flow by measurements in 1963 and 1965.
Fitzroy Crossing	802055	Fitzroy	1956	open	5min	y	irreg/ infreq	Low flow rating is variable and is not well defined prior to 2002. From 2002 it is reasonably well defined at low flows as it has ongoing annual measurements. Medium to high flow rating curve is reasonable. Extreme flood flows are poorly defined due to variable influence of the Margaret River across the floodplain. Department of Main Roads are carrying out theoretical modelling for extreme flooding events (2011). The rating curve is being reviewed to annually define the peak flow events to produce reliable annual flow data (in progress).
Alligator Pool	802197	Fitzroy	1964 1996	1979 2002	n/a	n	n	Site downstream of Fitzroy Crossing, before Cunningham River. The rating curve is being developed by theoretical modelling in 2011. This site may be more accurate for records of very high flood flows than that at Fitzroy Crossing.
Blue Bush	8021011	Fitzroy	1984	open	annual	n	n	This site has been used to monitor annual peaks on the Fitzroy floodplain to get a more accurate definition of the variation in flood levels across the floodplain. They will change or close when the Department of Main Roads upgrade the Great Northern Highway between Fitzroy Crossing and GoGo.

Name	WIN ref no.	River	Date open	Date close	Recording freq	Telem Y/N	W/Q freq	Reliability
2 Mile	8021012	Fitzroy	1984	open	annual	n	n	ditto
Brooking channel	8021013	Fitzroy	1984	open	annual	n	n	ditto
GoGo Homestead	8021016	Fitzroy	1956	open	annual	n	n	ditto
Plum Plain	8021017	Fitzroy	1984	open	annual	n	n	ditto
Margaret Floodway	8021018	Fitzroy	1983	open	annual	n	n	ditto
Coorie Floodway	8021019	Fitzroy	1984	open	annual	n	n	ditto
GoGo Floodway	8021020	Fitzroy	1983	open	annual	n	n	ditto
Bohemia Downs	802231	Christmas Creek		1979				The rating curve is fair based on 15 discharge measurements to medium flow.
Christmas Creek Homestead	802005	Christmas Creek	1997	open	10min	Y	irreg/ infreq	Rating curve developed by theoretical modelling in 2009. Needs to be confirmed by measurements. Variable low flow rating needs defining annually.
Noonkanbah	802006	Fitzroy	1997	open	5min	y	irreg/ infreq	Rating curve developed by theoretical modelling in 2009. Needs to be confirmed by measurements. Variable low flow rating needs defining annually.
Ellendale	802004	Mount Wynne Creek	1986	open			irreg/ infreq	Rating curve poor based on limited measurements in 1987, the curve has been improved during 2010–11.
Fitzroy Barrage	802003	Fitzroy	1980	open	5min	n	irreg/ infreq	Initial theoretical rating curve was refined by theoretical modelling in 2009. Barrage is stable structure for medium flows. Low flows are difficult to record accurately due to variable off-take from Fitzroy River for irrigation. At high flows the complex anabranch system is difficult to model.
Old Liveringa Homestead	8021027	Fitzroy	1985	open	annual	n	n	Annual peaks for homestead only to help with correlation to river sites and flood warning.
Myroodah	802077	Fitzroy	Jan-54	Jun-54	n/a	n/a	n	Very poor data set (level and flow).
Looma	802007	Fitzroy	1997	open	10min	y	irreg/ infreq	Rating curve was developed by theoretical modelling in 2009. Needs to be confirmed by measurements. Variable low flow rating needs defining annually.
Willare	802008	Fitzroy	1998	open	10min	y	irreg/ infreq	The cease to flow point varies from 10.0 to 10.6 m. Rating curve is reasonable based on discharge measurements in all flows. The variable low flow rating needs defining annually.

2.3.2. Northern Australia Sustainable Yields Project

The CSIRO Northern Australia Sustainable Yields (NASY) project was completed in August 2009 providing, for the first time, a regional scale assessment of water resources in the north and the likely impacts of potential future climate and development on these resources and the environmental assets they sustain. Importantly, the project did not collect any new data and was thus limited to a desktop analysis of historical information.

For the Fitzroy region, and many other reporting regions within the project area, the paucity of historical groundwater sampling and monitoring data meant that the assessment was largely qualitative. The only quantitative analyses conducted for the region were (i) modelling changes to diffuse recharge rates under different climate and development scenarios, and (ii) the development of a simple numerical groundwater flow model for the Fitzroy River alluvial aquifer (Dawes, 2008). The groundwater model represented the alluvial aquifer as a 275 km long strip of clay/sand, 25 km wide and 50 m deep. It was intended that the model be used for predicting the impacts of potential future groundwater extraction on reducing discharge to the river. However, due to a paucity of reliable groundwater monitoring data both this model and future recharge estimates had high uncertainty.

Arguably the most useful outcome of the NASY project for the Fitzroy region was the identification of key information and knowledge gaps to improve our understanding of the water balance. In terms of groundwater, these gaps included:

- long-term monitoring data for groundwater levels and water quality of the alluvial aquifer (and other adjacent/underling aquifers)
- reliable monitoring of river flow during low-flow conditions
- understanding the recharge processes, including floodplain recharge
- understanding surface water – groundwater interactions and, more specifically
- understanding the controls on dry season river flows to enable more reliable assessment of the potential impacts of future climate and development.

3. METHODS

The methodology employed to address the objectives of this project (Section 1.2) involved a combination of hydraulic and hydrochemical/isotopic techniques. The chemical sampling of groundwater and adjacent surface waters is a recognised technique in establishing the spatial and temporal variability of surface water – groundwater interactions. More generally, the application of environmental tracer techniques to hydrogeological studies is particularly valuable in highly heterogeneous systems, where spatial variations in aquifer hydraulic conductivity may range over several orders of magnitude, causing large uncertainty in hydraulic approaches.

This chapter outlines the methods used to undertake field investigations, including the drilling of piezometers and sampling of both groundwater and river water, and the general approach used to model the data (Section 3.4). It does not, however, provide a review of the individual chemical and isotopic species employed in the study, nor their transport and evolution in the hydrologic system—for this information the reader is referred to comprehensive text books such as Cook and Herczeg (1999).

3.1. Longitudinal river sampling

Synoptic sampling of river water for a range of chemical and isotopic species along the river provides a means of capturing a point-in-time snapshot of the spatial variability of surface water – groundwater interactions, particularly for reaches where the river is gaining. One of the most widely used tracers for studies such as this is radon-222. Due to the short half-life of radon-222 (3.8 days) it is necessary to collect all water samples and send them for analysis within 2 days of collection.

Because the Fitzroy River is characterised by shallow sand banks and rock bars, and is inhabited with both freshwater and saltwater crocodiles, sampling by small boat was not feasible. Instead we used a helicopter on two separate occasions.

On the 20th May 2008, longitudinal sampling of the river was conducted using a helicopter (Doble et al., 2008). Water sampling was undertaken from within the helicopter whist it hovered over the river at 20 locations, each approximately 20 km apart, between Willare and Fitzroy Crossing (Figure 3). Sampling began at Willare and continued upstream to just below the Cunningham Anabranch–Fitzroy River confluence (site 15), where a diversion to Fitzroy Crossing for refuelling was necessary. Subsequent sampling took place from Fitzroy Crossing downstream to site 15. A submersible pump with an attached float and sinker was used to take samples from approximately 200 mm below the river water level, and prevent radon degassing from exposure to the air, which would have occurred with a bailer. Samples were taken for radon-222 using the PET method (Leaney and Herczeg, 2006), while samples for stable H/O isotopes of water and major ion chemistry were taken in glass McCartney bottles and 250 mL plastic bottles respectively.

On 11 May 2010, almost exactly two years after the initial sampling, we returned to the Fitzroy River for a second round of longitudinal sampling, this time focussing on a 100 km reach of the river (Figure 3) where the first round had identified strong gaining conditions. We also sampled a shorter (~50 km) reach further down the river, where similar gaining conditions were thought to occur (Doble et al., 2008). The sampling was conducted over two days; the first day we flew upriver, deploying noble gas diffusion cells (Gardner and Solomon, 2009) and pumping water samples via a weighted pump as described previously. Sampling positions were predetermined at approximately 5 km spacing and entered as GPS waypoints for the flight. Diffusion cells were suspended approximately 1 m below a polystyrene buoy, with a small lead grapnel anchor attached further below to prevent buoy drift caused by river current and helicopter rotor wash. Water samples were again taken for radon-222, stable H/O isotopes and major ions, but on this occasion we also collected 250 mL samples for $^{87}Sr/^{86}Sr$ analysis.

The following day (12 May 2010) we flew downstream, recovering the helium diffusion cells by swinging a grapnel anchor from the hovering helicopter and retrieving the buoys (Plate 1).

All diffusion cells were allowed to equilibrate with dissolved gas concentrations in the river for at least 18 hours, which was considered ample for this application as the river flow could maintain constant concentration at the diffusive membrane.

Plate 1. *Recovery of buoy and gas diffusion cell from the hovering helicopter, 12 May 2010*

3.2. Noonkanbah piezometer transect

One of the required outcomes of the WA Department of Water's Raising National Water Standards (RNWS) project was the drilling of observation bores in the lower Fitzroy valley for the purposes of monitoring and interpreting surface water – groundwater interaction (NWC, 2010). The resulting bores were incorporated into the Department of Water's monitoring network to understand the groundwater regime of the floodplain of the lower Fitzroy valley.

Initially five bore transects were to be installed to investigate the thickness and lateral extent of the alluvial aquifer, and to measure the piezometric heads within the alluvial aquifer at various locations down the valley, from Fitzroy Crossing to Willare. The piezometric heads were to be compared with the river stages measured at the Department of Water's gauging stations. This work would measure and report on the temporal and spatial changes in the surface water and groundwater regime in the study area.

3.2.1. Site selection

The results from the longitudinal sampling of lower parts of the Fitzroy River in May 2008 (Sections 3.1 and 4.1) indicated that the Canning Basin sediments could be discharging groundwater to the alluvial aquifer, which in turn was discharging groundwater to the Fitzroy River in the vicinity of the confluence of the Cunningham Anabranch with the Fitzroy River. These results changed the scope of the drilling program that had been planned under the RNWS project; rather than only investigating the geometry of the alluvial aquifer and the interaction between groundwater in the alluvium and the river, the drilling program would also need to consider interactions involving groundwater from the Canning Basin sediments.

A review of the geology in the vicinity of the confluence of the Cunningham Anabranch with the Fitzroy River indicated that groundwater could be discharging where the sand facies-rich lower Liveringa Group sub crops against the mudstone-rich Noonkanbah Formation. As detailed in Section 2.2.1 and Appendix A, an unpublished coal exploration report (Galloway and Howell, 1975) indicates the existence of subdivisions within the Liveringa Group, and suggests the boundary of the Noonkanbah Formation and Liveringa Group is located further south from that published in the 1:250 000 Noonkanbah geological sheet (Crowe & Towner, 1981; included in Figure 3) and on the Department of Mines and Petroleum's web site (<www.dmp.wa.gov.au/7113.aspx>).

The Galloway and Howell (1975) report assisted with the site selection as it enabled the proposed drilling transect to target the base of the Liveringa Formation, near its contact with the Noonkanbah Formation. The transect was sited immediately north of the Fitzroy River, on Noonkanbah Station, and the nearest drill site to the river was adjacent a small waterfall (Plate 2) believed, at the time, to represent a change in lithology.

In parallel with reviewing the locations for the proposed bore transects, the Department of Water researched the names and contacts for the Native Title claimant groups in the lower Fitzroy floodplain. Advice was sought on Native Title and Heritage clearance to gain permission to drill. Early consultation with the Fitzroy Catchment Group's (FitzCAM) facilitator, Tropical Rivers and Coastal Knowledge (TRaCK) researchers and the Kimberley Land Council indicated that lengthy and expensive consultation was required with the traditional owners who spoke for country where drilling was proposed.

Plate 2. *Waterfall in the Fitzroy River immediately adjacent to Noonkanbah piezometer Nest #1*

Noonkanbah Station is the only Indigenous-owned pastoral station to hold its own Native Title. Early consultation by the Department of Water with the Native Title holder of Noonkanbah Station, Yungngora Association, indicated that it would be favourable to the Department of Water drilling bores on Noonkanbah Station for the purposes of water research. As the southeast corner of Noonkanbah Station is in the locality of the Liveringa Group – Noonkanbah Formation boundary (Galloway and Howell, 1975), the drilling of a transect on Noonkanbah station was fast-tracked in consultation with Yungngora Association.

Following Department of Water guidance a site meeting was held on Noonkanbah Station to select the drilling sites with Mr Dickey Cox, Chair of Yungngora Association. A further meeting was held with other members of Yungngora Association, with an interpreter from Kimberley Interpretative Services (KIS). The reasons for drilling, locations and depths of drilling were explained by the Department of Water's project manager to Yungngora Association.

The Department of Indigenous Affairs Heritage Unit in Perth was also consulted with respect to any sacred sites in the locality of the proposed drilling sites. The Department of Water was advised not to drill close to the Fitzroy River, a mythological site, however as the traditional owners had been consulted and were in agreement, it was deemed safe to proceed.

3.2.2. Drilling & construction

Prior to drilling, the access track to the Fitzroy River and the proposed drilling sites was graded by a local contractor. The drilling company Diverse Resources Group Pty Ltd. was awarded the contract to drill after a competitive tender process which required a Class 3 driller. Drilling of the bores commenced on 9 October 2009 and finished on 14 October 2009. All bores were drilled at 150 mm diameter, using rotary air drilling. As shown in Figure 5, three bores were drilled at each of three nest locations, chosen for their accessibility and increasing distance from the Fitzroy River.

The resident engineer and the driller consulted with the Department of Water's hydrogeologist regarding the depth of placement of piezometer screens. Slotted screen (50 mm internal diameter (ID) PVC with 1 mm slots) was installed at different depths in each bore, attached to the bottom of 50 mm ID PVC casing. A 6–8 mm gravel pack was poured into the bore annulus to just above the top of the screen, followed by approximately 1 m depth of bentonite pellets and then a grout plug. The bores were then backfilled almost to surface with drill cuttings. Finally, a concrete mix was used at surface to fill the annulus and install a lockable standpipe (e.g. see Plate 3).

Upon completion the piezometers were all developed/purged by airlifting for one hour to remove any fines in the bore water, screens and gravel packs. The driller estimated the bore yield during this airlift.

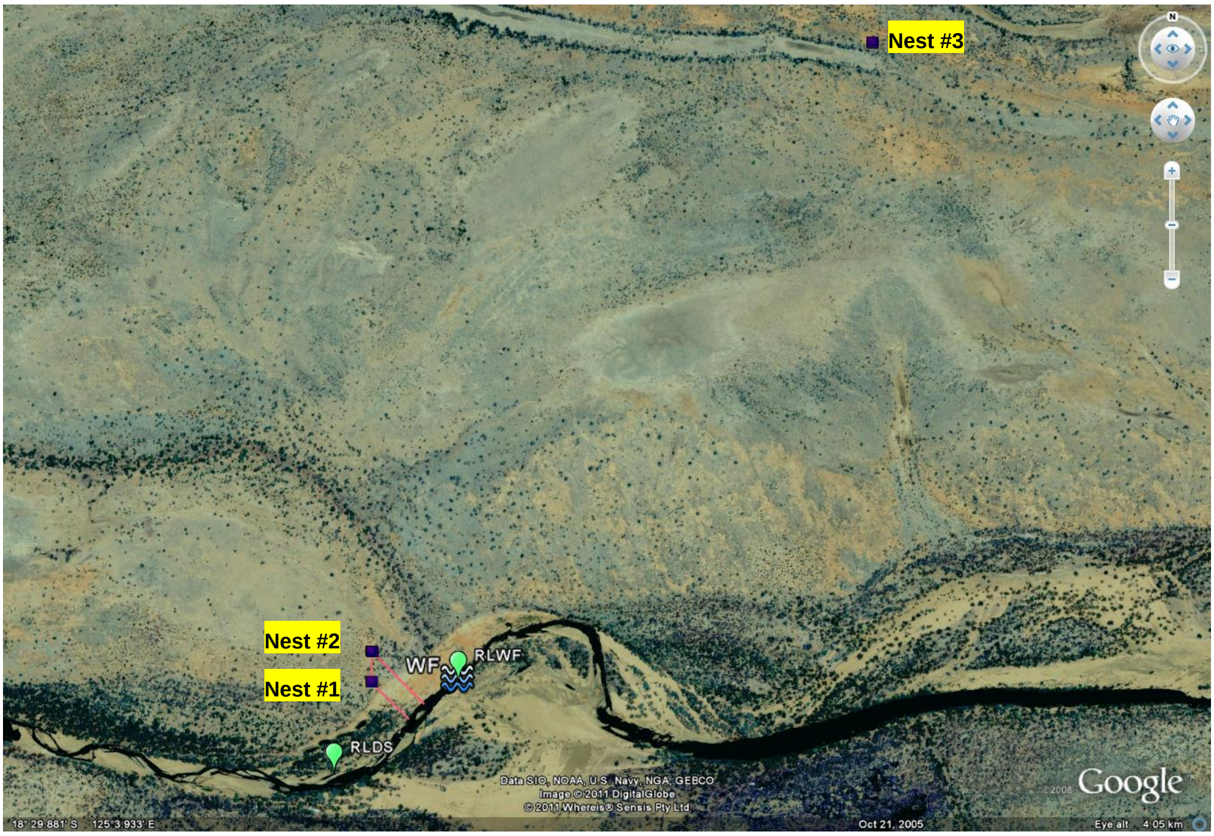


Figure 5. *Google Earth image showing the locations of the three piezometer nests drilled and constructed on Noonkanbah Station in October 2009, relative to a small waterfall (WF) on the Fitzroy River. Green dots represent locations of river level loggers and red lines represent profiles along which ground surface and piezometers were surveyed in August 2010. Distance from nest 1 to nest 3 is 3.1 km.*

Plate 3. *Noonkanbah piezometer Nest #1 with Fitzroy River in the immediate and distant background, looking upstream. Steel standpipes (approx. 600 mm height) were cemented over all piezometers to enable locks to be fitted and to minimise the risk of inundation by flood waters from the Fitzroy River.*

3.2.3. Surveying

During August 2010, contractors from Whelans Pty Ltd. surveyed the new transect of piezometers, as well as the river bank profiles adjacent nests #1 and #2, and the positions of two river level loggers (see Section 3.4.2). The locations of survey lines are shown in Figure 5.

3.2.4. Water level monitoring

Groundwater

The primary purpose of installing the Noonkanbah piezometer transect was to collect water samples and install water level loggers to improve our understanding of surface water – groundwater interactions during the contrasting wet and dry seasons. Accordingly, each piezometer was sampled in November 2009 (see Section 3.3) and installed with a Solinst Diver® continuous water level logger. The piezometers were visited on 16 December 2009 for manual water level measurement to enable subsequent logger data verification.

Surface water

In order to compare the river stage with the water levels recorded in piezometers, two star pickets were installed in the bed of the Fitzroy River, close to piezometer nest #1, with Solinst® loggers securely attached. The locations of these river loggers, installed in November 2009, are shown in Figure 5.

The river stage has been observed to vary by up to 13.5 m at Fitzroy Crossing road bridge and by up to 12.1 m at the river crossing below Noonkanbah Community. As a precautionary measure the two river loggers were installed in the event that a large flood could wash one of them away.

