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## Broome Sandstone aquifer, La Grange groundwater area: a preliminary report on the hydrochemistry and groundwater recharge rates, with recommendations for future drilling and environmental tracer sampling

Glenn A. Harrington  
*Innovative Groundwater Solutions*

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# Broome Sandstone Aquifer La Grange Groundwater Area



A preliminary report on the hydrochemistry and groundwater recharge rates, with recommendations for future drilling and environmental tracer sampling

Prepared for Department of Agriculture and Food, Western Australia

27<sup>th</sup> March 2014

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The information in this report is considered to be accurate with respect to information provided 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.

Innovative Groundwater Solutions Pty Ltd.  
PO Box 79, Blackwood, SA 5051  
Phone: 0458 636 988  
ABN: 17 164 365 495 ACN: 164 365 495  
Web: [www.innovativegroundwater.com.au](http://www.innovativegroundwater.com.au)  
Email: [glenn@innovativegroundwater.com.au](mailto:glenn@innovativegroundwater.com.au)



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## Introduction

Innovative Groundwater Solutions Pty Ltd. (IGS) has been engaged by the Department of Agriculture and Food, Western Australia (DAFWA) to assist with the initial planning and design of the drilling and groundwater sampling program for the Broome Sandstone aquifer in the La Grange groundwater area.

There are multiple objectives of the drilling program, including the definition of aquifer stratigraphy and position of the salt-water interface (SWI); assessment of groundwater recharge, residence time, lateral flow velocity and the source of water to culturally significant sites; enabling long-term monitoring of water level and water quality; and, ultimately, the development of a groundwater model for the aquifer.

The following four tasks were considered important preparatory steps for the drilling program, the results of which are detailed in this report:

- Review DAFWA's preliminary interpretation of groundwater chemistry data collected from existing bores in 2013, including the adequacy of the existing dataset, any concerning issues with respect to individual ions or trends, and gaps.
- Derive preliminary estimates of recharge rate for shallow groundwater using the steady-state chloride mass balance method with best available data.
- Work with the DAFWA project hydrogeologist to determine suitable locations and completion details for new bores along 4-6 potential transects, taking into account scientific value, accessibility and budget constraints. From south to north these transects, and the primary objectives they aim to address, are as follows:
  - Mandora transect – groundwater recharge, deep aquifer definition, long-term monitoring;
  - Anna Plains transect – monitoring SWI down-gradient of possible future horticulture, plus assessment/monitoring of Munro Springs cultural site;
  - Shelamar transect – groundwater recharge, plus monitoring down-gradient of existing horticulture;
  - Central transect – groundwater recharge and residence time, monitoring SWI down-gradient of existing horticulture at Shamrock Gardens, plus assessment and monitoring of Injudinah cultural site;
  - Shamrock transect – monitoring SWI down-gradient of proposed horticulture at Shamrock Station; and

- Roebuck transect – groundwater recharge and residence time, deep aquifer definition, plus monitoring SWI.
- For each of the proposed new bores, and the existing bores for which completion details are known along each transect, recommend a suite of chemical and isotopic analytes that will deliver the best possible information required to address the objective(s) of that site/transect. Provide a list of tracers with a justification, cost estimate and recommended analytical service provider for each tracer.

## Review hydrochemistry data and interpretation

The intention was to review DAFWA's preliminary interpretation of hydrochemical data for bores sampled in mid 2013. However, at the time IGS was commissioned for this work the data analysis or interpretation had not commenced. Therefore, it was agreed that IGS begin the analysis and interpretation, including the identification of any ion concentrations that may be problematic for irrigation.

