Groundwater recharge in the eastern Anangu Pitjantjatjara Yankunytjatjara Lands

DEWNR Technical report 2014/06

Government of South Australia
Department of Environment, Water and Natural Resources

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Foreword

The Department of Environment, Water and Natural Resources (DEWNR) is responsible for the management of the State's natural resources, ranging from policy leadership to on-ground delivery in consultation with government, industry and communities.

High-quality science and effective monitoring provides the foundation for the successful management of our environment and natural resources. This is achieved through undertaking appropriate research, investigations, assessments, monitoring and evaluation.

DEWNR's strong partnerships with educational and research institutions, industries, government agencies, Natural Resources Management Boards and the community ensures that there is continual capacity building across the sector, and that the best skills and expertise are used to inform decision making.

Allan Holmes
CHIEF EXECUTIVE
DEPARTMENT OF ENVIRONMENT, WATER AND NATURAL RESOURCES

Acknowledgements

We would like to thank the traditional owners and elders of the Anangu Pitjantjatjara Yankunytjatjara lands for granting access to their lands and providing navigation to remote areas. In many instances, they easily located wells for us which were inaccurately marked in maps, which highlighted their intimate knowledge of the landscape.

We would also like to thank Tony Davies (Davies Consulting Services Pty ltd) for his assistance with both fieldwork and communication with Pitjantjatjara and Yankunytjatjara people.

We would also like to thank Volmer Berens (DEWNR) for his assistance with fieldwork and project management in the office.

Finally we would like to thank the Alinytjara Wilurara Natural Resources Management Board for financing this investigation. We hope the report assists in understanding the potential and long-term management of groundwater resources in the region.

Contents

List of figures

List of tables

Summary

The communities in the Anangu Pitjantjatjara Yankunytjatjara Lands rely on groundwater to supply their drinking water needs and a growing cattle industry. This investigation has developed an improved knowledge of the regional groundwater resources in the region. The key findings are:

- Groundwater recharge is actively occurring in the region despite the current arid climate.
- Groundwater recharge rates calculated using the chloride mass balance approach are probably reflective of the current climate as most groundwater ages indicate recharge ages less than 100 years old.
- The chloride mass balance indicates that a small proportion of rainfall becomes recharge, yet the stable isotope signature indicates minor evaporation. This finding supports earlier conclusions that groundwater recharge is occurring rapidly after rainfall which is then followed by the complete drying of the upper unsaturated zone, removing the stable isotope evaporation signature with it.
- As a first-order estimate, the annual average recharge volume for the APY Lands is 56 500 ML/y. Within the extent of the investigation area and within the APY Lands, the annual average recharge volume is 15 500 ML/y. However, recharge will only occur in episodic pulses when cumulative rainfall is above 60-80 mm/month.
- The highest recharge rates are found in colluvial and alluvial sediments surrounding the Musgrave Ranges. The Pukatja, Umuwa and Yunyarinyi communities all have supply wells in or near these sediments.
- Flood waters from Officer Creek and Ernabella Creek may be the primary source of recharge to the aquifer for the area north of Kaltjiti, although further data are needed in that region to better characterise the hydrodynamics.
- The Iwantja well field extracts old groundwater which seems contradictory to the highly fractured ranges setting that would normally allow higher recharge rates. Further investigation will need to be undertaken at a detailed local scale to better characterise recharge rates in that area.
- There are two regional groundwater flow systems in the investigation area. While both originate in the Musgrave Ranges, the watertable slope shows that groundwater in the eastern side of the investigation area flows east and south-eastwards towards the Eromanga Basin, while groundwater in the central and western area of the investigation area flows southwards towards the Officer Basin.
- The aquifers supplying the Iwantja well field may be part of an entirely separate groundwater flow system

1. Introduction

1.1. Background

The Anangu Pitjantjatjara Yankunytjatjara (APY) Lands has a population of around 3000 people living in multiple communities which are entirely dependent on groundwater for their water supplies. Groundwater also supports the cattle and camel industries, and in recent years the region has been recognised as being prospective for mineral exploration (Musgrave Minerals 2011 [Online]) which if successful may require large volumes of groundwater. A recent review of groundwater resources in the region found a lack of necessary data prevented a confident assessment of the resource to be made. The review recommended that new data acquisition be completed to allow a more meaningful assessment of the resource to be undertaken (Watt and Berens 2011).

In 2013 the Alinytjara Wilurara Natural Resource Management Board received funding under the National Partnership Agreement (NPA) on Coal Seam Gas and Large Coal Mining program that was an initiative to identify water assets, their vulnerabilities and associated knowledge gaps. The region partnered with the Department of Environment, Water and Natural Resources (DEWNR), Science Monitoring and Knowledge Branch to deliver an asset database and vulnerability assessment component. With additional NPA funding from the Board, in combination with the Non-Prescribed Areas project under DEWNR's Groundwater Program, this investigation was initiated to address the scarcity of groundwater data in the APY Lands and start addressing key knowledge gaps about the groundwater resource.

1.2. Objectives

This report details the hydrogeological investigation of the eastern APY Lands which had three key objectives. They were to:

1. Estimate groundwater recharge and its relationship to rainfall in the investigation area
2. Identify likely zones of preferential groundwater recharge near community water-supply wells
3. Describe the regional interconnectivity and flow characterisation of the unconfined aquifer.

These objectives contribute to characterising groundwater recharge processes and are a step towards a volumetric water-budget for the unconfined aquifer. A water-budget collates information on water inputs (e.g. rainfall recharge) and water outputs (e.g. extraction, plant uptake and regional discharge to surrounding basins) for a given area over a given period of time (e.g. annual timescales). A water-budget is a valuable tool for assessing sustainable groundwater extraction rates and its development is a primary step to developing useful groundwater models to assist quantitative management of the resource in the long-term.

1.3. Location

The investigation area encompasses the eastern portion of the APY Lands situated in the northern portion of the Alinytjara Wilurara Natural Resource Management (AWNRM), South Australia. Due to time constraints, the eastern APY Lands, where most indigenous communities are located, were the focus of this investigation. The investigation area (Figure 1) mostly located to the west of the Stuart Highway, is bounded to the east by the APY Lands border, extends west of the Officer and Ernabella Creek systems, is bounded to the north by the South Australia–Northern Territory border and extends south of Mintabie community to the northern edge of the Great Victoria Desert. The region encompasses the Pukatja, Yunyarinyi, Kaltjiti, Mimili, Iwantja and Mintabie communities and is presented in Figure 1.

Geologically, the investigation area includes both the Musgrave Block and the northern-eastern margin of the Officer Basin (Figure 2). The Musgrave Block is comprised of Mesoproterozoic crystalline basement which forms extensive mountainous outcrops in the north of the area, known as the Musgrave and Mann Ranges. It is bounded by the Amadeus Basin to the north, by the Eromanga Basin to the east and by the Officer Basin to the south and west. Smaller areas of Musgrave Block outcrop also exist to the south of the investigation area such as the Everard Ranges. The Officer Basin is a mid-Neoproterozoic to Late Devonian sedimentary basin which extends south and west of the Musgrave Block. It has thick sequences of sandstones and in many parts, is overlain by Quaternary sand dunes of the Great Victoria Desert. The depth to groundwater increases over a short distance as it flows southwards from the Musgrave Block into the Officer Basin. Quaternary sand dunes cover most of the southern region, along with Pleistocene calcrete and Holocene alluvial, fluvial and aeolian deposits with occasional outcropping basement (Lewis et al. 2010). Palaeovalleys consisting of unconsolidated alluvial sediments exist in the Musgrave Block and some extend from the Musgrave Ranges southward towards the Officer Basin; the most prominent of these is the Lindsay Paleovalley, which is west of the investigation area.

Surface water features in the area are typically ephemeral and only flow after significant episodic rainfall events. Surface water from the Musgrave Ranges flows to the Ernabella Creek system and similar tributaries, several of these subsequently discharge to the Officer Creek. The surface water features which flow south, such as the Officer Creek, do not extend far into the Officer Basin indicating water may be lost rapidly due to infiltration. Surface water runoff in the area between Yunyarinyi and the Everard Ranges typically flows south-easterly towards the Eromanga Basin.

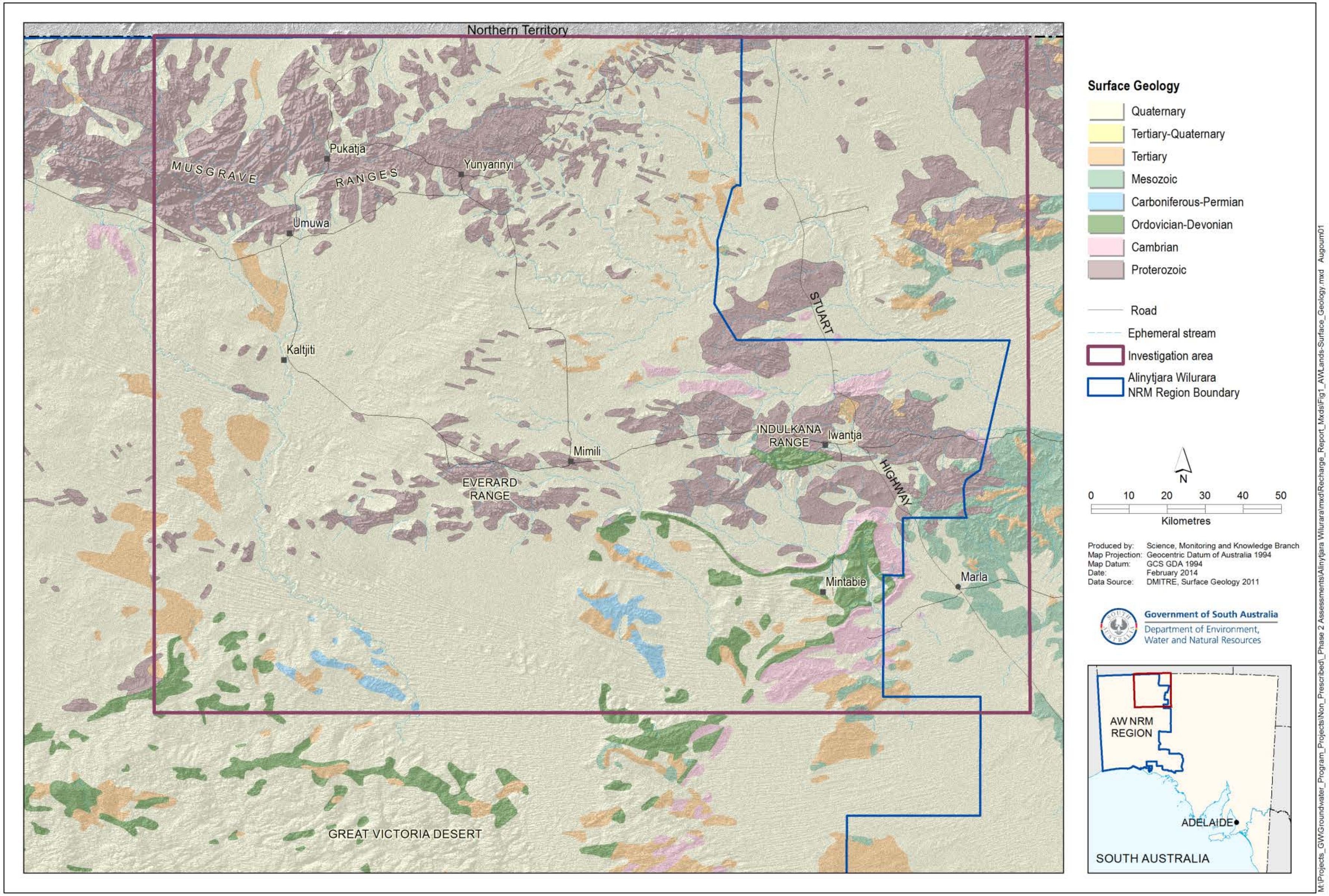


Figure 1. Investigation area and surface geology in the eastern APY Lands

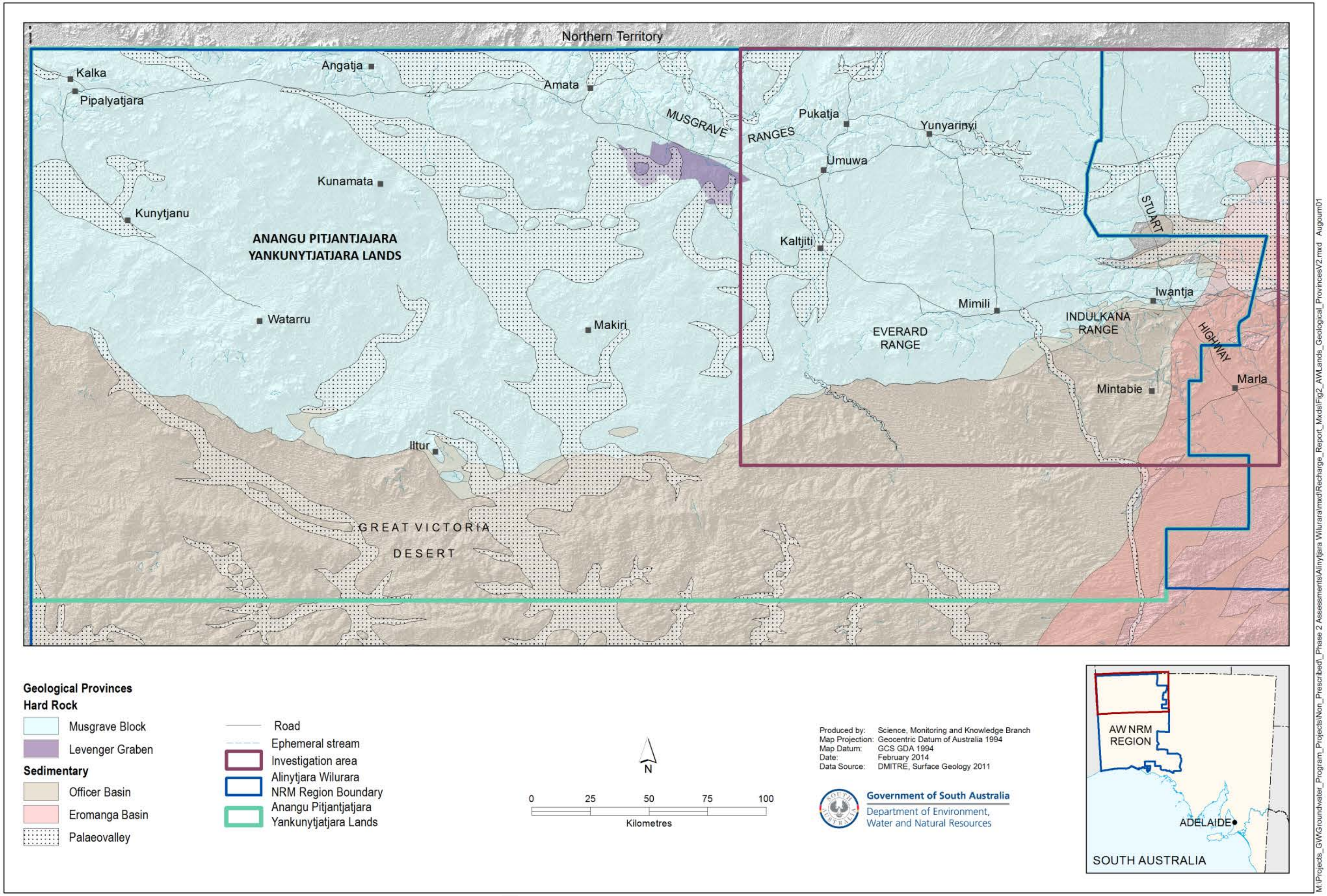


Figure 2. Geological provinces of the APY Lands

1.4. Climate

Based on the modified Koppen classification system, the climate of the area is hot desert with persistently dry conditions, while the ranges are classified as hot grasslands with persistently dry conditions (BOM, 2010). The area is dominated by hot day time temperatures (average maximum temperature between 27 and 30°C) and low annual rainfall. Annual rainfall varies between 240 mm/y at Mintabie to 280 mm/y at Amata (Table 1). The numbers of days recording rain is low, however, those rainfall events can be large and dominated by intense summer rainfall events (total monthly rainfalls of up to 250 mm have been observed at Pukatja). The rainfall record for Pukatja shows the high-variability of rainfall (Figure 3). Over the past 100 years, rainfall in Pukatja displayed a declining trend from the early 1900s to the 1970s. Since the 1970s, the long-term average has increased, with particularly high-rainfall years in close succession in the 1970s and early 1980s.

Potential evapotranspiration sourced from the SILO climate record database and calculated using the FAO 56 Penman-Monteith method (Allen et al. 1998) between 1913 and 2012 averaged 1794 mm/y and ranged between 1779 and 1949 mm/y. The distribution of total monthly evapotranspiration and total monthly total rainfall at Pukatja is presented in Figure 4.

Table 1. Average rainfall conditions at BOM rainfall stations as of June 2013

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Amata Airstrip	31	42	26	23	18	16	11	11.2	14	27	28	33	280
Pukatja*	39	33	26	15	18	17	11	12.2	11	22	23	34	259
Marla Police Station	15	31	24	10	13	14	13	7.9	11	21	24	40	241
Mintabie	18	32	16	11	12	16	17	8.1	12	28	26	32	240

Note: * Based on Silo Database information from 1913 to 2012.

