DWLBC REPORT

Groundwater Recharge Investigations in the Upper Marne River Catchment, South Australia

2007/19

Government of South Australia
Department of Water, Land and Biodiversity Conservation

Groundwater Recharge Investigations in the Upper Marne River Catchment, South Australia

Eddie Banks, Tania Wilson and Andrew Love

Knowledge and Information Division
Resource Investigation Group
Department of Water, Land and Biodiversity Conservation

July 2007

Report DWLBC 2007/19

Government of South Australia
Department of Water, Land and Biodiversity Conservation

Knowledge and Information Division Resource Investigation Group
Department of Water, Land and Biodiversity Conservation
25 Grenfell Street, Adelaide
GPO Box 2834, 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.dwlbc.sa.gov.au

Disclaimer

The Department of Water, Land and Biodiversity Conservation and its employees do not warrant or make any representation regarding the use, or results of the use, of the information contained herein as regards to its correctness, accuracy, reliability, currency or otherwise. The Department of Water, Land and Biodiversity Conservation and its employees expressly disclaims all liability or responsibility to any person using the information or advice.

© Government of South Australia, through the Department of Water, Land and Biodiversity Conservation 2006

This work is copyright. Apart from any use permitted under the *Copyright Act 1968* (Cwlth), no part may be reproduced by any process without prior written permission obtained from the Department of Water, Land and Biodiversity Conservation. Requests and enquiries concerning reproduction and rights should be directed to the Chief Executive, Department of Water, Land and Biodiversity Conservation, GPO Box 2834, Adelaide SA 5001.

ISBN 978-1-921218-61-3

Preferred way to cite this publication

Banks, EW, Wilson, T & Love, AJ 2006, *Groundwater recharge investigations in the Upper Marne River Catchment, South Australia,* Report DWLBC 2007/19, Department of Water, Land and Biodiversity Conservation, Adelaide.

FOREWORD

South Australia's unique and precious natural resources are fundamental to the economic and social wellbeing of the state. It is critical that these resources are managed in a sustainable manner to safeguard them both for current users and for future generations.

The Department of Water, Land and Biodiversity Conservation (DWLBC) strives to ensure that our natural resources are managed so that they are available for all users, including the environment.

In order for us to best manage these natural resources, it is imperative that we have a sound knowledge of their condition and how they are likely to respond to management changes. DWLBC scientific and technical staff continue to improve this knowledge through undertaking investigations, technical reviews and resource modelling.

Rob Freeman
CHIEF EXECUTIVE
DEPARTMENT OF WATER, LAND AND BIODIVERSITY CONSERVATION

CONTENTS

FOREWORD ..... **iii**

EXECUTIVE SUMMARY **1**

1. INTRODUCTION **3**

1.1 FRACTURED ROCK AQUIFERS 3
1.2 AIMS AND OBJECTIVES 4

2. UPPER MARNE RIVER CATCHMENT **5**

2.1 UPPER MARNE RIVER CATCHMENT STUDY AREA 5
2.1.1 Climate 5
2.1.2 Geological setting 5
2.1.3 Hydrogeology 8
2.2 DRILLING PROGRAM 11
2.2.1 EC, pH and temperature in open wells 11
2.2.2 Geophysical and EM flow surveys in open wells 11
2.2.3 Piezometer installation 13

3. METHODOLOGY **15**

3.1 INTRODUCTION 15
3.2 GROUNDWATER AGES AND DEPTH OF CIRCULATION 15
3.2.1 Major chemistry and isotopes 15
3.2.2 Carbon-14 and chlorofluorocarbons 16
3.3 VERTICAL FLOW RATES AND AQUIFER RECHARGE 17
3.3.1 Carbon-14 and chlorofluorocarbons 17
3.3.2 Aquifer pumping tests 18
3.3.3 Chloride mass balance 18
3.4 HORIZONTAL FLOW RATES 19
3.4.1 Radon 19

4. GROUNDWATER FLOW **21**

4.1 INTRODUCTION 21
4.2 GROUNDWATER AGES AND DEPTH OF CIRCULATION 21
4.2.1 Major chemistry and isotopes 21
4.2.2 Carbon-14 and chlorofluorocarbons 26
4.3 VERTICAL FLOW RATES AND AQUIFER RECHARGE 27
4.3.1 Carbon-14 and chlorofluorocarbons 27
4.3.2 Chloride mass balance 29
4.4 HORIZONTAL FLOW RATES 31
4.4.1 Radon 31

CONTENTS

5. DISCUSSION 33

5.1 GROUNDWATER FLOW AND RECHARGE 33

6. CONCLUSIONS AND RECOMMENDATIONS 35

6.1 FURTHER WORK 35

APPENDICES 37

A. CHEMISTRY RESULTS 37

B. LITHOLOGICAL LOG 39

UNITS OF MEASUREMENT 41

GLOSSARY 43

REFERENCES 45

CONTENTS

LIST OF FIGURES

Figure 2.1. Location map of the Upper and Lower Marne River Catchments, including the EMLR and WMLR Prescribed Water Resources Area 6
Figure 2.2. Topography and annual rainfall isohyets of the Upper Marne River Catchment, and location of the Eden Valley investigation site 7
Figure 2.3. Geology of the Upper Marne River Catchment 9
Figure 2.4. Potentiometric surface, well distribution and EC across the Upper Marne River Catchment 10
Figure 2.5. EC, pH and temperature variation with depth in the 8 and 10 inch open holes at the Eden Valley investigation site 12
Figure 2.6. Caliper (a) and EM Flowmeter (b) profiles in the 10 inch open hole at the Eden Valley investigation site 13
Figure 4.1. Piper plot of groundwater samples collected at the Eden Valley investigation site, September–November 2005 21
Figure 4.2. TDS, EC, pH, δ^2H and chloride profiles sampled at the Eden Valley investigation site, September–November 2005 22
Figure 4.3. Composition diagrams of major ions versus chloride sampled at the Eden Valley investigation site, September–November 2005 23
Figure 4.4. Calcium versus sulphate sampled at the Eden Valley investigation site, September–November 2005 24
Figure 4.5. Major ion/Cl ratio profiles sampled at the Eden Valley investigation site, September–November 2005 25
Figure 4.6. Isotopes δ^2H and δ^{18}O of the groundwater samples collected at the Eden Valley investigation site, September–November 2005, and rainfall samples collected at Mount Torrens stream gauging station 2002–05 26
Figure 4.7. CFC-12 and carbon-14 profiles from the nested piezometer at the Eden Valley investigation site 27
Figure 4.8. Apparent age (CFC-12 and ^{14}C) profiles from the nested piezometer at the Eden Valley investigation site, September–November 2005 28
Figure 4.9. Comparison of measured CFC-12 concentrations from the Eden Valley investigation site with results from an equivalent porous media recharge model below the watertable 29
Figure 4.10. Recharge estimates based on the CMB method across the Upper Marne River Catchment 30
Figure 4.11. Vertical distribution of recharge estimates according to the CMB method at the Eden Valley investigation site 31
Figure 4.12. ^{222}Rn concentrations of unpurged and purged piezometers sampled during September 2005 and March 2006, ratio of unpurged (C)/purged (Co), and horizontal flow rates within the piezometers at the Eden Valley investigation site 32

LIST OF TABLES

Table 2.1. Construction details of the shallow and nested piezometers at the Eden Valley investigation site 14

EXECUTIVE SUMMARY

The Mount Lofty Ranges provide important surface water and groundwater resources for domestic, industry and agricultural purposes. The development and implementation of Water Allocation Plans for the Eastern and Western Mount Lofty Ranges will ensure that current and future development of these resources are sustainable, and that the environment is also recognised as a user of the resource.

Technical investigations are being conducted to determine the various components of the water balance, which are essential to the development of each Water Allocation Plan. The most important components that need to be quantified in the groundwater balance are vertical recharge and discharge rates, and horizontal flow rates. Determining these components in fractured rock aquifers (FRA) is extremely difficult because the groundwater is stored in, and moves through, fractures and joints in what is essentially impervious rock.

The primary aim of this investigation is to assist in the water allocation policy by estimating the recharge rate to the FRA system in the Upper Marne River Catchment at the Eden Valley investigation site. This will provide sound knowledge with which to estimate recharge rates at a catchment scale and assist in the development of a conceptual model of the FRA system in the Upper Marne River Catchment.

Hydrochemistry, isotopes and radiogenic tracer profiles from the Eden Valley investigation site in the Upper Marne River Catchment were used to identify an upper and deeper groundwater flow system. The upper system is characterised by a thin regolith zone composed of sandy clay and weathered metamorphosed siltstone and sandstone of ~50 m thickness. Geological fracture mapping, together with aquifer test results and chlorofluorocarbon-12 vertical age profiling, have determined average active recharge to the shallow system of 16 mm/y, whilst the carbon-14 data and results from the chloride mass balance method determined a recharge rate of 9 mm/y. By comparison, a porous media model using the chlorofluorocarbon-12 concentrations showed that the average recharge is 27 mm/y. The horizontal flow rates were found to be very low in this system.

The deeper FRA system comprises unweathered metasandstone and metasiltstone units, and the estimated leakage using the carbon-14 age is much lower at 0.14 mm/y, whilst the chloride mass balance estimated recharge is 3 mm/y. The horizontal flow in the deeper system is ~1 m/y. Estimates of recharge to the deeper FRA system may not be entirely accurate due to the effects of regional horizontal flow and because equilibrium may not have been reached between the tracer concentrations in the fractures and the matrix. The estimates of recharge are dependent on the measured fracture spacing, fracture aperture, diffusion coefficient and matrix porosity.

Assuming that only two-thirds of the available resource can be extracted, according to the chlorofluorocarbon-12 recharge estimates, ~11 mm/y are available for allocation. The amount of water available to each user will need to be determined in accordance with the Water Allocation Plan.

1. INTRODUCTION

1.1 FRACTURED ROCK AQUIFERS

The Mount Lofty Ranges (MLR) provide important surface water and groundwater resources for domestic, industry and agricultural purposes locally, as well as metropolitan Adelaide's reticulated water supply. Development and implementation of Water Allocation Plans (WAP) for the Eastern Mount Lofty Ranges (EMLR) and Western Mount Lofty Ranges (WMLR) will ensure that current and future development of these resources are sustainable, and that the environment is also recognised as a user of the resource.