### Charge Balance

The first task was to perform standard charge balance calculations on the analytical results from the lab:

$$Error = \frac{\sum cations - \sum anions}{\sum cations + \sum anions} \times 100\% \quad [1]$$

where cation and anion concentrations are in meq L<sup>-1</sup>. Charge balance errors of <5% are generally considered to be reasonable, <10% is tolerable although potentially problematic for quantitative geochemical analysis, and >10% intolerable and requiring repeat analysis. Applying equation [1] to the database of 147 samples (141 Broome Sandstone, three Wallal Sandstone and three surface water) resulted in the identification of at least 4 samples having significant errors >10% (up to 79%). This led to a review of the reporting for these samples at the laboratory, which resulted in three samples having dilution errors and one sample having incorrect ICP results. Once the data had been correctly reported the errors for the four samples reduced significantly (i.e., to 1%, 2%, 2% and 6%). Moreover, for all 141 Broome Sandstone samples only have 12 have errors in the range 5-10% and only one sample has an error >10% (11%). Part of these error may be associated with the approximate conversion factor of 1.22 that the lab recommended to compute bicarbonate (HCO<sub>3</sub>) concentration from alkalinity.

### Hydrochemical Type

The range of hydrochemical types for the groundwater samples and surface water samples is summarised in Figure 1. 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-HCO<sub>3</sub> to Cl type with increasing salinity. It is currently unclear whether any of these trends are correlated with either location or depth in the aquifer from which samples were collected.

By comparison, Wallal Sandstone groundwater samples are generally more Na-Cl dominated, as are the three surface water samples.

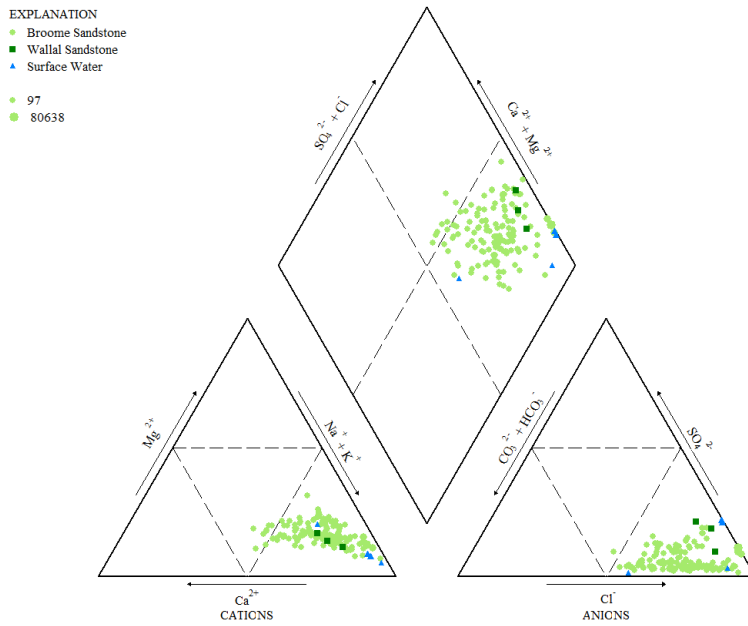


Figure 1. Piper diagram showing major ion compositions of groundwater from the Broome Sandstone and Wallal Sandstone, and surface water samples. The size of each symbol is proportional to calculated TDS concentration. Note that the  $\text{Cl}^-$  axis also includes  $\text{NO}_3^-$ .

### Sources of Solutes

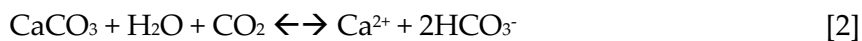
Plots of major ion concentration relative to chloride concentration are often used to investigate trends in hydrochemical data. The key benefit of using this approach – rather than plotting major ion concentrations alone – is that it normalizes the ion concentration by accounting for evaporative effects. For example, an evaporating body of water containing salts of marine origin will evolve chemically as a horizontal line in plots such as that shown in Figure 2. 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 2 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; again, further work is required to explore if these trends are correlated with location and/or depth in the aquifer. All samples are highly enriched in Ca and  $\text{HCO}_3^-$  relative to marine aerosols indicating an alternative source, which is most likely calcite weathering. The source of calcite may be either the unsaturated or saturated zones, however preliminary discussions with DAFWA's soils scientist suggest pedogenic carbonate minerals are present beneath some parts of the La Grange area. Stable carbon isotope analysis of groundwater samples may provides further clues as to the source rocks/areas for calcite weathering (see below).