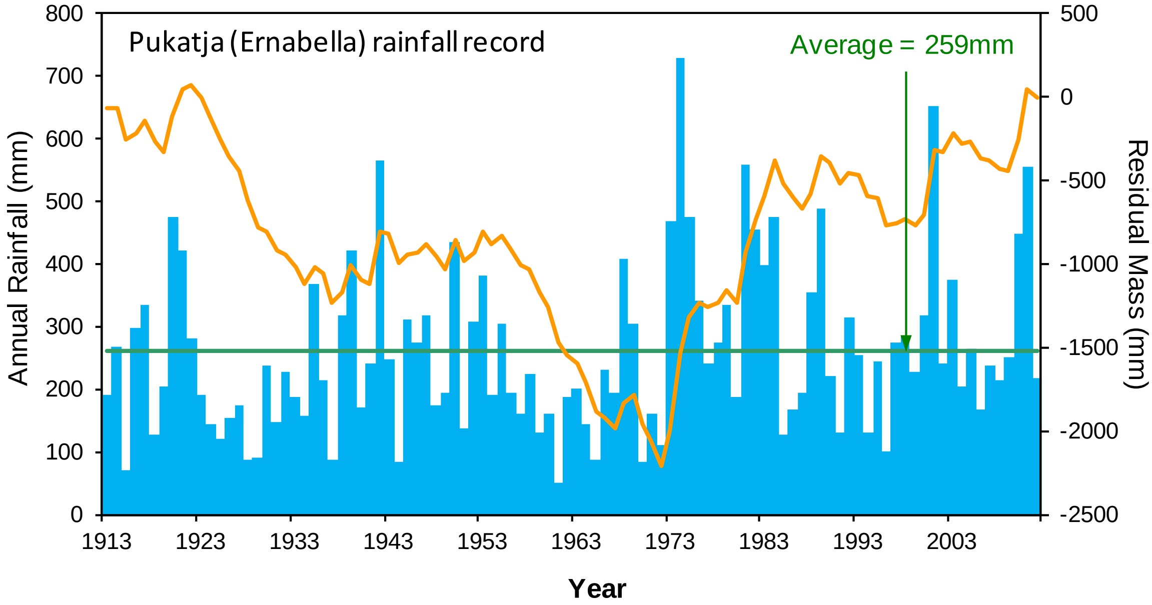


Figure 3. Rainfall record and cumulative deviation from mean rainfall for Pukatja

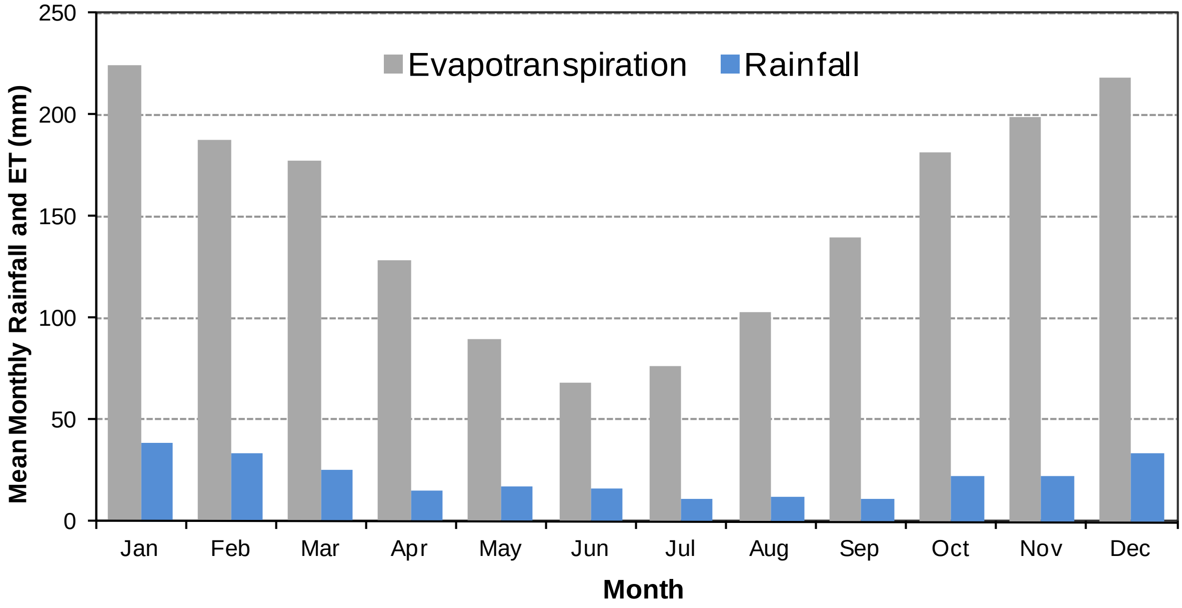


Figure 4. Measured mean monthly rainfall and estimated potential evapotranspiration (FAO56) at Pukatja Source: SILO 1913–2012

2. Methodology

To address the key objectives outlined in Section 1, this section outlines how hydraulic and hydrochemistry data were collected and interpreted. Section 2 is divided into two sub-sections. The first describes the selection of sample sites, collection of groundwater samples and the laboratory analysis. The second section describes the background and analytical methods used to analyse the laboratory results.

2.1. Sample site selection

Published literature consistently notes the occurrence of localised recharge around outcropping bedrock and ephemeral creeks (Tewkesbury & Dodds 1997, Leaney et al. 2013). Therefore given the proximity of communities to these environments, it was decided to target efforts to estimate recharge in these locations. The project aimed to sample a maximum of 30 additional wells to complement existing data sets. To make best use of these 30 sampling points, initial site selection was based on establishing three regional transects (Figure 5):

- Transect 1 runs parallel to the regional groundwater flow path to identify preferential recharge resulting from ephemeral creeks, as well as estimating recharge near the communities of Pukatja, Umuwa and Kaltjiti
- Transect 2 was selected to characterise groundwater flow from the Musgrave Block towards the Officer Basin
- Transect 3 was selected to estimate recharge rates near the town water supply areas for Mintabie, Iwantja, Mimili and Yunyarinyi and to assist in understanding the regional hydrodynamics. Flow-paths have also been identified flowing from the Musgrave Ranges to the southeast (Leaney et al. 2013).

Preliminary desktop interrogation of the State's drill hole database, SA Geodata, identified the most suitable wells to sample along each transect based on desirable characteristics including location, operational status, available geological logs and construction information. Tony Davies (Davies Consulting Services) provided local insights, which were beneficial in identifying priority target wells. Since some wells had not had their status updated in SA Geodata for up to 30 years, it was important that alternative sites were identified in case a preferred site could not be sampled. To facilitate this, a GIS enabled laptop computer allowed alternative sampling locations to be identified whilst in the field. This provided great assistance as many priority wells could not be located, or were found to be either collapsed or blocked. An initial preliminary technical note describing the field studies was provided to the AWNRM Board in 2013.

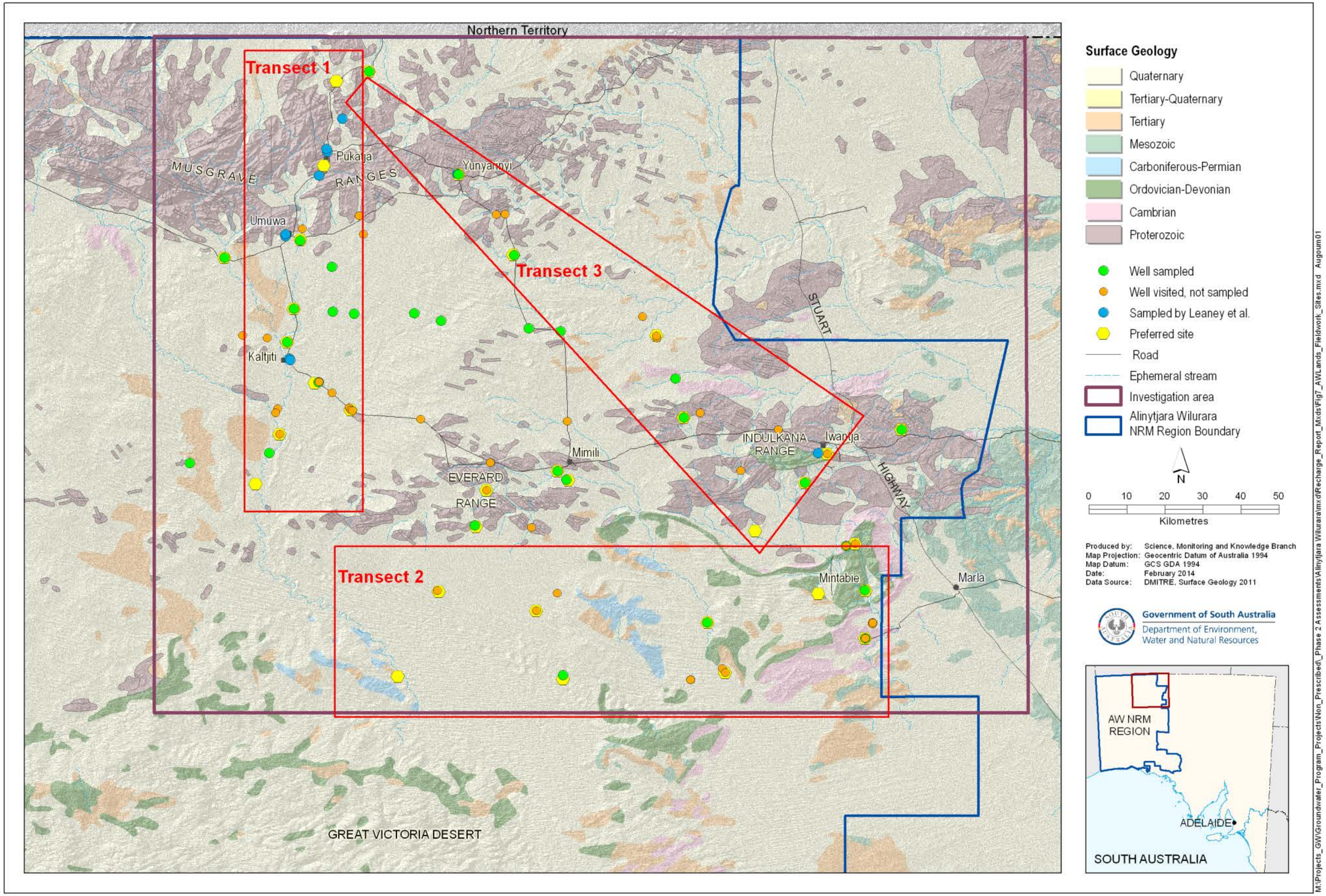


Figure 5. Groundwater sampling locations and wells visited in the investigation area

2.2. Field methods and parameters sampled

The field program collected both field parameters and samples for laboratory analysis to assist in assessing recharge rates in the region. Table 2 presents the groundwater parameters measured and analysed in the laboratory for each location. It also provides a short explanation of the purpose for each parameter measured.

In the field, the depth to water level was measured where the configuration of the well headworks allowed without need for significant alteration. Wells accessible for water sampling were pumped for at least three well volumes and until field parameters including temperature, salinity and pH had stabilised prior to being sampled. Care was taken to minimise air entrapment or excessive water agitation to minimise off-gassing of the chemical components to be measured. The following methods were used to measure the relevant parameters.

Temperature, electrical conductivity, pH and oxygen reduction potential

Measured using a YSI handheld multiparameter meter fitted to a closed cell sampling chamber. The parameters were checked regularly to ensure that they had stabilised during the extraction of three well volumes of water.

Alkalinity

Measured using a Hach® alkalinity test kit and digital titrator. A 100 mL groundwater sample was taken, to which a satchel of Bromocresol Green–Methyl Red indicator was added. Sulphuric acid was then titrated into the sample from which the distinctive colour change could be used to estimate the sample's alkalinity concentration.

Water level and bore depth

Sampled using a Solinst water level meter probe.

Anions and cations

At each site two 125 mL PET sample bottles were filled with a groundwater that had passed through a 0.45 μm glass filter paper. The sample prepared for anion analysis was then stored. The sample prepared for cation analysis had nitric acid added until the pH was less than two. pH indicator strips were used to measure the pH. The samples were sent to CSIRO Analytical Services unit for analysis using mass spectrometry.

Stable isotopes $\delta^{18}O$ and $\delta^{2}H$

An unfiltered sample was collected in a 28 mL McCartney jar at each site. Care is taken to ensure no air bubbles are trapped in the sample and the lids are crimped tightly and taped to ensure no evaporative enrichment occurs. The samples were sent to the University of California, Davis – stable isotope facility for analysis using laser spectroscopy.

Radiocarbon dating

A 1 L unfiltered sample was collected at each site in a PET bottle. Approximately 1 g of sodium hydroxide was added to each sample to raise the pH and help preserve the inorganic carbon content. The samples were sent to Beta Analytic Incorporated in Florida, USA. The samples were analysed using accelerator mass spectrometry.

Chlorofluorocarbons (CFC-11 and CFC-12)

Three 125 mL glass bottles, with metal-foil lid liners, were filled in a glass jar placed inside a stainless steel bucket continually filled with the sample groundwater to minimise the surface area in contact with the atmosphere. Each sample bottle was flushed and filled with the groundwater sample and then capped while submerged in the bucket. This method is outlined in greater detail in IAEA (2006). The samples were sent to CSIRO Isotopic Service unit for analysis.

Sulphur hexafluoride (SF_6)

A 1 L amber glass bottle was filled while submerged in a stainless steel bucket filled with the sample groundwater, in the same manner as the CFC sample procedure. The samples were analysed at CSIRO Isotopic Services unit using a gas chromatograph fitted with an electron capture device.

Noble Gases (^{4}He, ^{40}Ar and ^{20}Ne)

Noble gases were sampled using copper tubes fitted with pinch-clamps at each end. The tubes were flushed with sample water directly from the pump hose to exclude contact with the atmosphere. The clamps were tightened while the sample was pumped through the tube until the flow was completely shut-off. The tubes were then analysed at CSIRO Isotopic Services unit using cryogenic separation and measured on an accelerator mass spectrometer.

Table 2. Parameters measured and the purpose for measuring it

Parameter Type	Water quality parameter	Purpose
Field	Alkalinity	Measure of $CaCO_3$ concentration via titration. It is used to calculate the anion and cation balance from laboratory analyses.
	Temperature	Standard parameter that can be used to correct water level for density differences.
	Electrical Conductivity	Proxy for salinity.
	Total Dissolved Solids	Calculated salinity based on electrical conductivity.
	pH	Indicates whether the water is acidic or basic.
	Oxidation/Reduction Potential	Indicates the potential for the groundwater to oxidise material it comes into contact with.
	Depth to Water	Used to indicate flow-direction when corrected to a common datum.
	Bore Depth	Informs us to what extent the well has filled with silt or collapsed.
Sample for laboratory analysis	Anions (Br^-, NO_3^-, Cl^-, SO_4^{-2})	Indicates water quality. Chloride can be used to estimate recharge as a proportion of rainfall using the chloride mass balance approach.
	Cations (Ca^{2+}, K+, Mg^{2+}, Si^+)	Indicates water quality.
	Stable Isotopes – δ^2H and $\delta^{18}O$	Indicates recharge mechanisims and flow paths.
	Carbon dating – ^{14}C	Age-dating of water < 40,000 years.
	Strontium – $^{87}Sr/^{86}Sr$	Assess water-rock interaction and indentify recharge flowpaths.
	Chlorofluorocarbons – CFC11 and CFC12	Age-dating of water < 50 years.
	sulphur hexafluoride – SF_6	Age-dating of water < 50 years.
	Noble gases – ^{4}He, ^{40}Ar and ^{20}Ne	^{4}He is used for age dating > 10,000 years old, ^{40}Ar and ^{20}Ne are used to assist age dating with SF6, including recharge mechanisims

2.3. Analytical methods and background

The following section provides a brief summary on the analytical methods used to calculate groundwater ages and groundwater recharge rates in this study.

2.3.1 Radiocarbon dating correction

Carbon dating is a widely used method to date groundwater. Radiocarbon (^{14}C) is the radioactive isotope of carbon and has a half-life of 5730 ± 40 years. It is produced naturally in the atmosphere by cosmic rays and is oxidised to CO_2 from which it is incorporated into the biosphere and hydrosphere. Radiocarbon activity is normally presented as percent modern carbon (pMC), indicating the sample's radioactivity relative to the modern atmosphere. Groundwater that was recharged after large-scale nuclear testing in the 1950s is considered 'modern' due to the large amount of ^{14}C released into the atmosphere which has contaminated the atmospheric signal. To calculate the groundwater age, it is necessary to know the initial activity (A_0) of carbon in the groundwater as it recharges the aquifer. This value is rarely the same value as the atmosphere at the time of recharge due to a number of influencing factors. For example, the inorganic carbon content of groundwater will be influenced by soil CO_2 from plant root respiration and the dissolution of minerals containing carbon in the aquifer.

To correct for factors that influence the estimate of A_0, various correction models have been developed. These correction models require knowledge of the carbon speciation in the sample which is not normally measured; therefore geochemical models are used to calculate the likely speciation based on the known chemistry. In this investigation WEB-PHREEQ (Saini-Eidukat 1999 [online]) was used to calculate a likely value of the molar concentration of CO_2 in the groundwater sample. This value was applied to the Tamers (1975), Ingerson & Pearson (1964) and Fontes and Garnier (1979) groundwater age model equations in combination with the measured carbonate value in the groundwater. A detailed description of the models is provided in Plummer & Glynn (2013). These models provided an estimate of the groundwater age.

2.3.2 Chlorofluorocarbon, Sulphur hexafluoride and noble gases

Chlorofluorocarbon (CFCs) gases were produced in industrial scales since the 1930s for applications such as air conditioning, refrigerant and aerosol propellant. Since that time the atmospheric concentrations have been decreasing (Figure 6). The concentration of CFCs in groundwater can be used to estimate a groundwater age. However, due to reducing CFC concentration in the atmosphere its concentration in recently recharged groundwater may have the same concentration as water recharged during the 1990s. In addition, CFCs can also be used date groundwater based on the ratio of the different speciation (CFC-11, CFC-12 and CFC-113). CFCs can be used to date groundwater up to 50 years of age in the Southern Hemisphere (IAEA 2006). For this investigation CFC-11 and CFC-12 were analysed for age-dating purposes.

CFC groundwater ages were modelled using the USGS CFC2006 spreadsheet (Busenberg and Plummer 2006). The Southern Hemisphere atmospheric CFC concentrations were sourced from IAEA (2006). The spreadsheet analysis provides age-estimates based on the measured concentration of CFC-11 and CFC-12, an excess air concentration of 0.005 cc/g and recharge temperature of 15°C.

Sulphur hexafluoride (SF_6) is a colourless, odourless and stable gas which is mainly used an electrical insulator in high-voltage electrical devices (IAEA 2006). Industrial production began in 1953 and since then its production has increased (Figure 6). As a result the atmospheric concentration has increased from around 0.054 parts per trillion to 6 parts per trillion. It is currently increasing at a rate of around 6 percent per year (IAEA 2006). Therefore, the concentration of dissolved SF6 in groundwater can be used as a useful tool to date groundwater.

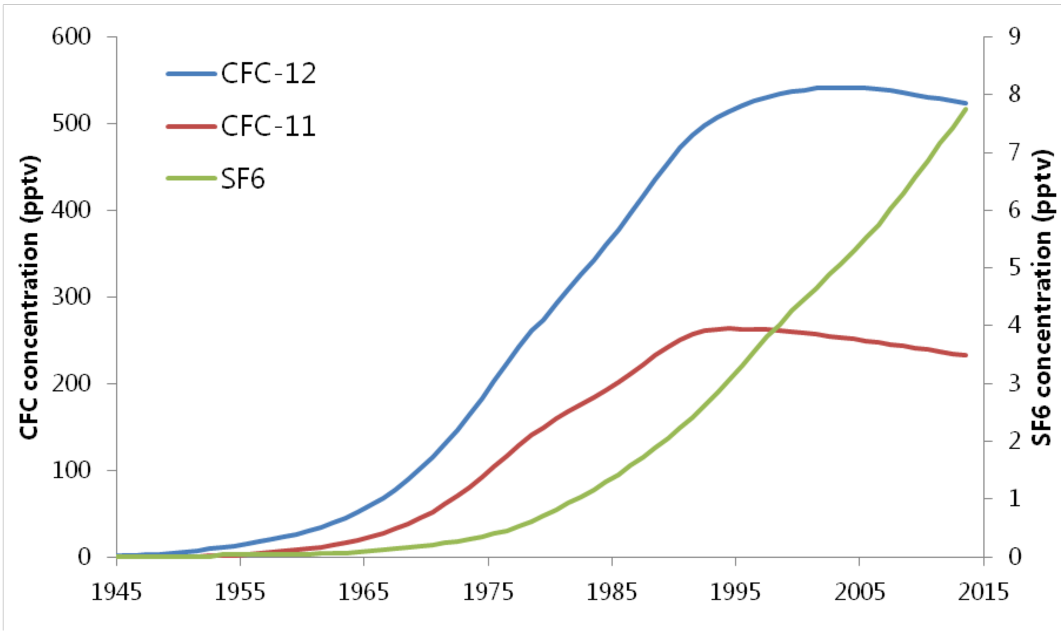


Figure 6. Atmospheric concentration of CFC-11, CFC-12 and SF6 in the southern hemisphere from 1945 to 2013 Source: NOAA/CDIAC 2014 [online]

The noble gases ^{40}Ar and ^{20}Ne are dissolved into groundwater at the time of recharge. They can be used to calculate the excess air portion in the groundwater which arises during rapid, episodic recharge which traps and dissolves gasses from the unsaturated zone into the groundwater. The gases can also be used to inform us of the approximate recharge temperature. Knowledge of excess air concentration and temperature can then be used to correct groundwater-age estimates made using SF_6 and CFCs. ^4He is produced by the decay of naturally occurring uranium and thorium on the aquifer geology. It is trapped in the groundwater over time and its rate of increase is proportional to the age of the water and the ^4He production rate of the geology.

