Non-prescribed groundwater resources assessment - Eyre Peninsula Natural Resources Management Region

Phase 2 - Hydrogeochemistry

DEWNR Technical report 2014/10

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

Non-prescribed groundwater resources assessment – Eyre Peninsula Natural Resources Management Region

Phase 2 – Hydrogeochemistry

Lyz Risby[1] and Glenn Harrington[2]

[1] Department of Environment, Water and Natural Resources

[2] Innovative Groundwater Solutions Pty Ltd

September, 2014

DEWNR Technical Report 2014/10

Department of Environment, Water and Natural Resources

GPO Box 1047, Adelaide SA 5001

Telephone National (08) 8463 6946

International +61 8 8463 6946

Fax National (08) 8463 6999

International +61 8 8463 6999

Website www.environment.sa.gov.au

ISBN 978-1-922174-92-5

Preferred way to cite this publication

Risby L and Harrington GA, 2014, *Non-prescribed groundwater resources assessment – Eyre Peninsula Natural Resources Management Region, Phase 2 – Hydrogeochemistry,* DEWNR Technical Report 2014/10, Government of South Australia, through Department of Environment, Water and Natural Resources, Adelaide

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.

Tim Goodes
ACTING CHIEF EXECUTIVE
DEPARTMENT OF ENVIRONMENT, WATER AND NATURAL RESOURCES

Acknowledgements

The authors gratefully acknowledge the cooperation and assistance of the many landholders and property managers across Eyre Peninsula who generously gave their time to help locate and access the wells sampled in this project. The local knowledge conveyed through this process provided valuable insights into the region.

The authors also wish to thank Dr Andrew Herczeg of Geochemical Solutions for reviewing an earlier version of this report and providing numerous useful comments that led to improvements to both readability and technical content.

Contents

List of figures

List of tables

Summary

This report documents the results of a regional-scale hydrochemistry investigation of the non-prescribed groundwater resources in the Eyre Peninsula Natural Resources Management (EP NRM) Region. The objective of the project was to acquire a large volume of data so as to improve current understandings of aquifer recharge rates, possible interactions or connectivity between the aquifers and any other physical and chemical characteristics that may assist future water resources planning and management in the region.

Following an extensive desktop review and field-based audit of available wells, a groundwater sampling program was undertaken from February–April 2013. A total of 49 groundwater wells were sampled for a suite of environmental tracers including major ion chemistry, naturally occurring isotopes and anthropogenic trace gases.

The chemical composition of groundwater samples ranges from a Na-Ca-HCO_3 type in low salinity parts of the southern EP NRM Region, through to Na-Cl type in more saline parts of the south as well as the northern Whyalla–Kimba region. The most likely sources of these salts are accession of marine aerosols in rainfall and weathering of both soil and marine carbonate minerals, followed by concentration as a result of evapotranspiration.

The steady-state chloride mass balance (CMB) method was considered the more reliable of two methods used to estimate long-term average annual recharge rates. The CMB method yielded average recharge estimates for the Lincoln–Koppio area of 16.8 mm/y for the basement aquifers, 15.8 mm/y for the Quaternary aquifers, and 7.8 mm/y for the Tertiary aquifers; for the Whyalla–Kimba area, rates were 1.5 mm/y for the basement aquifers, 1.3 mm/y for the Quaternary aquifers, and 0.4 mm/y for the Tertiary aquifers. Stable hydrogen and oxygen isotope compositions of groundwater indicate that recharge only occurs after significant rainfall events, for example, when at least 40–60 mm occurs in a month.

Major ion ratios, strontium isotopes and the groundwater age tracers helped to demonstrate that limited connectivity between basement and Quaternary aquifers occurs along a transect from Koppio Hills to the Uley South lens. However, there was consistent evidence of connectivity provided by all tracers near one well pair in the centre of the transect. The construction integrity of this well pair needs to be examined.

Groundwater ages are mostly modern according to both CFC-12 and carbon-14 dating methods, meaning that a significant component—if not all—of 46 out of the total 49 groundwater samples were recharged within the last 50–60 years. Only three samples had apparent 'corrected' carbon-14 ages of more than 500 years. That said, there is a general trend of increasing groundwater age with depth in the aquifers and distance along groundwater flow lines.

This study was a broad, reconnaissance-style project aimed at gathering as much information as possible over a regional scale to provide the initial baseline chemistry and process understanding for the region. Further work is required to focus on parts of the region where future water demands are likely to place stress on the groundwater resources and where high quality well completion details are available. This report provides some guidance for the tracers that can be most beneficial to such assessments, as well as the types of processes that may be occurring.

1 Introduction

1.1 Background

The Water for Good plan (Government of South Australia 2009) states that "resource assessment, monitoring and management of non-prescribed groundwater resources are crucial and necessary elements that will assist in achieving sustainable use of the resource." The Department of Environment, Water and Environment (DEWNR) has lead agency responsibility for ensuring the sustainable management of groundwater resources of the state of South Australia (the State) and has developed the Groundwater Program to fulfill responsibilities under the *Natural Resources Management Act 2004* and in response to water security issues facing the State. This report presents findings of the sub-program Non-prescribed groundwater resource assessments – Eyre Peninsula Natural Resources Management Region.

In an environment where water resources are increasingly scarce, a better understanding of both potable and non-potable water resources capacity and a more proactive approach to management is required. The Water for Good plan identified that the State's non-prescribed water resources require monitoring and management to enhance sustainable development opportunities and avoid them being over-exploited.

There is only limited understanding of groundwater resources in most non-prescribed regions across the State. Current knowledge gaps regarding the occurrence, storage and quality of groundwater resources present significant barriers to the management and future development of many groundwater systems. Addressing these gaps was especially important due to anticipated increases in demand for water, changes in land-use and potential impacts associated with a changing climate.

The demand for new water resources will also increase. The impacts of land use change such as mining and energy operations may go undetected unless suitable monitoring and assessment is in place (Government of South Australia 2009). In particular, there is likely to be increasing pressure to develop groundwater resources in non-prescribed areas. Baseline information is important to allow appropriate planning to avoid unsustainable extraction leading to resource decline and increasing salinity.

Through the DEWNR Groundwater Program, an opportunity existed to deliver improved understanding of the State's groundwater resources and better understand the potential for further groundwater development. Benefits to stakeholders include a better understanding of the potential for groundwater to support South Australia's social and economic development and the identification of resources that benefit from detailed scientific investigation and effective monitoring.

1.2 Objectives

The objective of this project is to build upon the current understanding of non-prescribed groundwater resources in the Eyre Peninsula (EP) Natural Resources Management (NRM) Region. The focus for the study is the 1:250 000 map sheet areas of Whyalla, Lincoln and, to a lesser degree, Kimba (Fig. A1 – Appendix A) using hydrochemistry and other environmental tracer techniques to investigate:

- recharge rates to different aquifers
- interactions or connectivity between the different aquifers, including the Quaternary and basement aquifers
- other physical and chemical characteristics of non-prescribed groundwater resources to assist decision making.

1.3 Project scope

This section of the report summarizes the general scope of works undertaken for Phase 2 of the Non-Prescribed Groundwater Resources Assessment Project. Phase 1 of the project was focused on the development of a regional, three-dimensional (3-D) hydrostratigraphic model and is reported elsewhere (Berens, Alcoe and Watt 2011). The scope of works for Phase 2 of the project included:

- review outcomes from the Phase 1 project component and collate other relevant data and information

- interpret drillers and lithological logs to create hydrostratigraphic logs for wells within the study area; validate construction details where possible and align with stratigraphic information to enable assigning of an 'aquifer monitored' to wells
- once data are validated, enter relevant details into SA Geodata and incorporate into assessment and information (mapping) products
- develop initial simple conceptual understanding of groundwater resources based on collated and validated existing data
- identify regions or areas that require sampling in order to improve/validate conceptual understanding
- undertake field works program including sampling wells within specific aquifers for water level, salinity and hydrochemistry (including isotopes)
- capture new well completion and hydrochemical information in SA Geodata
- with refined water level data, produce potentiometric surface maps and salinity raster layers for major units to better understand groundwater flow paths
- using chemistry data (where relevant) to possibly provide estimates of recharge based on chloride mass balance approach for target aquifer(s)
- using water level and chemistry data (i.e. isotopes where relevant), identify possible interactions (or lack thereof) between the different groundwater resources (e.g. basement and sedimentary aquifers)
- report on conceptual understanding of groundwater resources.

This report provides a summary of the well selection and auditing process, however the focus is on the sampling of wells, presentation of potentiometric surface maps and interpretation of hydrochemistry data.

2 Regional setting

The lower EP is located approximately 250 km west of Adelaide. The study area is defined by the EP NRM Region (Fig. A2, Appendix A), which covers an area of approximately 81 000 km^2 and is bounded to the east and west by the Spencer Gulf and the Southern Ocean, respectively. The Gawler Ranges and Great Victoria Desert (north of Ceduna and Fowlers Bay) delineate the region's northern extent.

2.1 Regional hydrogeology

This section has been repeated from Berens, Alcoe and Watt (2011) to provide a summary of the main aquifer types, their occurrence (Figure 2.1) and hydrogeological characteristics (Table 2.1).

2.1.1 Quaternary aquifers

Throughout the EP NRM Region, the largest potable groundwater storages are found within the Bridgewater Formation (Barnett 1982; Martin, Sereda and Clarke 1998). Most fresh groundwater lens extents are delineated by groundwater isohalines of less than 1000 mg/L. Quaternary limestone aquifers typically have hydraulic properties of an unconfined or semi-confined aquifer (Love *et al.* 1994) and the yield of the limestone can vary greatly. The majority of potable water is encountered in the Southern Basins and Musgrave Prescribed Wells Areas. The Southern Basins Prescribed Wells Area (PWA) is the major source of groundwater delivered through the Eyre Peninsula Water Supply Network (EPWSN). Elsewhere along the west coast, beyond the EPWSN extent, Independent Eyre Peninsula Water Supply Schemes (IEPWSS) supply a number of the larger communities (Coffin Bay, Elliston and formally Streaky Bay). Several smaller west coast communities (Venus Bay, Port Kenny, Penong and Fowlers Bay) source groundwater from local freshwater lenses. These small isolated resources are managed locally by councils and are potentially at risk of over-extraction and consequent degradation (Government of South Australia 2000). Observed salinity increases indicate current extraction may already exceed safe yields (Taylor 2003).

2.1.2 Tertiary aquifers

Tertiary sands are distributed throughout EP and contain aquifers that are either semi-confined or confined and generally overlain by Quaternary sediments and aquifers. Salinity in the Tertiary sediments can vary considerably but is generally higher (>5000 mg/L) than the overlying Quaternary sediments (Martin, Sereda and Clarke 1998). Groundwater wells are often difficult to construct in the unconsolidated and fine-grained Tertiary sands and yields are generally poorer in comparison to the Quaternary aquifers. Where extensive drilling and targeted investigations into groundwater resources have occurred, the presence of a Tertiary clay aquitard has been identified separating the Quaternary aquifers from the less-transmissive Tertiary sands (Love *et al.* 1994). Where these Tertiary clays are thin or absent, downward vertical leakage may form lenses of potable water within the Tertiary aquifers. These occurrences are likely to be very localised and difficult to sustain (Taylor 2003).

2.1.3 Fractured rock (basement) aquifers

Basement lithology includes gneisses, volcanics and granites of the Gawler Craton. Basement rocks crop out in places and may be weathered to a depth of as much as 50 m (Martin, Sereda and Clarke 1998). The understanding of fractured rock aquifers is limited and they are often irregular in occurrence, salinity and yield. The heterogeneous nature of fractured rock aquifers accounts for the observed unsystematic distributions of groundwater salinity. Basement outcrops and the shallowest occurrences are found inland of the east coast and along the northern boundary of the EP NRM Region, south of the Gawler Ranges. Isolated occurrences of surface basement outcrop occur throughout the region.

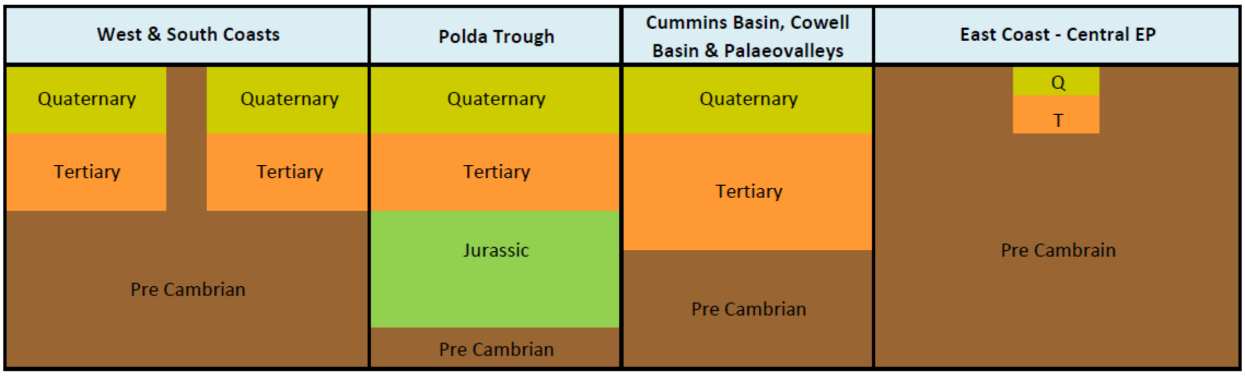


Figure 2.1 Simplified conceptual occurrence of stratigraphic ages across Eyre Peninsula (based on Taylor 2003)

2.2 Regional climate

The EP NRM Region experiences a temperate to semi-arid climate with hot, dry summers and cool, wet winters. The coastal areas experience a milder and wetter climate, while inland conditions are typically hot and dry. Average summer minima and maxima temperatures are 14°C and 31°C; average winter minima and maxima temperatures are 5°C and 18°C (Berens, Alcoe and Watt 2011).

Most rainfall occurs during the months of May through September, although local storms during summer often make considerable contributions to total annual rainfall (Parker and Fanning 1998). Mean annual rainfall varies from around 600 mm/y in the south to less than 300 mm/y in the north-west (Fig. A2, Appendix A), with mean annual evaporation rates ranging between 1800 mm/y in the south to 2200 mm/y in the north (Berens, Alcoe and Watt 2011).

Long-term daily rainfall data sourced from the SILO Climate Database has been examined for the 1:250 000 map sheet areas of Lincoln and Whyalla. The SILO dataset takes the raw rainfall data collected by the Bureau of Meteorology (BoM) and disaggregates data that is accumulated over weekends and also infills missing rainfall records typically by using interpolated data or taking data from nearby rainfall stations. This practise is commonly applied where data is limited and provides a complete long-term rainfall record.

The location of rainfall stations Westmere (18137), Koppio (18043) and Cleve (18014) are displayed in Fig. A2 (Appendix A).

2.2.1 Rainfall for Lincoln map sheet

Westmere rainfall station (18137) was selected to be most representative of the Lincoln map sheet region because the Port Lincoln rainfall station (18070) data have interpolated daily observations from 2002 up to and including 2013. In contrast, the Westmere rainfall station has a more complete dataset using actual station data as recorded by BoM, particularly over the last twenty years. Data displayed in Figure 2.2 shows annual rainfall from 1889 to June 2013; the long-term average annual rainfall for this period is 574 mm. Since the early 1990s the inter-annual variability of rainfall has not been as high as it was historically. While there have been a number of above-average rainfall years since the early 1990s, very few of these (with the exception of 1992) have reached 700 mm, whereas historically there were many years well in excess of this amount.

The orange line on Figure 2.2 displays the residual mass curve, representing deviations in annual rainfall from the long-term average value. An upwards trend in the curve indicates a wetter than average rainfall period while a downwards trend indicates a drier than average rainfall period. As evident by the downwards slope of the curve, a generally drier than average period has been experienced since 1992.

Data from the Koppio rainfall station (18043) show similar trends to Westmere data (Figure 2.3). The long-term average annual rainfall is 516 mm for the period 1889 to June 2013 and the amount of annual rainfall is only marginally above this long-term average for all but one year since 1992. The residual mass curve displays a declining trend from 1992, indicating a generally drier than average period, despite numerous above-average rainfall years during this time. The trendline displays a long-term decline in annual rainfall of about 50 mm over the period 1889 to June 2013 at this location.

Table 2.1 Detailed descriptions of stratigraphic units that exist within the Eyre Peninsula Natural Resources Management Region

Age			Unit	Lithology	Occurrence and Hydrogeology
Quaternary	Holocene		Yamba Formation	Halite, gypsite, gypsarenite, selenite and minor carbonate and gypsiferous mud	Kyancutta-Warramboo and Lake Yaninee; gypsum mine south-east of Penong
			Moornaba Sand	Dunes of white, pale grey and orange quartz sand and interdunal valleys of red-brown sandy clay which grade laterally into quartz sand	Southern, central and eastern EP. One well salinity of 18 000 mg/L and 0.5L/s.
	Pleistocene	Late	Glanville Formation	Soft, white to cream-fawn richly fossiliferous shelly sand and clay and calcreted shell beds	Small pockets occur in far north-western EP and south of Streaky Bay. Open aquifer intervals identified in but no salinity or yield data available
			Wiabuna Formation	Distinctive yellow to orange siliceous sand and clayey sand, seif dunes and thin veneers of calcareous silt	North-western and west-central EP. Small number of open aquifer intervals identified, two with water quality data; salinity 36 500 & 51 000 mg/L. Yield 0.0001 & 0.1 L/s
			Pooraka Formation	Alluvial, red-brown clayey sand and gravel, capped in general by soft powdery carbonate and/or calcrete	Eastern EP (Cleve Hills), between Kimba and Venus Bay and around Wanilla Palaeovalley. Limited water quality data available; Salinity between 7500–22 500 mg/L (median 10 000 mg/L). Yield between 0.08–2.7 L/s (median 0.8 L/s)
		Middle	Bridgewater Formation	Calcareous sands, broken shell fragments and limestone, often with calcrete at the surface, karstic	Along the most of the west coast, absent only around Smoky Bay. Extends inland as far as Lock, Wudinna and Poochera. Is the most utilised aquifer on EP, with much available historical well data. Salinity between 400–52 000 mg/L (median 1100 mg/L). Yield between 0.03–63L/s (median 0.6L/s)
Tertiary	Pliocene		Uley Formation	Sandstone, clayey to orange-brown quartz, well sorted and rounded, minor lateritic and non-lateritic gravel	Southern Eyre Peninsula, particularly the Wanilla Palaeovalley. A number of wells screened in this formation; salinity between 500–26 500 mg/L (median 1400 mg/L). Yield between 0.3–1.3 L/s (median 0.5 L/s)
			Pantoulbie Formation	Sand, orange-brown, clayey; interbedded with quartz sand, sandy clay and minor lateritic gravel	Occurrence east of Streak Bay and west of Poochera. Only two wells screened in this formation. Salinity 1200 & 1800 mg/L. Yield 1.3 L/s
	Miocene	Middle	Hampton Sandstone	Marine, estuarine and fluvial sandstone. Partly clayey at the base and glauconitic and fossiliferous at the top	Far north-western EP. Handful of wells screened in this area, three with water quality data. Salinity 8400, 26 000 & 31 000 mg/L. Yield 0.06 & 0.5 L/s
			Garford Formation	Mudstone and minor sandstone horizons of silt sand. Palaeovalley sediments are both lacustrine clays and fluviatile sand	North-western and west-central EP inc. the Narlaby Palaeovalley. Wells screened in the area between Streaky Bay, Elliston, Wudinna and Poochera. Salinity between 240–55 000 mg/L (median 2350 mg/L). Yield between 0.0001–1.4 L/s (median 0.3 L/s)
			Pidinga Formation	Fine-grained to gravelly fluviatile sands and silt with interbeds of carbonaceous clay	Far north-west and within the Narlaby, Wanilla palaeovalley. Open aquifer intervals identified in far north-west; salinity between 2200–51 000 mg/L (median 14 000 mg/L). Yield between 0.0001–6.5 L/s (median 0.25 L/s)
		Early	Nullarbor Limestone	Fossiliferous, bioclastic and micritic limestone with instances of quartz and quartz sand	Far north-western EP. Some open aquifer intervals identified with limited groundwater data; salinity 600–26 000 mg/L (median 6200 mg/L). Yield between 0.3–0.6 L/s (median 0.5 L/s)

Age			Unit	Lithology	Occurrence and Hydrogeology
Tertiary	Eocene	Middle	Ooldea Sand	Aeolian dunes of medium-grained, quartz sand with well sorted, well rounded frosted grains and trace quantities of heavy minerals	Far north-western EP. No groundwater data available
			Wilson Bluff Limestone	Mostly a white to grey wackestone with minor packstone and the basal part of the formation can be locally sandy	Far north-western EP. Open aquifer intervals identified, only two with water quality data. Salinity 1300 & 13 000 mg/L. Yield 0.5 L/s
			Wanilla Formation	Fine-grained to gravelly fluvial sand interbedded with variable thicknesses of carbonaceous clay	Cummins, Uley–Wanilla and Lincoln Basins in south-western EP. Open aquifer intervals identified in this area. Salinity between 500–7500 mg/L (median 1700 mg/L). Yield 0.13–0.9 L/s (median 0.5 L/s)
			Poelpena Formation	Poorly sorted, fine to coarse grained quartz sand, silt and clay which are carbonaceous, micaceous and pyritic. Correlative of the Pidinga Formation	A sequence of, but not limited to, the Polda Trough; found extensively in central EP, especially between Lock and the West Coast. Majority of wells identified to be open to the Poelpena Formation are within the Musgrave PWA. Salinity between 240–35 000 mg/L (median 950 mg/L). Yield 0.01–63 L/s (median 1.3 L/s)
Jurassic			Polda Formation	Sands, silts, carbonaceous clays and lignite	Primarily constrained to the Polda Trough but has been identified in the adjacent Yaninee Palaeovalley. Open aquifer intervals identified in five wells (three within the Musgrave PWA). Salinity between 680–2060 mg/L (median 1080 mg/L). Yield between 0.04–0.25 L/s (median 0.16 L/s)
Precambrian	Proterozoic	Meso-	Hiltaba Suite	Massive anorogenic granitoids forming large batholiths and smaller plutons. Includes the Calca Granite	West central, north-east and north-west EP, especially between Kyancutta and Kalanbi. Numerous open aquifer intervals identified north of Bairds Bay, Venus Bay and across to Buckleboo; salinity between 870–48 000 mg/L (median 12 500 mg/L). Yield between 0.01-1 L/s (median 0.1 L/s)
		Palaeoproterozoic	St Peter Suite	Complex comagmatic intrusive sequence, comprising fine to coarse, even-grained granite	North-western EP. Small number of open aquifer intervals identified, mainly near Penong; salinity between 700–47 250 mg/L (median 30 000 mg/L). Yield between 0.03–0.3 L/s (median 0.2 L/s)
			Donington Suite	Gneissic granite, granodiorite and adamellite with veins of pegmatite and aplite	Found along the eastern coast of EP and extends inland from Cowell towards the Gawler Ranges. A small number of open aquifer intervals identified in these areas. Salinity between 500–27 000 mg/L (median 6600 mg/L). Yield between 0.01–5 L/s (median 0.4 L/s)
			Hutchison Group	A basal massive to flaggy quartzite sequence (Warrow Quartzite, Lhw), overlain by carbonates, iron formation, amphibolite and pelitic to semi-pelitic schist. Includes Cook Gap Schist	Occurrence predominantly southern to eastern EP. Open aquifer intervals identified in the south and east; salinity between 500–35 000 mg/L (median 5000 mg/L). Yield between 0.001–10 L/s (median 0.3 L/s)
	Archaean		Mulgathing Complex	Granite; tonalite; gneiss; gabbro; basalt; pyroxenite; peridotite; komatiite	Limited occurrence identified in north-western EP. Some open aquifer intervals identified but no available groundwater data
			Sleaford Complex	Metasediments, granites and gniesses. Includes the Dutton Suite	Central and south-western EP; believed to extend to north-eastern EP but has not been confidently identified. Open aquifer intervals identified in these areas; salinity between 250–29 500 mg/L (median 1000 mg/L). Yield between 0.05–7.6 L/s (median 0.6 L/s)

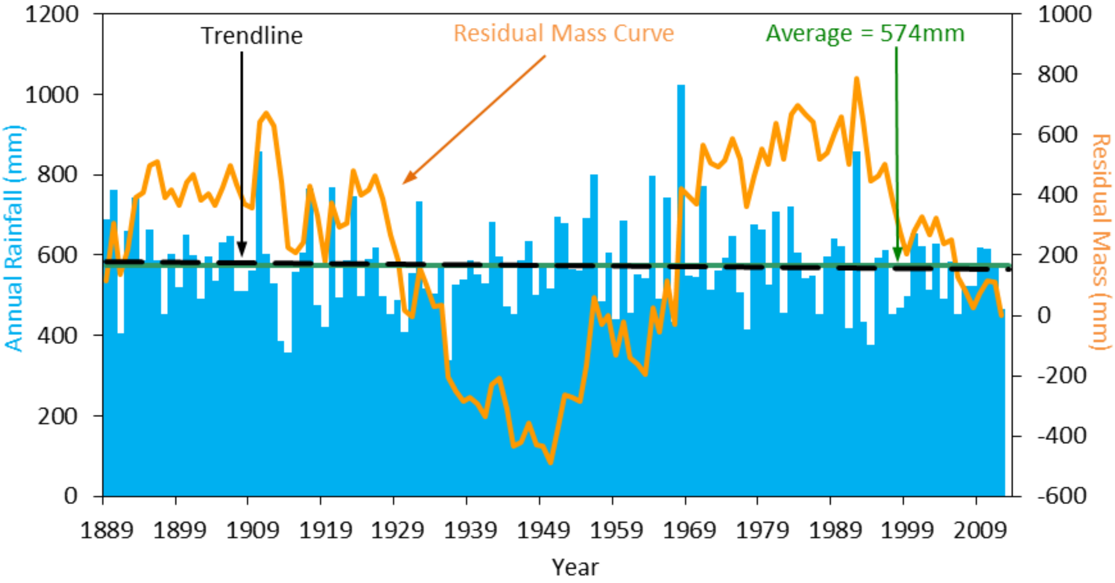


Figure 2.2 **Historical record of annual rainfall at Westmere Station (Bureau of Meteorology no. 18137) showing annual totals (blue bars), long-term annual average (green line), long-term trend (black dashed line) and residual mass (i.e. cumulative deviation from average) curve (orange line)**

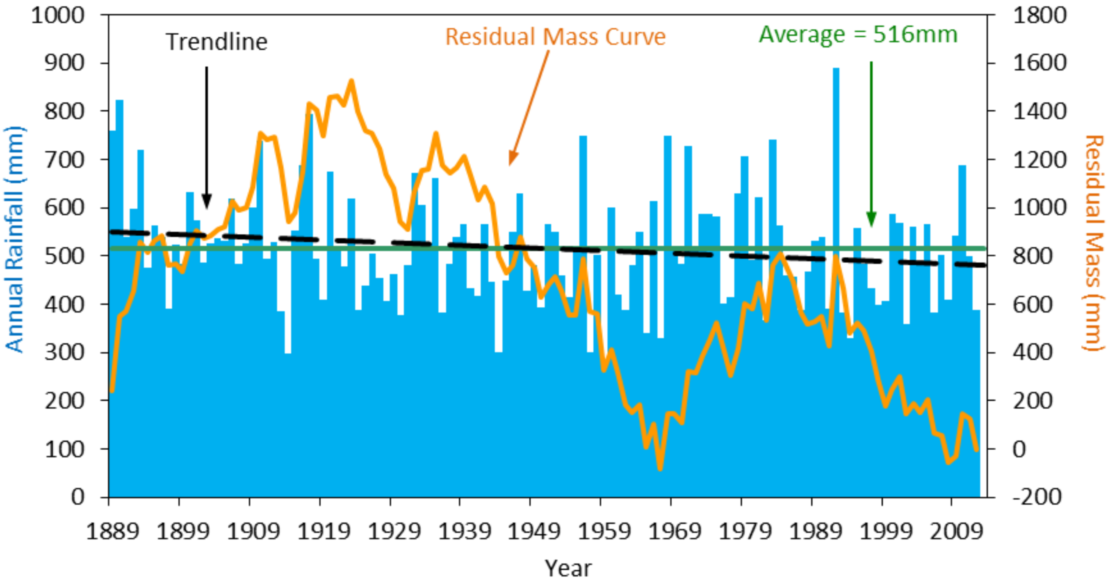


Figure 2.3 **Historical record of annual rainfall at Koppio Station (Bureau of Meteorology no. 18043) showing annual totals (blue bars), long-term annual average (green line), long-term trend (black dashed line) and residual mass (i.e. cumulative deviation from average) curve (orange line)**

2.2.2 Rainfall for Whyalla map sheet

Rainfall for the Whyalla map sheet region is best represented by data from the Cleve rainfall station (number 18014). Long-term average annual rainfall at this station (399 mm) is much lower compared with the two stations further south and inter-annual variability in rainfall is generally higher (Figure 2.4). However, in stark contrast to Westmere and Koppio, annual rainfall at Cleve was generally around or above the average value throughout the 1990s. Rainfall was generally well below average during the early to mid-2000s and only two years of the last decade have been wetter than average.