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 (see next section).

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 3 show that groundwater is much more enriched in Ca and HCO<sub>3</sub> (relative to Na) than would be expected from evaporation of rainwater containing marine aerosols. Furthermore, the Ca/HCO<sub>3</sub> 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/HCO<sub>3</sub> ratio <0.5 is consistent with weathering of a Mg-calcite rather than pure calcite. Finally, the Ca/SO<sub>4</sub> ratios suggest some samples may have acquired Ca and SO<sub>4</sub> through gypsum dissolution (Ca/SO<sub>4</sub> ~ 1), however the majority of samples have significant excesses of Ca over SO<sub>4</sub> providing further evidence for the importance of calcite weathering.

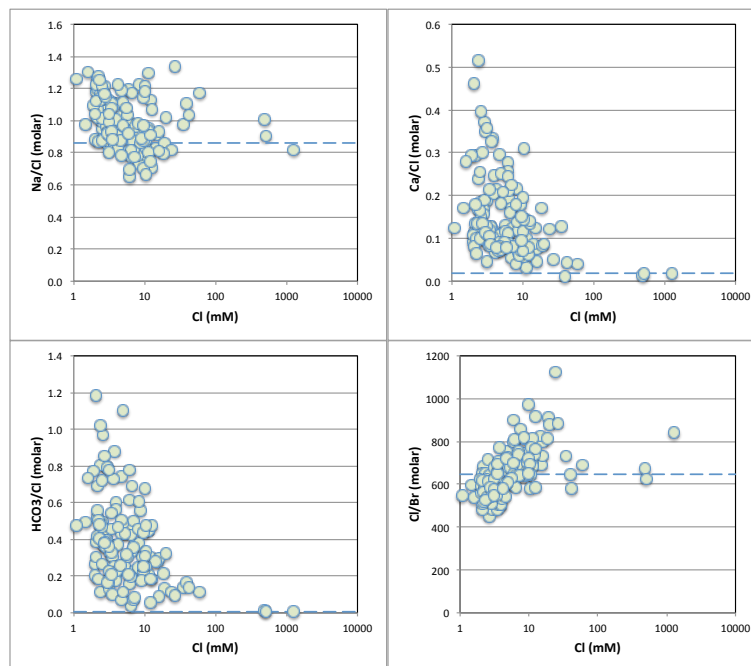


Figure 2. Major ion : chloride ratios as a function of chloride concentration (proxy for salinity) for Broome Sandstone groundwaters. Horizontal dashed blue lines represent expected composition of marine aerosols (i.e., seawater).