2.3.3 Calculating recharge rates

The chloride mass balance (CMB) approach has commonly been applied in arid settings to estimate recharge rates, although the method does have limitations due to the following assumptions (Herczeg & Edmunds 2000, Scanlon 2000). It assumes one-dimensional downward piston flow, chloride is conservative (does not precipitate), the input of chloride is solely derived from atmospheric fallout (mostly rainfall) and it has been added to the landscape at a consistent rate for a long period of time.

$$R = (P.C_P)/C_R$$

Where R = recharge rate (mm/y)

P = mean annual rainfall (mm/y)

C_P = concentration of chloride in rainfall (mg/L)

C_R = concentration of chloride in groundwater (mg/L)

Chloride is a commonly measured ion in groundwater sampling programmes and therefore there is an extensive set of wells in the APY Lands which have chloride data. For this investigation, groundwater chloride data were used when the major ion chemistry for a particular site had a charge balance with less than 10 percent error (417 measurements in total). An input chloride concentration from rainfall of 0.72 mg/L was used, based on the rainfall weighted chloride concentration at Alice Springs (Crosbie et al. 2012). This is similar to the rate of 0.5 mg/L adopted for studies in the Ti Tree Basin in southern Northern Territory (Harrington et al. 1999). The average rainfall at Pukatja for the past 100 years is 260 mm/y, at both Marla and Mintabie it is 240 mm/y since records began in 1985 and 1992 respectively. Rather than assign differing rainfall zones throughout the investigation area, a rainfall value of 250 mm/y was assigned for the CMB recharge rate calculations.

To upscale the point groundwater recharge rate estimates to a regional volumetric estimate, the point data was integrated with a regolith map that had been published by the Department of Manufacturing, Innovation, Trade, Resources and Energy (Krapf 2012). Regolith is the term applied to the geology located between the surface and underlying bedrock. CMB-derived recharge rates were assigned to regolith polygons using a simple three step process:

1) Where a single CMB recharge point intercepted a regolith polygon then that point recharge rate was applied to the total polygon area

2) Where multiple CMB recharge points intercepted a regolith polygon then the average of those point recharge rates were applied to the total polygon area

3) Where no CMB recharge points intercepted a regolith polygon then the recharge rate applied was taken from the nearest regolith polygon with the same classification code that did have a CMB rate assigned.

Radiocarbon age can also be used to estimate groundwater recharge rates (Cook & Bohlke 2000). For an unconfined aquifer the simplest method is to assume a one-dimensional downward piston flow and assume the sample depth is the mid-point of the open-hole/screened depth. It is calculated using:

$$R=(n.z)/t$$

Where R = recharge rate (mm/y)

n = effective porosity

z = depth of the sample below the watertable (mm)

t = age of the groundwater sample (ys)

Due to issues with the calculating radiocarbon ages (discussed later) estimates of recharge rate using radiocarbon were made to using the uncorrected groundwater age.

3. Results

To maximise the number of wells that could be used for an analysis of groundwater recharge in the APY Lands, this report includes data from Leaney et al. (2013) and Custance (2012). The additional groundwater sample points allow for an assessment of recharge variability across areas with differing geology. In total there were 61 samples from 60 sites (the well Walalkara 99B was sampled twice, by Leaney et al. 2013 and in this study), including 11 wells sampled by Custance (2012), 21 sampled by Leaney et al. (2013) and 29 wells sampled for this investigation. To assist with the interpretation of these data, samples were classified into four geographical zones as shown in Figure 7. The zones are described as:

- Rangelands (including Musgrave Ranges and Everard Ranges)
- Musgrave East (a cluster of wells in an area of mostly in situ weathered basement collected by Custance (2012).
- Plains (areas covered by minor relief surrounding the ranges)
- Officer (seven wells located in the south-east within the Officer Basin)

3.1. Water levels

Figure 8 presents regional water-level contours for the unconfined aquifer. The accuracy of this map can be considered only approximate as limited surveyed water-level information is available for wells in the APY Lands. The map illustrates the general north to south flow direction between Pukatja and Kaltjiti. Any effect of the Officer Creek as a recharge or discharge boundary could not be identified by water levels due to the low density of observation sites. A grey dashed line marks the approximate location of an interpreted groundwater flow divide separating south and south-eastward groundwater flows paths. In the area of the flow-divide, there are multiple outcrops of bedrock and insitu weathered sediments. At a qualitative level, this suggests the aquifer is probably thin and has low transmissivity in this area, which indicates little hydraulic connection on either side of the flow divide.

Wells sampled in the Everard Ranges were already pumping when visited, so natural water level conditions could not be measured. As a result, water level contours could not be used to determine whether the Everard Ranges act as a significant regional recharge area that further divides the afore mentioned flow paths.

3.2. Field chemistry

Field data are present in Table 3. The total dissolved solids (TDS) content, more commonly referred to as salinity, tends to be fresh to brackish, with a minimum of 531 mg/L, a maximum of 8258 mg/L and a median of 1249 mg/L. There is potentially a bias towards fresher sites in groundwater studies that target town water and stock water supply wells, as these wells will tend to have a water quality that suits the purposes. Wells which find more saline water are much more likely to be abandoned at the time of drilling as there is little benefit in completing the well.

The salinity results show several notable patterns (Figure 9). The salinity tends to be lowest in and near the ranges where rapid episodic recharge would occur, and highest in southern areas and within the Officer Basin where relatively slow diffuse recharge would occur. A transect of five wells that extend eastward from 5344-18 (adjacent Officer Creek), provides further information on the aquifer. Salinity trends generally increase to the east from 5344-18 (734 mg/L), 5344-8 (708 mg/L), 5344-35 (1183 mg/L) to 5344-50 (1495 mg/L). This is an indication that freshwater pulses from occasional flood events in the Officer Creek may recharge the aquifers in this area, as opposed to the creek acting as a regional groundwater sink. The exception is the eastern most well in the transect, 5344-71 (675 mg/L). Analysis of the digital elevation model of this area revealed a linear palaeovalley feature extending to the south-west that is now largely covered by aeolian dune deposits (blue dashed line). If the fresh groundwater extends along the length of this drainage line, this area may be a significant groundwater resource.

Groundwater pH tends to be near neutral in the area, with 57 of the 61 wells recording between pH 6.5 and 8.5. Interesting exceptions are 5543-136 (well name I98MJ-1) and 5544-101 (well name IMB-19), both of which are the two most acidic wells at pH 6.3 and pH 5.8 respectively and which will later be shown to contain the oldest groundwater of all sampled sites.

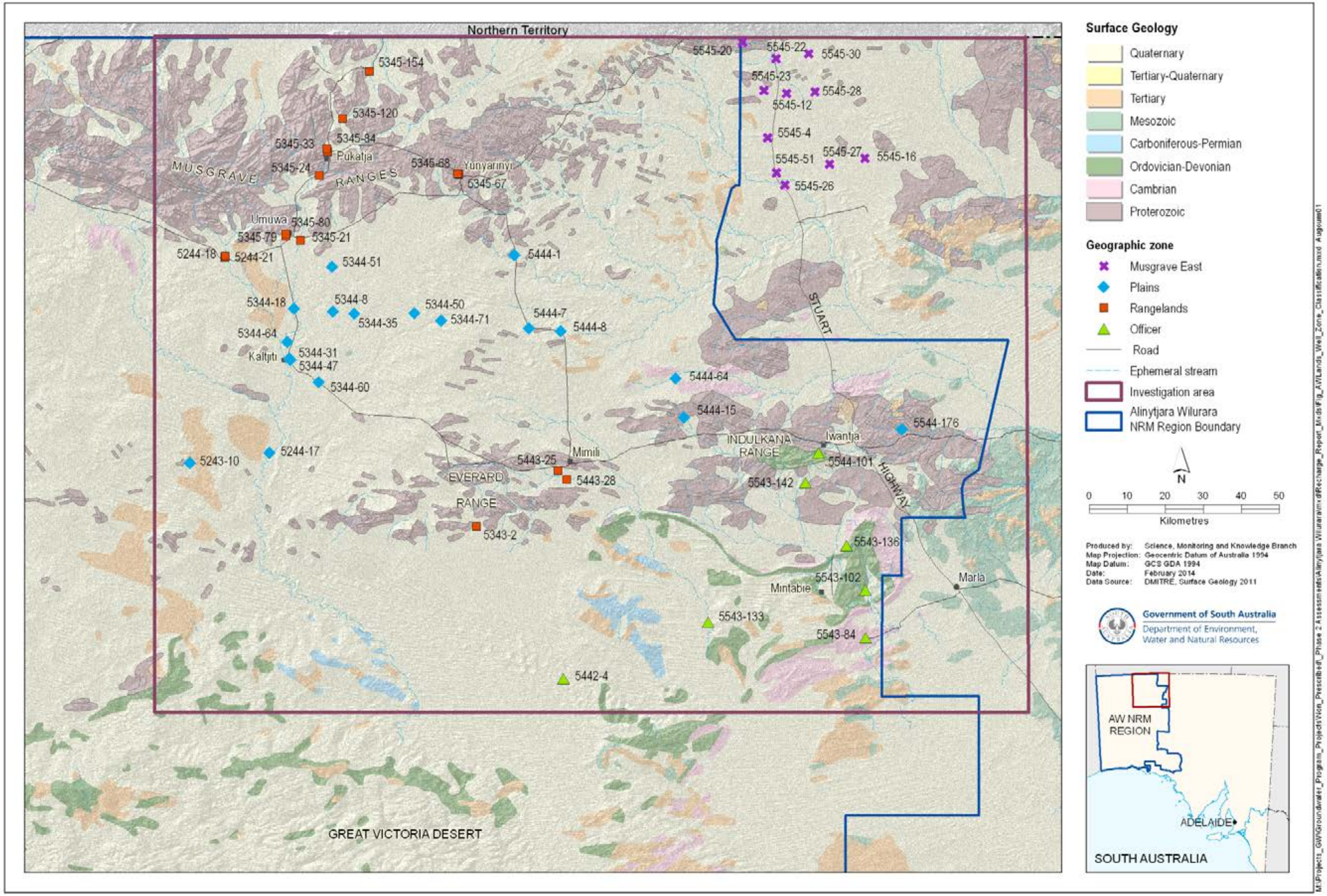


Figure 7. Well zone classifications into four geographic sub-regions

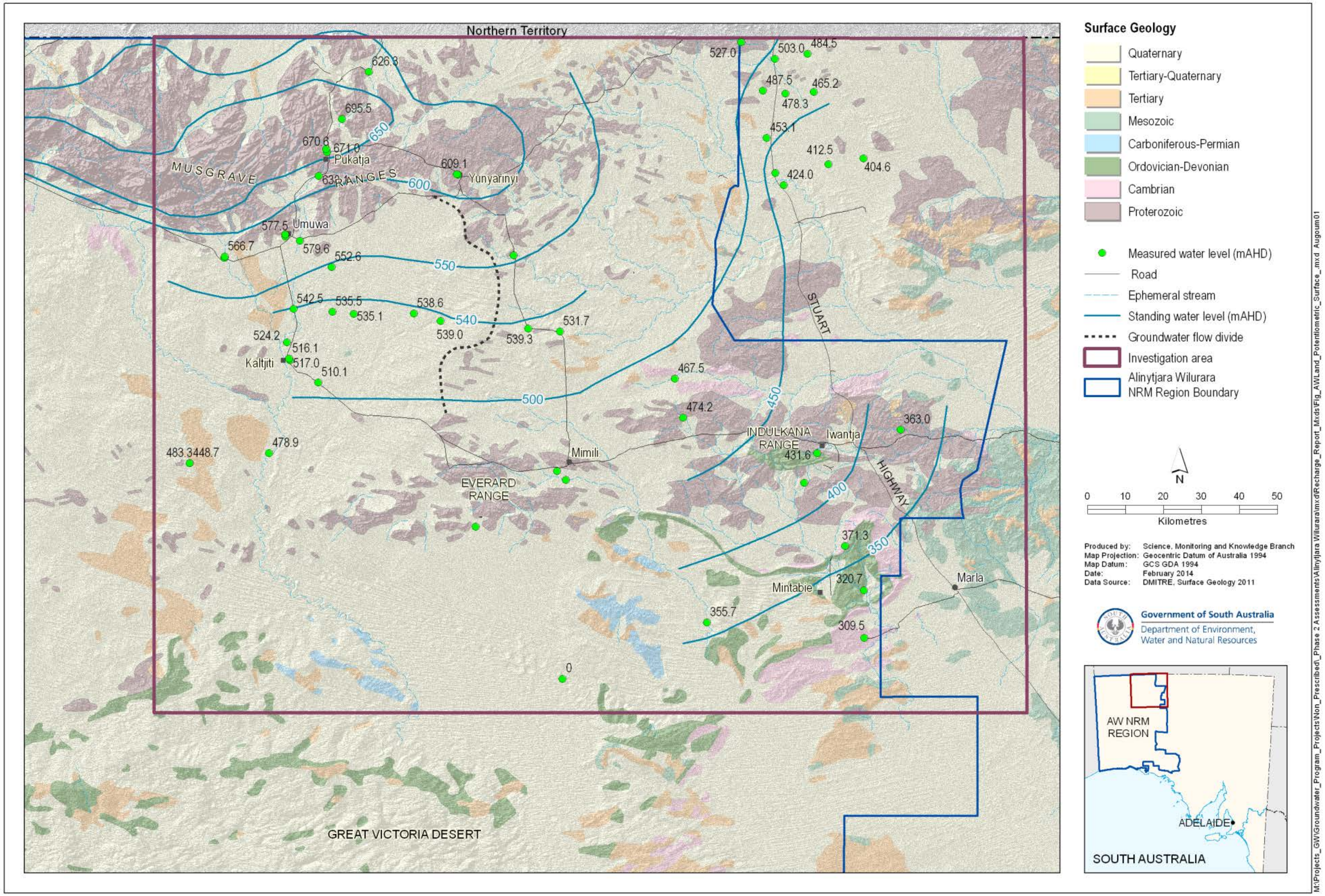


Figure 8. Watertable contours for the unconfined aquifer

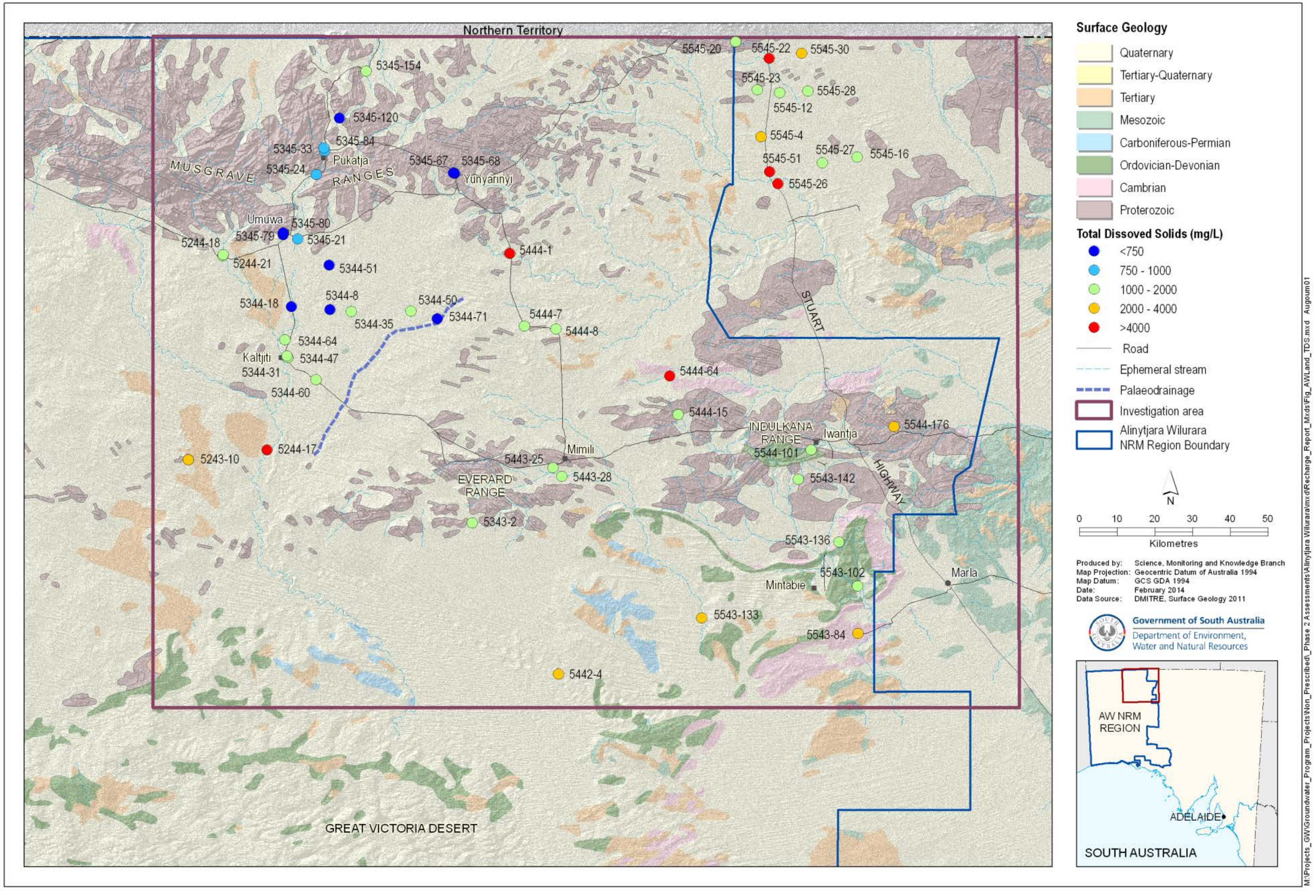


Figure 9. Groundwater salinity (TDS) in the investigation area with wells identified by their unit number

