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A hydrochemical assessment of groundwater recharge and flow in the Broome Sandstone Aquifer, La Grange area, Western Australia

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Harrington, GA & Harrington, NM 2016, A hydrochemical assessment of groundwater recharge and flow in the Broome Sandstone Aquifer, La Grange Area, Western Australia, report to Department of Agriculture and Food, Western Australia, Innovative Groundwater Solutions, Middleton, South Australia.

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A hydrochemical assessment of groundwater recharge and flow in the Broome Sandstone Aquifer, La Grange Area, Western Australia



A report prepared for Department of Agriculture and Food WA

FINAL REPORT – REVISED

21 June 2016

A hydrochemical assessment of groundwater recharge and flow in the Broome Sandstone Aquifer, La Grange Area, Western Australia

A report prepared for

Department of Agriculture and Food Western Australia

by

Glenn A. Harrington and Nikki M. Harrington

June 2016

Acknowledgements

The authors are extremely appreciative of DAFWA for the opportunity to work collaboratively on this important project since its inception. Particular thanks to Richard George, Bob Paul and Nicholas Wright for the numerous thought-provoking discussions. Also thanks to Bob, Nicholas and Paul Raper for their diligent work drilling and sampling in the field. Glenn Harrington was the grateful recipient of a Visiting Scientist fellowship with DAFWA in 2014-15.

Suggested Citation

Harrington, G.A., and Harrington, N.M., (2016). A hydrochemical assessment of groundwater recharge and flow in the Broome Sandstone Aquifer, La Grange Area, Western Australia. A report prepared for Department of Agriculture and Food, Western Australia by Innovative Groundwater Solutions.

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The information in this report is considered to be accurate with respect to information provided and conditions encountered at the site at the time of investigation. IGS has used the methodology and sources of information outlined within this report and has made no independent verification of this information beyond the agreed scope of works. IGS assumes no responsibility for any inaccuracies or omissions. No indications were found during our investigations that the information provided to IGS was false.

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Executive Summary

The Department of Agriculture and Food Western Australia (DAFWA) has undertaken a four-year Royalties for Regions funded project in the La Grange Groundwater Area south of Broome. The purpose of the project was to provide improved knowledge and confidence about soil suitability and water availability for potential expansion of irrigated agriculture in the region. A range of complementary techniques have been used to assess the groundwater resources in the Broome Sandstone Aquifer, including both contemporary approaches such as drilling and aquifer pumping tests, and state-of-the-art approaches such as airborne geophysical surveys and hydrochemistry investigations.

This report presents a synthesis of all hydrochemistry data collected from approximately two-hundred existing and recently-drilled bores over three campaigns from 2013 to 2015. Major ion chemistry data, stable hydrogen and oxygen isotopes of the water molecule, chlorofluorocarbons and radiocarbon have all been used to address key knowledge gaps in the context of future irrigation development and water allocation planning.

Most groundwater in the Broome Sandstone aquifer is exceptionally good quality with salinity less than 500 mg/L as total dissolved salts. Major ion compositions are consistent with a source of solutes from aerosols in rainfall of marine origin, followed by minimal water-rock interaction including weathering of soil carbonates.

Stable hydrogen and oxygen isotope compositions of groundwater samples indicate that recharge to the aquifer only occurs after intense monsoonal rainfall events in the wet season. These results are similar to those obtained from previous and ongoing work in the West Canning Basin, the Dampier Peninsula, and the Fitzroy River catchment.

Three different environmental tracer based methods for estimating recharge rates have produced remarkably consistent results, despite differences in the spatial and temporal scales over which they apply. There are no apparent spatial trends in recharge rate, which indicates that recharge is driven by large episodic events associated with tropical cyclones rather than mean annual rainfall. The mean values of recharge rates for the three methods range from 16.3 mm/yr. using radiocarbon to less than 22.9 mm/yr. using chlorofluorocarbons. However for each method the mean values are biased towards one or two very high recharge rates, which are not representative for most of the study area. The median values of recharge rates from the three methods (11.6 to <16.5 mm/yr.) are therefore considered to reflect the areal and temporal distribution of recharge and be better suited to future aquifer assessment.

Residence times of groundwater flow in the Broome Sandstone range from 'modern' for shallow bores to more than 20,000 years for deep bores in down-gradient parts of the aquifer. These residence times correspond to flow path lengths ranging from only a few kilometres for groundwater in the shallowest bores, to more than 150 kilometres for groundwater in the deep bores near the coast.

CONTENTS

Executive Summary	v
1. Introduction	1
1.1. Background	1
1.2. Objectives.....	1
2. Methods	2
2.1. Field Sampling	2
2.1.1. Bore Inventory 2013	2
2.1.2. Isotope Reconnaissance Study 2014	2
2.1.3. Chemistry & Isotope Survey 2015.....	5
2.2. Laboratory Analysis	5
2.3. Geochemical Modelling.....	5
2.4. Carbon-14 dating	6
2.5. Recharge Modelling	7
2.5.1. Steady State Chloride Mass Balance	7
2.5.2. One-dimensional CFC Modelling	8
2.5.3. Two-dimensional Carbon-14 Modelling.....	10
3. Results.....	12
3.1. Major ion chemistry of groundwater.....	12
3.2. Geochemical modelling	15
3.3. Radiocarbon dating	16
3.4. Chlorofluorocarbons	19
3.5. Stable isotopes.....	21
3.6. Recharge modelling.....	23
3.6.1. Steady State Chloride Mass Balance	23
3.6.2. One-dimensional CFC-12 Modelling	26
3.6.3. Two-dimensional Carbon-14 Modelling.....	27
4. Discussion	30
4.1. Recharge rates	30
4.2. Relationship between rainfall and recharge	30
4.3. Groundwater flow and residence times.....	31
4.4. Sources of salinity in deep coastal bores.....	31
4.5. Comparison with previous isotope studies in the West Kimberley	35
5. Conclusions and Recommendations.....	36
6. References	37
7. APPENDIX A. Chemistry results from 2013 bore inventory sampling..	39

8. APPENDIX B. Chemistry results from 2014 isotope reconnaissance sampling.	43
9. APPENDIX C. Chemistry results from 2015 chemistry and isotope survey.	45

1. Introduction

1.1. Background

The Department of Agriculture and Food Western Australia (DAFWA) has recently completed a four-year Royalties for Regions funded project in the LaGrange Groundwater Area south of Broome. The purpose of the project was to provide improved knowledge and confidence about soil suitability and water availability for potential expansion of irrigated agriculture in the region. Groundwater in the Broome Sandstone Aquifer (BSA) was the target water resource, however before the project commenced little was known about the physical and chemical attributes of the aquifer (Paul et al., 2013).

Over the last four years, DAFWA have used a range of complementary techniques to assess the groundwater resources in terms of the opportunities and constraints for future development. These techniques have included both contemporary approaches such as drilling and aquifer pumping tests, and state-of-the-art approaches such as airborne geophysical surveys and hydrochemistry investigations.

Innovative Groundwater Solutions Pty Ltd. (IGS) has worked closely with DAFWA on the hydrochemistry component since the commencement of the project, including the provision of advice and assistance on sampling program design, tracer selection, bore construction, field sampling, and interpretation and modelling of results. Three different sampling campaigns were carried out during the project: a regional bore inventory in 2013, an isotope reconnaissance study in late 2014, and a comprehensive chemistry and isotope survey on predominantly new bores in late 2015. This report presents the results and interpretation for all three campaigns, focusing on their implications for understanding groundwater recharge and flow processes.

1.2. Objectives

The La Grange groundwater chemistry and isotope data sets were collected to provide insight into groundwater flows and aquifer dynamics, in particular to define groundwater recharge sources and mechanisms and to determine recharge rates, groundwater age and rate of movement.

The specific objectives of the hydrochemistry component of the project were to provide a better understanding of the La Grange groundwater system in terms of: recharge rates, recharge areas, recharge processes, groundwater flow paths, groundwater flow rates, and groundwater residence times.

2. Methods

2.1. Field Sampling

2.1.1. Bore Inventory 2013

All known and accessible Broome Sandstone bores in the study area were sampled by DAFWA in 2013 (Figure 1) (Paul et al., 2013). Where possible, water levels were measured and samples were taken either from windmills, equipped pumps or via the installation of a submersible pump. Samples were collected from 142 Broome Sandstone bores and three Wallal Sandstone bores for cation, metal, nutrient and anion analysis. Four surface water samples were also collected but are not discussed or interpreted in this report (see Appendix A for results).

2.1.2. Isotope Reconnaissance Study 2014

Eleven existing and accessible bores were selected across the LaGrange area (Figure 1), in order to test the suitability of selected environmental tracers for the project. The 11 bores were either equipped with pumps or had water tables shallow enough to permit pumping with a portable Grundfos® SQ 7-50 submersible pump. One spring sample was also collected during this campaign from a flowing section of Munro Springs (Figure 1).

Each bore was purged by DAFWA and IGS staff during October 2014. At least three times the volume of water in the casing was purged from each bore, and samples were only taken after field measurements of electrical conductivity (EC), pH and temperature at the discharge pipe remained stable. These measurements were made on a WTW® 340i hand-held meter, with probes calibrated to known standards daily. A Hach® digital titration kit was also used to measure alkalinity as CaCO₃ in the field.

Groundwater samples were collected in separate 250 mL plastic bottles for cations and metals (0.45 µm filtered and acidified) and anions (not filtered or acidified). Samples were also collected for stable H/O isotope analysis in 2 mL glass vials, and for carbon isotope analysis in 1 L plastic bottles. All samples were filled directly from the pump discharge pipe, minimizing the opportunity for exposure to the atmosphere, and subsequently refrigerated for transportation to laboratories.

Rainfall samples were collected from DAFWA's existing network of rainfall gauging stations. Each of these stations have been equipped with bulk rainfall collection drums that contain a film of paraffin oil to prevent loss of moisture – and thus isotopic fractionation – by evaporation. Rainfall samples from October 2014 and other samples collected from the same sites earlier in the year were shipped, together with groundwater samples, for stable H/O isotope analysis.

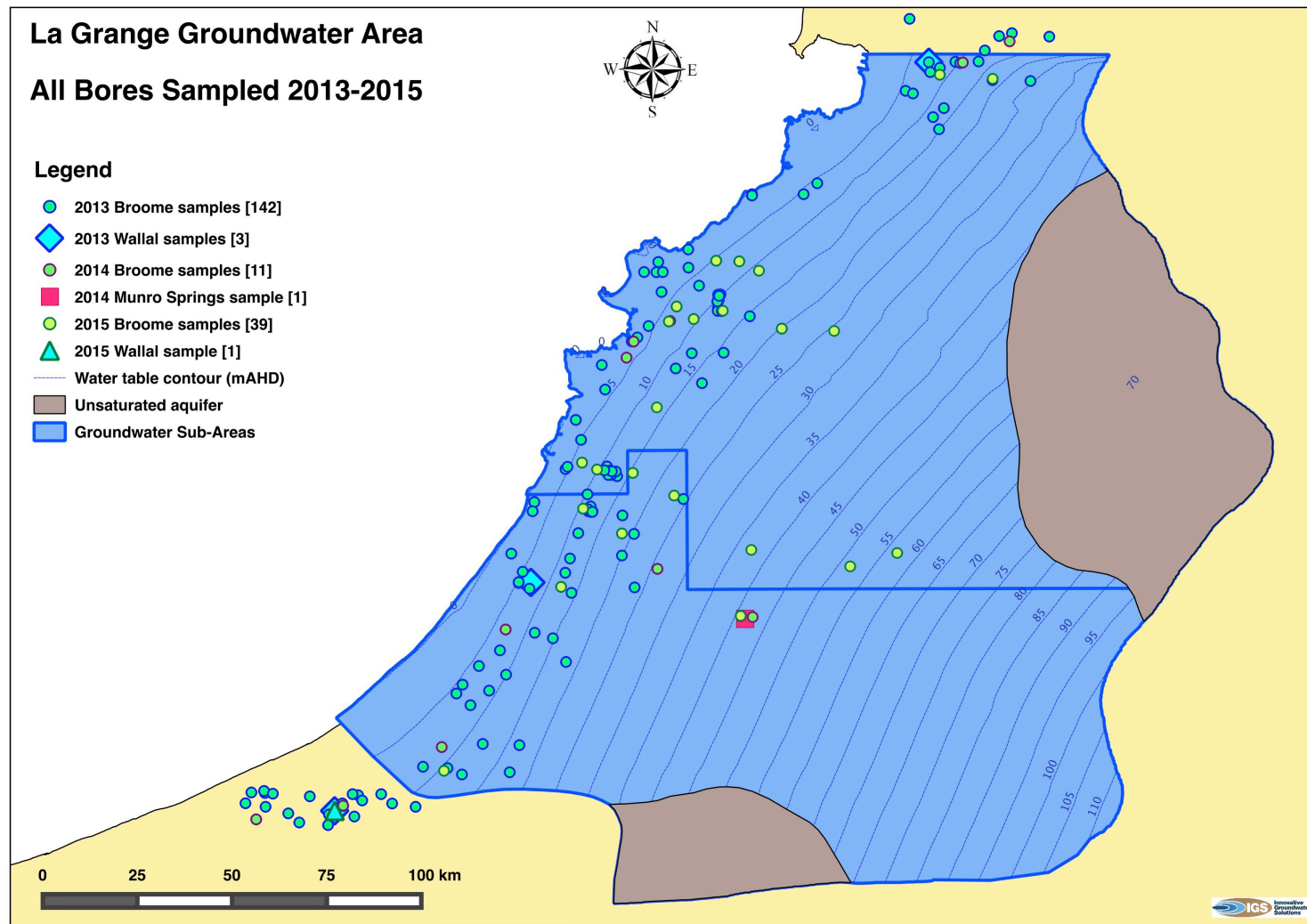


Figure 1. Map showing the distribution of Broome Sandstone and Wallal Sandstone bores sampled during the three campaigns in 2013, 2014 and 2015.

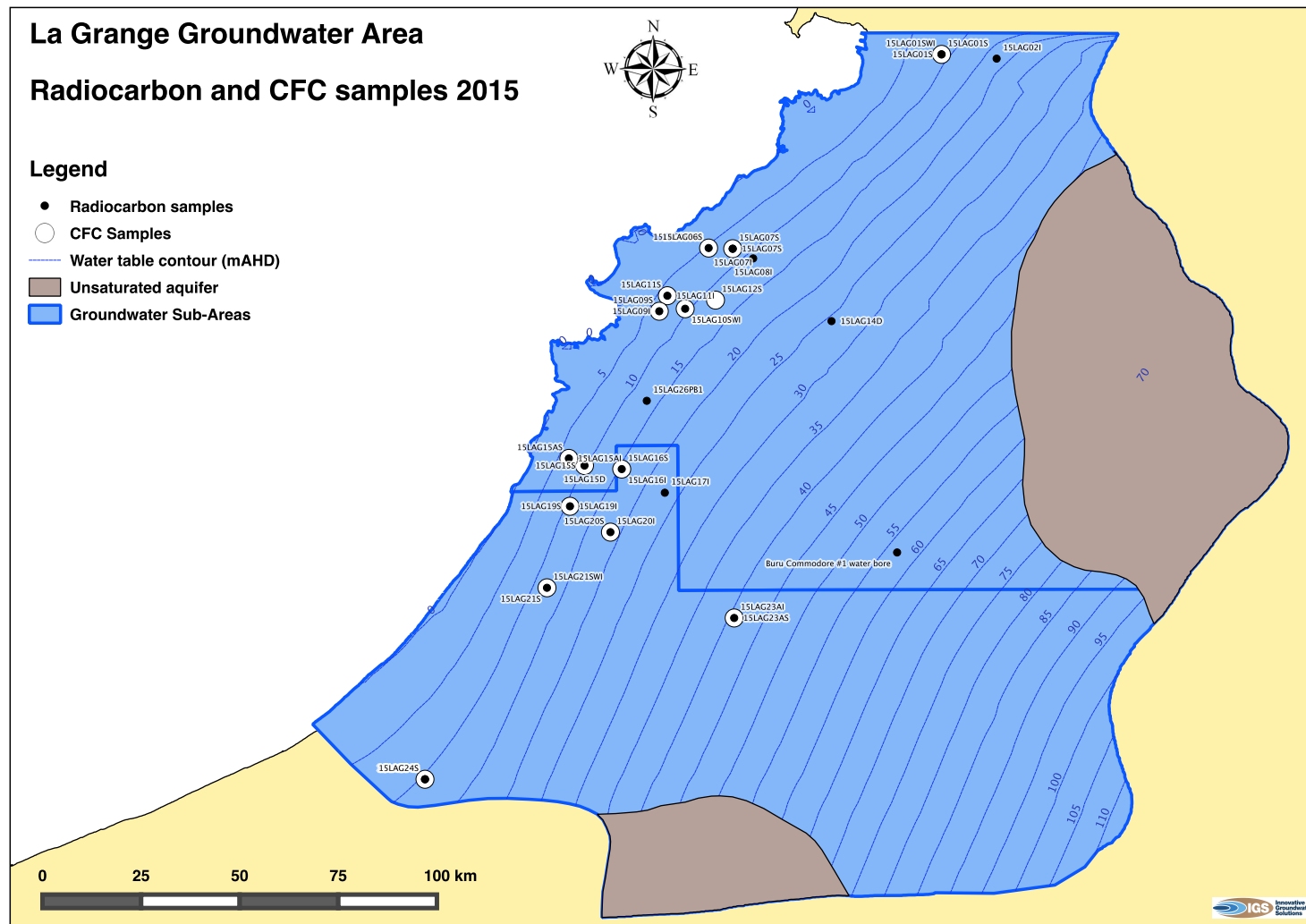


Figure 2. Map showing locations of Broome Sandstone bores used for analysis of groundwater recharge rates and residence times using radiocarbon or chlorofluorocarbons.

2.1.3. Chemistry & Isotope Survey 2015

The most meaningful hydrochemistry sampling was undertaken by DAFWA in November 2015, focusing on the purpose-built monitoring bores that had been installed as part of the project earlier in the year (Paul et al., 2016). A total of 39 Broome Sandstone bores were sampled, including five older bores that existed prior to the project, and one Wallal Sandstone bore was sampled (Figure 1). Bore purging and field measurements were consistent with the methods used in 2014. Water samples were collected for the same suite of tracers except that only 27 bores were sampled for carbon isotope analysis (i.e., 26 Broome Sandstone bores and one Wallal Sandstone bore). Unfortunately the construction details for three of the older Broome Sandstone bores that were sampled for carbon isotopes are either unknown or not suitable for detailed analysis of long-term average groundwater recharge rates; the remaining 23 bores that were suitable for detailed analysis are shown in Figure 2. This figure also shows the locations of 15 shallow, purpose-built monitoring bores that were sampled for chlorofluorocarbons (CFCs) using triplicate glass bottles submerged in a stainless steel bucket. Bulk rainfall samples were also collected during this campaign for major ion chemistry and stable H/O isotope analysis.

2.2. Laboratory Analysis

The 2013 and 2015 water samples for major ion and nutrient analyses were sent to the ChemCentre in Perth for determination by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICPAES) for cations and metals, and colorimetric reaction for anions. The 2014 water samples for chemistry analysis were sent to CSIRO Analytical Services Unit (Adelaide) for determination by ICP (cations and metals) and Ion Chromatography (anions).