Currently, technical investigations are being conducted to determine the various components of the water balance, which are essential to the development of each WAP. The long-term sustainability of the groundwater resource requires careful estimates of the magnitude of all components of the groundwater budget. In regards to recharge investigations, the most important components that need to be quantified are vertical recharge and discharge rates, and horizontal flow velocities. Determining these components in FRA is extremely difficult because the groundwater is stored in, and moves through, fractures and joints in what is essentially impervious rock. Traditional investigation techniques applied to sedimentary systems have limited applicability to FRA systems. However, several techniques developed recently have been applied to the FRA in the Clare Valley (Cook et al. 1999; Cook & Simmons 2000; Love et al. 2002, in prep.). These techniques were successful in estimating the components of the groundwater budget and provided sound knowledge in understanding some of the complexities of FRA to develop a conceptual model of the groundwater flow system.

A similar approach has been used in investigation of the Burra Creek, Angas and Finniss River Catchments as well as other regions in the MLR. The techniques include downhole geophysics, geological fracture mapping, aquifer tests and vertical profiling of groundwater chemistry, isotopes and radioactive tracers. Downhole geophysics was used to indicate physical properties, lithology and porosity of the rock formations. Fracture location, orientation and groundwater flow can also be determined using downhole geophysics. Structural mapping of surface outcrop provided details of fracture spacing and their dominant orientations. Aquifer tests provided information on fracture aperture. Groundwater chemistry, specifically chlorofluorocarbon and carbon-14 analyses, provided information on the groundwater age. From this estimated age it is possible to make inferences about the recharge rage — in general, young ages indicate relatively high recharge rates and conversely old groundwater ages indicate lower recharge rates.

1.2 AIMS AND OBJECTIVES

The following investigation aims to provide technical information to support the successful implementation of the MLR WAP for the EMLR.

Specifically, this investigation aims to:

- determine the recharge rate to the FRA system
- estimate horizontal flow at the Eden Valley investigation site
- assist in the development of a conceptual model of the FRA system in the Upper Marne River Catchment.

2. UPPER MARNE RIVER CATCHMENT

2.1 UPPER MARNE RIVER CATCHMENT STUDY AREA

The Marne River Catchment comprises upper and lower areas. The Upper Marne River Catchment (UMRC) covers an area of ~260 km^2 extending from the low rolling hills of the southern Barossa Highlands across to the eastern edge of the MLR through the steeply incised Marne Gorge. The Lower Marne River Catchment extends eastwards across the flat plains of the Murray Basin to the River Murray (Figs 2.1, 2.2). Flow in the Marne River (originating in the southwestern arm of the UMRC) and the River Somme (located in the northern arm of the UMRC) are highly ephemeral, and surface water only leaves the western part of the UMRC to transgress the Murray Plains after extended periods of heavy rainfall (Harrington 2004).

Extensive vegetation clearing for the development of pasture and livestock grazing in the last 100 years may have increased potential groundwater recharge, but increasing development of farm dams is likely to have mitigated this effect and also impacted on the surface hydrology in the UMRC and the catchments downstream (Savadamuthu 2002).

The Eden Valley investigation site, where the specialised hydrogeological techniques were applied, is located in the southwestern corner of the UMRC adjacent to the Marne River (Fig. 2.2).

2.1.1 CLIMATE

The climate in the region is characterised by hot dry summers and cool wet winters. The average annual rainfall varies significantly across the catchment, from ~700 mm/y in the western highlands decreasing towards 400 mm/y in the eastern side of the catchment (Fig. 2.2). The majority of the rainfall occurs between the months of late April–May through to September. Keyneton, located in the northern part of the UMRC, is the only rainfall station that has daily rainfall records, collected between September 1908 and present day. The mean annual rainfall for this station is 534 mm/y, although there is significant variability with consecutive years above and below average, making it difficult to produce reliable hydrological models of the catchment. A rainfall–runoff relationship for the UMRC (Savadamuthu 2002) found that surface runoff is generated only in years with above average rainfall. Due to the high variability, annual rainfall is commonly below the long-term average.

2.1.2 GEOLOGICAL SETTING

The geology of the UMRC is characteristic of the eastern margin of the Adelaide Geosyncline and is dominated by sequences of the Kanmantoo Group, specifically the Carrickalinga Head and Backstairs Passage Formations.

Deposition of Kanmantoo Group sediments occurred ~500 million years ago during the Cambrian Period. Predominantly siliciclastic sediments were deposited in the Kanmantoo Trough, a deep-water, fault-controlled basin that formed along the eastern margin of the

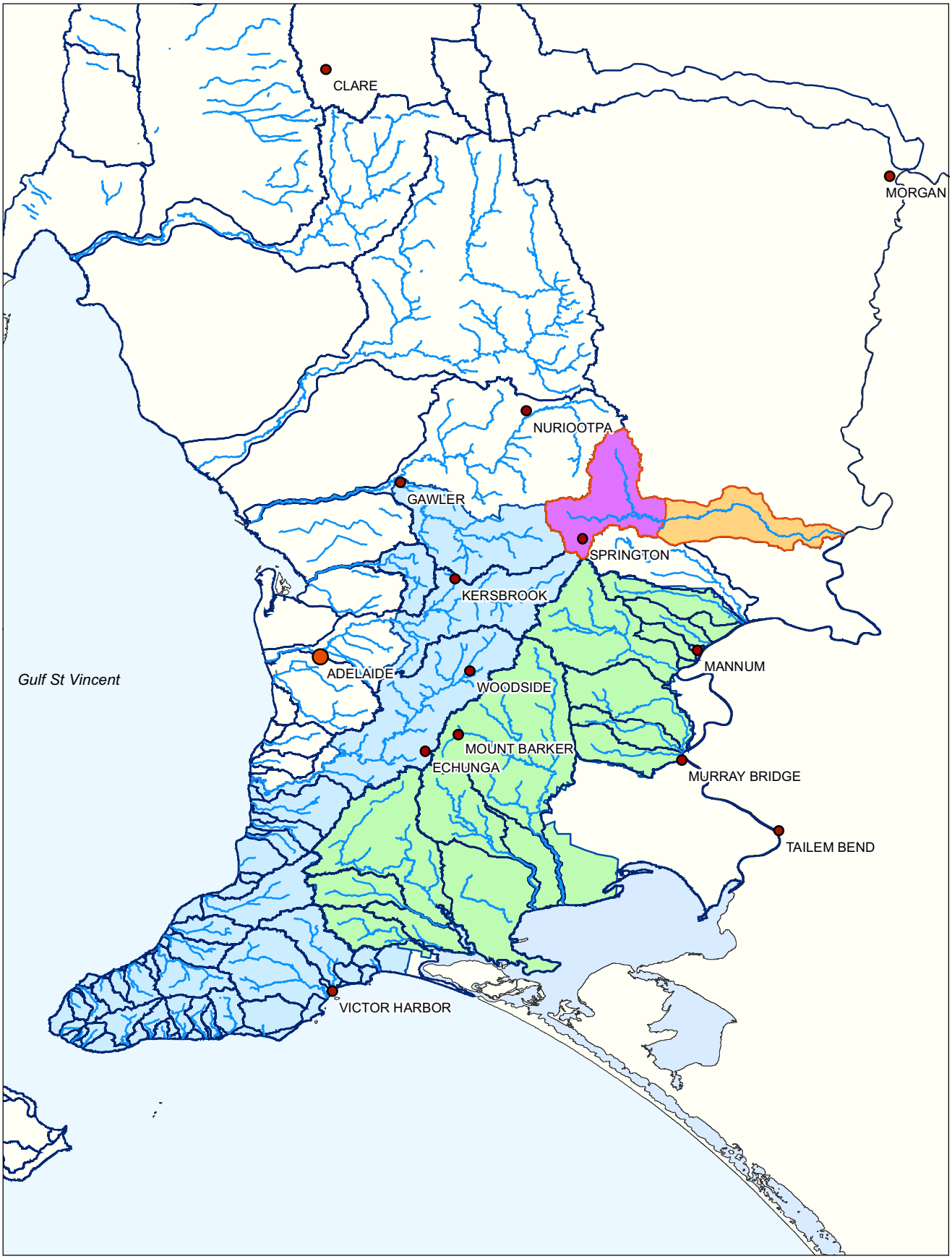

Figure 2.1 Marne River Catchment Location

Upper Marne River Catchment
Lower Marne River Catchment
Eastern Mount Lofty Ranges
Western Mount Lofty Ranges

Major towns
Major streams
Catchment boundaries

Produced By: Mount Lofty RangesTeam
Knowledge and Information Division
Department of Water, Land and Biodiversity Conservation

Datum: Geocentric Datum of Australia 1994 (GDA 94).

Date: 15th June 2006

0 10 20 30 40 50 km

N

© Government of South Australia, through the Department of Water, Land and Biodiversity Conservation 2007.
This work is Copyright. Apart from any use permitted under the Copyright Act 1968 (Cwlth), no part may be reproduced by any process without prior written permission obtained from the Department of Water, Land and Biodiversity Conservation. Requests and enquiries concerning reproduction and rights should be directed to the Chief Executive, Department of Water, Land and Biodiversity Conservation, GPO Box 2834, Adelaide SA 5001.

DISCLAIMER
The Department of Water, Land and Biodiversity Conservation, its employees and servants do not warrant or make any representation regarding the use, or results of use of the information contained herein as to its correctness, accuracy, currency or otherwise. The Department of Water, Land and Biodiversity Conservation, its employees and servants expressly disclaim all liability or responsibility to any person using the information or advice contained herein.