3.3. Groundwater sampling: piezometers and regional bores

Groundwater samples were obtained from the region during three separate campaigns between November 2009 and October 2010. On each occasion the piezometers or production bores to be sampled were initially purged by pumping out at least three times the casing volume, and ensuring water quality parameters (EC, pH, T) measured at the discharge pipe had stabilised prior to collecting samples. Piezometers and small-diameter or shallow bores were purged and sampled using a 12 volt submersible pump with high density Teflon tubing. Deep, larger diameter production bores were already equipped with electric or diesel pumps (Plate 4).

Plate 4. *Groundwater sampling from Balginjirr Community water supply bore "1-89" on Mt Anderson Station, 8 May 2010*

During November 2009 the entire Noonkanbah transect, comprising nine piezometers from three nest sites, was sampled for the following species: major cations and anions, radon-222, chlorofluorocarbons (CFCs), stable H/O isotopes of water, $^{87}Sr/^{86}Sr$ and carbon-14. The direct absorption method (Leaney and Herczeg, 2006) was used to sample for radon-222. At the cessation of pumping from each piezometer, gas diffusion cells were installed in the screens and allowed to equilibrate for 24 hours overnight before being recovered.

During this campaign it was determined that piezometer N1B (intermediate depth in nest #1) was worthless as it provided extremely low yields ($Q < 0.005$ L/s) of very alkaline ($pH > 10.7$) water; intrusion of cement grout into the gravel pack was attributed to be the cause. Also during this campaign, it was discovered that piezometer nest #3 had been drilled immediately adjacent a large billabong that formed part of an anabranch (see Figure 5). It was originally planned that nest #3 would be sited far enough away from the Fitzroy River that the impacts of bank storage from the river would be negligible, and that these piezometers would reflect more distal recharge processes such as diffuse infiltration beneath the floodplain. However, discovery of the billabong raised concerns that the piezometers might be influenced by localised infiltration throughout the dry season, in which case they would be inappropriate for the current project.

During May 2010, immediately prior to the second longitudinal river sampling campaign, the five Noonkanbah piezometers closest the river (i.e. those from nest #1 and #2) and nine regional bores shown in Figure 3 were sampled. The rationale for resampling nest #1 and nest #2 piezometers only 6 months after the November 2009 sampling campaign was twofold. Firstly these piezometers would likely have been affected by bank storage and return flow during the recent wet season, and thus the chemical/isotopic compositions may have changed. Secondly, preliminary CFC results for samples collected from these piezometers in November 2009 suggested they may have been contaminated by excess air introduced during the drilling and well development process, in which case several months of dynamic groundwater flow should have mitigated these effects. Nest #3 piezometers were excluded from the May 2010 sampling campaign as hydrochemical results from the November 2009 sampling confirmed hypotheses that these piezometers were reflecting localised interactions with the billabong.

Water samples were collected from the nine regional bores for major cations and anions, stable H/O isotopes of water, $^{87}Sr/^{86}Sr$ and one or more (depending on bore depth) of either sulfur hexafluoride (SF_6), chlorofluorocarbons (CFCs) or carbon-14. The five nest #1 and nest #2 piezometers were sampled for major cations and anions, stable H/O isotopes of water, and both SF_6 and CFCs. Samples were not collected from the piezometers for $^{87}Sr/^{86}Sr$ analysis as it was considered unlikely the composition would have changed since the last sampling, nor were they collected for carbon-14 given the high cost of analysis and anticipated modern radiocarbon activities. Where bore head works permitted, dissolved gas samples for helium-4 analysis were obtained by lowering a diffusion cell into the screened section of the bore and allowing 1–2 days to equilibrate. Where this approach was not possible, samples were obtained by installing a small-diameter tube into the main discharge pipe from the pump and collecting water via copper tubes (Plate 5).

Due to the logistics and timeframes associated with the helicopter sampling in May 2010, none of the groundwater samples from this campaign were submitted for radon-222 analysis. Accordingly, WA Department of Water staff undertook the third groundwater sampling campaign on the 5–6 October 2010, providing radon-222 samples for the five Noonkanbah piezometers from nest #1 and #2, and four of the most accessible regional bores (Noonkanbah 1-96, Mt. Anderson No. 5 and Balginjirr 1-89, Global Groundwater bore BG2/02-725).

Plate 5. *Sampling groundwater in copper tubes for noble gas analysis, Yungngora Community water supply bore "1-96" on Noonkanbah Station, 6 May 2010*

3.4. Chemical and isotopic analysis

Groundwater and river water samples were sent to CSIRO Land and Water, Waite laboratories in Adelaide for analysis of major ion concentrations by ICPMS; δ^2H and $\delta^{18}O$ by isotope ratio mass spectrometry (IRMS); chlorofluorocarbons by gas chromatography; radon-222 by liquid scintillation beta counting; and helium-4 and other nobles gases by quadrupole mass spectrometry (NB. concentrations of helium-4 are expressed as fractions (F^4He) relative to atmospheric concentration—see Gardner et al. (2011) for details). Carbon isotope analysis was performed after CSIRO Land and Water converted the dissolved inorganic carbon to CO_2 gas; $\delta^{13}C$ was determined in-house by IRMS and carbon-14 by accelerator mass spectrometry at Australian National University, Canberra. Strontium isotope analysis (i.e. $^{87}Sr/^{86}Sr$) was determined by thermal ionisation mass spectrometry at the University of Adelaide.

3.5. River chemistry modelling

The approach we used to simultaneously analyse river water and groundwater chemistry/isotopic data, and in doing so determine mechanisms and rates of groundwater discharge to the Fitzroy River, involves a water and tracer mass balance of the form (after Cook et al., 2006):

$$\frac{\partial Q}{\partial x} = Q - Q_o = I - L - Ew \qquad \text{(Equation 1)}$$

$$Q\frac{\partial c}{\partial x} = I(c_i - c) + wEc - kwc - dw\lambda c + \frac{\gamma hw\theta}{1+\lambda t_h} - \frac{\lambda hw\theta}{1+\lambda t_h}c \qquad \text{(Equation 2)}$$

where Q_o is the initial river flow rate at the top of the reach (m^3/day)

Q is the river flow rate (m^3/day) at distance x downstream

I is the groundwater inflow rate (m^3/m/day)

L is the river pumping rate (m^3/m/day)

E is the evaporation rate (m/day)

c is the concentration of tracer in river water

c_i is the concentration of tracer in groundwater

w is the river width (m)

x is horizontal distance along the river (m)

d is the river depth (m)

k is the gas exchange velocity (m/day), which is equivalent to the product of d (m) and the gas exchange coefficient of the tracer (1/day)

λ is the radioactive decay constant of the tracer (1/day)

γ is the hyporheic production rate (used only for radon-222, expressed in Bq/m/day)

h is the mean hyporheic depth (m)

t_h is the mean residence time of water in the hyporheic zone (days) and

θ is the hyporheic zone porosity.

In this project we divided the groundwater inflow rate I into local (l) and regional (r) components:

$$I = I_l + I_r \qquad \text{(Equation 3)}$$

Full details of the model assumptions and how it was applied for different tracer profiles (^4He, ^{222}Rn, chloride and $^{87}Sr/^{86}Sr$) along the river are provided in Gardner et al. (2011) and Harrington and Gardner (in prep).

4. RESULTS

4.1. Longitudinal river sampling

Tabulated hydrochemical and isotopic results for the May 2008 river sampling campaign are provided in Doble and Cook (2008) while results from May 2010 are provided in Appendix C.

The 2008 sampling campaign revealed a steep increase in the electrical conductivity (EC) of river water (Figure 6) between sample points 17 and 15 (see Figure 3 for locations), centred around the confluence of the Fitzroy River and Cunningham Anabranch. Coincident with this salinity increase was an observed rise in river water radon-222 activity, indicating significant groundwater discharge along this section of river. Whilst not shown in Figure 6, Doble et al., (2010) report a change in the hydrochemistry of the river from Ca-Mg-HCO_3 to Na-HCO_3 dominance associated with the increase in EC (and chloride concentration) near the Cunningham Anabranch confluence.

The 2010 sampling campaign provided further evidence of active groundwater discharge into the Fitzroy River around its confluence with the Cunningham Anabranch; importantly, the bed of the latter was dry at the time of sampling (see Plate 6). The improved spatial resolution of hydrochemical and isotopic data from 2010 enabled the identification of two distinct zones of groundwater discharge in this reach (Figure 7) compared with the broad zone identified in 2008 (Figure 6). Specifically, river water radon-222 activity rises steeply immediately prior to the Cunningham confluence, coincident with the section of river between sample points 28 and 24 shown in Figure 3. This local peak in radon-222 is matched by a steep rise in river water chloride and helium-4 concentrations, and a marked decline in $^{87}Sr/^{86}Sr$ composition (or an increase in the product of Sr concentration and isotopic ratio—see Figure 7). Slightly further downstream, between sample points 22 and 19 helium-4 concentration increases to the highest value measured anywhere along the river. Along the same reach, and with increasing distance down the river, chloride concentration decreases and $^{87}Sr/^{86}Sr$ composition increases (product of Sr concentration and isotopic ratio decreases). Downstream of sample point 19, between points 18 and 17, and also between point 14 and 11, local increases in both radon-222 activity and helium-4 concentration were observed. In the lowermost reaches sampled (i.e. points 10 to 1) the only clear trends in river chemistry are a slight increase in helium-4 concentration between points 8 and 5, and a rapid drop in $^{87}Sr/^{86}Sr$ composition between points 6 and 1. The latter most certainly reflects a contribution of seawater associated with tidal ingress.

Plate 6. *View of the dry Cunningham Anabranch on 11 May 2010, looking in a north-easterly direction immediately upstream of the confluence with the Fitzroy River*

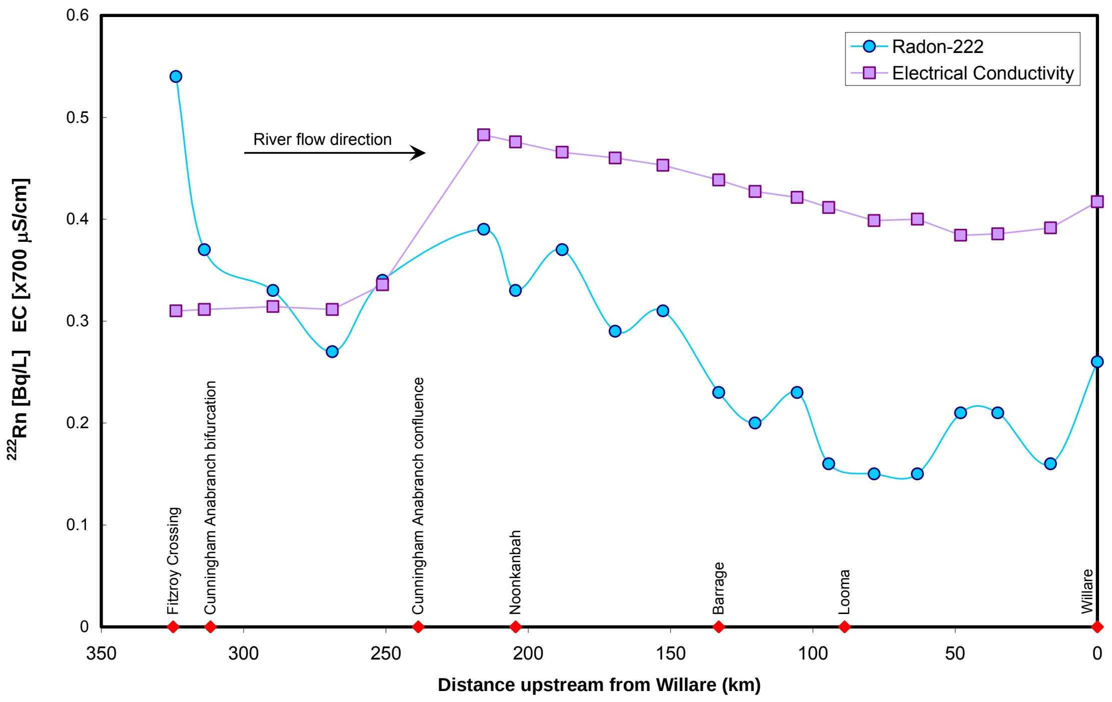


Figure 6. *Fitzroy River electrical conductivity (EC) and radon-222 activity at 20 May 2008*

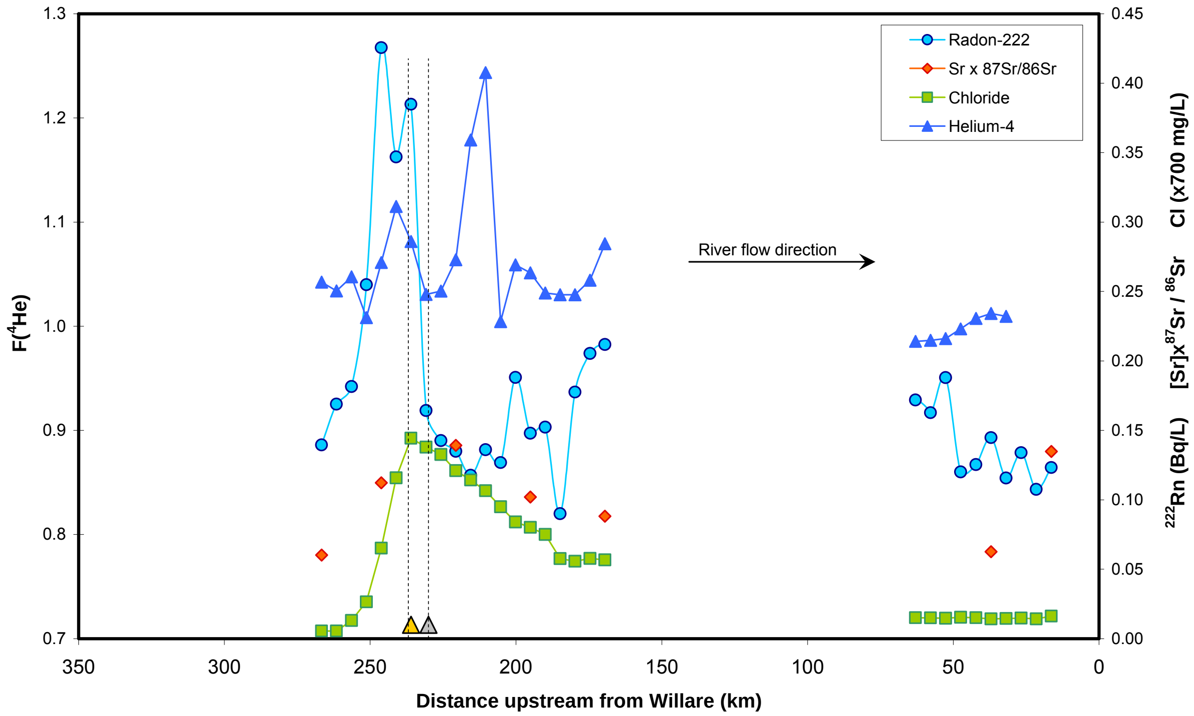


Figure 7. *Fitzroy River chemistry and isotopic composition at 11–12 May 2010. Gold triangle represents the location of confluence with Cunningham Anabranch, and silver triangle represents approximate location of Noonkanbah piezometer nest #1.*

4.2. Noonkanbah piezometer transect

4.2.1. Drilling & construction

Three bores were successfully drilled at each of the three locations shown in Figures 3 and 5. As outlined in Section 3.2.1, the Galloway and Howell (1975) report suggests the boundary of the Noonkanbah Formation and Liveringa Group should be further south than the position shown in Figure 3. This suggestion was confirmed from the drilling, with palynological testing by the Geological Survey of Western Australia revealing the bores were drilled high in the Lightjack Formation, possibly 200 m above the Noonkanbah Formation (pers. comm., Arthur Mory, GSWA, 10 December 2009).

Construction details for the nine piezometers installed at these sites are provided in Table 2, while stratigraphic logs and well completion diagrams are provided in Appendix B.

4.2.2. Surveying

The results of the surveying are summarised for the piezometers in Table 2, while the river bank profile is shown diagrammatically in the cross-section on Figure 8.

4.2.3. Water level monitoring

Groundwater levels for the piezometers, as measured manually on 6 November 2009 and 16 December 2009 are given in Table 2. Of the eight continuous water level loggers installed in the piezometers in November 2009 (NB. N1B didn't have a logger as the piezometer is worthless—see Section 3.3), only seven were recovered in May 2010; piezometer N3C had suffered major erosion around the annulus during the wet season and the bore cap could not be removed. Of the seven loggers recovered, one had stopped working (N2C) and two returned incomprehensible pressure trends (N2A and N2B) that suggested the piezometers may not have been properly constructed. As discussed in Section 3.3 the piezometers located at nest #3 were inappropriate for this project. Therefore, the only loggers results considered useful for this project are those from piezometers N1A and N1C, located immediately adjacent the river bank.

Referencing the logger data from these two piezometers against manual water level measurements and survey data (Table 2) produced the hydrographs shown in Figure 9. Also shown in this plot is a hydrograph of river water level generated from the logger placed above the waterfall. Unfortunately this logger had to be fixed to a large tree—rooted above the lowest river level—so as to minimise loss during the wet season floods. Accordingly the river water level varied between 0–1 m below the level of the logger for the period of time represented by the horizontal line in Figure 9. Nevertheless, the waterfall logger hydrograph is considered more useful than the hydrograph from the logger installed further downstream as it was located at more than 0.5 m lower elevation.

Comparing the river and groundwater level hydrographs in Figure 9 reveals the strong connection between the two systems, especially the timing and magnitude of groundwater response to high river flow events. Importantly, these hydrographs also reveal the timing for the 'bank storage' mound of water to either disperse further into the aquifer or, more likely, return to the river.

4.2.4. Groundwater sampling

Field and laboratory results from the three piezometer sampling campaigns are provided in Appendix C. When key results for the near-river piezometers are plotted on the cross-section of Figure 8 the data reveal two distinct groups of groundwater: shallow, modern groundwater presumably recharged by recent floods, and very old groundwater at depth.

4.3. Regional bore sampling

Field and laboratory results from the regional bore sampling of May 2010 and October 2010 are provided in Appendix C.