Both the 2014 and 2015 groundwater and rainfall samples for stable hydrogen ($^2\text{H}/^1\text{H}$) and oxygen ($^{18}\text{O}/^{16}\text{O}$) isotopes of water were sent to University of California (Davis, USA) for analysis by laser methods.

Likewise, the 2014 and 2015 groundwater and spring samples for radiocarbon (^{14}C) and stable carbon isotope ($^{13}\text{C}/^{12}\text{C}$) analysis were sent to Rafter Radiocarbon Laboratory (Lower Hutt, NZ) for measurement by Accelerator Mass Spectrometry (AMS).

CFC samples collected in 2015 were sent to the CSIRO Isotope Analysis Service (Adelaide) for analysis by gas chromatography and an electron detector.

2.3. Geochemical Modelling

The geochemical modelling software PHREEQC (Parkhurst and Appelo, 2013) was used to facilitate interpretation of the major ion chemistry data. This was particularly necessary to enable the determination of speciation for dissolved inorganic carbon (DIC), which is required for correcting radiocarbon ages (see next section). PHREEQC

also provides saturation indices for some of the minerals that commonly contribute to groundwater chemistry via water-rock interactions (i.e., calcite weathering and gypsum dissolution).

2.4. Carbon-14 dating

Carbon-14 is arguably the most useful environmental tracer for estimating the 'apparent age' or 'residence time' of groundwater up to about 30,000 years. Dissolved inorganic carbon (DIC) in groundwater is sourced primarily from dissolution of soil CO₂ gas and weathering of carbonate minerals. The principle of using ¹⁴C to date groundwater is that if the initial ¹⁴C activity (*A*₀) of DIC can be estimated, the age (*t*) of the water sample can be calculated as follows:

$$A = A_0 e^{-\lambda t} \quad \text{[EQUATION 1]}$$

where *A* is measured ¹⁴C activity in percent modern carbon (pMC), and λ is the radioactive decay constant for ¹⁴C ($1.209 \times 10^{-4} \text{ yr}^{-1}$). Estimating the initial ¹⁴C activity (*A*₀) is complicated by the addition ¹⁴C-free DIC due to weathering of carbonate minerals or oxidation of old organic matter.

Numerous correction schemes have been developed over the last five decades for estimating the value of *A*₀ for groundwater samples. The most commonly used models involve either a chemical mass balance (Tamers, 1967), a carbon-13 isotope mass balance (Ingerson and Pearson, 1964), a combined chemical and isotope mass balance that accounts for isotope exchange with either the gas phase or solid phase (Fontes and Garnier, 1979), and a similar model that considers isotope exchange with all phases (Mook, 1980).

For this project, there is no justification to exclude any of the models so all four were applied to explore the range of possible groundwater ages. Three of these models require input of dissolved carbon dioxide (CO₂) and bicarbonate (HCO₃⁻) concentrations, which were determined for each groundwater sample using the speciation functionality of PHREEQC (Parkhurst and Appelo, 2013).

The models also require an estimate of the δ¹³C composition and ¹⁴C activity of soil CO₂ gas and carbonate minerals. For soil CO₂ gas, values of -15‰ and 100 pMC were assumed based on knowledge of the predominance of C₄ plants (i.e., grasses including spinifex) in the region. While the Broome Sandstone is considered to be devoid of marine carbonates (i.e., 0‰ and 0 pMC) recent soil cores collected by DAFWA as part of this project have found several areas of pedogenic carbonates, mostly associated with a 'Gravelly Pindan over Limestone' classification (pers. comm. H. Smolinski, DAFWA, April 2016). Accordingly, values of -5‰ and 0 pMC were assumed for the carbonate weathering "end-member" in the correction models.

2.5. Recharge Modelling

2.5.1. Steady State Chloride Mass Balance

The steady state groundwater chloride mass balance (CMB) method is widely regarded as one of the most reliable tools for estimating net groundwater recharge, particularly in arid and semi-arid areas where recharge rates are low. The principle of the method is that chloride flux at the land surface, including marine aerosols in rainfall and dry deposition, is in equilibrium with the chloride flux entering the water table. Hence, key assumptions behind the method are that (a) the hydrology is in steady state, which is generally valid providing there hasn't been a change in land use, (b) surface runoff is negligible or can be reliably estimated, and (c) there is no additional source of chloride, such as halite dissolution. Proving these assumptions can be justified, the mean annual net recharge rate (R) can be estimated via the following:

$$R = \frac{PC_P}{C_{gw}} \quad [\text{EQUATION 2}]$$

where P is mean annual precipitation (mm/yr), C_P is chloride concentration in precipitation (mg/L), and C_{gw} is chloride concentration in groundwater (mg/L). Alternatively,

$$R = \frac{D}{C_{gw}} \quad [\text{EQUATION 3}]$$

where D is total chloride deposition, and usually expressed in units of kg/ha/yr.

Importantly, recharge rates estimated using the CMB method apply to the point in the landscape where the water sample travelled through the unsaturated zone and first entered the water table, which can be a significant distance up-gradient of the bore.

Numerous studies have measured chloride concentrations in rainfall and dry fallout across the Australian continent (e.g., Blackburn and McLeod, 1983; Keywood et al., 1997). Recently Crosbie et al. (2012) reported amount-weighted mean chloride concentrations for rainfall collected monthly between May 2007 and December 2011. Although they did not have any rainfall stations in the LaGrange area, the values they determined for Learmonth (9.94 mg/L) and Halls Creek (0.46 mg/L) provide useful guidance on what are realistic upper and lower bounds for this study.

Arguably the most relevant rainfall chemistry dataset for the LaGrange area is that reported by Hingston and Gailitis (1976). By measuring ionic concentrations in monthly rainfall samples during 1973, they derived mean annual chloride concentrations of between about 1.5 and 4 mg/L for sites in north-west Western Australia, including Broome and Nita Downs Station. Hingston and Gailitis (1976) also note that a large storm in Broome during January 1974 had a higher than normal chloride concentration of 6.8 mg/L. Therefore, an average value of approximately

5 mg/L is considered appropriate for this region, and should be compared with measurements of chloride in rainfall samples collected in this project (section 3.7).

Chloride deposition varies spatially across the study area, primarily as a decreasing trend with increasing distance inland from the coast. This trend has been mapped by Leaney et al. (2011) for the entire continent, using empirical formulae derived originally by Keywood et al. (1997) (Figure 3). This map suggests chloride deposition over most of the LaGrange area is in the range 3.5 – 13.2 kg/ha/yr., although Hingston and Gailitis (1976) suggest a value closer to 14 kg/ha/yr. is representative of near coastal areas in the Kimberley.

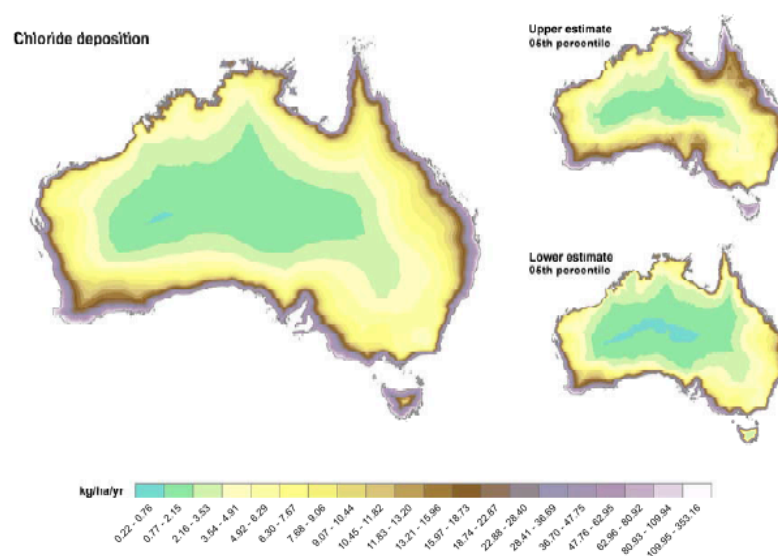


Figure 3. Modeled surface of mean atmospheric chloride deposition and upper and lower 95th percentiles (from Leaney et al., 2011).

In this report, mean annual recharge to the Broome Sandstone aquifer is calculated using the first form of the CMB method (Equation 2) as the measured rainfall chloride data from Hingston and Gailitis (1976) and this project is considered more reliable than the modelled surface presented above.

Mean annual rainfall is highly variable in the LaGrange area, ranging from 370 to 605 mm/yr. for the four Bureau of Meteorology stations between Mandora and Broome Airport (Paul et al., 2013). The average for these four stations is 473 mm/yr. and this report adopts a consistent value of 450 mm/yr. for recharge modelling purposes.

2.5.2. One-dimensional CFC Modelling

The interpretation of measured CFC concentrations in groundwater samples requires a comparison with 'expected' concentrations for an assumed (a) set of physical conditions at the time of recharge (i.e., temperature, elevation and salinity, as they

control CFC solubility in water), and (b) conceptual model of groundwater flow and mixing processes. While the solubility can be easily calculated using Henry's Law, the simulation of expected concentrations for different mixing processes can be complex. Fortunately, numerous solutions exist that enable rapid calculation of mean residence times for different idealized 'Lumped Parameter Models' (e.g., see Jurgens et al. 2012). The most commonly adopted models include the Piston Flow Model (PFM), Exponential Mixing Model (EMM) and Binary Mixing Model (BMM) and it is important to consider which model is appropriate for each project or application.

In this report, the PFM and EMM have been selected as being the most appropriate. The PFM assumes a tracer travels from the recharge area to the bore without mixing in the aquifer. It is most applicable for shallow, short- screened bores in unconfined aquifers. The EMM on the other hand is applicable for all depths in homogeneous, unconfined aquifers of uniform thickness and recharge (Figure 4). This model can be appropriate for fully penetrating bores, however it assumes that mixing occurs within the bore rather than in the aquifer by dispersion.

Once a CFC concentration has been converted to an apparent age or 'mean residence time' (t) the recharge rate can be estimated using a simple approximation of 1-D vertical flow:

$$R = \frac{z\theta}{t} \quad \text{[EQUATION 4]}$$

where z is the depth of the mid-point of the screen/slotted interval of the bore below water table [m], and θ is aquifer porosity. The assumption of 1-D vertical flow is valid provided the depth of each groundwater CFC sample is shallow compared to the total thickness of the aquifer (Cook and Böhlke, 2000).

Recharge rates estimated using this approach are directly proportional to porosity (θ) and the depth (z) of the production zone of the bore below the water table (Equation 4). A consistent porosity of 30% has been assumed for this study; if the uncertainty around this value is $\pm 33\%$ (i.e., $\theta = 20\text{-}40\%$) then the resulting recharge rates will have the same error.

The mid-point of the screen or slotted interval is generally adopted for z , and the error in recharge rate can be expressed by considering the full range of possible depths in the screen from which the sample was obtained. Smaller errors in recharge rate are achieved for groundwater samples collected from bores with shorter screen intervals. Hence all shallow, purpose built bores used for CFC sampling in this study had a total screen length of three metres. The average depth to the mid-point of the screen was six metres below water table ($n = 15$ bores); this means the average range in possible sample depths was 4.5 – 7.5 m and the average error in recharge rate is $\pm 25\%$.

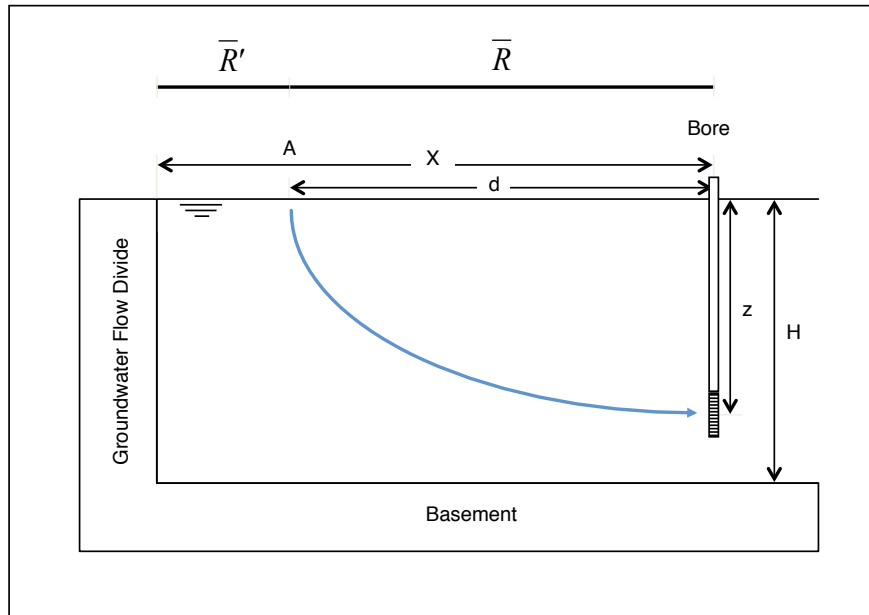


Figure 4. Vogel's (1967) 'exponential model' for an unconfined aquifer of uniform thickness (after Harrington et al., 2002)

2.5.3. Two-dimensional Carbon-14 Modelling

The CFC method for estimating recharge rates (outlined above) can only be applied where CFC concentrations are measurable, and therefore is limited to the shallowest parts of the aquifer. In order to obtain recharge estimates for deeper groundwaters, and therefore a more regional average, it is necessary to use the carbon-14 ages after correcting for addition of 'dead' carbon (see section 2.4).

Because the groundwater samples for carbon-14 dating generally come from all depths within the aquifer, the simple 1-D assumption of vertical flow (Equation 4) is not appropriate. Instead it is necessary to use a 2-D analytical solution that acknowledges the geometry of the aquifer. Vogel (1967) presents such a solution for a classical 'exponential model' of an unconfined aquifer receiving uniform recharge (Figure 4). Using this simplified geometry, Vogel (1967) derived the following expression for groundwater age (t), which can be rearranged to obtain an average recharge rate (\bar{R}) if the age can be estimated from alternative means:

$$t = \frac{H\theta}{\bar{R}} \ln \left(\frac{H}{H-z} \right) \quad [\text{EQUATION 5}]$$

Harrington et al. (2002) recognised that the recharge rate (\bar{R}) that comes from using this methods is an areal average that applies over the full distance (d) between the point in the landscape where the sample first entered the water table (point A in Figure 4) and the bore where the sample was collected. This differs from recharge rates estimated using the CMB method, which only apply to point A up-gradient of the bore.

Furthermore, Harrington et al. (2002) used the geometry of the simplified model presented in Figure 4 to derive an expression for estimating the distance (d):

$$d = \frac{zX\bar{R}'}{\bar{R}(H-z)+z\bar{R}'} \quad [\text{EQUATION 6}]$$

If the average recharge rates up-gradient and down-gradient of the point in the landscape where the sample first entered the water table are equal (i.e., $\bar{R} = \bar{R}'$) then Equation 6 simplifies to:

$$d = \frac{zX}{\bar{R}} \quad [\text{EQUATION 7}]$$

In this report, Equation 5 is used to estimate areal average recharge rates with corrected carbon-14 ages for groundwater samples collected in 2015, and Equation 7 is then used to estimate the distance over which this recharge rate applies up-gradient of each bore.

3. Results

3.1. Major ion chemistry of groundwater

The field chemistry and laboratory analytical results from the 2013, 2014 and 2015 sampling campaigns are presented in tabular form in Appendix A, B and C respectively. All of this data has been summarised in Figure 5 to show the range of hydrochemical compositions for the groundwater samples. Groundwater in the Broome Sandstone has a cation composition ranging from Na-Ca to Na type with increasing salinity. Similarly, anion composition ranges from Cl-HCO₃ to Cl type with increasing salinity. By comparison, the two Wallal Sandstone groundwater samples are more Cl dominated for the anions, and Na-Ca type for the cations.

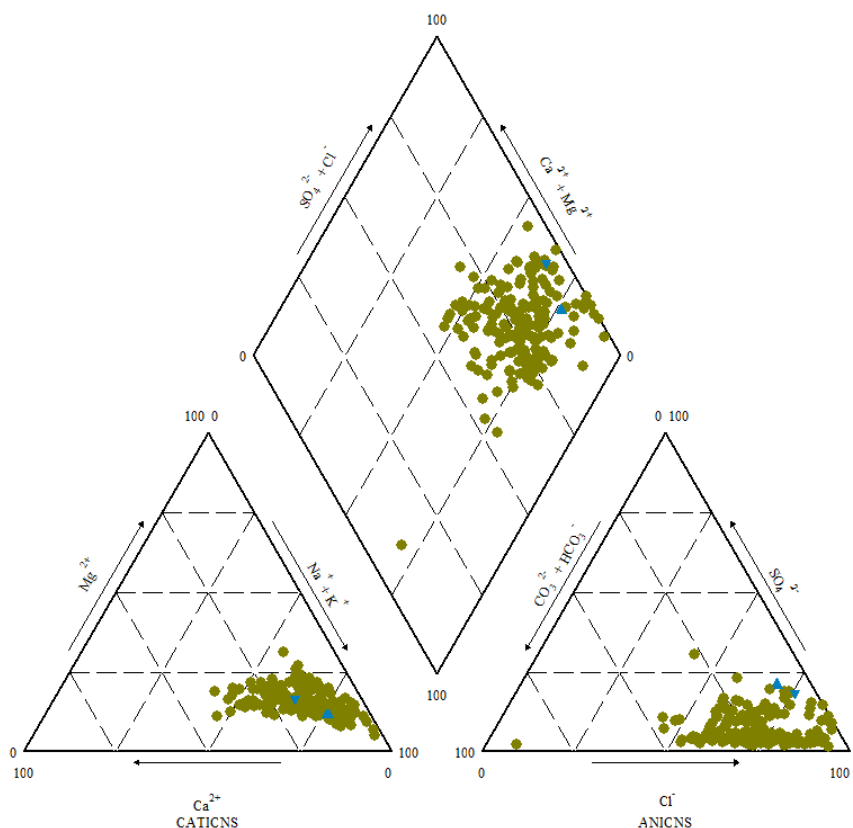


Figure 5. Piper diagram showing major ion composition for all groundwater samples collected during the project (2013-2015). Green circles represent the Broome Sandstone aquifer, blue triangle is the Wallal aquifer at bore MRD025, and inverted blue triangle is the Wallal aquifer at bore Talgarno #1.

Plots of major ion concentration relative to chloride concentration are often used to investigate trends in hydrochemical data. The key benefit of using this approach – rather than plotting major ion concentrations alone – is that it normalizes the ion concentration by accounting for evaporative effects. For example, an evaporating body of water containing salts of marine origin will evolve chemically as a horizontal line in plots such as those shown in Figure 6. Deviations away from this line will only occur

when additional processes, such as water-rock interaction or mixing with different waters, become important.

The plots shown in Figure 6 for groundwater samples from the Broome Sandstone reveal that, on average, Na concentrations are consistent with evaporation of rainwater containing marine aerosols, although about half of samples are enriched in Na and about half are depleted. All samples are highly enriched in Ca and HCO_3 relative to marine aerosols indicating an alternative source of these ions, which is most likely calcite weathering. This process can occur in either the unsaturated or saturated zones, and has important implications for interpreting radiocarbon data (section 2.4).