Government of South Australia
Department of Water, Land and Biodiversity Conservation

M:\Projects_GW\Mt_Lofty_Ranges\Marne 2006\Work_temp\MarneUpper_State_Locn.mxd 15th June 2006 G. Green

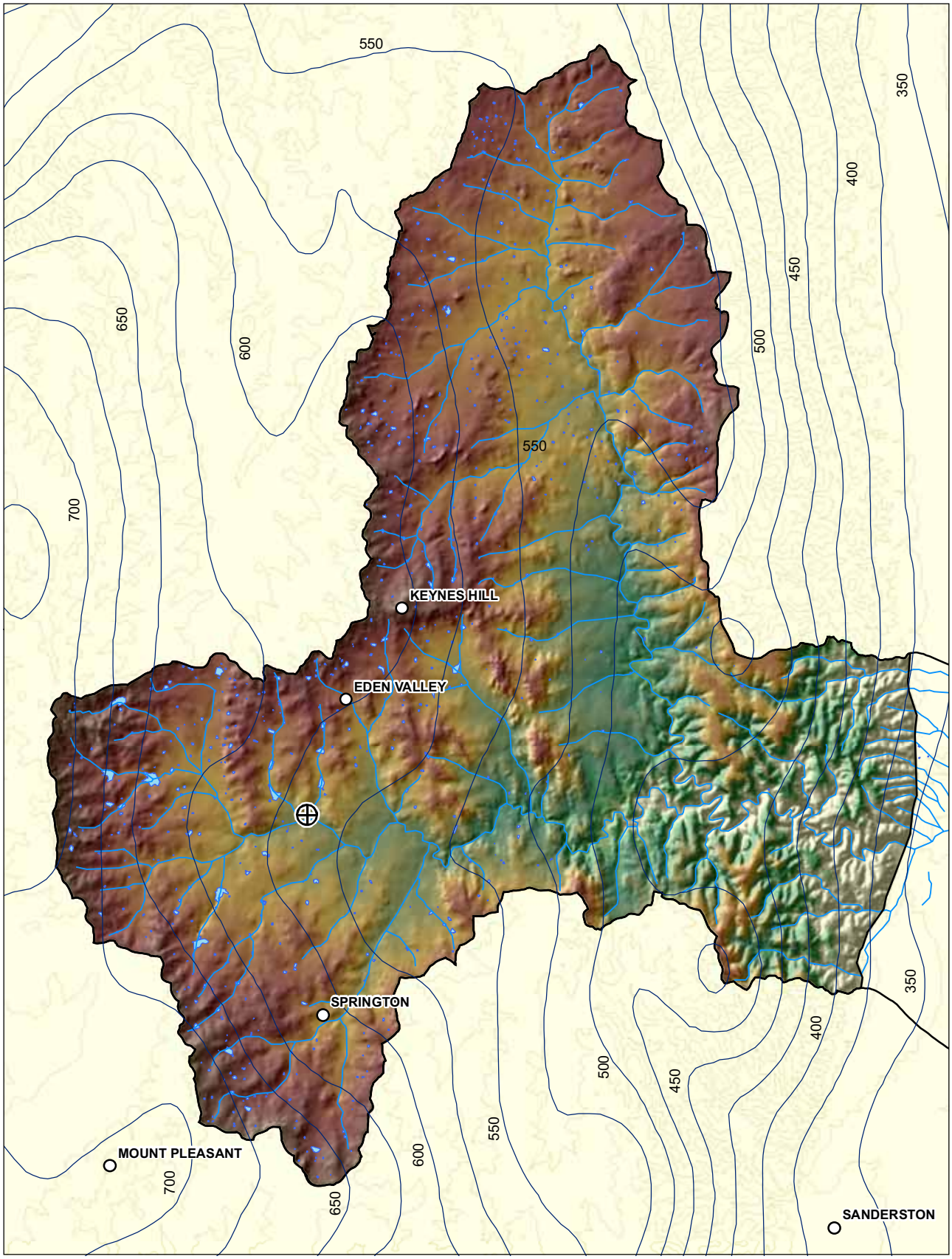

Figure 2.2 Upper Marne River Catchment

Elevation (m AHD)

Value

High : 540

Low : 100

Eden Valley investigation site

Marne catchment boundary

Town

Farm dams

Annual rainfall isohyets (50 mm)

Topographic contours (40 m)

Streams

Produced By: Mount lofty Ranges Team
Knowledge and Information Division
Department of Water, Land and Biodiversity Conservation

Datum: Geocentric Datum of Australia 1994 (GDA 94).

Date: June 2006

0 1 2 3 4 5 km

N

© Government of South Australia, through the Department of Water, Land and Biodiversity Conservation 2007.
This work is Copyright. Apart from any use permitted under the Copyright Act 1968 (Cwlth), no part may be reproduced by any process without prior written permission obtained from the Department of Water, Land and Biodiversity Conservation. Requests and enquiries concerning reproduction and rights should be directed to the Chief Executive, Department of Water, Land and Biodiversity Conservation, GPO Box 2834, Adelaide SA 5001.
DISCLAIMER
The Department of Water, Land and Biodiversity Conservation, its employees and servants do not warrant or make any representation regarding the use, or results of use of the information contained herein as to its correctness, accuracy, currency or otherwise. The Department of Water, Land and Biodiversity Conservation, its employees and servants expressly disclaim all liability or responsibility to any person using the information or advice contained herein.

Government of South Australia
Department of Water, Land and Biodiversity Conservation

M:\Projects_GW\Mt_Lofty_Ranges\Marne 2006\Work_temp\Marne_Upper_Chloride_2005.mxd 13 June 2006 G. Green

Adelaide Geosyncline, which underwent subsidence during the Cambrian. Subsequent deformation and low-grade metamorphism occurred during the Cambro-Ordovician Delamerian Orogeny. This orogenic event resulted in north–south-trending folds and complex faulting (Fig. 2.3; Gravestock & Gatehouse 1995).

On a local scale, the investigation site at Eden Valley is situated in the Backstairs Passage Formation. Local geology is dominated by metasiltstone of unknown thickness, overlain by metasandstone of 35 m apparent thickness. A shallow regolith zone overlies these Adelaidean sequences.

The metasiltstone unit is finely laminated, with interbedded metasandstone and minor quartzite, overlain by a medium-grained, laminated, mica-rich metasandstone. Biotite and muscovite occurring throughout the metasandstone define a moderately developed schistosity.

Minor chloritic alteration is observed in both the metasiltstone and metasandstone units from drilling samples recovered from depths exceeding 50 m. Weathering and minor iron staining are also observed in both units to depths of 50 m. Detailed lithological drilling logs for these fractured metasediments are available in Harrington et al. (2004).

Overlying the metasandstone is a surficial regolith zone extending to ~10 m depth. The basal section (2–10 m) consists of a fine-grained, mica-rich, clayey sand with minor weathered metasandstone fragments. Overlying this is ~2 m of fine to medium-grained sand. Detailed lithological drilling logs for this regolith zone are included in Appendix B.

2.1.3 HYDROGEOLOGY

The Marne River Catchment is characterised by an FRA system in the western part (the UMRC) and a topographically lower sedimentary valley system in the east, separated by the north–south-trending Palmer Fault (Fig. 2.3). It has been inferred that the FRA system discharges across the fault and into the sedimentary system. There is some debate as to whether the sedimentary system receives water from a local or regional aquifer system. This investigation addresses the FRA in the UMRC, as there are currently no suitably constructed wells in the sedimentary system to apply the specialised hydrogeological techniques.

As mentioned previously, the primary stratigraphic units in the UMRC are the Cambro-Ordovician rocks of the Kanmantoo Group. These units are all generally regarded as poor aquifers with groundwater salinity typically >1500 mg/L TDS and bore yields <3 L/s (Zulfic & Barnett 2003).

The majority of bores are located in the northern and southwestern area of the UMRC (Fig. 2.4), and are generally in close proximity to surface water features where the watertable is at a shallower depth. Groundwater flow in the catchment mirrors the topography, with flow moving from the western margin towards the east where it discharges across the Palmer Fault to the Lower Marne River Catchment. On a local scale, the potentiometric surface suggests groundwater flow moving towards the valley bottoms where it may discharge to streams and/or receive recharge from losing streams before exiting the FRA towards the east across the fault. A previous groundwater – surface water investigation by Harrington (2004) found that the Marne River and its tributaries are both gaining and losing streams.

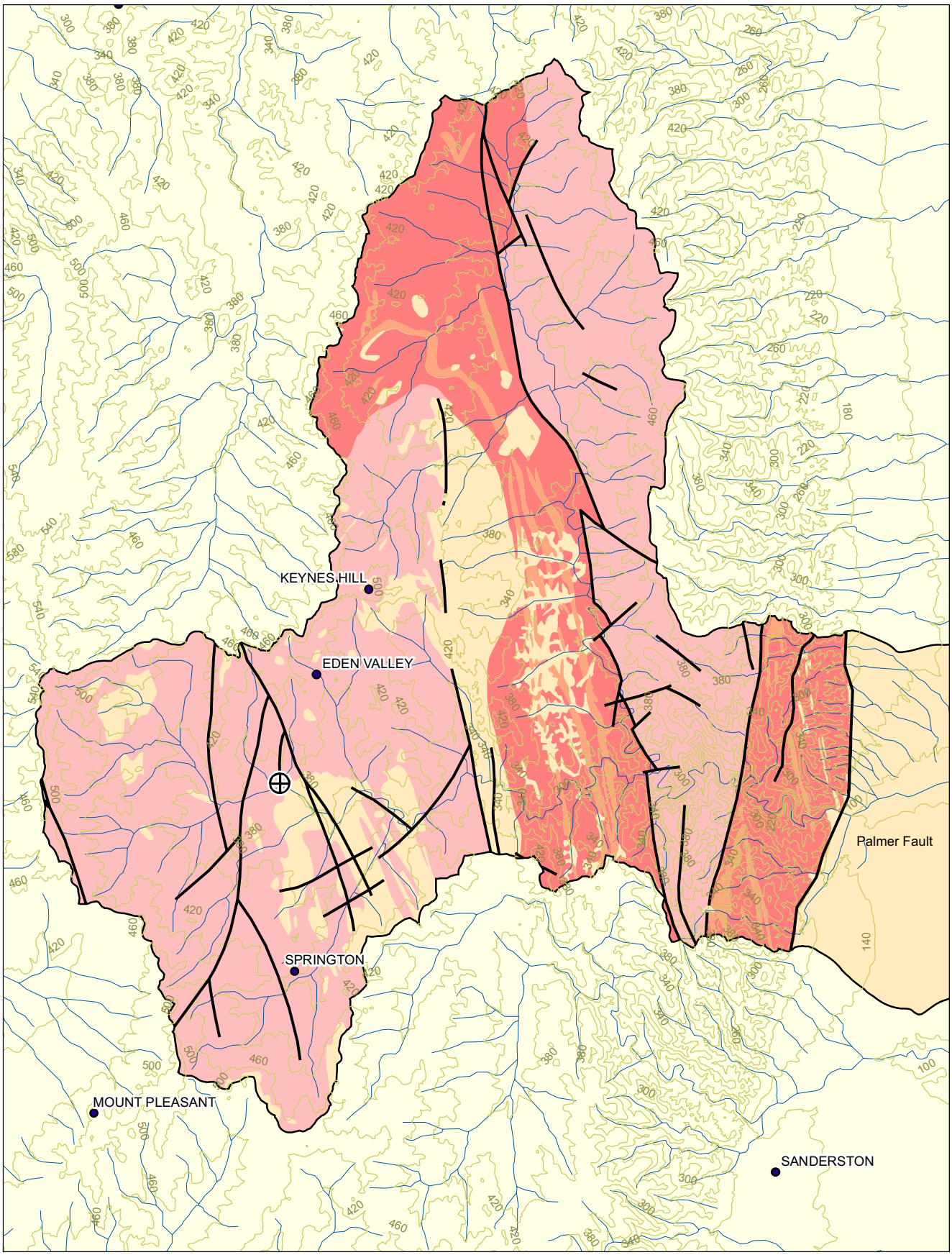

Figure 2.3 Upper Marne River Catchment Geology

- Towns
- Eden Valley investigation site
- Stream
- Contour (40 m)
- Major Faults
- Marne catchment boundary