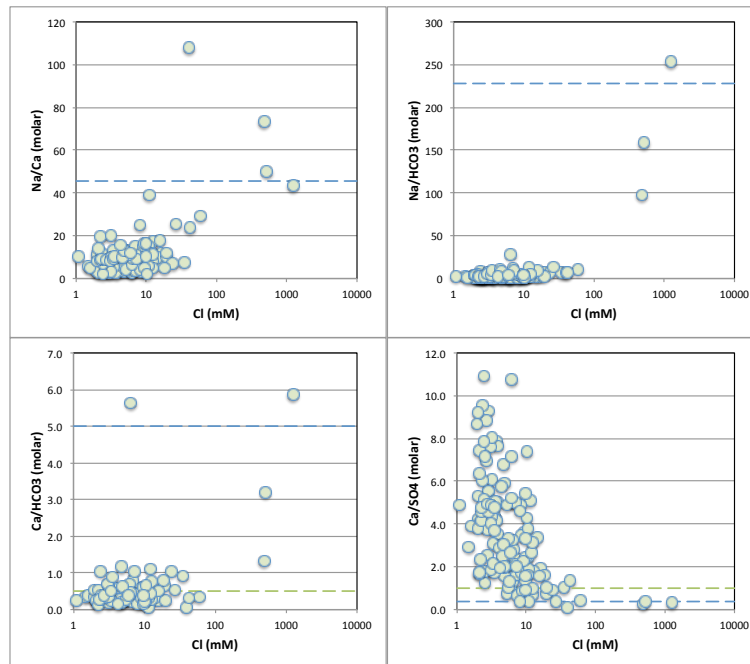


Figure 3. Major ion : ion ratios as a function of chloride concentration (proxy for salinity) for Broome Sandstone groundwaters. Horizontal dashed blue lines represent expected composition of marine aerosols (i.e., seawater) while green dashed lines in (c) and (d) represent ratios associated with calcite weathering and gypsum dissolution, respectively.

### Suitability for Irrigation

Initial inspection of the hydrochemical database suggests the quality of groundwater in the Broome Sandstone presents very few concerns for irrigation development. Water quality parameters most likely to have an adverse impact include total dissolved solids (through reduced crop yields and enhanced corrosion of pumps/pipework), sodium adsorption ratio (through changing soil structure), boron (through plant toxicity) and iron (through precipitation in pumps/pipework).

Only 17 of the 141 samples collected in 2013 have TDS greater than a desirable limit of 1000 mg/L for irrigated crops. Of the 124 samples with TDS less than 1000 mg/L only 11 have boron concentrations that exceed the long-term trigger level of 0.5 mg/L (ANZECC/ARMCANZ, 2000), and all of these samples have concentrations in the range 0.5 – 1.3 mg/L. Of the 113 samples with TDS less than 1000 mg/L and boron concentrations less than 0.5 mg/L only 16 have total iron concentrations exceeding the limit of 0.2 mg/L (ANZECC/ARMCANZ, 2000).

The sodium adsorption ratio (SAR) for all but three of the most saline 141 Broome Sandstone groundwater samples ranges from 2 – 36 (Figure 4b), which, through comparison with Figure 4a suggests that soil structure problems are unlikely with most groundwaters.

Given the sandy pindan soils of the LaGrange area, it is therefore likely that irrigation could occur with most groundwater, although some pre-treatment by aeration may be necessary to remove excessive iron.