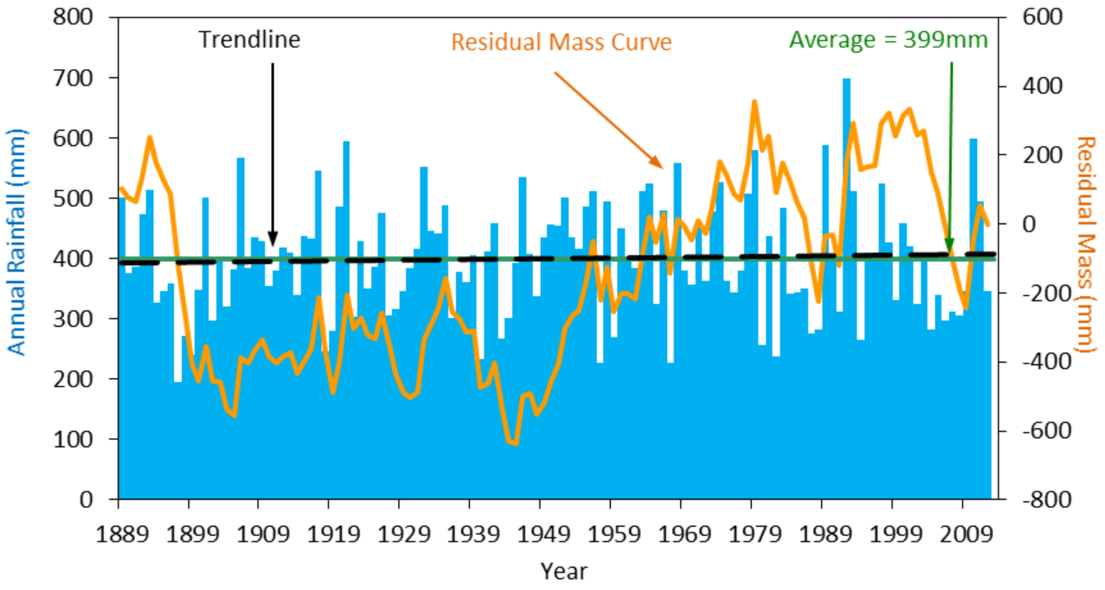


Figure 2.4 **Historical record of annual rainfall at Cleve Station (Bureau of Meteorology no. 18014) showing annual totals (blue bars), long-term annual average (green line), long-term trend (black dashed line) and residual mass (i.e. cumulative deviation from average) curve (orange line)**

2.3 Environmental tracers

This section describes the environmental tracers used in the project and provides a brief overview of the techniques and assumptions used to interpret the data.

2.3.1 Major ion chemistry

The chemical composition of groundwater can provide valuable insights to a number of processes including water–rock interactions, geochemical evolution and mixing between different waters (Herczeg and Edmunds 1999). Variations in absolute concentrations can be a useful indicator of recharge rates, particularly the conservative chloride ion (see Section 3.8.2). Additionally, trends in major ion ratios—especially ion:Cl ratios—can allow the interpretation of geochemical controls on groundwater chemistry after accounting for evaporation effects. Differences in ion ratios of more than about 10% between wells suggests different physical and/or chemical histories for groundwater in the different wells.

2.3.2 Stable hydrogen and oxygen isotopes of water

The stable hydrogen ($^2H/^1H$) and oxygen ($^{18}O/^{16}O$) isotope composition of water molecules in a groundwater sample can provide important clues on the nature of rainfall events and infiltration processes that occur prior to recharge (Coplen *et al.* 1999). Compositions are normally expressed in delta (δ) notation as the $^{18}O/^{16}O$ ratio ($\delta^{18}O$) and the $^2H/^1H$ ratio (δ^2H) and it is usual practice to plot groundwater compositions on a δ^2H-$\delta^{18}O$ diagram to enable comparison with the World Meteoric Water

Line (Craig 1961). Where rainfall has been sampled for stable isotope analysis, it is also possible to construct a Local Meteoric Water Line for more meaningful analysis of rainfall-recharge dynamics.

2.3.3 Strontium isotopes

Strontium isotope composition is often used as a tool for determining sources of major ions in groundwater; for example, distinguishing between weathering of marine carbonate rocks and silicate minerals. The composition is generally expressed as the $^{87}Sr/^{86}Sr$ ratio and high analytical precision allows reporting to five significant figures (e.g., 0.70925 for modern seawater; Burke *et al*. 1982). When comparing groundwater from two or more wells, differences in the $^{87}Sr/^{86}Sr$ ratio at the second or third decimal place are considered significant.

2.3.4 Chlorofluorocarbons (CFC-11 and CFC-12)

CFCs are anthropogenic gases that were first produced in the 1930s. Since the early 1950s they have been used extensively as refrigerants, aerosol propellants and solvents. In 1974, CFC gases where first identified as contributing to ozone depletion and the subsequent production of CFCs has since been phased out by targets set in the Montreal Protocol. Despite the phase out of CFC production, CFC gases have a very long residence time in the atmosphere (Plummer and Busenberg 1999) and both historical and current concentrations are well known for various locations in the both the Southern and Northern Hemispheres.

CFCs have been used widely to estimate the age or residence time of young groundwater, that is, groundwater recharged within the last 50 to 60 years. Estimating the age of groundwater with CFCs assumes that the concentration of CFCs in newly recharged groundwater is in equilibrium with the atmosphere at the time of recharge and there are no other sources or sinks of CFCs. However, Darling *et al*. (2012) suggest additional sources of CFCs (likely to exceed atmospheric equilibrium concentrations) are typically due to inputs for industrial activities and leaking landfills. They also cite a study by Morris *et al*. (2006) that calculated less than 1/10th the amount of CFC-12 in an old domestic refrigerator could potentially contaminate a moderately-sized aquifer to more than ten times the atmospheric equilibrium levels. Such sources of contamination are unlikely in the current study of regional groundwater because most wells are in rural areas.

In relation to sinks of CFCs, numerous studies (e.g. Kahalil and Rasmussen 1989b; Oster, Sonntag and Münnich 1996; Hinsby *et al*. 2007; Sebol *et al*. 2007; Horneman *et al*. 2008) as cited in Darling *et al*. (2012) have found CFCs to be degraded by microbial processes under anoxic conditions and the effects are typically more apparent on CFC-11 (and CFC-13) than CFC-12. This trend is manifested as differences in the apparent ages for the different CFCs.

A consequence of the reduction in the production of CFCs is that groundwater age since the 1990s, calculated based on atmospheric CFC concentrations alone, can be non-unique. For example, using the graph shown in Figure 2.5, the concentration of CFC-12 in the atmosphere in June 1998 was 534 pptv (parts per trillion by volume) which is the same concentration recorded for June 2009.

While the concentrations of CFCs in the atmosphere have continued to decline in recent times, the atmospheric concentration of another anthropogenic gas, sulphur-hexafluoride (SF_6) has steadily increased. Sampling of both CFCs and SF_6 was undertaken as part of this project in an attempt to be able to provide a more accurate estimate of groundwater 'age' should the CFC results return non-unique values.

2.3.5 Sulphur-hexafluoride (SF_6)

Sulphur-hexafluoride (SF_6) is a stable and primarily anthropogenic gas that is used as an electrical insulator. Production of SF_6 began in 1953 and its concentration in the atmosphere continues to increase and is expected to continue to increase in the future (unlike CFCs). Due to the known atmospheric concentration history and continued rate of increase, SF_6 has been found to be a useful environmental tracer for a number of purposes, including for dating young groundwater (Busenberg and Plummer 2000).

Estimating the age (or dating) of groundwater with SF_6, (as with CFCs) assumes that the concentration of SF_6 in shallow groundwater is in equilibrium with the atmosphere at the time of recharge (i.e. when the water is isolated from the atmosphere). It further assumes that there are no other significant sources or sinks of SF_6.

Unlike CFCs, SF_6 is not susceptible to microbial breakdown in reducing conditions, but research by Busenberg and Plummer (2000) indicates that elevated SF_6 concentrations can occur in igneous and volcanic rocks. Harnisch and Eisenhauer (1998) and Koh *et al*. (2007) as cited in Darling *et al*. (2012) reported excess SF_6 from rocks containing fluorite and areas of metallic sulphide mineralisation. Harnisch and Eisenhauer (1998) also reported excess SF_6 detected in granites where fluorite is an accessory mineral and concluded that SF_6 can be released from natural rocks and minerals through dissolution in water. They further concluded that the natural occurrence appears to be confined to the presence of fluorite, typically occurring in vein deposits and commonly associated with granites and carbonates.

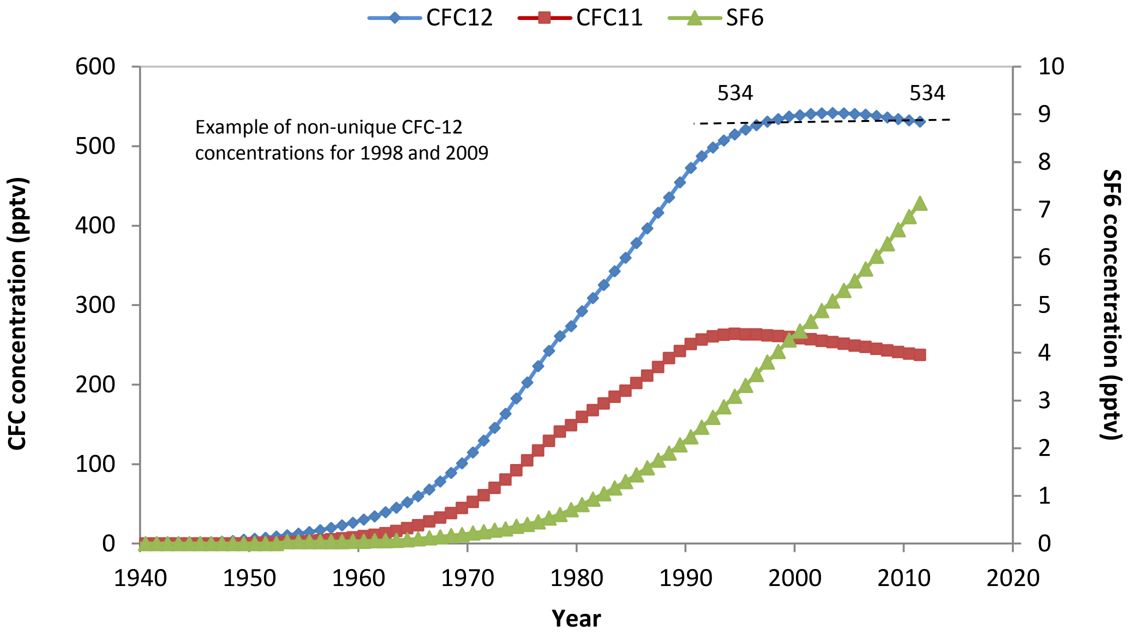


Figure 2.5 **Southern Hemisphere atmospheric concentrations of CFC-12, CFC-11 and SF_6 expressed as parts per trillion by volume (pptv). Both CFC-12 and CFC-11 data display declines in concentrations post 1990 while SF_6 displays a steady increase in concentration (Source: Bullister 2011)**

2.3.6 Carbon-14

Radiocarbon (or carbon-14) is produced naturally in the upper atmosphere and subsequently becomes part of the global carbon cycle, entering the hydrosphere by gas exchange with surface waters and through plant root respiration in the unsaturated zone and exchange with soil water. A large amount of ^{14}C was added to the atmosphere by above-ground nuclear weapons testing in the 1950s and 60s substantially increasing the global atmospheric inventory of ^{14}C, though this has declined as radiocarbon is taken up by vegetation and absorbed slowly by the ocean.

The carbon-14 activity of dissolved inorganic carbon (DIC) in groundwater, expressed as percent modern carbon (pmC), can be a very useful tool for estimating groundwater residence times in the range 500–25 000 years. This time scale is similar to that for the residence time of many regional-scale groundwater systems in Australia. In its simplest form, carbon-14 activities of 100 pmC or more represent modern groundwater that has been recharged within the last 50 years, while carbon-14 activities of 50 pmC and 25 pmC indicate that the groundwater has been isolated from the atmosphere for one half-life (5730 years) and two half-lives (11 460 years) respectively.

Natural weathering reactions in the soil zone or the aquifer can complicate the interpretation of carbon-14 data due to the addition of very old 'dead' carbon to the groundwater via carbonate mineral dissolution or oxidation of old organic matter. Fortunately, numerous correction models have been developed using a range of chemical and isotopic parameters that can be measured or estimated to provide model ages that are closer to the 'true' ages. This approach is described in greater detail in Section 3.9.

3 Methodology

3.1 Initial well identification

Although the state drillhole database, SA Geodata, indicates that more than 8329 water wells are known to have been drilled within the EP NRM Region, the majority of these wells lack the necessary construction and stratigraphic information necessary to assess if they are suitable for hydrochemical sampling. For wells to be suitable for sampling, they should have known construction details, in particular the type and length of casing and the production zone interval. Ideally, the production zone should be relatively short (e.g., less than 3 m) to minimize the amount of mixing—and therefore vertical averaging—of water chemistry during pumping. It is also necessary to know the corresponding stratigraphy that aligns with the well production zone so that the aquifer from which the sample is being taken, is identified.

An initial review of SA Geodata was undertaken to identify wells that had the necessary construction details and assigned aquifer monitored. Very few wells within the non-prescribed part of the EP NRM Region were identified through this process, which meant that further analysis of the data was required to identify wells with construction details and either driller's logs and/or lithological logs. Once these wells were identified, stratigraphic logs were derived and/or an aquifer monitored was assigned to the well and updated in SA Geodata. This was typically done by a combination of interpreting the driller's logs and reviewing surface geology maps for the area where the well was located.

Through this process 377 wells were identified in the study area as possibly being suitable for sampling, however, there was little information available on the current status of the wells. For example, for older wells there was uncertainty regarding their exact location and there was also no information on whether the wells were dry, equipped or collapsed etc. Due to project time constraints it was necessary to further refine the number of possible sites to sample and consequently a landholder well survey was undertaken.

3.2 Landholder well survey

To better guide the field program and to collect current well status information, a targeted landholder well survey was conducted during January and February 2013, with letters and well surveys sent to 246 EP landholders seeking information on the 377 identified wells.

A total of 100 individual landholders responded to the survey providing valuable information on 152 wells. This information was used to target the field program and was also used to update SA Geodata and assist with the development of a simplified hydrostratigraphic 3-D model of the region.

3.3 Field sampling program

The sampling of wells commenced in late February 2013 and continued for seven weeks. During this time, 50 individual landholders were visited and 78 wells were sampled. Full or partial suites of water chemistry samples were collected from 49 of these 78 wells. The remaining 29 were unable to be sampled for a variety of reasons, but water level, salinity and location details were collected and updated in SA Geodata.

Groundwater samples were taken from 49 wells that included a mix of unequipped and currently non-operational wells, equipped wells used predominantly for stock watering, domestic water supply wells and several existing observation wells (see Figure A3 for locations and depiction of aquifers sampled).

3.3.1 Location and water levels

Prior to purging wells for sampling, the location of the well was recorded using a hand held GPS device. Well water levels were measured using an electronic Solinst® water level meter. Measurements were recorded of:

- the depth to groundwater from the reference point (typically the top of well casing)
- the height of the reference point above ground level
- the total well depth; the total well depth was later cross checked with SA Geodata.

3.3.2 Well purging and sampling procedure

A YSI® handheld multi-parameter meter and flow-through cell were used to continuously monitor the following chemical and physical parameters at the pump discharge pipe during purging: pH, electrical conductivity (EC), redox potential (ORP) and temperature (Appendix B). The meter was calibrated daily with known standards prior to use in the field.

Water samples were ideally collected after purging a volume of water equivalent to at least three times the volume of the well casing and ensuring field parameters had stabilised. For wells that had very low yields and dried out during purging, at least one well casing volume was purged before sampling, but only after water quality parameters had stabilised.

3.3.3 Field and laboratory sample analysis

The total alkalinity of groundwater samples was measured in the field using a HACH® alkalinity test kit and digital titrator. A 100 mL sample was taken and a satchel of HACH® Bromocresol Green-Methyl Red Indicator was added. Sulphuric acid was then titrated into the sample until a distinctive colour change from green to light pink was observed, marking the endpoint. The number of digits titrated were then converted to alkalinity as $CaCO_3$, which was subsequently converted to bicarbonate concentration using a multiplier of around 1.22.

Water samples for major and trace element analysis were collected either directly from the pump outlet (anions, unfiltered) or via a 6 L plastic pressure pack and 0.45 µ membrane filter (cations and trace) into rinsed 125 mL plastic sample bottles. Samples for analysis of anions were refrigerated. Samples for analysis of cations (Na^+, Mg^{2+}, K^+, Ca^{2+}, NH_4^+) and trace elements were acidified with nitric acid (1% v/v HNO_3) to a pH of less than 2 in order to keep the ions in solution (pH indicator strips were used to measure the pH). Samples were sent to the Analytical Services Unit in CSIRO Land and Water (Adelaide, South Australia) for analysis by Ion Chromatography (anions) and Radial Inductively Coupled Plasma Optical Emission Spectrometry (cations and trace elements).

Samples for the analysis of stable H and O isotopes were collected directly from the pump outlet and sealed in pre-rinsed 35 mL glass McCartney bottles. The pump discharge pipe was held in the bottom of the McCartney bottles contained within a beaker. The lid of the bottle was placed in the bottom of the beaker. The bottles were continuously filled until the beaker was also filled and overflowing. The lid was placed on the McCartney bottle while submerged in the beaker to ensure no headspace in the bottle. The pH was checked to ensure it was between the ranges of 5–9 in accordance with the CSIRO Land and Water sampling procedure. Lids were crimped tightly and subsequently taped to ensure no gas exchange. Samples were stored inverted and sent to CSIRO Land and Water for analysis by Isotope Ratio Mass Spectrometry (IRMS).

Samples for the analysis of strontium isotopes were collected directly from the pump outlet and pressure-filtered through a 0.45 µ membrane filter into rinsed 500 mL plastic bottles. They were sent to The University of Adelaide for analysis by Thermal Ionisation Mass Spectrometry (TIMS).

Samples for the analysis of carbon isotopes (radioactive ^{14}C and stable $^{13}C/^{12}C$) were collected in 1 L rinsed plastic bottles directly from the pump outlet. The samples were preserved with 3–5 mL of NaOH (50%) to help to ensure that any dissolved CO^2 is fixed and not lost, and sent to Beta Analytic Incorporated in Florida, USA for analysis by accelerator mass spectrometry (AMS).

Samples for the analysis of CFC-11 and CFC-12 were collected in triplicate 125 mL glass bottles with metal foil cap liners. The bottles were flushed, filled and capped whilst submerged in water in a stainless steel bucket, as detailed in IAEA (2006). Samples were sent to CSIRO Land and Water Isotope Analysis Service for analysis by ECD gas chromatography.

Samples for the analysis of SF_6 were collected in a 1 L amber glass bottle that were filled from the bottom, flushed of at least two volumes and then sealed with a convex plastic cap. Again, samples were analysed at CSIRO Land and Water Isotope Analysis Service using a gas chromatograph fitted with an electron capture detector.

3.4 Potentiometric surface mapping

Regional potentiometric surfaces for the Quaternary and basement aquifers were developed by incorporating the newly-acquired data from the field sampling program. There were insufficient data to generate a regional potentiometric surface for the Tertiary aquifer, other than for prescribed wells areas.

Due to absence of surveyed wells constructed in the Quaternary and basement aquifers the following method was used to generate the potentiometric surfaces (water level elevation in m AHD). Firstly, all wells with available standing water level (SWL) data were extracted from SA Geodata and imported to ESRI® ArcGIS along with the State's 1 second DEM raster coverage. The 'extract raster value to point data' tool was used to provide a reference elevation to the wells with available SWL data. It should be noted that all available SWL data was used, regardless of the time the SWL was collected and includes both current and historical data.

Once the elevation data was added to the well point data set, the SWL data was subtracted from the elevation data to give an approximated reduced standing water level (RSWL) value. The 'kriging interpolation' tool was then used to generate a water level elevation raster (in m AHD) for the region. Areas with sparse point data were considered to have low confidence.

3.5 Major ion charge balance

All analytical results were checked using the standard charge balance equation:

$$Error = \frac{\sum cations - \sum anions}{\sum cations + \sum anions} x100\%$$

where cation and anion concentrations are in milliequivalents of solute per litre of solvent (meq L^{-1}). Charge balance errors of less than 5% are generally considered to be reasonable; less than 10% is tolerable although potentially problematic for quantitative geochemical analysis; errors greater than 10% are considered intolerable and requiring repeat analysis.

3.6 Stable H/O isotope composition of rainfall

Monthly stable isotope data for rainfall was extracted from IAEA/WMO (2013) Global Network of Isotopes in Precipitation (GNIP) database for the period 1962 to 1984. Additional monthly data for the period April 2008 to May 2010 was sourced from Crosbie *et al*. (2012) to extend the existing GNIP database record. Data from both sources were collected from Adelaide rainfall station and are assumed to be representative of the Local Meteoric Water Line (LMWL) for the EP.

The monthly rainfall isotope data was sorted, cleaned and then used to compute precipitation amount-weighted mean compositions for months of 1–20 mm, 21–40 mm, 41–80 mm and greater than 80 mm. This enabled direct comparison of groundwater isotopic compositions with those of different size monthly rainfall, providing insight to the types of rainfall events that lead to recharge.

3.7 Estimating groundwater age by CFCs

As discussed in section 2.3.4, the age of groundwater can be estimated by comparing measured concentrations of CFCs (and SF_6) with historical curves of atmospheric concentration (e.g., Figure 2.5) and assuming piston flow (i.e., no mixing or dispersion) of groundwater from the recharge source to the well (Cook *et al*. 2005). However, in order to convert measured groundwater concentrations back to equivalent concentrations in air (or convert air concentrations to dissolved concentrations in water) an estimate of the recharge temperature is necessary as this affects the solubility of the gas in water. While the recharge temperature is typically taken to be the mean annual air temperature (Gooddy *et al*. 2006), the average shallow groundwater temperature of 20°C was used for consistency with previous studies: 18°C in Evans (1993) and 20°C in Cook *et al*. (1996). Shallow groundwater temperature can give a reasonable indication of recharge temperature where noble gases are not available for more accurate analysis (Plummer, Busenberg and Cook 2006).

An estimate of excess air concentration and recharge elevation is also required to convert concentrations and in turn determine apparent age. Excess air was not measured in the field and for the purpose of this report was assumed to be zero (NB assuming an excess air value of 1 cc/kg reduced the apparent ages by 0.5–1.5 years). Cook & Herczeg (1998) suggest corrections for excess air should be made if possible, but this is usually unnecessary. Given the majority of sites in this study are located in either basement outcrop or Quaternary sediments that are directly recharged by rainfall, the recharge elevation was taken to be the elevation of the wells. Elevation data was obtained by extracting the raster value from the 1 second DEM to the point location of the well using ArcGIS.

The U.S. Geological Society spreadsheet program TracerLPM (http://pubs.usgs.gov/tm/4-f3/) was used to derive apparent ages (or 'recharge years') from the measured concentrations and assumed parameters and the piston flow model discussed above.

3.8 Groundwater recharge rate

3.8.1 Using CFC age

Given estimates of groundwater ages, such as those determined by CFCs, the net groundwater recharge rate (*R*) can be approximated by:

$$R = \frac{z\theta}{t}$$

where z is depth below watertable, taken as mid-point of the screened/open section of the well;
θ is aquifer porosity;
t is apparent age.

The following porosity values were assumed for the different aquifer types: fractured rock 5%, Quaternary 35%, Tertiary 10%.

This approach for estimating recharge assumes only one-dimensional flow, which in regional aquifers is often not the case. However, this assumption results in acceptable error provided the depth of sampling is small relative to the thickness of the aquifer (e.g., Cook and Böhlke 1999).