Geology

- Quaternary & Tertiary sediments, acid intrusives and basic igneous rocks
- Backstairs Passage Formation
- Milendella Limestone Member
- Carrickalinga Head Formation

Produced By: Water Information Group
Knowledge and Information Division
Department of Water, Land and Biodiversity Conservation

Datum: Geocentric Datum of Australia 1994 (GDA 94).

Date: 14th June 2006

N

0 1 2 3 4 5 km

© Government of South Australia, through the Department of Water, Land and Biodiversity Conservation 2007.
This work is Copyright. Apart from any use permitted under the Copyright Act 1968 (Cwlth), no part may be reproduced by any process without prior written permission obtained from the Department of Water, Land and Biodiversity Conservation. Requests and enquiries concerning reproduction and rights should be directed to the Chief Executive, Department of Water, Land and Biodiversity Conservation, GPO Box 2834, Adelaide SA 5001.

DISCLAIMER
The Department of Water, Land and Biodiversity Conservation, its employees and servants do not warrant or make any representation regarding the use, or results of use of the information contained herein as to its correctness, accuracy, currency or otherwise. The Department of Water, Land and Biodiversity Conservation, its employees and servants expressly disclaim all liability or responsibility to any person using the information or advice contained herein.

Government of South Australia
Department of Water, Land and Biodiversity Conservation

M:\Projects_GW\MT_Lofty_Ranges\Marne2006\Work_temp\Marne_Upper_Geology_1.mxd 14/6/2006 G. Green

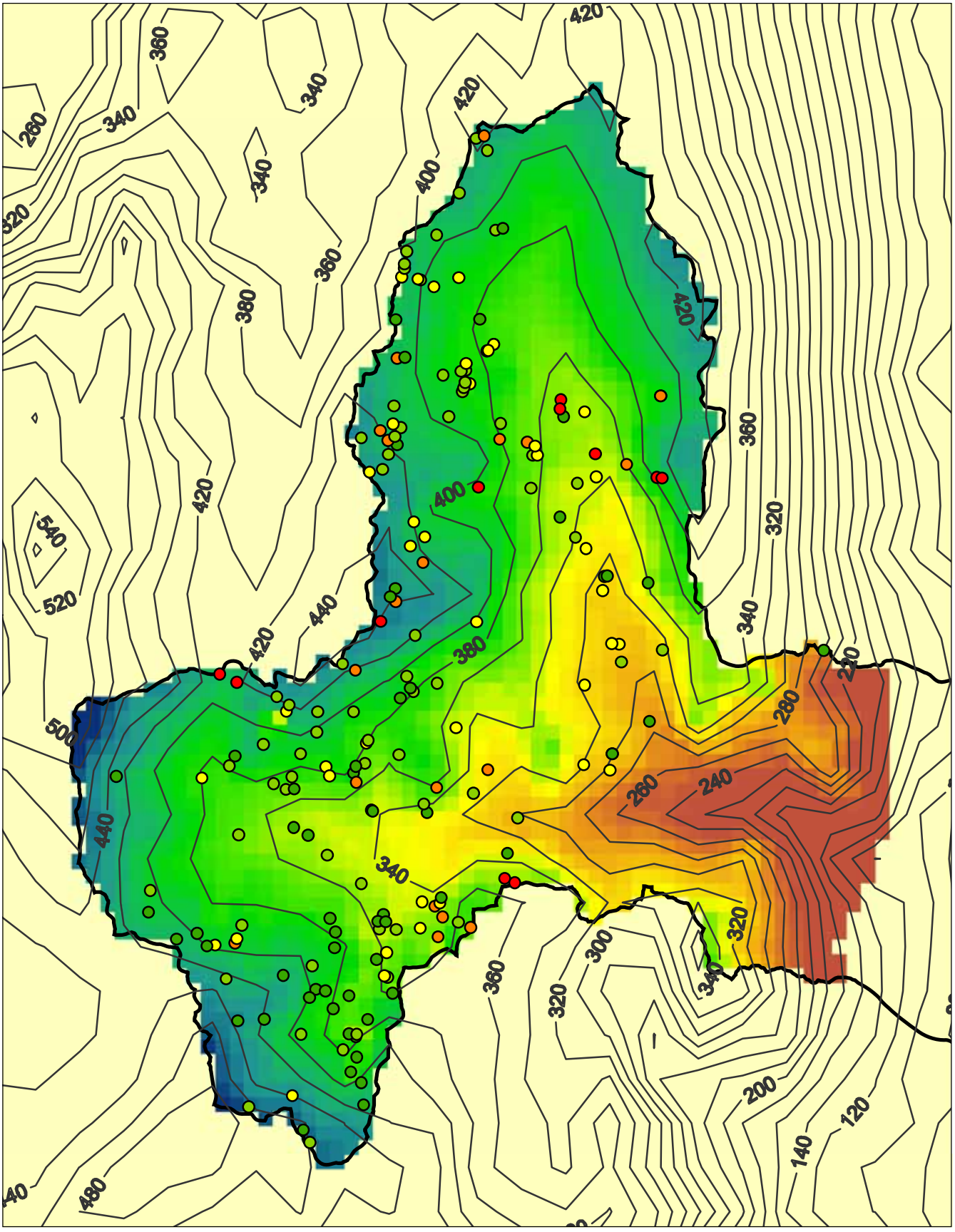

Figure 2.4 Upper Marne River Catchment Groundwater Potential Surface

Bore water EC (uS/cm)

- 105 - 2500
- 2501 - 5000
- 5001 - 7500
- 7501 - 10000
- 10001 - 17500

Marne River catchment boundary

Groundwater potential surface elevation (m AHD)

High : 500

Low : 100

GW potential contours (20 m)

Produced By: Mount Lofty Ranges Team
Knowledge and Information Division
Department of Water, Land and Biodiversity Conservation

Datum: Geocentric Datum of Australia 1994 (GDA 94).

Date: 22nd June 2006

N

0 1 2 3 4 5 km

© Government of South Australia, through the Department of Water, Land and Biodiversity Conservation 2007.
This work is Copyright. Apart from any use permitted under the Copyright Act 1968 (Cwlth), no part may be reproduced by any process without prior written permission obtained from the Department of Water, Land and Biodiversity Conservation. Requests and enquiries concerning reproduction and rights should be directed to the Chief Executive, Department of Water, Land and Biodiversity Conservation, GPO Box 2834, Adelaide SA 5001.

DISCLAIMER
The Department of Water, Land and Biodiversity Conservation, its employees and servants do not warrant or make any representation regarding the use, or results of use of the information contained herein as to its correctness, accuracy, currency or otherwise. The Department of Water, Land and Biodiversity Conservation, its employees and servants expressly disclaim all liability or responsibility to any person using the information or advice contained herein.

Government of South Australia
Department of Water, Land and Biodiversity Conservation

M:\Projects_GW\Mt_Lofty_Ranges\Marne 2006\Work_temp\Marne_Upper_Potl_Contours.mxd 22 June 2006 G. Green

There are no obvious trends in groundwater electrical conductivity (EC) across the catchment, which ranges from ~105–17 500 μS/cm (Fig. 2.4). The large variation in EC is likely to be a reflection of the irregular recharge processes, the variability of hydrogeological flow processes throughout the FRA systems, and the variable depth at which some of the bores are completed.

2.2 DRILLING PROGRAM

The site at Eden Valley was selected because the local geology and hydrogeology is thought to be representative of the northern region of the EMLR. The catchment in this area is characterised by high topography along the western margin, with an annual rainfall of ~700 mm/y, grading down to low topography with annual rainfall <400 mm/y on the eastern margin. Drilling reports and construction details of existing wells were used extensively in the site selection process, combined with geological field data measured at outcrops across the catchment. Fracture spacing, fracture aperture, strike and dip details were measured from outcrops, whilst well yields and EC measurements were retrieved from SA Geodata.

Two deep holes were drilled — an 8 inch hole to 60 m depth with 6 m of surface casing, and a 10 inch hole to 100 m depth, which was cased from zero to 60 m. Due to instability of the metasediments, the 8 inch hole had to be screened with slotted 150 mm PVC casing from the base of the 6 m steel casing to the bottom of the hole to prevent collapse. Drilling was completed in May 2003 by Frank Walsh Drilling Pty Ltd; the lithological logs are provided in Harrington et al. (2004).

2.2.1 EC, PH AND TEMPERATURE IN OPEN WELLS

EC, pH and temperature were measured, using a multi-parameter YSI Sonde®, for the 8 and 10 inch holes (Fig. 2.5). The EC in the 10 inch hole was at least 150 μS/cm higher than in the 8 inch hole. The pH profile in the 10 inch hole shows low pH in the first 60 m, and may reflect poor field sampling technique in which the probe was not allowed enough time to equilibrate prior to lowering the sonde down the hole. The temperature profiles in both the 8 and 10 inch holes match closely. Temperature decreases from ~18.5 °C at the surface to 15.5 °C at ~15 m depth, then steadily increases by 1.5 °C over the remainder of the profile to 100 m depth.