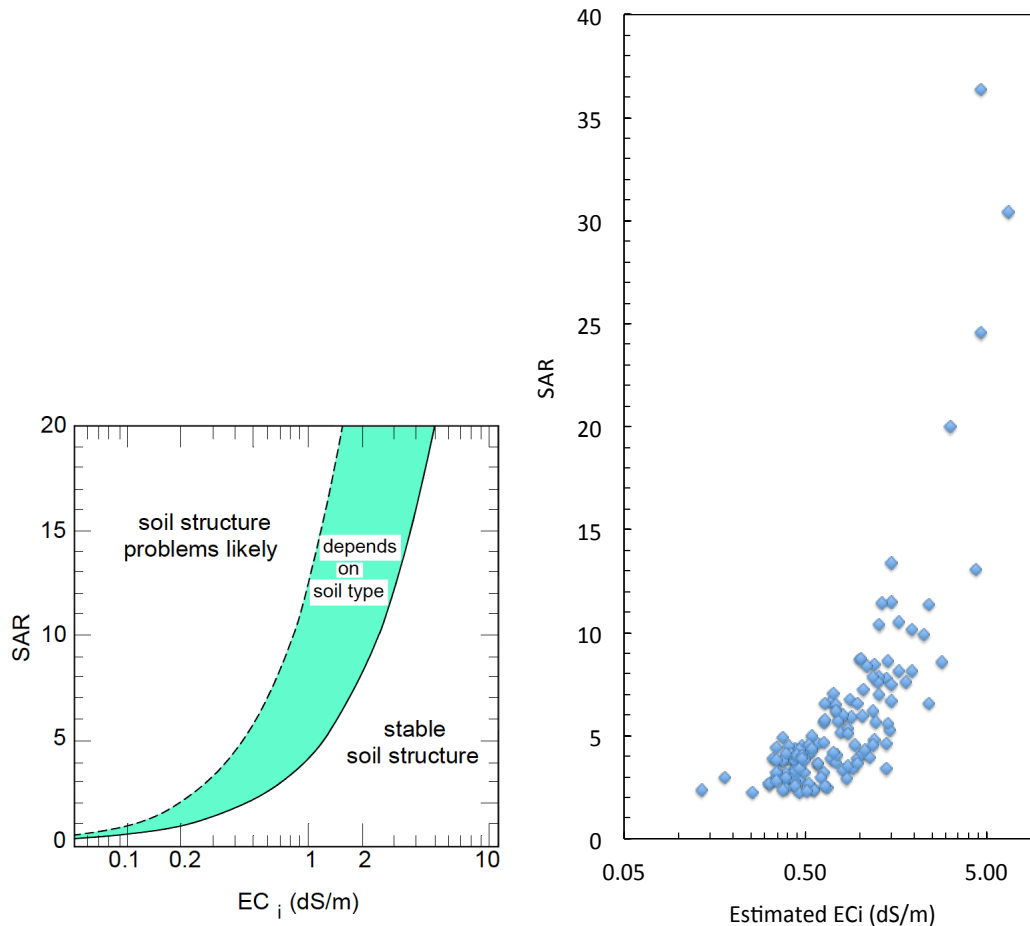


Figure 4. (a) Soil structure as a function of the sodium adsorption ratio (SAR) and electrical conductivity (EC<sub>i</sub>) of irrigation water (after ANZECC/AMCANZ, 2000). (b) Broome Sandstone groundwater samples, with EC estimated using the following approximation,  $EC_i \text{ (dS/m)} \sim 0.0015 \times \text{TDS (mg/L)}$ .

### Further Work

In order to more fully explore the physical and geochemical controls on groundwater chemistry, the following work is recommended:

- Compute saturation indices with respect to common minerals, including calcite, gypsum and halite.
- Map major ion ratios and salinity trends to investigate spatial variability in groundwater chemistry, beginning with those ratios showing the most interesting trends (i.e., Na/Cl, Ca/HCO<sub>3</sub> and Ca/SO<sub>4</sub>).

## Preliminary estimate of recharge rates

### Theory

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 some steady state, which is generally valid providing there hasn't been a change in land use, and (b) 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:

$$R = \frac{P C_P}{C_{gw}} \quad [3a]$$

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,

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

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

### Method

Mean annual recharge to the Broome Sandstone aquifer has been calculated using the two different forms of the CMB, firstly using equation [3a] and then [3b]. This section summarizes the data sources for each approach.

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, a range of approximately 2 – 5 mg/L is considered appropriate for this study.

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 5). This map suggests chloride deposition over the LaGrange area is generally in the range 3.5 – 10.4 kg ha<sup>-1</sup> yr<sup>-1</sup>, although Hingston and Gailitis (1976) suggest a value closer to 14 kg ha<sup>-1</sup> yr<sup>-1</sup> is representative of near coastal areas in the Kimberley.

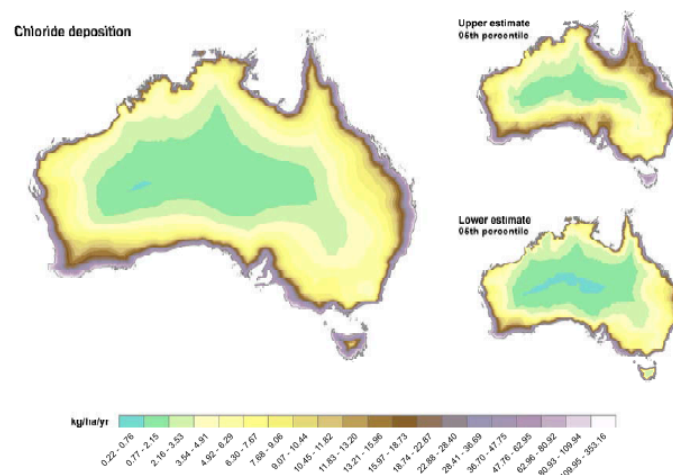


Figure 5. Modeled surface of mean atmospheric Cl deposition and upper and lower 95<sup>th</sup> percentiles (from Leaney et al., 2011).