Table 2. *Construction details and manual groundwater level measurements for the piezometers on Noonkanbah Station*

Bore	AMG zone 51		Construction dates		Drilled depth (m BGL)	Elevation		Casing		Geological formation screened	Airlift Yield (L/min)	SWL (m BGL) 14/10/09	06-November-2009			16-December-2009	
	Easting	Northing	From	To		Natural surface (m AHD)	TOIC (m AHD)	Installed depth (mbgl)	Screen interval (mbgl)				Salinity (mg/L TDS)	SWL (m TOIC)	RSWL (m AHD)	SWL (m TOIC)	RSWL (m AHD)
N1A	717148	7952473	9/10/2009	9/10/2009	41	79.59	80.02	29.2	26.2-29.2	Lightjack Formation (sandstone)	4	9.43	687	9.76	70.26	9.88	70.14
N1B	717149	7952476	10/10/2009	10/10/2009	23	79.6	80.1	22.8	19.8-22.8	Quaternary & Lightjack Formation (sands & gravels & sandstone)	nil	10.45	-	10.86	69.24	not measured	not measured
N1C	717146	7952475	10/10/2009	11/10/2009	17	79.61	80.11	17	14.0-17.0	Quaternary (clay-loam, sands & gravels)	7	10.72	249	11.16	68.95	11.3	68.81
N2A	717154	7952588	11/10/2009	12/10/2009	28	80.9	81.38	17	14.0-17.0	Quaternary (clay-loam, sands & gravels)	0.5	11.5	231	12.16	69.22	12.3	69.08
N2B	717151	7952589	12/10/2009	12/10/2009	21	80.9	81.38	21	19.5-21.0	Lightjack Formation (sandstone)	3	11.6	234	12.16	69.22	12.3	69.08
N2C	717149	7952591	13/10/2009	13/10/2009	27	80.91	81.41	27	23.0-27.0	Lightjack Formation (grey mudstone)	8	11.42	622	12.17	69.24	12.32	69.09
N3A	719133	7954889	13/10/2009	13/10/2009	29	79.55	79.98	29	26.0-29.0	Lightjack Formation (grey mudstone)	8	7.37	239	8.03	71.95	8.12	71.86
N3B	719132	7954891	14/10/2009	14/10/2009	18	79.51	80.3	13.5	10.5-13.5	Quaternary (sands & gravels)	1	7.5	145	7.87	72.43	8.43	71.87
N3C	719131	7954894	13/10/2009	13/10/2009	23	79.47	79.82	22.8	19.8-22.8	Lightjack Formation (sandstone)	0.5	7.55	145	8.33	71.49	7.95	71.87

BGL = Below Ground Level

TOIC = Top Of Inner (PVC) Casing

SWL = Standing Water Level

RSWL = Referenced Standing Water Level

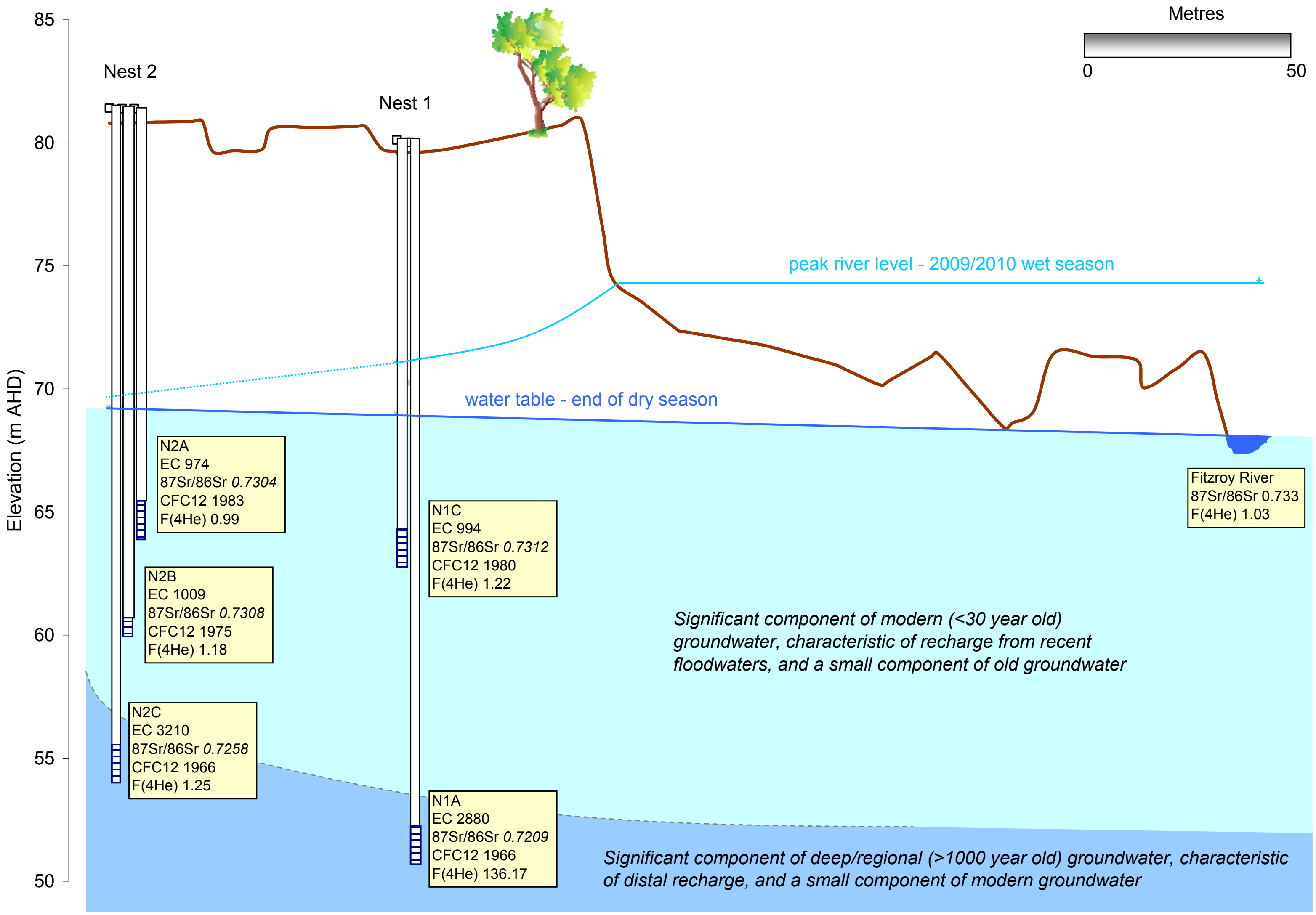


Figure 8. *Cross-section of groundwater electrical conductivity (EC in* □*S/cm), isotopic composition and apparent CFC age along the Noonkanbah piezometer transect, May 2010 (NB. numbers in italics reflect samples taken in November 2009)*

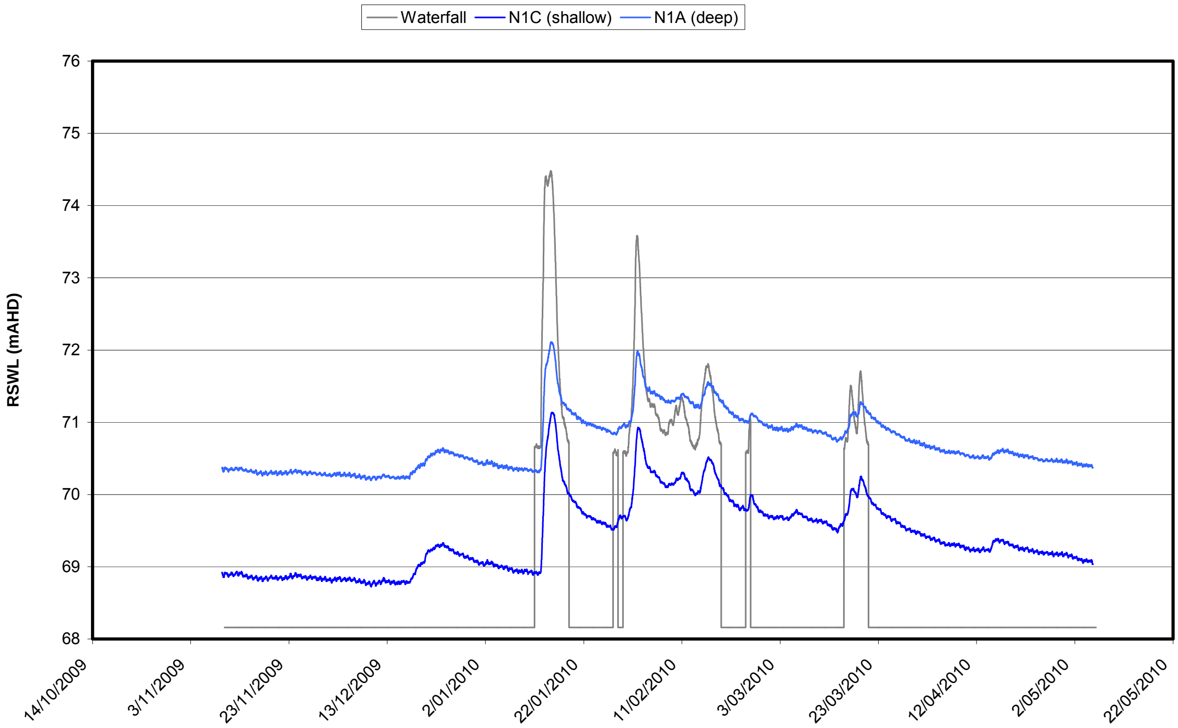


Figure 9. *River water level measured at a logger installed immediately upstream of the waterfall shown in Plate 3, and adjacent groundwater level responses measured in Noonkanbah piezometers N1A and N1C*

4.4. River chemistry modelling

A spreadsheet model was configured with equations [1] and [2] (Section 3.4) to simulate river water chemistry/isotopic composition along a 98 kilometre long reach between sample points 30 (upstream at 0 km) and 11 (downstream at 98 km). Full details of the model assumptions and fitting parameters are provided in a paper by Gardner et al. (2011) for ^{4}He and ^{222}Rn, and a later paper by Harrington and Gardner (in prep.) that also includes chloride concentration and ^{87}Sr/^{86}Sr isotope ratio (NB. the product of ^{87}Sr/^{86}Sr isotope ratio and strontium concentration was simulated to ensure conservation of mass). The 98 km reach was discretised into 1000 model cells, each approximately 100 m long. A summary of the model parameter values is provided in Appendix D. Values for the depth, porosity, residence time and radon production rate of the hyporheic zone were initially set equal to those used by Gardner et al. (2011), which were based on values used by Cook et al. (2006), but were ultimately changed during the model calibration procedure.

The primary objective of the modelling was to simulate observed concentrations of each species in the river by altering the magnitudes of input fluxes along the river. Whilst this was achieved (as discussed below) it was found that the observed river chemistry could only be simulated by spatially varying the concentrations/isotopic compositions of the two different groundwater types (Figure 10). Groundwater chemical analyses obtained for both the Noonkanbah piezometer transect and regional bores provided constraints for these variations in input concentrations (see Appendix C).

A comparison of modelled and observed tracer concentrations is shown in Figure 11, indicating a very good match for ^{4}He and ^{222}Rn, and a reasonable match for chloride concentration and ^{87}Sr/^{86}Sr x [Sr]. Better matches for the latter two tracers, particularly in the lower half of the modelled reach, could only have been achieved through imposing unreasonable input concentrations for the local and regional sources.

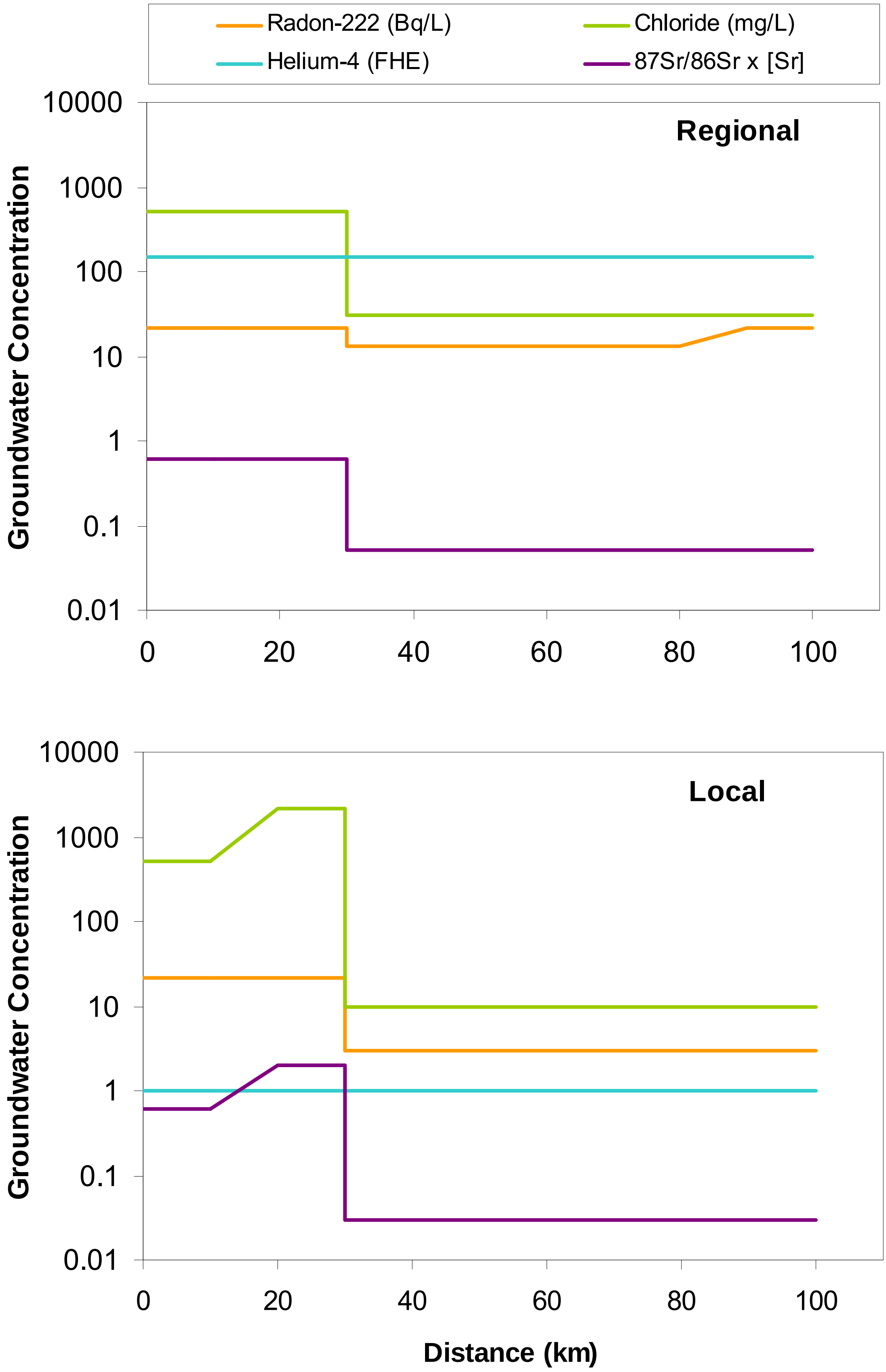


Figure 10. *Spatial distribution of both regional and local groundwater chemical/isotopic concentrations adopted as input for the river tracer modelling. NB. Distance along x-axis is kilometres downstream from sample point 30 (cf. 267 km upstream of Willare on Figure 7).*

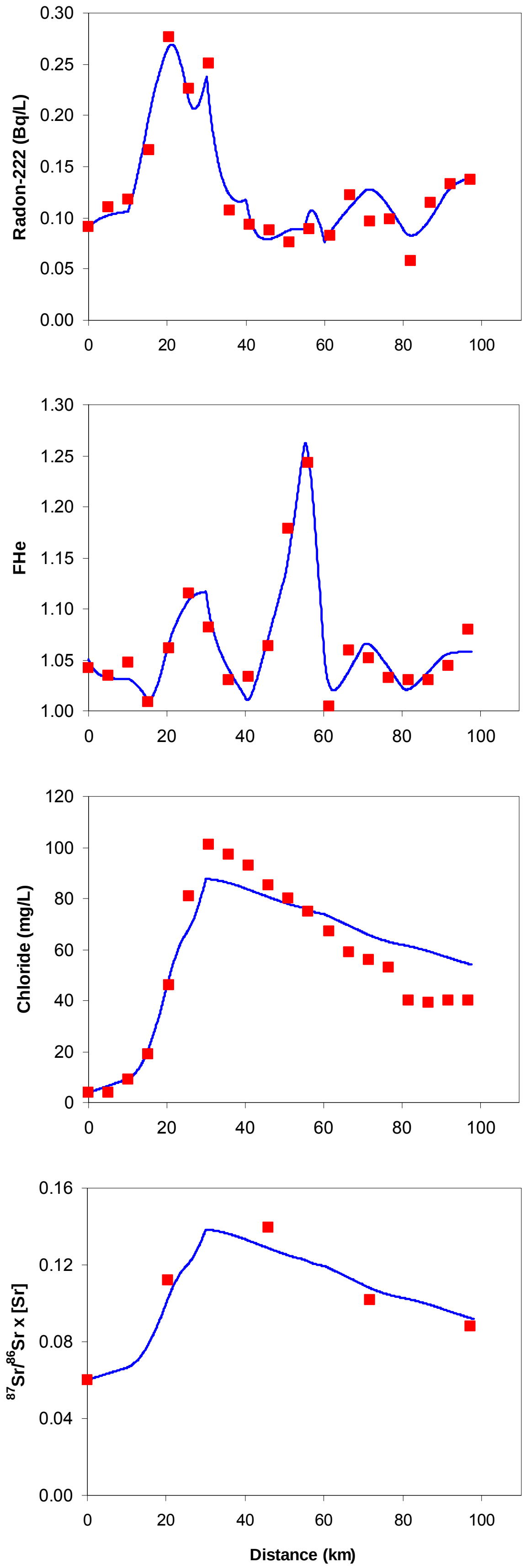


Figure 11. *Comparison of simulated (blue line) and observed (red marker) river chemistry, corresponding to sample sites 30 (0 km) through 11 (98 km) from May 2010. NB. Distance along x-axis is kilometres downstream from sample point 30 (cf. 267 km upstream of Willare on Figure 7).*

5. INTERPRETATION AND MODELLING

5.1. Controls on groundwater discharge to the Fitzroy River

The first increase in river water radon-222 activity, chloride and helium-4 concentrations, and a concomitant decrease in $^{87}Sr/^{86}Sr$ composition, was observed in May 2010 between river sampling points 28 and 24 (see Figure 3 for locations). Peak concentrations occur immediately upstream of the Cunningham Anabranch confluence (Figure 7). When viewed from the helicopter this particular reach of the river was noted to have significantly more outcropping rock in the river bed (e.g. Plate 7) compared with other reaches surveyed. According to recent revisions of the stratigraphic boundaries and structural features in the area (Figure 12; see Appendix A for details) these sampling points overlay the Liveringa Group adjacent its boundary with the underlying Noonkanbah Formation. Both formations dip to the northeast in this area.

From the increase in radon-222 we infer that groundwater in the Liveringa Group flows towards the river (following the topographic gradient) and is forced upwards into the alluvium and then the river, or into the river directly, as it meets the less permeable mudstones of the Noonkanbah Formation. Concomitant increases in helium-4 indicate this is regional groundwater, with an apparent age of at least several thousand years. The increase in chloride concentration and decrease in $^{87}Sr/^{86}Sr$ ratio is consistent with a groundwater concentration/composition measured in Panorama Bore, which is completed in the Liveringa Group (Appendix C).

Plate 7. *Outcropping strata, presumed to be sandstone of the Liveringa Group—or old Alluvium—were commonly observed in the Fitzroy River between May 2010 sample points 27 and 23*

The second sharp rise in river water helium-4 concentration was observed between sample points 22 and 19, peaking at the latter location higher than anywhere else measured along the river. Coincident with this increase in helium-4 is a decrease in chloride concentration, which can only occur by addition of a fresher source of groundwater. $^{87}Sr/^{86}Sr$ composition may increase slightly over the same reach, although the spatial resolution of these samples means that this trend cannot be confirmed. The most remarkable trend however, despite a pronounced increase in helium-4, is the decline in radon-222 activity over this reach. This apparent contradiction of tracer trends (i.e. between helium-4 and radon-222) can only be attributed to small, localised inputs of old groundwater with very high helium-4 concentration.

When these sample points (22 to 19) are viewed in the context of the revised stratigraphy and structure (Figure 12), it becomes evident their locations are coincident with a large swarm of faults. Airborne electro-magnetic (AEM) surveys conducted during the course of the current project have confirmed the presence of these faults and suggested the underlying Poole Sandstone may be locally uplifted (Fitzpatrick et al., 2011). The community water supply bores at Noonkanbah are completed in the Poole Sandstone. Several of these bores, including “1-96” listed in Appendix C, have historically been recorded as artesian—either at the time of drilling or after recovery from pumping. An indicative value of piezometric head for these bores is in the range 74–75 m AHD. By comparison, the floodplain at Noonkanbah gauging station (situated below the community) is at 71.82 m AHD. There is therefore potentially 2–3 m of upward hydraulic head between the Poole Sandstone and the river/alluvial aquifer in this area.