2.2.2 GEOPHYSICAL AND EM FLOW SURVEYS IN OPEN WELLS

Geophysical logs and EM Flowmeter surveys were recorded in the 8 and 10 inch holes. The caliper log and EM Flowmeter could not be conducted in the 8 inch hole because of the slotted PVC casing. The DWLBC Geophysical Technical Services group completed down-hole geophysical surveys for the following parameters:

- *Gamma log* — Measures natural presence of gamma rays. Aids in defining lithology changes, bed boundaries and clay content.
- *Neutron log* — Measures the amount of hydrogen around the probe. Can provide an indication of porosity and clay content (in combination with gamma).
- *Density (or gamma-gamma) log* — Gamma source and gamma receiver measures the electron density, which is a function of the bulk density of the formation. This can also be used for fracture identification in some instances.

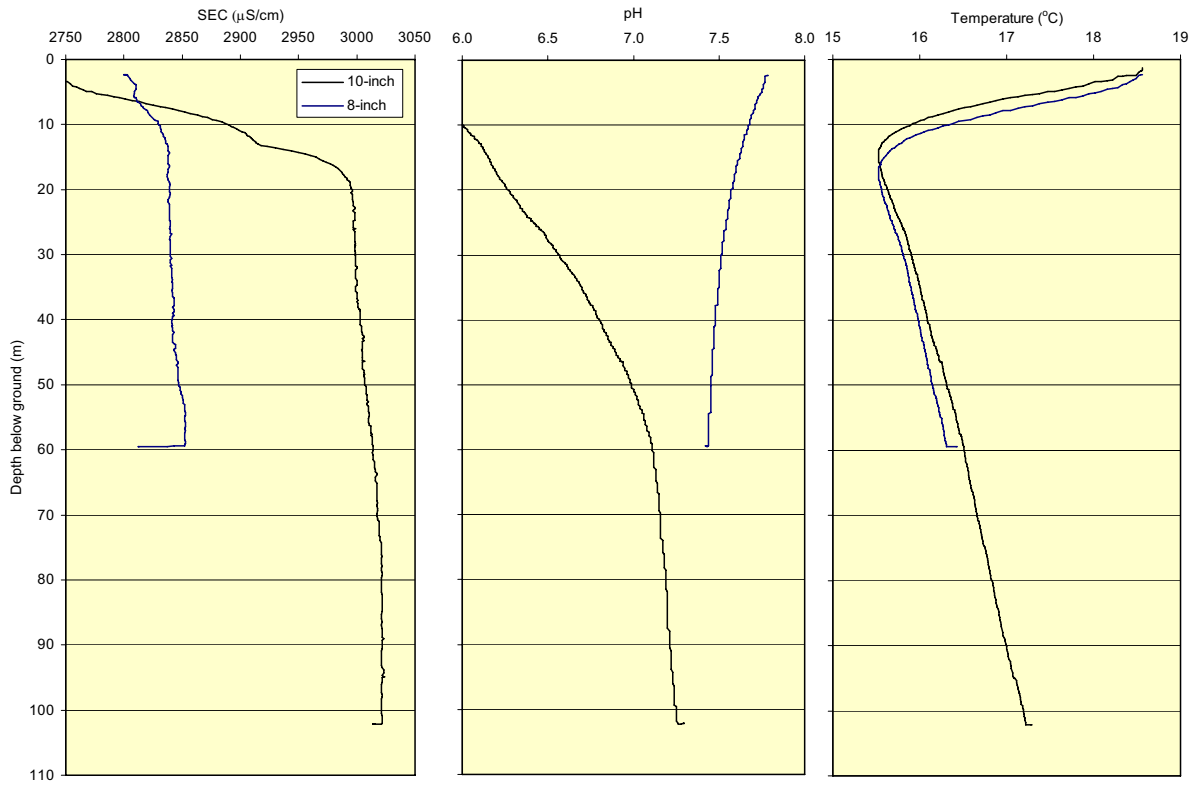

Figure 2.5. EC, pH and temperature variation with depth in the 8 and 10 inch open holes at the Eden Valley investigation site.

- *Induction (medium and deep) log* — The induction tool uses electromagnetics to sense the conductivity (inverse of resistivity) of the adjacent formation. Comparisons between deep and medium results can indicate porosity.
- *Point Resistance (PR) log* — Changes between a down-hole electrode and a reference surface electrode reflect changes in the formation resistivity. This can represent changes in porosity, water salinity, and fluid connectivity.
- *Caliper log* — Spring-loaded arms that press against the side of the hole and can indicate well and casing integrity. It can also be used to identify fractures in the lithology intercepted by the well.
- *EM Flowmeter* — Determines the vertical flow at discrete intervals sealed by inflatable packers under ambient and pumped conditions. Changes in flow can indicate groundwater either entering or leaving the well, indicating the presence of fractures.

Figure 2.6 shows the caliper and EM Flowmeter results from the 10 inch hole. The caliper log exhibits notable increases in the diameter of the hole at 65, 67.5, 75, 85 and 96 m depth, indicating significant fractures intercepting the hole. In the EM Flowmeter log, under ambient conditions, there is very little vertical flow in the hole, showing only a slight downward flow (<0.042 L/min) from 62–81 m, and a slight upward flow (<0.024 L/min) from 84–95 m. Under pumped conditions of 1 L/min, there is a significant groundwater contribution (>0.65 L/min) from 62–69 m. From 74–81 m, the groundwater contribution is significantly less (0.18 L/min), and vertical flow in the hole is insignificant below 81 m.

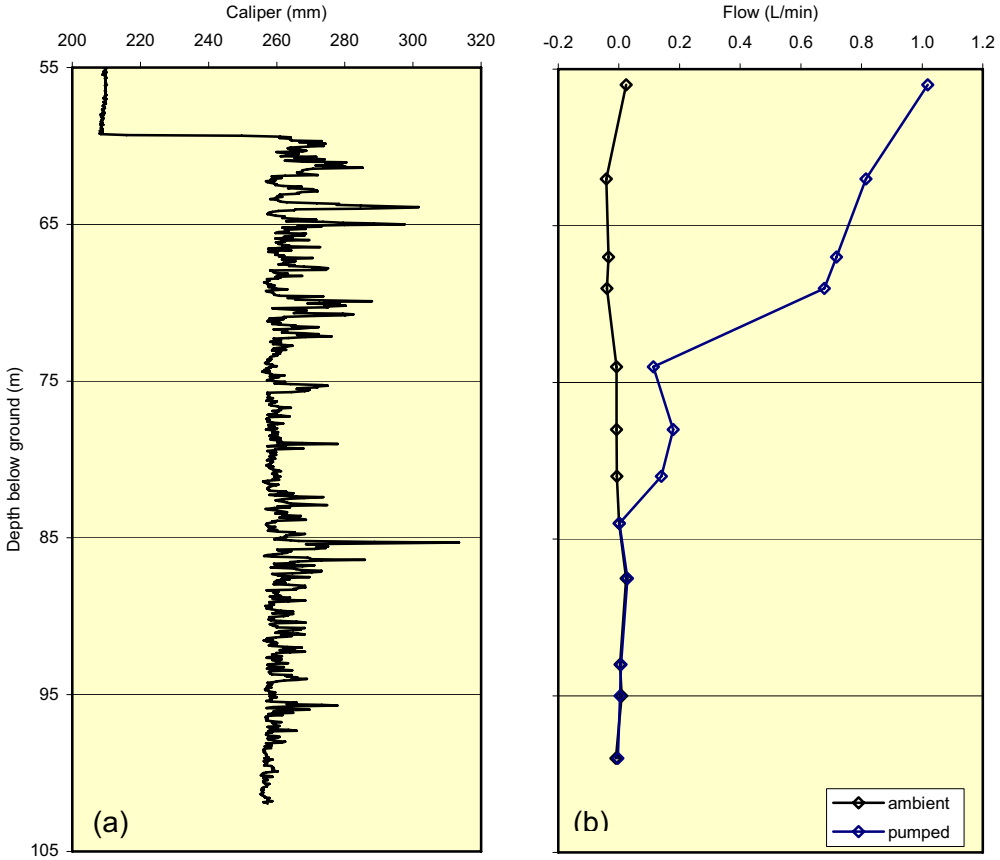

Figure 2.6. Caliper (a) and EM Flowmeter (b) profiles in the 10 inch open hole at the Eden Valley investigation site. Diamonds on the flowmeter profile represent intervals where the packers were inflated to measure flow.

The results have been used to aid in the definition of strata changes and identify the principle flow zones where the nested piezometer screen intervals have been set. FRA can display highly variable flow rates at different depth intervals due to complex and irregular fracture spacings, apertures and orientations, and hence it is necessary to conduct the geophysical investigations to ensure that the constructed piezometer nests will yield water.

2.2.3 PIEZOMETER INSTALLATION

A nest of four piezometers was installed in the open 10 inch hole. PVC casing of 50 mm diameter was used with slotted PVC screens positioned at intervals determined by the geophysical and EM Flowmeter surveys. The 8 inch hole could not be modified to a nested piezometer due to the slotted PVC casing over its entire depth. Three shallow piezometers were installed next to the 8 inch hole to provide discrete sampling points from the surficial regolith and weathered bedrock zones. A full description of their construction is listed in Table 2.1, and the corresponding lithological logs are provided in Appendix B.

Table 2.1. Construction details of the shallow and nested piezometers at the Eden Valley investigation site.