3.8.2 Using chloride mass balance

A steady-state groundwater chloride mass balance (CMB) method is commonly used to estimate net groundwater recharge in semi-arid areas where recharge rates are low. The principle of the method is that chloride flux at the land surface, including marine aerosols in rainfall and dry deposition, is in equilibrium with the chloride flux entering the watertable. Hence, key assumptions behind the method are that (a) the hydrology is in some steady state and (b) there is no additional source of chloride, such as halite dissolution. Proving these assumptions can be justified, the mean annual recharge rate (*R*) can be estimated via the following:

$$R = \frac{P.C_P}{C_{gw}}$$

where P is mean annual precipitation (mm/y);
C_P is chloride concentration in precipitation (mg/L);
C_{gw} is chloride concentration in groundwater (mg/L).

$P.C_P$ was estimated using average annual rainfall and chloride deposition in rainfall data, both of which are accessible through the Geoscience Australia MapConnect website (Geoscience Australia 2014).

3.9 Estimating groundwater age by radiocarbon

Directly converting measured groundwater carbon-14 activities into an apparent age yields numbers that are almost always too old because of the addition of old carbon in the unsaturated zone. It is therefore necessary to use chemical or isotopic correction schemes such as those alluded to in Section 2.3.6. These corrections use algorithms to estimate the radiocarbon concentration of soil-water at the point at which it enters the watertable. The algorithms represent processes in a conceptual model of interactions between gaseous CO^2, soil-water and soil-carbonate minerals. Because soil-gas, DIC of soil-water and organic carbon interact during the transit of soil-water through the unsaturated zone, a significant fraction of carbon added to the DIC will be from so-called dead carbon. A consequence is that starting radiocarbon concentration at the watertable can be half that of the equivalent atmospheric value (currently ~106pMC).

The major ion chemistry data (Section 4.2.1) coupled with knowledge of the geology in the region suggests addition of carbonate and/or bicarbonate to groundwater above the concentrations that can be expected from rainfall and soil CO_2 dissolution and subsequent enrichment by evapotranspiration. Therefore a carbon-14 correction scheme is necessary if accurate estimates of apparent age are required.

Kalin (2000) summarised most of the twenty or so correction schemes that have appeared in the literature over the past 60 years. For south-eastern Australian aquifers, the correction scheme known as the “Pearson model” (Ingerson and Pearson 1964) is the most consistent and widely used correction scheme for adjusting initial radiocarbon values. This model utilises groundwater $\delta^{13}C$ compositions to determine relative contributions of DIC from two end-member sources: mineral carbonates and soil CO_2 gas. This requires estimating the average ^{14}C and $\delta^{13}C$ of soil carbonates and soil CO_2 for the area of interest. The model also assumes that there is limited re-equilibration of the soil CO_2 with the above ground atmosphere—a so-called closed-system model.

In this work, an estimated value of 95 pmC was used for soil gas at the bottom of the unsaturated zone based on measured soil gas in the Murray–Mallee region of South Australia (SA). Values slightly lower than atmospheric values reflects some contribution of old carbon to the soil CO_2. A value of 0 pmC is assigned for ^{14}C of carbonate minerals. As for $\delta^{13}C$, the carbonate minerals are likely to be a mixture of pedogenic and marine carbonate sands, so we use –3‰ for the solid minerals and values of -20‰ for soil gas CO_2, which is also based on measured values in similar areas of SA.

Several of the measured $\delta^{13}C_{DIC}$ results in this work are suspected of being contaminated (or spurious measurements) because they are much more negative than any that had been measured in previous studies and they are even more depleted in ^{13}C than the best estimates of soil gas $\delta^{13}C$ (Table 4.2). The ages calculated using the apparent spurious $\delta^{13}C$ values are generally much older than $\delta^{13}C$ values in the 'normal' range that would be expected for this region and in some cases, older than the uncorrected ages.

Given this study is a reconnaissance over a very large regional scale, it is suggested that the radiocarbon interpretations are regarded as tentative, pending further investigations in areas of interest. This is particularly true where corrected and uncorrected ages differ by many thousands of years.

4 Results and discussion

4.1 Regional groundwater flow directions

Maps of the potentiometric surface for Quaternary and basement aquifers are shown in Appendix A, Figures A4 and A5, respectively. Arrows on the maps indicate inferred regional groundwater flow directions, which generally follow topographic gradients; that is south-westerly on the western side of the EP and south-easterly on the eastern side of the EP.

4.2 Regional hydrogeochemical trends

4.2.1 Major ion chemistry

Results of field measurements and hydrochemical analyses are tabulated in Appendix B. The charge balance error for all but three of the 59 groundwater samples was less than 5%, which gives high confidence in the data. Two of three samples with charge balance errors in the range of 13–15% were lacking a bicarbonate result because field alkalinity was not measured. Field alkalinity was also not measured at two other wells (i.e. four wells in total) but charge balance errors for these two were low.

The Lincoln map sheet region is dominated by Na-Cl-HCO_3 and Na-Ca-HCO_3-Cl water types associated with the Quaternary Bridgewater Formation (Appendix A, Figure A6; also tabulated in Appendix C). The basement aquifer water type in this area is similar. The remainder of the Quaternary aquifer water samples display a Na-Cl water type. There is a general trend in compositions from a Na-Ca-HCO_3-Cl to Na-Cl type (Figure 4.1), however, it is not clear that this trend evolves with increasing salinity. This suggests the dominant controls on groundwater chemistry in the region are (i) acquisition of marine aerosols via rainfall, with subsequent evapo-concentration, and (ii) weathering of marine (limestone) and pedogenic (calcrete) carbonate minerals.

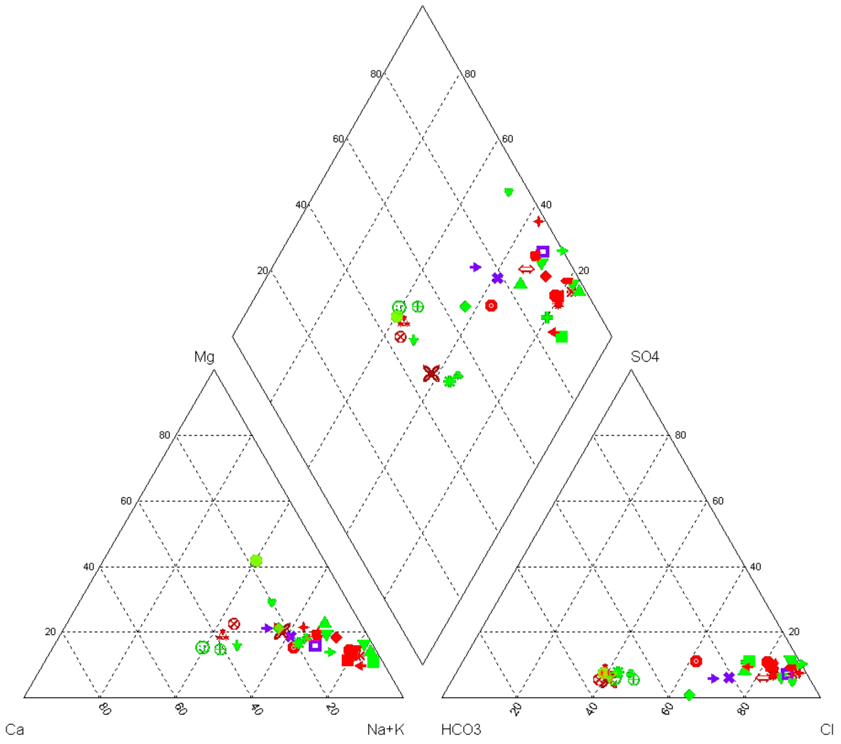


Figure 4.1 Piper diagram for groundwater samples of the Lincoln and Koppio map sheet regions displaying the dominant water type from different aquifers: green indicates Quaternary, purple indicates Tertiary and red indicates basement

In stark contrast, the Whyalla and Kimba map sheet regions have groundwater compositions that are all Na-Cl dominated (Figure 4.2 and Appendix A, Figure A6) reflecting the different geology in this part of the EP, particularly an absence of carbonate rocks. Instead, groundwater chemistry in this region is almost entirely reflective of rainfall chemistry (albeit more concentrated), with minor evidence of mineral weathering processes.

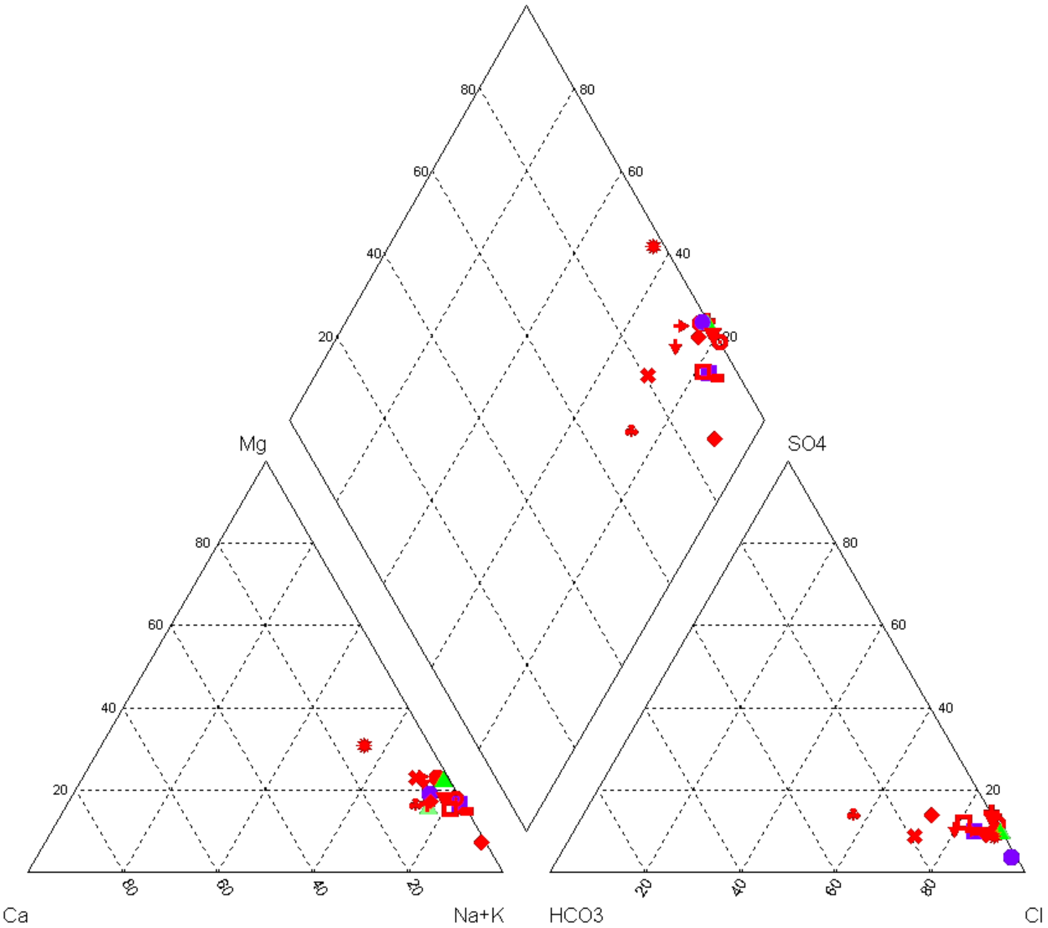


Figure 4.2 Piper diagram for groundwater samples of the Whyalla and Kimba map sheet regions displaying the dominant water type from different aquifers: green indicates Quaternary, purple indicates Tertiary and red indicates basement

Plots of major ion concentration relative to chloride concentration are often used to investigate trends in hydrochemical data. The key benefit of using this approach—rather than plotting major ion concentrations alone—is that it normalises the ion concentrations by accounting for evaporative effects. This is because chloride is only affected by evapotranspiration and there are no significant Cl-bearing minerals that contribute to chloride in groundwater. Therefore, an evaporating body of water containing salts of marine origin will evolve chemically as a horizontal line in plots such as that shown in Figure 4.3. Deviations away from this line will only occur when additional processes, such as water–rock interaction or mixing with different waters, become important.

The plots shown in Figure 4.3 for all groundwater samples collected in this study demonstrate how the freshest groundwater (i.e., Cl less than ~100 meq/L) often has a chemical composition distinct from that of seawater. In particular, these samples are generally enriched in Na and depleted in K, possibly reflective of cation exchange reactions, and enriched in Ca, Mg and HCO_3 likely due to weathering of carbonate minerals. They also have NO_3 and SO_4 compositions that are different from seawater; possibly mechanisms for these trends include anthropogenic nitrate contamination, gypsum dissolution, oxidation of sulfide minerals and either nitrate or sulfate reduction. Further investigation into the importance of these mechanisms is beyond the scope of this report.

The more saline groundwater samples shown on Figure 4.3 are generally consistent with evapo-concentration of marine aerosols, except in the case of K as this is readily adsorbed onto clay mineral surfaces. Finally, Br/Cl ratios are consistent with the range expected for marine aerosols and soil organic processes, suggesting there is no halite dissolution (Sonney and Vuataz 2010). This has important implications for justifying the use of a steady-state chloride mass balance approach to estimate recharge (see Section 4.5).

Plots of ionic ratios (e.g., Na/Ca) against Cl (a useful proxy for salinity) help to reveal changes in concentration of one of the ions relative to the other. The first plot shown in Figure 4.4 indicates that Ca/HCO_3 ratios of the groundwater are somewhat consistent with those expected from calcite weathering (i.e., unity):

$$CaCO_3 + H_2O + CO_2 \leftarrow\rightarrow Ca^{2+} + 2HCO_3^-$$

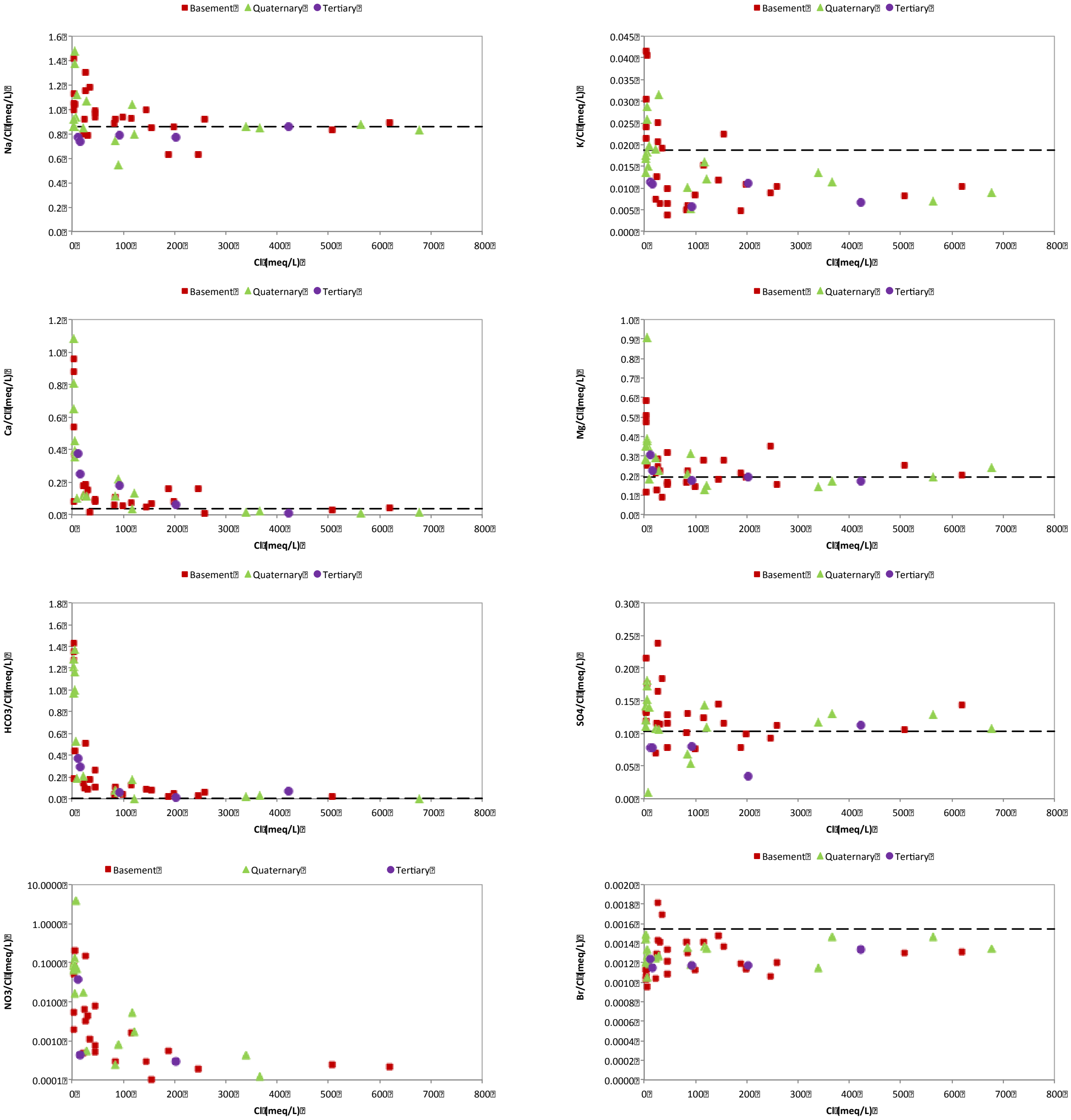


Figure 4.3 Major ion/chloride ratios for all groundwater samples. Dashed lines represent seawater dilution/evaporation

The observation that many groundwater samples exhibit a Ca/HCO_3 equivalents ratio of less than 1 is consistent with weathering of Mg-calcite rather than pure calcite. If instead all Ca was acquired through gypsum dissolution:

$$CaSO_4 + \leftarrow\rightarrow Ca^{2+} + SO_4^{2-}$$

then Ca/SO_4 ratios of about unity would be expected. However the majority of samples have significant excesses of Ca over SO_4, providing further evidence for the importance of calcite weathering (second plot in Figure 4.4).

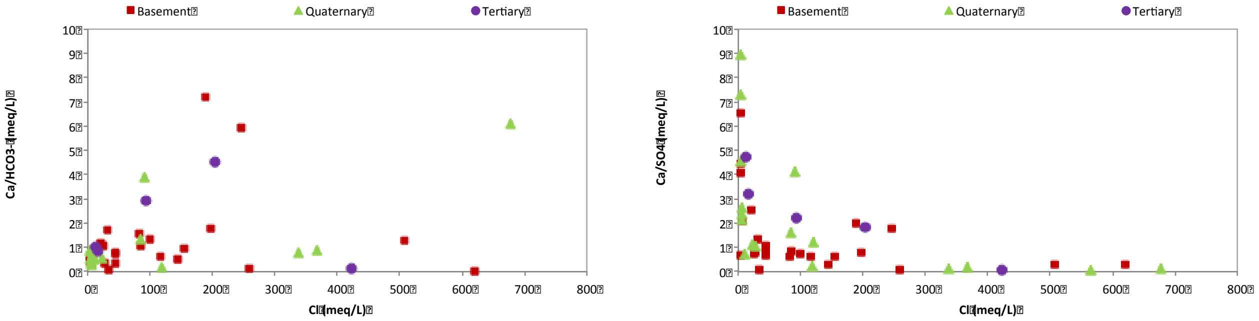


Figure 4.4 Major ion/ion ratios for all groundwater samples

4.2.2 Stable H/O isotopes

Results of the stable H/O isotope analysis for all groundwater samples are shown spatially in Appendix A (Figure A7) and the data is tabulated in Appendix D. Groundwater samples from the Lincoln and Koppio map sheet regions plot close to the LMWL, indicating very little evaporation of the water prior to recharge (Figure 4.5). In contrast, groundwater samples from the Whyalla and Kimba map sheet regions (with the exception of one Quaternary aquifer sample) plot parallel to, but to the right of, the LMWL. This suggests that either groundwater in this region is highly evaporated prior to recharge, or that the Adelaide meteoric water line is perhaps not representative of the LMWL for this region, or both.

Figure 4.6 shows the relationship between groundwater H/O isotope compositions and amount-weighted monthly rainfall compositions. Despite the possibility that the Adelaide rainfall dataset is not an accurate representation of rainfall in the Whyalla–Kimba region, the data provide convincing evidence that groundwater is only recharged after intense events; that is, recharge to the different aquifers occurs after at least 40–60 mmm of rainfall in a month. This finding is consistent with observations in the Southern Basins PWA by Evans (1997) who suggested that, for the shallow Quaternary aquifer, more than 10 mm of rainfall per day for three consecutive days was required to see any evidence of recharge in shallow well hydrographs.

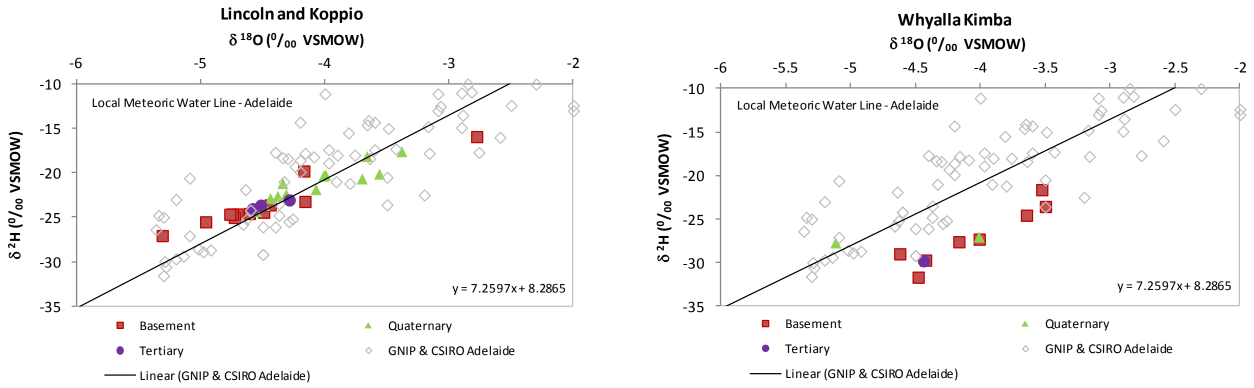


Figure 4.5 Groundwater stable isotope compositions for the Lincoln–Koppio and Whyalla–Kimba map sheet regions, showing relationship to rainfall samples and the local meteoric water line for Adelaide

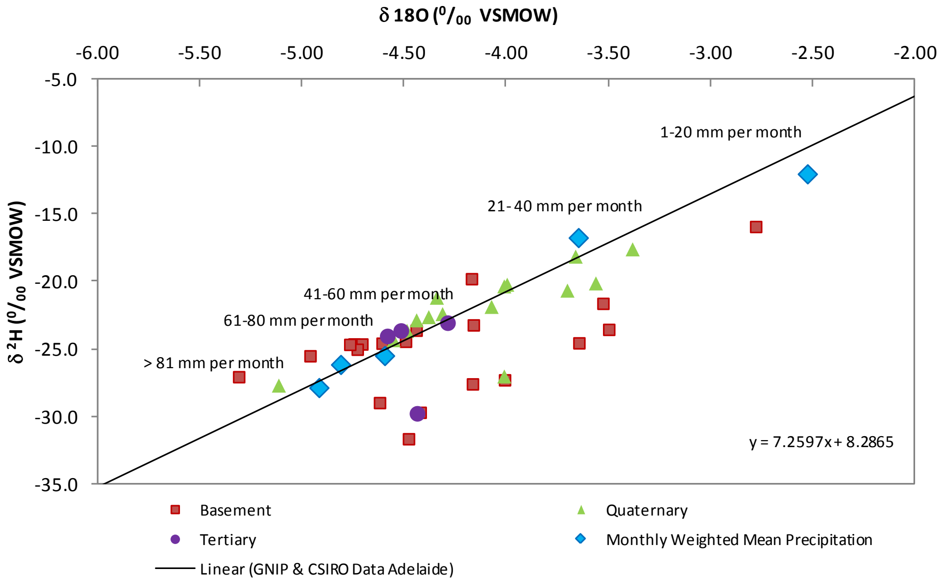


Figure 4.6 **Groundwater stable isotope compositions for the Lincoln–Koppio and Whyalla–Kimba map sheet regions, showing relationship to amount-weighted mean rainfall amounts for Adelaide**

4.2.3 Strontium isotope ratio

Strontium isotope ratios for groundwater samples range from 0.70921 and 0.74014 across the study area (Appendix A, Figure A8; also tabulated in Appendix E). All Whyalla–Kimba groundwater samples have relatively high ratios, ranging between 0.72681–0.73128, which are reflective of weathering old silicate minerals and no marine carbonates. Elsewhere in the study area, groundwater samples from the Quaternary aquifer typically have strontium ratios around 0.709–0.710, consistent with the Sr isotope ratio of modern day seawater (and thus marine aerosols) and Quaternary limestone. There are no obvious trends in the Sr ratio of groundwater with increasing depth below water table, however, some parts of the Lincoln–Koppio region exhibit similar compositions in Quaternary, Tertiary and basement aquifers, which may indicate connectivity between these units (Figure 4.7). Further analysis of Sr isotopes and other tracers is presented in Section 4.4 in the context of aquifer connectivity.