Based on this evidence, we infer that the set of north–south trending faults transecting the river provide preferential pathways for deep, regional groundwater from the Poole Sandstone to discharge into the Fitzroy River, most likely via the shallow alluvial aquifer. This conceptualisation is also supported by the relatively low chloride concentration measured at bore 1-96 (29 mg/L; Appendix C) compared with all other regional bores sampled.

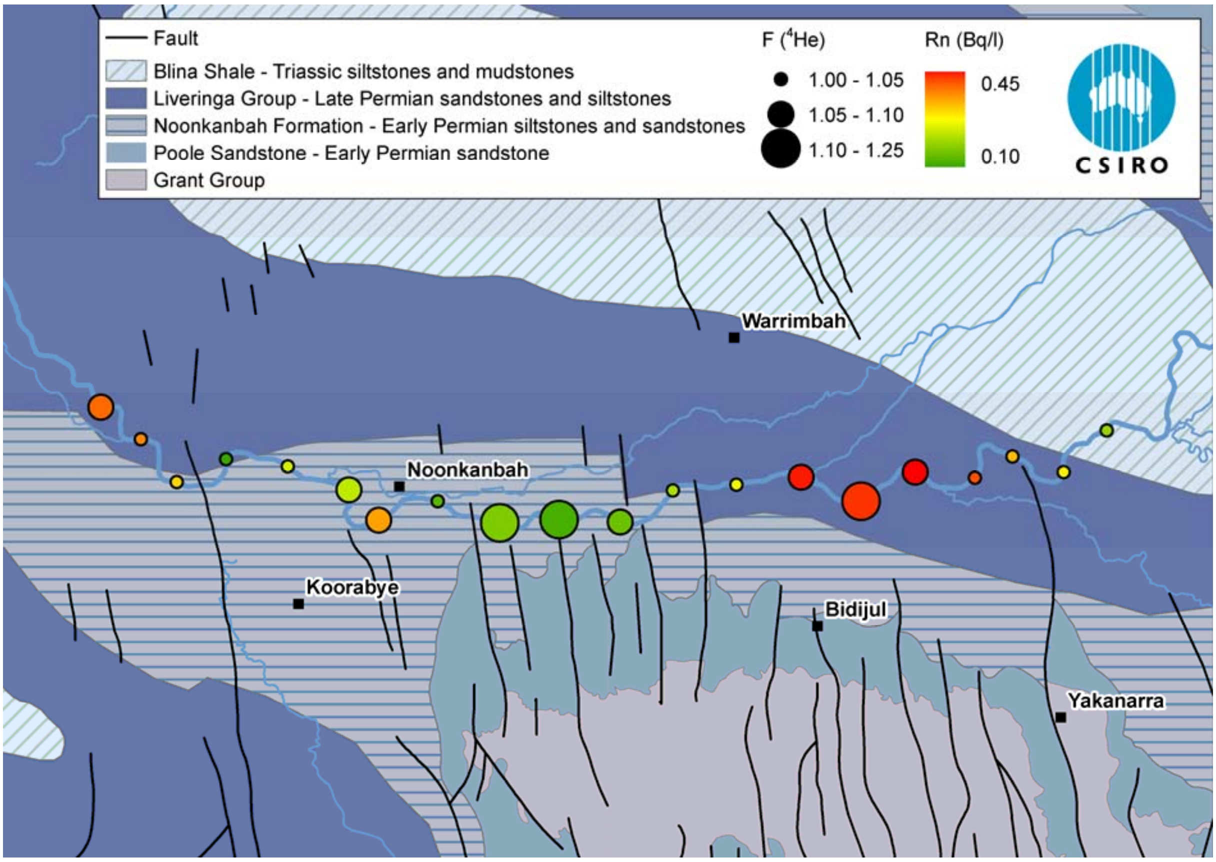


Figure 12. *Map showing revised stratigraphic boundaries and faults in the context of river water radon-222 activity and helium-4 concentration at sample points 11–30. (Geology extents provided by A.J. Mory, WA Department of Mines and Petroleum, 2010).*

In the lowermost sampled reach of the Fitzroy River (i.e. sites 10 to 1) both helium-4 concentration and radon-222 activity rise between points 7 and 5 (Figure 7). While both of these trends are indisputably indicative of groundwater input, the source of the groundwater cannot to reconciled, as chloride concentration remains constant and $^{87}Sr/^{86}Sr$ was not analysed for these samples. One possible source is the Poole Sandstone and Grant Group rocks that outcrop at Mt Anderson (Plate 8). Two alternative mechanisms for this groundwater discharge, readily apparent from the geology map (Figure 3) are (i) constriction of the Liveringa Group sediments, which in turn may force regional flow upwards into the river, and (ii) the close proximity of the river to the outcropping Wallal sandstone to the south. All of these mechanisms warrant further investigation.

Plate 8. *View of the Fitzroy River downstream of Mt Anderson (shown in left background) looking towards the north-east*

5.2. Estimates of groundwater discharge rates

The modelling of May 2010 river chemistry has produced a profile of the inferred fluxes of regional and local groundwater discharge into the Fitzroy River (Figure 13). This plot reveals the greatest inflows occur towards the lower end of the studied reach, primarily between sample points 20 and 11 (Figure 3). Cumulative groundwater discharge over the entire 100 km reach is estimated to be 102 ML/day, comprising 3.7 ML/day from regional sources and 98.3 ML/day from local sources. While the overall contribution of regional groundwater into the river is comparatively small, it is important to note that in some sections of the modelled reach regional groundwater accounts for almost 30% of the total groundwater discharge.

While the locations and estimated fluxes of groundwater discharge are useful for informing future management of the water resources in the region, it should be noted the modelling approach has a number of assumptions and uncertainties. One of the greatest uncertainties in the modelling is the spatial variability of river width and depth (e.g. see Plate 9). While we have assumed a constant river width of 20 m throughout the modelled reach, and a single step change in river depth (see Appendix D), this simplification is likely to produce some error in the estimated fluxes.

Another potential source of error arises through the assumption that both river flow and chemistry are at some quasi steady state, and that measurements made in the river over the course of the sampling campaign are not confounded by, for example, recent high flow events that have contributed river water into bank storage and subsequent return flow. The latter could be problematic for interpreting any of the tracer data, but it would be especially important for radon-222 if a high flow event had occurred within the last 2–3 weeks—the time required for secular equilibrium of radon-222 to occur in most aquifer types (Cecil and Green, 2009). However, a comparison of river stage measurements at both Fitzroy Crossing and Noonkanbah (Figure 14) reveals that the last minor flood pulse prior to May 2010 sampling occurred almost one month earlier on 14–15 April 2010, suggesting this potential error is negligible.

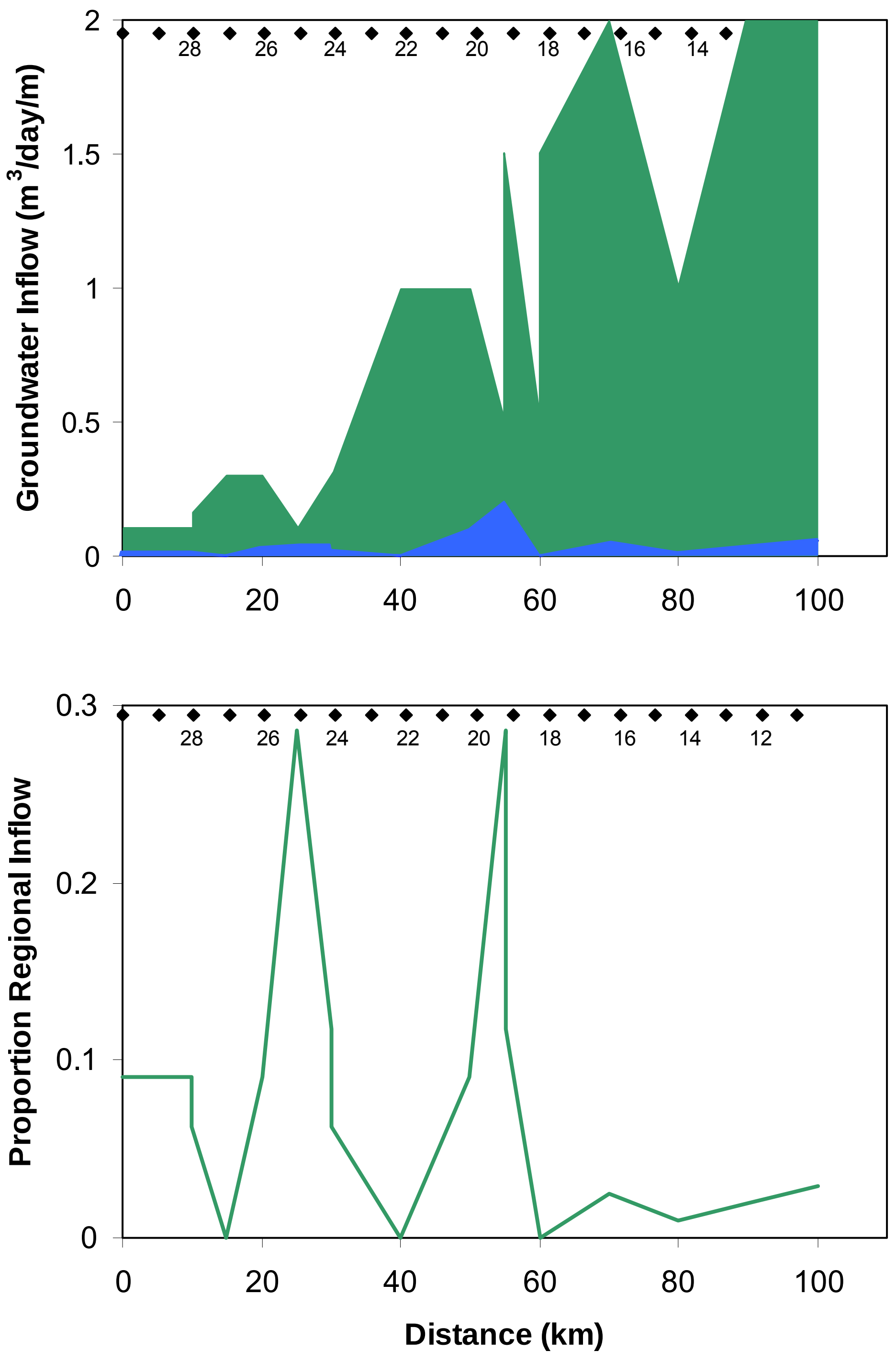


Figure 13. *Plots of modelled groundwater discharge flux into the Fitzroy River at May 2010; (a) local (green) and regional (blue) sources as a function of distance downstream from sample point 30, and (b) regional inflow as a proportion of total inflow over the same reach. Black diamonds with number labels represent sample points for comparison with Figure 3.*

Plate 9. *An example of the variability in geometry of the Fitzroy River channel between May 2010 sample points 11 and 15*

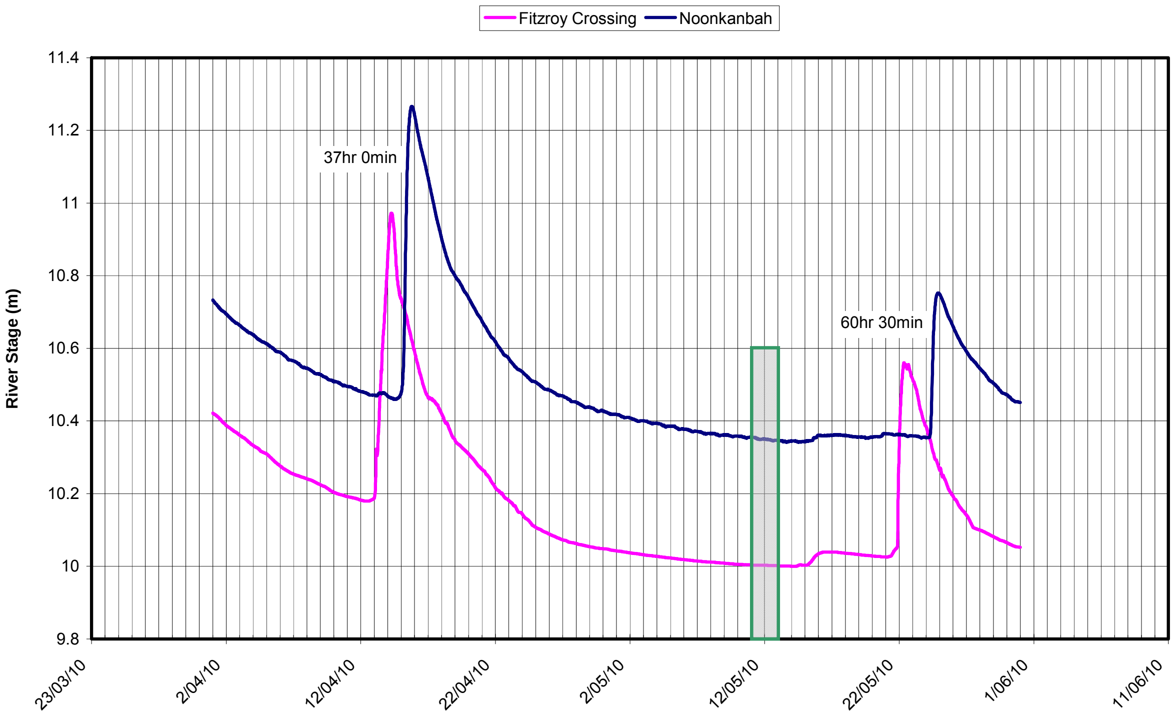


Figure 14. *Comparison of antecedent river flow conditions at two gauge locations prior to the May 2010 sampling campaign (green box). Times shown on the graph represent time intervals between peak flows at Fitzroy Crossing and Noonkanbah gauges.*

When modelling the gas tracers it was assumed that observations had been made at a sufficiently high spatial resolution in the river to ensure any groundwater discharge is detected by the ^{4}He and ^{222}Rn measurements before it degasses (and decays to background concentrations in the case of ^{222}Rn). Cook et al. (2006) suggest that the spacing between sample locations should ideally be less than the ‘scale length’ (x) which they define as

$$x = \frac{Q}{kw + dw\lambda} \qquad \text{(Equation 3)}$$

Using the model input parameters from Appendix D and the range of modelled total flow (Q) values (i.e., a range from 1.2 $m^3.s^{-1}$ at the start of the reach to 2.2 $m^3.s^{-1}$ at the end of the reach) we derive a range of scale lengths from 1.0 - 3.7 km and 2.2 - 8.0 km for ^{4}He and ^{222}Rn respectively. The shorter scale lengths for ^{4}He compared to ^{222}Rn reflect the higher gas exchange coefficient, while the lower end of each range of lengths reflect the shallower river conditions imposed in the first 40 km of the modelled reach (Appendix D). Given that sample spacing was approximately 5 km throughout the modelled reach, this analysis suggests that most of the groundwater discharge was likely detected by ^{4}He and ^{222}Rn, although some discharge of groundwater with high ^{4}He might have been missed in the first 40 km.

5.3. Temporal variability of groundwater discharge

The high interannual variability of rainfall in the Fitzroy region (Section 2.1) means there is also very high interannual variability in runoff. Accordingly, surface water – groundwater interactions at any one location along the Fitzroy River are likely to be highly variable in time, both during seasons and between seasons. This hypothesis is supported in a comparison of dry season gauged river flows for a series of years at Noonkanbah (Figure 15), which reveals vastly different slopes in the dry season recession curves. During the wettest of wet seasons, large areas of floodplain are inundated and there will be some associated vertical recharge to the alluvial aquifers beneath the floodplains. Whilst these high flow events are occurring, there will also be lateral groundwater recharge through river banks. Then, as floodwaters and river levels begin to recede, groundwater discharge to the river is sourced initially from proximal bank storage and later from wider alluvial aquifers (as well as the deeper, regional groundwater flow systems proposed in Section 5.1). In stark contrast, after a relatively dry wet season, when little or no overbank flooding has occurred, groundwater discharge into the river will mainly be sourced from proximal bank storage (and the regional source where geology permits). It is these latter conditions that are responsible for the steeper recession curves in Figure 15, whereas the more prolonged recessions reflect wetter preceding wet seasons.

While the spatial resolution of river water sampling points was different for May 2008 and May 2010, there are significant differences in the measured radon-222 profiles from each campaign (Figure 16). We propose that these differences can be explained by the differences in the wet season flow conditions that preceded to two sampling campaigns (Figure 17). In general, radon-222 activities were higher during May 2008 across the entire reach, reflecting a greater input of groundwater due to higher wet season recharge. This conceptualisation is very complex, and ideally requires further testing in future.