Unit number	Easting	Northing	Sample name	Ground elevation (m ASL)	Piezometer depth from ground (m)	TOC (PVC) above ground (m)	Screen Interval from ground (m)	Average RSWL (m ASL)
6728–3630	324635	6162505	E1	348.02	10.93	0.56	7.93–10.93	345.52
6728–3629	324635	6162503	E2	347.90	15.96	0.60	12.96–15.96	345.62
6728–3628	324634	6162502	E3	347.82	21.91	0.63	18.91–21.91	345.77
6728–3637	324632	6162494	E4	347.54	65.00	0.73	62–65	346.95
6728–3636	324632	6162494	E5	347.54	72.00	0.72	69–72	347.15
6728–3635	324632	6162494	E6	347.54	76.00	0.71	74–76	347.05
6728–3634	324632	6162494	E7	347.54	84.00	0.72	78–84	347.11
6728–3486	324633	6162498	E8	347.58	60.00	0.72	6–60	345.79

3. METHODOLOGY

3.1 INTRODUCTION

The following section describes the methodology used to understand the groundwater recharge mechanisms and flow processes at the Eden Valley investigation site. The approach used a suite of hydrochemical, isotopic and radiogenic tracers to investigate the apparent groundwater age, depth of circulation, vertical and horizontal flow rates, and sources of groundwater. Aquifer tests were also conducted to determine some of the physical characteristics of the aquifer systems.

3.2 GROUNDWATER AGES AND DEPTH OF CIRCULATION

3.2.1 MAJOR CHEMISTRY AND ISOTOPES

Prior to sampling the groundwater, the static water level was measured from top of casing (TOC) using an electric water level probe. The bores were then purged using a 12 volt Supertwister® submersible pump for the low-flow shallow piezometers and a Grundfos-MP1 submersible pump for the deeper piezometers. A YSI® multi-parameter meter was used to monitor the physical parameters of pH, EC, dissolved oxygen (DO), redox and temperature during purging. The meter was calibrated with known standards prior to use in the field. Samples were collected after the physical parameters had stabilised, indicating that the sample was representative of groundwater within the section of the aquifer sampled. The total alkalinity (assumed to be HCO_3^- for the ranges of pH sampled) was also measured in the field using a HACH titration kit.

Major ion analysis was conducted on the groundwater samples that had been filtered through a 0.45 μm membrane filter in the field. Cations (Na^+, Mg^{2+}, K^+, Ca^{2+}, NH_4^+) and trace elements were acidified with nitric acid (1% v/v HNO_3) to keep the ions in solution and analysed by Inductively Coupled Plasma Emission Spectrometry (ICP-ES). Anions (Cl^-, Br^-, SO_4^{2-} and NO_3^-) were analysed by ion chromatography (IC). Samples were also collected and analysed for the stable isotopes of the water molecule (deuterium (δ^2H) and oxygen-18 ($\delta^{18}O$)).

Adelaide is the closest rainfall station to the Marne River Catchment with rainfall isotopic data provided by the International Atomic Energy Agency (IAEA) Global Network of Isotopes in Precipitation (GNIP) service. For this study, only complete annual data sets from the GNIP database were used to derive the weighted average precipitation and the meteoric water line (MWL) for Adelaide ($\delta 2H = 7.25 \times \delta 18O + 7.9$).

Precipitation at any given location will display isotopic variation due to the effects of air temperature, latitude, altitude, amount of rainfall and distance from the water source (Dansgaard 1964). To determine the representative isotopic composition of rainfall, the

measured isotopic ratios of individual rainfall events are weighted by the amount of rainfall represented in each event. The weighted average precipitation gives greater influence to the isotopic values that represent the majority of precipitation.

The stable isotopes of the water molecule are conservative tracers (i.e. they remain conservative during passage through the unsaturated zone and record the rainfall signature modified by evapotranspiration) and provide information on physical processes of the hydrological system over time as opposed to a point in time such as the potentiometric surface. They are also not removed from water by exchange processes in most low temperature aquifer systems (Coplen et al. 1999). In particular, they can be used for the delineation of groundwater flow systems, determining the extent of the discharge zone beneath a water body, determining recharge processes, and for quantification of mass balance relationships.

3.2.2 CARBON-14 AND CHLOROFLUOROCARBONS

Groundwater samples were collected for chlorofluorocarbons (CFCs), carbon-14 (^{14}C) and dissolved inorganic carbon ($\delta^{13}C$) analysis to determine the apparent age of the water and provide information on the groundwater flow processes, including depth of circulation and vertical aquifer connection.

CFCs are stable organic compounds that were first manufactured in the 1930s and are solely from anthropogenic sources. Concentrations of CFCs in water vary as a function of the atmospheric partial pressures of CFCs and CFC solubility, which is a function of salinity and temperature, and can be used to determine apparent groundwater age. CFCs can be measured in groundwater that has been recharged since ~1940 or in a mixture of groundwater younger than 1940 with older waters. CFCs have been used as age indicators for groundwater studies since ~1979 (Szabo et al. 1996).

Processes that affect the CFC age include sorption, contamination, microbial degradation, hydrodynamic dispersion and soil gas diffusion in the unsaturated zone.

Analysis of ^{14}C can be used to support the CFC data and provide information for the older waters that are beyond the capacity of the CFC dating technique. For a radioactive environmental tracer, where radioactive decay is the dominant process causing change in activity and the input activity of the tracer is relatively constant, then the groundwater age (t) can derived by:

$$t = -\lambda^{-1} \ln\left(\frac{A}{A_o}\right) \qquad \textbf{Equation 3.1}$$

where λ is the decay constant [T^{-1}], A is the measured activity and A_o is the estimated initial activity.

One of the complications with interpretation of ^{14}C data is using an appropriate correction model to account for geochemical interactions that modify the initial activity (A_o) of ^{14}C at the time of recharge. The correction models include a chemical mixing model (Tamers 1967), isotopic dilution model (Pearson & Hanshaw 1970), and a complete soil gas exchange model (Fontes & Garnier 1979). The models require input of the chemical and isotopic end members of soil gas $\delta^{13}C$, ^{14}C and partial pressure of CO_2 (pCO_2), and carbonate mineral

$\delta^{13}C$ and ^{14}C, which can be measured from samples in the laboratory and also approximated using the computer code PHREEQC (Parkhurst & Appelo 1999).

3.3 VERTICAL FLOW RATES AND AQUIFER RECHARGE

3.3.1 CARBON-14 AND CHLOROFLUOROCARBONS

Vertical profiles of groundwater age have been used successfully to estimate rates of vertical groundwater flow in sedimentary aquifers (Cook & Bohlke 1999). Assuming that sampling takes place near the watertable, then the horizontal component of groundwater flow will be relatively small and the recharge rate (*R*) may be approximated by:

$$R = \frac{z\theta}{t} \qquad \textbf{Equation 3.2}$$

where *z* is the depth below the watertable, *t* is the groundwater age and θ is the porosity.

There are relatively few established and reliable techniques for estimating vertical flow rates in FRA (Love et al. 2002). One approach for determining vertical flow rates, and hence recharge rates, in FRA assumes that groundwater flow occurs through vertical, planar, parallel fractures with uniform matrix properties. This assumption also implies a vertical distribution of groundwater ages. It is therefore necessary to have knowledge of various aquifer parameters including fracture aperture (*2b*) that is determined from aquifer tests, fracture spacing (from fracture mapping) and estimates of the matrix diffusion coefficient (see equation 3.3). Where fracture orientations and distribution are more complex, groundwater ages are more likely to represent depth of groundwater circulation than provide information on vertical flow rates (Love et al. 2002).

For a conservative tracer with a constant source and subject to radioactive decay, the concentrations within the fractures can be related to vertical flow within the fractures by:

$$V_w = \left[1 + \frac{\theta_m D^{1/2}}{b\lambda^{1/2}} \tanh(BD^{-1/2}\lambda^{1/2})\right] \Big/ \left[\frac{\delta t_a}{\delta z}\right] \qquad \textbf{Equation 3.3}$$

(after Neretnieks 1981) where V_w is the water velocity in the fracture [LT^{-1}], *b* is the fracture half-aperture [L], *B* is the fracture half-spacing [L], θ_m is the matrix porosity [unitless], *D* is the effective diffusion coefficient within the matrix [L^2T^{-1}], λ is the decay constant [T^{-1}], and $\delta t_a/\delta z$ is the age gradient [T/L]. The decay constant for ^{14}C is 1.21×10^{-4}/y. Cook and Simmons (2000) substituted the ^{14}C decay constant with the exponential growth rate for CFC-12 (k=0.06/y) to determine vertical flow rates from CFC-12 age gradients.

The mean volumetric flow rate through the fracture, Q_v [$L^3\ T^{-1}$] is given by:

$$Q_v = V_w \frac{b}{B} \qquad \textbf{Equation 3.4}$$

[L is length and T is time].

3.3.2 AQUIFER PUMPING TESTS

Single-well pump tests were conducted on several of the piezometers using the Cooper-Jacob straight-line method (Fenner 2001) to determine the bulk hydraulic conductivity over the length of the screen interval. Pump tests are typically more suited to sedimentary systems, but their application to nested piezometers can provide valuable information on the vertical variation of hydraulic conductivity, and can be used to derive other physical characteristics of the aquifer (Cook 2003).

Having determined the bulk hydraulic conductivity over the screened interval from the aquifer tests, the equivalent average fracture aperture ($2b_{eq}$) can be derived from the following equation:

$$K_b = \frac{\rho g (2b)^3}{12\mu(2B)} \qquad \textbf{Equation 3.5}$$

then by rearranging to solve for $2b_{eq}$:

$$2b_{eq} = \left(\frac{12\mu(2B)K_b}{\rho g} \right)^{1/3} \qquad \textbf{Equation 3.6}$$

where K_b is the bulk hydraulic conductivity over the test interval [LT^{-1}], p is the fluid density [ML^{-3}], g is acceleration due to gravity [LT^{-2}], $2b$ is the fracture aperture [L], μ is the dynamic viscosity [MT./L] and $2B$ is the fracture spacing [L], which we have assumed to be the same as that in nearby outcrops of similar lithology (L is length, T is time, M is mass).

3.3.3 CHLORIDE MASS BALANCE

Groundwater recharge rates can also be estimated using the chloride mass balance (CMB) technique. The method assumes that the only source of chloride in groundwater is via rainfall, that the rate of chloride accession to the landscape is constant, and that there are no sources or sinks of chloride in the subsurface. The following steady state mass balance equation can be used to estimate recharge (R):

$$R = \frac{(P - RO)}{C_{gw}} C_p \qquad \textbf{Equation 3.7}$$

where P is the mean annual precipitation rate [L], RO is the annual runoff rate [L], C_p is the chloride concentration in the precipitation [M/L], C_{gw} is the chloride concentration in groundwater (recharge water) [M/L].