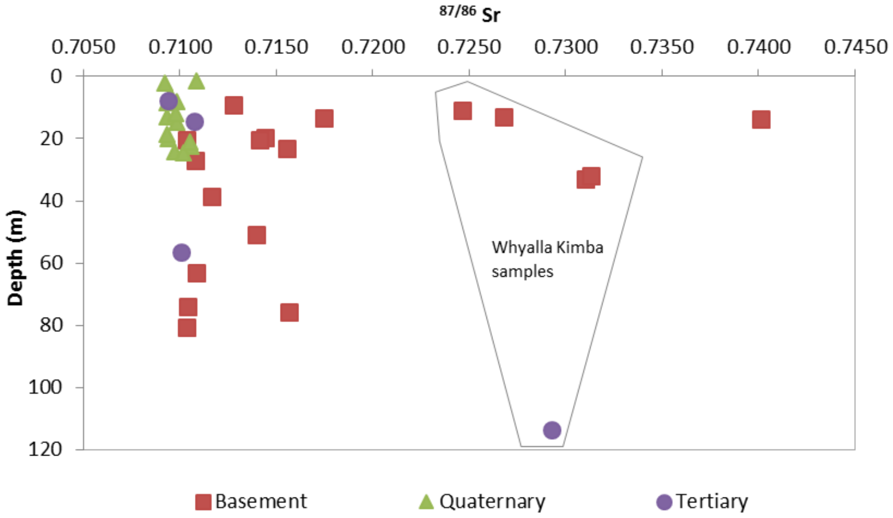


Figure 4.7 **Strontium isotope ratio for all groundwater samples versus depth below water table to mid production zone**

4.3 Groundwater age tracers

4.3.1 CFCs and SF_6

Distributions of groundwater CFC-11 and CFC-12 concentration are shown in Appendix A, Figure A9, while modelled groundwater ages—presented as 'recharge years'—are given in Table 4.1. Importantly, all groundwater samples have CFC-12 concentrations above the analytical detection limit, which means a significant proportion (if not all) of each sample was recharged within the last 50–60 years. Figure 4.8 displays the concentrations of CFC-11 plotted against CFC-12 and corresponding recharge year for atmospheric concentrations of CFC-11 and CFC-12 as recorded at Cape Grim, Tasmania. Figure 4.8 also displays theoretical curves for two possible flow models, namely piston flow and binary mixing of two water bodies. If piston flow is occurring, the groundwater CFC-11 and CFC-12 concentrations should plot along the blue line. If binary mixing is occurring, the groundwater samples should plot along straight lines between the two end-member concentrations (the grey dashed line in Fig. 4.8 represents binary mixing between water recharged in the 1950s and water recharged within the last 1–2 years). An infinite number of other binary mixing lines are plausible, as are other flow models such as Exponential Mixing; in either case, the theoretical curves would plot in-between the piston flow and binary mixing models shown. Examination of Figure 4.8 shows most data consistently plotting below the binary mixing model line, which is commonly observed and likely due to degradation of CFC-11. Accordingly, recharge years derived from CFC-11 concentrations are older than those of CFC-12 (Table 4.1) and will hereafter be disregarded.

Table 4.1 Groundwater CFC-11 and CFC-12 concentrations and estimated recharge year assuming piston flow. NP indicates that dual dates are not possible.

Unit Number	CFC-11 (pptv)	CFC-12 (pptv)	CFC-11 Recharge year	CFC-11 Recharge year	CFC-12 Recharge Year	CFC-12 Recharge Year
602802074	37.9	137.5	1968	NP	1972	NP
602802730	1.8	19.6	1954	NP	1957	NP
602802732	11.8	34.2	1961.5	NP	1961	NP
602802746	6.9	20.8	1958.5	NP	1958	NP
602802747	137.7	424.0	1978	NP	1988	NP
602802749	2.3	12.1	1955	NP	1954	NP
602901390	8.0	38.2	1959.5	NP	1962	NP
602901391	12.1	33.8	1962	NP	1961	NP
613001023	14.4	36.1	1962.5	NP	1962	NP
623000844	141.6	431.2	1978.5	NP	1988	NP
633100228	3.1	20.7	1956	NP	1958	NP
602802724	17.3	88.2	1963.5	NP	1968	NP
602800049	174.9	494.4	1982	NP	1992	NP
592900196	165.5	461.2	1981	NP	1990	NP
602802744	221.8	500.4	1987	NP	1993	NP
602802745	204.2	534.5	1985.5	NP	1999	2009
602801750	211.5	531.9	1986.5	NP	1998	2009.5
602802112	242.5	534.8	1989.5	2008.5	1999	2009
602801725	3.1	10.4	1956	NP	1953	NP
592900580	121.7	348.0	1976.5	NP	1984	NP
602800745	4.1	9.7	1956.5	NP	1953	NP
602901393	4.1	26.3	1957	NP	1959	NP
633100224	1.3	8.3	1953.5	NP	1952	NP

The apparent ages shown in Table 4.1 assume a recharge temperature of 20°C based on our measurements of shallow groundwater temperatures and previous studies (Section 3.6). The use of mean winter–spring air temperature as a proxy for recharge temperature was trialled, as this lower temperature was considered plausible if the majority of recharge to the aquifers occurs over the cooler winter months. When this value (15°C for a period of 30 years for the months May to September) was input to the model, the apparent age of groundwater decreased by between 1.5–9.5 years and provided less meaningful results (not shown). Use of the higher recharge temperature is also supported by the stable H/O isotope data

(Figure 4.6) that indicated recharge is largely driven by intense rainfall events, including summer thunderstorms, therefore not restricted to the cooler months.

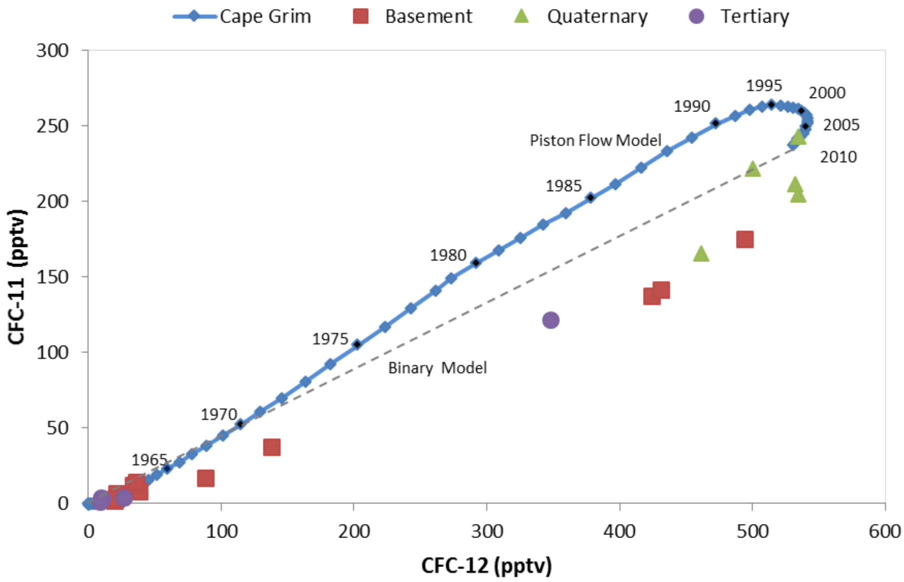


Figure 4.8 Groundwater CFC-11 versus CFC-12 concentrations relative to (a) Piston Flow model derived from atmospheric concentrations at Cape Grim, and (b) Binary Mixing model between pre-1960 water and recent rainfall (grey dashed line)

SF_6 was used in this study to provide increased confidence in dating very modern groundwater; that is, groundwater recharged within the last 10–15 years where CFC ages are ambiguous. However, the results displayed in Figure 4.9 reveal that more than half the samples have a component of additional SF_6, possibly due to in-situ production from fluoride-bearing rocks (see Section 2.3.5). Alternatively, the source of additional SF_6 could be explained by excess air, especially if large, intense rainfall events are responsible for the majority of recharge. In either case, SF_6 is hereafter disregarded and CFC-12 is adopted as the most reliable tracer for dating young groundwater in the study area.

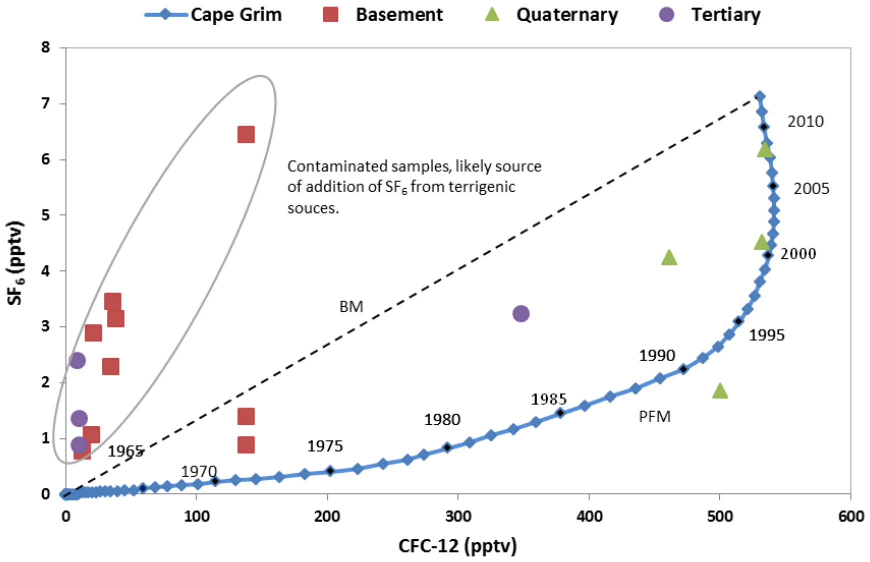


Figure 4.9 Groundwater SF_6 versus CFC-12 concentrations relative to (a) Piston Flow model derived from atmospheric concentrations at Cape Grim, and (b) Binary Mixing model between pre-1960 water and recent rainfall

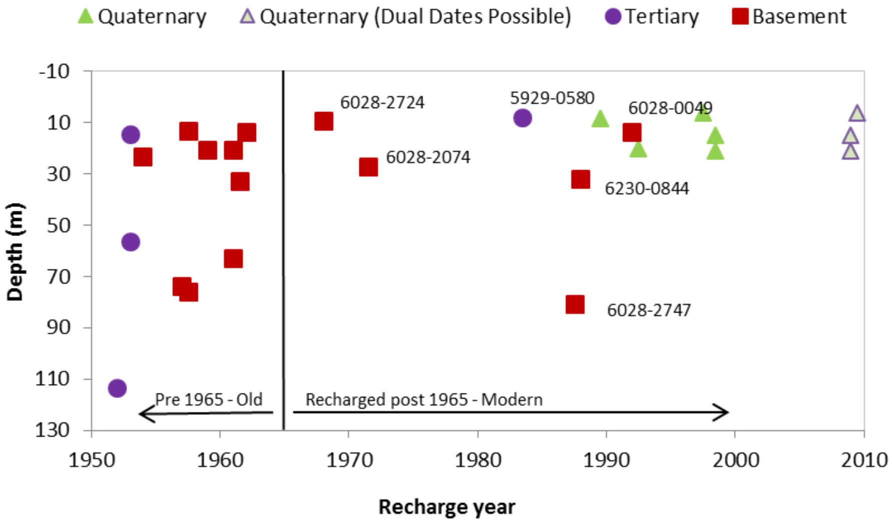


Figure 4.10 Estimated recharge year based on CFC-12 concentrations and a piston flow model, plotted against sample depth below water table (mid production zone)

Figure 4.10 shows that the youngest groundwater (i.e., highest concentrations of CFC-12) occurs in the shallow Quaternary aquifers, consistent with a conceptual model of dynamic recharge from recent rainfall. Most Tertiary and basement wells produced older (i.e., pre-1965) groundwater samples. A notable exception to this trend is Tertiary well 5929-0580, which is shallow and completed beneath Quaternary sediments—the modern age of groundwater from this well is evidence of vertical connection between the two aquifers.

Several basement wells produced groundwater with relatively young ages, including well 6028-0049 in the Koppio Hills, well 6230-0844 in the Cleve Hills and well 6028-2074 located west of Port Lincoln. The deep well 6028-2747 is located in the vicinity of Gum Flat. While it displays a CFC-12 age of the late 1980s and a modern corrected ^{14}C model age (see next section), it has a carbon-14 activity (57 pMC) that corresponds to an uncorrected age of several thousand years. More generally, discrepancies between ^{14}C ages and CFC ages in fractured rock aquifers can be explained by matrix diffusion, whereby modern DIC is lost from active fractures into the matrix of the basement rock more rapidly than CFCs are lost; that is, CFCs penetrate deeper in the aquifer than modern DIC. This is due to the difference in diffusion coefficients of the two tracers and has been observed previously in areas such as the Clare Valley (Cook *et. al*. 2005).

4.3.2 Carbon-14

Radiocarbon activity of DIC in groundwater samples ranges from 103.7 pMC down to ~16 pMC (Appendix A, Figure A10). All three aquifers display a wide range of ^{14}C activities, with a general decrease as a function of depth below the water table, albeit with some notable exceptions. The uncorrected (apparent) ages range from modern to about 15 000 years (Table 4.2). The Quaternary Bridgewater Formation aquifer typically has a lower groundwater ^{14}C activity (ranging from 50–70 pMC) than other Quaternary sediments (ranging from 83.2–98.3 pMC). Because this study covers a large regional area with a variety of topographic, geological and vegetation characteristics, it cannot be explicitly determined whether these differences reflect different recharge and flow characteristics of the aquifers, or differences in mineral–solution interactions.

In the absence of carbonate weathering reactions, the plot of groundwater radiocarbon activity versus CFC-12 concentration (Figure 4.11) should look like an exponential curve that is essentially horizontal across the bottom and near vertical up the right hand side. The fact that there are numerous groundwater samples plotting above such a trend is a strong indication that dead carbon has diluted the ^{14}C activity of DIC in these samples, which means their uncorrected ages are grossly overestimated.

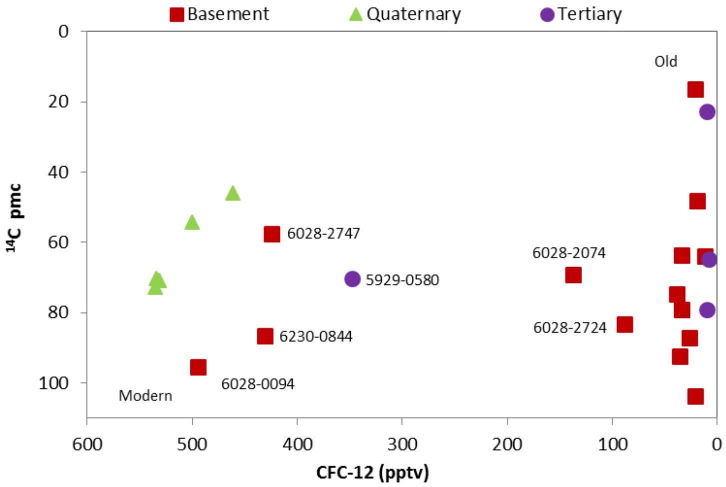


Figure 4.11 Groundwater radiocarbon activity and CFC-12 concentration

As described in section 3.9, the groundwater ages based on radiocarbon data were converted to ‘corrected’ ages using the ‘Pearson model’ resulting in 22 of the 36 groundwater samples for which we have radiocarbon data yielding model ages that are modern (Table 4.2). In other words they likely contain some component of radiocarbon from the nuclear-testing era and therefore contain a component of water recharged in the last 50 years. At face value this concurs with CFC-12 data showing a modern recharge component in practically all the sampled wells. The remaining 14 samples with older radiocarbon ages fall into two groups—those that have low ^{14}C values and $\delta^{13}C$ values ≥20‰, which are credible, and those with relatively higher ^{14}C values (but $\delta^{13}C$ values ≤20‰), which we consider to be dubious, possibly due to contamination during sampling. Figure 4.12 compares results of this study with those of Evans (1997).

If the sampling process, which involves converting the sample to an alkaline solution, were to have had substantial exchange with the atmosphere, the result would increase ^{14}C content and make $\delta^{13}C$ values more negative, due to very large discrimination against ^{13}C during CO_2 input into in alkaline solutions. The latter data mentioned above should therefore be treated as tentative until they can be confirmed through re-sampling.

Just three samples out of the 36 yielded what could be considered as genuine ‘old’ samples, or ages greater than 500 years (wells 6029-01394, 6028-02746, 6028-00745). Two of these wells are relatively deep, but still contain measureable CFC-12. The apparent coexistence of young groundwater (indicated by measureable CFC-12) and old groundwater (from low ^{14}C values) may be due to matrix diffusion, as discussed in section 4.3.1 above.

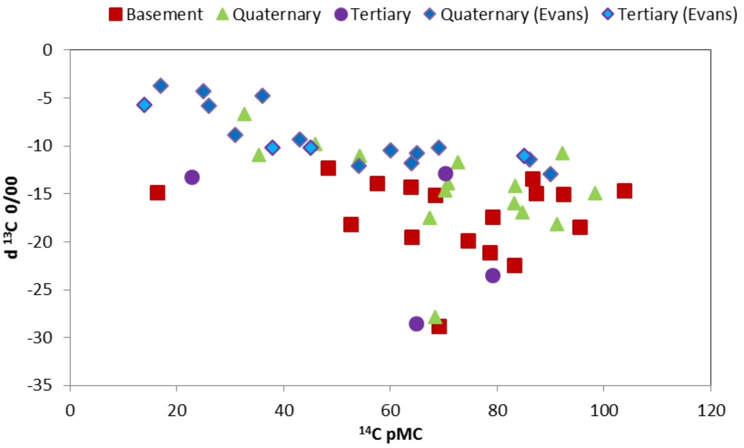


Figure 4.12 Groundwater $\delta^{13}C$ and ^{14}C activity, showing significantly depleted $\delta^{13}C$ compared to previous work by Evans (1997)

Table 4.2 Groundwater stable and radioactive carbon isotope composition and apparent and corrected ages using the isotope mixing model (Ingerson and Pearson 1964)

Unit Number	Aquifer Monitored	^{14}C (pMC)	δ^{13}C (‰, VPDB)	Apparent Age (years BP)	Corrected Age (Years BP)
602901390	Basement	74.5	-19.9	2360 ± 130	590
602901391	Basement	79.0	-17.4	1890 ± 130	Modern
602901394	Basement	52.5	-18.2	5180 ± 130	2620
602802071	Basement	68.3	-15.1	3060 ± 130	Modern
602802074	Basement	69.1	-28.8	2910 ± 30	4710
602802197	Basement	78.5	-21.1	1940 +/- 30 BP	725
602802730	Basement	48.2	-12.3	5860 +/- 30 BP	modern
602802732	Basement	63.7	-14.3	3620 +/- 30 BP	modern
602802746	Basement	16.3	-14.8	14550 +/- 60 BP	10 200
602802747	Basement	57.5	-13.9	4440 +/- 30 BP	modern
602802749	Basement	63.9	-19.5	3600 +/- 30 BP	1670
613001023	Basement	92.3	-15.0	640 +/- 30 BP	Modern
623000844	Basement	86.7	-13.4	1150 +/- 30 BP	Modern
633100228	Basement	103.7	-14.6	Modern	Modern
602802724	Basement	83.2	-22.4	1480 +/- 30 BP	825
602901393	Basement	87.2	-14.9	1100 +/- 30 BP	Modern
602800049	Basement	95.5	-18.4	370 +/- 30 BP	Modern
592900196	Quaternary	45.9	-9.8	6250 +/- 40 BP	Modern
602901023	Quaternary	84.6	-16.9	1340 +/- 30 BP	Modern
592800445	Quaternary	35.3	-10.9	8090 +/- 40 BP	480
602801750	Quaternary	70.8	-13.9	2780 +/- 30 BP	Modern
602802744	Quaternary	54.2	-11.0	4920 +/- 30 BP	Modern
602802745	Quaternary	70.2	-14.6	2840 +/- 30 BP	Modern
592900002	Quaternary	92.1	-10.7	660 +/- 30 BP	Modern
592900730	Quaternary	98.3	-14.9	140 +/- 30 BP	Modern
602901298	Quaternary	83.2	-16.0	1480 +/- 30 BP	Modern
592800083	Quaternary	32.7	-6.7	8970 +/- 40 BP	Modern
592800397	Quaternary	67.3	-17.5	3180 +/- 30 BP	170
602801635	Quaternary	83.4	-14.2	1460 +/- 30 BP	Modern
602802112	Quaternary	72.6	-11.7	2570 +/- 30 BP	Modern
602802118	Quaternary	68.3	-27.8	3060 +/- 30 BP	4480
602801595	Quaternary	91.2	-18.2	740 +/- 30 BP	Modern
602801725	Tertiary	79.0	-23.5	1890 +/- 30 BP	1700
592900580	Tertiary	70.2	-12.8	2840 +/- 30 BP	Modern
602800745	Tertiary	22.7	-13.2	11900 +/- 50BP	6230
633100224	Tertiary	64.8	-28.5	3480 +/- 30 BP	5140

Another potentially useful tracer for understanding the carbon isotope systematics—and therefore potentially correcting groundwater ^{14}C data—is ^{87}Sr/^{86}Sr (Harrington and Herczeg 1999). The principle behind the method is that groundwaters with more radiogenic ^{87}Sr/^{86}Sr are less likely to have a component of 'dead' carbon added to the DIC pool via weathering of marine carbonates, and thus require no correction to the apparent age estimate. Conversely, groundwaters with ^{87}Sr/^{86}Sr similar to seawater are likely to have a significant component of dead carbon from weathering and require correction. The data from this study tend to support this conceptualisation in that those samples with the lowest ^{14}C also have the lowest ^{87}Sr/^{86}Sr (Figure 4.13).

However, two factors limit the reliability of this method for developing a correction scheme. Firstly, modern rainfall has a ^{87}Sr/^{86}Sr equal to that of seawater and marine carbonate minerals, so groundwater that has not undergone any water–rock interactions could not be distinguished from groundwater that has weathered marine carbonates. Secondly, pedogenic carbonates such as the calcrete that dominates much of the land surface on western EP, have a ^{87}Sr/^{86}Sr composition equal to that of the water from which they were deposited. Therefore, weathering of these non-marine carbonates could produce a range of $^{87}Sr/^{86}Sr$ compositions.

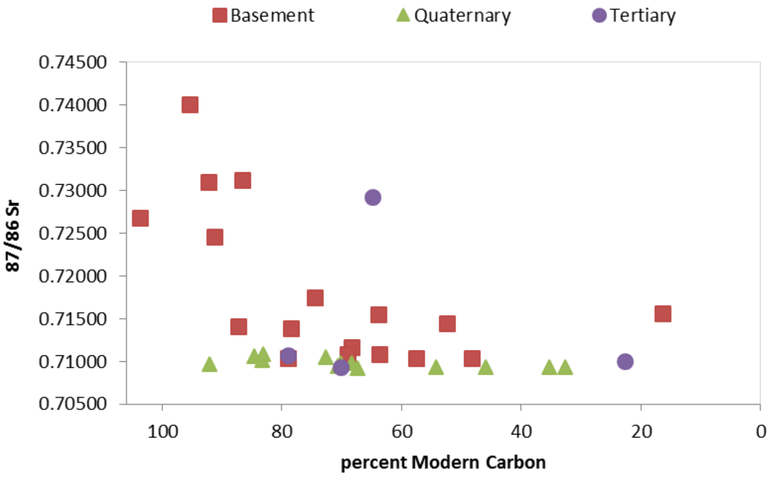


Figure 4.13 Relationship between groundwater $^{87}Sr/^{86}Sr$ and carbon-14 activity

4.4 Regional groundwater flow and inter-aquifer leakage

Two transects were constructed to assess regional groundwater flow and the potential for inter-aquifer connection. The locations of these transects are shown in Appendix A, Figure A11 and are based upon the regional potentiometric surface. This indicates flow travelling from the cropping out recharge area of the Koppio Hills in a south easterly direction towards Port Lincoln and the coast (Transect 1), and from Koppio Hills in a south westerly direction towards the Uley South lens and the coast (Transect 2). It should be noted that local topographic features will superimpose a local groundwater flow system on top of the regional flow system in some areas and may therefore complicate the interpretation.

4.4.1 Transect 1

Transect 1 was selected primarily to investigate changes in hydrochemistry and groundwater age along an inferred regional groundwater flow path. The most interesting tracers for these purposes are presented in Figure 4.14. Both carbon-14 activity and CFC-12 concentration decrease with increasing distance along the flow path and with increasing depth below water table, reflecting increasing groundwater age in these directions. As discussed in Section 4.3.1 and Section 4.3.2, apparent groundwater ages from uncorrected carbon-14 data are often one to two orders of magnitude higher than ages estimated from CFC-12 data. Accordingly, the residence time of groundwater from the first well in Transect 1 to the last well is approximately 2700 years based on carbon-14 and approximately 20 years based on CFC-12. Such a high discrepancy between tracers is most likely due to progressive addition of newly recharged groundwater to the regional flow which acts to bias the ages towards that provided by the younger tracer (McCallum *et al*. 2014), as well as the process of matrix diffusion discussed previously.

Strontium isotope ratios shows a general trend of becoming less radiogenic with increasing distance along the flow path (Figure 4.14(d)), reflecting changes in the geology of the basement aquifer from the Hutchinson Group to the Donington Suite (Appendix A, Figure A11).

4.4.2 Transect 2

Transect 2 was selected for examination of possible interaction between aquifers because there was a reasonable distribution of sampled wells that penetrated a variety of aquifers along the regional groundwater flow path, including three ‘paired sites’ where two separate wells are completed in different aquifers (Figure 4.15). The three paired well sites occur at distances of approximately 11 km (6028-02744 and 6028-02746), 17 km (6028-02745 and 6028-02747) and 29 km (6028-1750 and 6028-

0745) along the transect. The first two well pairs are completed in the Quaternary (Bridgewater Formation) and basement aquifers in the Uley East lens, whereas the third pair is completed in the Quaternary and Tertiary aquifers in the Uley South lens.