Cl/Br ratios are consistent with the range expected for marine aerosols and soil organic processes, suggesting there is no indication of halite dissolution (Sonney et al., 2010). This has important implications for justifying the use of a steady state chloride mass balance approach to estimate recharge rates (section 2.5.1).

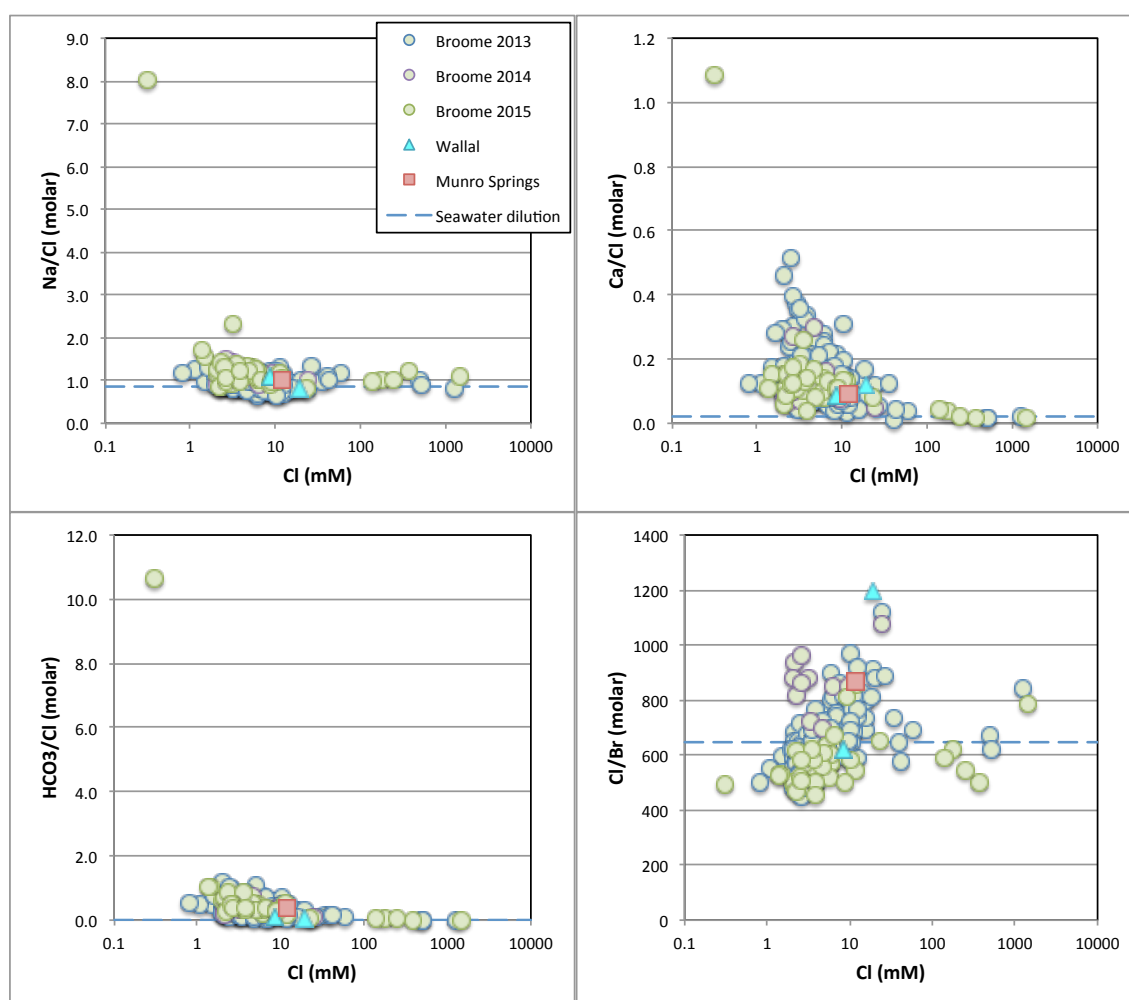
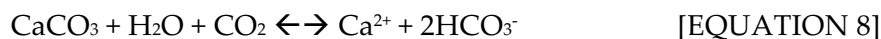


Figure 6. Major ion to chloride ratios as a function of chloride concentration for all groundwater samples collected during the project (2013-2015).

Plots of ionic ratios (e.g., Na/Ca) against Cl (a useful proxy for salinity) help to reveal changes in concentration of one of the ions relative to the other. The plots shown in Figure 7 show that groundwater is much more enriched in Ca and HCO₃ (relative to Na) than would be expected from evaporation of rainwater containing marine aerosols. Furthermore, the Ca/HCO₃ ratios of the groundwater are broadly consistent with those expected from calcite weathering (i.e., 0.5):



The observation that many groundwater samples exhibit a Ca/HCO₃ ratio less than 0.5 is consistent with weathering of a Mg-calcite rather than pure calcite.

The Ca/SO₄ ratios suggest some samples may have acquired Ca and SO₄ through gypsum dissolution (Ca/SO₄ ~ 1), however the majority of samples have significant excesses of Ca over SO₄ providing further evidence for the importance of calcite weathering.

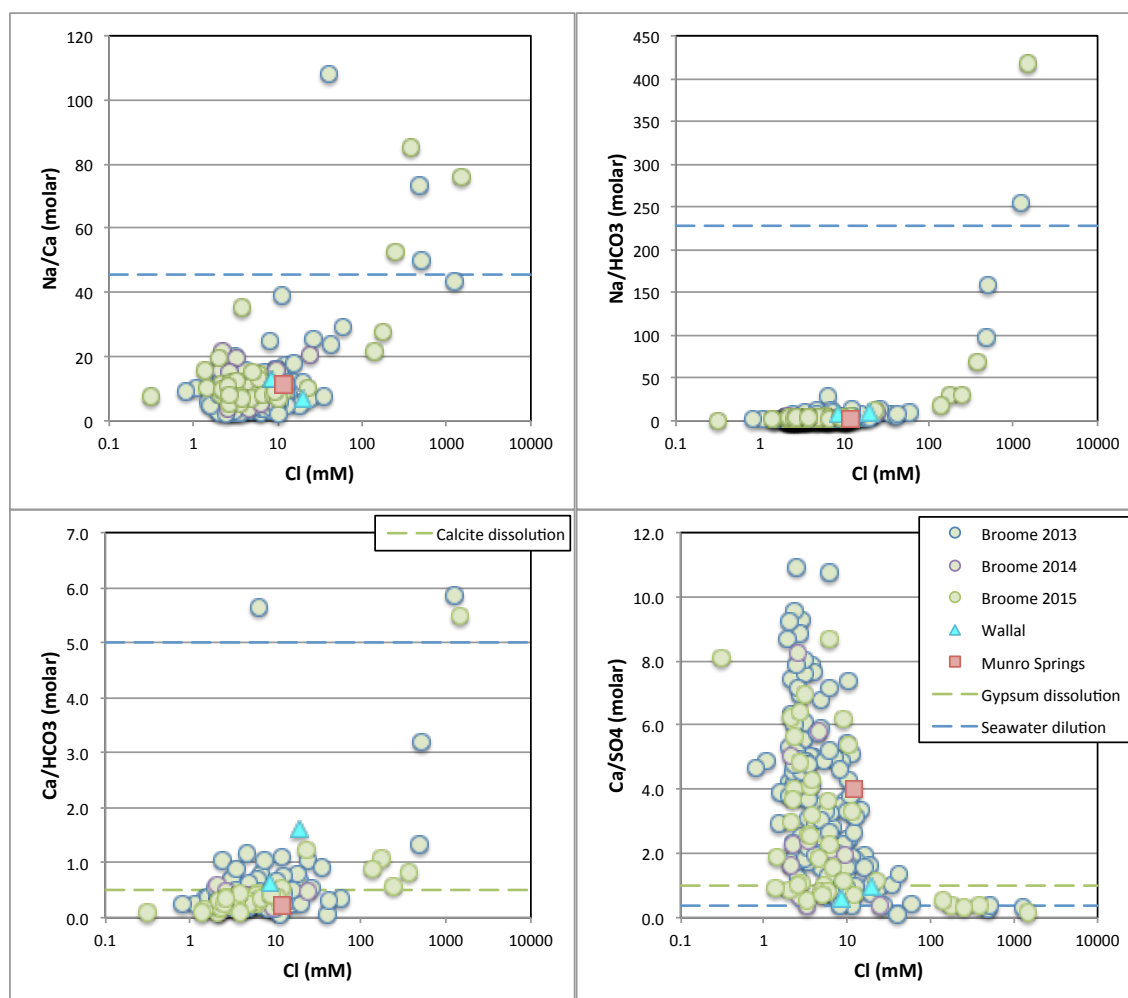


Figure 7. Major ion ratios as a function of chloride concentration for all groundwater samples collected during the project (2013-2015).

Table 1. Measured carbon isotope composition of groundwater samples collected from bores and Munro Springs in October 2014, as well as calculated concentrations of DIC species and saturation indices (SI) for calcite and gypsum.

Sample ID		$\delta^{13}\text{C}$	^{14}C	CO_2 (aq)	HCO_3^- (aq)	SI	SI
		‰	pMC	mM	mM	Calcite	Gypsum
ROE015	East Crab Creek bore	-10.20	93.84	1.38	0.62	-2.96	-3.48
ROE005	Cow bore	-12.62	84.41	0.87	1.00	-2.40	-3.75
ROE012	Sheep camp bore	-11.60	75.79	0.72	0.35	-3.06	-3.74
FRA022	Bidyadanga 2/93	-11.64	79.81	1.34	1.53	-1.81	-2.94
NIT019	Schultz's bore	-12.58	84.44	2.91	4.53	-0.91	-2.52
NIT025	Munro Springs bore	-9.60	18.66	1.47	1.09	-2.40	-2.59
NITMUN	Munro Springs	-11.58	42.49	0.28	1.21	-1.51	-2.74
MRD024	MRD gravel pit bore	-8.70	94.49	1.02	3.38	-0.52	-2.36
MRD026	MRD Teds bore	-10.09	81.73	0.87	1.48	-1.39	-2.98
MRD021	MRD Anna Plains #1	-9.21	66.92	0.43	2.47	-0.68	-1.61
ANA053	Mono bore	-10.85	75.94	0.37	2.47	-0.48	-2.19
FRA027	Tip bore east	-13.10	95.45	4.79	3.80	-1.42	-2.50

3.2. Geochemical modelling

PHREEQC modelling was not performed for the 2013 'bore inventory' samples due to a lack of field alkalinity measurements and the fact that lab derived values were most likely affected by CO_2 degassing between sample collection and analysis. However, PHREEQC modelling was performed for the 2014 'isotope reconnaissance' samples (Table 1) and the 2015 'chemistry and isotope survey' samples (Table 2 shows results for samples that had carbon isotope analysis). Five bores from the 2015 sampling (15LAG1D, 15LAG14D, 15LAG15D, Gilberts Bore (SHA010) and Sandfire Artesian (MRD025)) did not have field measurements of alkalinity and thus laboratory data had to be used. Two of these five bores (15LAG14D and Sandfire Artesian) also had no field measurements of temperature or pH, so these values were assumed based on values measured in other bores (i.e., 34 degrees and pH 7).

The speciation results indicate that all samples have a significant proportion of their DIC in the form of aqueous CO_2 , with almost 25% of samples having more of this species than bicarbonate. These results highlight the importance of measuring alkalinity in the field before any degassing.

All groundwater samples from 2014 and most samples from 2015 were determined to be below saturation with respect to calcite and gypsum (i.e., $\text{SI} < 0$). Two samples from 2015 (15LAG23AI and 15LAG24D) were over-saturated with respect to calcite, and one sample (15LAG24S) was near saturation. All three of these samples had the highest (i.e., least negative) $\delta^{13}\text{C}$ compositions, confirming a strong influence of carbonate

weathering on their chemistry. Two samples from 2015 (15LAG11S and 15LAG24D) were over-saturated with respect to gypsum.

Table 2. Measured carbon isotope composition of groundwater samples collected from bores in November 2015, as well as calculated concentrations of DIC species and saturation indices (SI) for calcite and gypsum.

Bore ID	$\delta^{13}\text{C}$	^{14}C	CO_2 (aq)	HCO_3^- (aq)	SI	SI
	‰	pMC	mM	mM	Calcite	Gypsum
15LAG01S	-11.1	76.08	1.27	1.19	-2.47	-3.48
15LAG01D	-11.0	13.65	0.47	1.43	-0.97	-1.69
15LAG02I	-13.5	53.76	1.07	0.72	-2.60	-3.66
15LAG06D	-13.3	14.20	0.29	2.36	-0.62	-2.29
15LAG07S	-12.7	102.76	0.55	1.24	-1.48	-3.29
15LAG07I	-12.2	70.87	1.04	1.30	-1.72	-3.19
15LAG08I	-12.0	64.64	1.46	1.43	-1.95	-3.49
15LAG09I	-13.0	53.23	0.69	1.49	-1.74	-3.40
15LAG10D	-12.0	39.18	0.67	1.49	-1.61	-2.81
15LAG11I	-12.0	60.69	0.61	1.90	-1.33	-3.08
15LAG14D	-15.5	62.48	0.37	1.99	-0.92	-2.04
15LAG15AI	-12.1	30.76	0.34	1.24	-1.52	-2.80
15LAG15BD	-12.3	5.68	0.18	2.28	-0.30	-2.02
15LAG16I	-14.1	55.98	1.02	1.49	-1.92	-3.28
15LAG17I	-12.2	75.90	2.57	0.60	-3.14	-3.66
15LAG19I	-10.1	37.43	0.47	2.07	-1.00	-2.24
15LAG20I	-11.6	28.10	0.43	1.54	-1.35	-2.48
15LAG21D	-10.7	35.65	0.48	2.05	-0.80	-1.74
15LAG23AI	-8.6	60.5	0.99	6.52	0.18	-0.83
15LAG24S	-9.3	79.62	0.29	2.94	-0.24	-2.31
15LAG24D	-4.4	27.98	0.29	2.43	0.06	0.00
15LAG26PB1	-11.8	60.28	0.75	1.19	-1.64	-2.95
Buru Commodore #1	-13.5	96.41	0.58	1.90	-1.29	-3.40
Cudalgarra #1	-11.3	74.92	0.82	2.35	-0.93	-2.74
Gilberts bore (SHA010)	-11.0	64.71	1.47	0.93	-2.30	-3.47
Sandfire artesian (MRD025)	-6.0	13.24	0.20	1.1	-1.12	-1.97
Stubby's bore	-12.5	43.52	0.46	1.43	-1.76	-3.27

3.3. Radiocarbon dating

The results of stable carbon ($^{13}\text{C}/^{12}\text{C}$) and radiocarbon (^{14}C) analyses for the 2014 and 2015 sampling campaigns are shown above in Table 1 and Table 2. $\delta^{13}\text{C}$ compositions show a large range from -15.5‰ to -4.4‰ indicating variable contributions of soil gas dissolution and carbonate weathering for controlling DIC concentrations. Hence the measured radiocarbon activities (5.7 – 102.8 pMC) cannot be directly converted to an

apparent age; instead there is a clear need to correct radiocarbon ages for addition of 'dead' carbon.

With the exception of Munro Springs and the adjacent Munro Springs bore, all samples have a measured ^{14}C activity in the range 67-94 pMC, indicating they are all very young; that is, apparent 'uncorrected' ages of less than a few thousand years. This was not surprising given the shallow depth of bores compared to the total aquifer thickness. The $\delta^{13}\text{C}$ composition does vary slightly, reflecting some contribution of DIC from carbonate weathering, and therefore a need to apply correction schemes.

The radiocarbon ages achieved using four different correction schemes are presented for the 2014 and 2015 samples in Table 3 and Table 4 respectively. Due to the potential errors introduced through sampling, analysis and (most importantly) assumptions required for the correction schemes, the uncertainty in these age estimates is at least 200 years, and possibly up to 500 years. Nevertheless, all but three of the shallow groundwater samples from 2014 are essentially modern. Sheep Camp bore on Roebuck Plains has an apparent groundwater age in the range 200 - 800 years, which is consistent with this part of the Broome Sandstone being locally confined by marine clays (Roebuck Bay Clay); hence the groundwater was recharged locally up-gradient of the bore.

Table 3. Corrected carbon-14 ages of groundwater samples collected from bores and Munro Springs in October 2014 using four different models (NB. all values rounded to the nearest hundred years).

Sample ID	Name	Age TAMERS	Age PEARSON	Age F&G	Age MOOK
years					
ROE015	East Crab Creek bore	0	0	0	0
ROE005	Cow bore	0	0	0	0
ROE012	Sheep camp bore	800	200	200	500
FRA022	Bidyadanga 2/93	0	0	0	0
NIT019	Schultz's bore	0	0	0	0
NIT025	Munro Springs bore	11,900	10,200	10,300	11,100
NITMUN	Munro Springs	2,800	4,900	4,300	4,000
MRD024	MRD gravel pit bore	0	0	0	0
MRD026	MRD Teds bore	0	0	0	0
MRD021	MRD Anna Plains #1	0	0	0	0
ANA053	Mono bore	0	0	0	0
FRA027	Tip bore east	0	0	0	0

Munro Springs bore had the oldest sampled groundwater from the 2014 campaign, with an age in the range 10,200 – 11,900 years, while surface water sampled from Munro springs had the second oldest age of 2,800 – 4,900 years (Table 3). The younger apparent age of water in Munro Springs compared with the adjacent bore most likely reflects the depth that the groundwater sample was taken from the bore. Alternatively, the springs may appear younger due to the addition of modern DIC, either through plant root respiration or oxidation of recent organic matter in the springs, or gaseous exchange with the atmosphere.

Table 4. Corrected carbon-14 ages of groundwater samples collected in November 2015 using four different models (NB. all values rounded to the nearest one hundred years). The adopted age was determined as the higher value of either the mean of all four models or 500 years, with the latter reflecting cumulative errors in sampling, analysis and modelling.

Bore ID	Age TAMERS	Age PEARSON	Age F&G	Age MOOK	Adopted Age
	years				
15LAG01S	0	0	0	0	500
15LAG01D	12,600	12,200	12,800	12,400	12,500
15LAG02I	3,300	3,800	3,300	3,500	3,500
15LAG06D	11,200	14,600	14,200	12,800	13,200
15LAG07S	0	0	0	0	500
15LAG07I	100	100	400	100	500
15LAG08I	1,300	700	1,100	1,000	1,000
15LAG09I	1,700	3,400	3,100	2,500	2,700
15LAG10D	4,300	4,800	5,000	4,500	4,600
15LAG11I	200	1,200	1,400	600	900
15LAG14D	0	4,300	3,200	1,800	2,300
15LAG15AI	5,600	6,900	6,700	6,200	6,400
15LAG15BD	18,600	21,100	21,100	19,700	20,100
15LAG16I	1,900	4,000	3,500	2,800	3,100
15LAG17I	1,500	0	0	700	500
15LAG19I	3,800	2,600	4,000	3,300	3,400
15LAG20I	6,400	7,000	7,300	6,700	6,900
15LAG21D	4,200	3,900	4,900	4,100	4,300
15LAG23AI	0	0	0	0	500
15LAG24S	0	0	0	0	500
15LAG24D	5,600	0	0	500	1,500
15LAG26PB1	1,200	1,000	1,200	1,100	1,100
Buru Commodore #1	0	0	0	0	500
Cudalgarra #1	0	0	0	0	500
Gilberts bore (SHA010)	1,800	0	0	900	700
Sandfire artesian (MRD025)	12,200	0	1,400	8,700	5,600
Stubby's bore	2,900	4,500	4,300	3,600	3,800

Groundwater samples from the 2015 campaign exhibit a much wider range of apparent ages than the 2014 samples (Table 4). Values range from modern (i.e., 0 ± 500 years) through to more than 21,000 years and reflect a much more representative distribution of depths in the aquifer and distances along regional flow paths than the 2014 samples, which targeted fewer and only shallow bores. While the four different correction schemes produced generally consistent ages for each sample, and there is no reason to consider one model as being more appropriate than the others, it was necessary to derive an adopted age for calculating recharge rates. The adopted age was determined to be either the mean result of the four models, or 500 years, whichever the greater. The lower limit of 500 years was chosen to acknowledge the cumulative error inherent in sampling, measuring and modelling the radiocarbon data.