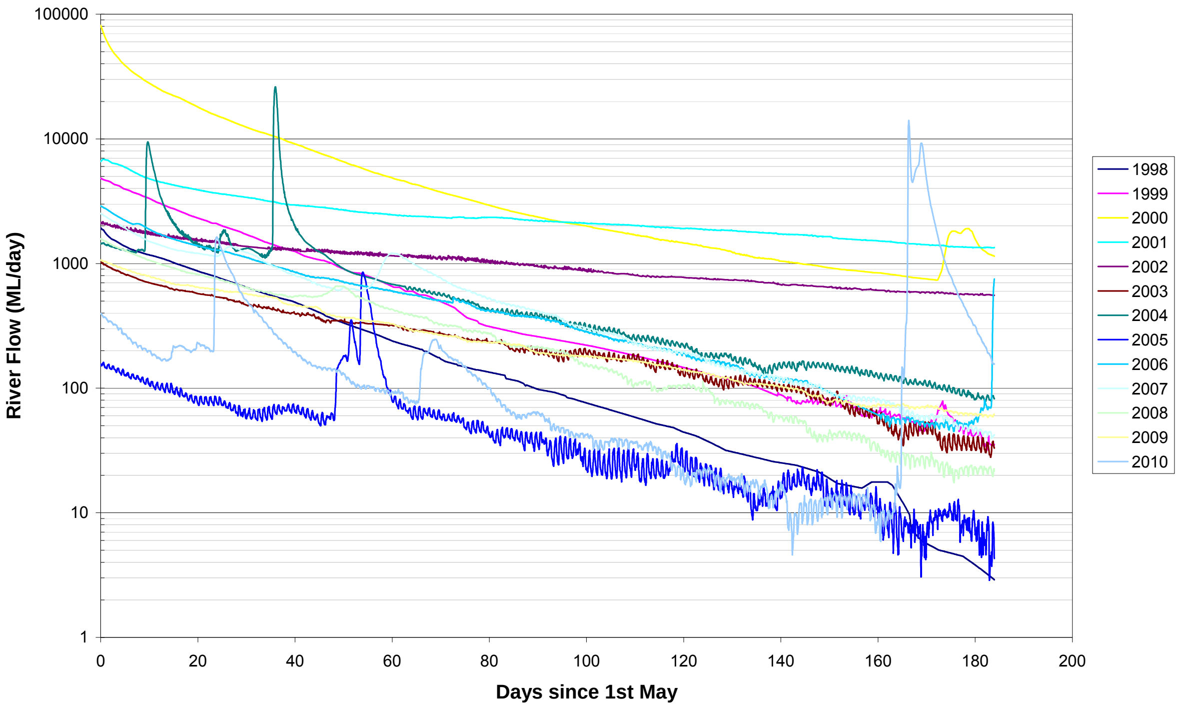


Figure 15. *Comparison of dry season river flow recession for each year between 1998–2010 at Noonkanbah gauging station*

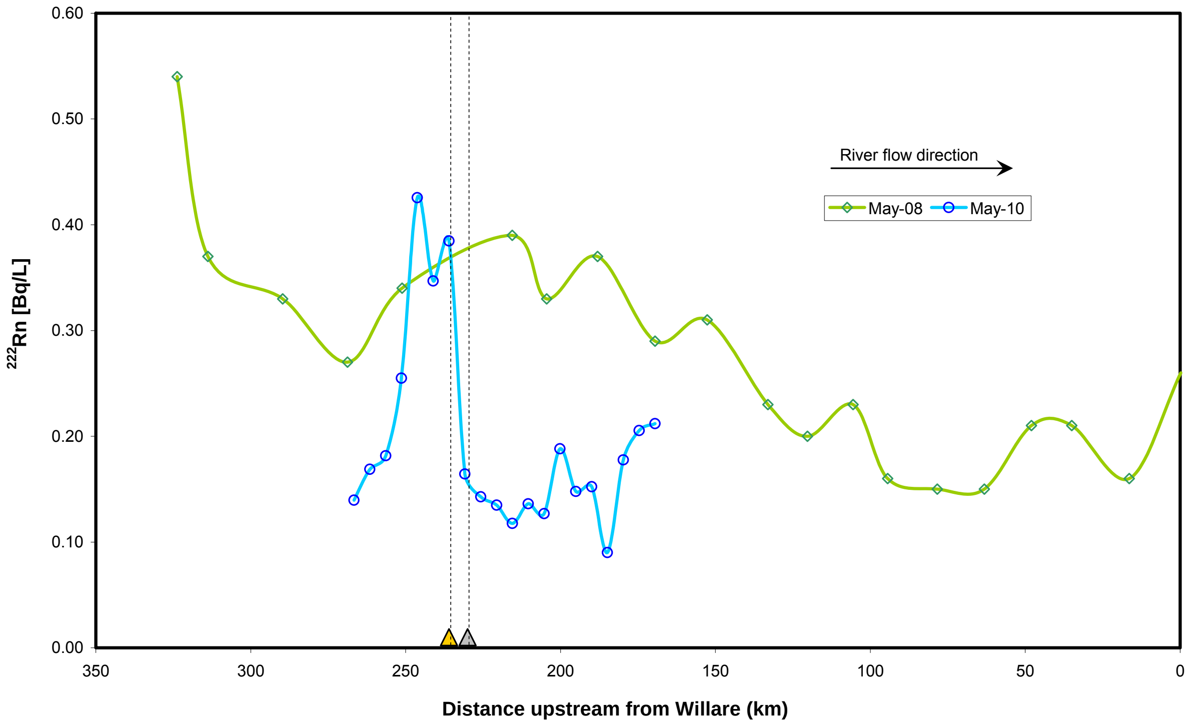


Figure 16. *Comparison of Fitzroy River radon-222 activity between May 2008 and May 2010. Gold triangle represents location on confluence with Cunningham Anabranch, and silver triangle represents approximate location of Noonkanbah piezometer Nest #1.*

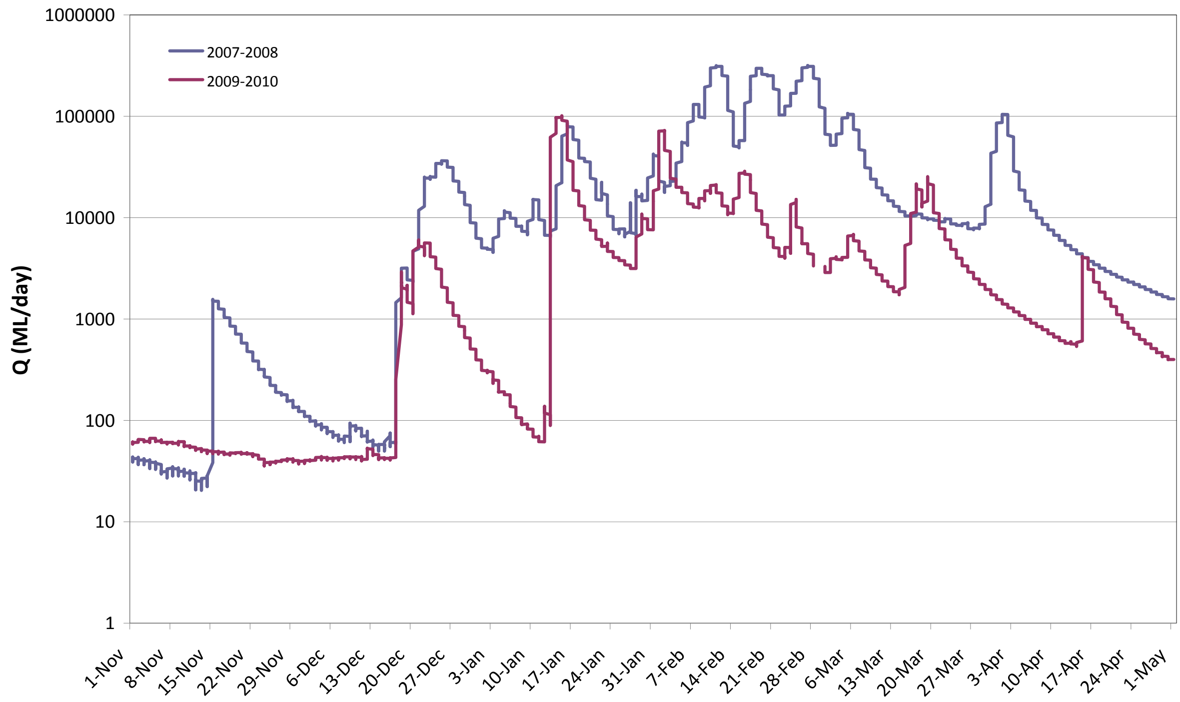


Figure 17. *A comparison of wet season flow hydrographs from Noonkanbah gauging station during the wet seasons prior to each river sampling campaign. The 2007–08 wet season produced both larger peak flow events and more persistent high flows compared with the 2009–10 wet season.*

5.4. Groundwater recharge and residence times

While not part of the original intention of this research, the hydrochemical and isotopic data collected from both groundwater bores and the Fitzroy River provides insights to groundwater recharge mechanisms and apparent ages of groundwater in different aquifers.

The stable H/O isotope compositions of the water molecules in each type of sample provide insight to both recharge and discharge mechanisms. When plotted on a conventional δ^2H versus $\delta^{18}O$ chart (Figure 18) it is evident that groundwater sampled from both Noonkanbah piezometers and the regional bores is significantly depleted in the heavier H/O isotopes relative to all of the river water samples. In some ways this trend was to be expected, as the river water should become further enriched in the heavier isotopes with increasing distance along the river due to progressive fractionation during evaporation. However, when δ^2H or $\delta^{18}O$ are plotted against distance down the river (not shown), the values actually decline (i.e. become more depleted) through the zone of most significant regional groundwater discharge, before increasing further downstream in the expected manner.

The slope of the regression line for the river samples (5.92) is consistent with evaporation from an open water body, rather than evaporation from an unsaturated soil—which would typically lead to lower slopes of five or less (Allison, 1982). While it should be noted the regional bore samples represent a range of aquifers and depths, the fact that they exhibit a similar slope (6.02) to the river samples suggests they too may have been evaporated from an open water body (e.g. floodwater) prior to recharge.

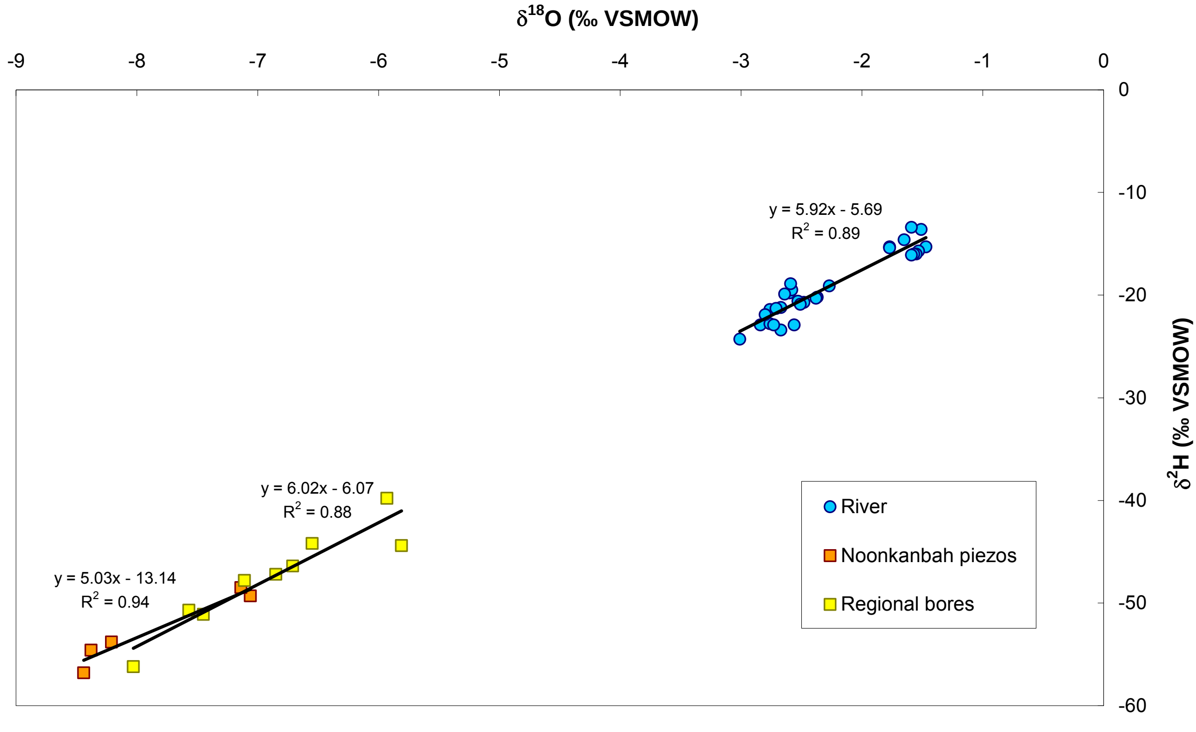


Figure 18. *Stable H/O isotope composition of groundwater and river samples, May 2010*

The apparent age of groundwater can be estimated for samples that were analysed for either chlorofluorocarbons, SF_6 or carbon-14. In the case of CFCs or SF_6 the apparent age is determined using the methodology of Busenberg and Plummer (1992) and assuming a recharge temperature and elevation for the sample. In the case of carbon-14, the apparent age (t) is determined using the conventional radioactive decay law:

$$A = A_0 e^{-\lambda t} \quad \text{(Equation 4)}$$

where A is the measured ^{14}C activity, A_0 is the initial ^{14}C activity, and λ is the radioactive decay constant (0.000120968 /year for ^{14}C). Values of A_0 can either be modelled to account for any water-rock interactions that might have altered the initial ^{14}C activity from that of atmospheric carbon dioxide (to yield a 'corrected' age) or estimated (to yield an 'uncorrected' age).

For the purposes of this study, we have chosen to use consistent values for recharge temperature (35°C), recharge elevation (80 m above mean sea level) and initial ^{14}C activity (90 pmC) to yield the apparent ages presented in Table 3. The two deep Noonkanbah piezometers located near the river (i.e. N1A and N2C) have very old apparent ages of approximately 15,000 years and 5,000 years (respectively). The remaining piezometers in the transect appear to contain mostly modern groundwater (i.e. recharged in the last 50 years). The particularly old age for N1A is consistent with the elevated F(^4He) observed in the same bore (Figure 8). However, there is a contradiction between the carbon-14 ages for N1A and N2C and the ages estimated using SF_6 and CFCs for the same bores. This suggests one of two things, both of which are considered equally plausible. Firstly, the groundwater sampled from these bores is a mixture of waters of different age, including some very old water and some very modern water. Alternatively, given that these bores were sampled only one month (in the case of CFCs) or six months (in the case of SF_6) after drilling, it is possible they are still 'contaminated' with compressed air used during the drilling process.

For the nine regional bores sampled, carbon-14 and/or CFC or SF_6 concentrations indicate all but two of the bores (i.e., No. 5 Bore and Nicko1) contain very old groundwater, ranging in apparent age from about 6,000 years to over 30,000 years. Again there are some discrepancies between ^{14}C-derived ages and SF_6 ages.

Table 3. *Apparent ages of groundwater sampled from bores in May 2010*

Bore Name	^{14}C pmC	Apparent 'Uncorrected' ^{14}C Age (years)	SF_6 year	CFC-12 year
N1C	95.9	Modern	2005	1980
N1A	13.7	15588	2000	1966
N2A	95.0	Modern	2004	1983
N2B	96.8	Modern	2000	1975
N2C	51.2	4658	1997	1966
N3A	82.5	724		
N3B	89.9	13		1986
N3C	89.2	71		
1_96	2.1	31014		
San Miguel	6.8	21353		
1_89	7.0	21115	2007	<1965
No. 5 Bore			1975	<1965
Jarlmadangah Burr	24.7	10691	1972	<1965
Global BG2/02-725	26.3	10159	2007	<1965
Big Moana	4.9	24111	1972	
Panorama	42.3	6245		
Nicko1	87.5	237	1994	

6. CONCLUSIONS AND RECOMMENDATIONS

This suite of research projects has significantly improved our understanding of the mechanisms by which groundwater discharges to the lower Fitzroy River in the dry season. The research should not be viewed as completed, but rather as the preliminary steps required to obtain sufficient technical data and process understanding to underpin future quantitative assessments of water availability and potential impacts of groundwater extraction. The two reaches of the river that we have focussed on—an upper reach between Fitzroy Crossing and Noonkanbah and a lower reach between Mt Anderson and Willare—have complex hydrogeological processes, which may or may not occur elsewhere in the catchment.

The first major zone of groundwater discharge into the river occurs around the confluence with the Cunningham Anabranch. Based on hydrochemical and isotopic data, and recent revisions to the geology maps for the area, we infer that old, regional groundwater in the Liveringa Group flows in a westerly direction towards the river before being forced upwards into the alluvium and then the river, or into the river directly, as it meets the less permeable mudstones of the Noonkanbah Formation.

The second major zone of groundwater discharge was identified on Noonkanbah Station between a well-known waterfall (adjacent the new transect of monitoring bores) and Yungngora Community. In this zone, a combination of increasing helium-4 and decreasing radon-222 is attributed to small, localised inputs of old groundwater with very high helium-4 concentration. Based on this evidence, coupled with knowledge of artesian heads in the underlying Poole Sandstone and the results of recent airborne geophysical surveys, we infer that a series of north–south trending faults provide preferential pathways for deep, very old, regional groundwater to discharge into the river, most likely via the shallow alluvial aquifer.

In the lowermost sampled reach of the Fitzroy River there is evidence of groundwater input, however the source of this groundwater, nor the mechanisms through which it discharges into the river, remains unknown. Two possible mechanisms that warrant further assessment are (i) constriction of the Liveringa Group sediments, which in turn may force regional flow upwards into the river, and (ii) the close proximity of the river to the outcropping Wallal sandstone to the south.

Modelling of the river chemistry profiles obtained in May 2010 has provided estimates for the fluxes of groundwater discharge over the 100 kilometre study reach. At the time of sampling we estimate a total discharge of about 102 ML/day, comprising about 3.7 ML/day sourced from the regional aquifers. The remaining discharge is sourced from local groundwater flow systems in the alluvial aquifer.

Implications for management

Future groundwater management in the lower Fitzroy River valley must consider and account for the impacts that extracting groundwater will have on reducing discharge to this river during the dry season. This project has shown that, depending on location along the valley and the aquifer being pumped, groundwater abstraction from either the shallow alluvium and/or the deeper Canning Basin aquifers is likely to cause a reduction in stream flow during the dry season. Such reductions may have adverse and potentially irreversible impacts on the riparian and in-stream ecology of this iconic river system.

Future work

The ecology of the Fitzroy valley floodplain has adapted to the seasonal wets and dries, and supports Indigenous cultural values. It is recommended that further work is carried out to identify the environmental habitats and the reliance of these to the surface and groundwater regimes, both temporally and spatially, with respect to flows, heads and water quality.

It is recommended that future management rules take into account the time delay for groundwater abstractions to impact on the surface water regime. Long term pumping tests—with associated monitoring—are required to establish the impact of any large future groundwater abstractions. Monthly, rather than annual, water balance calculations are recommended in future modelling exercises.

Further work is required to understand the magnitude of piezometric heads within the major aquifers (e.g. the Wallal Sandstone, major sandstone units within the Liveringa Formation, Poole Sandstone, Grant Group) acting into the alluvial aquifer, and the locations and impact of faulting on deep groundwater discharge to the Fitzroy River and the floodplain.
Further investigation of the hydrochemistry of the confined Canning Basin aquifers to understand geochemical evolution and hence the age of groundwaters, the travel times from recharge to discharge and any chemical limitations to water use.

REFERENCES

Allison, G., 1982. The relationship between 18O and deuterium in water in sand columns undergoing evaporation. Journal of Hydrology 55:163–169.

Busenberg, E. and Plummer, L. N., 1992. Use of chlorofluorocarbons (CCl3F and CCl2F2) as hydrologic tracers and age dating tools: the alluvium and terrace system of central Oklahoma. Water Resources Research, 28(9): 2257–2283.

Cecil, L.D. and Green, J.R., 1999. Radon-222. In: Cook, P.G. and Herczeg, A.L. (Eds.) Environmental tracers in subsurface hydrology, pp. 175–194, Kluwer Academic Publishers, Norwell, Mass.

Cook, P.G. and Herczeg, A.L., 1999. Environmental tracers in subsurface hydrology. Kluwer Academic Publishers, Norwell, Mass. 529 pp.

Cook, P.G., Favreau, G., Dighton, J.C. and Tickell, S. 2003. Determining natural groundwater influx to a tropical river using radon, chlorofluorocarbons and ionic environmental tracers. Journal of Hydrology, 277: 74–88.

Crowe, R.W.A. and Towner, R.R., 1981. 1:250 000 Geological Series - Explanatory Notes Noonkanbah Sheet SE/51-12 International Index, Australian Government Publishing service, Canberra.

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. 508 pp.

Dawes, W., 2008. Numerical groundwater flow model for the Fitzroy alluvium, unpublished.

Department of Water, 2008. Aboriginal Heritage and Native Title Guidelines for On-Ground Works'. Internal guidance (September 2008 draft used).

Doble, R.C., Palmer, D., Cook, P.G. and McCallum, J.L., 2010. Sampling for stream-aquifer connections by helicopter in a remote, inaccessible area, in Proceedings of Groundwater 2010: The Challenge of Sustainable Management.

Doble, R.C and Cook, P.G., 2008. Surface water – groundwater interactions in the Fitzroy River, WA. Unpublished report to the Tropical Rivers and Coastal Knowledge program.

Fitzpatrick, A., Munday, T.J., Cahill, K. and Stelfox, L., 2011. An interpretation of SkyTEM Airborne EM data for the Fitzroy River, Western Australia: Final report. CSIRO Water for a Healthy Country Flagship, Technical Report No. CESRE P2010/1235.

Galloway, M and Howell, D 1975. Relinquishment Report of TR 5851H to 5869H, 5878H to 5880H, Fitzroy Trough, Western Australia; Esso Australia: Geological Survey of Western Australia, Statutory mineral exploration report, A63549 V1 (unpublished).