Table 3. Field chemistry, including TDS for all groundwater sites

Unit number	Data source	Name	Easting	Northing	Zone	Latitude	Longitude	Recharge Zone	Collected date	Alkalinity (mg/L)	Electrical cond (µS/cm)	TDS (mg/L)	Temp. (°C)	Field pH	Reduction potetnial (Eh)
474400010	Leaney	Kunytjanu Roads East 97A	540248	7047118	52	26.696478	129.40458	Plains	8/10/2012	-	2755	1782	-	6.9	156
474500096	Leaney	PIP-96	513242	7106302	52	26.162603	129.1325	Rangelands	18/04/2010	-	1500	1018	-	7.3	160
484300012	Leaney	Wataru Solar 1	590834	7012548	52	27.006204	129.91556	Plains	16/05/2003	-	2360	1430	-	6.91	117
484400002	Leaney	Bull Dust Borea	583169	7015673	52	26.978474	129.83809	Plains	7/10/2012	-	6003	3763	-	7.32	90
484400003	Leaney	Mallee Borea	568418	7026360	52	26.882797	129.68887	Plains	8/10/2012	-	12650	8258	-	7.12	126
494300007	Leaney	The Numbers	628399	6976259	52	27.330782	130.2979	Plains	7/10/2012	-	11570	7308	-	6.7	123
514300006	Leaney	Makari No 2 94A	727211	7006650	52	27.04378	131.29061	Plains	5/10/2012	-	2575	1475	-	7.08	146
514500084	Leaney	A-17	714279	7106258	52	26.147107	131.1435	Rangelands	17/04/2010	-	2065	1339	-	7.06	8.7
514500109	Leaney	A-109	713678	7106310	52	26.146727	131.13748	Rangelands	17/04/2010	-	1447	1011	-	7.04	86.8
524300010	Leaney	Walalkara 99B	778657	7009598	52	27.007802	131.80814	Plains	15/05/2003	-	5320	3235	-	7.24	129
524300010	DEWNR	Walalkara 99B	778657	7009598	52	27.007802	131.80814	Plains	18/07/2013	-	5063	3692	19.3	7.19	146.7
524400017	DEWNR	Yankis Bore/Tjilpil 3	797354	7011813	52	26.98395	131.99582	Plains	18/07/2013	-	8443	5492	25	7.35	162.5
524400018	DEWNR	Watinuma Solar 97B	787997	7063266	52	26.521953	131.88989	Rangelands	17/05/2013	280	1626	1053	25.2	7.42	171.3
524400021	Leaney	Watinuma Solar Bore 99A	788100	7063574	52	26.519155	131.89085	Rangelands	17/05/2003	-	1690	1159	-	7.32	80
534300002	DEWNR	Sandy Bore	250872	6993580	53	27.157898	132.48596	Rangelands	18/05/2013	110	1908	1241	25	7.49	-160.4
534400008	DEWNR	Morrison Bore	215916	7049155	53	26.649995	132.14619	Plains	20/05/2013	233	1080	708	25.1	7.56	123.4
534400018	DEWNR	Double Tank Bore	206767	7049702	53	26.643188	132.0545	Plains	16/05/2013	290	1145	734	25.5	7.11	163.7
534400031	Leaney	FRG-7	206001	7036634	53	26.760862	132.04377	Plains	16/04/2010	-	2300	1401	-	7.49	21
534400035	DEWNR	Parakilya Bore	220966	7048769	53	26.654485	132.19678	Plains	20/05/2013	170	1807	1183	25.2	7.44	145
534400047	Leaney	FRG-14	206233	7036277	53	26.764129	132.04602	Plains	16/04/2010		2076	1249	-	7.38	194
534400050	DEWNR	Ironwood Bore	235200	7049208	53	26.653274	132.33974	Plains	20/05/2013	172	2318	1495	25.3	7.08	102.9
534400051	DEWNR	Kuniya Bore	215468	7060943	53	26.543602	132.14433	Plains	17/07/2013	-	962	624	25.1	7.54	162.9
534400060	DEWNR	Mulga Bore 99A	213060	7030625	53	26.816509	132.11331	Plains	16/07/2013	-	1621	1040	25.7	7.56	163.4
534400064	DEWNR	FRG-64	205430	7040965	53	26.72169	132.03905	Plains	15/07/2013	-	2340	1508	25.5	7.37	185.3
534400071	DEWNR	Crombies Bore	241512	7047361	53	26.671106	132.40272	Plains	17/07/2013	-	1095	675	26	7.59	162.6
534500021	DEWNR	McCaul Bore	207853	7067575	53	26.481047	132.06944	Rangelands	13/05/2013	330	1231	819	23.9	7.56	146.9
534500024	Leaney	Turkey Bore B	211894	7084741	53	26.328274	132.11385	Rangelands	18/05/2003	-	1385	985	-	7.06	177
534500033	Leaney	E-42	213693	7091079	53	26.271479	132.13326	Rangelands	15/04/2010	-	1152	855	-	7.18	231.7
534500067	DEWNR	KP 6	244928	7085812	53	26.324894	132.44471	Rangelands	16/05/2013	207	988	650	24.3	7.42	149.7
534500068	Leaney	KP-7	244635	7085904	53	26.324011	132.44179	Rangelands	15/04/2010		771	573	-	7.36	185
534500079	Leaney	Umawa Solar 1	204407	7068740	53	26.471028	132.03524	Rangelands	16/04/2010	-	675	531	-	7.5	217.4
534500080	Leaney	Umuwa Electric	204388	7069229	53	26.466615	132.03517	Rangelands	16/04/2010	-	750	574	-	7.48	-
534500084	Leaney	E-45	213549	7091860	53	26.264407	132.132	Rangelands	15/04/2010	-	1274	881	-	6.94	183.1
534500120	Leaney	Ernabella E-97H	217090	7099830	53	26.193233	132.16916	Rangelands	15/04/2010	-	879	666	-	7.43	140
534500154	DEWNR	New Well 2001A	223158	7112314	53	26.08175	132.23247	Rangelands	17/07/2013	-	1561	1014	25.1	7.47	175.1
544200004	DEWNR	Amoco Survey 86B	272030	6954053	53	27.518128	132.69195	Officer	11/05/2013	140	4797	2970.5	27.5	7.11	141.8
544300025	DEWNR	M-1	269725	7008483	53	27.026738	132.67886	Rangelands	17/05/2013	210	1787	1150	25.5	7.42	145.3
544300028	DEWNR	M-3	271846	7006235	53	27.047368	132.69981	Rangelands	17/05/2013	198	1870	1209	25.2	7.66	133.6
544400001	DEWNR	Arapingie No. 13	258469	7064877	53	26.516106	132.57631	Plains	19/07/2013	-	6241	4205	23.2	7.26	121.1
544400007	DEWNR	Corkwood Bore	262229	7045742	53	26.689364	132.61043	Plains	19/07/2013	-	1966	1300	24.1	7.53	97.2
544400008	DEWNR	No. 17 Bore	269754	7045120	53	26.696227	132.68589	Plains	19/07/2013	-	2629	1729	24.5	7.88	36.4
544400015	DEWNR	Marble Hill 93A	299179	7023018	53	26.900171	132.97794	Plains	16/05/2013	380	1591	1020	25.7	7.42	423.7
544400064	DEWNR	Marble Hill 94A	297015	7033159	53	26.808355	132.9578	Plains	20/07/2013	-	7304	4732	25.2	7.09	138.2
554300084	DEWNR	Wallatinna 93C	342524	6965819	53	27.42196	133.40691	Officer	14/05/2013	154	4275	2641	27.7	7.36	108
554300102	DEWNR	Sailors Well 95A	342301	6978373	53	27.308639	133.40628	Officer	14/05/2013	170	2014	1287	26.1	6.96	124.2
554300133	DEWNR	Aquitaine 97A	305600	6969371	53	27.385143	133.0341	Officer	10/05/2013	162	4510	2736.5	26.6	7.07	131.4
554300136	DEWNR	I98MJ 1	337781	6989885	53	27.20422	133.36214	Officer	15/05/2013	133	1608	1033	25.7	6.26	113.3
554300142	DEWNR	Rodda 93-3 3	327909	7006316	53	27.054742	133.26479	Officer	15/05/2013	254	1783	1131	26.2	6.99	133.5
554400101	Leaney	IMB-19	330843	7014151	53	26.984397	133.29543	Officer	4/05/2008	-	1825	1008	-	5.8	65
554400176	DEWNR	Granite Downs 2001E	350425	7020550	53	26.928889	133.49347	Plains	20/07/2013	-	7743	2411	25.5	7.62	140
554500004	Custance	Sundown Well	317815	7096708	53	26.237707	133.17608	Musgrave East	22/05/2012	190	3660	2342	25.3	8.16	-
554500012	Custance	Doug's Well	322087	7108390	53	26.132818	133.22042	Musgrave East	23/05/2012	249	1610	1030	25.6	8.48	-
554500016	Custance	Giveaway Bore	340834	7091615	53	26.286425	133.40582	Musgrave East	24/05/2012	166.5	1590	1018	25.5	8.44	-
554500020	Custance	Independence Bore	311416	7121746	53	26.010923	133.11566	Musgrave East	23/05/2012	235	2600	1664	24.7	8.45	-
554500022	Custance	Holywater Well	319466	7117400	53	26.051176	133.19546	Musgrave East	23/05/2012	192.5	7074	4527	23.7	8.23	-
554500023	Custance	Ian's Bore	316680	7109026	53	26.126401	133.16645	Musgrave East	23/05/2012	199	1725	1104	24.0	8.43	-
554500026	Custance	Guy Fawke's Bore	322022	7084316	53	26.350082	133.21646	Musgrave East	25/05/2012	267.5	7035	4502	23.7	8.37	-
554500027	Custance	Coultys Hole	332553	7089973	53	26.3003	133.32269	Musgrave East	24/05/2012	201.5	3120	1997	25.0	8.48	-
554500028	Custance	East Bore	328757	7108902	53	26.129006	133.28718	Musgrave East	24/05/2012	222.5	2263	1448	24.8	8.86	-
554500030	Custance	Branson's Well	327207	7118860	53	26.038945	133.273	Musgrave East	24/05/2012	205	4985	3190	16.1	8.99	-
554500051	Custance	Hawke's Bore	319984	7087544	53	26.320693	133.19649	Musgrave East	25/05/2012	315	9639	6169	25.5	8.36	-

3.3. Major anions and cations

All samples were analysed for major anions and cations. The samples collected by Leaney et al. (2013) and DEWNR were analysed by CSIRO Analytical Services using an ICP-Mass Spectrometer. The analysis for the samples collected by Custance (2012) were analysed by ACME laboratories also using an ICP-Mass Spectrometer. The Custance (2012) samples tended to have an anion – cation balance error of near 10 percent, while the samples analysed by CSIRO mostly had a balance error of less that

5 per cent. For the purpose of this investigation the differences are likely to have only a minor effect on interpretation. The results are presented in Table 4 below.

The major ion chemistry can provide information on flow paths and the geology of the material that the groundwater flows through. For this investigation, understanding mineral dissolution and precipitation processes is important to the radiocarbon age-dating process (discussed later), as the addition of inorganic carbon and weathering of the aquifer matrix can alter apparent ages.

For the purposes of testing the validity of applying the CMB approach in the region it was necessary to identify whether chloride had been added to the groundwater from evaportites (salt deposits such as halite) using the bromide-chloride ratio (Br^-/Cl^-). Since halite is low in bromide, the Br^-/Cl^- ratio in the resulting groundwater would have decreased. In Figure 10, this would have been identified by groundwater data trending below the seawater ratio (molar ratio of 1.57×10^{-3}) (Herczeg and Edmunds 2000), which is not evident.

The relationship between $\delta^{13}C$ of dissolved inorganic carbon to both HCO_3 (Figure 11a) and calcite saturation index (Figure 11b) provides direct evidence that inorganic carbon is added to the groundwater through weathering of carbonate rocks in the unsaturated zone and/or aquifer matrix. Furthermore, the negative calcite saturation index values indicate a tendency for the groundwater to dissolve available carbonate. This weathering reaction has the effect of adding old, or 'dead-carbon', and causes the groundwater apparent ages to appear older than what they are likely to be in reality. As a consequence, these 'uncorrected' apparent ages should be considered as maximum ages, and any recharge rates calculated from them should be considered under-estimates of the actual recharge rate. The trends shown in Figure 11 (a, b) suggest a ^{14}C-correction scheme that uses $\delta^{13}C$ data (e.g., Pearson or Fontes & Garnier) would enable the determination of more accurate apparent ages, and thus recharge rates.

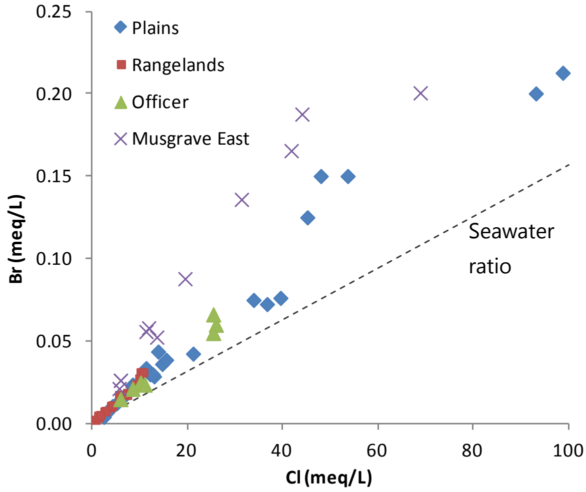
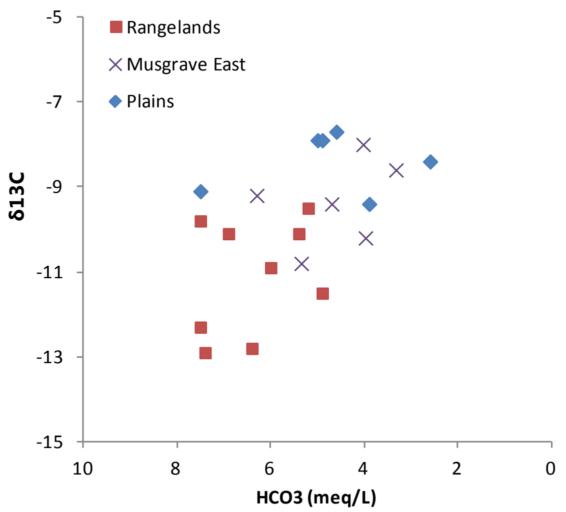
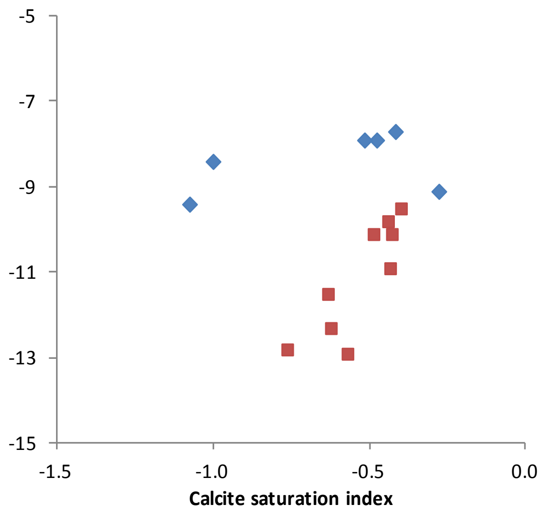


Figure 10. Left; Br^-/Cl^- ratio.

Figure 11a. Lower left; $\delta^{13}C$ vs. HCO_3

Figure 11b. Lower right; $\delta^{13}C$ vs. Calcite saturation index





The Ca^{2+} and SO_4^{2-} plot (Figure 10a), shows that sulphate increases in concentration relative to calcium, particularly on the plains. This indicates that gypsum dissolution or precipitation is not a major process in the groundwater evolution. Rather, this may be the result of either calcite precipitation or pyrite oxidation (Hounslow 1995). Pyrite oxidation is found in areas where the oxygenated water reacts with pyrite to create sulphuric acid, which may be a possible source of SO_4^{2-}in the region. However, calcite precipitation in the shallow subsurface (such as calcrete formation below the root zone) is an alternative explanation for the low Ca^{2+}/SO_4^{2-} ratio. A review of lithology logs indicates shallow calcrete is found in the region. Dissolution of carbonate would affect the radiocarbon age and therefore this can be further investigated by analysing the SiO_2/HCO_3^- ratio.

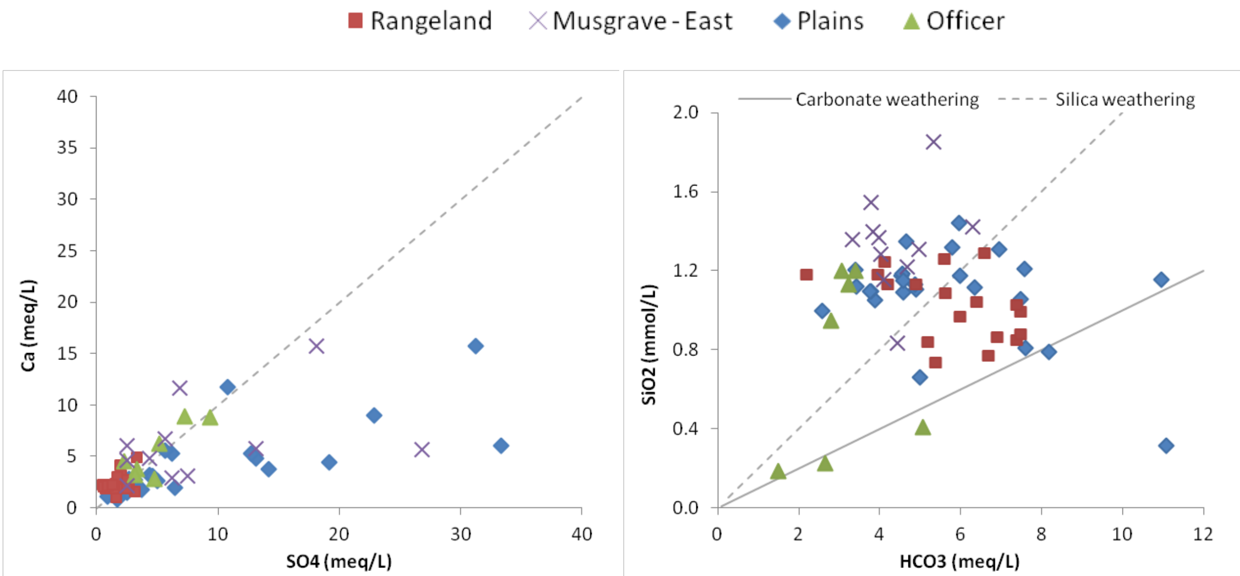


Figure 12. a) Na–Cl plot with dashed seawater ratio line; b) Ca–SO_4 plot with line indicating

The SiO_2/HCO_3^- ratios of less than five may indicate silicate weathering and ratios of greater than ten may indicate carbonate weathering (Hounslow 1995). The two ratio lines have been plotted on Figure 10b. Approximately half the samples lie to the left of the silicate weathering value, indicating the groundwater has dominantly flowed through either the mafic fractured rock or silica-rich clastic sediments (sands and clays). The cluster between the two lines consists of many Rangeland samples which may be young and not have had enough time to weather significant amounts of silica, causing the carbonate ratio to appear more reflective of the ratio found in rainfall. A group of three samples from the Officer Basin region at the lower left of the graph are from the area south of Iwantja and show carbonate dominant weathering. These wells are I98MJ-1, IMB-19 and Rodda 93-3-3. The addition of 'dead' carbon from the aquifer matrix to these sample sites has possibly contributed to the old measured and modelled ages estimated for two of these sites using the carbon dating method. The two right-most 'Plains' samples (blue) are from the far west of the APY Lands outside of the main investigation area (data sourced from Leaney et al. 2013). Local geological differences such as palaeovalley deposits may be altering the hydrochemistry at those sites.