Mean annual rainfall is also highly variable in the LaGrange area, ranging from 370–605 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.

## Results

Mean annual recharge rates estimated using the two different forms of the CMB (with different input data) are similar (Table 1), although method 2 consistently produced lower rates than Method 1. The recharge rates for shallow bores that are known to be completed less than 15 m below the water table are considerably lower than recharge rates for deeper bores accessing older water; this may reflect a change in recharge dynamics over the last several hundreds to thousands of years, with higher recharge rates occurring in the past.

The decision to present the recharge estimates in Table 1 as ranges rather than single values reflects the uncertainty in input parameters. This uncertainty may be reduced during course of the project through collection and analysis of rainfall samples.

TABLE 1. Recharge rates for the Broome Sandstone aquifer determined by CMB.

Method 1: Equation [3a]	
Mean annual precipitation	370 – 605 mm/yr
Chloride concentration in precipitation	2 – 5 mg/L
Chloride concentration in groundwater (141 bores)	29 – 44900 mg/L
Recharge rate – mean for all bores	5 – 21 mm/yr
Recharge rate – mean for bores <15m below water table	2 – 9 mm/yr
Method 2: Equation [3b]	
Chloride deposition	3.5 – 14 kg $ha^{-1}yr^{-1}$
Recharge rate – mean for all bores	2 – 8 mm/yr
Recharge rate – mean for bores <15m below water table	1 – 4 mm/yr

### Further Work

It is recommended that a spatial analysis of CMB recharge rates be undertaken using the chloride deposition surface from Leaney et al. (2011), a BoM mean annual rainfall surface, and shallow groundwater chloride results. Ongoing collection of rainfall samples, including both discrete storm events and bulk wet season and annual rainfall, is advisable to provide further constraints on the chloride concentration of rainfall and thereby recharge estimates.

## Location and design of new bores

### Bore design and development

Numerous discussions with DAFWA's project hydrogeologist resulted in the decision to install three main types of bores:

- Shallow bores – completed close to the water table with 50 mm PVC, screw couplings to avoid the use of glues (which may contaminate groundwater for trace gas analysis<sup>1</sup>), 3m screen to allow for collection of discrete water samples for age determination. The primary purposes of these bores are recharge estimation and investigation of groundwater dependent ecosystems (GDEs).
- Intermediate bores – completed in the main high-yielding zone of the aquifer with 155 mm PVC, glued couplings and 6m screen. The primary purposes of these bores area residence time determination and long-term monitoring of current and future groundwater extraction.
- Deep bores – drilled to (or near to) the base of the Broome Sandstone and completed with 100 mm Class 18 PVC and glued couplings. Bores drilled to enable monitoring of the position of the saltwater interface (SWI) may be completed as either fully-slotted or blank casing; either approach has its drawbacks – fully-slotted bores can facilitate vertical mixing within the bore that confounds the interpretation of the SWI, while blank casing completions require down-hole geophysical tools to infer water salinity outside the casing. Deep bores drilled for the purpose of stratigraphic mapping will be completed with a 12 m screen.

All bores will be drilled with a mud-rotary rig, which is preferable over air-rotary methods due to the reduced chance of contaminating groundwater with atmospheric concentrations of anthropogenic trace gases (e.g., CFCs and SF<sub>6</sub>). However, particular care will need to be taken when developing the Shallow bores by airlifting, so as to minimize the chances of contamination. It would be preferable to only develop Shallow bores by pumping, however this may not be practical.

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<sup>1</sup> Many adhesives, including some of those used by plumbers for PVC joins, contain CFCs that may contaminate groundwater that is to be sampled for these compounds. Whilst no conclusive study has demonstrated that PVC glues cause anomalous results in groundwater, or determined the timeframe for possible contamination, it is common practice to try to avoid the use of such glues whenever possible.