The CMB technique has been used successfully in sedimentary aquifer systems and has been suggested the most reliable technique for determining recharge rates to FRA systems (Cook 2003). However, the recharge rate determined from CMB should be considered as a minimum because of the addition of other sources of chloride. Changes in environmental conditions (i.e. vegetation clearing) will also impact on the equilibrium of chloride in the fractures within the rock matrix and may take a significant amount of time for the diffusion of salts from the matrix into the fractures to re-equilibrate.

Cook et al. (1996) derived a simple approach to determine the approximate time (t) required for the chloride concentration in the matrix to become the same as in the water flowing through the fractures by:

$$t \geq \frac{(2B)^2}{2D}$$ **Equation 3.8**

where 2*B* is the fracture spacing [L] and *D* is the effective diffusion coefficient for the aquifer matrix. Therefore, assuming $D = 10^{-4}$ m^2/y, for *2B* = 1 m, *t* ≥5000 years and for *2B* = 0.1 m, t ≥50 years.

3.4 HORIZONTAL FLOW RATES

3.4.1 RADON

Radon (^{222}Rn) is a radioactive, inert gas that is generated from the decay of uranium and thorium series isotopes in the aquifer matrix. It has a half-life of ~3.8 days, is highly soluble in water, and its concentration will depend on the mineralogy of the aquifer and the pore space geometry (Love et al. 2002).

Cook et al. (1999) developed a technique to estimate horizontal flow rates by comparing unpurged to purged radon concentrations from piezometers, where a purged sample is assumed to be representative of the concentration of radon in the aquifer. For high horizontal flow rates, the concentration of radon of an unpurged sample, measured over the length of the screen of the piezometer, will be similar to the concentration of a purged sample from the piezometer. If the horizontal flow rate were low then the concentration of radon of an unpurged sample would have decayed to background levels. Hence, the ratio of radon concentration from an unpurged sample to a purged sample will depend on the amount of radioactive decay, which occurs as the water moves through the well under natural flow conditions. Assuming a perfectly mixed well, the groundwater flow rate *q* [LT^{-1}] is given by:

$$q = \frac{c}{c_0 - c}\frac{\lambda \pi r}{2}$$ **Equation 3.9**

where *c* and c_0 are the radon concentrations in the well and in the aquifer respectively, *r* is the well radius [L] and λ is the decay constant for radon (0.18/d). Groundwater flow rates calculated by this method refer to groundwater flow within the well. Due to hydrodynamic dispersion, the horizontal flow rate within the well will be higher than in the aquifer. To estimate flow within the aquifer, the calculated flow rate needs to be multiplied by a factor of 0.5 for an open well or 0.25 for a piezometer.

4. GROUNDWATER FLOW

4.1 INTRODUCTION

This chapter provides an examination and interpretation of the data sets that were used to establish a conceptual model of groundwater recharge mechanisms, horizontal flow processes and sources to the aquifer systems at the Eden Valley investigation site.

4.2 GROUNDWATER AGES AND DEPTH OF CIRCULATION

4.2.1 MAJOR CHEMISTRY AND ISOTOPES

The groundwater samples collected from the Eden Valley investigation site are shown on a Piper plot in Figure 4.1. The samples from the three upper piezometers are of Mg–Na–Ca–Cl type, whilst the majority of the samples from the deeper piezometers are of Na–Ca–Mg–Cl–SO_4 type. The compositions of all samples are dominated to a greater extent by sodium and chloride ions indicating that the water is of marine aerosol origin, but there is some contribution from atmospheric precipitation (partial dissolution of dust particles) or acquisition during weathering and water–rock interactions.

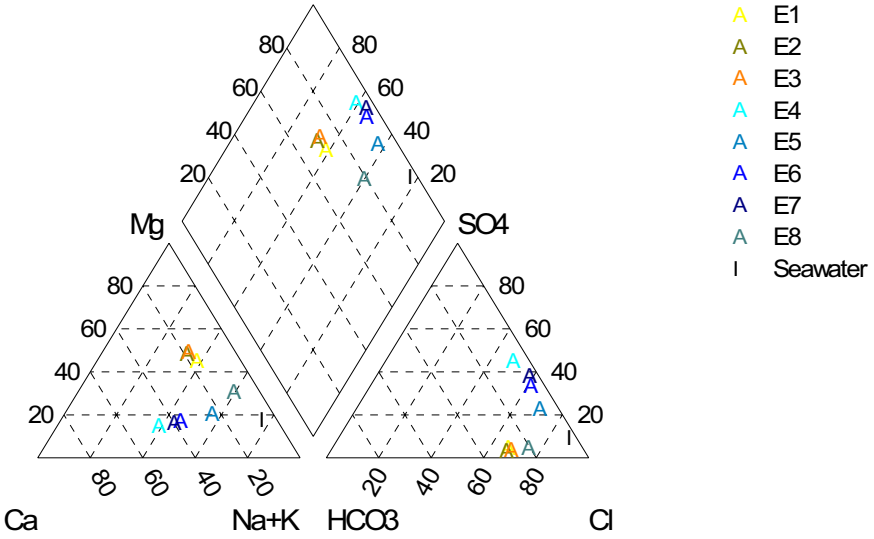

Figure 4.1. Piper plot of groundwater samples collected at the Eden Valley investigation site, September–November 2005.

Figure 4.2 shows the measured TDS, EC, pH, δ^2H and chloride profiles, each increasing with depth, at the Eden Valley investigation site. There appears to be two main flow systems at the site indicated by the step-like increase occurring between 20.4–63.5 m depth below ground. The TDS in the upper system (~1000 mg/L) is significantly lower than in the deeper system (~2500 mg/L). The deuterium profile shows depletion in the isotopic signature from

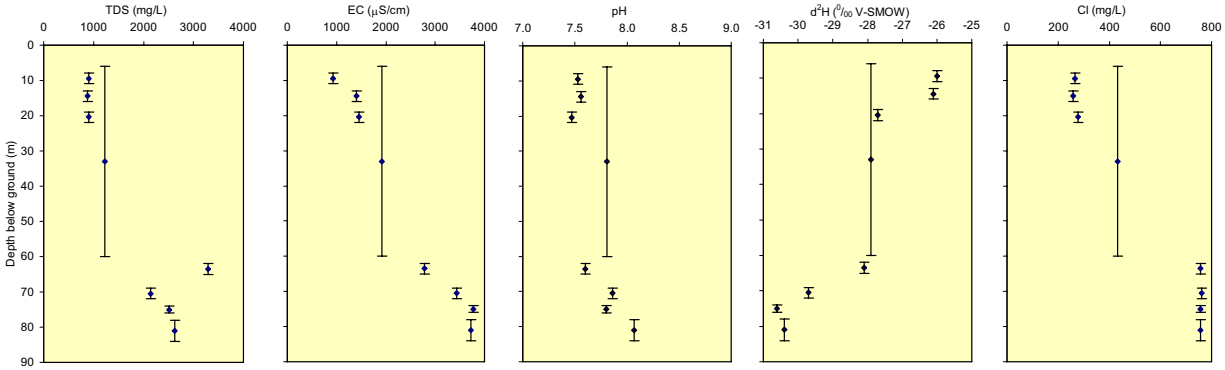

Figure 4.2. TDS, EC, pH, δ^2H and chloride profiles sampled at the Eden Valley investigation site, September–November 2005. The average watertable depth was 2 m below ground for November 2005 when sampling was completed. The error bars represent the length of screen of the piezometer from which the sample was taken.

about -26‰ at 9.4 m to -31‰ at 75 m depth. The sample collected from the 8 inch hole completed with slotted casing is representative of a mixed sample of the upper and deeper flow system over the 54 m interval. The chloride profile in the four deepest piezometers shows little variation with depth compared to the TDS profile at the same intervals, which suggests that there are additional sources to the other major ion concentrations.

According to the lithological logs (Harrington et al. 2004) there is a boundary between the weathered metasandstone–metasiltstone and unweathered metasiltstone at ~50 m depth. If this is the case, then it can be inferred that the regolith and weathered bedrock represent an upper flow system that has vertical circulation in the top ~50 m and a deeper fractured rock system (unweathered metasiltstone) below ~50 m. The inability to install screened piezometers between 20.4–63.5 m depth makes it difficult to pinpoint the extent of vertical circulation demonstrated by the chemistry data.

To examine the relationships of major element species against chloride, relative to the dilution of a seawater aerosol, composition diagrams are used. Figure 4.3 shows the concentrations of major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_4^{2-} and HCO_3^{-}) against chloride for groundwater samples at the Eden Valley site. Chloride generally does not participate in common geochemical reactions that occur in aquifers and subsequently behaves as a conservative tracer until halite saturation is reached (Herczeg & Edmunds 1999). Sodium versus chloride ion concentrations show a slight increase in concentration in the deeper piezometers, indicating processes of water–rock interaction, which would be expected given the greater residence time of water in the deeper system.