Table 4. Major anion and cation analysis for all groundwater sites

Unit number	Data source	TDS (mg/L)	Lab pH	Lab EC (µS/cm)	Total Alkalinity	NO_2-N (mg/L)	PO_4-P (mg/L)	F^- (mg/L)	Cl^- (mg/L)	Br^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	Ca^{2+} (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Na^+ (mg/L)	S (mg/L)	TC (mg/L)	DIC (mg/L)	DOC (mg/L)	TN (mg/L)	Si (mg/L)
474400010	Leaney	1782	7.6	2600	6.0	-	-	-	520	2.9	99	300	105	43.4	71.6	244	-	-	-	-	-	43.4
474500096	Leaney	1018	8.0	1395	7.4	-	-	-	200	1.3	41	79	21	3.91	94.6	104	-	-	-	-	-	36.8
484300012	Leaney	1430	7.6	2216	3.9	-	-	-	460	2.3	56	240	54	46.3	56.6	248	-	-	-	-	-	38.1
484400002	Leaney	3763	7.8	5590	7.5	-	-	-	1400	6.1	71	680	75	124	107	813	-	-	-	-	-	34.3
484400003	Leaney	8258	7.7	12640	8.2	-	-	-	3500	17	110	1600	121	384	236	1770	-	-	-	-	-	39.3
494300007	Leaney	7308	7.3	11330	5.0	-	-	-	3300	16	71	1500	316	154	350	1280	-	-	-	-	-	38.5
514300006	Leaney	1475	7.5	2365	2.6	-	-	-	550	3.1	86	210	65	49.1	53.3	271	-	-	-	-	-	52.0
514500084	Leaney	1339	7.6	1928	6.7	-	-	-	360	2.5	40	160	98	3.95	62.7	183	-	-	-	-	-	36.1
514500109	Leaney	1011	7.8	1368	6.9	-	-	-	200	1.4	20	94	84	2	54.3	112	-	-	-	-	-	23.4
524300010	Leaney	3235	7.8	5045	3.8	-	-	-	1200	6.0	140	630	96	104	119	676	-	-	-	-	-	32.4
524300010	DEWNR	-	7.7	5335	3.8	-	-	0.8	1300	5.8	130.0	610.0	106	115.0	139.0	832.0	185.0	42.5	42.4	0.1	25.0	39.9
524400017	DEWNR	-	8.1	7750	6.0	-	-	1.8	1900	12.0	210.0	920.0	89	91.6	172.0	1440.0	285.0	66.9	66.1	0.8	40.6	33.0
524400018	DEWNR	-	7.7	1623	6.5	0.057	<0.005	0.4	260	1.5	20.0	150.0	32	5.7	61.6	239.0	42.5	73.9	71.8	2.1	4.7	29.5
524400021	Leaney	1159	7.7	1567	7.5	-	-	-	220	1.4	18	130	46	6.18	33.7	223	-	-	-	-	-	29.6
534300002	DEWNR	-	7.9	1817	3.5	0.042	<0.005	0.9	380	2.5	75.0	98.0	64	12.8	48.4	249.0	28.0	39.3	38.3	1.0	17.6	22.1
534400008	DEWNR	-	8.0	1079	5.1	0.051	<0.005	0.8	140	0.8	35.0	73.0	35	12.1	30.3	159.0	19.9	56.9	56.9	0.0	8.0	18.6
534400018	DEWNR	-	8.0	1154	4.9	0.048	<0.005	1.1	150	0.9	56.0	67.0	29	7.8	20.4	202.0	18.9	55.5	54.6	0.9	12.4	28.0
534400031	Leaney	1401	7.9	2207	4.6	-	-	-	490	3.5	44	150	54	22.9	49.5	273	-	-	-	-	-	30.8
534400035	DEWNR	-	7.8	1822	3.2	0.045	<0.005	0.3	330	1.9	45.0	220.0	63	33.4	44.8	246.0	63.9	35.6	34.6	1.0	11.0	-
534400047	Leaney	1249	7.9	1923	4.9	-	-	-	400	2.7	41	130	52	16.7	38.8	241	-	-	-	-	-	-
534400050	DEWNR	-	7.3	2282	3.8	0.036	<0.005	0.2	430	2.4	75.0	270.0	112	45.9	63.9	248.0	81.8	42.5	41.6	0.8	18.4	-
534400051	DEWNR	-	7.9	876	4.5	-	-	1.1	110	0.6	27.0	44.0	23	6.8	30.3	131.0	12.8	53.0	51.3	1.7	6.0	-
534400060	DEWNR	-	8.1	1453	4.6	-	-	1.5	230	1.3	69.0	120.0	40	27.3	32.4	223.0	37.5	52.8	50.9	2.0	13.9	30.6
534400064	DEWNR	-	7.9	2102	4.9	-	-	1.3	450	2.4	53.0	130.0	56	16.1	52.7	319.0	38.8	56.2	55.5	0.6	10.8	-
534400071	DEWNR	-	8.1	932	4.6	-	-	1.8	86	0.3	48.0	83.0	17	21.7	17.2	171.0	25.9	52.7	51.3	1.5	10.5	31.1
534500021	DEWNR	-	8.3	1237	7.3	0.060	<0.005	1.2	140	0.9	8.6	74.0	37	5.2	40.6	194.0	21.9	81.2	79.4	1.8	2.3	-
534500024	Leaney	985	7.8	1260	7.5	-	-	-	140	0.8	3.2	110	54	2.1	39.4	153	-	-	-	-	-	-
534500033	Leaney	855	7.7	1050	7.4	-	-	-	91	0.6	2.2	74	46	0.849	30.7	131	-	-	-	-	-	-
534500067	DEWNR	-	7.7	1000	5.6	0.046	<0.005	0.6	100	0.6	38.0	62.0	45	2.9	48.1	106.0	17.7	64.1	61.2	2.9	9.5	-
534500068	Leaney	573	7.9	694	4.9	-	-	-	45	0.4	30	36	38	2.9	31.1	59.6	-	-	-	-	-	-
534500079	Leaney	531	8.0	616	5.2	-	-	-	26	0.20	21	22	44	4.76	30.2	40.8	-	-	-	-	-	-
534500080	Leaney	574	8.0	689	5.4	-	-	-	46	0.31	16	27	42	3.83	32.8	54	-	-	-	-	-	-
534500084	Leaney	881	7.8	1166	6.4	-	-	-	150	0.9	6.7	83	60	0.934	37.6	123	-	-	-	-	-	-
534500120	Leaney	666	7.9	806	6.0	-	-	-	60	0.4	6.1	44	43	1.62	28.4	88.5	-	-	-	-	-	-
534500154	DEWNR	-	8.0	1448	5.6	-	-	1.6	260	1.4	41.0	63.0	44	13.2	50.7	193.0	18.5	65.0	63.3	1.7	8.8	-
544200004	DEWNR	-	7.2	3902	2.8	0.029	0.042	0.1	920	4.8	59.0	350.0	179	44.9	74.6	502.0	107.0	32.0	31.3	0.7	16.2	-
544300025	DEWNR	-	7.7	1765	4.0	0.056	<0.005	0.9	320	1.9	80.0	110.0	37	20.4	27.1	295.0	32.7	45.8	44.4	1.5	18.9	23.8
544300028	DEWNR	-	8.13	1865	4.347	0.04713	<0.005	1.3	350	2.2	76	120	38	17.2	32.1	315	33.8	49.6	48.9	0.7	17.7	21.6

Unit number	Data source	TDS (mg/L)	Lab pH	Lab EC (µS/cm)	Total Alkalinity	NO_2-N (mg/L)	PO_4-P (mg/L)	F^- (mg/L)	Cl^- (mg/L)	Br^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	Ca^{2+} (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Na^+ (mg/L)	S (mg/L)	TC (mg/L)	DIC (mg/L)	DOC (mg/L)	TN (mg/L)	Si (mg/L)
544400001	DEWNR	-	7.9	5952	6.4	-	-	2.3	1700	12.0	75.0	520.0	235	21.9	350.0	560.0	159.0	69.3	66.4	2.9	18.4	24.2
544400007	DEWNR	-	8.2	1955	6.9	-	-	2.0	300	1.9	170.0	120.0	29	21.3	65.0	300.0	36.3	81.2	78.8	2.5	33.3	-
544400008	DEWNR	-	8.2	1902	7.6	-	-	1.2	300	1.8	48.0	180.0	35	15.0	74.3	276.0	55.5	88.0	85.0	3.0	13.8	24.6
544400015	DEWNR	-	7.8	1483	7.2	0.076	<0.005	1.4	180	1.0	48.0	83.0	39	11.9	26.9	265.0	24.7	82.6	81.6	0.9	12.6	-
544400064	DEWNR	-	7.8	7097	11.1	-	-	5.5	1600	10.0	110.0	1100.0	181	13.6	187.0	1340.0	350.0	121.8	119.0	2.9	22.5	-
554300084	DEWNR	-	7.5	3914	3.5	0.041	0.018	0.3	900	4.4	180.0	250.0	124	50.9	84.7	511.0	72.8	40.1	39.1	1.1	45.5	27.9
554300102	DEWNR	-	7.3	1933	4.2	0.048	<0.005	0.7	360	2.0	62.0	160.0	75	40.2	45.6	246.0	46.3	47.8	46.3	1.4	15.8	28.8
554300133	DEWNR	-	7.5	4125	3.6	0.037	<0.005	0.4	900	5.3	110.0	450.0	177	53.6	102.0	530.0	145.0	41.2	37.8	3.4	31.5	-
554300136	DEWNR	-	6.5	1581	3.0	0.006	0.020	0.5	300	1.7	24.0	150.0	63	23.4	39.4	195.0	43.3	34.5	32.9	1.6	6.4	31.7
554300142	DEWNR	-	7.8	1715	8.1	0.018	<0.005	0.8	210	1.2	94.0	110.0	91	7.9	51.7	219.0	32.9	58.0	57.3	0.7	23.3	23.5
554400101	Leaney	1008	6.7	1671	1.5	-	-	-	390	1.9	0.7	230	56	14.3	46.9	171	-	-	-	-	-	20.7
554400176	DEWNR	-	8.3	3610	11.0	-	-	2.7	750	3.4	31.0	310.0	40	7.5	44.5	730.0	95.6	128.4	124.0	4.4	5.6	29.3
554500004	Custance	-	-	-	-		-	-	690	7.0	-	-	58	80.8	156.8	519	100	-	-	-	-	27.2
554500012	Custance	-	-	-	-	-	-	-	210	2.1	-	-	121	10.1	81.7	106	40	-	-	-	-	-
554500016	Custance	-	-	-	-	-	-	-	200	1.7	-	-	42	31.8	46.2	210	40	-	-	-	-	-
554500020	Custance	-	-	-	-	-	-	-	400	4.5	-	-	134	5.7	125.8	302	90	-	-	-	-	-
554500022	Custance	-	-	-	-	-	-	-	1560	15.0	-	-	315	16.4	350.3	912	290	-	-	-	-	-
554500023	Custance	-	-	-	-	-	-	-	210	2.1	-	-	93	28.4	56.9	188	40	-	-	-	-	-
554500026	Custance	-	-	-	-	-	-	-	1480	13.2	-	-	116	69.8	290.7	1091	210	-	-	-	-	-
554500027	Custance	-	-	-	-	-	-	-	480	4.2	-	-	63	39.2	82.9	538	120	-	-	-	-	-
554500028	Custance	-	-	-	-	-	-	-	420	4.7	-	-	96	38.9	117.3	299	70	-	-	-	-	-
554500030	Custance	-	-	-	-	-	-	-	1110	10.9	-	-	234	38.4	251.5	546	110	-	-	-	-	-
554500051	Custance	-	-	-	-	-	-	-	2440	16.0	-	-	114	58.5	210.7	1935	430	-	-	-	-	5.2

3.4. Stable isotopes

The stable isotope analysis for deuterium (δ^2H) and oxygen-18 ($\delta^{18}O$) in groundwater was plotted against the local meteoric water line calculated from rainfall data collected at Alice Springs (IAEA-GNIP [online], Hughes & Crawford 2012). Typically on a plot of this type, the groundwater will angle away to the right of the meteoric water line at a lower slope and this represents the local evaporation trend. The left-hand side of a linear evaporation trend through groundwater data points towards the approximate size of the rainfall events that recharge the aquifer. These data shows that the evaporative signature is not well developed, with the evaporation trend being close to parallel with the rainfall trend. However, Figure 13a does indicates that the evaporation trend starts near the isotopic signature of rainfall events sized greater than 100 mm/month. Figure 13b shows the same information but applies the interpretation method described in Leaney et al (2013). The premise of this method is that the groundwater signature is a collective signature for all rainfall events over a given volume, referred to as a threshold value. The weak evaporative trend in groundwater data was also noted by Custance (2012). It was described as being the result of rapid infiltration of recharge of large events, while smaller rainfall events were mostly evaporated from the unsaturated zone without contributing to recharge. This has the effect of increasing chloride content in the unsaturated zone without leaving an obvious evaporative signature in the form of stable isotopes.

Further analysis reveals that some of the samples with a depleted isotopic signature may be affected by altitude related fractionation. A group of high elevation Rangeland samples to the depleted (more negative) end of the x-axis can be seen in Figure 14. The samples with a depleted $\delta^{18}O$ ratio of less than -8 ‰ are likely to have been at least partially affected by altitude effects as they correspond to wells located within the Musgrave Ranges. The Rangeland samples most enriched in $\delta^{18}O$ are located in the lower altitude Everard Ranges. Another potential influence causing depleted ratios in the Musgrave Ranges is the likely high rate of recharge during and following rainfall. The fractured outcropping rocks of the Musgrave Ranges can allow recharge to rapidly penetrate the shallow sediments, leaving little time for evaporation too enrich (make more positive) the $\delta^{18}O$ ratio in the recharging water.

Since samples that are likely to be affected by altitude are located at the lower left of the evaporation trend in Figures 13a and 13b, they cause the evaporation trend to point towards more depleted isotopic rainfall events (bigger rain events). Therefore, qualitatively the actual rainfall threshold is probably closer towards events greater than 60 mm/month. Photos of the landscape following a 45 mm rainfall event in May 2013 does show that in some areas surface water can pool which will assist in saturating the soil profile and increase recharge (Figure 15).

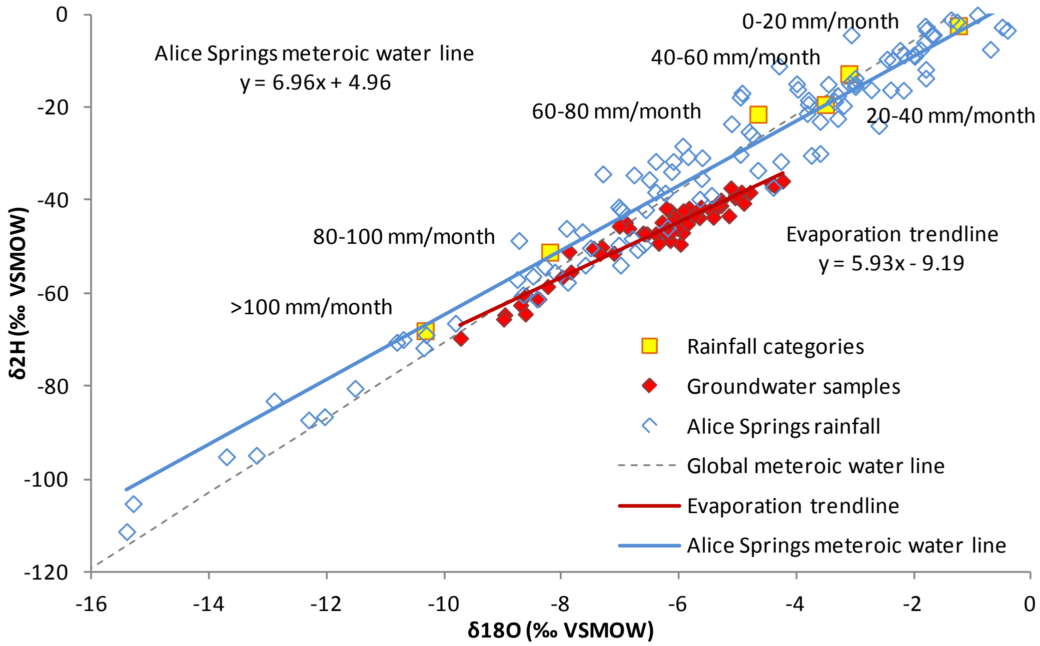


Figure 13a. Groundwater stable isotope ratio relative to amount weighted-mean monthly rainfall volume categories

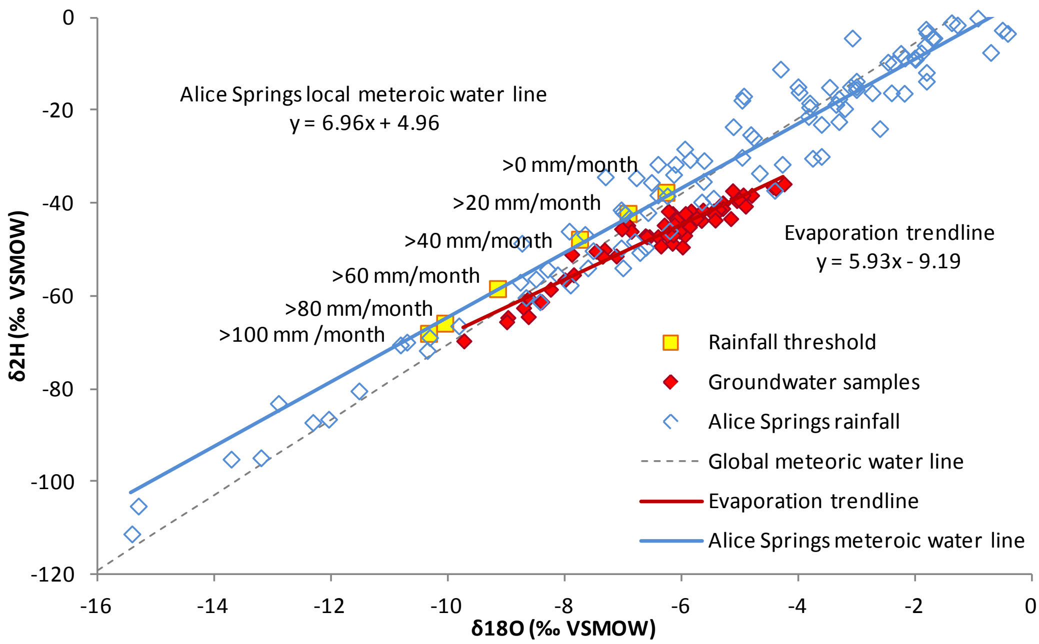


Figure 13b. Groundwater stable isotope ratio relative to amount weighted-mean monthly rainfall thresholds

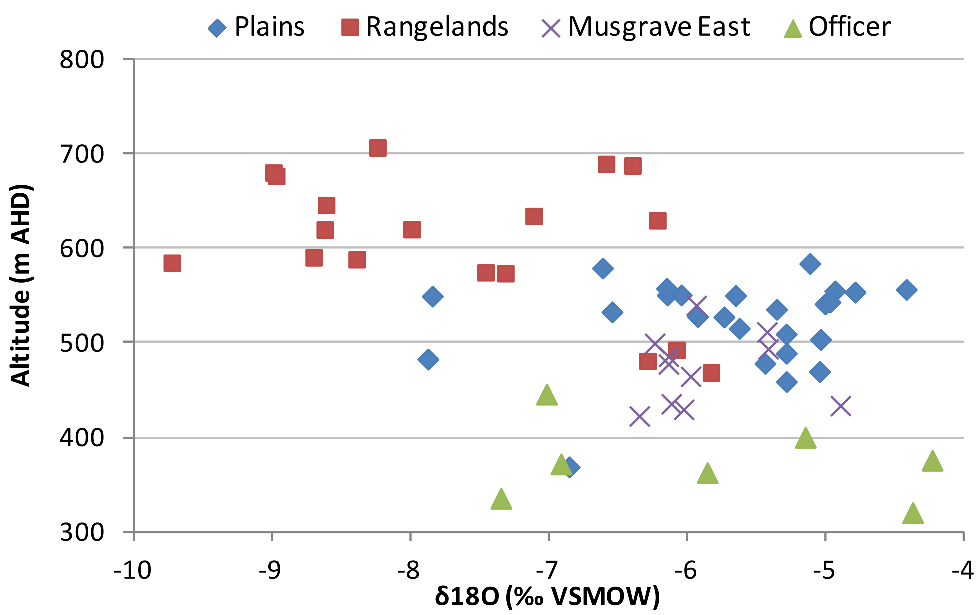


Figure 14. The graph of altitude of wells versus $\delta^{18}O$ in the corresponding groundwater indicates there is likely to be some altitude effect on the isotopic ratio of groundwater recharge.