3.4. Chlorofluorocarbons

The results of CFC-11 and CFC-12 analysis for 15 samples collected from shallow bores in 2015 are presented in Figure 8. All but one of the samples returned CFC-11 concentrations that are lower than simulated concentrations using either lumped parameter model, which indicates that CFC-11 has been degraded in the aquifer and therefore cannot be used for groundwater dating or recharge estimation purposes.

However, CFC-12 concentrations can be used for these purposes, with eight of the samples returning concentrations above the limit of detection of 0.16 pMol/kg (Table 5). These results indicate a mean residence time of between 20 and >45 years using a Piston Flow Model, or between 13 and >250 years using an Exponential Mixing Model. For the seven samples with a concentration at this limit, the estimated mean residence times are lower limits (i.e., 45 years for PFM and 250 years for EMM), and therefore the derived recharge rates (discussed later) are upper limits.

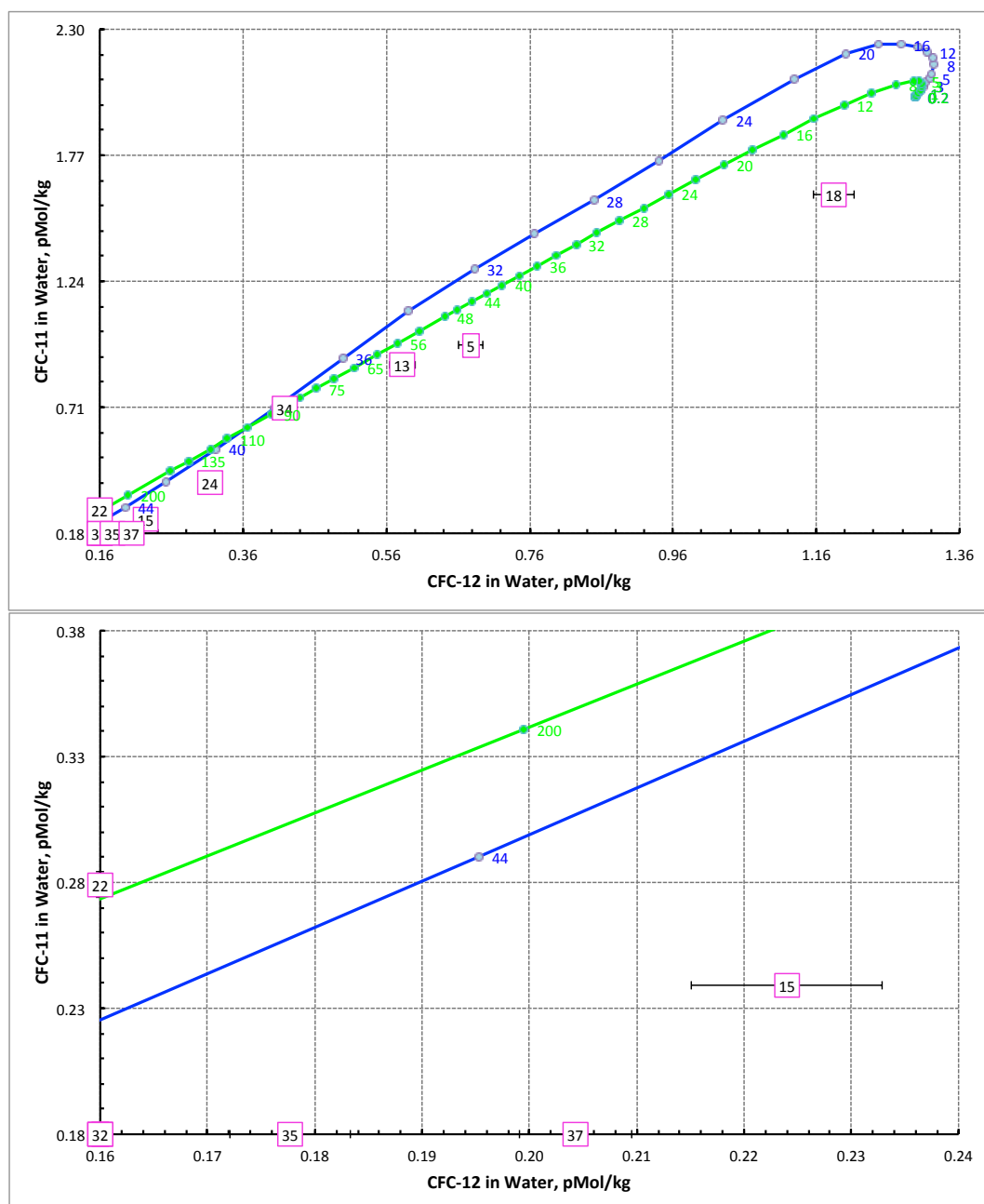


Figure 8. Measured CFC concentrations in water samples collected from shallow bores in 2015 (pink squares and labeled with sample number) relative to simulated concentrations using a Piston Flow Model (blue line) and an Exponential Mixing Model (green line). Both models assume a consistent recharge temperature, elevation and salinity for all groundwater samples of 30 °C, 20 m AHD and 1,000 mg/L respectively. Numbers adjacent each model curve correspond to estimated mean residence time. (NB. same data plotted at two different scales).

Table 5. Measured CFC-12 concentrations in groundwater samples collected in November 2015, with mean residence times (MRT) and recharge rates determined using a Piston Flow Model (PFM) and Exponential Mixing Model (EMM).

Bore ID	CFC-12 in Water	MRT PFM	MRT EMM	Recharge Rate PFM	Recharge Rate EMM	Adopted Recharge
	pMol/kg	years			mm/year	
15LAG01S	< 0.16	> 45	> 250	< 30.0	< 5.4	< 30.0
15LAG07S	0.68	32	44	43.9	31.9	43.9
15LAG06S	< 0.16	> 45	> 250	< 102.5	< 18.5	< 18.5
15LAG11S	< 0.16	> 45	> 250	< 26.7	< 4.8	< 26.7
15LAG09S	< 0.16	> 45	> 250	< 12.8	< 2.3	< 12.8
15LAG10S	0.58	34	56	25.9	15.8	25.9
15LAG12S	0.22	43	183	70.3	16.5	16.5
15LAG19S	1.18	20	13	61.2	94.2	61.2
15LAG20S	< 0.16	> 45	> 250	< 77.5	< 14.0	< 14.0
15LAG23AS	< 0.16	> 45	> 250	< 38.1	< 6.9	< 6.9
15LAG16S	0.31	40	120	14.7	4.9	14.7
15LAG24S	< 0.16	> 45	> 250	< 60.8	< 10.9	< 10.9
15LAG21S	0.42	38	85	38.3	17.1	38.3
15LAG15BS	0.18	45	231	41.7	8.1	8.1
15LAG15AS	0.20	44	200	14.5	3.2	14.5

3.5. Stable isotopes

The measured stable H/O isotope compositions of rainfall and groundwater samples collected in 2014 and 2015, as well as Munro Springs, are plotted in the conventional manner in Figure 9. This plot shows that wet season rainfall samples are more depleted in the heavy isotopes (i.e. more negative $\delta^2\text{H}$ and $\delta^{18}\text{O}$) than dry season rainfall samples, which is consistent with the well-known 'amount effect'. This effect is better illustrated in Figure 10, which shows how the largest rainfall amounts correspond to the most depleted compositions. However, it is important to note that these are bulk rainfall samples from multiple events, and therefore cannot be used to determine rainfall thresholds for recharge from individual storm events.

Broome Sandstone groundwater samples and the Munro Springs sample are more depleted in the heavy isotopes compared to most wet season rainfall samples, suggesting that recharge only occurs after the most intense (i.e. isotopically depleted) rainfall events. The similar composition of Munro Springs and Wallal aquifer bore Sandfire Artesian (MRD025) cannot be used to infer the source aquifer for the springs without further evidence such as hydraulic head measurements.

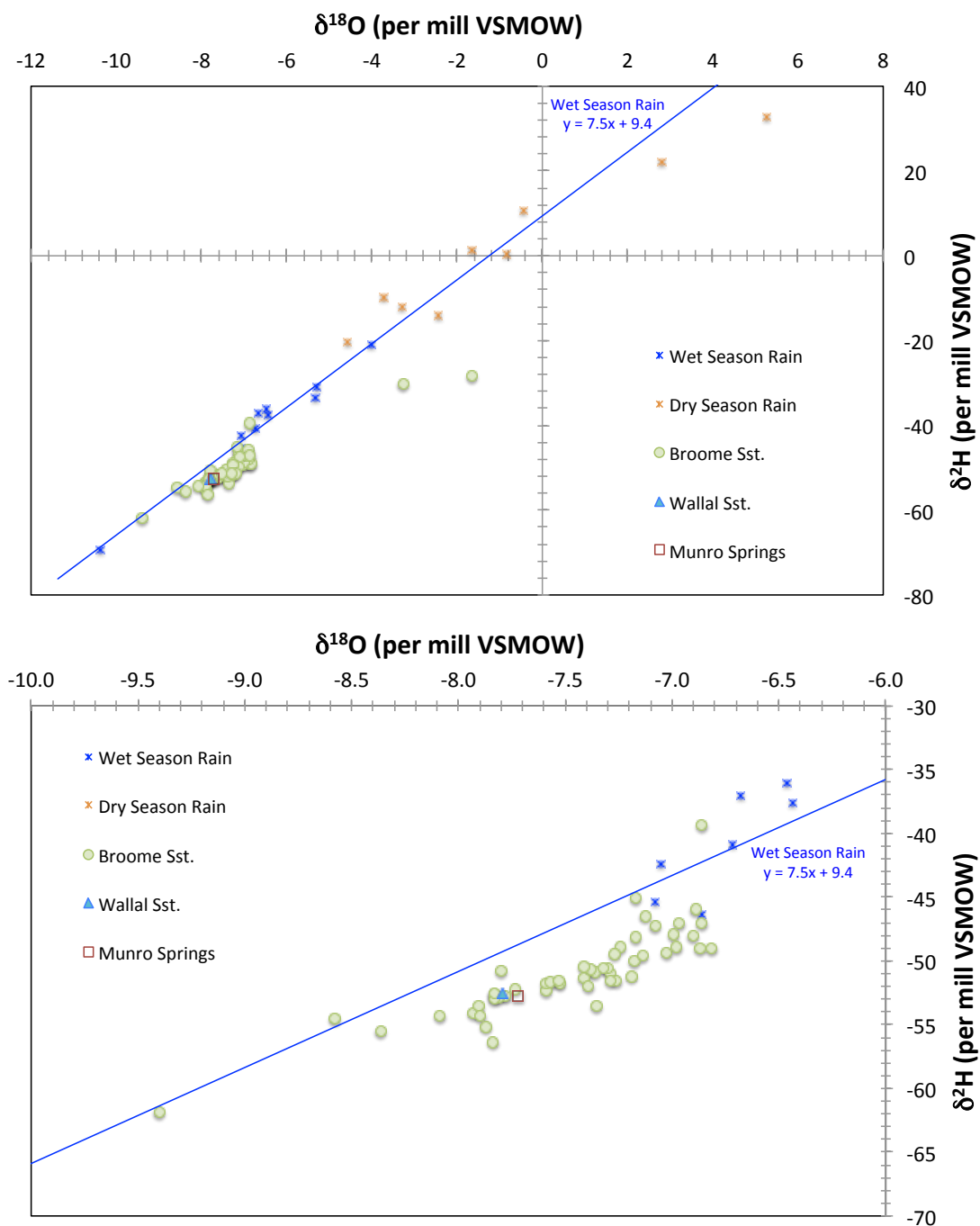


Figure 9. Stable hydrogen and oxygen isotope composition of groundwater, rainfall and spring samples collected in 2014 and 2015 (NB. same data plotted at two different scales).

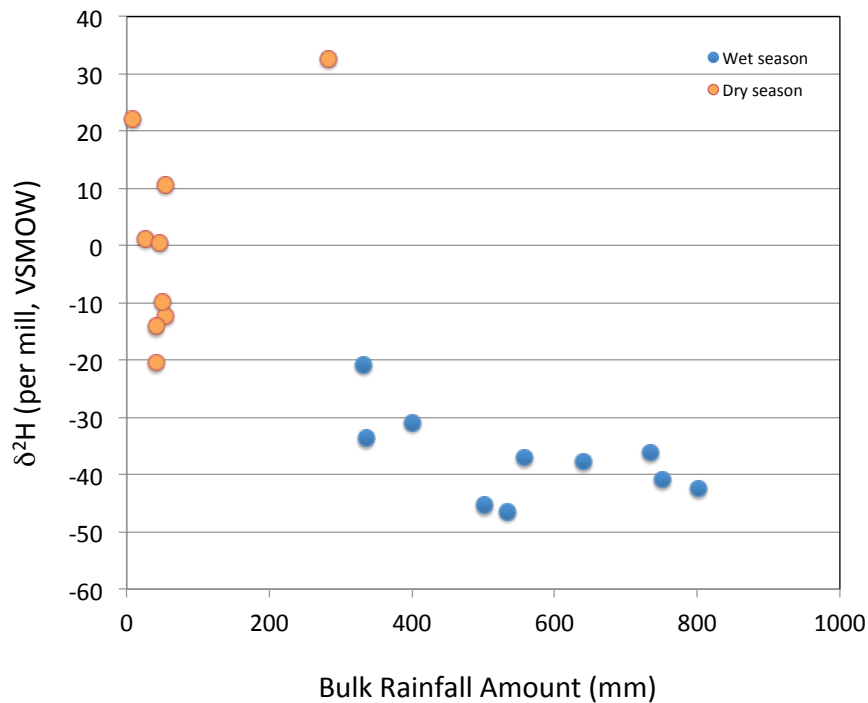


Figure 10. Relationship between bulk rainfall amount from multiple events and stable hydrogen isotope composition. Smaller rainfall events in the dry season are generally enriched in the heavy isotopes (^2H and ^{18}O), whereas large rainfall events in the wet season are generally depleted in the heavy isotopes.

3.6. Recharge modelling

3.6.1. Steady State Chloride Mass Balance

Chloride concentrations measured in rainfall samples during the project range from <0.5 mg/L to 65 mg/L (Table 6) and provide an amount-weighted average of 5.4 mg/L, which is consistent with previous studies and the value of 5 mg/L adopted for CMB recharge estimation (section 2.5.1). Recharge rates were estimated for all Broome Sandstone bores sampled in 2013 (n=142), 2014 (n=11) and 2015 (n=39); summary statistics for each campaign and all samples combined are presented in Table 7. Based on all 192 samples, the range in CMB recharge estimates is from 0 to 205 mm/yr. and the mean value is 16.9 mm/yr. The 10th, 50th and 90th percentile values are 4.0, 13.6 and 30.0 mm/yr. respectively.

The CMB recharge rates show no clear spatial trends (Figure 11) however this may in part be due to the constant values adopted for mean annual rainfall (450 mm/yr.) and chloride concentration in rainfall (5 mg/L). It is also worth noting that CMB recharge rates apply to locations up-gradient of the bores from which groundwater samples were collected, as illustrated schematically in Figure 4. Given that the up-gradient distance will be different for each bore, depending on its depth relative to the thickness

Table 6. Chloride concentration in rainfall samples

Site & Sample ID	Collection Date	Rainfall Amount (mm)	Chloride Conc. (mg/L)
Dampier Downs West RF	4/05/2015	647.6	<0.5
Cyrene #1 RF	4/05/2015	558.2	0.9
Munro Springs RF	5/05/2015	400.6	1
Junction Bore RF	5/05/2015	331.4	1.5
McGregors Bore RF	8/05/2015	735.4	0.8
McGregors Bore RG	5/11/2015	8.0	14
Munro Springs RG	12/11/2015	47.4	65
Dampier Downs West RG	14/11/2015	53.6	31
Lyngettes Well RG	17/11/2015	282.8	33
Weighted Average			5.4

Table 7. Summary of chloride mass balance recharge rates for each sampling campaign.

Sampling Campaign	Recharge Rate (mm/year)						
	n	Min	Max	Mean	Median	10th Percentile	90th Percentile
2013	142	0.1	77.6	15.8	13.4	4.1	29.5
2014	11	2.6	30.4	17.3	18.9	5.3	30.0
2015	39	0.0	205	20.9	13.6	0.4	30.2
All Samples	192	0.0	205	16.7	13.6	4.0	30.0

Table 8. Comparison of chloride mass balance recharge rates (R in mm/year) for shallow and deep samples collected in 2014 and 2015 (NB. four bores from 2015 have unknown construction details).

Sample Depth	2014 Samples			2015 Samples		
	n	Mean R	Median R	n	Mean R	Median R
Shallow < 15m below w/table	5	13.8	13.7	16	24.4	10.7
Deep > 15m below w/table	6	20.2	24.0	19	17.5	18.6

of the aquifer, this may provide further explanation for the lack of spatial trends in CMB recharge rate.

Differences in the summary statistics between the three sampling campaigns (Table 7) are most likely due to differences in the spatial extents of each campaign. Horizontal variability in groundwater recharge rates is to be expected given natural variability in rainfall, soil type and vegetation. However, vertical variability can also be expected because the deeper samples reflect recharge rates long ago at locations far up-gradient of the bores, whereas shallow samples reflect recharge rates at comparably recent times and near the bores. This is illustrated in Table 8, which shows marked differences between shallow and deep samples collected in 2014 and 2015; overall the shallow samples tend to produce lower recharge rates. A similar analysis for the 2013 samples was not possible as many of these bores have unknown construction details.