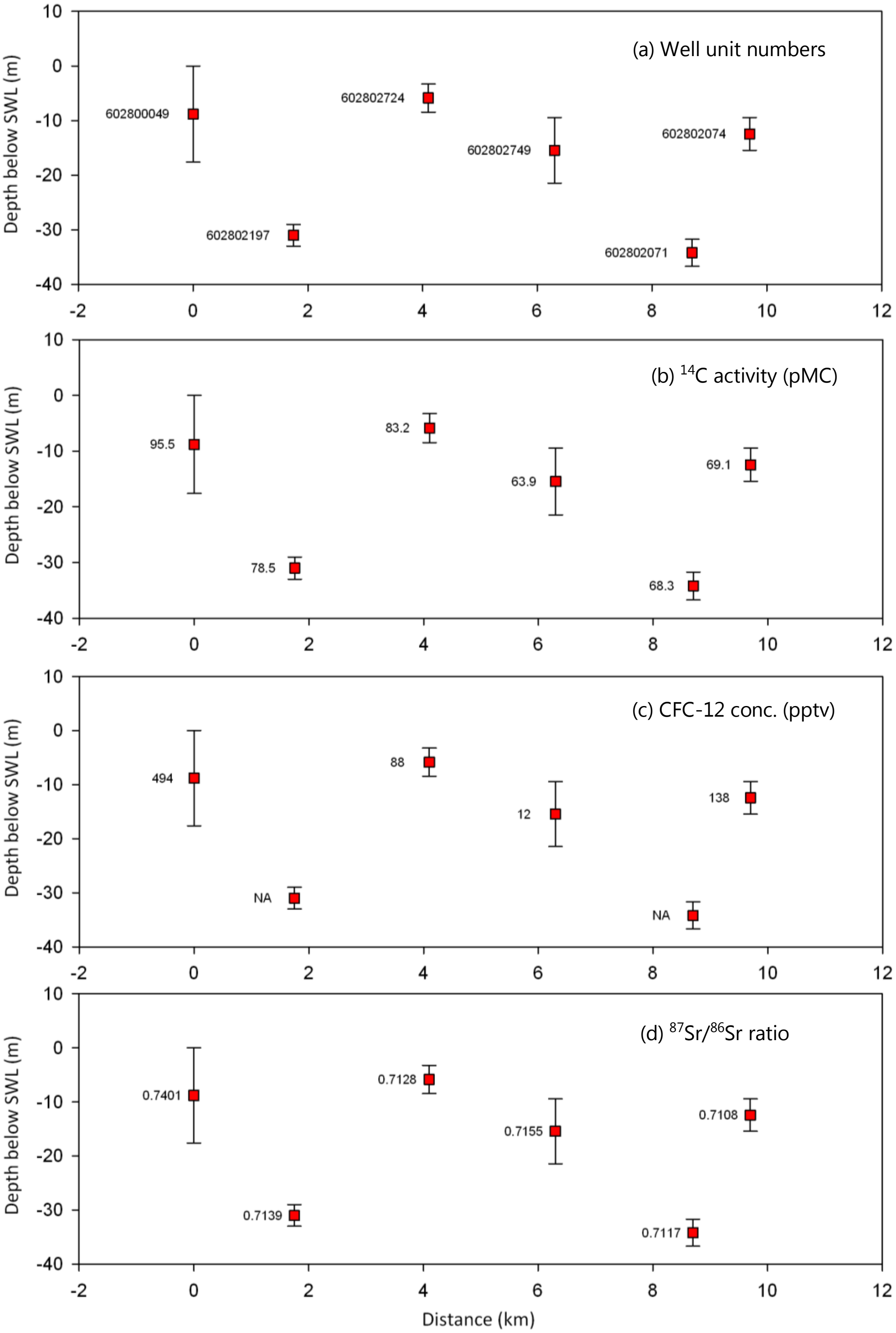


Figure 4.14 Groundwater wells and tracer concentrations along Transect 1: Koppio Hills to Port Lincoln

Inter-aquifer leakage—like all groundwater flow—is governed by Darcy's Law, such that potential flow is directly proportional to hydraulic gradient and hydraulic conductivity. Therefore when hydraulic heads (i.e. water levels) between two wells completed in the same location but at different depths are very different, the inference is that there is large *potential* for vertical leakage. However, maintenance of a large head difference may reflect limited *actual* leakage. This contradiction has plagued hydrogeologists for decades and means that interpreting head differences alone provides inconclusive evidence for inter-aquifer leakage. The use of environmental tracers such as ion chemistry and isotopes can provide direct evidence for actual inter-aquifer leakage.

Notwithstanding the aforementioned ambiguity, the data plotted in Figure 4.16 suggests limited potential for inter-aquifer leakage around the first (11 km) and last (29 km) paired sites, but greater potential exists at the middle site (17 km). Aquifer pumping tests at all three sites has indicated no hydraulic connection between the Uley East lens and the basement aquifer (Lincoln Minerals Limited 2013, p. 15).

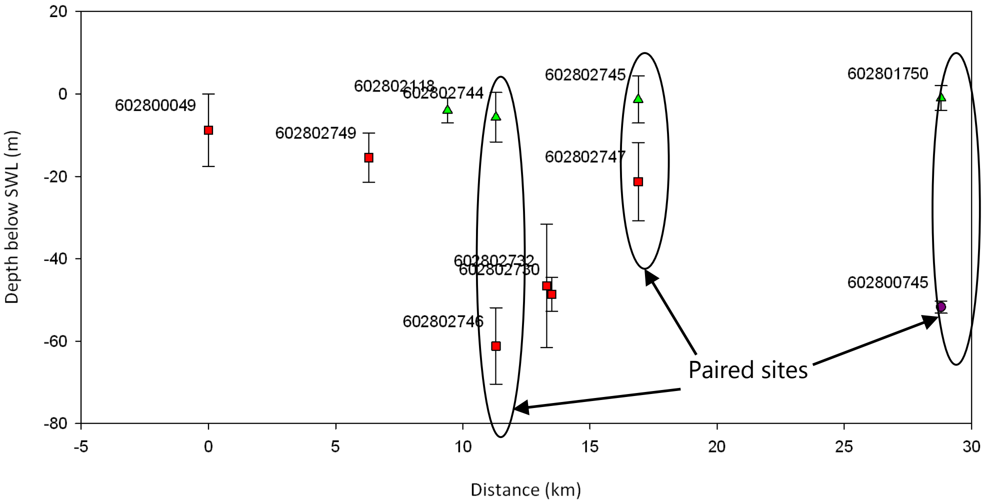


Figure 4.15 Production zones below standing water level of well along Transect 2: Koppio Hills to Uley South; displaying the middle (symbols) and upper/lower extents (error bars); green triangles represent wells completed in the Quaternary aquifer, purple circles the Tertiary aquifer and red squares the basement aquifer

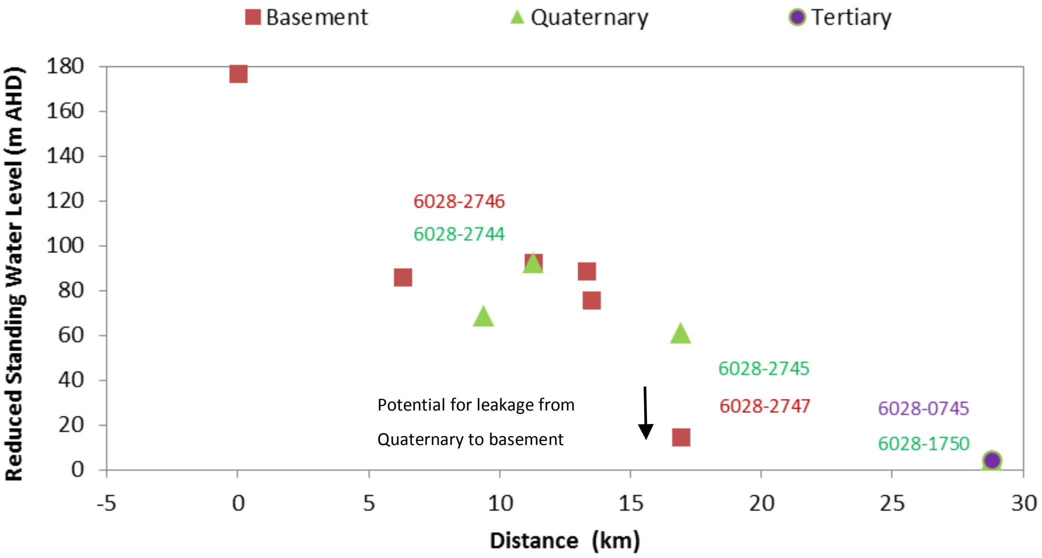
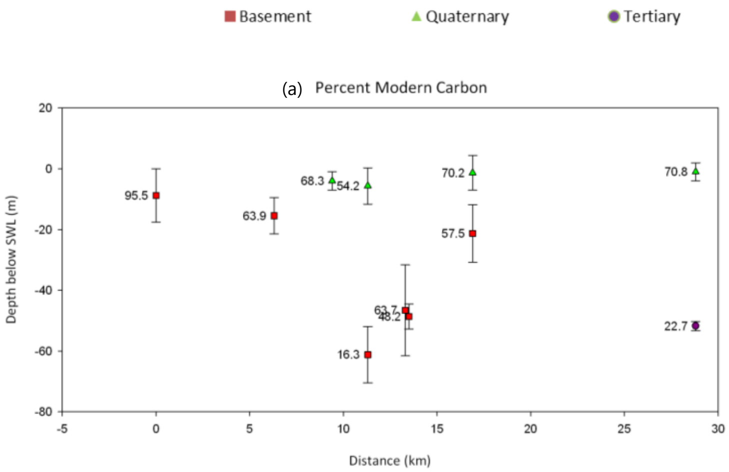


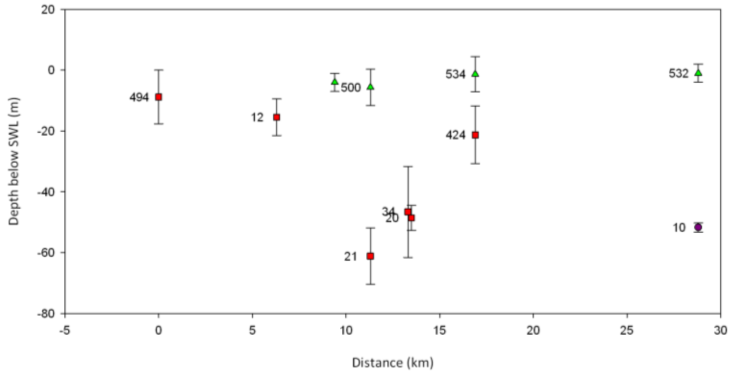
Figure 4.16 Groundwater levels in wells along Transect 2: Koppio Hills to Uley South

Figure 4.17(a) shows groundwater carbon-14 activity at each well along Transect 2. The fact that activities are so different between wells at all three paired sites suggests the groundwater age is highly stratified in this system. Therefore the carbon-14 data generally indicates limited inter-aquifer leakage, although data from the second well pair (~17 km) may reflect some connection in that part of the Uley East lens. Figure 4.17(b) shows CFC-12 concentrations along Transect 2 and reveals similar insights to inter-aquifer leakage as the carbon-14 data. That is, large differences in concentration between wells indicating limited leakage at the first and third well pairs, and more similar concentrations indicating a higher degree of connection at the second well pair (~17 km). Figure 4.17(c) shows $^{87}Sr/^{86}Sr$ ratio of groundwater along Transect 2. Quaternary and Tertiary aquifer samples generally have lower ratios that are reflective of weathering marine carbonate minerals, while basement aquifer samples have much higher ratios reflective of weathering silicate minerals. Large differences between $^{87}Sr/^{86}Sr$ ratios of wells at the first and third paired sites indicate limited inter-aquifer connectivity, while similar $^{87}Sr/^{86}Sr$ ratios at the second paired site suggest possible connection at, or immediately up-gradient of, this site. Therefore, all three tracers provide consistent insight to the main zone of inter-aquifer leakage along Transect 2.



(a) Percent Modern Carbon

(b) CFC-12 (pptv)



(c) Strontium Ratio

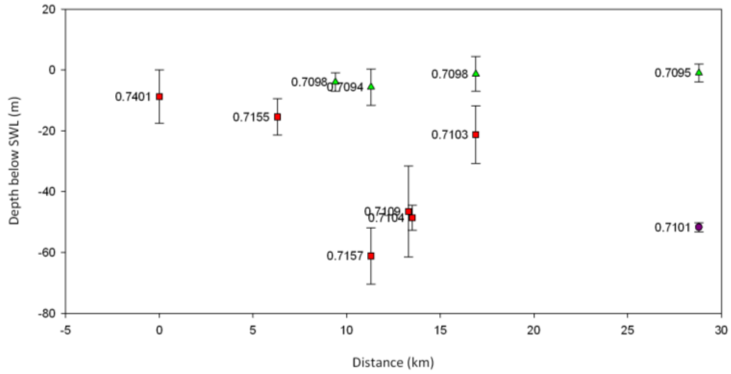


Figure 4.17 Groundwater tracer concentrations along Transect 2: Koppio Hills to Uley South

Major ion ratios of groundwater samples along Transect 2 (Figure 4.18) also provide supporting evidence:

- distinct ratios and thus negligible inter-aquifer leakage occurs at the first paired site (~11 km)
- more similar ratios and thus potentially localised inter-aquifer leakage at the second paired site (~17 km)
- distinct ratios and thus negligible inter-aquifer leakage at the third paired site (Uley South lens wells at ~29 km).

These findings are also consistent with previous hydrochemical analyses in the region (Lincoln Minerals Limited 2013; see Fig. 4.1) that suggested groundwater types were distinctly different at the first paired site, and similar at the second paired site.

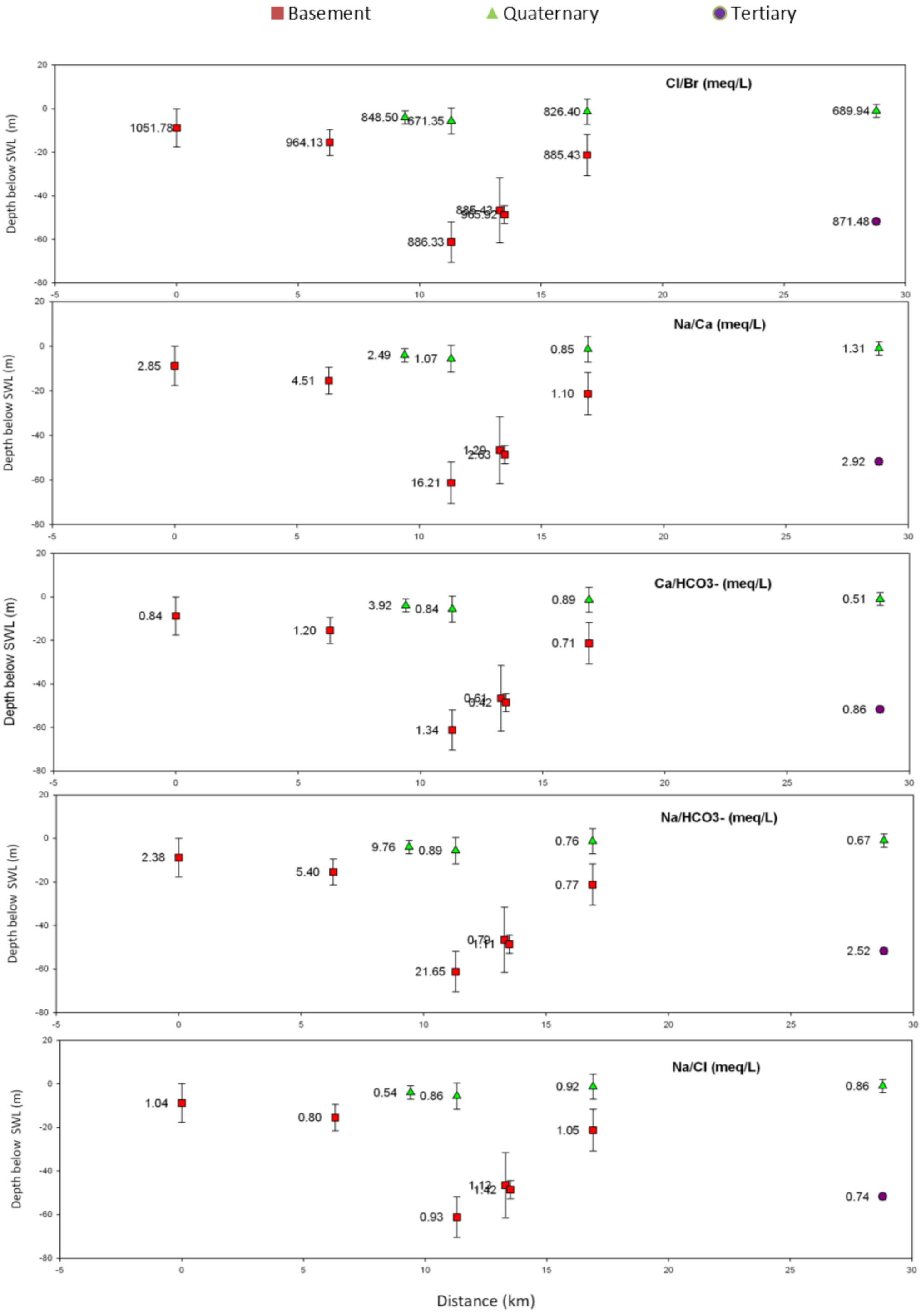


Figure 4.18 Groundwater major ion ratios in wells along Transect 2: Koppio Hills to Uley South

4.5 Recharge estimates

Long-term mean annual recharge rates have been estimated using the steady-state chloride mass balance (CMB) method and a one-dimensional (1-D) vertical flow model involving CFC-12 ages (Table 4.3). For the Lincoln–Koppio region the mean recharge rate determined using the CMB method was 16.8 mm/y for the basement aquifers (n=14), 15.8 mm/y for the Quaternary aquifers (n=15) and 7.8 mm/y for the Tertiary aquifers (n=3). Mean recharge rates using the CFC-12 method were consistently higher, with 23.5 mm/y for the basement aquifers (n=11), 35.5 mm/y for the Quaternary aquifers (n=5) and 41.9 mm/y for the Tertiary aquifers (n=3).

For the Whyalla–Kimba map sheet regions the mean recharge rate determined using the CMB method was 1.5 mm/y for the basement aquifers (n=12), 1.3 mm/y for the Quaternary aquifers (n=3) and 0.4 mm/y for the Tertiary aquifers (n=2). Mean recharge rates using the CFC-12 method were again consistently higher, with 15.3 mm/y for the basement aquifers (n=3), and 116.3 mm/y for the Tertiary aquifers (n=1) (NB no CFC-12 recharge estimates were obtained for the Quaternary aquifer in this region).

Both recharge estimation techniques have their own set of assumptions and limitations. Importantly, the rates determined by the CMB method apply to the location in the landscape where the groundwater sample first entered the saturated zone, some distance up-gradient of the well from which chloride was sampled. Recharge rates determined by the CFC-12 dating method apply at the well location. Therefore spatial variability in recharge may partly explain the discrepancy between different methods, notwithstanding that CFC-12 rates were consistently higher than CMB rates.

The region has undergone some land-use change since the mid-20th century and it is possible that the CFC data represent recharge rates in the modern era, while the CMB technique retains the memory of pre-European water balance due to the inertia of Cl in the groundwater system. That is, the more recent, putative higher recharge regime indicated by presence of CFC-12 due to change in the hydrological balance has yet to be manifested in the Cl in groundwater and will take centuries to reach a new steady-state with respect to salt input and output.

Given the regional reconnaissance nature of this study, it would be useful to compare the results on a site by site basis and consider the depth of the sampling points below the water table in assessing whether the recharge regime has changed in recent times. For the time being, due to the large uncertainty associated with estimating CFC-12 ages (i.e., assuming recharge temperature, elevation and piston flow) and assuming both 1-D vertical flow and constant values for aquifer porosity for each aquifer type, we propose the more conservative recharge rates determined using the CMB method are more reliable for future long-term water resource planning and management.

Table 4.3 Comparison of groundwater recharge estimates based on chloride mass balance (CMB) and CFC-12 ages

Unit number	Aquifer monitored	Chloride GW (mg/L)	Rainfall (mm/y)	Chloride rainfall (mg/L)	CMB recharge (mm/y)	CFC-12 recharge (mm/y)
602800049	Basement	210	543	10	26.6	21.0
602802071	Basement	1600	485	13	3.8	
602802074	Basement	6700	494	13	1.0	15.0
602802197	Basement	130	596	8	38.5	
602802724	Basement	1100	596	8	4.6	6.5
602802730	Basement	150	554	9.0	34.7	43.4
602802732	Basement	110	505	13.0	58.8	44.8
602802746	Basement	3500	561	9.0	1.4	55.1
602802747	Basement	110	574	9.0	47.0	41.7
602802749	Basement	770	532	11.0	7.5	13.1
602901390	Basement	1600	502	8.0	2.5	4.6
602901391	Basement	890	489	11.0	6.0	3.1
602901393	Basement	3000	489	11.0	1.8	10.1
602901394	Basement	2900	500	8.0	1.4	
613001023	Basement	18000	345	13.0	0.3	5.5
623000368	Basement	1200	377	9.0	2.7	
623000411	Basement	9200	352	12.0	0.5	
623000435	Basement	5500	396	9.0	0.6	
623000468	Basement	1600	367	12.0	2.8	
623000664	Basement	900	371	12.0	5.0	
623000717	Basement	5100	336	14.0	0.9	
623000844	Basement	4100	373	11.0	1.0	35.7
633100228	Basement	930	286	12.0	3.7	4.8
633100229	Basement	7000	309	12.3	0.5	
623100062	Basement	8750	324	7.8	0.3	
603000803	Basement	22000	380	4.9	0.1	
592800445	Quaternary	220	516	11.9	27.9	
592900196	Quaternary	300	587	8.5	16.6	14.0
602801750	Quaternary	150	536	11.9	42.5	22.6
602802744	Quaternary	140	561	8.5	34.0	96.3
602802745	Quaternary	110	574	9.0	47.0	9.2
602901023	Quaternary	12000	462	8.2	0.3	
592800083	Quaternary	820	516	11.9	7.5	
592800397	Quaternary	3000	516	11.9	2.0	
592900002	Quaternary	4200	441	9.1	1.0	
592900730	Quaternary	4300	438	9.6	1.0	
602801635	Quaternary	210	472	14.0	31.5	
602802112	Quaternary	220	381	4.6	8.0	
602802118	Quaternary	3200	522	11.2	1.8	
602901298	Quaternary	13000	480	8.0	0.3	
623000687	Quaternary	24000	306	17.9	0.2	
623000441	Quaternary/Bsmnt	20000	352	13.8	0.2	
602801595	Quaternary	370	543	10.3	15.1	
603000056	Quaternary	980	411	8.3	3.5	
592900580	Tertiary	430	587	8.5	11.6	20.3
602800745	Tertiary	580	529	11.0	10.0	86.2
602801725	Tertiary	3300	522	10.5	1.7	19.2
613001053	Tertiary	15000	344	11.1	0.3	
633100224	Tertiary	7200	258	16.2	0.6	116.3

5 Summary and conclusions

Forty-nine groundwater samples were collected from existing water wells in the non-prescribed areas of the EP NRM Region between February and April 2013. The sampling program followed an extensive desktop and field-based audit of suitable wells for sampling. In addition to taking field measurements of groundwater physical and chemical characteristics, samples were collected for a number of environmental tracers including major ion chemistry, naturally occurring isotopes and anthropogenic trace gases.

Groundwater chemical composition in the southern Lincoln–Koppio region ranges from Na-Ca-HCO_3 to Na-Cl type, indicating the dominant controls are likely acquisition of marine aerosols via rainfall with subsequent evapo-concentration, and weathering of marine (limestone) and pedogenic (calcrete) carbonate minerals. Further north, in the Whyalla–Kimba region, all groundwater sampled has a Na-Cl type suggesting they are further along the evolutionary path.

Groundwater ages have been estimated using carbon-14 and CFC-12 dating methods, which generally produced consistent results. CFC-12 ages range from about 1 to 60 years in the wells that were tested. Uncorrected carbon-14 ages range from modern to less than 15 000 years; however, after correcting these ages for addition of dead carbon using the 'Pearson' model, most of the groundwater was determined to be modern, that is, recharged within the last 50 years. Trends in CFC-12 age and carbon-14 activity and age support a conceptual model in which the shallow Quaternary aquifers are characterised by relatively young, recently recharged groundwater. Groundwater age generally increases with distance along a flow line and with increasing depth in the aquifer.

Stable H/O isotope compositions of groundwater indicate that recharge to all aquifer types only occurs after significant rainfall events, for example, when at least 41 to 60 mm occurs in a month. Recharge rates were estimated using two methods: a steady state chloride mass balance (CMB) and a 1-D vertical CFC-12 age model. The CMB method was selected as being more reliable due to the number of untestable assumptions required for the CFC-12 method. The CMB method yielded average recharge estimates for the Lincoln–Koppio area of 16.8 mm/y for the basement aquifers, 15.8 mm/y for the Quaternary aquifers and 7.8 mm/y for the Tertiary aquifers; and rates for the Whyalla–Kimba area of 1.5 mm/y for the basement aquifers, 1.3 mm/y for the Quaternary aquifers, and 0.4 mm/y for the Tertiary aquifers.

Analysis of several tracers including major ion ratios, strontium isotopes and the groundwater age tracers, revealed important insight to the potential for inter-aquifer connection via leakage along a transect from Koppio Hills to the Uley South lens. The tracer data indicated limited connectivity between basement and Quaternary aquifers along most of the transect, but consistent support for connectivity was provided by all tracers near one well pair in the centre of the transect. The construction integrity of this well pair needs to be examined.

This reconnaissance-style project provides region-wide baseline hydrogeochemistry data and hydrogeological knowledge. The work expands significantly on local-scale groundwater investigations previously undertaken in prescribed areas of the EP. However, process knowledge is still at a relatively high level for aspects including water–rock interactions, groundwater recharge and inter-aquifer leakage.

Further work is required in parts of the region where future water demands are likely to place stress on the groundwater resources and where high quality well completion details are available. This report provides some guidance for the tracers that can be most beneficial to such assessments, as well as the types of processes that may be occurring.