Gardner, W. P., and Solomon, D.K., 2009. An advanced passive diffusion sampler for the determination of dissolved gas concentrations. Water Resources Research, 45, W06423, doi:10.1029/2008WR007399.

Gardner, W.P., Harrington, G.A., Solomon, D.K and Cook, P.G., 2011. Using terrigenic ^{4}He to identify and quantify regional groundwater discharge to streams. Water Resources Research, vol. 47, doi:10.1029/2010WR010276.

Gibson D.L. & Crowe R.W.A., 1982, 1:250 000 Geological Series - Explanatory Notes Mount Anderson Sheet SE/51-11 International Index, Australian Government Publishing service, Canberra.

Harrington, G.A. and Gardner, W.P., in prep. On the benefits of using multiple tracers of different types to constrain sources of groundwater discharge to large river systems. For submission to Ground Water.

Laws, A.T., 1990. Outline of the groundwater resource potential of the Canning Basin, Western Australia. International Conference on Groundwater in Large Sedimentary Basins, Perth 1990, Proceedings Australian Water Resource Council, Conference Series no. 20, p 47–58.

Leaney, F. W. and Herczeg, A. L., 2006. A rapid field extraction method for determination of radon-222 in natural waters by liquid scintillation counting. Limnology and Oceanography Methods, 4: 254–259.

Lindsay, R.P. and Commander, D.P., 2005. Hydrogeological assessment of the Fitzroy alluvium, Western Australia, Department of Water, Hydrogeological Record Series HG 16.
Middleton, M.F., 1990. Canning Basin, in Geology and Mineral Resources of Western Australia. Western Australia, Geological Survey, Memoir 3, p.425–457.

Mory, A.J., 2010. Report 107. A review of mid-Carboniferous to Triassic stratigraphy, Canning Basin, Western Australia, Geological Survey of Western Australia, Government of Western Australia, Department of Mines & Petroleum.

National Water Commission, 2010. Deed in relation to Raising National Water Standards project: Fitzroy River integrated ground and surface water hydrology assessment, variation no. 1. Commonwealth of Australia and State of Western Australia.

Nicholls, R.S., Laurie, J.R., Kelmen, A.P., Mantle, D.J., Haines, P.W., Mory, A.J. and Hocking, R.M., 2009. Canning Basin Biozonation and Stratigraphy Chart 31: Australian Government, Geoscience Australia.

Smith, R.A., 1992, Explanatory Notes on the Derby 1:250 000 Hydrogeological Sheet, Geological Survey of Western Australia, Perth.

APPENDICES

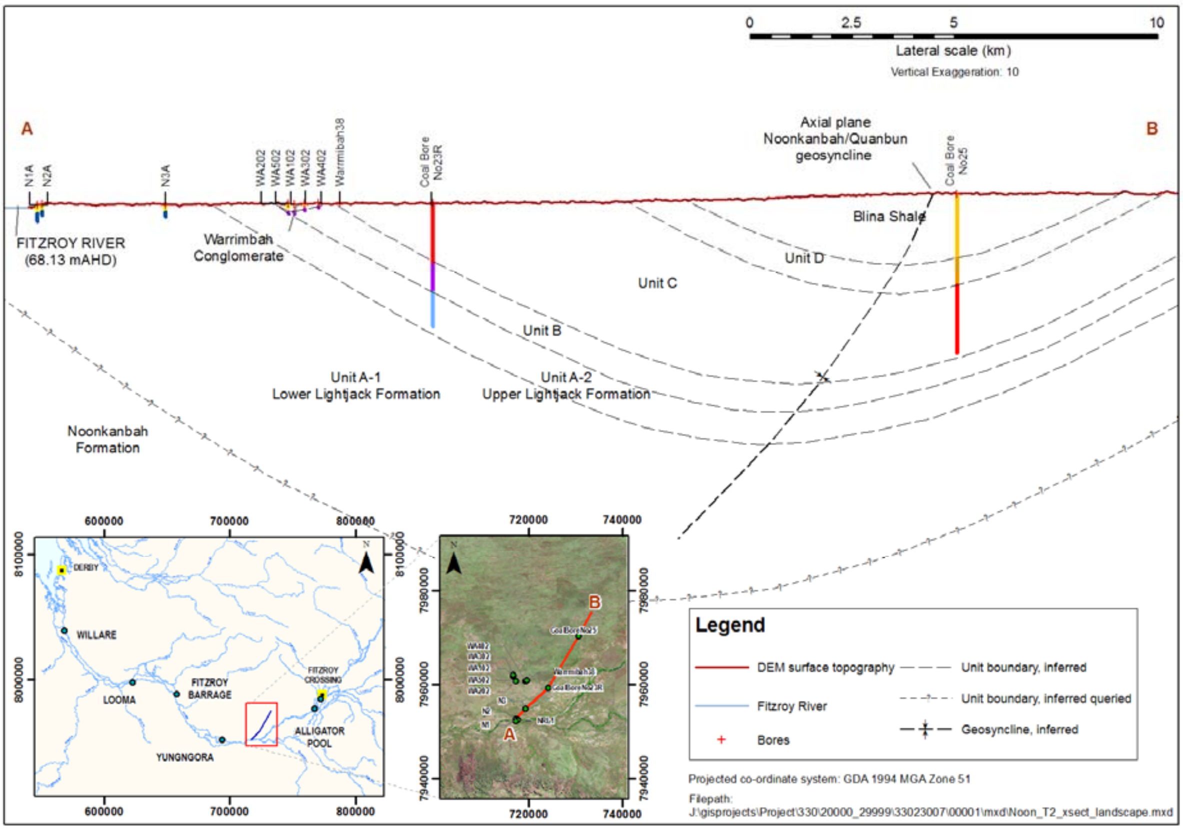
APPENDIX A – LIVERINGA GROUP

Coal exploration drilling along the Quanbun – Noonkanbah syncline in the early 1970s indicates the Liveringa Group is about 300 m thick in this region. Of this, 60 m can be assigned to the Lightjack Formation (Units A-1 and A-2 of Galloway and Howell, 1975), 200 m to undifferentiated Liveringa Group (Units B and C), and 45 m to the Hardman Formation (Unit D). Galloway and Howell (1975) describe the Lightjack Formation as a richly fossiliferous, micaceous sandstone sequence with a plant-bearing sandstone and coal at the top. Their undifferentiated Liveringa Formation may be a lateral equivalent of the Condren Sandstone, but the nearest outcrop of that unit lies 100 km to the southeast in Millyit Range where it is about 50 m thick. The Hardman Formation consists of richly fossiliferous sandstone with interbedded massive and current-bedded, well-sorted quartz sandstone.

Unit A is predominantly sandstone, and is thickest in the south and west of the Quanbun – Noonkanbah syncline. It has been speculated that its origin is from the influx of eroded sediments being washed in from the Kimberley block, and migrating in a westerly direction, down the axis of the Fitzroy Trough (Galloway and Howell, 1975).

Palynology and down hole geophysics were used to correlate Galloway and Howell's (1975) units. All were observed to grade from fine-grained interbedded shales, siltstones and sandstones at the bottom to coarse sandstones at the top, with the exception of Unit A-2 which grades from sandstone at the base to shale and back to sandstone, and contains coal seams throughout. Units A-2 and B were encountered in hole 23R (Figure 3) (approximately 5.4 km immediately north of the Cunningham – Fitzroy confluence and approximately 1 km NE of the Department of Water's drilling on Noonkanbah Station (Section 3.2)). Both contain sandstones in their upper sections.

The base of the Units A, B, C and D plotted in m AHD from drilling information were used to create isopach maps for the various units. Coal exploration data was used to modify the location of the boundary between the Liveringa Group and underlying Noonkanbah Formation from that published on the Noonkanbah 1:250,000 geological sheet (Crowe and Towner, 1981)—the same as that currently available on the Western Australian Government's Department of Minerals and Petroleum web site. Galloway and Howell (1975) indicate that the Liveringa – Noonkanbah boundary should lie west of the Cunningham – Fitzroy confluence, and south of the Fitzroy River, so that the Fitzroy River to the east is underlain by the Lightjack Formation (cf. Figure 3). Recent mineral exploratory drilling, and drilling within this research project, has further refined the Liveringa Group – Noonkanbah Formation boundary beneath the Fitzroy River from Fitzroy Crossing to Noonkanbah Community (Figure 12).



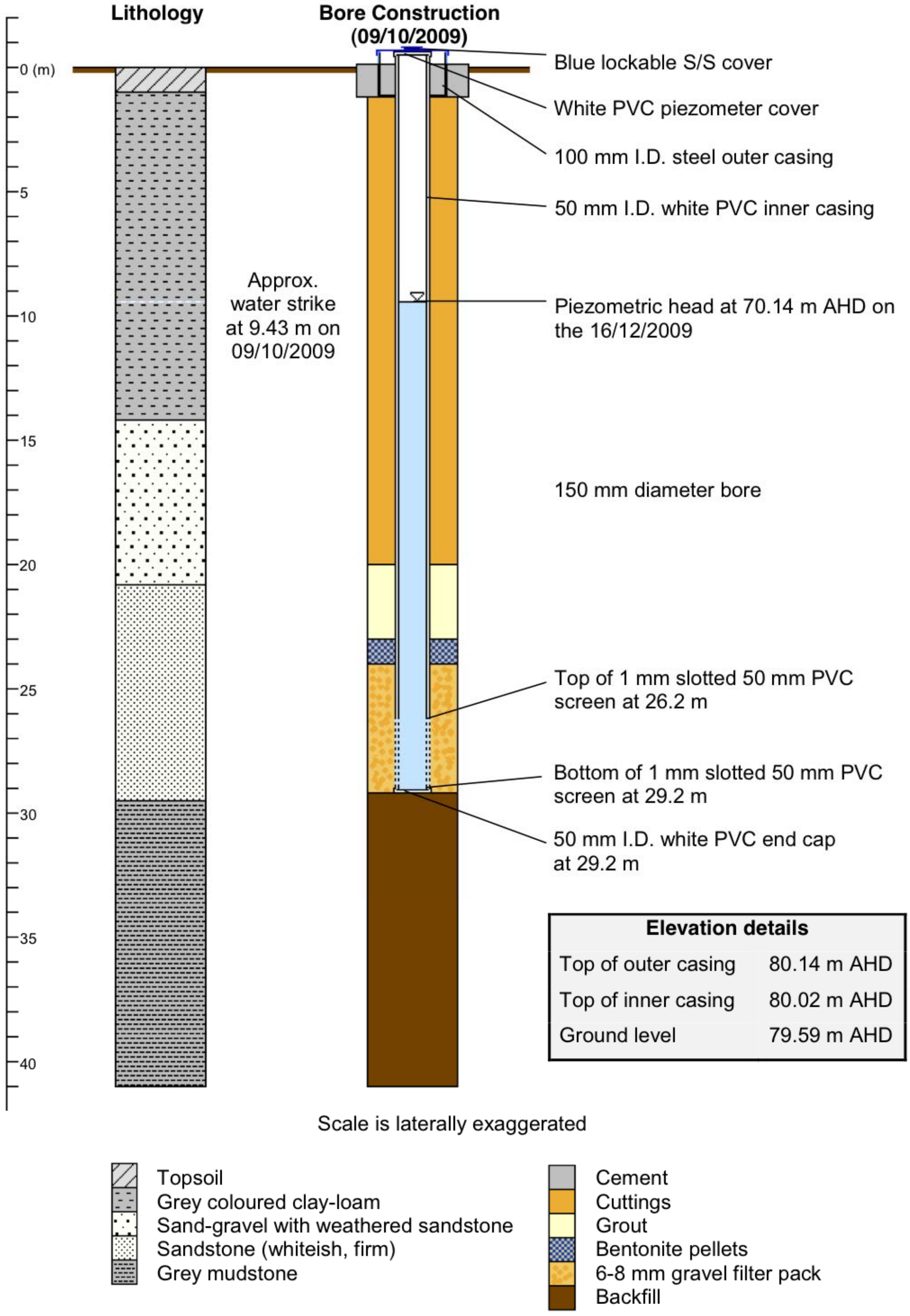
Cross-sections through the coal exploration bores on Quanbun Downs and Noonkanbah stations show sandstone, siltstone and shale beds with coal horizons. Approximately 170 m of sandstone was encountered in coal bore 3 within Unit B.

Adapted from Galloway and Howell, 1975.

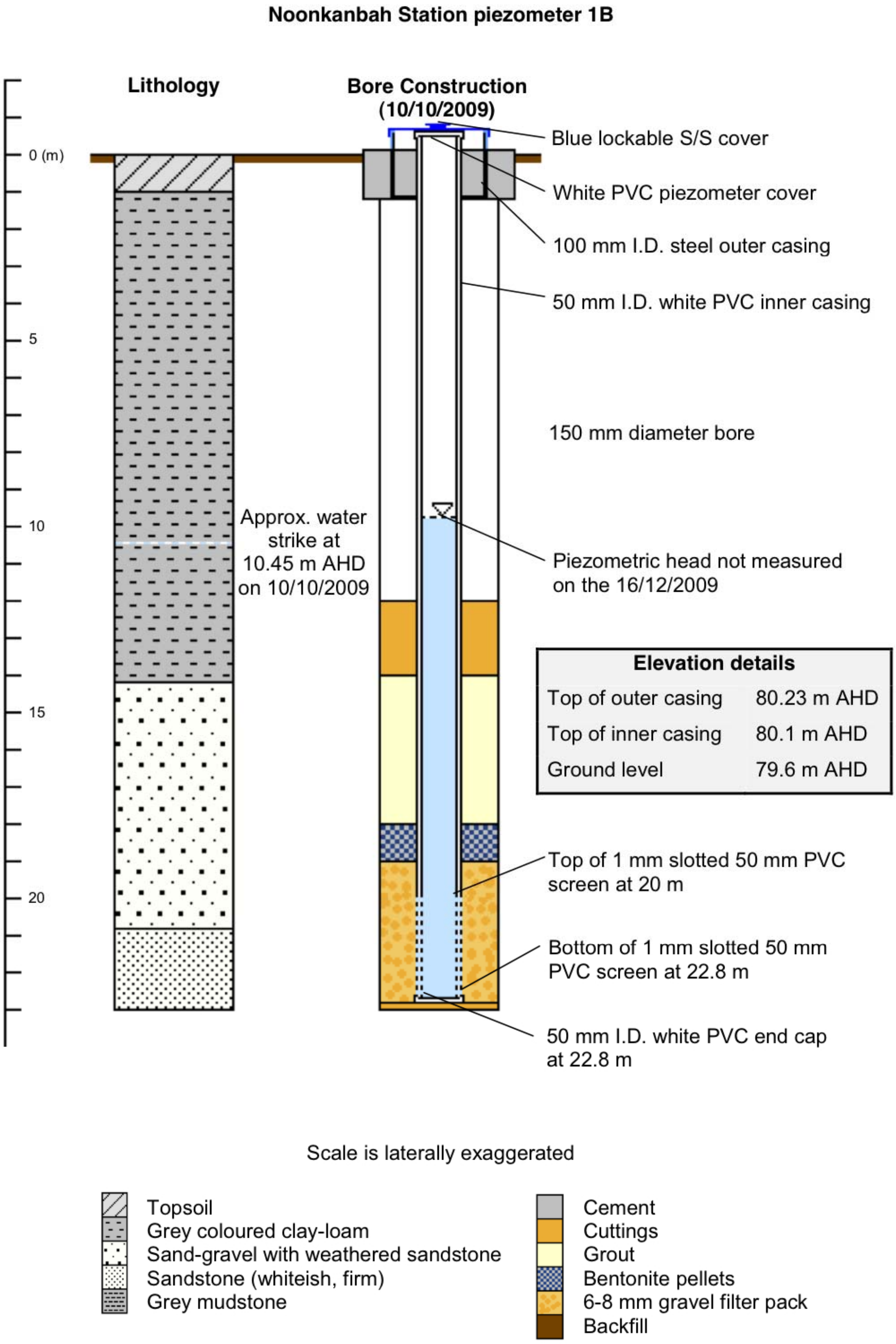
Group	Formation	Member	Unit
	Blina Shale		
Liveringa Group	Hardman Formation	Cherrabun Member	Unit D
		Hicks Range Member	Unit C
		Kirkby Range Member	Unit B
	Condren Sandstone		
	Lightjack Formation	Upper Lightjack	Unit A-2
		Middle Lightjack	Unit A-1
		Lower Lightjack	
	Noonkanbah Formation		

APPENDIX B – DRILLING LOGS FOR NOONKANBAH PIEZOMETERS, OCTOBER 2009

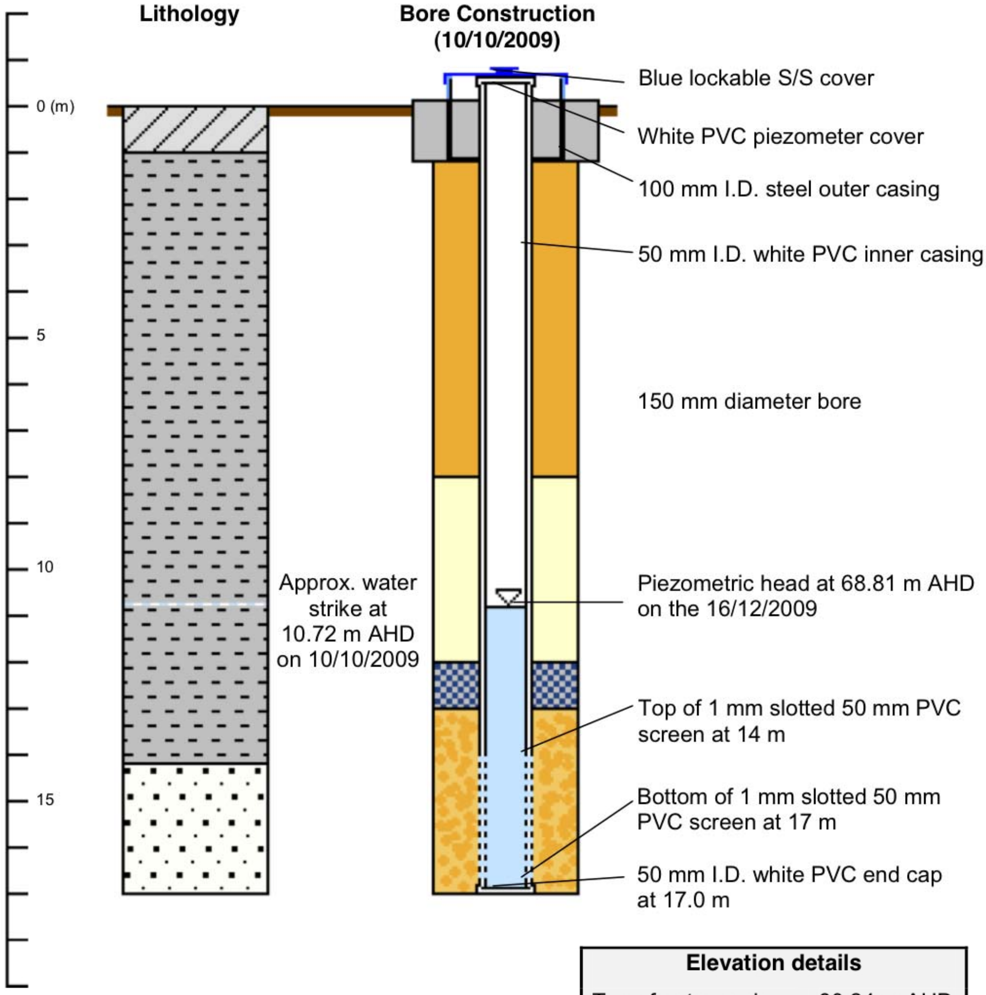
Noonkanbah Station piezometer 1A



Elevation details	
Top of outer casing	80.14 m AHD
Top of inner casing	80.02 m AHD
Ground level	79.59 m AHD