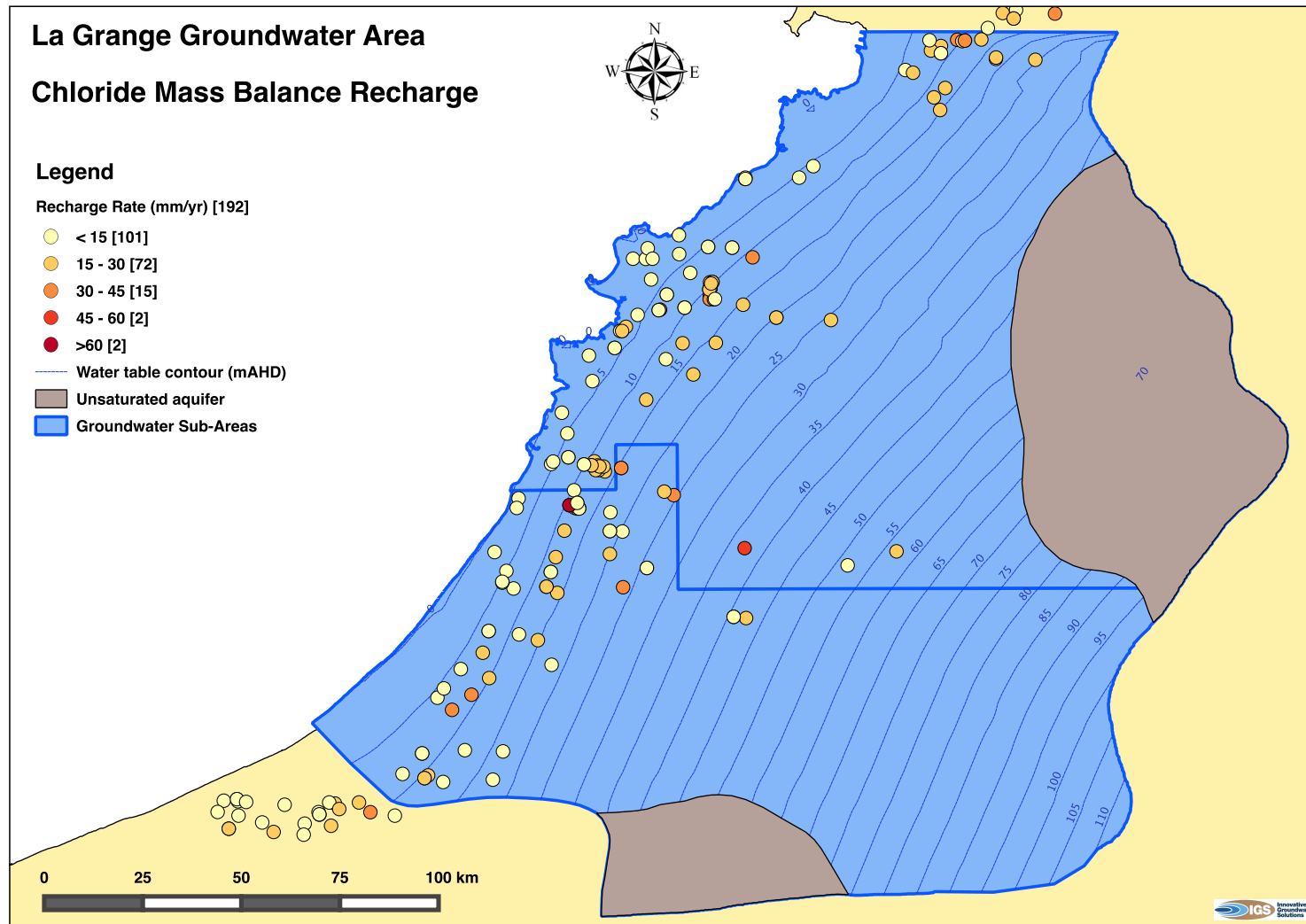


Figure 11. Chloride mass balance recharge rates determined for all 192 Broome Sandstone bores sampled between 2013-2015.

3.6.2. One-dimensional CFC-12 Modelling

A comparison of simulated CFC-12 profiles using the PFM and EMM (Figure 12) demonstrates the importance of selecting an appropriate model to interpret the CFC-12 measurements. Because neither model can produce a reasonable match to measurements at all depths, the PFM has been adopted for the shallowest samples (< 5 m below water table) and the EMM has been adopted for the deeper samples (> 5 m below water table).

Hence the 'adopted' CFC-12 recharge rates presented in Table 5 are a combination of results from the two models. These were determined using Equation 4 with a consistent value of 30% for aquifer porosity. Adopted rates range from less than 6.9 mm/yr. up to a maximum of 61.2 mm/yr. Unlike recharge rates determined using the CMB approach, these CFC-12 derived rates are an average between the location where the sample entered the saturated zone (point A in Figure 4) and the bore. Given that most of the CFC samples were collected from bores with a mid-screen depth of less than 10 m below the water table, it is reasonable to assume a recharge area for these rates of a few kilometres at most.

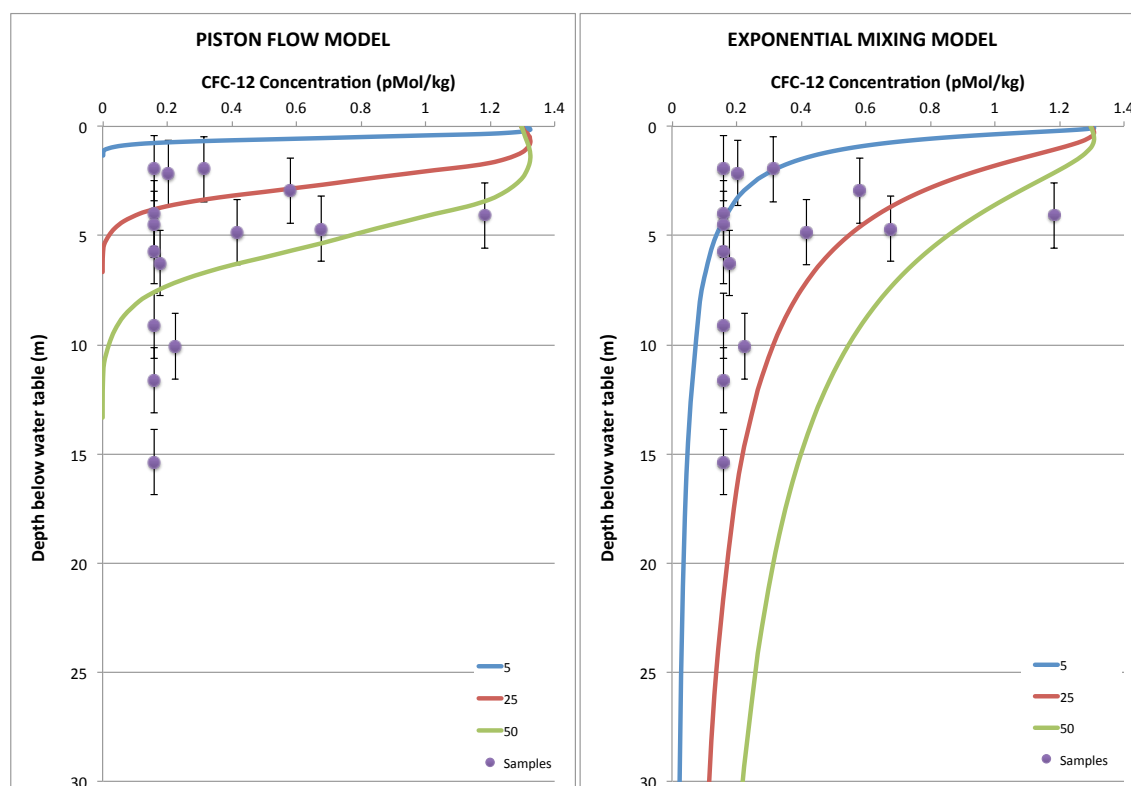


Figure 12. Measured CFC-12 concentrations in groundwater samples compared to simulated profiles for three different recharge rates (5, 25 and 50 mm/yr.) using either the PFM or EMM. Plots show that groundwater samples have lower concentrations – consistent with longer residence times – with increasing depth below water table. Adopting the PFM for shallow samples (< 5 m depth) and the EMM for deeper samples (> 5 m depth) suggests recharge rates for most samples in the range 5 – 25 mm/year.

3.6.3. Two-dimensional Carbon-14 Modelling

Radiocarbon ages have been calculated for 2014 groundwater samples (Table 3) and therefore it is possible to estimate recharge rates, using either a one-dimensional model (Equation 4) or a two-dimensional model (Equation 5). However this has not been done due to the shallow depths and large uncertainty in bore construction details which, if applied, would yield very high errors and render the recharge rates meaningless.

Instead the preferred radiocarbon dataset for recharge estimation is the 2015 samples. Although 27 radiocarbon ages have been calculated for 2015 samples (Table 4), one of these is for a Wallal Sandstone bore (Sandfire artesian MRD025) and three of the Broome Sandstone bores have unknown construction details (Cudalgarra #1, Gilberts bore (SHA010), and Stubby's bore). Hence the remaining 23 bores (Figure 2) have been used to estimate recharge rate (Equation 5) and the distance over which this rate applies up-gradient of the bore (Equation 7).

The results of this analysis are shown as different coloured flow lines propagated up-gradient of each bore location in Figure 13. Radiocarbon-derived recharge rates range from 1.9 mm/yr. to 72.6 mm/yr., with mean and median values of 16.3 and 11.6 mm/yr. respectively (n=23). They are not correlated with CMB recharge rates (Table 9), however this was not expected because the radiocarbon method provides spatially averaged rates whereas the CMB method provides point recharge estimates. There are no discernible spatial trends in radiocarbon derived recharge rates as most areas have flow lines reflecting average rates in the ranges < 15 mm/yr. or 15 – 30 mm/yr. Horizontal flow path distances range from just over one kilometre for one of the shallowest bores (15LAG01S) to around 150 kilometres for two of the deep bores (15LAG15BD and 15LAG21D) (Table 9).

Table 9. Summary of radiocarbon (^{14}C) derived recharge rates and estimated flow-path distances, compared to chloride mass balance (CMB) derived recharge rates.

Bore ID	Horizontal flow-path distance (km)	^{14}C -derived Recharge (mm/yr.)	CMB-derived Recharge (mm/yr.)
15LAG01D	45.1	6.8	2.8
15LAG01S	1.3	1.9	30.8
15LAG02I	21.9	8.2	27.4
15LAG06D	132.7	10.3	12.1
15LAG07I	30.5	72.6	20.5
15LAG07S	2.4	2.0	10.5
15LAG08I	28.2	19.7	30.0
15LAG09I	32.4	5.6	29.6
15LAG10D	112.5	19.1	22.3
15LAG11I	38.8	21.2	18.6
15LAG14D	42.0	14.2	19.9
15LAG15AI	36.2	2.7	25.0
15LAG15BD	148.7	13.1	7.0
15LAG16I	50.9	8.1	43.3
15LAG17I	31.1	23.1	28.5
15LAG19I	60.9	8.0	10.7
15LAG20I	34.1	1.9	12.8
15LAG21D	157.1	43.2	5.4
15LAG23AI	38.3	25.7	0.5
15LAG24D	36.7	40.1	0.0
15LAG24S	5.8	5.3	17.9
15LAG26PB1	34.5	12.8	16.9
Buru Commodore #1	15.8	9.3	27.8

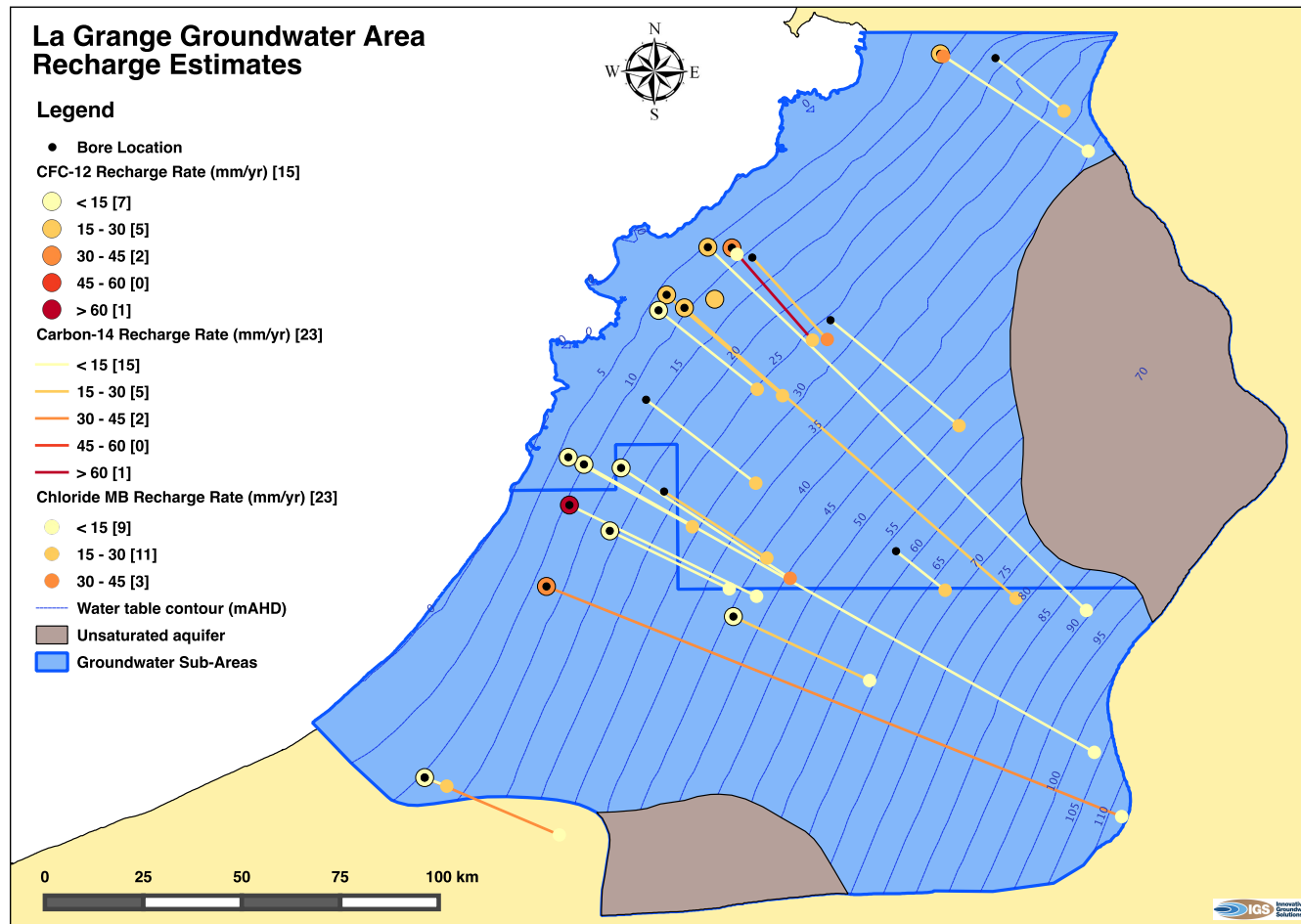


Figure 13. Spatial distribution of recharge rates determined using three different methods. Radiocarbon recharge estimates are spatial averages shown as coloured lines projected up-gradient of the bore locations, with the distance of the line representing the length of the flow path for each bore sample. Chloride mass balance recharge rates are point estimates and are shown as coloured dots at the up-gradient ends of the flow lines. CFC-12 recharge estimates are spatial averages but can be shown at this scale as a point around the bore location due to the shallow depth of samples.

4. Discussion

4.1. Recharge rates

The three different environmental tracer based methods for estimating recharge (i.e., chloride mass balance, 1-D CFC modelling and 2-D radiocarbon modelling) have produced remarkably consistent results, despite recognised differences in the spatial and temporal scales over which they apply (Table 10). Observed differences in the mean recharge rate determined using chloride mass balance for the three sampling campaigns (section 3.6.1) were attributed to differences in the spatial (horizontal and vertical) extents of each campaign, and this is also likely to be the case for the other methods employed. For each method the mean recharge rates are biased towards one or two very high values, which are not consistent between bores. Therefore, the median values of recharge rates are considered most appropriate for regional groundwater modelling and broader water allocation planning purposes.

Table 10. Summary statistics for annual recharge rates to the Broome Sandstone aquifer.

Method	Scale of Estimate	Number of Samples	Mean Recharge Rate (mm/yr.)	Median Recharge Rate (mm/yr.)
Chloride Mass Balance	point	192	16.9	13.6
CFC-12 Models	small spatial ave.	15	< 22.9	< 16.5
Radiocarbon Models	large spatial ave.	23	16.3	11.6

4.2. Relationship between rainfall and recharge

While each of the methods employed to estimate recharge rate have revealed some spatial variability (Figure 11 and Figure 13) there are no consistent trends, most notably with the strong north-south and west-east gradients in mean annual rainfall. As discussed above, one reason why this may not be evident for the CMB results is that a constant value was adopted for annual rainfall amount (450 mm/yr.) and chloride concentration (5 mg/L) in the absence of any reliable spatial data for these parameters.

However an equally plausible explanation, which is independent of the recharge method, is that groundwater recharge to the Broome Sandstone aquifer in the La Grange area is not driven by annual rainfall as depicted in regional isohyet maps. Instead recharge is driven by large episodic events associated with tropical cyclones that have highly variable paths and therefore footprints of rainfall distribution (BOM, 2016). Despite the importance of this rainfall mechanism the range in estimated recharge rates is relatively narrow, particularly for the CFC and radiocarbon methods, because they represent average rates over long spatial and temporal scales.

4.3. Groundwater flow and residence times

CFC-12 measurements have enabled the calculation of mean residence times for young groundwater sampled from shallow bores. These residence times range from 20 years to more than 45 years if it is assumed that groundwater of different ages has not mixed in the aquifer or in the bore (i.e. the Piston Flow Model) (Table 5). Alternatively, if groundwater of different ages has mixed in the bore (i.e. the Exponential Mixing Model), then the mean residence times range from 13 years to more than 250 years (Table 5). The latter value is older than the lifetime of CFCs in the hydrosphere because it represents the mean residence time of a mixture containing some modern water (less than 50 years since recharge) and some much older water (greater than 50 years since recharge).

Residence times of regional groundwater flow have been obtained from radiocarbon dating. Apparent ages range from 'modern' (i.e. 0 years) at shallow depths through to more than 20,000 years in deeper and down-gradient parts of the aquifer (Table 3 and Table 4). Accordingly, recharge rates estimated from these radiocarbon ages apply over the same range of timescales.

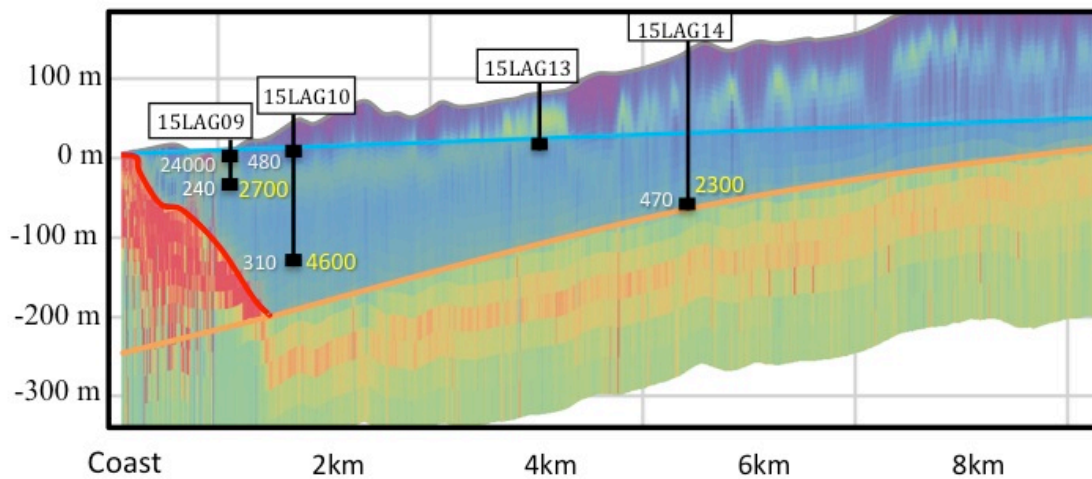
4.4. Sources of salinity in deep coastal bores

Groundwater generally becomes older towards the coast and with increasing depth in the aquifer, independent of salinity or chemical composition (e.g., see Figure 14(a)). However, very old groundwater (adopted radiocarbon age of 20,100 years) with a higher than expected salinity (TDS 770 mg/L) has been observed at the bottom of the aquifer in bore 15LAG15BD (Figure 14(b)). Higher than expected salinities also occur in deep bores 15LAG01D, 15LAG21D and 15LAG24D.