Stable isotope data can also provide an indication of whether the evaporation trend is being driven by direct evaporation from the soil profile or from plant root uptake (transpiration). Direct evaporation results in fractionation of the isotopes, enriching the groundwater in δ^2H and $\delta^{18}O$, as well as chloride, in the remaining groundwater. Transpiration does not discriminate between isotopes during water uptake; therefore, it results in the enrichment of chloride in groundwater but not isotopes. The plot of $\delta^{18}O$ versus chloride in groundwater shows two trends (Figure 16). If the circled samples are ignored as they may be indicating an altitude effect, then remaining data show only a slight evaporative trend in isotope data relative to large increase in chloride content. To verify the enrichment in chloride was not being dominated by evaporation, these $\delta^{18}O$ data were plotted against the theoretical Rayleigh curve for the distillation of $\delta^{18}O$ under direct evaporation (not shown). The analysis demonstrated that the chloride concentrates much more rapidly than could be justified by enrichment of $\delta^{18}O$ if the process was driven by evaporation only.

Therefore, the increase in chloride concentration without increasing fractionation is possibly a result of transpiration. Groundwater stable isotopes cannot separate whether the transpiration occurs while the recharge percolates downwards, or once it has recharged the aquifer via transpiration from deep-rooted vegetation. Deep-rooted vegetation may access the watertable as the watertable is on average 10 m below ground level in the Rangelands, and 15 m on the Plains. *Eucalyptus* species growing along river channels are possibly a deep-rooted vegetation type that could be groundwater dependent but their extent is limited. Mulga trees, *Acacia aneura*, on the other hand are typically considered to be a shallow-rooted tree (Hill & Hill 2003).

An alternative explanation that does not require deep-rooted vegetation to explain the observed trend was put forward by Custance (2012). It suggests that the concentration of chloride in groundwater, without a corresponding enrichment of $\delta^{18}O$ or $\delta^{2}H$, is the result of rapid infiltration of recharge of large events, while smaller rainfall events are largely evaporated from the unsaturated zone without contributing to recharge. This process creates an enriched chloride concentration in the groundwater but leaves little evaporative signature in the $\delta^{18}O$ or $\delta^{2}H$ ratios. This final explanation is favoured by the author as it highlights the importance of large rainfall events to groundwater recharge which was seen in earlier plots.

Figure 15. Extensive flooding of the road south of Umuwa after 45 mm of rain in the previous 24 hours. Photo taken in May 2013.

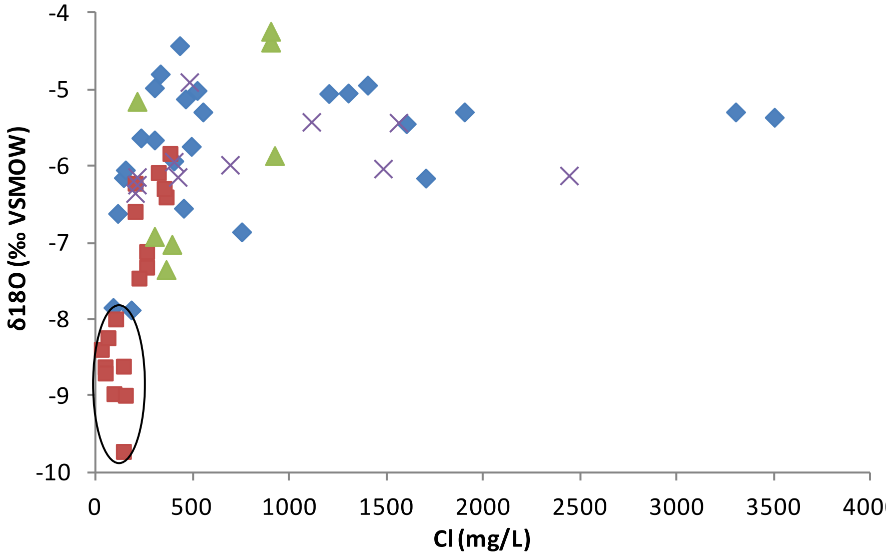


Figure 16. δ^{18}O versus chloride. The graph shows a clear separation in evaporation trends. The lower cluster indicates data which are probably influenced by altitude effects. These remaining data support a hypothesis that transpiration and rainfall events <60 mm/month contribute to

3.5. Groundwater dating

Groundwater dating is a useful approach to estimate groundwater recharge rates and determine whether the recharge rates are reflective of the current or past climate. It is important to understand that groundwater ages measured with natural tracers are normally a mixture of water of multiple ages. This is exacerbated by sourcing samples from wells screened over a large thickness of the aquifer. For example in an unconfined aquifer, groundwater at the bottom of the aquifer would normally be older than the groundwater at the top. Diffusion and groundwater mixing will also affect the accuracy of the result. It is therefore prudent to remember that while the ages may be provided as an absolute value, the value is a guide only and the groundwater measured is a mixture of older and younger groundwater at each site. One of the key aims of dating in this investigation is to identify areas where the unconfined aquifer is being actively recharged in the current arid climate.

3.5.4 Radiocarbon dating

Initial analysis of the raw ^{14}C 'uncorrected' groundwater age shows that in the Rangelands and Musgrave East area, groundwater ranges between modern and 3066 years (Table 5). On the plains the ages were generally older, varying between modern (Arapingie No. 13) to 8050 years (Ironwood Bore). Groundwater was found to be old in the Officer Basin, ranging between 2560 years (Wallatinnia 93C) to 12,190 years (I98MJ1). The old age of the water at I98MJ1 was a surprise as rapid local recharge was expected at its location in a small valley surround by fractured sandstones, with a groundwater level only 1.24 m below ground level.

Analysis of the laboratory results for radiocarbon dating, seen in Figure 17a, showed that the δ^{13}C measured by Beta Analytic (blue dots) are consistently more negative than the two previous studies in the same region. Differences of >5 ‰ were found for wells located within close proximity when analysed at different labs. Data from groundwater investigations in southern Northern Territory in areas with similar climate and vegetation, presented in Leaney et al. (2013), also had δ^{13}C values constrained between -6 ‰ and -14 ‰. Since the results of Custance (2012) and Leaney et al. (2013) were found to be consistent despite being analysed in two separate laboratories, it was deemed necessary to apply a correction factor to the data DEWNR had received from the laboratory. To correct the δ^{13}C values a polynomial line of best fit was put through the good data from the two previous studies (black line, Figure 17a). The equation of the line provided a relationship between the δ^{13}C to ^{14}C. Applying the equation to DEWNR data provided an acceptable approximation of δ^{13}C to be used for groundwater age correction (Figure 17b). Note, that this technique is less than desirable, as the two variables are not necessarily related by balanced chemical reactions. However, in this situation we argue that the earlier data were collected in the same aquifer, in the same region and along similar flow paths, therefore, the $\delta^{13}C$ /^{14}C relationship is expected to be maintained. Some basic sensitivity analysis found that the error associated with the uncertainty of the corrected $\delta^{13}C$ would almost certainly be substantially less than ignoring the age correction process completely.

An expected outcome of age correction is the estimate of a younger age, as the uncorrected age is normally an overestimate due to the fore mentioned addition of dead carbon from the dissolution of calcite in the aquifer. The Tamers model is dependent on the ^{14}C concentration only, where as the Pearson and Fontes and Garnier correction models use both ^{14}C and $\delta^{13}C$ to account for carbonate dissolution. The following modelling assumptions were applied for the correction models:

- For samples that recorded no detectable CFCs, the $\delta^{13}C$ and ^{14}C activities of soil CO_2 was assumed to be -14 ‰ and 95 pMC, respectively.
- For samples that did have detectable CFC concentration, the $\delta^{13}C$ and ^{14}C activities of soil CO_2 was assumed to be -14 ‰ and 106 pMC, respectively.
- The $\delta^{13}C$ and ^{14}C activities of aquifer matrix carbonate sources were assumed to be -8 ‰ and 0 pMC, respectively.

The separation of samples that did or did not contain detectable CFCs was considered appropriate, as those which did contain CFCs were likely to be influenced by ^{14}C concentrations in groundwater recharge which reflected the post-1950 (post-bomb) atmospheric concentration. The -8 ‰ carbonate ratio is based on Australian arid zone investigations (Harrington 1999).

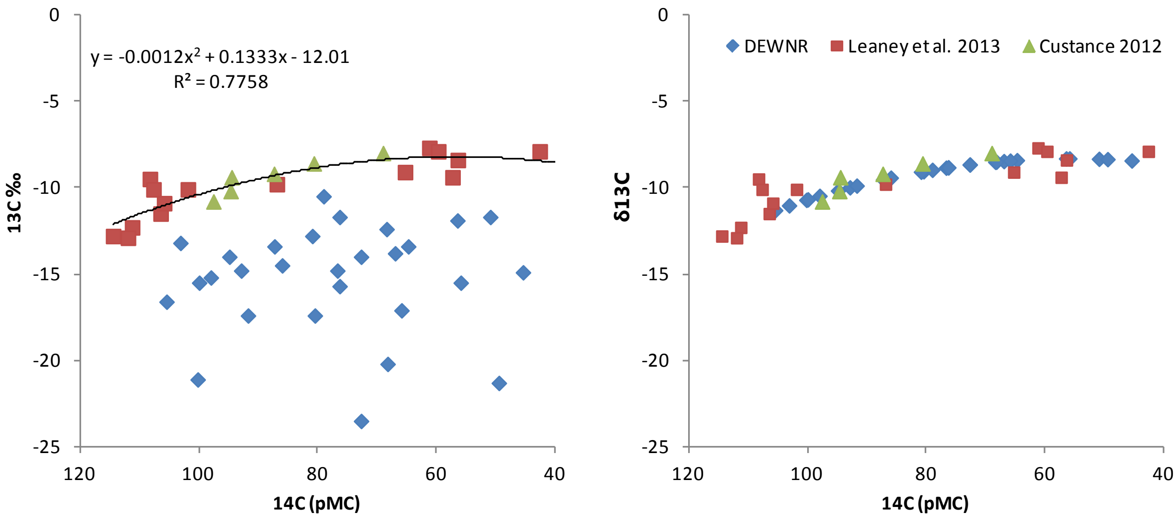


Figure 17 a) Left, $\delta^{13}C$ and ^{14}C prior to correction and b) right, after correction of data collected for this investigation

The results of the Tamers (1975), Pearson (Ingerson & Pearson 1964) and Fontes and Garnier (1979) groundwater age model equations showed that the groundwater were modern in nearly all wells sampled. The exception was I98MJ-1 that had an age range between 1368 and 9067 years. The corrected ages are much younger than expected for the arid environment. There are two possible explanations; the ages are an 'over-correction' or the samples are contaminated by very shallow groundwater. The issue of over-corrected groundwater ages using standard models was recognised in a study of the Ti-Tree Basin in southern Northern Territory (Harrington 1999). The cause of the over-correction was attributed to the applied models assuming all alkalinity was derived from carbonate dissolution while ignoring the contribution of silica weathering. An alternative age correction method put forward by Harrington (1999) may be worth considering in future studies in the region. Contamination by younger shallow groundwater is also a possibility as many of the wells are open-hole. The large number of wells containing CFCs may be indicative of the later process occurring.

3.5.5 Sulphur hexafluoride and noble gases

The measured concentration of SF_6 at 15 of the 50 sites sampled had measured values that exceeded 5 fMol/L, with several values exceeding 10 fMol/L and one value exceeding the laboratories measurement rage (>20 fMol/L) (Table 5). This is well outside the range of values which would normally be expected for groundwater in equilibrium with atmospheric concentrations at the time of recharge (<5 fMol/L). Furthermore, analysis of the relationship between CFC concentration and SF_6 from collected samples indicates that the SF_6 concentrations do not fit with any standard infiltration of groundwater mixing model (Dr A. Suckow, (CSIRO) 2013, pers. comm. 22 October).

While it is well established that atmospheric concentrations of SF_6 have been increasing due to man-made production, in recent years there have been several investigations into natural sources of SF_6 (Harnisch and Eisenhauer 1998, Busenberg and Plummer 2000, Darling et al. 2012). It is apparent that felsic igneous rocks (many types of granite), particularly those containing fluorites (Harnisch et al. 1998), are natural sources of SF_6. In some locations trace fluorite has been recorded in Musgrave Province crystalline rocks (Tucker et al. 2012). However, the large number of geologically-contaminated results was not expected. The results were analysed to see if the high SF_6 concentrations could be related to a particular granite type, or geologic feature such as fault zones, but no relationship was identified. Therefore, it was decided not to rely on any of the SF_6 results for age due to the inability to reliably separate geologically-contaminated samples and atmospherically-contaminated results.

It had been intended to use the noble gas analysis (^{4}He, ^{20}Ne, ^{40}Ar and N_2) to assist with correction of groundwater age estimated using SF_6, in particular, for quantifying the excess air trapped and estimating the temperature during recharge. A post analysis discussion with the laboratory that analysed the data indicated that the analysis may not be accurate enough to achieve this. The two problems mean that little new knowledge could be leveraged from the SF_6 and noble gas data. Analysis of the results indicated that excess air concentration varied between 0.001 and 0.01 cc/g across the sampled sites (Dr A. Suckow, (CSIRO) 2013, pers. comm. 22 October.). Indicatively the recharge temperature is estimated to be around 15^{o}C based on noble gas data.

^{4}He could only be used to provide basic qualitative information on the groundwater age at this stage as production rates from the aquifer geology have not been measured. Analysis of ^{4}He–^{20}Ne plots showed that the helium concentration has a comparably high concentration in most samples. This could be interpreted to indicate the groundwater was thousands of years old; however, this would not be consistent with CFC or radiocarbon measurements (discussed in the following section). The reasonable explanation is that the groundwater is a mixture of young and older water.