One option that DAFWA may wish to consider during drilling is the addition of a conservative tracer such as potassium bromide (KBr) to the mud. This simple approach provides a means of identifying possible contamination of water samples by drilling mud, in the event the inexplicable results are obtained.

### Bore locations

A meeting was held with DAFWA's project hydrogeologist in Perth on 11<sup>th</sup> March 2014 to discuss and confirm bore locations. A total of 25 sites comprising 37 bores is proposed – locations are shown in Figure 6, while design depths and purposes are specified in Table 2.

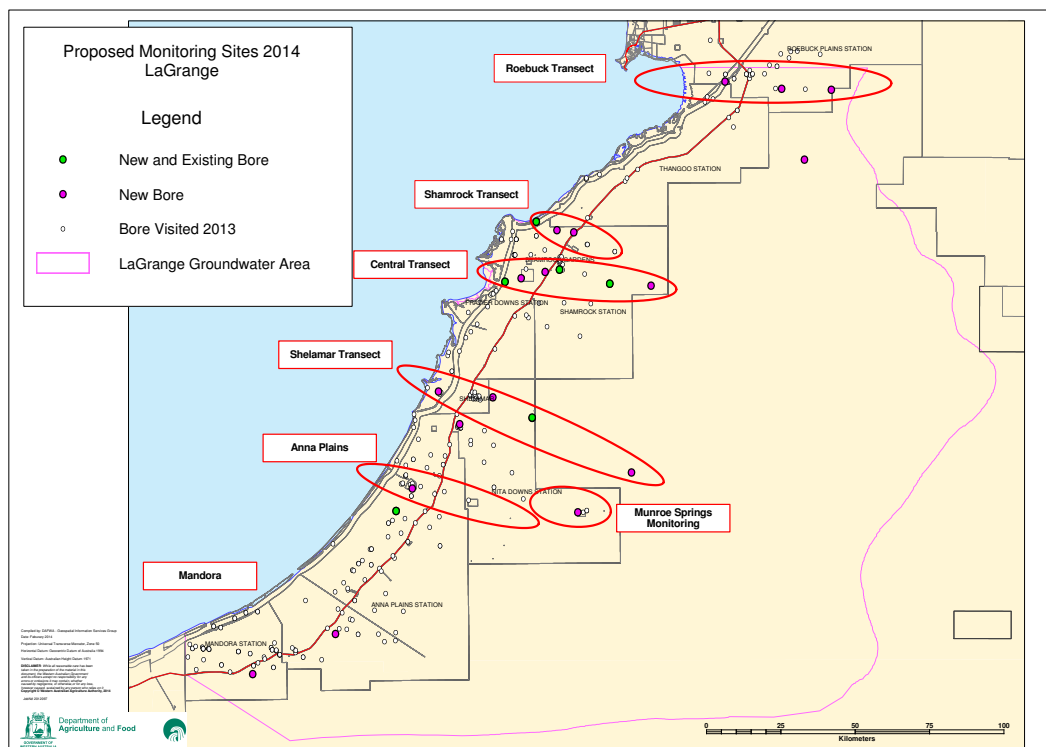


Figure 6. Location of proposed bore transects in the LaGrange groundwater area. Numbering of the sites along each transect (see Table 2) increases with distance from the coast.



TABLE 2. Proposed new bores for the Broome Sandstone aquifer.