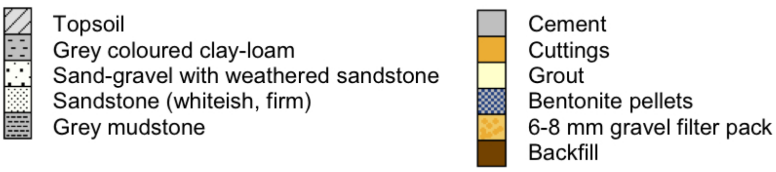

Noonkanbah Station piezometer 1B
Lithology
Bore Construction (10/10/2009)
0 (m)
5
10
15
20
Blue lockable S/S cover
White PVC piezometer cover
100 mm I.D. steel outer casing
50 mm I.D. white PVC inner casing
150 mm diameter bore
Approx. water strike at 10.45 m AHD on 10/10/2009
Piezometric head not measured on the 16/12/2009
Elevation details
Top of outer casing 80.23 m AHD
Top of inner casing 80.1 m AHD
Ground level 79.6 m AHD
Top of 1 mm slotted 50 mm PVC screen at 20 m
Bottom of 1 mm slotted 50 mm PVC screen at 22.8 m
50 mm I.D. white PVC end cap at 22.8 m
Scale is laterally exaggerated
Topsoil
Grey coloured clay-loam
Sand-gravel with weathered sandstone
Sandstone (whiteish, firm)
Grey mudstone
Cement
Cuttings
Grout
Bentonite pellets
6-8 mm gravel filter pack
Backfill

Noonkanbah Station piezometer 1C

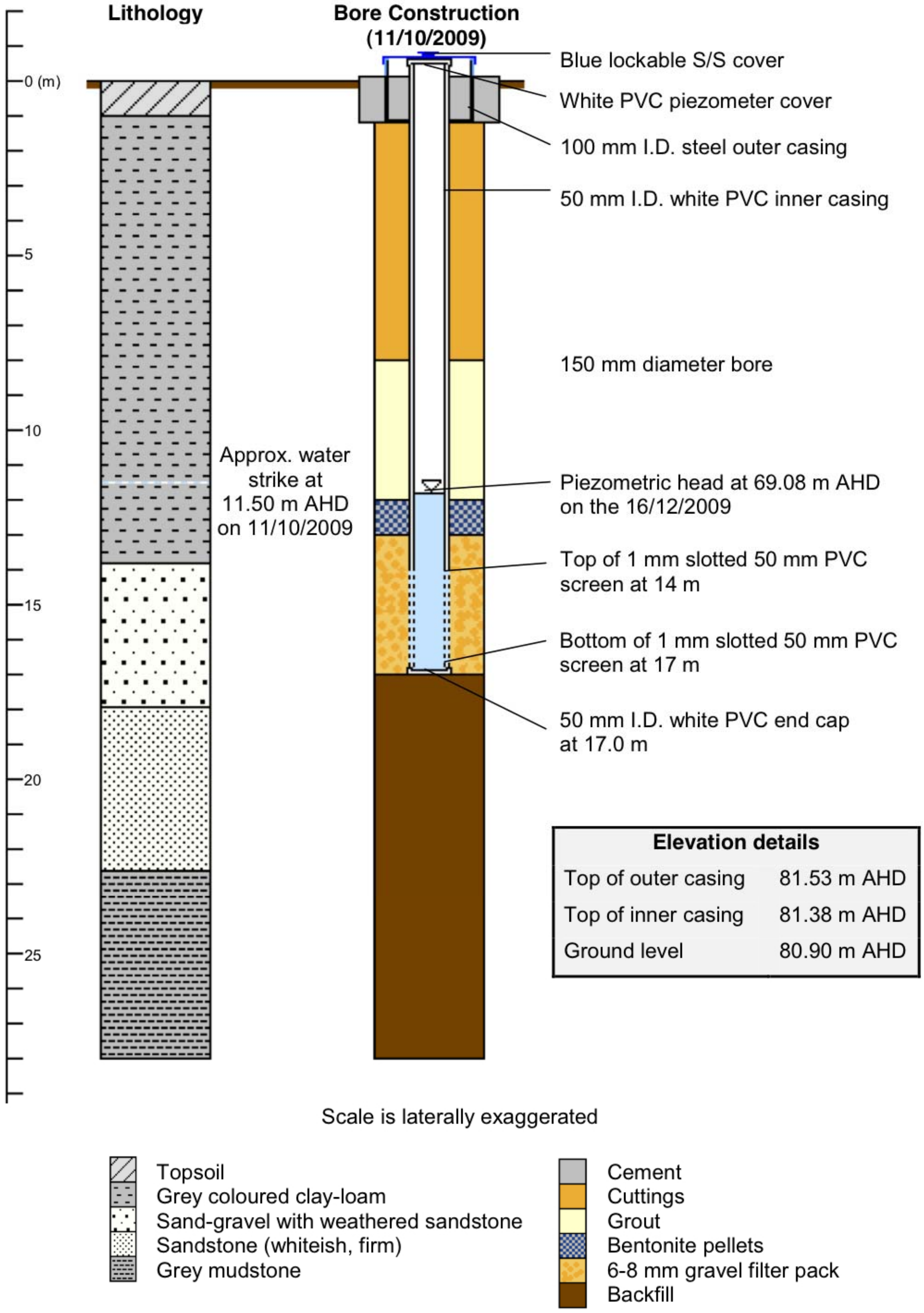


Elevation details	
Top of outer casing	80.24 m AHD
Top of inner casing	80.11 m AHD
Ground level	79.61 m AHD