Table 5. Laboratory results for data used in age-dating analysis

Unit number	Data source	CFC-11 (pg/kg)	CFC-12 (pg/kg)	SF6 (fMol)	$\delta^{13}C$ (‰ PDB)	^{14}C (pMC)	^{14}C Apparent Age (BP)	Apparent age error (^{14}C)	He-4 (cc/g @ STP)	Ne-20 (cc/g @ STP)	Ar-40 (cc/g @ STP)	N_2 ccSTP/g	Ae (cc/g @ STP)
474400010	Leaney	–	–	0.30	–	61.8	3870	25	1.41E-07	1.86E-07	6.66E-04	–	2.86E-03
474500096	Leaney	–	–	0.63	–	76.5	2160	30	1.38E-07	2.14E-07	3.85E-04	–	4.79E-03
484300012	Leaney	11	1	7.25	-9.4	57.3	4480	25	6.52E-07	2.00E-07	5.75E-04	–	3.80E-03
484400002	Leaney	–	–	1.61	-9.1	65.3	3430	25	5.79E-08	1.90E-07	6.20E-04	–	3.14E-03
484400003	Leaney	16	8	6.86	–	67.9	3120	25	6.82E-06	2.15E-07	3.77E-04	–	4.81E-03
494300007	Leaney	47	29	10.17	-7.9	42.6	6870	35	6.86E-06	9.25E-07	1.23E-03	–	5.23E-02
514300006	Leaney	35	21	3.97	-8.4	56.4	4610	30	2.06E-07	1.77E-07	3.04E-04	–	2.30E-03
514500084	Leaney	–	–	0.47	–	93.5	540	25	6.15E-08	2.97E-07	7.31E-04	–	1.03E-02
514500109	Leaney	–	–	0.89	-10.1	101.9	>modern	–	8.53E-08	3.65E-07	8.14E-04	–	1.49E-02
524300010	DEWNR	13	10	1.15	-14.9	45.4	6340	30	–	–	–	–	–
524300010	Leaney	–	–	0.65	–	43.4	6710	30	3.49E-07	2.22E-07	5.19E-04	–	5.27E-03
524400017	DEWNR	163	97	11.01	-14.8	76.7	2130	30	–	–	–	–	–
524400018	DEWNR	43	26	1.79	-14.5	86.0	1210	30	2.94E-08	8.81E-08	4.94E-04	2.04E-02	–
524400021	Leaney	–	–	1.79	-9.8	86.9	1130	30	1.22E-07	2.75E-07	8.12E-04	–	8.87E-03
534300002	DEWNR	66	39	4.1	-13.4	87.3	1090	30	1.27E-07	2.97E-07	4.37E-04	1.91E-02	–
534400008	DEWNR	32	<25	2.1	-11.9	56.5	4590	30	3.36E-07	2.33E-07	4.02E-04	1.52E-02	–
534400018	DEWNR	33	<20	9.17	-13.8	67.0	3220	30	1.51E-07	2.23E-07	5.12E-04	1.84E-02	–
534400031	Leaney	–	–	0.50	-7.7	61.2	3950	45	1.89E-07	2.17E-07	5.00E-04	–	4.97E-03
534400035	DEWNR	49	27	1.53	-11.7	50.9	5420	30	1.16E-07	2.26E-07	3.54E-04	1.68E-02	–
534400047	Leaney	–	–	0.41	-7.9	59.7	4150	30	1.30E-07	1.91E-07	3.17E-04	–	3.23E-03
534400050	DEWNR	53.5	53.5	5.65	-17.4	80.5	8050	40	2.82E-07	6.42E-07	6.87E-04	3.03E-02	–
534400051	DEWNR	9	8	3.91	-12.4	68.4	3050	30	–	–	–	–	–
534400060	DEWNR	205	129	10.81	-15.5	55.9	4670	30	–	–	–	–	–
534400064	DEWNR	17	16	>20	-13.4	64.8	3490	30	–	–	–	–	–
534400071	DEWNR	142	89	4.51	-14.8	92.9	590	30	–	–	–	–	–
534500021	DEWNR	233	112.5	2.5	-13.2	103.2	+/- 0.4 pMC	>modern	9.19E-08	3.60E-07	3.59E-04	1.91E-02	–
534500024	Leaney	221	164	8.54	-12.3	111.3	>modern	–	8.93E-08	3.48E-07	8.25E-04	–	1.37E-02
534500033	Leaney	–	–	2.40	-12.9	112	>modern	–	8.53E-08	2.54E-07	8.41E-04	–	7.43E-03
534500067	DEWNR	254	130	12.92	-16.6	105.5	+/- 0.3 pMC	>modern	5.92E-07	1.97E-07	5.57E-04	1.84E-02	–
534500068	Leaney	258	154	3.51	-11.5	106.5	>modern	–	5.37E-07	2.65E-07	3.95E-04	–	8.17E-03
534500079	Leaney	–	–	1.55	-9.5	108.3	>modern	–	6.01E-08	2.23E-07	5.56E-04	–	5.33E-03
534500080	Leaney	–	–	1.01	-10.1	107.7	>modern	–	7.28E-08	2.90E-07	4.18E-04	–	9.86E-03
534500084	Leaney	–	–	2.22	-12.8	114.5	>modern	–	8.05E-08	2.95E-07	5.35E-04	–	1.02E-02
534500120	Leaney	–	–	0.97	-10.9	105.9	>modern	–	2.53E-07	2.74E-07	7.60E-04	–	8.74E-03
534500154	DEWNR	158	103	7.21	-17.4	91.8	690	30	–	–	–	–	–
544200004	DEWNR	<25	<20	4.42	-21.3	49.5	5650	30	5.24E-06	3.24E-07	4.35E-04	2.66E-02	–
544300025	DEWNR	58.5	30.5	8.21	-10.5	79.0	1890	30	2.47E-06	2.56E-07	5.31E-04	1.47E-02	–
544300028	DEWNR	34.5	<20	4.53	-11.7	76.3	2170	30	1.14E-07	2.54E-07	3.38E-04	1.61E-02	–
544400001	DEWNR	214	148	5.16	-21.1	100.3	+/- 0.4 pMC	>modern	–	–	–	–	–
544400007	DEWNR	250	156	5.54	-15.2	98.0	160	30	–	–	–	–	–
544400008	DEWNR	172	116	2.6	-14.0	72.7	2560	30	–	–	–	–	–
544400015	DEWNR	136	65.5	11.49	-14.0	94.9	420	30	1.40E-07	2.16E-07	4.84E-04	1.95E-02	–
544400064	DEWNR	205	129	4.84	-15.7	76.3	2170	30	–	–	–	–	–
554300084	DEWNR	208	96.5	1.95	-23.5	72.7	2560	30	2.62E-07	2.32E-07	3.44E-04	1.40E-02	–
554300102	DEWNR	<25	<20	1.81	-17.1	65.9	3350	30	1.54E-07	2.66E-07	4.32E-04	1.82E-02	–
554300133	DEWNR	80.5	34.5	2.77	-20.2	68.2	3070	30	7.99E-08	2.77E-07	3.97E-04	1.79E-02	–
554300136	DEWNR	<25	<20	0.61	-18.0	22.1	12120	50	2.94E-07	2.74E-07	6.70E-04	3.14E-02	–
554300142	DEWNR	167	91	2.12	-12.8	80.9	1700	30	–	–	–	–	–
554400101	Leaney	–	–	0.32	–	31.9	9190	30	4.46E-07	2.39E-07	4.62E-04	–	6.41E-03
554400176	DEWNR	254	164	3.22	-15.5	100.0	0	30	–	–	–	–	–
554500016	Custance	–	–	–	-8.6	80.67	1776	–	–	–	–	–	–
554500020	Custance	–	–	–	-9.4	94.53	465	–	–	–	–	–	–
554500023	Custance	–	–	–	-10.2	94.69	451	–	–	–	–	–	–
554500026	Custance	–	–	–	-10.8	97.6	201	–	–	–	–	–	–
554500027	Custance	–	–	–	-8.0	69.01	3066	–	–	–	–	–	–
554500051	Custance	–	–	–	-9.2	87.38	1115	–	–	–	–	–	–

3.5.6 Chlorofluorocarbons

CFCs were more successful than SF_6 in providing a reasonable estimate of groundwater age. However, unlike SF_6, dissolved-CFC compounds can be prone to degradation under certain redox conditions. The plot of CFC-11 against CFC-12 shows the measured data trending below the binary-mixing curve (Figure 18). This is an indicator that the CFC-11 has degraded from its original concentration when the groundwater was recharged. Degradation would cause groundwater age estimated from CFC-11 to appear older than what it actually is, although the age calculated using CFC-12 is not affected. Due to the partial degradation of CFC-11, the age based on CFC-12 is considered the most accurate estimate of groundwater age.

The results (Table 6) indicate that the groundwater age in many cases is 30–50 years old, with no groundwater age less than 25 years. A total of 31 wells recorded an age which indicates that groundwater recharge has occurred during the current arid climate in the past 50–60 years, compared to only four wells which had CFC concentrations below the limit of detection for the laboratory analysis. However, caution should be taken with these results due to nature of the wells sampled.

An analysis of estimated recharge rates based on CFC-12 was undertaken for this study, however, the results indicated high recharge rates that were considered to be extremely unlikely in the arid setting and for this reason they were not included. In arid areas, groundwater at the top of the aquifer can have higher concentrations of CFCs due to the downward diffusion of atmospheric gasses through the unsaturated zone. This has the effect of causing the upper layer of groundwater to appear younger than it is. As the wells were mostly open hole (uncased from above the watertable downwards), the relatively shallow groundwater can disproportionately 'contaminate' the sample with the shallow young groundwater as it flows towards the pumped well. Ideally, wells used for age dating would have a discrete screen depth set below the watertable.

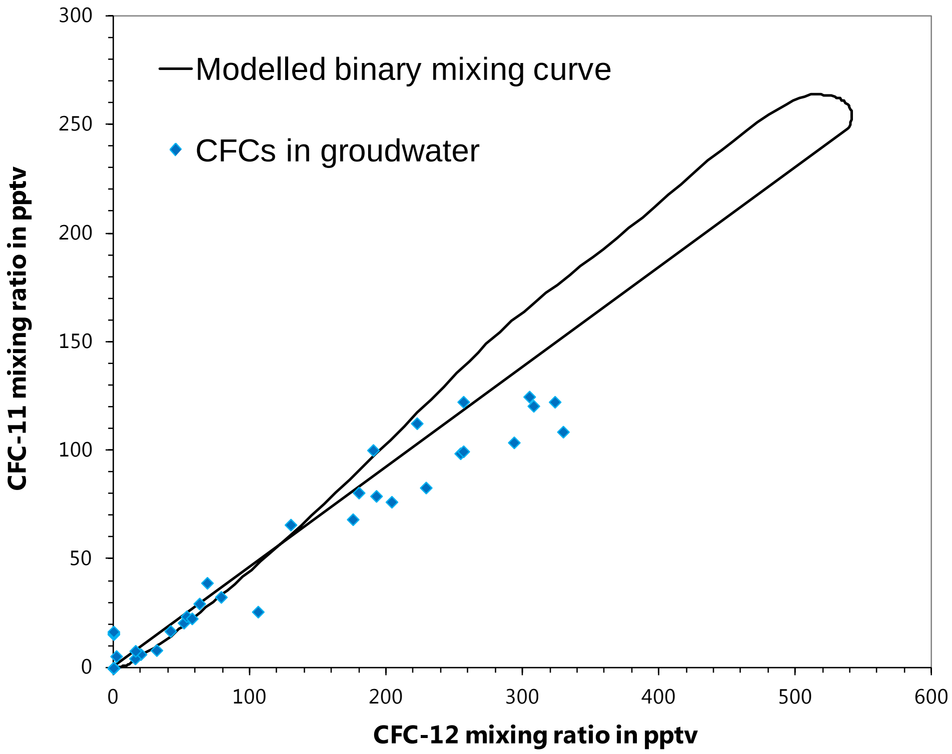


Figure 18. The graph of CFC-11 versus CFC-12 shows that the CFC-11 concentration falls outside the binary-mixing curve (black line) used to identify mixing of waters of two different ages, indicating degradation of CFC-11.

Table 6. Carbon-14 and CFC groundwater-age

Unit Number	Source	Well ID	A (pmC)	Adjusted δ13C	Original δ13C	Uncorrected age (y)	Tamers age (y)	Fontes & Garnier age (y)	Modelled date CFC-11	Modelled date CFC-12
554500016	Custance	Giveaway Bore	80.67	-8.6	-8.6	2257	Modern	Modern	not tested	
554500020	Custance	Independence Bore	94.53	-9.4	-9.4	947	Modern	Modern	not tested	
554500023	Custance	Ian's Bore	94.69	-10.2	-10.2	933	Modern	Modern	not tested	
554500026	Custance	Guy Fawke's Bore	97.60	-10.8	-10.8	683	Modern	Modern	not tested	
554500027	Custance	Coultys Hole	69.01	-8.0	-8.0	3548	Modern	Modern	not tested	
554500051	Custance	Hawke's Bore	87.38	-9.2	-9.2	1597	Modern	Modern	not tested	
474400010	Leaney et al.	Kunytjanu Roads East 97A	61.80			4460	Modern		not tested	
484300012	Leaney et al.	Wataru Solar 1	57.30	-9.4	-9.4	5085	Modern	613	1958	1947
484400002	Leaney et al.	Bull Dust Bore	65.30	-9.1	-9.1	4005	Modern	Modern	not tested	
484400003	Leaney et al.	Mallee Bore	67.90			3682	Modern		1960	1956
494300007	Leaney et al.	The Numbers	42.60	-7.9	-7.9	7536	1806	1708	1965	1965
514300006	Leaney et al.	Makari No 2 94A	56.40	-8.4	-8.4	5216	Modern	Modern	1964	1963
524300010	Leaney et al.	Walalkara 99B	43.40			7382	3319		not tested	
524300010	DEWNR	Walalkara 99B	45.42	-9.4	-14.9	7006	2949	2630	1958	1957
524400017	DEWNR	Yankis Bore/Tjilpil 3	76.71	-9.3	-14.8	2674	Modern	Modern	1973	1975
534400008	DEWNR	Morrison Bore	56.47	-6.4	-11.9	5206	841	Modern	1963	
534400018	DEWNR	Double Tank Bore	66.98	-8.3	-13.8	3795	62	Modern	1964	
534400031	Leaney et al.	FRG-7	61.20	-7.7	-7.7	4541	Modern	Modern	not tested	
534400035	DEWNR	Parakilya Bore	50.93	-6.2	-11.7	6060	1860	Modern	1966	1965
534400047	Leaney et al.	FRG-14	59.70	-7.9	-7.9	4746	Modern	Modern	not tested	
534400050	DEWNR	Ironwood Bore	36.71	-11.9	-17.4	8766	5024	6246	1966	1970
534400051	DEWNR	Kuniya Bore	68.41	-6.9	-12.4	3620	Modern	Modern	1957	1956
534400060	DEWNR	Mulga Bore 99A	55.91	-10.0	-15.5	5288	Modern	1315	1975	1978
534400064	DEWNR	FRG-64	64.76	-7.9	-13.4	4074	Modern	Modern	1960	1961
534400071	DEWNR	Crombies Bore	92.92	-9.3	-14.8	1089	Modern	Modern	1972	1974
544400001	DEWNR	Arapingie No. 13	100.25	-15.6	-21.1	461	Modern	17	1975	1981
544400007	DEWNR	Corkwood Bore	98.03	-9.7	-15.2	646	Modern	Modern	1977	1981
544400008	DEWNR	No. 17 Bore	72.71	-8.5	-14.0	3116	Modern	Modern	1974	1977
544400015	DEWNR	Marble Hill 93A	94.91	-8.5	-14.0	914	Modern	Modern	1972	1972
544400064	DEWNR	Marble Hill 94A	76.33	-10.2	-15.7	2715	Modern	Modern	1975	1978
554400176	DEWNR	Granite Downs 2001E	100.00	-10.0	-15.5	482	Modern	Modern	1977	1982
474500096	Leaney et al.	PIP-96	76.50			2696	Modern		not tested	
514500084	Leaney et al.	A-17	93.50			1037	Modern		not tested	
514500109	Leaney et al.	A-109	101.90	-10.1	-10.1	326	Modern	Modern	not tested	
524400018	DEWNR	Watinuma Solar 97B	86.02	-9.0	-14.5	1727	Modern	Modern	1965	1964
524400021	Leaney et al.	Watinuma Solar 99A	86.90	-9.8	-9.8	1642	Modern	Modern		
534300002	DEWNR	Sandy Bore	87.31	-7.9	-13.4	1604	Modern	Modern	1967	1968
534500021	DEWNR	McCaul Bore	103.16	-7.7	-13.2	225	Modern	Modern	1976	1976
534500024	Leaney et al.	Turkey Bore B	111.30	-12.3	-12.3	Modern	Modern	Modern	1976	1983
534500033	Leaney et al.	E-42	112.00	-12.9	-12.9	Modern	Modern	Modern	not tested	
534500067	DEWNR	KP 6	105.50	-11.1	-16.6	39	Modern	Modern	1977	1978
534500068	Leaney et al.	KP-7	106.50	-11.5	-11.5	Modern	Modern	Modern	1977	1981
534500079	Leaney et al.	Umawa Solar 1	108.30	-9.5	-9.5	Modern	Modern	Modern	not tested	
534500080	Leaney et al.	Umuwa Electric	107.70	-10.1	-10.1	Modern	Modern	Modern	not tested	
534500084	Leaney et al.	E-45	114.50	-12.8	-12.8	Modern	Modern	Modern	not tested	
534500120	Leaney et al.	Ernabella E-97H	105.90	-10.9	-10.9	8	Modern	Modern	not tested	
534500154	DEWNR	New Well 2001A	91.77	-11.9	-17.4	1192	Modern	Modern	1973	1976
544300025	DEWNR	M-1	79.03	-5.0	-10.5	2427	Modern	Modern	1967	1966
544300028	DEWNR	M-3	76.33	-6.2	-11.7	2715	Modern	Modern		1940
544200004	DEWNR	Amoco Survey 86B	49.49	-15.8	-21.3	6297	1206	5963	below detection limit	
554300084	DEWNR	Wallatinna 93C	72.71	-18.0	-23.5	3116	Modern	3818	1975	1975
554300102	DEWNR	Sailors Well 95A	65.90	-11.6	-17.1	3929	Modern	1155	below detection limit	
554300133	DEWNR	Aquitaine 97A	68.24	-14.7	-20.2	3641	Modern	2733	1969	1967
554300136	DEWNR	I98MJ 1	22.12	-12.5	-18.0	12954	9973	10859	below detection limit	
554300142	DEWNR	Rodda 93-3 3	80.93	-7.3	-12.8	2231	Modern	Modern	1974	1974
554400101	Leaney et al.	IMB-19	31.90			9927	8347		below detection limit	

3.6. Groundwater recharge rate and recharge areas

An estimate of the groundwater recharge rate has been made using the CMB approach. In addition, a volumetric estimate of the recharge rate has been made using the CMB approach and upscaling method described earlier in the Methods section. An attempt was made to estimate recharge rates using the radiocarbon ages but the suspected erroneous age-estimates that resulted from age-correction models did not provide sufficient confidence to warrant reporting the quantitative results. Qualitatively, the radiocarbon analysis indicates to us that groundwater recharge is an ongoing process despite the arid climate

The results of the volumetric recharge rate estimate using the CMB approach are provided in Table 7 and Figure 19. The point recharge rates were highest in the Musgrave Ranges, varying between 0.5 mm/y and 7.2 mm/y. In the Everard Ranges recharge rates were closer to 0.5 mm/y. On the plains recharge rates varied between 0.05 mm/y and 2 mm/y, but averaged around 0.5 mm/y.

The CMB approach provided an estimate of 56 500 ML/y of recharge to the groundwater over an area of 102 529 km^2 (the entire APY Lands). Over the smaller investigation area (but within the APY Lands boundary), the total recharge is estimated to be 15 500 ML/y over 29 790 km^2. Fresh to moderately weathered bedrock recorded the highest recharge rate, averaging 3.4 mm/y. Colluvial sediments recorded the second highest recharge rate, averaging 0.9 mm/y. This is likely to be partly due to the close proximity of these sediments to outcropping bedrock which provides additional runoff-recharge, particularly close to the Musgrave Ranges. Lacustrine sediments recorded the lowest average recharge rate of 0.1 mm/y, possibly due to evaporative losses concentrating chloride as well as a lack of data points in that regolith class. The average recharge rate for the entire region is just 0.55 mm/y.

Figure 19 illustrates the estimated groundwater recharge rates across the region. As found in previous studies, recharge rates are highest in the ranges (Dodds et al. 2001, Leaney et al. 2013). This investigation highlights that this is particularly the case for the colluvial regolith adjacent granitic bedrock outcrops. The sheetflow regolith east of Kaltjiti and south of Mimili also stand out as having moderate recharge rates. The residual material class regolith in the eastern APY Lands (clayey, in-situ weathered granites) tends to have lower recharge rates. Based on the numerous creek lines in those areas that flow eastwards, this material seems more prone to surface runoff than gradual infiltration.

There results of the volumetric estimate (Table 7) show there were several benefits from the upscaling method applied here when compared to a more simple approach of applying an average rate for each regolith type. The assigning of ‘local’ point values to polygons minimised undue influence of distant point values on recharge rates for a particular regolith type. For example, the Musgrave Ranges and Everard Ranges are more than 70 km apart and the latter have a much lower elevation, yet both have a regolith type of ‘fresh to moderately weathered bedrock’. By using local recharge point values the fresh to moderately weather bedrock in the Musgrave Ranges has recharge rates between 0.7 mm/y to 6 mm/y (depending on individual regolith polygons), whereas the Everard Ranges are constrained to 0.7 mm/y. Importantly from a scientific perspective, another advantage is the method is easily repeatable.

One disadvantage of the upscaling method is that it still allowed some anomalous values to impact recharge values at local scales. For example, a well near Walalkara (southwest of Kaltjiti) located in a regolith denoted as ‘sheet flow deposits’ recorded a recharge rate of 3.4 mm/y, resulting in all sheet flow deposit polygons nearby being assigned the same value. In reality, the well was located close to outcropping bedrock where a narrow zone of preferential runoff-recharge probably exists. Another shortfall is that mixed groundwater from high-recharge rate areas in the ranges and low-recharge rate areas on the plains means that recharge rates may be overestimated on the plains, particularly in areas close to the ranges. This is a problem that is inherent with the assumption of one-dimensional piston flow when using the CMB approach.