Transect	Site No.	Depth	Purpose*	Comments
Roebuck	1	Shallow	R	
		Deep	SWI	
	2	Shallow	R	Lake influence?
		Intermediate	A	
	3	Shallow	R	
Deep		S		
4	Deep	S & EM		
Shamrock	5	Shallow	R	
	6	Shallow	R	
		Intermediate	A	
	7	Shallow	R	Down-gradient of new production/obs. bores
Intermediate		A		
Central	9	Deep	SWI	
	10	Shallow	R, C, GDE	Down-gradient Injudina Swamp
		Intermediate	A	
	11	Shallow	R, C, GDE	Up-gradient Injudina Swamp
		Intermediate	A	
	12	Shallow	R	Near Shamrock H/S
	13	Shallow	R	Adjacent Gilberts Bore, up-gradient of dam
14	Shallow	R		
	Deep	S		
Shelamar	15	Shallow	M	
		Deep	SWI	
	16	Shallow	R	
		Intermediate	A	
	17	Shallow	R	Adjacent Junction Bore
	18	Shallow	R	Emerald Bay Fault
Intermediate		A		
Nita Downs	19		M	Adjacent prod. bore
	20		M	High salinity
Anna Plains	21	Shallow	C, GDE	Munro Springs
		Intermediate	C, GDE, A	
		Deep	S	
	22	Intermediate	M	Adjacent prod. bore
	23	Deep	SWI	
Mandora	24	Shallow	R	marsh
	25	Shallow	R	Adjacent new stock bore

\* R = recharge, SWI = saltwater interface, A = age/residence time, S = stratigraphy, EM = investigate AEM survey result, C = cultural, GDE = groundwater dependent ecosystem, M = monitoring.

## Suite of tracers and analysis costs

The following environmental tracers are proposed to be sampled from new bores and appropriate existing bores along the transects:

- Major ion chemistry and trace metals – origin of solutes and spatial variability of water chemistry/salinity;
- Stable H/O isotopes of water – recharge mechanisms and paleo-recharge;
- CFCs – groundwater age (up to ~50 years) and recharge rates (shallow bores);
- SF<sub>6</sub> – groundwater age (up to ~50 years) and recharge rates (shallow bores);
- Carbon-14 (and <sup>13</sup>C/<sup>12</sup>C) – groundwater residence time (~500 – 30,000 years) and flow velocity (source of Dissolved Inorganic Carbon for correcting <sup>14</sup>C ages).

The isotopic composition of strontium (<sup>87</sup>Sr/<sup>86</sup>Sr) in groundwater can also be a useful tool for assessing water-rock interactions, particularly where DIC is derived from a several sources including weathering of marine carbonates (e.g., limestone) and silicate minerals. It can also be a useful tracer to identifying inter-aquifer mixing of waters from contrasting geologies. For the purposes of this project, sampling and analysing for <sup>87</sup>Sr/<sup>86</sup>Sr is unlikely to provide significant improvements in understanding the hydrogeology.

Each class of bore will be sampled only for a subset of the full suite of tracers, as outlined in the table below. It is also recommended that five surface samples be collected from the culturally significant (GDE) sites of Munro Springs and Injudinah. Analysis of these samples should include radon-222, major ion chemistry, stable H/O isotopes and at least one of the age tracers. This would add approximately \$8,000 to the analysis budget outlined below.

TABLE 3. Summary of all environmental tracers to be sampled from bores and estimated analytical cost. (No. bores includes new bores + existing bores).

Bore depth	No. bores	Tracer	Analytical service provider	Analysis Cost (\$)	
				per sample	Total
Shallow	18 +3	Chemistry	WA Govt.	TBA	
		$\delta^2\text{H}$ $\delta^{18}\text{O}$	U. California Davis	40	840
		CFCs	CSIRO IAS	460	9,660
		SF <sub>6</sub>	CSIRO IAS	530	11,130
		<sup>14</sup> C / <sup>13</sup> C	GNS Rafter	750	15,750
Intermediate	9 +2	Chemistry	WA Govt.	TBA	
		$\delta^2\text{H}$ $\delta^{18}\text{O}$	U. California Davis	40	440
		<sup>14</sup> C / <sup>13</sup> C	GNS Rafter	750	8,250
Deep	4	Chemistry	WA Govt.	TBA	
		$\delta^2\text{H}$ $\delta^{18}\text{O}$	U. California Davis	40	160
		<sup>14</sup> C / <sup>13</sup> C	GNS Rafter	750	3,000
<b>Grand Total</b>	<b>36</b>				<b>\$49,230</b>

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