6 Appendices

A. Maps

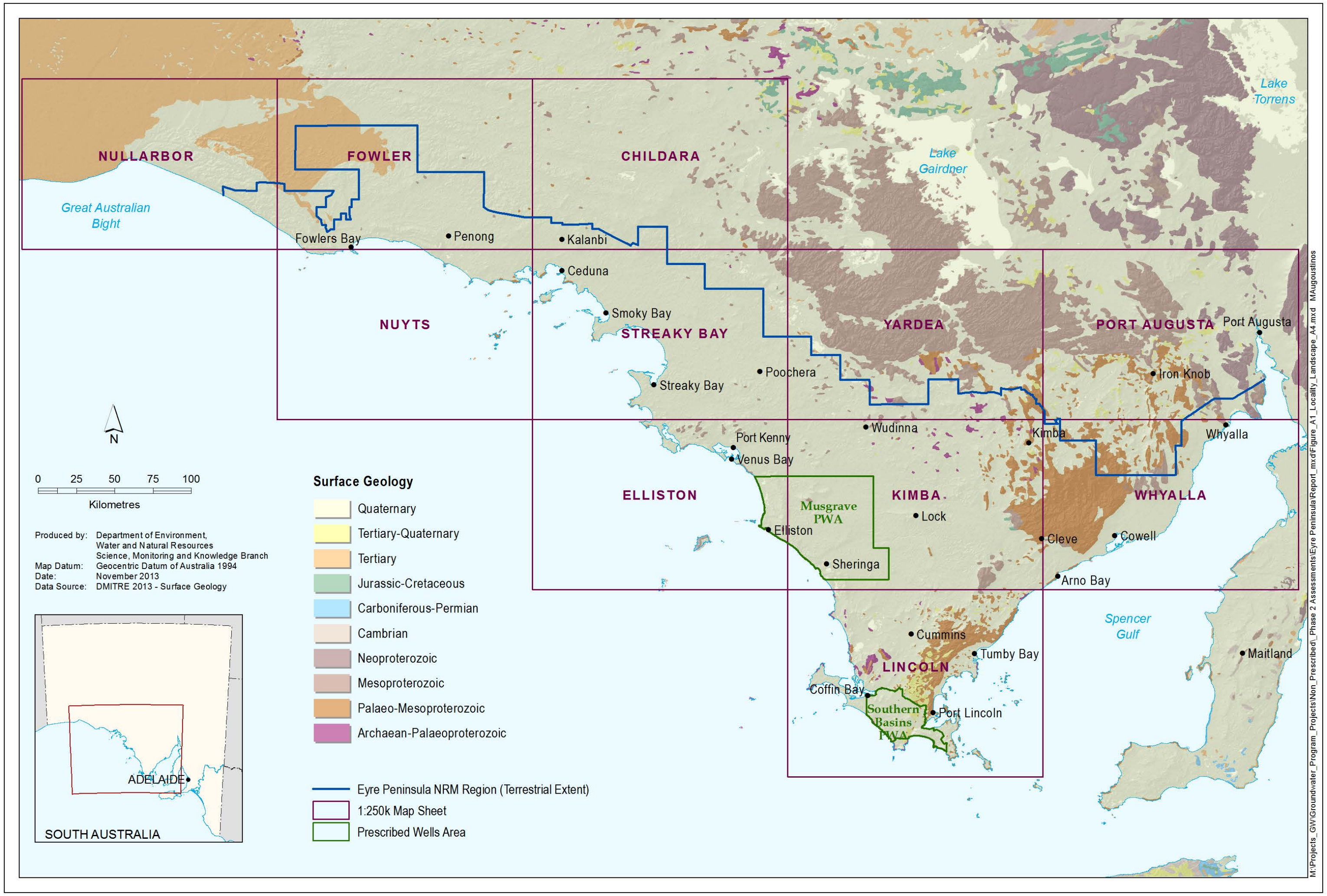


Figure A1. **Location of the EP NRM Region and Prescribed Wells Areas, with surface geology (age) as background**

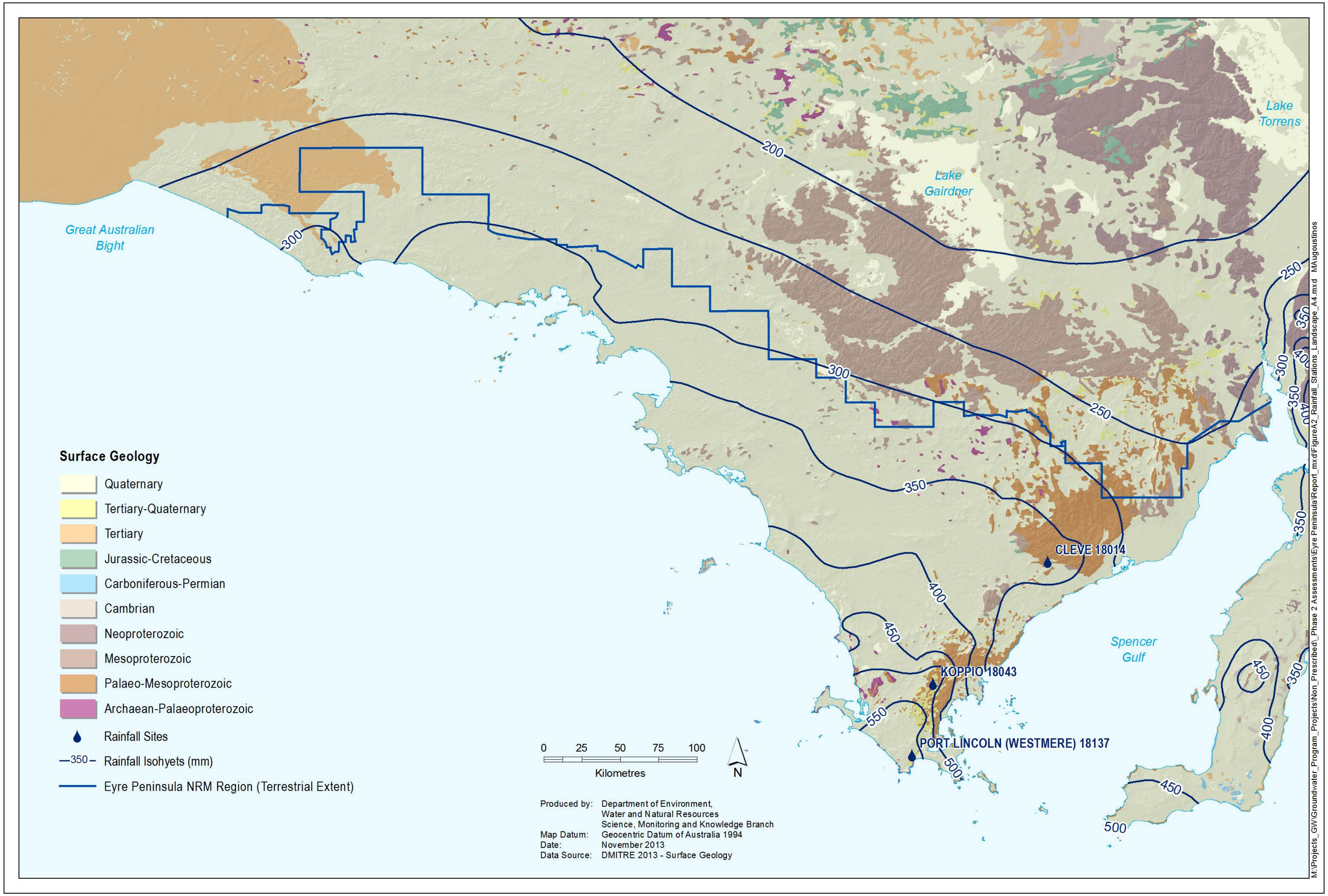


Figure A2. Location of Westmere, Koppio and Cleve rainfall stations and annual rainfall isohyets, with surface geology (age) as background

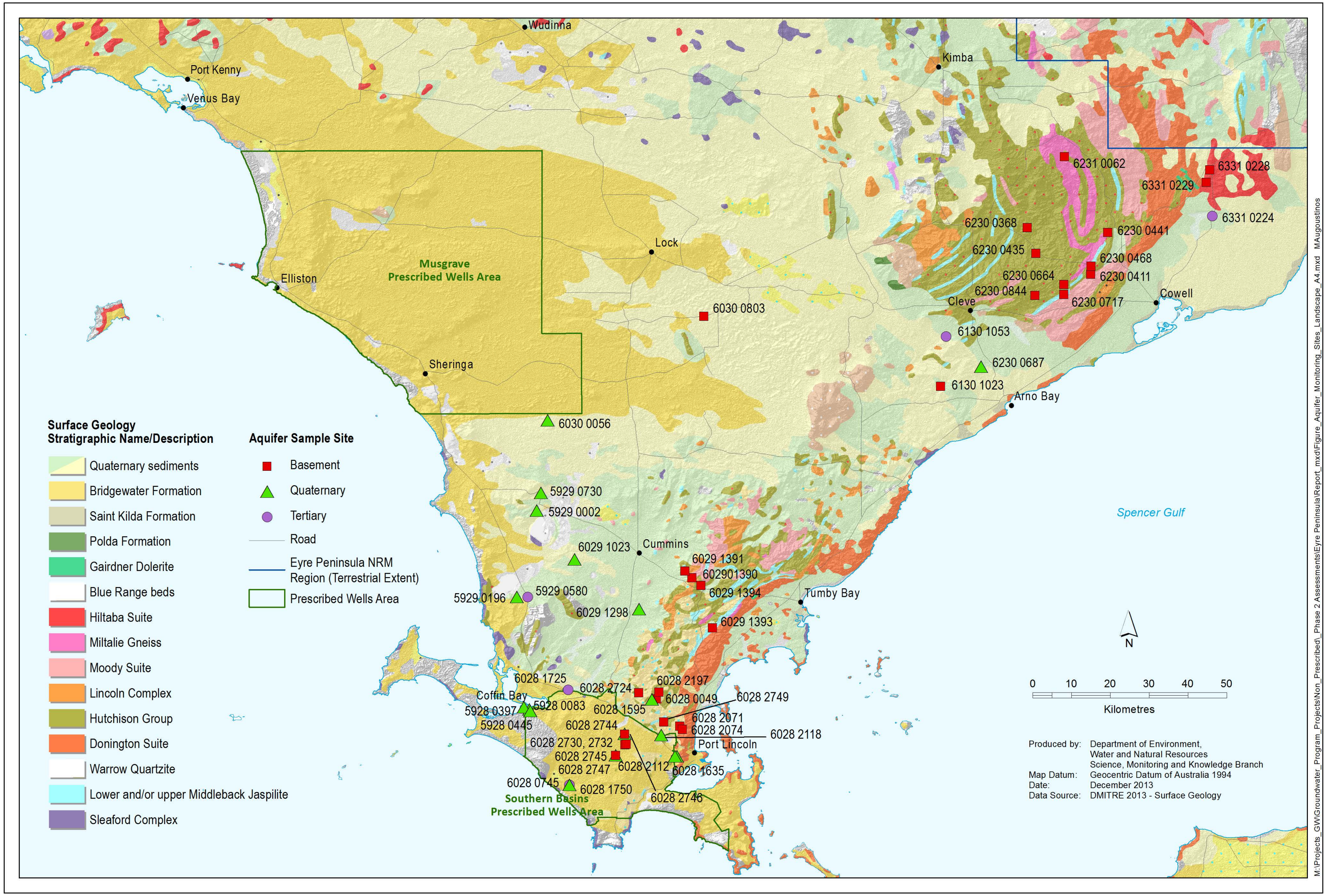


Figure A3. **Location of sampled groundwater wells symbolised by aquifer type, with surface geology (stratigraphy) as background**

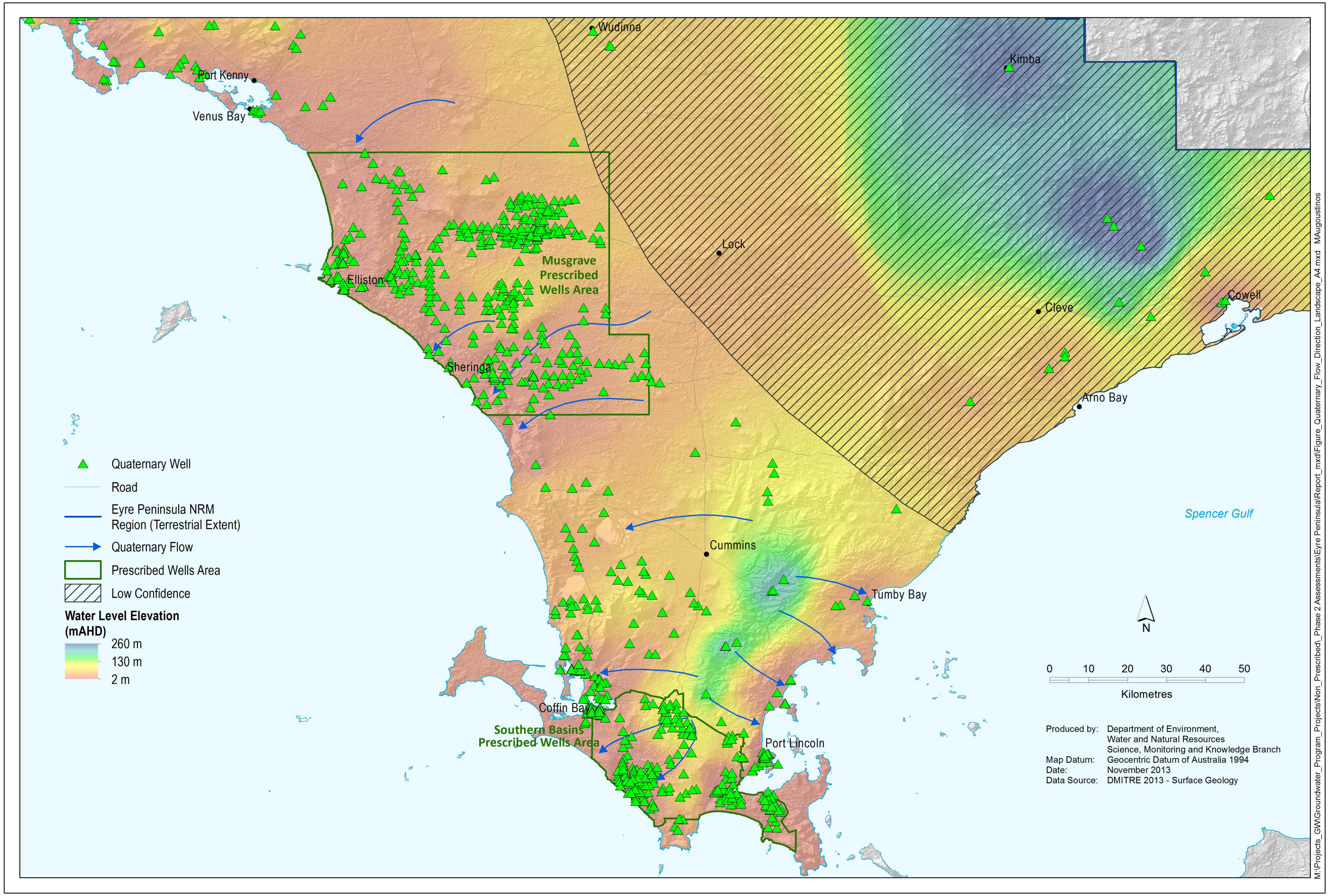


Figure A4. **Interpolated potentiometric (water level) surface for the Quaternary aquifers**

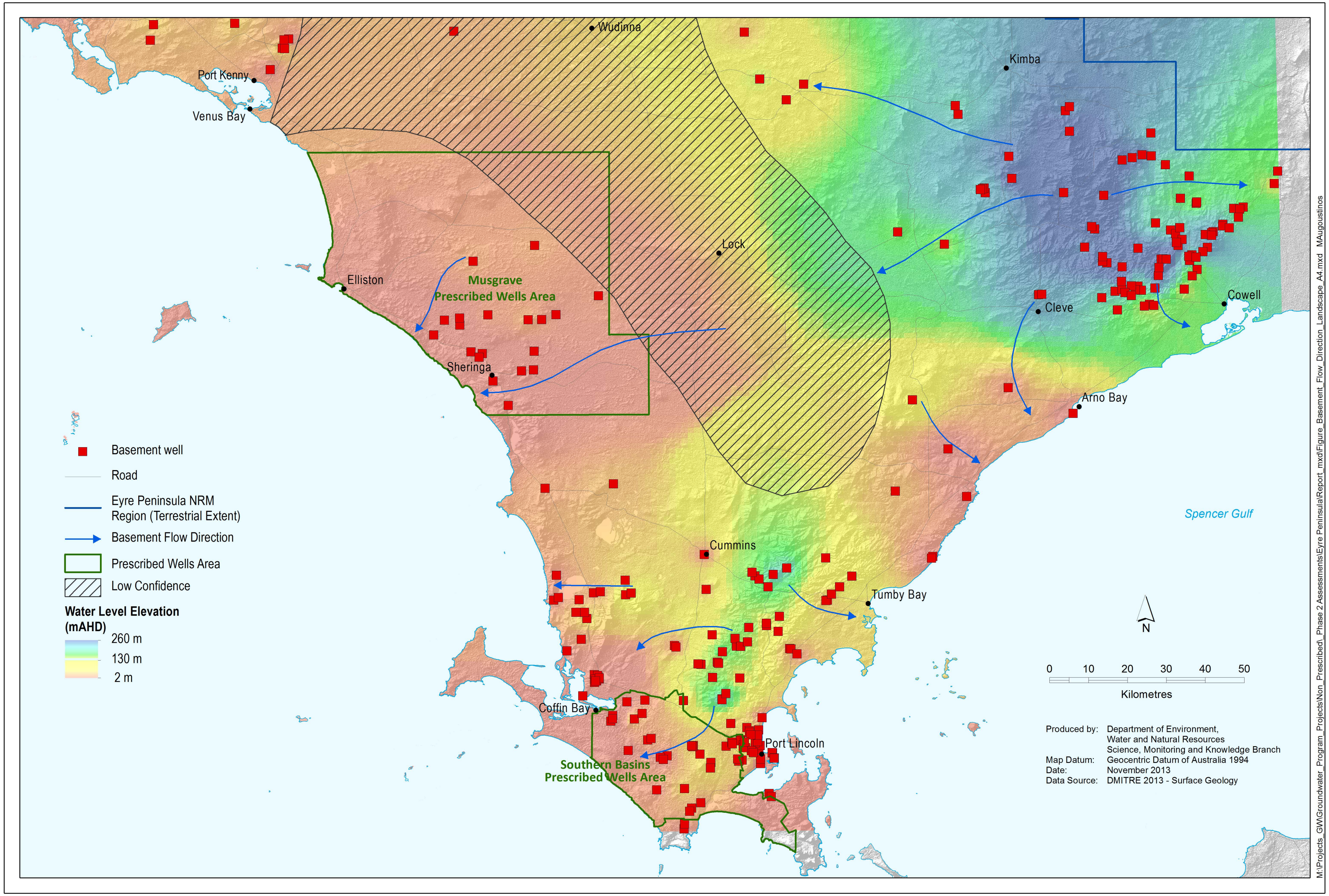


Figure A5. Interpolated potentiometric (water level) surface for the basement fractured rock aquifers

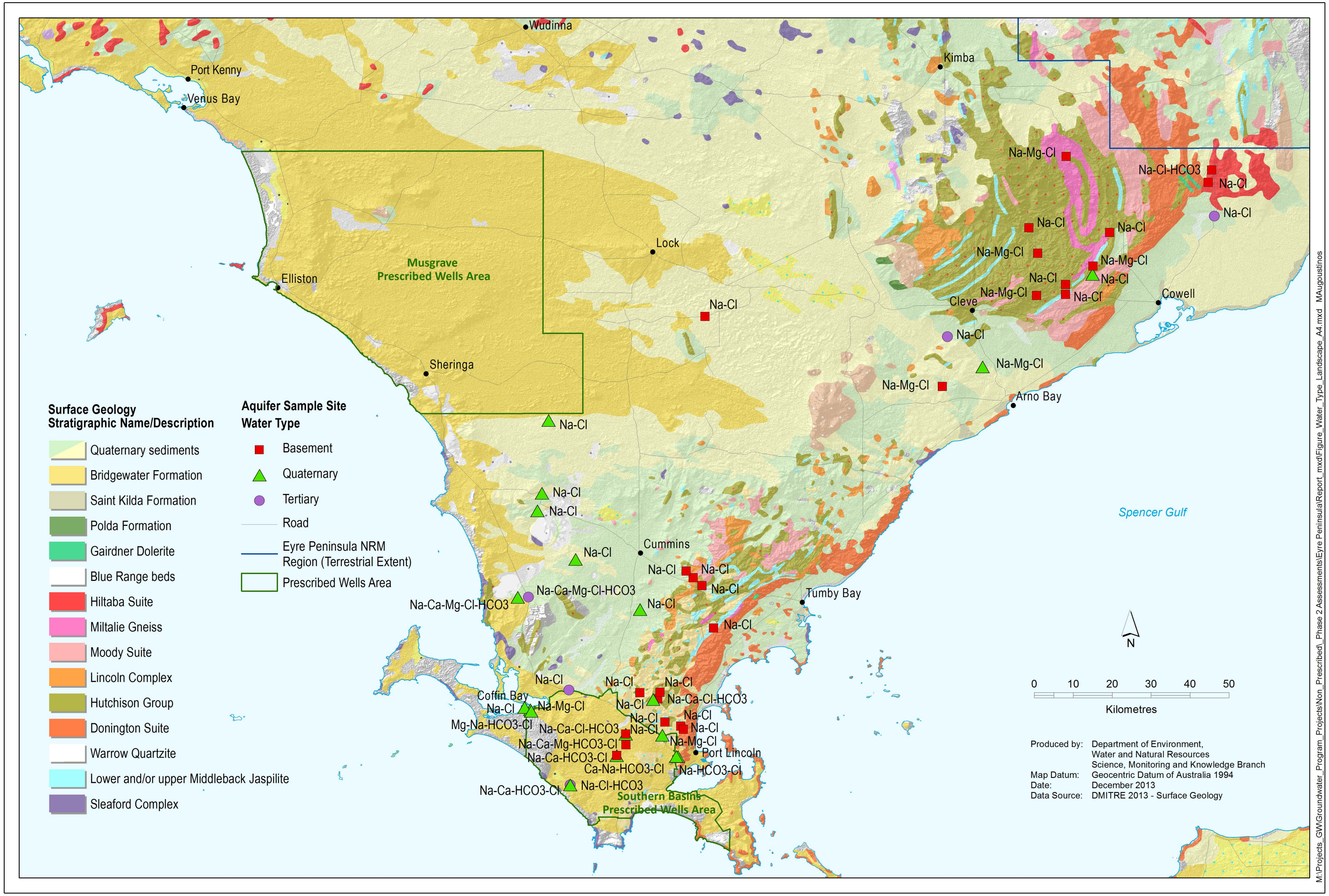


Figure A6. Dominant water type at sampled groundwater wells, with surface geology (stratigraphy) as background

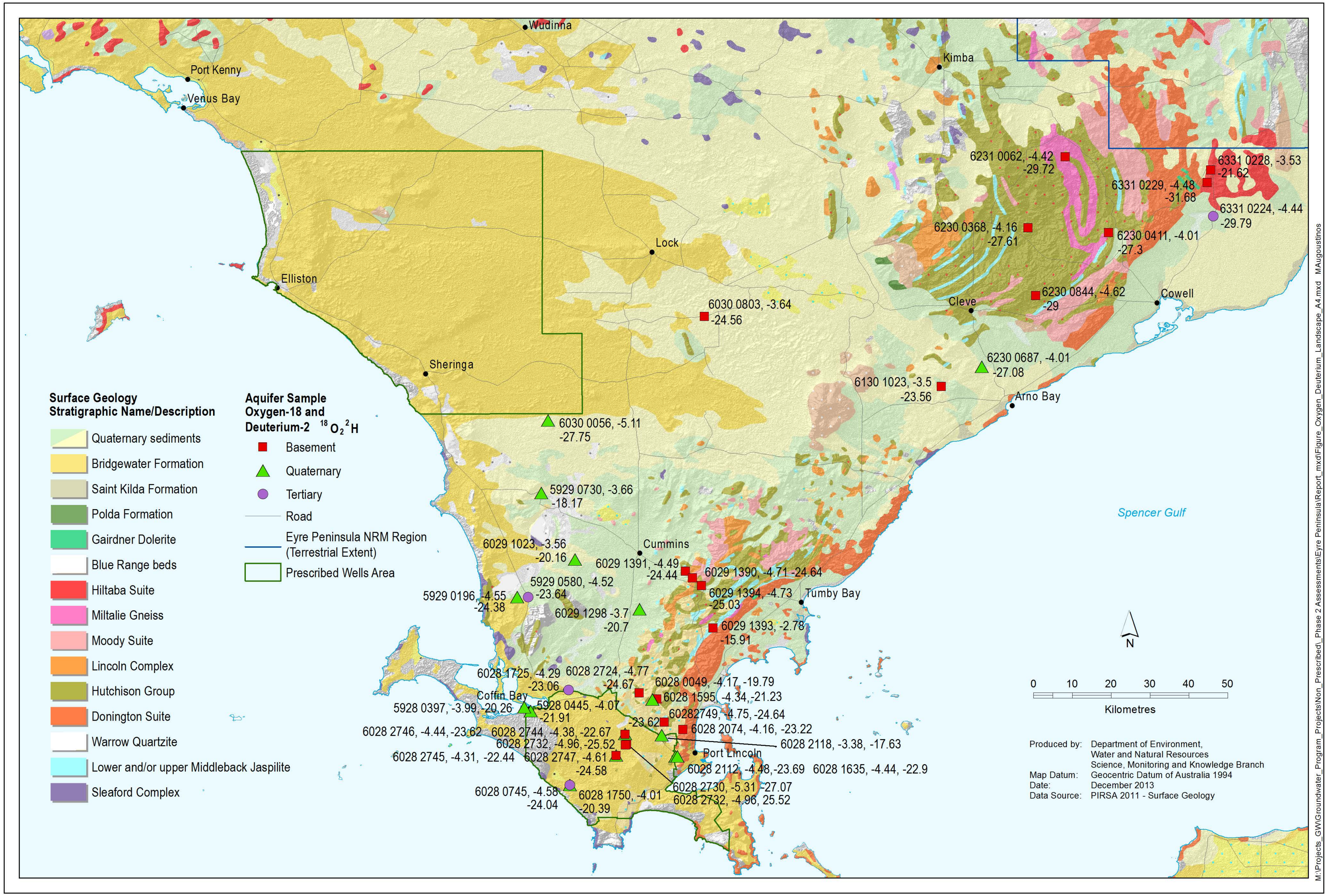


Figure A7. Groundwater stable H/O isotope composition, with surface geology (stratigraphy) as background