However, within the scope of this investigation and at the regional scale, it is believed this approach provides a reasonable approach to quantify the average annual groundwater recharge volume in the region

Infiltration during infrequent but sometimes very large flood events in creek lines would also be important for groundwater recharge in locations such as Umuwa and Kaltjiti. The existence of shallow palaeovalley features such as that intercepted by Crombies Bore may also be significant groundwater storages.

Table 7. Regional groundwater recharge in the APY lands derived from the CMB approach.

Regolith type	Regolioth code	Area (km^2)	Min. rate (mm/y)	Max. rate (mm/y)	Avg. Rate (mm/y)	Volume (ML)	Number of points
Alluvial sediments	SDA00	1321	0.3	2.7	0.6	844	40
Colluvial sediments	SDC00	5639	0.2	3.1	0.9	5150	95
Sheet flow deposits	SDC05	17 744	0.1	3.4	0.6	10 023	96
Aeolian sediments	SDE00	53 149	0.1	0.6	0.3	13 658	70
Lacustrine sediments	SDL00	86	0.1	0.1	0.1	11	2
Fresh to moderately weathered bedrock	SFM	5861	0.5	6.6	3.4	19 965	37
Moderately to highly weathered bedrock	SMH	4114	0.03	1.9	0.7	2793	38
Transported sediments	STR	9866	0.1	0.6	0.2	2283	17
Residual material	WIR20	4749	0.11	0.5	0.4	1804	22
Total		102 529			0.55	56 531	417

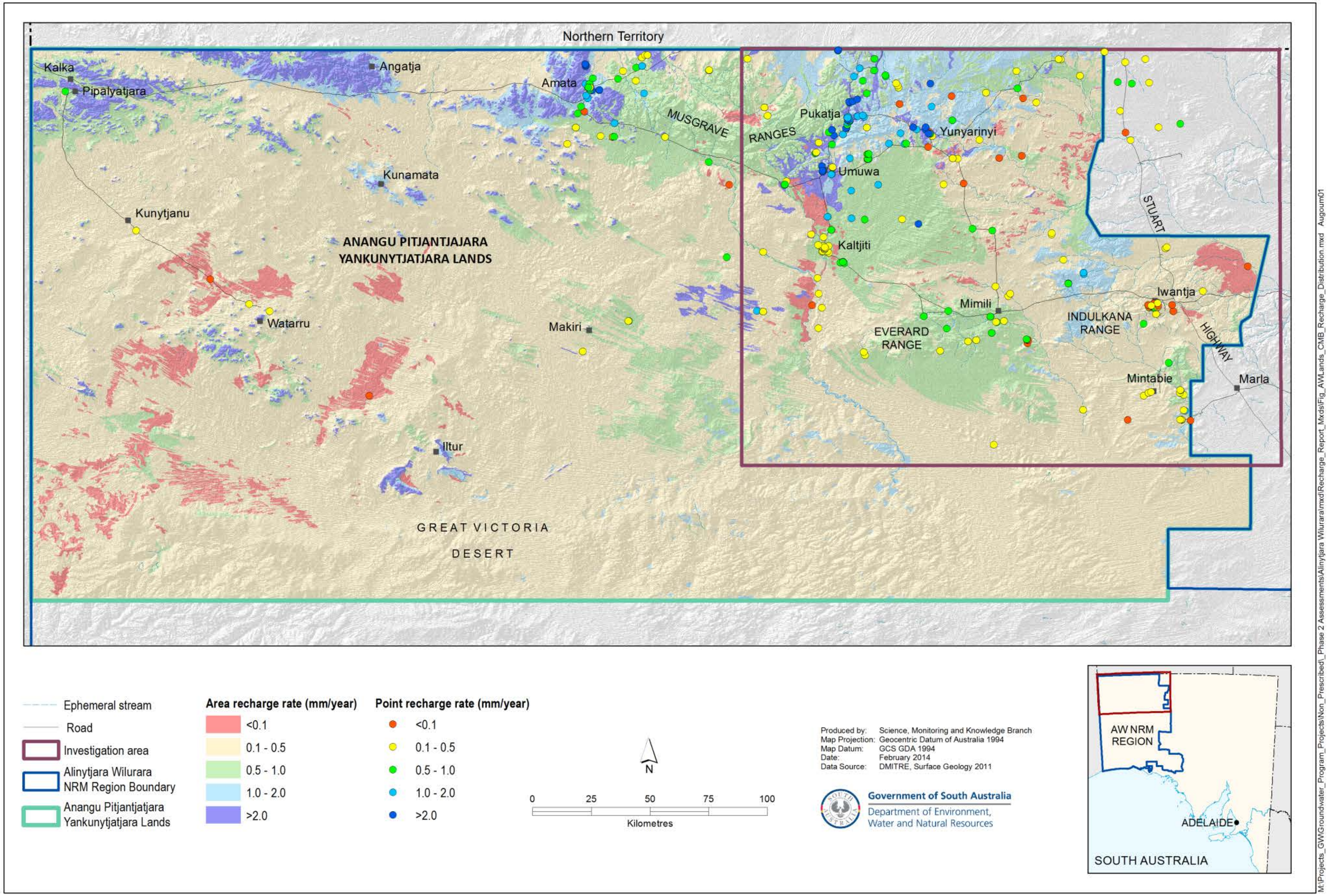


Figure 19. Recharge rates based on the CMB approach at wells and upscaled across the APY Lands

4. Discussion

4.1. Groundwater recharge processes

Groundwater recharge in the eastern APY Lands is an actively occurring process despite the arid climate. Rapid, episodic recharge in the Musgrave Ranges was suggested previously (Cresswell 2002), then indicated by the stable isotope data which shows little evaporation of groundwater prior to recharge. Stable isotope data show that months in which rainfall is in excess of 80 mm are the major contributor to recharge. In this project we had intended to develop a detailed understanding of recharge processes based on multiple methods to constrain uncertainty. However, the anomalously high estimates of recharge from CFCs and radiocarbon dating suggest to us that the diffusion of atmospheric gases into the watertable independent of recharge may be causing underestimates of the groundwater age, and by consequence over-estimates of the recharge rate. The anomalously high SF_6 results indicate rarely encountered sub-surface production of the gas from the granitic Musgrave Block, making it unsuitable as a groundwater investigation tool in the area. However, the stable isotope and CMB approach in combination do give us confidence to state that rapid, episodic recharge is the dominant driver of groundwater recharge in the region.

4.2. Groundwater age and regional flow dynamics

The groundwater age analysis showed that most sites have modern groundwater based on CFCs and radiocarbon. In general the two methods were consistent; however the estimates of young groundwater age should be viewed with a degree of caution. Low recharge rates (<1 mm) can lead to diffusion of modern CO_2 though the unsaturated zone and impact the signature of older water (Cresswell et al. 1999). Whilst modern groundwater ages on the ranges seem reasonable, but for the more arid areas on the plains, the low recharge rates estimated using the CMB approach are not consistent with the modern age for groundwater. For example, if the effective saturated thickness of the aquifer was considered to be 20 m with a low porosity of 0.05, a recharge rate of 1 mm/y would take approximately 1000 years for complete water exchange. The diffusion of modern CO_2 and CFCs through the soil zone and into the shallow aquifer would seem a reasonable explanation for altering the age. An alternative explanation might be that the young age is a result of preferential flow of the upper saturated zone (where water is youngest) to the open-hole wells. If this was occurring, the CMB approach could be considered to reflect modern recharge rates. To further investigate this process, nested well sites with multiple wells screened at discrete depths in the aquifer would be required.

The key exceptions to the mostly young ages were the two wells located in sediments of the Officer Basin, IMB-19 and I98MJ-1. Both wells are located in small, but separate, highly-fractured sandstone ranges. Due to the fractured characteristics of the surrounding sandstone, rapid local recharge was expected. However, the groundwater age at IMB-19 was dated to be between 7441 and 9927 years old. Similarly, the well I98MJ-1 was age-dated to be between 9067 and 10 007 years old, which are the two oldest ages of all sites that were sampled. The correction methods applied to the age dating should have provided a reasonable degree of correction for dissolution of carbonate in the sandstone, and the low pMC values (I98MJ-1, 22 pMC; IMB-19, 32 pMC) indicate that the correction methods are not the explanation for the older age. Furthermore, the lack of detectable CFCs indicates the groundwater is at least 60 years old. Therefore, the old groundwater age is reflective of a poorly understood flow-system and further work is required to understand the groundwater hydrodynamics in this area.

4.3. Regtional groundwater hydrodynamics near community water supply wells

The regional flow patterns show the well-known north–south flow pattern from the Musgrave Ranges to the Officer Basin. As is typical in unconfined aquifers, the groundwater flow direction typically follows the general direction of the topographic relief. At the smaller local scale, multiple factors can influence recharge rates. The following discussion provides a brief summary of areas likely to have preferential recharge.

4.3.7 Pukatja, Umuwa, and Yunyarinyi

The northern communities of Pukatja, Umuwa and Yunyarinyi located in and near the Musgrave Ranges have water supply wells located in high recharge environments where runoff from the nearby ranges assists in saturating the soil profile and increasing recharge. The colluvial sediments immediately surrounding the outcropping bedrock had the highest estimates of recharge based on the CMB approach. Sheetflow regolith deposits and moderately to highly weathered bedrock regolith also had higher recharge rates relative to surrounding fresh to moderately weathered bedrock regolith.

4.3.8 Kaltjiti

The understanding of the aquifer hydrodynamics where Kaltjiti sources its community water supply is less certain. Limited water level data adjacent to the Officer Creek makes it difficult to interpret the nature of the interaction between the creek and the regional aquifer. Flow paths flowing south from the area where Ernabella Creek floods out onto the plain may be an important source of recharge. Increasing salinity and groundwater age from west to east indicates that occasional flood events may recharge the shallow aquifer in the area north-west of Kaltjiti, however a time-series of water level data would be required to prove this more conclusively. Water level monitoring wells and river flow recordings during several flood events would provide a clearer understanding of recharge volumes around Kaltjiti.

4.3.9 Mimili

Near the Mimili community well field, recharge from the surrounding Everard Ranges will no doubt be a significant component of the local water-budget. Hydrographs of community water supply wells (not shown) record water level fluctuations exceeding 5 m, which would indicate a system susceptible to rapid-recharge following large rainfall events, Although the water level observations have not been corrected for fluctuating water extraction, it is likely water demand would reduce in the immediate period following rainfall which may cause the recovery in the hydrograph to look larger than what would occur in a dedicated monitoring well.

4.3.10 Iwantja

The aquifers supplying the Iwantja community in the south-east of the investigation area recorded the oldest groundwater ages. The wells are located within a small range developed from folded sedimentary sandstones of the Officer Basin. Initial observations of the area would suggest the aquifers are largely dependent on local recharge as the range consists of highly fractured sandstone, but the old groundwater ages did not fit with this expectation. Further investigation of the hydrochemistry and water levels at a local scale would be required to better characterise the hydrodynamics surrounding the Iwantja well field.

5. Conclusions

As a result of this investigation, an improved knowledge of the regional groundwater resources in the APY Lands has been developed. The key findings in relation to the objectives of the project are:

Objective 1: Estimate groundwater recharge and its relationship to rainfall in the investigation area

- Groundwater recharge is actively occurring in the APY lands despite the current arid climate.
- Groundwater recharge rates calculated using the chloride mass balance approach are probably reflective of the current climate, as most groundwater ages indicate modern groundwater recharge.
- The chloride mass balance indicates that a small proportion of rainfall becomes recharge, yet the stable isotope signature indicates minor evaporation. This finding supports earlier interpretations that groundwater recharge is occurring rapidly after rainfall which is then followed by drying of the upper unsaturated zone which removes most of the stable isotope evaporation signature.
- As a first-order estimate, the annual average recharge for the APY Lands is 56 500 ML/y. Within the extent of the investigation area and within the APY Lands 15 500 ML/y is recharged on average. However, recharge will only occur in occasional pulses when total rainfall is above 60-80 mm/month. The highest recharge rates are found in colluvial and alluvial regolith surrounding the Musgrave Ranges.

Objective 2: Identify likely zones of preferential groundwater recharge near community water supply wells

- The highest groundwater recharge rates are located adjacent to the Musgrave Ranges, particularly in the areas mapped as being composed of colluvial regolith. Pukatja, Umuwa and Yunyarinyi all have wells in or near this type of regolith.
- Flood waters from Officer Creek and Ernabella Creek may be the primary source of recharge to the aquifer for the area north of Kaltjiti, although further data are needed in that region to better characterise the hydrodynamics.
- The Iwantja well field draws groundwater that appears to be old which seems contradictory to the highly fractured range setting that would normally allow higher recharge rates. Further investigation will need to be undertaken at a detailed local scale to better characterise recharge rates in that area.

Objective 3: Describe the regional interconnectivity and flow characterisation of the unconfined aquifer

- There are two regional groundwater flow systems in the investigation area. While both originate in the Musgrave Ranges, the watertable contours show that the eastern side of the investigation area flows east and south-eastwards towards the Eromanga Basin, while the central and western area of the investigation area flows southwards towards the Officer Basin.
- The aquifers for the Iwantja well field may be part of an entirely separate groundwater flow system.

6. Units of measurement

6.1. Units of measurement commonly used (SI and non-SI Australian legal)

Name of unit	Symbol	Definition in terms of other metric units	Quantity
day	d	24 h	time interval
gigalitre	GL	10^6 m^3	volume
gram	g	10^{-3} kg	mass
hectare	ha	10^4 m^2	area
hour	h	60 min	time interval
kilogram	kg	base unit	mass
kilolitre	kL	1 m^3	volume
kilometre	km	10^3 m	length
litre	L	10^{-3} m^3	volume
megalitre	ML	10^3 m^3	volume
metre	m	base unit	length
microgram	µg	10^{-6} g	mass
microliter	µL	10^{-9} m^3	volume
milligram	mg	10^{-3} g	mass
millilitre	mL	10^{-6} m^3	volume
millimetre	mm	10^{-3} m	length
minute	min	60 s	time interval
second	s	base unit	time interval
tonne	t	1000 kg	mass
year	y	365 or 366 days	time interval

6.2. Shortened forms

pH acidity

pMC percent of modern carbon

7. Glossary

Anion — A negatively charged ion, in this context, dissolved in groundwater

Alluvial — A general term for sand, silt and clay sediments that have been deposited by flowing water. Often seen as alluvial fans at the base of hills where floodwater spreads out on the floodplain

Aquifer — An underground round layer of permeable rock/sediment that can yield groundwater

Arid lands — In South Australia, arid lands are usually considered to be areas with an average annual rainfall of less than 250 mm and support pastoral activities instead of broad acre cropping

BoM — Bureau of Meteorology, Australia

Cation — A positively charged ion, in this context, dissolved in groundwater

Colluvial — A general term for loose, unconsolidated sediments that have deposited at the base of hill slopes

DEWENR — Department of Environment, Water, and Natural Resources (Government of South Australia)

Dissolution — The process of weathering and dissolving minerals in the aquifer

EC — Electrical conductivity; 1 EC unit = 1 micro-Siemen per centimetre (µS/cm) measured at 25°C; commonly used as a measure of water salinity as it is quicker and easier than measurement by TDS

Ephemeral streams or wetlands — Those streams or wetlands that usually contain water only on an occasional basis after rainfall events. Many arid zone streams and wetlands are ephemeral

Evapotranspiration — The total loss of water as a result of transpiration from plants and evaporation from land, and surface water bodies

Fluvial — A general term for loose, unconsolidated sediments that have been deposited by the processes of rivers and creeks

Geological features — Include geological monuments, landscape amenity and the substrate of land systems and ecosystems

Geomorphology — The scientific study of the landforms on the Earth's surface and of the processes that have fashioned them

GIS — Geographic Information System; computer software linking geographic data (for example land parcels) to textual data (soil type, land value, ownership). It allows for a range of features, from simple map production to complex data analysis

Groundwater — Water occurring naturally below ground level or water pumped, diverted and released into a well for storage underground; see also 'underground water'

Groundwater recharge — The process by which water percolates from the surface to the watertable

Holocene — The name given to the period of time between the current day and 11,700 years before present

Hydrodynamics — The physical flow of water, in this context, the flow and interaction of groundwater in the unconfined aquifer

Hydrology — The study of the characteristics, occurrence, movement and utilisation of water on and below the Earth's surface and within its atmosphere; see also 'hydrogeology'

Lacustrine —Unconsolidated and usually fine grained to clayey sediments that have been deposited at the base of lakes, swamps and wetlands

Mesoproterozoic — The name given to the period of time between 1000 and 1600 million years before present

Model — A conceptual or mathematical means of understanding elements of the real world that allows for predictions of outcomes given certain conditions. Examples include estimating storm run-off, assessing the impacts of dams or predicting ecological response to environmental change

Monitoring — (1) The repeated measurement of parameters to assess the current status and changes over time of the parameters measured (2) Periodic or continuous surveillance or testing to determine the level of compliance with statutory requirements and/or pollutant levels in various media or in humans, animals, and other living things

Natural resources — Soil, water resources, geological features and landscapes, native vegetation, native animals and other native organisms, ecosystems

NRM — Natural Resources Management; all activities that involve the use or development of natural resources and/or that impact on the state and condition of natural resources, whether positively or negatively

Paleovalley — A former valley formed by a creek or river which has incised into the landscape before filling back up with sedimentary material. The new valley fill may have very different hydraulic properties to the surrounding geology.

Pleistocene — The name given to the period of time between 11,700 and 2.6 million years before present

Quaternary — The name given to the period of time between today and 2.6 million years before present

Regolith — Refers to the layer of sometimes unconsolidated layer of sedimentary material that covers solid rock underneath.

Saturated zone — The layer of the aquifer below the watertable

Stock use — The taking of water to provide drinking water for stock other than stock subject to intensive farming (as defined by the Act)

Surface water — (a) water flowing over land (except in a watercourse), (i) after having fallen as rain or hail or having precipitated in any another manner, (ii) or after rising to the surface naturally from underground; (b) water of the kind referred to in paragraph (a) that has been collected in a dam or reservoir

Sustainability — The ability of an ecosystem to maintain ecological processes and functions, biological diversity, and productivity over time

Unsaturated zone — The layer of the aquifer between the surface and the watertable. It can contain varying amounts of moisture but it is always less than fully saturated

Watercourse — A river, creek or other natural watercourse (whether modified or not) and includes: a dam or reservoir that collects water flowing in a watercourse; a lake through which water flows; a channel (but not a channel declared by regulation to be excluded from the this definition) into which the water of a watercourse has been diverted; and part of a watercourse

Water-dependent ecosystems — Those parts of the environment, the species composition and natural ecological processes, that are determined by the permanent or temporary presence of flowing or standing water, above or below ground; the in-stream areas of rivers, riparian vegetation, springs, wetlands, floodplains, estuaries and lakes are all water-dependent ecosystems

Water quality monitoring — An integrated activity for evaluating the physical, chemical, and biological character of water in relation to human health, ecological conditions, and designated water uses

Weathering — The process by which rocks decompose and breakdown.

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