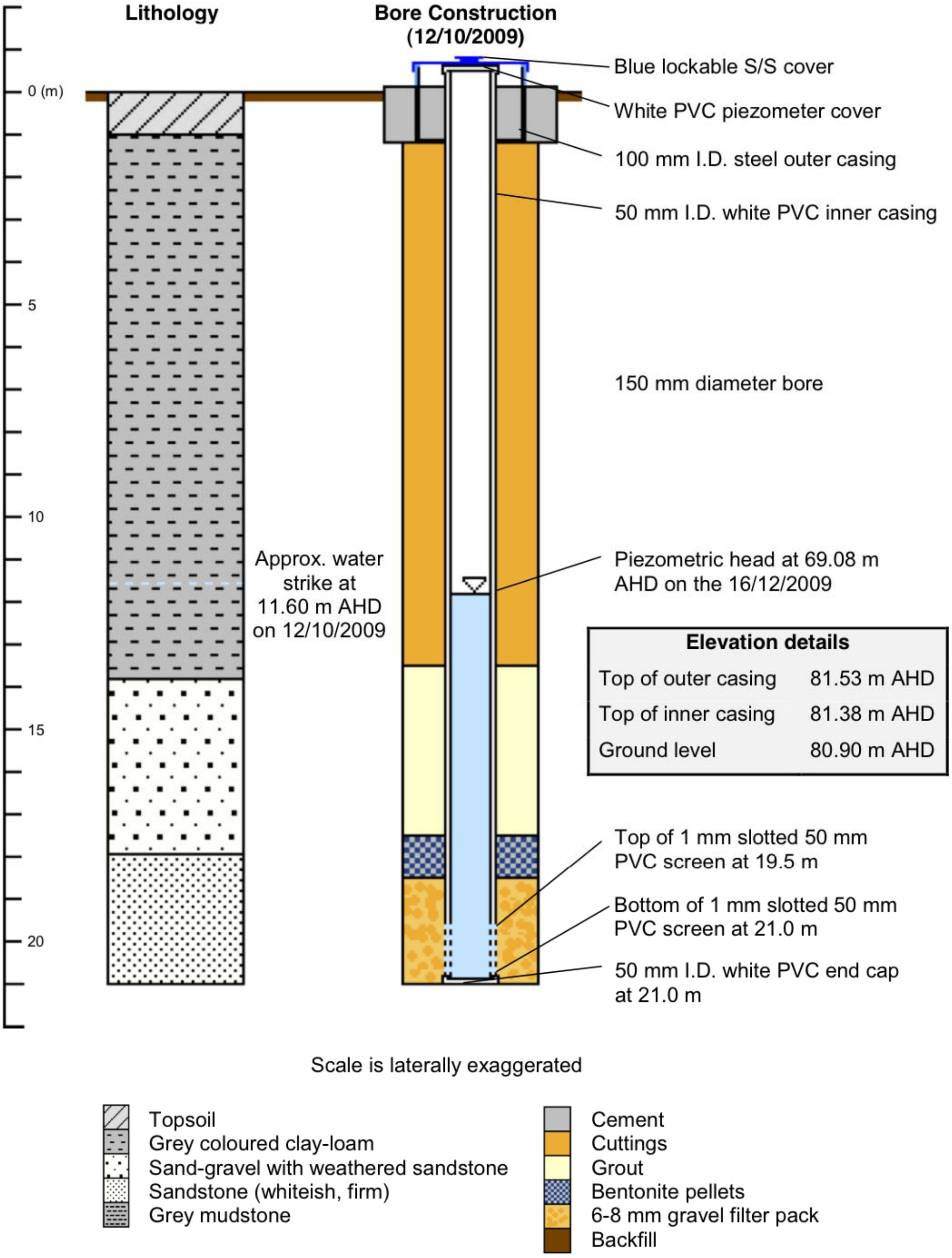
Scale is laterally exaggerated



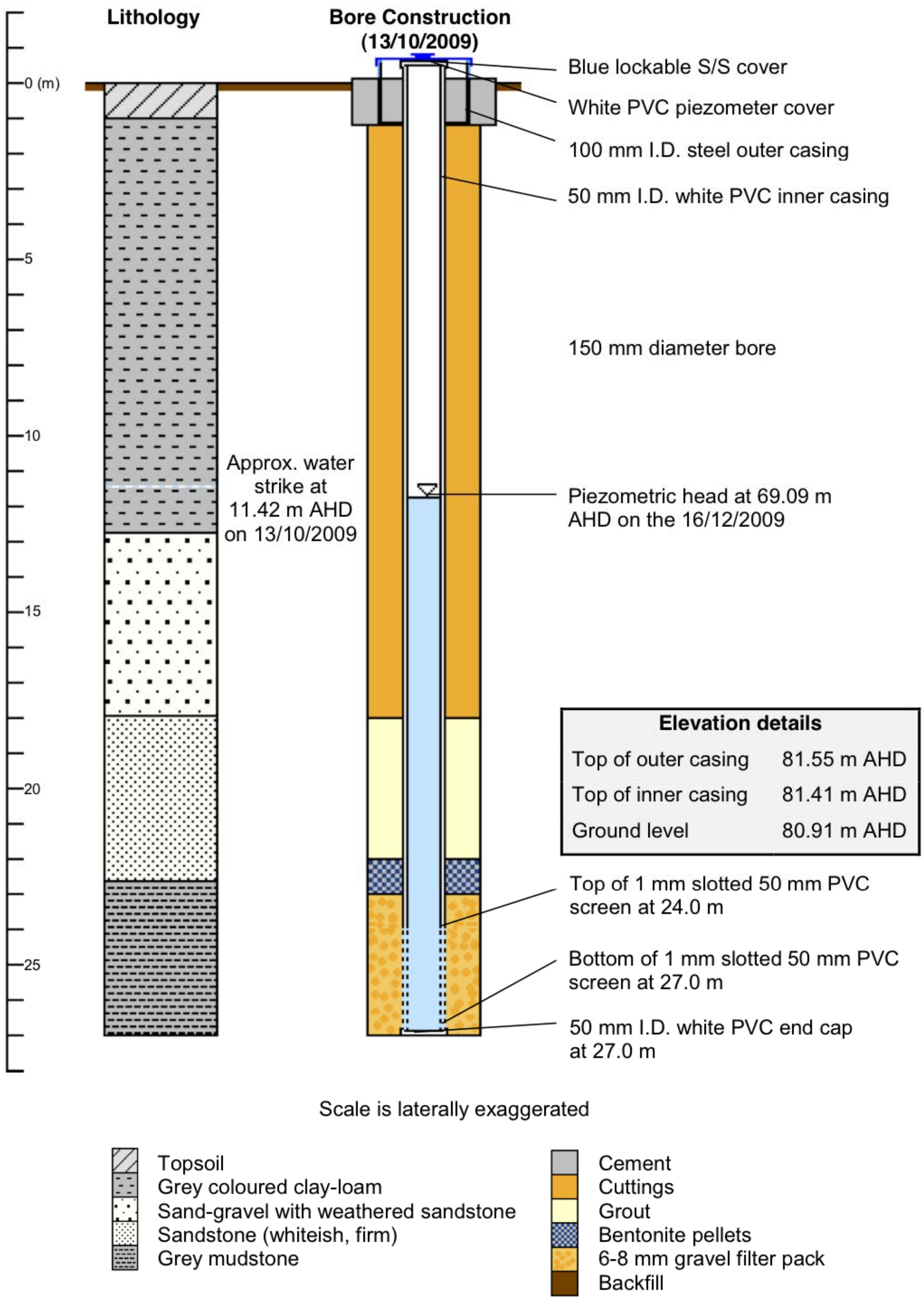
Noonkanbah Station piezometer 2A



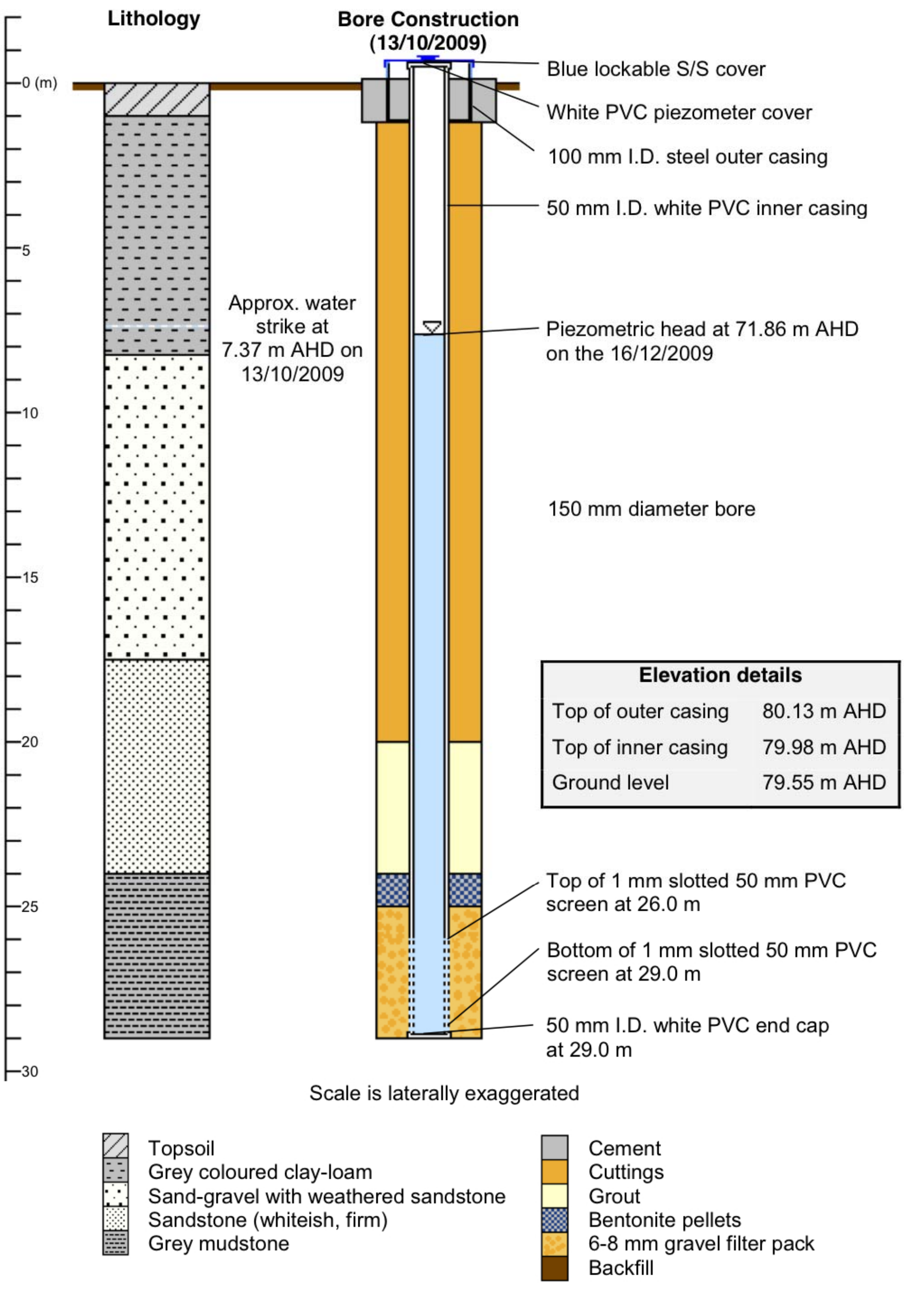
Noonkanbah Station piezometer 2B



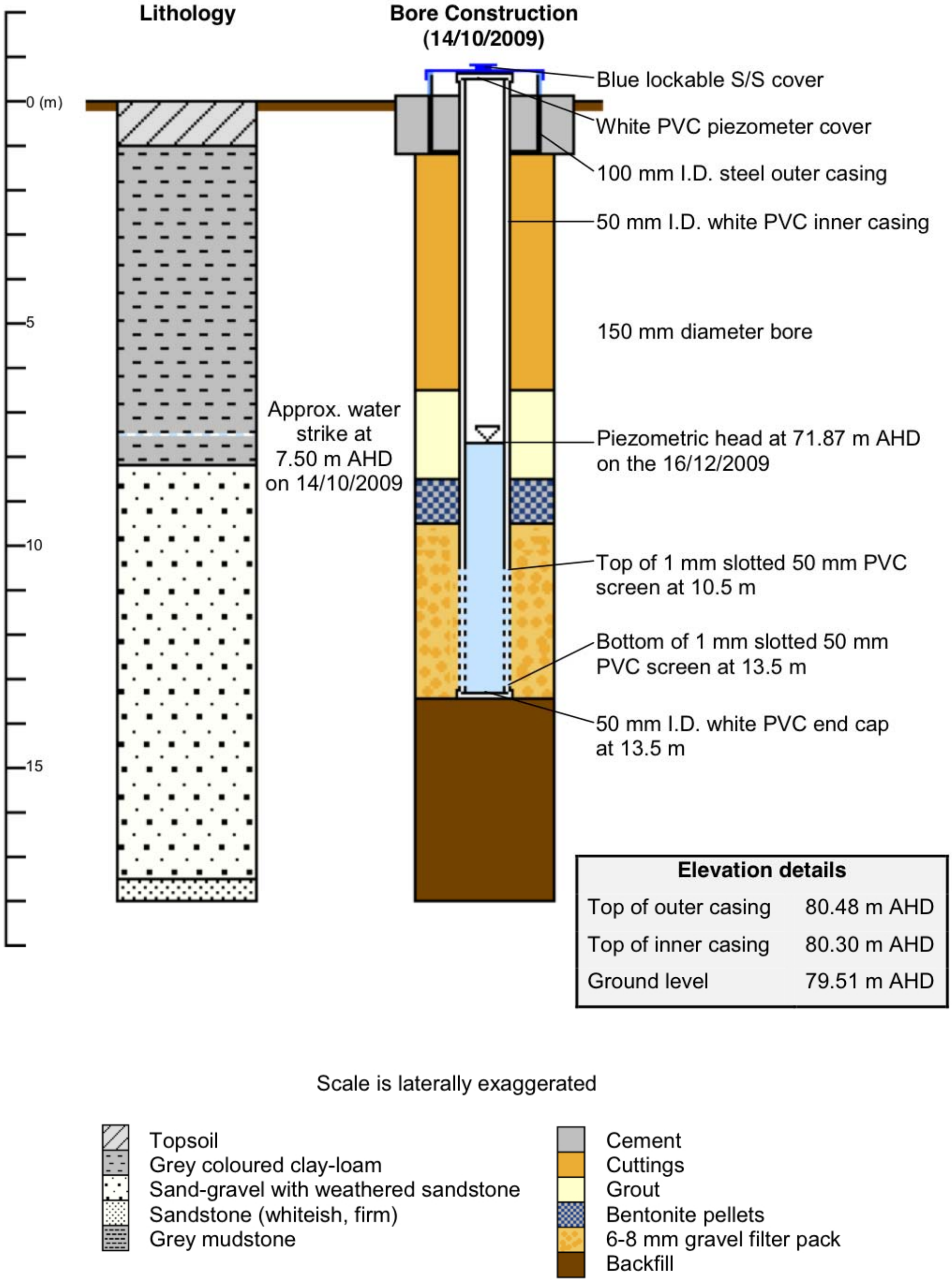
Noonkanbah Station piezometer 2C



Noonkanbah Station piezometer 3A

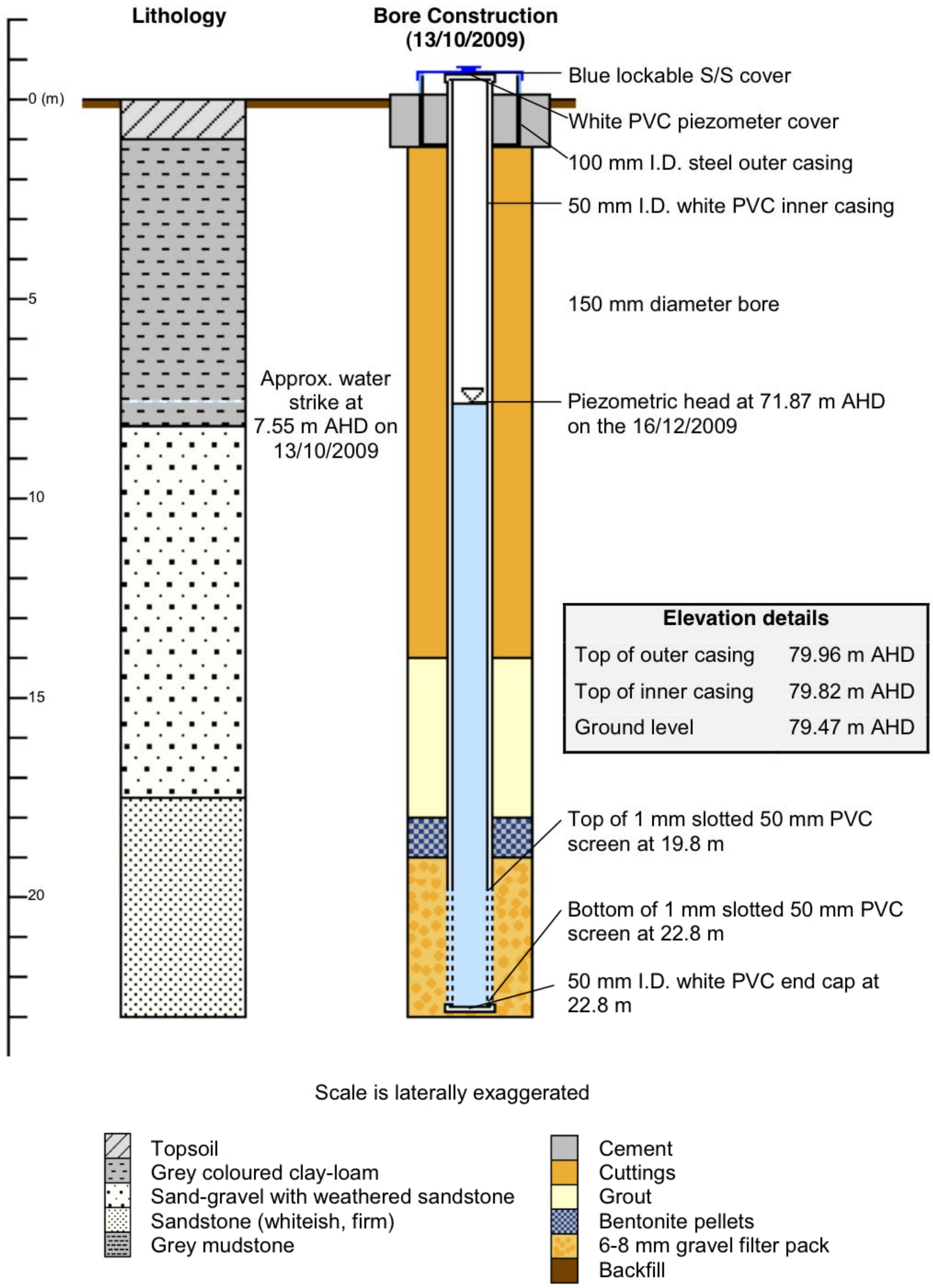


Noonkanbah Station piezometer 3B



Elevation details	
Top of outer casing	80.48 m AHD
Top of inner casing	80.30 m AHD
Ground level	79.51 m AHD

Noonkanbah Station piezometer 3C



APPENDIX C – CHEMICAL AND ISOTOPIC RESULTS FOR GROUNDWATER AND RIVER WATER SAMPLES

Location	Bore Name	Easting	Northing	Sample date	EC uS/cm	pH (field)	T °C	F(^{4}He)	δ^2H ‰ SMOW	δ^{18}O ‰ SMOW	δ^{13}C ‰ PDB	^{14}C pmC	^{87}Sr/^{86}Sr	^{222}Rn Bq/L	SF_6 year	CFC11 pg/kg	CFC12 pg/kg	CFC11 year	CFC12 year	pH (lab)	Total Alkalinity meq/L	F^- mg/L	Cl^- mg/L	Br^- mg/L	NO_3^- mg/L	$SO_4^=$ mg/L	Ca^{++} mg/L	K^+ mg/L	Mg^{++} mg/L	Na^+ mg/L	S mg/L	Si mg/L	Sr^{++} mg/L
GROUNDWATER SAMPLES																																	
Noonkanbah Piezo Transect	N1C	717147	7952470	6/11/09	1063	7.15	32.8		-58.6	-8.33	-14.4	95.87	0.731236			255	194	1988	NA	7.7	5.0	0.4	120	0.6	4.4	78	72.8	1.45	39.3	98.8	27.2	33.6	0.494
				5/05/10	994	7.02	32.3	1.2	-54.6	-8.38					2004.5	91	80	1973	1980	7.4	4.9	0.3	120	0.4	3.7	72	73	0.882	38.5	91.1	25.6	36.8	0.496
				4/10/10	1188		35							16.4																			
Noonkanbah Piezo Transect	N1A	717149	7952472	6/11/09	2930	7.43	32.8		-50.2	-7.09	-13.8	13.66	0.720911			10	49	<1965	1974	7.7	4.6	0.2	590	2.5	0.2	310	38.4	3.01	24.1	580	110	8.79	0.776
				5/05/10	2880	7.53	32.1	136.2	-49.3	-7.06					1999.5	<25	20	<1965	1966	7.6	4.6	0.2	610	2.4	2.9	300	39.2	3.26	23.2	583	106	8.95	0.817
				4/10/10	3720		34.8							23.5																			
Noonkanbah Piezo Transect	N2A	717155	7952585	6/11/09	949	7.31	32.3		-57.3	-8.55	-13.2	94.96	0.730431			271	180	1990	NA	7.6	4.3	0.3	110	0.6	1.8	72	59.6	1.35	31.9	96.2	24.7	34.7	0.474
				6/05/10	974	7.1	32.2	1.0	-56.8	-8.44					2004.0	96	95	1973	1983	7.5	4.9	0.2	110	0.4	3.3	68	69.7	1.02	37	93.9	24.3	38.4	0.537
				4/10/10	1073		34.6							21.6																			
Noonkanbah Piezo Transect	N2B	717152	7952586	6/11/09	975	7.1	32.5		-55.2	-8.46	-14.5	96.82	0.730822			91	99	1973	1984	7.7	4.5	0.2	120	0.6	3.5	72	65.9	1	36.2	92.3	25.2	36.8	0.533
				6/05/10	1009	7.01	32.3	1.2	-53.8	-8.21					1999.5	69	59	1971	1975	7.3	4.6	0.2	130	0.5	3.7	78	71.4	0.933	38.9	98.1	27.7	37.6	0.56
				4/10/10	1082		34.6							32.9																			
Noonkanbah Piezo Transect	N2C	717149	7952588	7/11/09	2570	7.27	32.4		-52.3	-7.46	-14.7	51.23	0.725788			62	73	1970	1979	7.7	4.1	0.2	490	2.1	1.1	280	72.6	2.15	43.2	379	93.9	15.9	0.846
				6/05/10	3210	7.17	32.7	1.3	-48.5	-7.14					1997.0	<25	21	<1965	1966	7.4	3.7	<0.2	710	2.7	1.9	380	87.8	2.95	51.8	538	130	13.4	1.08
				4/10/10	3730		35							59.1																			
Noonkanbah Piezo Transect	N3A			7/11/09	995	7.32	32.5		-40.2	-5.18	-12.3	82.451	0.728061			74.5	192	1972	NA	7.8	4.1	0.4	130	0.7	1.3	61	33.8	3.28	19.4	145	21	22.7	0.317
Noonkanbah Piezo Transect	N3B			7/11/09	612	7.2	32.7		-23.9	-2.06	-15.2	89.863	0.730162			108	105.5	1974	1986	7.6	3.3	0.4	60	0.5	0.7	30	36.4	2.95	10.9	76.5	10.2	23.3	0.143
Noonkanbah Piezo Transect	N3C			7/11/09	607	7.07	32.6		-38.4	-4.81	-13	89.228	0.729596			129.5	205	1976	NA	7.4	3.3	0.3	62	0.4	1.5	22	24.3	2.51	11.1	87.3	7.62	24.2	0.155
Noonkanbah Community	1_96	693117	7953296	6/05/10	888	7.45	51.4	1372.9	-51.1	-7.45	-12.3	2.113	0.720080							8.0	4.1	0.11	29	0.07	<0.05	1.5	3.42	3.57	0.642	201	2.07	10.9	0.0717
				4/10/10	1506		51							13.3																			
GoGo Station	San Miguel	775385	7960849	7/05/10	1272	7.94	32.3		-50.7	-7.57	-9.8	6.799	0.720177							8.1	3.7	0.4	210	0.9	0.5	110	16.7	5.6	10.1	245	37.1	7.33	0.864
Balginjirr Community	1_89	583916	8019400	8/05/10	1523	7.01	33.2	170.3	-46.4	-6.71	-8.4	6.998	0.722128		2007.5	contam	<20	contam	<1965	7.6	3.9	0.9	260	0.8	0.3	110	13.6	9.94	24.8	259	40.3	7.6	0.102
				5/10/10	1856		33.8							22.4																			
Mt Anderson Station	No. 5 Bore	588481	8015287	9/05/10	3550	7.8	33.2	322.1	-47.8	-7.11			0.720497		1975.0	<25	<20	<1965	<1965	8.2	12.2	1.0	670	1.7	0.4	98	9.98	4.65	9.76	773	33.9	7.08	0.387
				5/10/10	4190		33.2							2.9																			
Jarlmadangah Burr Community	unknown	606367	8008675	10/05/10	632	7.52	34.6	22.5	-47.2	-6.85	-11.9	24.694	0.722681		1971.5	97	<20	1973	<1965	8.0	3.4	0.54	43	0.17	<0.05	58	25.2	8.57	7.65	104	20.4	9.53	0.28
Mt Anderson Station	Global BG2/02-725	583584	8020013	11/05/10	8750	6.79	33.7	11.6	-39.8	-5.93	-13.4	26.334	0.723699		2007.5	<25	<20	<1965	<1965	7.3	2.7	0.8	2000	8.2	<0.5	1600	166	35.5	271	1360	527	5.85	2.29
				5/10/10	10670		32.8							17.9																			
GoGo Station	Big Moana	747723	7937575	13/05/10	1667	7.98	35.5	3094.1	-56.2	-8.03	-12.4	4.87	0.722773		1971.5					8.1	2.6	0.6	370	1.2	<0.2	78	14.5	3.78	1.04	320	26.9	7.35	0.722
GoGo Station	Panorama			13/05/10	5910			1.1	-44.4	-5.81	-9.4	42.28	0.719540							7.4	6.0	3.0	1000	6.0	11	1200	159	53.9	191	862	416	11	4.32
GoGo Station	Nicko1	792748	7974968	14/05/10	579	6.97	32.7		-44.2	-6.55	-9.0	87.454	0.719491		1993.5					7.5	4.9	0.06	8.4	<0.05	0.70	1.7	118	1.77	1.37	4.18	0.765	7.49	0.092
RIVER SAMPLES																																	
	Sample No.																																
Fitzroy River - waterfall	FR1			7/11/09	3450	8.38	35	1.23	-27.1	-2.12										8.0	3.3	0.2	840	3.2	0.4	360	82.8	1.39	78.5	506	117	17.8	0.952
Fitzroy River - Noonkanbah Xing	NC			9/11/09	1989	8.38	30.7		-21.3	-0.86										8.1	2.8	0.2	450	1.7	0.3	180	48.9	1.8	47.7	274	59.6	14.6	0.476
Fitzroy River	1	576426	8026250	11/05/10					-13.6	-1.51			0.720491	0.123						7.8	1.4	<0.2	11	0.8	<0.2	37	21.8	6.63	24.6	157	13.4	6.15	0.187
Fitzroy River	2	578204	8022107	11/05/10					-13.4	-1.59				0.108									10										
Fitzroy River	3	578884	8017934	11/05/10					-15.3	-1.47				0.134									10										
Fitzroy River	4	581261	8014222	11/05/10				1.01	-15.3	-1.77				0.116									10										
Fitzroy River	5	583928	8010025	11/05/10				1.01	-15.7	-1.53			0.735013	0.145						7.6	1.3	0.08	10	0.05	0.70	4.2	17	1.92	7.95	12.1	1.55	6.23	0.0852
Fitzroy River	6	587539	8006747	11/05/10				1.01	-16.0	-1.55				0.125									11										
Fitzroy River	7	591221	8004129	11/05/10				1.00	-16.0	-1.57				0.120									11										
Fitzroy River	8	594528	8000680	11/05/10				0.99	-14.6	-1.65				0.188									10										
Fitzroy River	9	599359	7999733	11/05/10				0.99	-15.4	-1.77				0.163									11										
Fitzroy River	10	602184	7996103	11/05/10				0.99	-16.1	-1.59				0.172									11										
Fitzroy River	11	671116	7960468	11/05/10				1.08	-19.1	-2.27			0.733990	0.212						7.7	1.5	0.09	40	0.15	<0.05	16	21.8	2.05	11	30.5	5.88	7.05	0.12
Fitzroy River	12	673995	7957925	11/05/10				1.04	-20.2	-2.37				0.205									40										
Fitzroy River	13	676520	7954608	11/05/10				1.03	-20.3	-2.38				0.178									39										
Fitzroy River	14	680324	7956117	11/05/10				1.03	-20.7	-2.48				0.090									40										
Fitzroy River	15	684947	7955332	11/05/10				1.03	-20.6	-2.53				0.152									53										
Fitzroy River	16	689445	7953339	11/05/10				1.05	-19.8	-2.60			0.733546	0.148						7.8	1.6	0.09	56	0.22	0.05	25	24.5	2.19	12.6	43.2	8.8	7.58	0.139
Fitzroy River	17	691573	7950956	11/05/10				1.06	-20.9	-2.51				0.188									59										
Fitzroy River	18	696080	7952148	11/05/10				1.00	-22.9	-2.56				0.127									67										
Fitzroy River	19	700670	7950278	11/05/10				1.24	-21.2	-2.67				0.136									75										
Fitzroy River	20	705141	7950289	11/05/10				1.18	-23.4	-2.67				0.118									80										
Fitzroy River	21	709723	7949870	11/05/10				1.06	-21.4	-2.76			0.732699	0.135						7.9	1.8	0.09	85	0.33	0.05	40	31.3	2.23	16.2	63.2	14.2	7.99	0.19
Fitzroy River	22	713819	7952019	11/05/10				1.03	-22.9	-2.84				0.143									93										
Fitzroy River	23	718628	7952192	11/05/10				1.03	-22.8	-2.76				0.164									97										
Fitzroy River	24	723517	7952516	11/05/10				1.08	-24.3	-3.01				0.385									101										
Fitzroy River	25	727942	7950477	11/05/10				1.11	-21.3	-2.71				0.347									81										
Fitzroy River	26	732138	7952431	11/05/10				1.06	-21.9	-2.80			0.733680	0.426						7.8	1.7	0.08	46	0.20	<0.05	20	27.9	2.26	13.1	33.9	7.25	7.18	0.153
Fitzroy River	27	736589	7951769	11/05/10				1.01	-22.9	-2.73				0.255									19										
Fitzroy River	28	739514	7953211	11/05/10				1.05	-19.5	-2.58				0.182									9.2										
Fitzroy River	29	743306	7951845	11/05/10				1.03	-18.9	-2.59				0.169									3.9										
Fitzroy River	30	746701	7954776	11/05/10				1.04	-19.9	-2.64			0.736866	0.140						7.9	2.5	0.08	3.9	<0.05	0.11	1.6	17.7	2.22	7.39	6.7	0.602	6.44	0.0817

APPENDIX D – RIVER MODELLING PARAMETERS

Parameter	Description	Value (Gardner et al. 2011)	Value (this report)	Units
E	evaporation rate	5	same	mm/day
k	gas exchange velocity ^{222}Rn ^{4}He	 1 2.5	 1 (0-40 km) 2 (40-100 km) 2.5 (0-40 km) 5 (40-100 km)	 m/day
w	river width	20	same	m
d	average depth	1	1 (0-40 km) 2 (40-100 km)	m
h	depth of hyporheic zone	1	0.1	m
θ	hyporheic porosity	0.4	same	[-]
τ_h	hyporheic residence time	0.25	1	days
γ	radon prod. rate hyporheic zone	0.2	same	Bq/L/d
c_i	groundwater concentration	25 (Rn) 150 (He)	variable	Bq/L $F(^{4}He)$
Q_o	initial river flow rate	2.5	1.2	m^3/day
C_o	initial river concentration ^{222}Rn ^{4}He Cl $^{87}Sr/^{86}Sr$ x [Sr]	 0.14 1.05	 0.09 1.05 3.9 0.06	 Bq/L $F(^{4}He)$ mg/L [-]

Contact Us

Phone: 1300 363 400
+61 3 9545 2176
Email: enquiries@csiro.au
Web: www.csiro.au

Your CSIRO

Australia is founding its future on science and innovation. Its national science agency, CSIRO, is a powerhouse of ideas, technologies and skills for building prosperity, growth, health and sustainability. It serves governments, industries, business and communities across the nation.