Two hypotheses are provided for the origin of very old and brackish groundwater at depth near the coast. The first is that the age of the water simply reflects a very long residence time from the up-gradient margin of saturated Broome Sandstone. Based on a simple Darcy calculation using hydraulic conductivity of > 10 m/d, hydraulic gradient of 0.001, and porosity of 30%, the apparent age suggests a flow path of > 245 km, which is greater than the lateral extent of the aquifer inferred by the AEM survey (Annetts et al., 2014). However, if the 'parcel' of water has flowed along the bottom of the aquifer for at least 150 km, then radiocarbon would have been lost from the aquifer via downward diffusion into the ^{14}C -devoid aquitard, causing the apparent age to be much older than the true water age.

Diffusion could also explain the higher salinity of deep groundwater in the aquifer near the coast, that is, upward diffusion of salts out of the aquitard and into the aquifer. These processes have been well documented in the international literature, however accurate determination of whether they can fully explain the observations in this system would likely require further modelling.

(a)



(b)

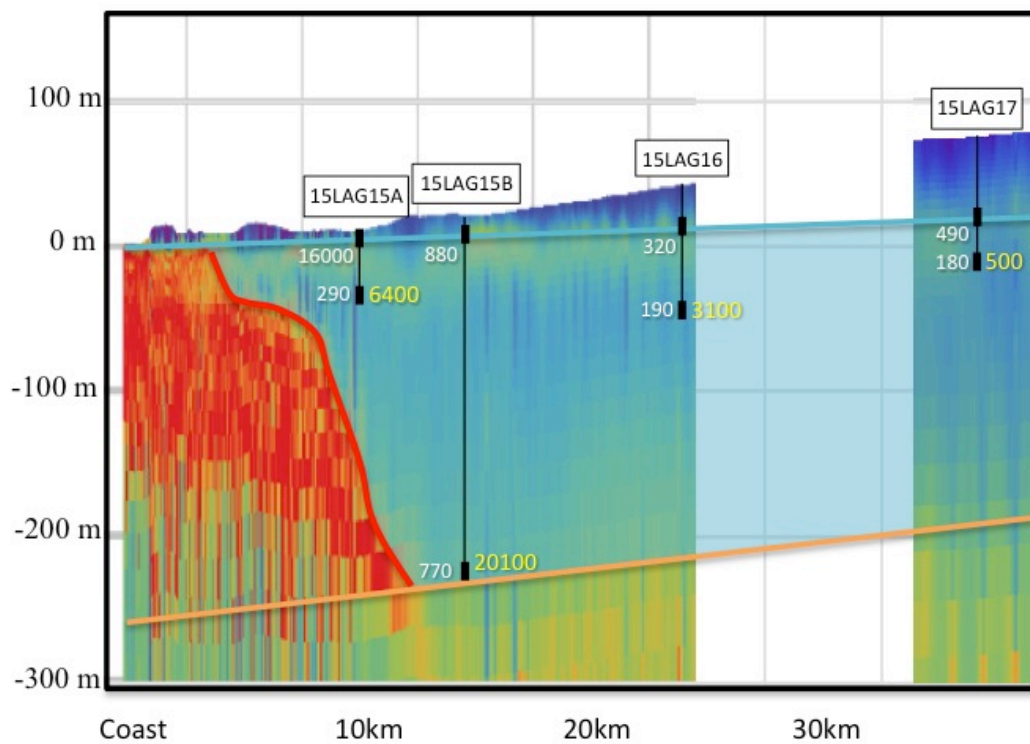


Figure 14. Distribution of apparent age and salinity along two inferred groundwater flow transects, superimposed on an AEM conductivity-depth sections that show base of Broome Sandstone and position of the saltwater interface (sections courtesy N. Wright, DAFWA). Bore locations are shown in black, ages in years are shown in yellow text, and salinities in mg/L as TDS are shown in white text.

The second hypothesis is that the age and salinity of the groundwater reflects upward leakage from the Wallal Sandstone aquifer, driven by the artesian heads and resulting hydraulic gradient. This hypothesis differs from the previous one in that advection is the driving transport mechanism, rather than diffusion. While it is theoretically possible to estimate the upward advective flux between the Wallal Sandstone and Broome Sandstone aquifers, this would have very large uncertainty due to the unknown vertical hydraulic conductivity of the aquitard, particularly if most flux occurs via faults and fractures. Hence the only way to test this hypothesis with the current data is to use hydrochemistry and stable isotope results along the transect from bore 15LAG17I to 15LAG15BD (Figure 14(b)). The closest Wallal Sandstone bore with chemistry data is Talgarno #1 (approx. 35 km from 15LAG15BD) and the next closest bore is Sandfire Artesian MRD025 (approx. 110 km. from 15LAG15BD); the latter also has stable H/O isotope data. Based on the chemical compositions alone (Figure 15) there may be some evidence of groundwater at bore 15LAG15BD receiving upward leakage from the Wallal Sandstone. Likewise, the stable isotope data (Figure 16) may provide some evidence, but neither dataset can confirm or refute this hypothesis.

Based on the available information, the first mechanism (i.e. diffusion from the underlying aquitard) is considered to be the most plausible explanation for higher salinity observations in deep bores near the coast. Regardless, this is unlikely to impact future groundwater development opportunities in the region, as they will likely target shallower depths of the aquifer that are higher yielding and less expensive to drill. The only direct implication to this study is that recharge rates estimated using chloride mass balance for these bores should not be used for future water allocation planning purposes. Hence the recommendation to use the median recharge rate from all bores.

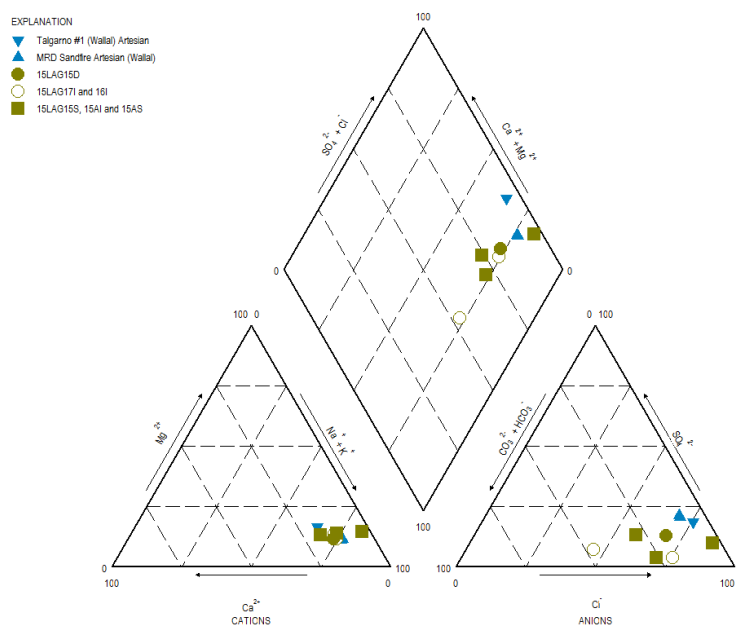


Figure 15. Piper diagram showing possible evidence for groundwater in deep Broome Sandstone bore 15LAG15BD being a mixture of water from up-gradient (e.g., bores 15LAG17I/16I) and the underlying Wallal Sandstone aquifer.

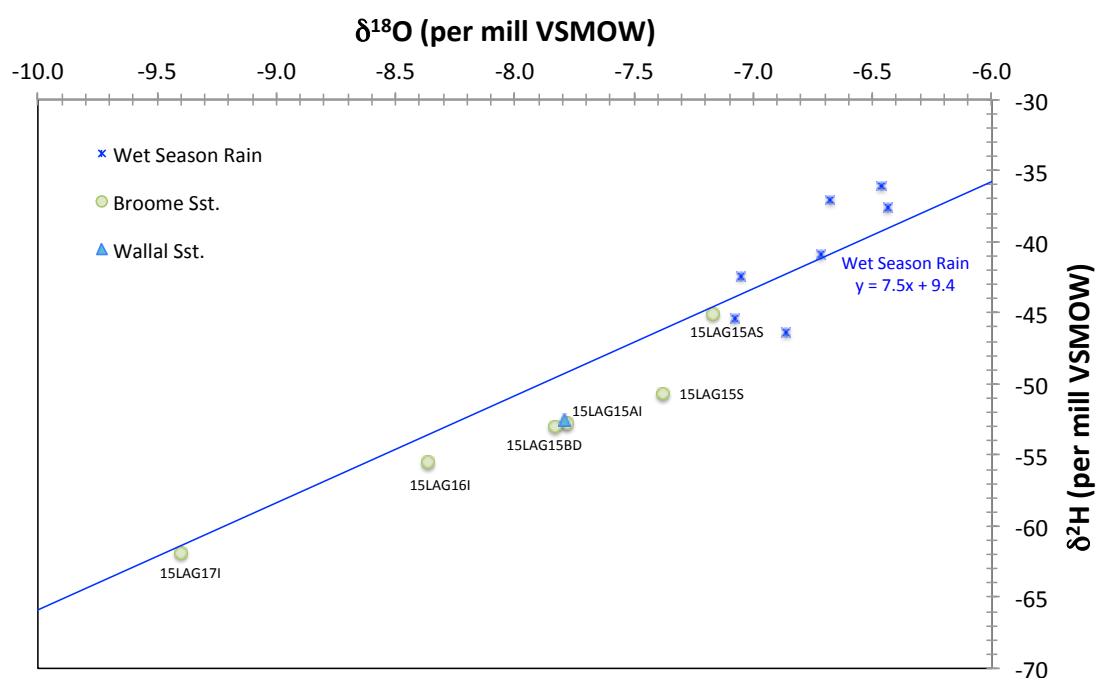


Figure 16. Stable H/O isotope plot showing possible evidence for groundwater in deep Broome Sandstone bore 15LAG15BD being a mixture of water from up-gradient (e.g., bores 15LAG17I/16I) and the underlying Wallal Sandstone aquifer.

4.5. Comparison with previous isotope studies in the West Kimberley

The stable hydrogen and oxygen isotope compositions of LaGrange groundwater samples are remarkably similar to those measured in groundwater from other parts of the West Kimberley region, including the Broome Sandstone Aquifer on Dampier Peninsula (unpublished data provided courtesy of J. Searle, Department of Water) and the Wallal Sandstone Aquifer in the West Canning Basin (Meredith, 2009; 2010; Meredith et al., 2014) (Figure 17). This similarity reveals a consistency in the recharge mechanism of rapid infiltration, without significant evaporative loss, following only the heaviest rainfall events. However, it remains unknown what is the threshold rainfall event required to generate recharge. Similar compositions have also been measured in regional groundwater samples taken from the Fitzroy River catchment (Harrington et al., 2011), although the spread of data shown for this area in Figure 17 reflects some samples from shallow piezometers adjacent a billabong.

The range of estimated groundwater ages for shallow bores sampled in LaGrange (modern to about 12,000 years) is also consistent with the results of other studies in the region. For example, Meredith et al. (2014) report sub-modern ages (greater than 60 years but less than ~500 years) for two bores in the Broome Sandstone in the West Canning Basin, and a range of ages from modern to 37,000 years for the underlying Wallal Sandstone. Groundwater samples from even further down the flow-path in the Wallal Sandstone have been estimated to be up to 45,300 years old (Meredith, 2009; 2010). Samples from the Broome Sandstone on Dampier Peninsula are currently being analysed and interpreted, and will allow further comparison with LaGrange samples when available.

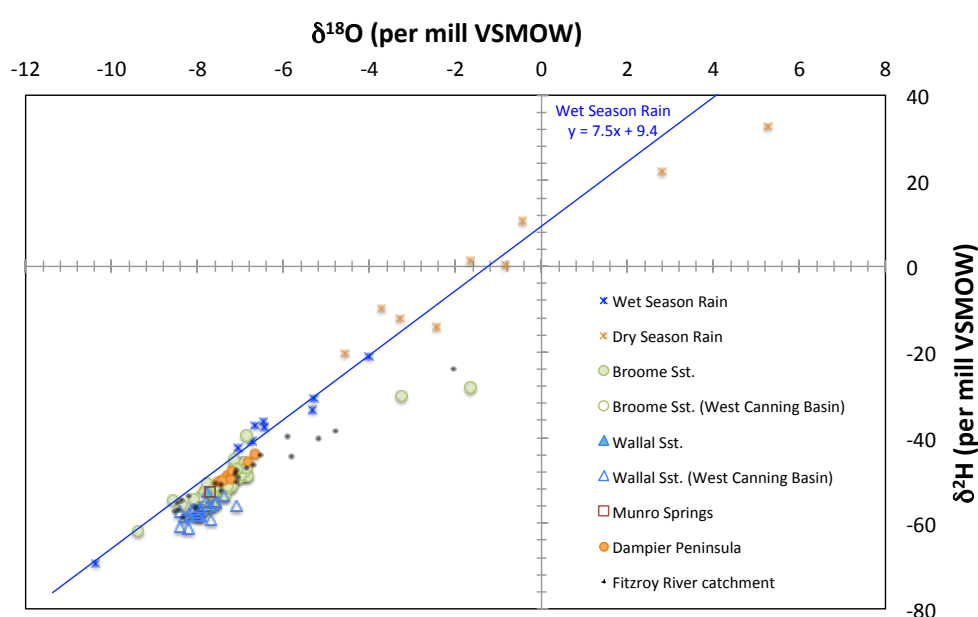


Figure 17. Comparison of stable H/O isotope compositions measured in this project with previous studies in West Canning Basin (Meredith, 2009, 2010; Meredith et al., 2011), Dampier Peninsula (data courtesy of J. Searle, Department of Water WA), and Fitzroy River catchment (Harrington et al., 2011).

5. Conclusions and Recommendations

The Na-Ca-Cl-HCO₃ to Na-Cl compositions of groundwater in the Broome Sandstone aquifer are consistent with a source of solutes from aerosols in rainfall of marine origin, followed by minimal water-rock interaction including weathering of soil carbonates.

Stable hydrogen and oxygen isotope compositions of groundwater samples are all relatively depleted in the heavy isotopes compared to the composition of bulk rainfall samples, particularly rainfall in the dry season. This data supports a conceptual model of recharge occurring after intense monsoonal rainfall events in the wet season. These results are similar to those obtained from previous work in the West Canning Basin, the Dampier Peninsula, and the Fitzroy River catchment.

Three different environmental tracer based methods for estimating recharge rates have produced remarkably consistent results, despite recognised differences in the spatial and temporal scales over which they apply. For each method the mean values are biased towards one or two very high values, which are not consistent between bores. Therefore, median values of recharge rates for the three methods (11.6 – 16.5 mm/yr.) are considered to reflect the areal and temporal distribution of recharge and be better suited to future aquifer assessment.

Residence times of groundwater flow range from 'modern' (i.e., effectively 0 years) for shallow bores to more than 20,000 years for deep bores in down-gradient parts of the aquifer. The available groundwater chemistry and stable H/O isotope information provides inconclusive evidence for the source of water to Munro Springs, however the age of one spring sample is consistent with upwelling groundwater from deeper parts of the Broome Sandstone originating further east.

Future investigations in the region should aim to better characterise the hydrochemistry of the Wallal Sandstone aquifer, particularly in areas where upward leakage may be occurring to springs (e.g., Mandora Marsh) and to further understand the potential for preferential leakage into deep coastal regions of the Broome Sandstone.

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7. APPENDIX A. Chemistry results from 2013 bore inventory sampling.