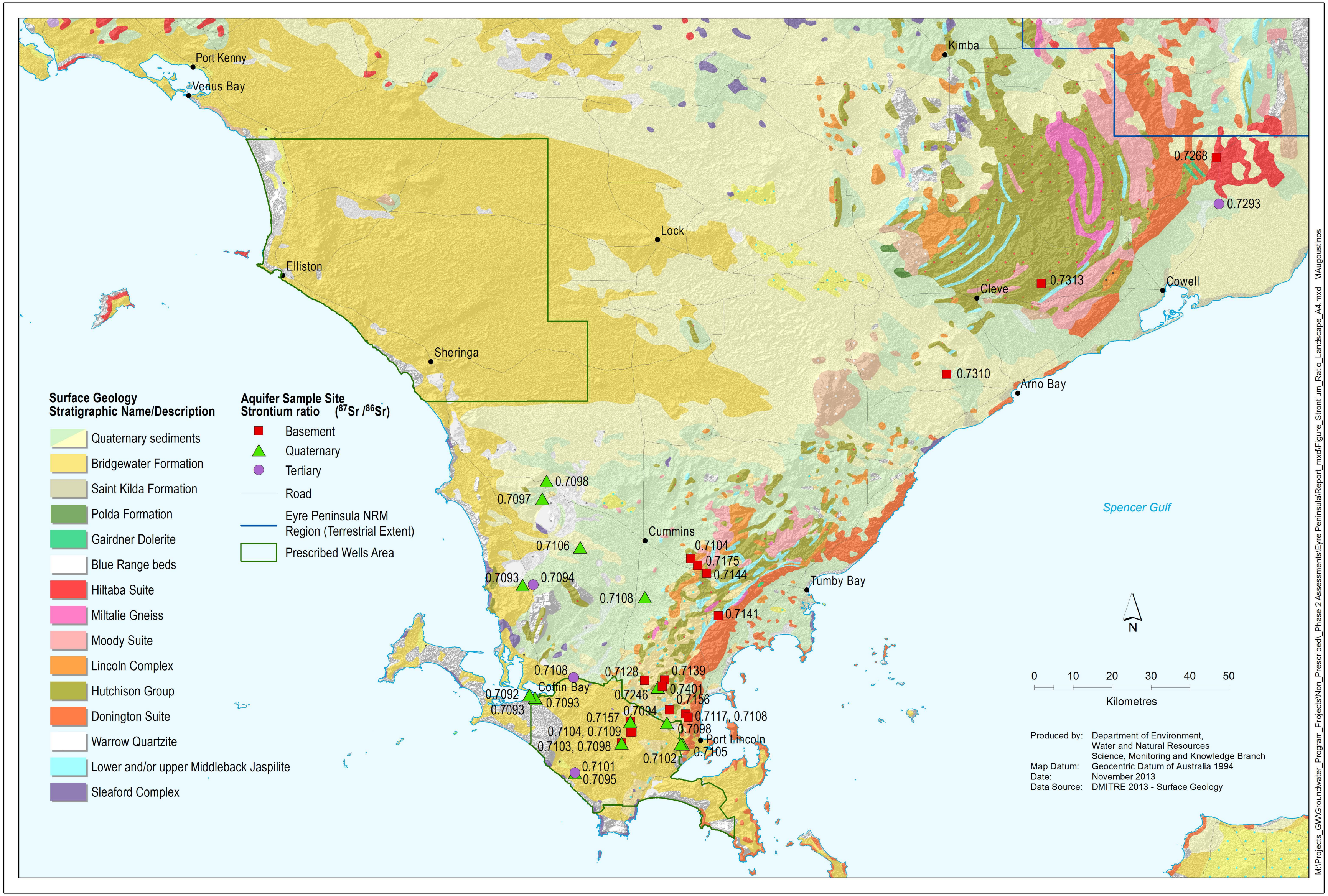


Figure A8. **Groundwater strontium isotope ratio, with surface geology (stratigraphy) as background**

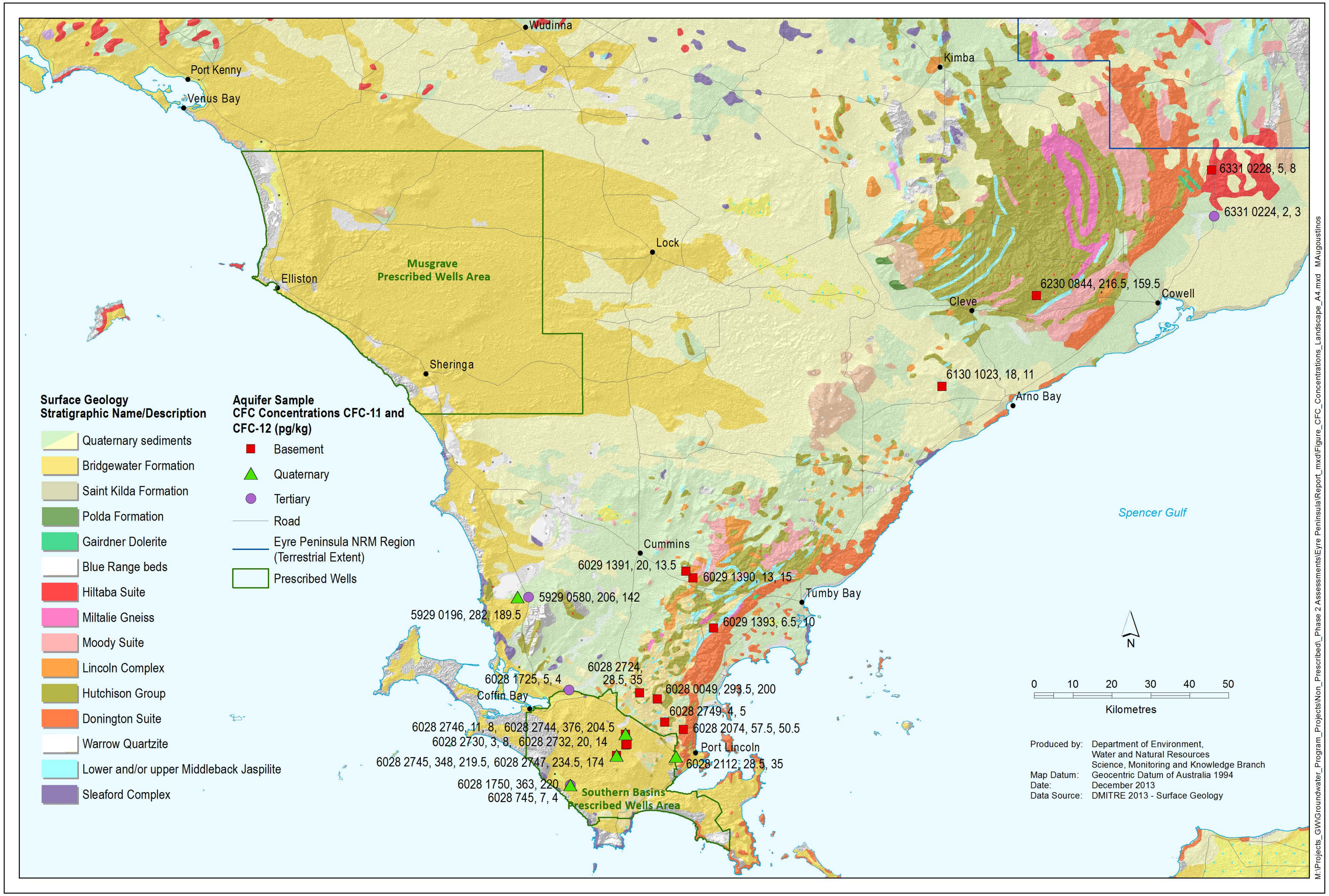
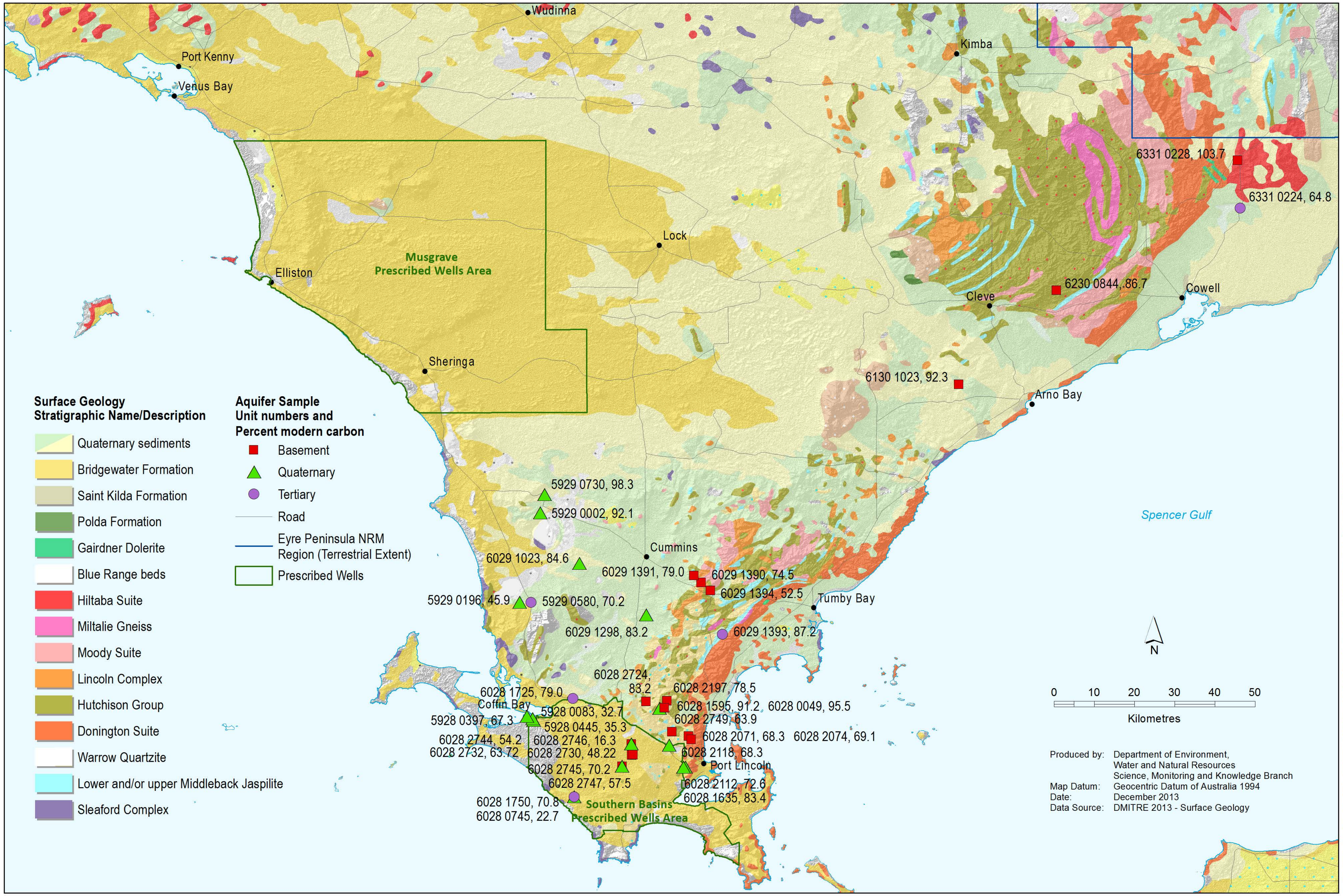


Figure A9. Groundwater CFC-11 and CFC-12 concentration, with surface geology (stratigraphy) as background



Produced by: Department of Environment, Water and Natural Resources Science, Monitoring and Knowledge Branch
Map Datum: Geocentric Datum of Australia 1994
Date: December 2013
Data Source: DMITRE 2013 - Surface Geology

M:\Projects_GW\Groundwater_Program_Projects\Non_Prescribed_Phase 2 Assessments\Eyre Peninsula\Report_mxd\Figure_Carbon_Landscape_A4.mxd MAugoustinos

Figure A10. Groundwater carbon-14 activity, with surface geology (stratigraphy) as background

Figure A11. Location of Transect 1 (Koppio Hills to Port Lincoln) and Transect 2: Koppio Hills to Uley South, with surface geology (stratigraphy) as background

B. Anions, Cations and Metals

	FIELD				LAB																												Charge
	E.C.	pH	T	HCO_3^-	F^-	Cl^-	Br^-	NO_3^-	$SO_4^=$	Ca^{2+}	K^+	Mg^{2+}	Na^+	S	Al	As	B	Cd	Co	Cr	Cu	Fe	Mn	Mo	Ni	P	Pb	Sb	Se	Si	Sr	Zn	Balance
Sample ID	µS/m		°C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	Error
592800083	2789	7.95	N/A	292	0.8	820	2.3	25	120	55.2	17.3	81.5	452	31.1	<0.1	<0.05	0.369	<0.05	<0.05	<0.05	<0.05	<0.1	<0.1	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	4.08	4.13	0.168	-1%
592800397	7089	7.47	18.5	428	0.5	3000	9.2	1.3	280	190	34	213	1450	71.6	<0.5	<0.25	<1	<0.25	<0.25	<0.25	<0.25	<0.5	<0.5	<0.25	<0.25	<2.5	<0.5	<0.5	<0.25	<2.5	4.28	<0.25	-3%
592800445	1184	7.44	20.9	518	1.0	220	0.5	6.3	54	49	4.44	68.5	123	14.3	<0.1	<0.05	<0.2	<0.05	<0.05	<0.05	<0.05	0.11	<0.1	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	3.8	4.63	0.226	-8%
592900002	13554	8.36	N/A	1268	<1	4200	13	39	820	77.3	74.1	183	2830	223	<0.5	<0.25	5.14	<0.25	<0.25	<0.25	<0.25	<0.5	<0.5	<0.25	<0.25	<2.5	<0.5	<0.5	<0.25	28	1.67	0.52	-4%
592900196	1355	6.51	19.8	272	<1	300	<1	21 (?)	4.0	64.6	5.03	36.1	183	11.8	<0.1	<0.05	<0.2	<0.05	<0.05	<0.05	<0.05	<0.1	<0.1	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	16.3	3.12	<0.05	5%
592900580	1881	7.36	19.9	273	0.3	430	1.2	28	46	91.3	5.39	45.1	216	13	<0.1	<0.05	<0.2	<0.05	<0.05	<0.05	<0.05	<0.1	<0.1	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	12.2	4.26	0.18	1%
602800049	939	6.88	17.4	159	0.2	210	0.5	74	50	43.5	9.39	18.3	142	12.7	<0.1	<0.05	<0.2	<0.05	<0.05	<0.05	<0.05	<0.1	<0.1	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	11.1	0.221	0.193	3%
602800745	2014	7.14	20.5	292	<0.2	580	1.5	0.5	62	82.7	7.02	44.5	277	16	<0.1	<0.05	<0.2	<0.05	<0.05	<0.05	<0.05	0.688	0.172	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	7.34	1.54	0.224	-6%
602801635	1321	6.22	19.1	420	0.3	210	0.6	50	49	54.3	5.98	27.9	201	13.4	<0.1	<0.05	0.244	<0.05	<0.05	<0.05	<0.05	0.248	<0.1	<0.05	0.054	<0.5	<0.1	<0.1	<0.05	23.7	1.21	0.425	0%
602801725	9346	6.57	19.0	351	<0.5	3300	8.7	<0.5	360	335	20.8	203	1690	107	<0.5	<0.25	<1	<0.25	<0.25	<0.25	<0.25	0.585	<0.5	<0.25	<0.25	<2.5	<0.5	<0.5	<0.25	5.87	3.07	0.269	1%
602801750	792	7.36	20.3	330.62	0.17	150	0.49	23	29	55.3	2.24	14.3	83.2	7.49	<0.1	<0.05	<0.2	<0.05	<0.05	<0.05	<0.05	<0.1	<0.1	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	4.82	0.981	<0.05	-15%
602802071	5036	7.25	19.8	301	0.6	1600	3.9	2.2	170	75.4	6.78	83.7	1030	49.5	<0.5	<0.25	<1	<0.25	<0.25	<0.25	<0.25	<0.5	<0.5	<0.25	<0.25	<2.5	<0.5	<0.5	<0.25	9.93	0.798	<0.25	2%
602802074	17500	6.47	23.6	253	<2	6700	18	6.5	710	598	35.6	491	2750	191	<0.5	<0.25	<1	<0.25	<0.25	<0.25	<0.25	0.24	<0.5	<0.25	<0.25	<2.5	<0.5	<0.5	<0.25	19.2	6.21	0.594	-4%
602802112	1277	6.19	18.6	379	0.7	220	0.7	32	45	44.7	6.97	28.5	196	12	<0.1	<0.05	0.214	<0.05	<0.05	<0.05	<0.05	<0.1	<0.1	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	18.6	1.1	0.172	0%
602802118	9041	7.17	20.0	307	<0.5	3200	8.5	4.5	230	396	18.8	345	1130	64.3	<0.5	<0.25	<1	<0.25	<0.25	<0.25	<0.25	0.985	<0.5	<0.25	<0.25	<2.5	<0.5	<0.5	<0.25	13.5	6.42	<0.25	-1%
602802197	508	6.45	18.8	43	0.021	130	0.31	1.2	21	5.76	3.08	5.15	84.1	5.49	<0.1	<0.05	<0.2	<0.05	<0.05	<0.05	<0.05	<0.1	<0.1	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	11.9	0.0539	0.13	-4%
602802724	3839	6.09	19.9	171	<0.2	1100	3.5	8.8	170	95.5	7.93	85.6	566	47.3	<0.1	<0.05	0.212	<0.05	<0.05	<0.05	<0.05	0.183	<0.1	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	27.8	0.674	0.328	-1%
602802730	1055	6.42	19.6	329	0.13	150	0.35	0.53	27	45.8	5.06	26.2	138	7.47	<0.1	<0.05	<0.2	<0.05	<0.05	<0.05	<0.05	0.127	<0.1	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	20.4	0.808	0.175	2%
602802732	772	5.78	19.6	271	0.07	110	0.28	16	20	54.7	5.04	22	80.8	5.56	<0.1	<0.05	<0.2	<0.05	<0.05	<0.05	<0.05	0.104	<0.1	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	17.7	0.833	0.202	1%
602802744	778	5.80	19.2	233	0.14	140	0.47	16	21	64	2.59	13.7	78.2	5.64	<0.1	<0.05	<0.2	<0.05	<0.05	<0.05	<0.05	<0.1	<0.1	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	5.12	1.07	0.141	-3%
602802745	711	6.07	19.4	229	0.10	110	0.3	18	18	67.3	2.12	13.2	65.9	5.04	<0.1	<0.05	<0.2	<0.05	<0.05	<0.05	<0.05	<0.1	<0.1	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	6.64	0.743	0.195	1%
602802746	10633	7.50	20.5	260	<0.5	3500	8.9	<0.5	360	114	33.1	170	2120	106	<0.5	<0.25	<1	<0.25	<0.25	<0.25	<0.25	3.63	0.655	<0.25	<0.25	<2.5	<0.5	<0.5	<0.25	16.2	1.19	0.264	1%
602802747	744	5.93	20.0	256	0.11	110	0.28	10	32	59.4	2.94	17.9	74.7	9.01	<0.1	<0.05	<0.2	<0.05	<0.05	<0.05	<0.05	0.121	<0.1	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	9.81	0.713	0.243	-1%
602900379	12570	7.11	21.0	N/A	<1	4300	13	13	640	332	57.6	220	2230	166	<0.5	<0.25	3.17	<0.25	<0.25	<0.25	<0.25	<0.5	<0.5	<0.25	<0.25	<2.5	<0.5	<0.5	<0.25	21.1	2.79	<0.25	-1%
602901023	33704	3.06	23.6	373	<2	12000	31	8.9	1900	99.6	179	598	6670	563	40.8	<0.5	4.45	<0.5	<0.5	<0.5	<0.5	<1	<1	<0.5	<0.5	<5	<1	<1	<0.5	27.4	5.55	<0.5	-5%
602901298	34077	3.04	20.9	589	0.3	13000	43	2.9	2300	170	162	765	7200	691	51.8	<0.5	4.26	<0.5	<0.5	<0.5	<0.5	56.7	<1	<0.5	<0.5	<5	<1	<1	<0.5	45.5	9.38	0.564	-4%
602901390	5805	6.50	21.2	301	0.2	1600	4.4	22	280	77.7	11.6	92.2	969	73.3	<0.5	<0.25	<1	<0.25	<0.25	<0.25	<0.25	<0.5	<0.5	<0.25	<0.25	<2.5	<0.5	<0.5	<0.25	14.3	0.821	0.406	-2%
602901391	3386	6.48	19.9	151	0.2	890	2.6	9.8	140	53.6	12.3	39.6	533	39.8	<0.1	<0.05	0.764	<0.05	<0.05	<0.05	<0.05	0.138	<0.1	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	24.8	0.664	0.151	-2%
602901393	10477	6.91	19.8	545	<1	3000	8.8	1.6	530	186	19.6	233	1790	154	<0.5	<0.25	<1	<0.25	<0.25	<0.25	<0.25	<0.5	<0.5	<0.25	<0.25	<2.5	<0.5	<0.5	<0.25	21.5	1.8	0.339	1%
602901394	8897	6.66	19.0	203	1.1	2900	9.2	<0.5	400	104	16.3	165	1670	111	<0.5	<0.25	1.03	<0.25	<0.25	<0.25	<0.25	<0.5	<0.5	<0.25	<0.25	<2.5	<0.5	<0.5	<0.25	10.5	1.31	0.433	-1%
603000056	3957	6.82	21.1	N/A	0.5	980	2.8	1.0	140	61.5	34.1	75.9	681	41.2	<0.1	<0.05	1.32	<0.05	<0.05	<0.05	0.0599	0.119	<0.1	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	19.4	1.77	0.256	13%
603000228	57061	6.54	22.2	165	<5	22000	65	8.3	4300	495	253	1530	12800	1300	<2.5	<1.25	6.21	<1.25	<1.25	<1.25	<1.25	27.1	<2.5	<1.25	<1.25	<12.5	<2.5	<2.5	<1.25	15.3	7.92	<1.25	0%
613001023	44528	6.22	21.1	684	<5	18000	53	7.9	2600	292	163	1560	9750	752	<2.5	<1.25	<5	<1.25	<1.25	<1.25	<1.25	<2.5	<2.5	<1.25	<1.25	<12.5	<2.5	<2.5	<1.25	25.2	2.52	<1.25	0%
613001053	39017	3.25	24.8	1800	3.4	15000	45	<2	2300	71.8	112	881	8390	669	242	<1.25	<5	<1.25	<1.25	<1.25	<1.25	12.8	<2.5	<1.25	<1.25	<12.5	<2.5	<2.5	<1.25	41.7	2.83	3.61	-6%
623000368	4840	7.03	21.7	367	1.5	1200	4.6	2.4	300	11.4	25.6	36.7	920	98.5	<0.1	<0.05	1.93	<0.05	<0.05	<0.05	<0.05	42.2	0.645	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	4.56	0.184	0.135	-2%
623000411	28356	7.16	22.6	1000	<2	9200	25	<2	1400	51.9	106	498	5480	398	<2.5	<1.25	<5	<1.25	<1.25	<1.25	<1.25	412	10.3	<1.25	<1.25	<12.5	<2.5	<2.5	<1.25	<12.5	1.74	73.4	-3%
623000435	16637	6.30	19.5	705	1.5	5500	17	1.0	860	216	136	531	3030	271	<0.5	<0.25	2.09	<0.25	<0.25	<0.25	<0.25	1.24	<0.5	<0.25	<0.25	<2.5	<0.5	<0.5	<0.25	11.5	3.08	0.254	1%
623000441	55241	4.21	20.2	N/A	<2	20000	66	<2	3500	119	153	1310	11400	1020	95.3	<1.25	13.8	<1.25	<1.25	<1.25	<1.25	<2.5	<2.5	<1.25	<1.25	<12.5	<2.5	<2.5	<1.25	36.6	7.45	<1.25	-2%
623000468	5458	5.50	19.6	727	<0.5	1600	4.8	1.5	250	88.1	17.6	174	1010	71.5	<0.5	<0.25	<1	<0.25	<0.25	<0.25	<0.25	<0.5	<0.5	<0.25	<0.25	<2.5	<0.5	<0.5	<0.25	21.7	0.603	<0.25	1%
623000687	54746	7.35	21.9	94	<5	24000	73	<5	3500	188	235	2010	12900	1010	<2.5	<1.25	8.36	<1.25	<1.25	<1.25	<1.25	<2.5	<2.5	<1.25	<1.25	<12.5	<2.5	<2.5	<1.25	21.9	4.28	<1.25	-1%
623000717	15688	7.22	18.8	784	1.1	5100	17	2.7	1000	135	66.7	323	3290	322	<0.5	<0.25	3.66	<0.25	<0.25	<0.25	<0.25	<0.5	<0.5	<0.25	<0.25	<2.5	<0.5	<0.5	<0.5	25.8	1.45	<0.5	0%
623000844	12852	6.72	20.5	891	1.7	4100	13	12	690	179	69.8	392	2460	214	<0.5	<0.25	2.01	<0.25	<0.25	<0.25	<0.25	<0.5	<0.5	<0.25	<0.25	<2.5	<0.5	<0.5	<0.5	11.7	1.84	<0.5	2%
623100062	24	6.36	21.4	414	<2	9000	21	4	1100	806	87.2	1060	3610	324	<1	<0.5	<2	<0.5	<0.5	<0.5	<0.5	2.33	<1	<0.5	<0.5	<5	<1	<1	<0.5	21.2	8.97	<0.5	1%
633100224	20504	9.81	24.9	171	<2	7200	19	3.8	330	252	88.7	481	3600	87.8	<1	<0.5	<2	<0.5	<0.5	<0.5	<0.5	2.51	<1	<0.5	<0.5	<5	<1	<1	<0.5	<5	3.79	<0.5	0%
633100228	7279	6.44	21.8	820	4.7	930	3.8	240	300	96.8	21.2	91.2	785	85.5	<0.5	<0.25	<1	<0.25	<0.25	<0.25	<0.25	<0.5	<0.5	<0.25	<0.25	<2.5	<0.5	<0.5	<0.25	22.8	1.2	<0.25	1%
633100229	22717	7.12	23.0	533	<2	7000	18	<2	950	311	85	460	3910	270	<1	<0.5	3.63	<0.5	<0.5	<0.5	<0.5	2.11	<1	<0.5	<0.5	<5	<1	<1	<0.5	17.2	4.24	<0.5	0%
602802749	2603	6.60	N/A	196	<0.2	770	1.8	0.7	73	77.3	6.37	56.4	400	19.1	<1	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<1	<0.5	<0.5	<5	<1	<1	<0.5	22.7	0.614	<0.5	-1%
602801595	1560	6.76	20.6	121	0.81	370	1.0	45	70	21.2	8.01	22.8	268	20.4	<0.1	<0.05	<0.2	<0.05	<0.05	<0.05	<0.05	<0.1	<0.1	<0.05	<0.05	<0.5	<0.1	<0.1	<0.05	19.5	0.22	0.219	3%
623000664	3665	6.83	20.8	N/A	1.9	900	2.9	5.2	200	60.9	24.9	77.3	674	56.8	<1	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<1	<0.5	<0.5	<5	<1	<1	<0.5	22.2	<0.5	<0.5	14%

C. Hydrochemical types

Unit number	Area/Region	Aquifer monitored	Dominant water type
592800083	Lincoln	Quaternary	Na-Mg-Cl
592800397	Lincoln	Quaternary	Na-Cl
592800445	Lincoln	Quaternary	Mg-Na-HCO_3-Cl
592900002	Koppio	Quaternary	Na-Cl
592900196	Koppio	Quaternary	Na-Ca-Mg-Cl-HCO_3
592900580	Koppio	Tertiary	Na-Ca-Mg-Cl-HCO_3
592900730	Koppio	Quaternary	Na-Cl
602800049	Lincoln	Basement	Na-Ca-Cl-HCO_3
602800745	Lincoln	Tertiary	Na-Cl-HCO_3
602801595	Lincoln	Quaternary	Na-Cl
602801635	Lincoln	Quaternary	Na-HCO_3-Cl
602801725	Lincoln	Tertiary	Na-Cl
602801750	Lincoln	Quaternary	Na-Ca-HCO_3-Cl
602802071	Lincoln	Basement	Na-Cl
602802074	Lincoln	Basement	Na-Cl
602802112	Lincoln	Quaternary	Na-HCO_3-Cl
602802118	Lincoln	Quaternary	Na-Mg-Cl
602802197	Lincoln	Basement	Na-Cl
602802724	Lincoln	Basement	Na-Cl
602802730	Lincoln	Basement	Na-Ca-Mg-HCO_3-Cl
602802732	Lincoln	Basement	Na-Ca-Mg-HCO_3-Cl
602802744	Lincoln	Quaternary	Na-Ca-Cl-HCO_3
602802745	Lincoln	Quaternary	Ca-Na-HCO_3-Cl
602802746	Lincoln	Basement	Na-Cl
602802747	Lincoln	Basement	Na-Ca-HCO_3-Cl
602802749	Lincoln	Basement	Na-Cl
602901023	Koppio	Quaternary	Na-Cl
602901298	Koppio	Quaternary	Na-Cl
602901390	Koppio	Basement	Na-Cl
602901391	Koppio	Basement	Na-Cl
602901393	Koppio	Basement	Na-Cl
602901394	Koppio	Basement	Na-Cl
603000056	Whyalla/Kimba	Quaternary	Na-Cl
603000803	Whyalla/Kimba	Basement	Na-Cl
613001023	Whyalla/Kimba	Basement	Na-Mg-Cl
613001053	Whyalla/Kimba	Tertiary	Na-Cl
623000368	Whyalla/Kimba	Basement	Na-Cl
623000411	Whyalla/Kimba	Basement	Na-Cl
623000435	Whyalla/Kimba	Basement	Na-Mg-Cl
623000441	Whyalla/Kimba	Quaternary and basement	Na-Cl
623000468	Whyalla/Kimba	Basement	Na-Mg-Cl
623000664	Whyalla/Kimba	Basement	Na-Cl
623000687	Whyalla/Kimba	Quaternary	Na-Mg-Cl
623000717	Whyalla/Kimba	Basement	Na-Cl
623000844	Whyalla/Kimba	Basement	Na-Mg-Cl
623100062	Whyalla/Kimba	Basement	Na-Mg-Cl
633100224	Whyalla/Kimba	Tertiary	Na-Cl
633100228	Whyalla/Kimba	Basement	Na-Cl-HCO_3
633100229	Whyalla/Kimba	Basement	Na-Cl

D. Groundwater $\delta^{18}O$ and $\delta^{2}H$ values.

Unit number	Aquifer monitored	$\delta^{18}O$	$\delta^{2}H$
602800049	Basement	-4.17	-19.79
602802074	Basement	-4.16	-23.22
602802724	Basement	-4.77	-24.67
602802730	Basement	-5.31	-27.07
602802732	Basement	-4.96	-25.52
602802746	Basement	-4.44	-23.62
602802747	Basement	-4.61	-24.58
602802749	Basement	-4.75	-24.64
602901390	Basement	-4.71	-24.64
602901391	Basement	-4.49	-24.44
602901393	Basement	-2.78	-15.91
602901394	Basement	-4.73	-25.03
613001023	Basement	-3.50	-23.56
623000368	Basement	-4.16	-27.61
623000411	Basement	-4.01	-27.30
623000844	Basement	-4.62	-29.00
633100228	Basement	-3.53	-21.62
633100229	Basement	-4.48	-31.68
623100062	Basement	-4.42	-29.72
603000803	Basement	-3.64	-24.56
592800445	Quaternary	-4.07	-21.91
592900196	Quaternary	-4.55	-24.38
602801750	Quaternary	-4.01	-20.39
602802744	Quaternary	-4.38	-22.67
602802745	Quaternary	-4.31	-22.44
602901023	Quaternary	-3.56	-20.16
592800397	Quaternary	-3.99	-20.26
592900730	Quaternary	-3.66	-18.17
602801635	Quaternary	-4.44	-22.90
602802112	Quaternary	-4.48	-23.69
602802118	Quaternary	-3.38	-17.63
602901298	Quaternary	-3.70	-20.70
623000687	Quaternary	-4.01	-27.08
602801595	Quaternary	-4.34	-21.23
603000056	Quaternary	-5.11	-27.75
592900580	Tertiary	-4.52	-23.64
602800745	Tertiary	-4.58	-24.04
602801725	Tertiary	-4.29	-23.06
633100224	Tertiary	-4.44	-29.79

E. Groundwater Strontium ratio ($^{87}Sr/^{86}Sr$).

Unit number	Aquifer monitored	Mid-production zone depth (m)	$^{87}Sr/^{86}Sr$
602800049	Basement	13.8	0.740136
602802071	Basement	38.5	0.711671
602802074	Basement	27	0.710813
602802197	Basement	51	0.713941
602802730	Basement	73.9	0.710432
602802732	Basement	63	0.710887
602802746	Basement	75.75	0.715675
602802747	Basement	80.5	0.710343
602802749	Basement	23	0.715534
602901390	Basement	13.5	0.717459
602901391	Basement	20.5	0.710369
602901393	Basement	20.5	0.714141
602901394	Basement	19.5	0.714438
613001023	Basement	33	0.730999
623000844	Basement	32	0.731277
633100228	Basement	13	0.726813
592800445	Quaternary	13	0.709343
592900196	Quaternary	8.5	0.709346
602801750	Quaternary	6	0.709491
602802744	Quaternary	20	0.709368
602802745	Quaternary	14.75	0.709828
602901023	Quaternary	22.5	0.710604
592800083	Quaternary	18.5	0.709311
592800397	Quaternary	2.25	0.709213
592900002	Quaternary	24.3	0.709708
602801635	Quaternary	24.5	0.71018
602802112	Quaternary	21	0.710537
602802118	Quaternary	8	0.709837
602901298	Quaternary	1.32	0.710835
602801595	Quaternary	11	0.724615
592900580	Tertiary	7.75	0.709395
602800745	Tertiary	56.5	0.710078
602801725	Tertiary	14.5	0.710758
633100224	Tertiary	113.5	0.729284

7 Units of measurement

7.1 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

7.2 Shortened forms

~	approximately equal to
bgs	below ground surface
EC	electrical conductivity (µS/cm)
K	hydraulic conductivity (m/d)
pH	-log hydrogen ion concentration
pMC	percent of modern carbon
pptv	parts per trillion volume

8 Glossary

Act (the) — In this document, refers to the *Natural Resources Management (SA) Act 2004,* which supercedes the *Water Resources (SA) Act 1997*

Aquiclude — In hydrologic terms, a formation that contains water but cannot transmit it rapidly enough to furnish a significant supply to a well or spring

Aquifer — An underground layer of rock or sediment that holds water and allows water to percolate through

Aquifer, confined — Aquifer in which the upper surface is impervious (see 'confining layer') and the water is held at greater than atmospheric pressure; water in a penetrating well will rise above the surface of the aquifer

Aquifer test — A hydrological test performed on a well, aimed to increase the understanding of the aquifer properties, including any interference between wells and to more accurately estimate the sustainable use of the water resources available for development from the well

Aquifer, unconfined — Aquifer in which the upper surface has free connection to the ground surface and the water surface is at atmospheric pressure

Aquitard — A layer in the geological profile that separates two aquifers and restricts the flow between them

Artesian — An aquifer in which the water surface is bounded by an impervious rock formation; the water surface is at greater than atmospheric pressure and hence rises in any well which penetrates the overlying confining aquifer

Baseflow — The water in a stream that results from groundwater discharge to the stream; often maintains flows during seasonal dry periods and has important ecological functions

Basin — The area drained by a major river and its tributaries

Binary mixing – combination of two end-member compositions

BoM — Bureau of Meteorology, Australia

Bore — See 'well'

Catchment — That area of land determined by topographic features within which rainfall will contribute to run-off at a particular point

Catchment Water Management Board — A statutory body established under the Act whose prime function is to implement a catchment water management plan for its area

Catchment water management plan — The plan prepared by a CWMB and adopted by the Minister in accordance with the Act

Confining layer — A rock unit impervious to water, which forms the upper bound of a confined aquifer; a body of impermeable material adjacent to an aquifer; see also 'aquifer, confined'

DES — Drillhole Enquiry System; a database of groundwater wells in South Australia, compiled by the South Australian Department for Water (DFW)

DFW — Department for Water (Government of South Australia)

Domestic purpose — The taking of water for ordinary household purposes; includes the watering of land in conjunction with a dwelling not exceeding 0.4 hectares

Drillhole — See 'well'. A hole or passage made by a drill; usually made for exploratory purposes, typically used in the mining industry.

Dryland salinity — The process whereby salts stored below the surface of the ground are brought close to the surface by the rising watertable. The accumulation of salt degrades the upper soil profile, with impacts on agriculture, infrastructure and the environment.

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

EP — Eyre Peninsula

EPA — Environment Protection Authority (Government of South Australia)

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.

EPNRMB — Eyre Peninsula Natural Resources Management Board

Fully-penetrating well — In theory this is a wellhole that is screened throughout the full thickness of the target aquifer; in practice, any screen that is open to at least the mid 80% of a confined aquifer is regarded as fully-penetrating

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

Geomorphic — Related to the physical properties of the rock, soil and water in and around a stream

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'

Hydraulic conductivity (K) — A measure of the ease of flow through aquifer material: high K indicates low resistance, or high flow conditions; measured in metres per day

Hydrogeology — The study of groundwater, which includes its occurrence, recharge and discharge processes and the properties of aquifers; see also 'hydrology'

ICCWR — Impacts of Climate Change on Water Resources Projects (DFW)

Infrastructure — Artificial lakes; dams or reservoirs; embankments, walls, channels or other works; buildings or structures; or pipes, machinery or other equipment

Integrated catchment management — Natural resources management that considers in an integrated manner the total long-term effect of land and water management practices on a catchment basis, from production and environmental viewpoints

Intensive farming — A method of keeping animals in the course of carrying on the business of primary production in which the animals are confined to a small space or area and are usually fed by hand or mechanical means

Irrigation — Watering land by any means for the purpose of growing plants

Lake — A natural lake, pond, lagoon, wetland or spring (whether modified or not) that includes part of a lake and a body of water declared by regulation to be a lake. A reference to a lake is a reference to either the bed, banks and shores of the lake or the water for the time being held by the bed, banks and shores of the lake, or both, depending on the context.

Land — Whether under water or not and includes an interest in land and any building or structure fixed to the land

m AHD — Defines elevation in metres (m) according to the Australian Height Datum (AHD)

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 recharge — The infiltration of water into an aquifer from the surface (rainfall, streamflow, irrigation etc). See also recharge area, artificial recharge

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

Observation well — A narrow well or piezometer whose sole function is to permit water level measurements

Obswell — Observation Well Network

PACE 2020 — Plan for Accelerated Exploration

Palaeovalleys — Ancient buried river channels in arid areas of the state. Aquifers in palaeovalleys can yield useful quantities of groundwater or be suitable for ASR

Penetrating well — See 'fully-penetrating well'

Perennial streams — Permanently inundated surface stream courses. Surface water flows throughout the year except in years of infrequent drought.

Permeability — A measure of the ease with which water flows through an aquifer or aquitard, measured in m^2/d

Piezometer — A narrow tube, pipe or well; used for measuring moisture in soil, water levels in an aquifer, or pressure head in a tank, pipeline, etc

PIRSA — Primary Industries and Resources South Australia (Government of South Australia)

Piston flow – as if along a tubular flow line from recharge to discharge without mixing

Pluviometer — An automated rain gauge consisting of an instrument to measure the quantity of precipitation over a set period of time

Population — (1) For the purposes of natural resources planning, the set of individuals of the same species that occurs within the natural resource of interest. (2) An aggregate of interbreeding individuals of a biological species within a specified location

Potable water — Water suitable for human consumption such as drinking or cooking water

Potentiometric head — The potentiometric head or surface is the level to which water rises in a well due to water pressure in the aquifer, measured in metres (m); also known as piezometric surface

Prescribed area, surface water — Part of the state declared to be a surface water prescribed area under the Act

Prescribed lake — A lake declared to be a prescribed lake under the Act

Prescribed watercourse — A watercourse declared to be a prescribed watercourse under the Act

Prescribed water resource — A water resource declared by the Governor to be prescribed under the Act and includes underground water to which access is obtained by prescribed wells. Prescription of a water resource requires that future management of the resource be regulated via a licensing system.

Prescribed well — A well declared to be a prescribed well under the Act

Production well — The pumped well in an aquifer test, as opposed to observation wells; a wide-hole well, fully developed and screened for water supply, drilled on the basis of previous exploration wells

PWA — Prescribed Wells Area

PWCA — Prescribed Watercourse Area

PWRA — Prescribed Water Resources Area

Recharge area — The area of land from which water from the surface (rainfall, streamflow, irrigation, etc.) infiltrates into an aquifer. See also artificial recharge, natural recharge

SA Geodata — A collection of linked databases storing geological and hydrogeological data, which the public can access through the offices of PIRSA. Custodianship of data related to minerals and petroleum and groundwater, is vested in PIRSA and DWLBC, respectively. DWLBC should be contacted for database extracts related to groundwater

SARIG — South Australian Resources Information Geoserver

SA Water — South Australian Water Corporation (Government of South Australia)

Seasonal watercourses or wetlands — Those watercourses or wetlands that contain water on a seasonal basis, usually over the winter–spring period, although there may be some flow or standing water at other times

Specific storage (S_s) — Specific storativity; the amount of stored water realised from a unit volume of aquifer per unit decline in head; it is dimensionless

Specific yield (S_y) — The volume ratio of water that drains by gravity, to that of total volume of the porous medium. It is dimensionless

State Water Plan — Policy document prepared by the Minister that sets the strategic direction for water resource management in the State and policies for achieving the objects of the *Natural Resources Management (SA) Act 2004*

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

(S) — Storativity; storage coefficient; the volume of groundwater released or taken into storage per unit plan area of aquifer per unit change of head; it is dimensionless

Stormwater — Run-off in an urban area

Sub-catchment — The area of land determined by topographical features within which rainfall will contribute to run-off at a particular point

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

Surface Water Archive — An internet-based database linked to Hydstra and operated by DWLBC. It contains rainfall, water level, streamflow and salinity data collected from a network of surface water monitoring sites located throughout South Australia

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

SWL — Depth to groundwater below the natural ground surface

T — Transmissivity; a parameter indicating the ease of groundwater flow through a metre width of aquifer section (taken perpendicular to the direction of flow), measured in m^2/d

TDS — Total dissolved solids, measured in milligrams per litre (mg/L); a measure of water salinity

Tertiary aquifer — A term used to describe a water-bearing rock formation deposited in the Tertiary geological period (1–70 million years ago)

Transmissivity (T) — A parameter indicating the ease of groundwater flow through a metre width of aquifer section

Tributary — A river or creek that flows into a larger river

Underground water (groundwater) — Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground

Volumetric allocation — An allocation of water expressed on a water licence as a volume (eg. kilolitres) to be used over a specified period of time, usually per water use year (as distinct from any other sort of allocation)

Water affecting activities — Activities referred to in Part 4, Division 1, s. 9 of the Act

Water allocation — (1) In respect of a water licence means the quantity of water that the licensee is entitled to take and use pursuant to the licence. (2) In respect of water taken pursuant to an authorisation under s.11 means the maximum quantity of water that can be taken and used pursuant to the authorisation

Water allocation, area based — An allocation of water that entitles the licensee to irrigate a specified area of land for a specified period of time usually per water–use year

WAP — Water Allocation Plan; a plan prepared by a CWMB or water resources planning committee and adopted by the Minister in accordance with the Act

Water body — Includes watercourses, riparian zones, floodplains, wetlands, estuaries, lakes and groundwater aquifers

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 cut — The depth at which a water bearing unit is intersected during the process of drilling a well.

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 licence — A licence granted under the Act entitling the holder to take water from a prescribed watercourse, lake or well or to take surface water from a surface water prescribed area; this grants the licensee a right to take an allocation of water specified on the licence, which may also include conditions on the taking and use of that water; a water licence confers a property right on the holder of the licence and this right is separate from land title

Water plans — The State Water Plan, catchment water management plans, water allocation plans and local water management plans prepared under Part 7 of the Act

Water quality criteria — comprised of both numerical criteria and narrative criteria. Numerical criteria are scientifically derived ambient concentrations developed by the EPA (Commonwealth Government of Australia) or the states for various pollutants of concern, so that human health and aquatic life can be protected. Narrative criteria are statements that describe the desired water quality goal.

Water quality data — Chemical, biological and physical measurements or observations of the characteristics of surface and groundwaters, atmospheric deposition, potable water, treated effluents and wastewater and of the immediate environment in which the water exists

Water quality information — Derived through analysis, interpretation and presentation of water quality and ancillary data

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

Water quality standard — A law or regulation that consists of the beneficial designated use or uses of a water body, the numerical and narrative water quality criteria that are necessary to protect the use or uses of that particular water body and an anti-degradation statement

Water resource monitoring — An integrated activity for evaluating the physical, chemical and biological character of water resources, including (1) surface waters, groundwaters, estuaries and near-coastal waters; and (2) associated aquatic communities and physical habitats, which include wetlands

Water resource quality — (1) The condition of water or some water-related resource as measured by biological surveys, habitat-quality assessments, chemical-specific analyses of pollutants in water bodies and toxicity tests. (2) The condition of water or some water-related resource as measured by habitat quality, energy dynamics, chemical quality, hydrological regime and biotic factors

WDE — Water dependent ecosystem

Well — (1) An opening in the ground excavated for the purpose of obtaining access to underground water. (2) An opening in the ground excavated for some other purpose but that gives access to underground water. (3) A natural opening in the ground that gives access to underground water

9 References

Barnett S, 1982, *Eyre Peninsula Groundwater Investigations, Progress Report to 1 July 1982*, Report Book No. 82/63, Government of South Australia, through Department of Mines and Energy South Australia, Adelaide

Berens V, Alcoe DW, Watt EL, 2011, *Non-prescribed groundwater resources assessment – Eyre Peninsula Natural Resources Management Region. Phase 1 - Literature and Data Review,* DFW Technical Report 2011/16, Government of South Australia, through Department for Water, Adelaide

Bullister JL, 2011, *Atmospheric CFC-11, CFC-12, CFC-113, CCl4 and SF6 Histories*, viewed September 2013, http://cdiac.ornl.gov/oceans/new_atmCFC.html

Burke WH, Denison RE, Hetherington EA, Koepnick RB, Nelson HF and Otto JB, 1982, 'Variation of seawater 87Sr/86Sr throughout Phanerozoic time', in *Geology,* 10, pp. 516–519

Busenberg E and Plummer NL, 2000, 'Dating young groundwater with sulphur hexafluoride: Natural and anthropogenic sources of sulphur hexafluoride', in *Water Resources Research*, 36(10), pp. 3011–3030

Cook PG, Solomon DK, Sanford WE, Busenberg E, Plummer LN and Poreda RJ, 1996, 'Inferring shallow groundwater flow in saprolite and fractured rock using environmental tracers', in *Water Resources Research*, 32(6), pp. 1501–1509

Cook P and Herczeg A, 1998, 'Groundwater chemical methods for recharge studies', in Zhang L and Walker G (eds), *Studies in Catchment Hydrology: The Basics of Recharge and Discharge*, CSIRO Publishing, Melbourne

Cook PG and Böhlke JK, 1999, 'Determining timescales for groundwater flow and solute transport', in Cook PG and Herczeg A (eds), Environmental tracers in subsurface hydrology, Kluwer, Boston, pp. 1–30

Cook PG, Love AJ, Robinson NI and Simmons CT, 2005, 'Groundwater ages in fractured rock aquifers', in *Journal of Hydrology*, 308(1), pp. 284–301

Coplen TB, Herczeg AL and Barnes C, 2000, 'Isotope engineering—using stable isotopes of the water molecule to solve practical problems', in *Environmental tracers in subsurface hydrology,* pp. 79–110

Craig H, 1961, 'Isotopic variations in meteoric waters', in *Science*, 133(3465), pp. 1702–1703

Crosbie RS, McCallum JL, Walker GR and Chiew FHS, 2012, 'Episodic recharge and climate change in the Murray-Darling Basin, Australia', in *Hydrogeology Journal,* 20(2), pp. 245–261

Darling WG, Gooddy DC, MacDonald AM and Morris BL, 2012*, The practicalities of using CFCs and SF6 for groundwater dating and tracing,* British Geological Survey, MacLean building, Wallingford OX10 8BB, UK

Department of Geosciences North Dakota State University, Web-Phreeq: Aqueous Geochemical Modeling. viewed September 2013, http://www.ndsu.nodak.edu/webphreeq/

Evans S, 1997, 'Estimating long term recharge to thin, unconfined carbonate aquifers using conventional and environmental isotope techniques: Eyre Peninsula, South Australia', MSc Thesis, Flinders University, Adelaide

Geoscience Australia, 2014, MapConnect: Groundwater datasets for recharge and/or discharge, viewed 2 January 2014, http://mapconnect.ga.gov.au/MapConnect/?site=Groundwater&accept_agreement=on

Gooddy DC, Darling WG, Abesser C and Lapworth DJ, 2006, 'Using chlorofluorocarbons (CFCs) and sulphur hexafluoride (SF_6) to characterise groundwater movement and residence time in a lowland Chalk catchment', in *Journal of Hydrology*, 330, pp. 44–52

Government of South Australia, 2000, State water plan 2000: Policies for a sustainable future, Government of South Australia, Adelaide

Harnisch J and Eisenhauer A, 1998, 'Natural CF4 and SF6 on Earth', in *Geophysical Research Letters*, 25, pp. 2401–2404

Harrington GA and Herczeg AL, 1999, 'Estimation of 14C derived groundwater ages in the arid Ti-Tree basin, Central Australia: Use of 87Sr/86Sr to elucidate sources of inorganic carbon', IAEA-SM-361, Symposium on Isotopes in Water Resources Development and Management, International Atomic Energy Agency, Vienna, 10–14 May 1999

Herczeg AL and Edmunds WM, 2000, 'Inorganic ions as tracers', in *Environmental tracers in subsurface hydrology*, pp. 31–77

Hinsby K, Højberg AL, Engesgaard P, Jensen KH, Larsen F, Plummer L and Busenberg E, 2007, 'Transport and degradation of chlorofluorocarbons (CFCs) in the pyritic Rabis Creek aquifer, Denmark', in *Water Resources Research*, 43

Horneman A, Stute M, Schlosser P, Smethie Jr W, Santella N, Ho D, Mailloux B, Gorman E, Zheng Y and Van Geen A, 2008, 'Degradation rates of CFC-11, CFC-12 and CFC-113 in anoxic shallow aquifers of Araihazar, Bangladesh', in *Journal of Contaminant Hydrology*, 97, pp. 27-41

IAEA/WMO, 2013, Global Network of Isotopes in Precipitation, The GNIP Database, viewed October 2013, http://www.iaea.org/water

Ingerson R and Pearson FJ, 1964, 'Estimation of age and rate of motion of groundwater by the 14C method', in Miyake Y and Koyama T (eds), *Recent Research in the Field of Hydrosphere, Atmosphere and Nuclear Geochemistry*, Maruzen, Tokyo, pp. 263–283

Kalin RM, 2000, 'Radiocarbon dating of groundwater systems', in *Environmental tracers in subsurface hydrology,* pp. 111–144

Khalil M and Rasmussen R, 1989, 'The potential of soils as a sink of chlorofluorocarbons and other man-made chlorocarbons', in *Geophysical Research Letters*, 16, pp. 679–682

Koh D-C, Plummer LN, Busenberg E and Kim Y, 2007, 'Evidence for terrigenic SF_6 in groundwater from basaltic aquifers, Jeju Island, Korea: Implications for groundwater dating', in *Journal of Hydrology*, 339, pp. 93–104

Lincoln Minerals Limited, 2013, *Gum Flat Iron Ore Project Groundwater Extraction Model*, Report prepared by Lincoln Minerals Limited, Sinclair Knight Merz and Lisdon Associates, Adelaide

Love AJ, Dowie J, Smith PC, Dodds S and Dennis K, 1994, *Musgrave Proclaimed Wells Area Groundwater Assessment*, Government of South Australia, through Department of Mines and Energy (Geological Survey of South Australia), Adelaide

Martin R, Sereda A and Clarke D, 1998, *Spencer Regions strategic water management study*, Report Book 98/19, Government of South Australia, through Department of Primary Industries and Resources South Australia, Adelaide

McCallum JL, Cook PG, Simmons CT and Werner AD, 2014, 'Bias of apparent tracer ages in heterogeneous environments', in *Groundwater*, 52(2), pp. 239–250

Morris BL, Darling WG, Cronin AA, Rueedi J, Whitehead EJ and Gooddy DC, 2006, 'Assessing the impact of modern recharge on a sandstone aquifer beneath a suburb of Doncaster, UK', in *Hydrogeology Journal*, 14, pp. 979–997

Oster H, Sonntag C and Münnich K, 1996, 'Groundwater age dating with chlorofluorocarbons', in *Water Resources Research*, 32, pp. 2989–3001

Parker AJ and Fanning CM, 1998, *Explanatory notes for the WHYALLA 1:250 000 Geological Map*, Primary Industries and Resources South Australia, Geological Survey of South Australia, Adelaide

Plummer LN and Busenberg E, 2000, 'Chlorofluorocarbons', in *Environmental tracers in subsurface hydrology,* pp. 441–478

Plummer L, Busenberg E and Cook P, 2006, 'Principles of chlorofluorocarbon dating', in *Use of chlorofluorocarbons in hydrology: A Guidebook*, International Atomic Energy Agency, Vienna, pp. 17–29

Sebol L, Robertson W, Busenberg E, Plummer L, Ryan M and Schiff S, 2007, 'Evidence of CFC degradation in groundwater under pyrite-oxidizing conditions', in *Journal of Hydrology*, 347, pp. 1–12

Sonney R and Vuataz F-D, 2010, 'Use of Cl/Br ratio to decipher the origin of dissolved mineral components in deep fluids from the Alps range and neighbouring areas', in *Proceedings World Geothermal Congress 2010*, Bali, Indonesia, 25–29 April 2010

Taylor N, 2003, *Eyre Peninsula Water Supply Master Plan*, Parsons Brinckerhoff, prepared for SA Water Corporation, Adelaide

Government of South Australia

Department of Environment,
Water and Natural Resources