ChemCentre ID	Bore ID	Client ID	Sampled	Na_total Sodium mg/L	K_total Potassium mg/L	Ca Calcium mg/L	Mg Magnesium mg/L	Cl Chlorine mg/L	S_total Sulfur mg/L	N_Nox Nitrogen as Nitrogen mg/L	Alkalin Alkalinity mg/L	Br Bromide mg/L	Fe_total Iron mg/L	Si_total Silicon mg/L	Sr_total Strontium mg/L	B_total Boron mg/L	TDS_calc Total Dissolved Solids mg/L	
Method Code				IMET1WTICP	IMET1WTICP	IMET1WTICP	IMET1WTICP	ICO1WCD	IMET1WTICP	INTAN1WFIA	IALK1WATI	IBROW1WAIC	IMET1WTICP	IMET1WTICP	IMET1WTICP	IMET1WTICP	ISOL1WDC	
Limit of Reporting				0.2	0.1	0.1	0.1	1	0.5	0.01	1	0.02	0.01	0.05	0.002	0.02	5	
Units																		
BME SST	12E2243/001	Bluetongue	SHA009_20130612_001	12/06/2013	72.1	4.8	15.8	8.2	115	2.5	7	53	0.52	<0.01	35	0.26	0.32	310
BME SST	12E2243/002	Gilberts	SHA010_20130612_002	12/06/2013	64.9	6.2	13.1	7.6	94	1.5	7.6	49	0.47	<0.01	33	0.2	0.27	270
BME SST	12E2243/003	Redwing	SHA014_20130612_003	12/06/2013	80.6	3.4	18.2	10.4	139	2.9	6.1	40	0.6	0.04	38	0.36	0.27	330
BME SST	12E2243/004	Brains	SHA011_20130612_004	12/06/2013	81.7	1.8	15.9	8.8	138	3.6	5.5	35	0.62	<0.01	39	0.29	0.29	320
BME SST	12E2243/005	Nowhere	SHA012_20130612_005	12/06/2013	73.6	2	14.1	7.3	105	2.5	6.5	57	0.49	0.04	36	0.24	0.34	290
BME SST	12E2243/006	Homestead	SHA006_20130612_006	12/06/2013	80.3	3.9	18	10.3	124	3.3	7	64	0.58	0.03	36	0.31	0.37	350
BME SST	12E2243/007	Homestead	SHA006_20130612_006_N	12/06/2013	82.4	4	18	10.4	128	3.4	7.1	64	0.57	0.03	37	0.31	0.4	360
BME SST	12E2320/001	Silent Valley 2	NIT021_20130623_007	23/06/2013	33.6	5.9	10.3	6.7	53	2.8	4.2	37	0.2	<0.01	25	0.2	0.1	170
BME SST	12E2320/002	No. 3 solar	NIT017_20130623_008	24/06/2013	318	20.2	32.3	24.8	433	36	0.71	187	1.4	<0.01	34	0.51	0.6	1000
BME SST	12E2320/003	Foxes solar	NIT018_20130623_009	24/06/2013	98.5	14	38.4	10.3	137	15	4.1	116	0.61	<0.01	29	0.27	0.3	460
BME SST	12E2320/004	Pauls bore	NIT012_20130623_010	24/06/2013	325	14.8	77.4	42.1	551	34	6.4	217	1.8	0.01	55	1.4	0.6	1300
BME SST	12E2320/005	Station yards bore	NIT007_20130623_011	24/06/2013	162	9.4	29.1	14.5	209	21	3.1	136	0.78	<0.01	33	0.49	0.5	590
BME SST	12E2320/006	HB02	NIT008_20130623_012	24/06/2013	168	10.6	67.8	24.1	335	15	7.8	143	1.1	<0.01	34	0.96	0.49	800
BME SST	12E2320/007	Schultz bore	NIT019_20130623_013	25/06/2013	248	7.6	45.8	30.2	401	7.2	1.6	254	1.3	<0.01	34	1.2	0.72	940
BME SST	13E0080/001	PB EF	SHG003_20130703_014	3/07/2013	31.8	1.2	5.5	3	39	0.9	2.8	26	0.16	0.05	4.8	0.1	0.11	120
BME SST	13E0080/002	PB JK	SHG005_20130703_015	3/07/2013	22.2	1.7	4.1	2.4	29	0.7	2.2	21	0.13	<0.01	3.1	0.062	0.08	89
BME SST	13E0080/003	PB AB	SHG001_20130703_016	3/07/2013	55.9	2.5	9.5	6	73	1.8	5.6	40	0.34	<0.01	7	0.17	0.18	220
BME SST	13E0080/005	3S	SHG007_20130704_018	4/07/2013	145	94.3	49.6	24.6	227	30	94	11	0.7	0.26	21	0.75	0.43	940
BME SST	13E0080/006	3D	SHG008_20130704_019	4/07/2013	68.7	4.5	14.6	8.5	102	2.1	6.9	58	0.45	0.01	30	0.23	0.23	290
BME SST	13E0080/007	Shamrock bore #1	SHA007_20130705_020	5/07/2013	61.7	4.9	9	5.6	75	1.8	5.7	55	0.33	0.02	31	0.15	0.22	230
BME SST	13E0080/008	Shamrock bore #2	SHA006_20130705_021	5/07/2013	72.5	2.5	17.7	9.9	123	2.9	7.1	53	0.46	0.1	32	0.29	0.28	310
BME SST	13E0080/009	MB01	NIT006_20130706_022	6/07/2013	125	11	16.5	10	187	18	2.9	66	0.64	0.13	30	0.27	0.28	460
BME SST	13E0080/010	PB01	NIT004_20130707_023	7/07/2013	130	8.6	30.3	17.7	204	15	2	137	0.72	<0.01	25	0.49	0.37	520
BME SST	13E0080/011	Old hort bore SE	NIT011_20130707_024	7/07/2013	135	6.3	24.3	11.9	192	19	3.1	120	0.63	0.02	35	0.38	0.39	510
BME SST	13E0080/012	Old hort bore NW	NIT005_20130707_025	7/07/2013	133	11	31.1	15.5	241	16	3.6	114	0.79	0.1	30	0.44	0.37	570
BME SST	13E0080/013	HB01	NIT010_20130708_026	8/07/2013	152	7	36.1	14.1	254	18	3.3	131	0.82	<0.01	35	0.55	0.43	600
BME SST	13E0080/014	Shelamar 2	SHL002_20130708_027	8/07/2013	59.9	3.2	23.7	10.1	112	3.1	4.8	59	0.45	0.37	33	0.37	0.17	310
BME SST	13E0080/015	Shelamar 4	SHL004_20130708_028	8/07/2013	55.1	2.4	15.9	7.4	84	2.1	4.2	56	0.3	0.04	36	0.27	0.2	240
BME SST	13E0080/016	Shelamar 11	SHL011_20130709_029	9/07/2013	59	4	18.7	9	98	4	5.3	50	0.38	0.16	33	0.33	0.17	280
BME SST	13E0080/017	Shelamar 9	SHL009_20130709_030	9/07/2013	68.1	7.2	13.5	8.2	91	8.5	4.1	55	0.38	<0.01	24	0.24	0.18	280
BME SST	13E0080/018	shelamar 12	SHL012_20130709_031	9/07/2013	64.1	5	17.6	8.7	99	5.5	5.1	54	0.4	<0.01	29	0.29	0.18	290
BME SST	13E0080/019	Shelamar 14	SHL014_20130709_032	9/07/2013	66.7	6.1	15.5	8.3	91	6.9	4.2	63	0.36	<0.01	26	0.26	0.2	290
BME SST	13E0080/020	Shelamar 13B	SHL013B_20130709_033	9/07/2013	111	4.2	20.4	8.9	166	2.4	6.4	101	0.56	0.48	37	0.34	0.47	420
BME SST	13E0080/021	Shelamar 8	SHL008_20130708_034	9/07/2013	54.8	2.9	18.5	8.8	89	2	4.2	60	0.34	<0.01	35	0.33	0.19	260
BME SST	13E0080/022	Shelamar 15	SHL015_20130709_035	9/07/2013	59.2	5.5	11.7	6.9	76	5.5	3.6	60	0.33	0.02	26	0.21	0.19	250
BME SST	13E0080/023	Shelamar 10	SHL010_20130709_036	9/07/2013	58	3.5	16.8	8.6	90	2.9	6.1	50	0.36	0.06	34	0.3	0.2	260
BME SST	13E0080/024	Shelamar 13A	SHL013A_20130709_037	9/07/2013	58.4	3.2	22.2	10.2	103	3.2	4.8	57	0.4	0.02	32	0.37	0.18	290
BME SST	13E0080/025	MRD La Grange #1	MRD012_20130710_038	10/07/2013	83.4	1	15.8	11.6	135	3	4.7	48	0.52	0.03	37	0.32	0.25	340
BME SST	13E0351/001	New Corbetts bore	MAA048_20130819_039	19/08/2013	63.8	3.6	43	8.6	102	3.7	7.8	115	0.34	<0.01	35	0.52	0.25	370
BME SST	13E0351/002	MRD Teds bore	MRD026_20130819_040	19/08/2013	50.4	2.8	25.2	7.6	76	2.7	5	74	0.25	1.2	34	0.36	0.19	260
BME SST	13E0351/003	MRD Gravel pit	MRD024_20130820_041	20/08/2013	104	4.9	57.1	14.7	171	7.7	7.9	178	0.51	1.8	44	0.87	0.47	540
BME SST	13E0351/004	Sampsom well	MAA043_20130820_042	20/08/2013	115	3	67.4	17.6	216	5	9.1	188	0.61	0.1	44	0.78	0.32	610
BME SST	13E0351/005	House bore west	MAA026_20130820_043	20/08/2013	130	5.3	62.9	20.5	216	7	4.6	238	0.54	0.07	39	0.82	0.43	650
BME SST	13E0351/006	Moojan well	MAA041_20130820_044	20/08/2013	129	52.2	50.6	22.6	178	20	9.4	276	0.55	0.03	42	1.6	0.58	690
BME SST	13E0351/007	Nalgi well	MAA018_20130820_045	20/08/2013	342	17.9	49.4	35.2	567	20	8.1	238	1.6	0.19	34	0.93	0.58	1300
BME SST	13E0351/008	House Garden Well tank	MAA014_20130820_046	20/08/2013	181	13.8	40.4	23.2	303	9.3	5.5	238	0.84	0.04	38	0.81	0.47	790
BME SST	13E0351/009	Glugs bore	MAA029_20130820_047	20/08/2013	275	14.5	50.6	34.5	513	12	6.1	201	1.4	<0.01	37	0.8	0.58	1100
BME SST	13E0351/010	Tank bore	MAA034_20130820_048	20/08/2013	72.9	4.4	50.4	13.7	133	5.1	7.3	165	0.39	<0.01	44	0.77	0.3	440
BME SST	13E0351/011	Gravel pit 1 (north)	MAA030_20130820_049	21/08/2013	94.7	5.4	61.7	18.9	223	9.8	6.3	150	0.62	0.01	37	0.84	0.28	560
BME SST	13E0351/013	Tafts bore	MAA051_20130821_051	21/08/2013	82	4.1	37.3	11.5	153	5.2	10	81	0.49	0.32	38	0.59	0.25	420
BME SST	13E0351/014	House garden well	MAA014_20130821_052	21/08/2013	232	21	62.2	28.5	381	13	6.6	249	1.1	0.06	38	0.98	0.51	990
BME SST	13E0351/015	Old Tafts bore	MAA047_20130821_053	21/08/2013	142	5.9	73.2	23.1	300	12	10	161	0.91	1.8	42	1.1	0.44	750
BME SST	13E0427/001	Unnamed coast bore 2	54 ANA017_20130827_054	27/08/2013	11300	631	268	789	17300	830	0.2	252	58	0.13	30	18	7.8	27000
BME SST	13E0427/002	Curdigby Solar	55 ANA026_20130827_055	27/08/2013	334	37.2	15	31.6	398	33	2.2	254	1.1	0.13	43	0.35	1.3	1000
BME SST	13E0427/004	Anna Plains PB1	57 ANA042_20130827_057	27/08/2013	167	20.1	21.9	26.6	267	27	3.3	87	0.7	0.06	35	0.38	0.35	650
BME SST	13E0427/005	No. 4 bore	58 ANA028_20130827_058	27/08/2013	52.2	5.2	15.1	7.6	75	1.9	5.5	44	0.26	<0.01	58	0.3	0.19	230
BME SST	13E0427/006	Phire bore	59 ANA044_20130827_059	27/08/2013	89.1	4.4	31.6	13.1	137	3.3	3.8	109	0.51	<0.01	49	0.51	0.34	390
BME SST	13E0427/007	Spinifex 2	60 ANA021_20130828_060	28/08/2013	63.6	7.3	22.7	9.4	84	1.9	3.5	95	0.29	1.5	36	0.34	0.3	290
BME SST	13E0427/008	Milly Milly bore	61 ANA060_20130828_061	28/08/2013	74	9.4	32.1	8.4	94	2.9	5.1	113	0.33	0.04	41	0.34	0.31	330
BME SST	13E0427/009	MRD Anna Plains #5	62 MRD017_20130828_062	28/08/2013	385	30.6	65.9	47	690	72	3.7	126	1.7	0.03	27	1.1	0.44	1500
BME SST	13E0427/010	MRD Anna Plains #4	63 MRD018_20130828_063	28/08/2013	58.3	8.4	25.7	13.4	89	4.4	4.2	91	0.28	0.09	34	0.44	0.23	300
BME SST	13E0427/011	Curlys bore	64 ANA059_20130828_064	28/08/2013	65	8.9	42.8	15.4	108	4.5	6.1	121	0.					

ChemCentre ID	Bore ID	Client ID	Sampled	Na_total Sodium IMET1WTICP	K_total Potassium IMET1WTICP	Ca Calcium IMET1WTICP	Mg Magnesium IMET1WTICP	Cl Chlorine ICO1WCDA	S_total Sulfur IMET1WTICP	N_Nox Nitrogen as Nitrogen Oxides INTAN1WFIA	Alkalini Alkalinity ALK1WATI	Br Bromide IBLOW1WAIC	Fe_total Iron IMET1WTICP	Si_total Silicon IMET1WTICP	Sr_total Strontium IMET1WTICP	B_total Boron IMET1WTICP	TDS_calc Total Dissolved Solids ISOL1WDCA	
Method Code				0.2	0.1	0.1	0.1	1	0.5	0.01	1	0.02	0.01	0.05	0.002	0.02	5	
Limit of Reporting				mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
Units																		
BME SST	13E0427/028	MRD Sandfire #2	81 MRD022_20130831_081	31/08/2013	23800	1360	958	1870	44900	2500	0.23	204	120	0.25	23	21	11	54000
BME SST	13E0427/029	Nurdy bore	82 ANA068_20130831_082	31/08/2013	463	63.9	67.8	56.3	701	52	4.4	321	1.8	0.11	41	1.1	1.1	1600
BME SST	13E0427/030	MRD Nita Plains #2	83 MRD014_20130901_083	1/09/2013	86.3	6.3	28.8	13.6	119	7.4	3.3	91	0.48	0.03	35	0.41	0.33	390
BME SST	13E0427/031	MRD Stanley #1	84 MRD013_20130901_084	1/09/2013	138	10	27.4	14.6	206	17	3.1	89	0.76	0.03	37	0.44	0.37	530
BME SST	13E0427/032	Garden bore solar	85 MAA036_20130903_085	3/09/2013	178	9	42.6	24.1	234	12	6.7	227	0.9	0.02	41	0.77	0.49	690
BME SST	13E0427/033	Mooglie bore	86 MAA044_20130903_086	3/09/2013	114	3.7	44.1	14.2	186	7.2	7.1	113	0.62	<0.01	41	0.71	0.32	500
BME SST	13E0427/034	Bakers bore	87 MAA050_20130903_087	3/09/2013	81.8	5.3	45.3	12.8	112	4.5	14	123	0.44	0.03	42	0.62	0.27	410
BME SST	13E0427/035	Woolenappa bore	88 MAA042_20130903_088	3/09/2013	286	9.2	80.1	29.5	362	15	6.7	347	1.4	0.15	49	1.2	0.8	990
BME SST	13E0427/036	Sandfire roadhouse boundary bore	89 SAF002_20130903_089	3/09/2013	64.2	2.8	50.7	8	87	3.7	7	125	0.33	0.01	40	0.56	0.24	340
BME SST	13E0427/037	MRD Anna Plains #1	90 MRD021_20130903_090	3/09/2013	817	58.2	55.4	69	943	110	4.7	127	2.4	0.17	31	0.9	0.52	2100
BME SST	13E0427/038	Unnamed coast bore 1	91 ANA004_20130904_091	4/09/2013	1600	84.9	95.1	112	2110	180	0.01	341	6.9	0.28	13	4.3	2	4400
BME SST	13E0427/039	McPhee well	92 ANA007_20130904_092	4/09/2013	309	39.2	68.7	54.4	444	55	2.5	298	1.7	0.01	19	4.2	0.56	1200
BME SST	13E0427/040	Anna Plains Garden bore	93 ANA039_20130904_093	4/09/2013	144	15.9	57.6	27.1	284	10	1.4	182	0.95	0.12	51	0.86	0.44	710
BME SST	13E0427/041	Anna Plains Homestead bore	94 ANA038_20130904_094	4/09/2013	205	22.5	71	42.5	448	32	1.8	116	1.1	<0.01	46	1.1	0.39	980
BME SST	13E0607/001	Burnies bore	ROE006_20131001_095	1/10/2013	129	9.5	14.7	19.3	244	5.5	11	23	0.85	<0.01	33	0.3	0.18	540
BME SST	13E0607/002	Jerricop bore	ROE002_20131001_096	1/10/2013	86.3	10.5	11.1	15.2	146	3.1	11	47	0.62	<0.01	35	0.24	0.25	390
BME SST	13E0607/003	Ungani bore	ROE001_20131001_097	1/10/2013	93	10.8	13.3	16.5	164	4.3	8.7	60	0.68	<0.01	35	0.32	0.28	420
BME SST	13E0607/004	Frog Hole bore	ROE003_20131001_098	1/10/2013	48.8	7.2	7.6	9.8	72	1.6	12	27	0.29	0.02	47	0.18	0.17	230
BME SST	13E0607/005	McGregors bore	ROE025_20131001_099	1/10/2013	49.3	6.6	11.8	16	86	1.2	22	14	0.31	0.05	35	0.31	0.16	290
BME SST	13E0607/006	Fraser Lake bore	ROE024_20131001_100	1/10/2013	59.7	5.1	8.9	9.3	82	1.7	8.3	47	0.32	<0.01	36	0.2	0.16	250
BME SST	13E0607/007	Sheep Camp bore	ROE012_20131002_101	2/10/2013	40.6	5.3	8.7	8.8	71	1.3	9	20	0.27	<0.01	35	0.18	0.13	210
BME SST	13E0607/008	Coomacop bore	ROE019_20131002_102	2/10/2013	44.9	5.7	9.1	10.3	80	1.6	9.2	21	0.31	<0.01	35	0.2	0.14	230
BME SST	13E0607/009	Chainpump 1 Solar	ROE022_20131002_103	2/10/2013	58.8	5.8	11.9	12.6	113	2.2	11	21	0.43	<0.01	42	0.26	0.17	290
BME SST	13E0607/011	Ram bore	ROE008_20131002_105	2/10/2013	201	27.8	61.2	35	375	20	9.1	179	1.1	<0.01	45	1.5	0.32	950
BME SST	13E0607/012	East Crab Creek camp bore	ROE015_20131003_106	3/10/2013	53.7	5.3	6.7	7.8	74	3.1	7.8	32	0.27	<0.01	40	0.16	0.24	230
BME SST	13E0607/013	Cow Bore camp bore	ROE005_20131003_107	3/10/2013	64.3	5.6	5.8	7	78	2	7.5	56	0.31	0.19	38	0.13	0.27	250
BME SST	13E0607/014	Overflow bore	ROE010_20131003_108	3/10/2013	51.3	6.3	10.3	12.3	90	1.7	9.4	34	0.33	0.09	35	0.24	0.15	260
BME SST	13E0607/015	Jills bore	ROE016_20131003_109	3/10/2013	87.4	5	11.5	11.4	122	5.3	8.9	57	0.42	<0.01	39	0.24	0.36	360
BME SST	13E0607/016	House bore (Generator)	ROE027_20131003_110	3/10/2013	64.3	3.1	5.6	9.5	110	2.4	3.1	35	0.42	0.04	44	0.18	0.21	270
BME SST	13E0678/003	Bidyadanga 2-93	FRA022_20131008_113	8/10/2013	83	3.5	16.1	8.7	119	5.9	6.1	76	0.49	<0.01	42	0.24	0.33	350
BME SST	13E0678/004	Bidyadanga 1-93	FRA021_20131008_114	8/10/2013	132	5	17.6	8.9	171	7.2	5.5	122	0.64	<0.01	46	0.27	0.48	480
BME SST	13E0678/005	Winstons Community (Wanamulynedong)	FRA031_20131009_115	9/10/2013	99.5	2.9	27.5	14.7	220	4.2	7	49	0.76	0.01	37	0.46	0.26	480
BME SST	13E0678/006	Frazier Downs Homestead north	FRA040_20131009_116	9/10/2013	207	16.2	30.5	25.5	396	13	2.8	118	1.3	0.04	42	0.58	0.42	840
BME SST	13E0678/007	Kitty well (Brumbungial)	FRA052_20131009_117	9/10/2013	174	16	24.1	19	312	22	2.4	103	1.1	0.07	37	0.39	0.31	700
BME SST	13E0678/008	Rollah bore	FRA028_20131010_118	10/10/2013	212	14.5	24.3	22.8	374	12	2.8	135	1.3	0.09	37	0.43	0.54	800
BME SST	13E0678/009	Red Tank bore	FRA065_20131010_119	10/10/2013	182	15.5	12.7	20	285	27	3.4	100	0.94	0.29	32	0.29	0.38	670
BME SST	13E0678/010	Garimba Community bore	FRA001_20131011_120	11/10/2013	196	3	25.8	15	344	8.4	7	110	1.1	0.02	49	0.41	0.57	730
BME SST	13E0678/011	Red Tank new bore	FRA064_20131012_121	12/10/2013	1010	66.2	16.3	41.1	1410	100	11	329	4.9	0.05	33	0.36	1.6	3100
BME SST	13E0678/012	Gingers new bore	FRA055_20131012_122	12/10/2013	156	4.7	58.7	29.9	342	8.6	13	122	1.1	<0.01	56	0.84	0.41	790
BME SST	13E0678/013	Port Smith cove bore	FRA010_20131012_123	12/10/2013	10700	401	375	1090	18200	790	0.11	146	66	0.09	31	7.8	0.48	28000
BME SST	13E0678/014	Port Smith old bore	FRA011_20131013_124	13/10/2013	186	6.1	21.2	12.7	321	7.4	4	81	1.1	1.7	32	0.4	0.36	680
BME SST	13E0678/015	New Tip monitoring bore	FRA027_20131013_125	13/10/2013	255	5.6	27.5	17.6	343	14	1.8	212	1.2	0.25	36	0.48	0.88	850
BME SST	13E0678/016	Tips bore	FRA018_20131013_126	13/10/2013	291	14.5	28	29.2	554	14	4.1	71	1.7	0.24	35	0.53	0.31	1100
BME SST	13E0678/017	Gourdon Bay camp bore	FRA002_20131013_127	13/10/2013	997	27.7	72.3	51.4	1490	43	2.1	297	5.8	0.75	45	1.2	1.2	3100
BME SST	13E0678/018	Port Smith park bore	FRA009_20131014_128	14/10/2013	123	3.1	23.5	11.5	231	5.8	5.8	64	0.81	0.1	34	0.41	0.31	510
BME SST	13E0773/001	PB EF	SHG003_20131016_129	16/10/2013	69.2	2.8	13.6	7.5	88	2.1	6	58	0.37	<0.01	35	0.21	0.26	280
BME SST	13E0773/002	PB AB	SHG001_20131016_130	16/10/2013	75.5	3.5	14.2	9	101	2.5	7.1	55	0.42	0.07	35	0.23	0.28	310
BME SST	13E0773/003	PB GH	SHG004_20131016_131	16/10/2013	71.5	5.3	15.9	8.9	111	2.6	6.2	56	0.4	<0.01	32	0.23	0.25	300
BME SST	13E0773/004	PB JK	SHG005_20131016_132	16/10/2013	66.5	5.2	12.6	7	82	2.1	5.6	56	0.35	<0.01	32	0.19	0.24	260
BME SST	13E0773/005	PB CD	SHG002_20131016_133	16/10/2013	72.7	3	14.8	9.4	96	2.4	8	51	0.37	0.02	37	0.26	0.26	300
BME SST	13E0773/006	Ringers bore	THA010_20131017_134	17/10/2013	74.4	4.8	13.6	12.1	110	2.7	11	25	0.43	0.04	48	0.31	0.24	320
BME SST	13E0773/007	Fly Flat house bore	THA002_20131017_135	17/10/2013	207	10.3	29.9	35.1	427	9	8.4	34	1.3	0.03	53	0.69	0.26	860
BME SST	13E0773/008	No. 5 bore	THA003_20131017_136	17/10/2013	65	5.9	14	13.4	109	2.3	10	25	0.45	0.02	41	0.31	0.18	310
BME SST	13E0773/009	No. 4 bore	THA005_20131017_137	17/10/2013	130	5.1	24	24.4	258	9.6	9.8	29	0.91	<0.01	52	0.6	0.26	570
BME SST	13E0773/010	Eco Beach Production bore	EC0004_20131018_138	18/10/2013	137	3.5	20.7	12.6	196	5	6.8	88	0.7	<0.01	42	0.38	0.25	490
BME SST	13E0773/011	MRD Fly Flat #1	MRD004_20131019_139	19/10/2013	73.4	6.7	14.3	13.5	121	2.4	12	36	0.42	0.01	53	0.32	0.24	330
BME SST	13E0773/012	MRD Fly Flat #2	MRD003_20131019_140	19/10/2013	70.7	5.6	12	12.9	123	2.6	12	17	0.4	0.04	58	0.3	0.25	320
BME SST	13E0773/013	MRD Godwyns #2	MRD007_20131019_141	19/10/2013	83.9	3.2	15.2	12.5	166	4	7.1	16	0.52	<0.01	44	0.36	0.17	360
BME SST	13E0773/014	MRD Maffia	MRD006_20131019_142	19/10/2013	108	2.1	14.2	12.2	172	5.6	8.5	28	0.64	2.8	46	0.34	0.29	430
BME SST	13E0773/015	Toms tank bore	FRA020_20131020_143	20/10/2013	118	1	13.3	10.9	149	5.4	4.4	99	0.58	49	57	0.25	0.4	430
BME SST	13E0773/016	Injudinah bore No 4	FRA005_20131020_144	20/10/2013	261	9.4	39.4	28.8	441	10	6.9	113	1.3	0.1	47	0.71	0.5	950
BME SST	13E0773/017	Pindan bore	FRA012_20131020_															

	ChemCentre ID	Bore ID	Client ID	Sampled	Na_total	K_total	Ca	Mg	Cl	S_total	N_NOx		Alkalin	Br	Fe_total	Si_total	Sr_total	TDS_calc
					Sodium	Potassium	Calcium	Magnesium	Chlorine	Sulfur	Nitrogen as Nitrogen Oxides		Alkalinity	Bromide	Iron	Silicon	Strontium	Total Dissolved Solids
Method Code					iMET1WTICP	iMET1WTICP	iMET1WCICP	iMET1WCICP	iCO1WCDA	iMET1WTICP	iNTAN1WFIA		iALK1WATI	iBRLOW1WAIC	iMET1WTICP	iMET1WTICP	iMET1WTICP	iSOL1WDCA
Limit of Reporting					0.2	0.1	0.1	0.1	1	0.5	0.01		1	0.02	0.01	0.05	0.002	5
Units					mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
SURFACE WATER	13E0427/026	Salt Creek site 2	79 ANASC2_20130831_079	31/08/2013	9050		874	442	436	13400	1600 <0.01		222		29	0.03	14	11
SURFACE WATER	13E0427/027	Salt Creek site 1	80 ANASC1_20130831_080	31/08/2013	8380		894	470	454	12900	1600 <0.01		139		27	0.06	12	12
SURFACE WATER	13E0678/001	Injudinah lake	FRALAK 20131008 111	8/10/2013	575		34.5	14.3	17.1	891	13 <0.01		112		3.6	0.03	23	0.53
SURFACE WATER	13E0678/002	Injudinah inflow	FRAINP 20131008 112	8/10/2013	128		8.6	29.8	22	202	2.1 <0.01		210		0.44	0.06	54	0.43
WALLAL SST	13E0351/012	MRD Artesian bore	MRD025_20130821_050	21/08/2013	201		8.2	28.1	16	306	42 <0.01		58		0.96	0.68	7.4	0.49
WALLAL SST	13E0427/003	Talgarno Artesian #1	56 ANA029_20130827_056	27/08/2013	360		43.5	92.5	52.1	690	76 <0.01		72		1.3	2	7.8	0.99
WALLAL SST	13E0607/010	Flowing bore (Crab Creek #1)	ROE014_20131002_104	2/10/2013	355		40.3	75.5	39.2	681	36 <0.01		102		1.1	6.3	8	0.77

8. APPENDIX B. Chemistry results from 2014 isotope reconnaissance sampling.

ACU No.	Sample ID	EC	pH	T	Alk	Alk	F ⁻	Cl ⁻	Br ⁻	NO ₃ ⁻	SO ₄ ⁼	Ca	K	Mg	Na	S	B	Fe	Si	Sr
					CaCO3	HCO3	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
1	ROE015	411	5.94	32.4	31.0	37.8	<0.05	75	0.18	35	9.5	6.5	4.8	8.3	58	3.1	0.3	<0.1	38	0.16
2	ROE005	459	6.35	32.3	50.5	61.6	0.06	80	0.22	33	6.0	5.7	6.2	7.4	71	1.9	0.3	<0.1	36	0.13
3	ROE012	387	5.98	31.3	17.5	21.4	<0.05	74	0.19	39	4.0	8.4	5.9	9.9	45	1.3	<0.2	0.2	35	0.18
4	FRA022	647	6.34	32.9	77.4	94.4	<0.05	119	0.37	27	16	16	4.1	9.1	97	5.3	0.4	<0.1	40	0.25
5	NIT019	1880	6.45	32.6	231.5	282.4	<0.2	422	1.1	8.3	26	44	9.1	33	277	8.3	0.7	<0.1	31	1.3
6	NIT025	654	6.15	32.6	54.7	66.7	0.18	113	0.29	2.9	62	9.3	9.5	6.6	103	20	0.3	<0.1	28	0.15
7	NIT-MUN	558	6.90	36.1	61.1	74.5	0.22	94	0.22	20	40	10	10	8.6	91	13	0.2	0.2	29	0.21
8	MRD024	974	6.79	33.1	172.5	210.5	<0.05	164	0.53	38	23	56	5.2	16	115	7.5	0.4	1.0	41	0.89
9	MRD026	528	6.51	33.5	74.7	91.1	<0.05	92	0.24	26	8.2	28	3.2	8.8	59	2.7	<0.2	1.9	34	0.41
10	MRD021	3500	6.99	34.8	127.3	155.3	<0.2	862	1.8	27	290	48	51	59	557	91	0.5	<0.1	29	0.82
11	ANA053	1084	7.09	34.6	126.0	153.7	0.13	226	0.6	19	47	41	14	20	128	15	0.3	<0.1	34	0.50
12	FRA027	1555	6.16	33.4	193.0	235.5	<0.2	340	0.9	10	36	29	6.2	19	263	11	0.9	<0.1	34	0.51

9. APPENDIX C. Chemistry results from 2015 chemistry and isotope survey.

ChemCentre Id	Client Id	Site ID	Sampled	Field EC	ECond	Field pH	pH	Field Alkalinity	Alkalin	Field Temp	Na_total	K_total	Ca_total	Mg_total	Cl	SO4	Br	F	Fe_total	N_NOx	N_total	Si_total
Method Code				IEC1WZSE		IPH1WASE		IALK1WATI			IMET1WTICP	IMET1WTICP	IMET1WTICP	IMET1WTICP	ICO1WCDA	ICO1WCDA	IBRLOW1WAIC	IF1WASE	IMET1WTICP	INTAN1WFIA	INP1WTFIA	IMET1WTICP
Limits of Reporting				0.2		0.1		1			0.2	0.1	0.5	0.1	1	1	0.02	0.05	0.01	0.01	0.01	0.05
Units				mS/m	mS/m			mg/L as CaCO3	mg/L		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
15S1356/001	2015LG01	15LAG01S	4/11/2015	37.5	36.5	6.26	6.9	60	24	33.5	53.4	3.1	4.8	7	73	13	0.33	0.08	0.26	4	4.6	58
15S1356/002	2015LG02	15LAG01D	4/11/2015	303.0	297	6.72	7.4	74	74	34.4	432	26.9	72.5	66.8	807	150	2.8	0.4	0.93	0.76	0.94	8
15S1356/003	2015LG03	15LAG02I	5/11/2015	42.4	41.2	6.11	6.8	36	17	33.6	46.4	6.4	8.4	11.7	82	5	0.37	0.12	<0.01	9.1	9.3	38
15S1356/004	2015LG04	15LAG07I	6/11/2015	57.3	56.2	6.38	7.1	66	56	33.3	67.7	2.2	20.3	12.5	110	7	0.43	0.11	0.02	6.4	6.6	33
15S1356/005	2015LG05	15LAG07S	7/11/2015	97.4	96.5	6.62	7.3	63	51	34.7	144	1.5	21.8	13.9	215	6	0.85	0.4	0.3	19	22	62
15S1356/006	2015LG06	15LAG06D	7/11/2015	102.9	101	7.17	7.8	120	107	35.9	155	15	25	14.6	186	58	0.66	0.34	1.5	0.3	0.55	9.2
15S1356/007	2015LG07	15LAG06S	7/11/2015	103.0	102	6.51	7.3	99	73	34.6	168	3.4	19.9	9.3	215	21	0.85	<0.05	1.3	12	12	51
15S1356/008	2015LG08	15LAG11I	7/11/2015	62.7	61.5	6.77	7.3	96	84	33.4	95.6	5.7	14	8.1	121	13	0.49	0.32	<0.01	5.2	5.9	30
15S1356/009	2015LG09	15LAG11S	7/11/2015	193.8	191	6.62	7.5	300	269	32.8	312	11.6	60.9	26.9	409	44	1.7	0.14	0.09	1.8	4.4	56
15S1356/010	2015LG10	15LAG09I	8/11/2015	45.6	44.3	6.63	7.3	75	64	30.9	64.5	5.6	9.9	7.7	76	8	0.35	0.29	<0.01	5.2	6.1	28
15S1356/011	2015LG11	15LAG09S	8/11/2015	4580.0	4420	7.3	7.7	336	278	33.8	10600	449	217	316	13300	1300	60	0.62	0.01	0.09	0.36	44
15S1356/012	2015LG12	15LAG10D	8/11/2015	56.6	55.5	6.62	7.4	75	66	35.3	84.3	8.1	12.4	7.7	101	27	0.4	0.34	<0.01	1.5	3.2	21
15S1356/013	2015LG13	15LAG10S	9/11/2015	93.5	87.4	6.62	7.3	105	87	32.6	143	2.5	22.6	11.4	166	65	0.62	0.14	4.9	5.7	6.9	59
15S1356/014	2015LG14	15LAG14D	9/11/2015		85.5		8		101		169	10.9	23.8	12.4	113	110	0.43	0.55	44	11	15	45
15S1356/015	2015LG15	15LAG12S	9/11/2015	101.7	101	6.36	7.1	99	87	33.4	147	3.3	32.1	16.6	205	21	0.89	0.21	3.3	8.4	8.5	38
15S1356/016	2015LG16	15LAG08I	9/11/2015	45.5	44.5	6.27	7	72	58	34.3	60.4	4.9	13	8.5	75	5	0.34	0.11	0.15	5.9	7	30
15S1356/017	2015LG17	15LAG19I	11/11/2015	108.2	107	6.91	7.6	105	101	33.2	172	13.3	23.4	15.5	210	71	0.79	0.56	0.04	3.1	3.2	24
15S1356/018	2015LG18	15LAG19S	11/11/2015	34.2	33.2	7.8	8	165	144	34.0	57.3	2.9	13.5	4.9	11	4	0.05	0.77	0.68	1.1	1.9	45
15S1356/019	2015LG19	Nita Downs PB1 (NIT004)	11/11/2015	90.6	91.4		7.7	123	131	33.3	126	8.7	30.9	18	165	40	0.67	0.73	<0.01	1.1	1.7	27
15S1356/020	2015LG20	15LAG20I	11/11/2015	90.0	88.9	6.83	7.5	78	80	33.4	139	14.4	16	11.6	176	53	0.65	0.47	<0.01	1.8	2.6	29
15S1356/021	2015LG21	15LAG20S	11/11/2015	110.2	109	6.92	7.6	126	115	33.7	159	12	35	16.3	238	53	0.8	0.35	0.35	4.5	5.1	45
15S1356/022	2015LG22	15LAG23S	12/11/2015	2170.0	2120	7.16	7.7	300	291	33.7	4090	226	258	347	6310	1600	23	0.87	0.08	1.2	1.6	40
15S1356/023	2015LG23	15LAG23I	12/11/2015	1669.0	1640	7	7.7	360	345	31.3	3130	129	252	274	4950	1100	19	1.1	0.05	1.2	1.7	30
15S1356/024	2015LG24	15LAG16S	13/11/2015	58.8	58.6	6.03	7	57	55	34.9	82.3	3.3	18.7	8.9	127	11	0.49	0.1	0.59	3.9	4.4	38
15S1356/025	2015LG25	15LAG16I	13/11/2015	36.1	34.8	6.45	7.4	75	66	33.9	52.4	5.7	8.8	5.4	52	11	0.22	0.32	0.22	1.4	1.8	30
15S1356/026	2015LG26	Water bore near Cudalgarra #1	15/11/2015	133.2	133	6.72	7.5	120	118	33.0	180	10.7	38.6	27.7	310	15	1.4	0.46	0.01	10	10	35
15S1356/027	2015LG27	Buru Commodore #1 water bore	15/11/2015	53.8	52.2	6.8	7.6	96	94	33.0	75.5	6.4	14.1	9.7	81	6	0.39	0.19	<0.01	7	7.7	45
15S1356/028	2015LG28	Stubbys bore	15/11/2015	34.6	33.6	6.78	7.5	72	57	34.3	54.3	5.6	6.1	4.5	49	16	0.21	0.5	<0.01	3	3.5	29
15S1356/029	2015LG29	15LAG17I	16/11/2015	33.7	32.5	5.65	6.6	30	21	35.0	42.8	9.8	7.7	4	79	5	0.29	0.08	0.2	1.1	1.1	28
15S1356/030	2015LG30	MRD Sandfire atresian bore (MRD025)	16/11/2015		134		7.2		56		214	8.5	28.7	17	303	120	1.1	0.22	0.67	<0.01	<0.01	7.4
15S1356/031	2015LG31	15LAG24D	17/11/2015	13680.0	13100	6.85	7.2	195	179	33.2	37500	2600	858	2140	52300	12000	150	1	0.55	0.03	1.7	7
15S1356/032	2015LG32	15LAG24S	17/11/2015	86.0	85.6	7.28	8	150	143	34.1	113	12	37.3	12.9	126	35	0.46	0.34	0.64	5.4	6.2	36
15S1356/033	2015LG33	15LAG21D	17/11/2015	189.4	188	6.88	7.7	105	83	34.2	281	25.2	46.4	33.6	417	160	1.1	0.61	1.3	2	3.4	25
15S1356/034	2015LG34	15LAG21S	17/11/2015	46.8	46.1	6.77	7.5	60	38	33.8	58.6	4.6	18.1	7.7	93	9	0.36	0.24	0.22	7.3	7.7	48
15S1356/035	2015LG35	15LAG15BS	18/11/2015	159.2	159	6.7	7.6	189	180	33.9	232	6.7	56.2	23.9	362	25	1.4	0.28	0.23	4.6	5.5	44
15S1356/036	2015LG36	15LAG15AI	18/11/2015	53.5	52.2	6.85	7.6	63	57	31.1	76	8	12	8	90	28	0.39	0.41	0.02	3.6	4	21
15S1356/037	2015LG37	15LAG15AS	18/11/2015	2910.0	2840	7.09	7.7		415	31.9	5630	350	186	538	8700	1300	36	0.48	0.24	0.37	0.67	49
15S1356/038	2015LG38	15LAG26PB1	18/11/2015	67.7	67.5	6.48	7.3	60	58	33.3	85.7	6.4	21.5	11.3	133	12	0.6	0.13	0.11	6	6.8	33
15S1356/039	2015LG39	Shamrock station Gilberts bore (SHA010)	23/11/2015	49.3	48.6	6.08	7		47	35.1	64.4	6.3	13.4	8.1	94	5	0.42	0.08	<0.01	7.2	7.3	32
15S1356/040	2015LG40	15LAG15BD	25/11/2015	140.6	141	7.35	7.8		117	35.5	206	26.8	38.7	18.2	321	81	0.89	0.56	0.85	<0.01	0.09	8.4
15S1356/041	2015LG41	DAM001	4/05/2015		67.5		7.6		66		107	8.8	5.3	12.3	134	4	0.66	0.23	<0.01	8.6	8.8	36