The calcium, sulphate and bicarbonate versus chloride plots indicate that there are additional sources to the calcium, sulphate and bicarbonate ion concentrations in the deeper part of the aquifer (63.5–89 m) other than a contribution from rainfall, which is characterised by a seawater signature. It has been inferred that a large proportion of the concentration of these ions in the deeper piezometers represents contamination from cement and/or gypsum. A cement seal was used between each of the nested piezometers to prevent vertical leakage between the piezometers. The sodium, magnesium and potassium ion to chloride ratios show very little variation over the 63.5–89 m interval, which is expected as they are not major constituents in the ingredients of cement. The calcium versus sulphate ion concentrations

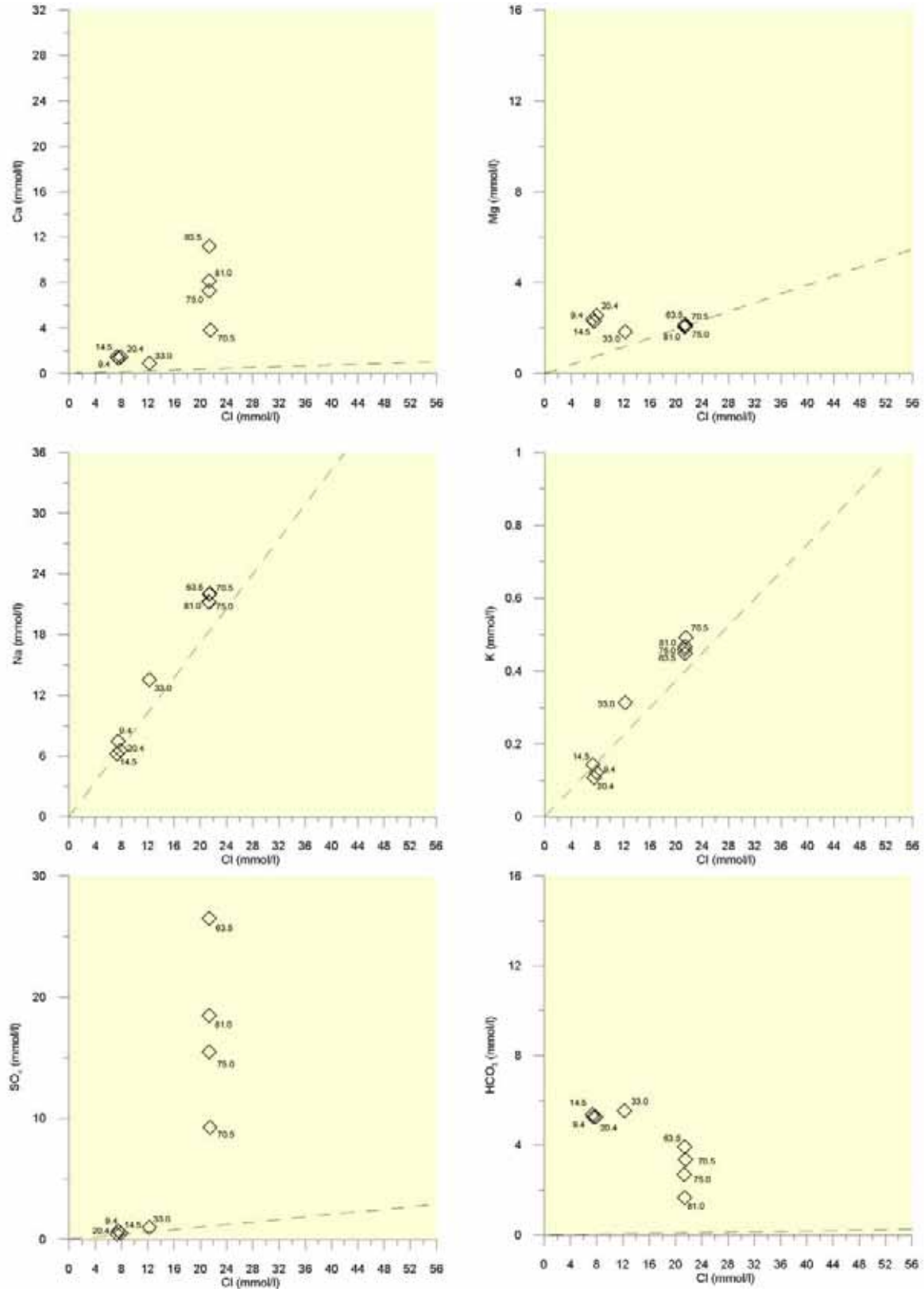

Figure 4.3. Composition diagrams of major ions versus chloride sampled at the Eden Valley investigation site, September–November 2005. The dashed line is the dilution line for seawater. Piezometer mid-screen depths are shown beside each point.

show that the samples from the deeper piezometers plot along a straight line with increasing concentrations compared to the shallow piezometers, which have a similar composition (Fig. 4.4). It can be inferred that the deeper piezometers are all contaminated from the same source of Ca^{2+} and SO_4^{2-}.

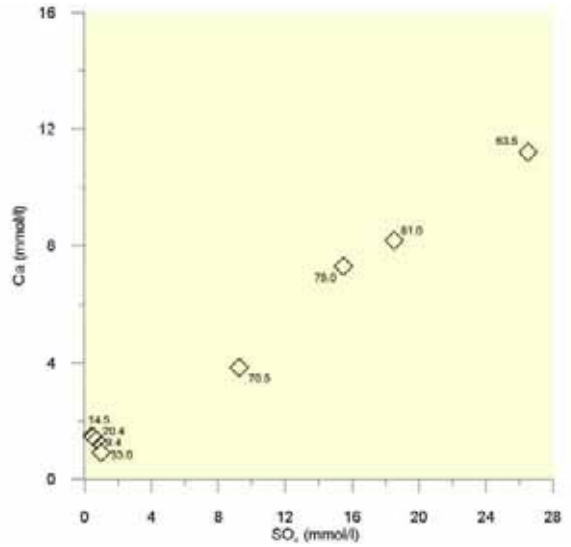

Figure 4.4. Calcium versus sulphate sampled at the Eden Valley investigation site, September–November 2005. Piezometer mid-screen depths are shown beside each point.

The pH profile (Fig. 4.2) supports this argument, showing significant variation between 63.5–89 m depth within the same lithological type. It was also noted in the field that a white–grey milky substance was being removed from the deeper piezometers when purging and pH values of greater than 9 were observed. Well construction investigations by Nielsen (1991) reported that high pH values are typical for wells contaminated with alkaline grout (cement and/or bentonite) used to seal the annular space during well completion. Initial sonding of the 8 and 10 inch holes prior to piezometer installation showed a fairly constant pH (~7) over the entire depth of the holes (Fig. 2.5).

The magnesium and bicarbonate versus chloride plots show a higher concentration of these ions in part of the shallower aquifer (chloride concentration <8 mmol/L), which is much greater than the dilution line for seawater and the concentrations from the deeper aquifer. This may be a result of more active cation exchange processes occurring through processes of rock weathering in the upper regolith and weathering zone (Fig. 4.3).

The major ion to chloride ratios plotted against depth show more clearly that there are two different flow systems at the Eden Valley site. Additional contributions from other sources to the ion concentrations, relative to the ion to chloride ratios of seawater, are also apparent. The calcium, sulphate and bicarbonate ion to chloride ratios in the upper system (at least 20.4 m in depth) are similar, whilst the same ion ratios in the deeper flow system (greater than 20.4 m depth) display large variability over 63.5–89 m (Fig. 4.5).

It is reasonable to assume that the different geological features (fracture aperture and spacing, degree of weathering) above and below ~50 m coincides with the boundary between the two flow systems, and if it were possible to sample the hydrochemistry directly above and below this depth it is anticipated that an inflection point would be observed.

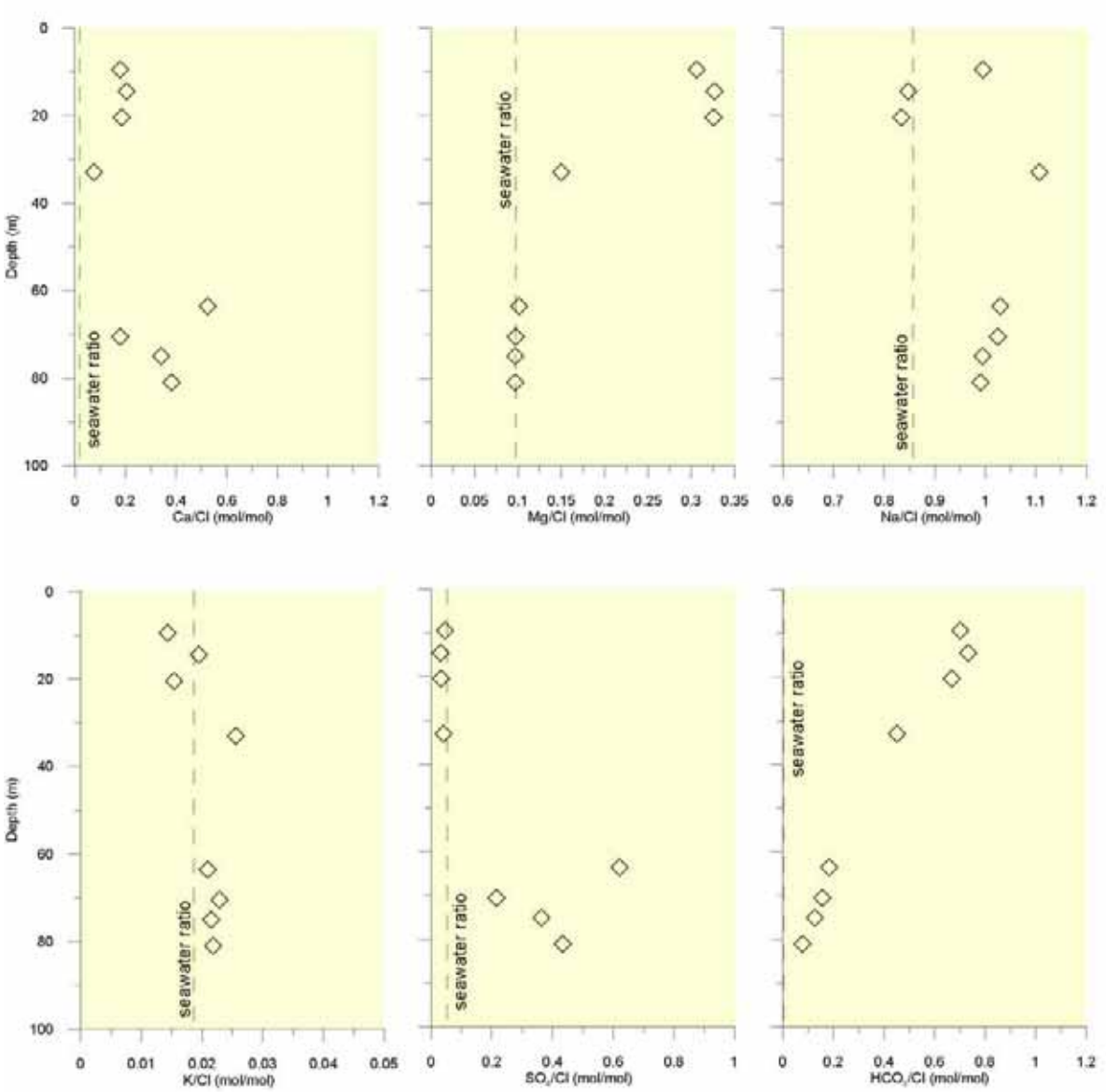

Figure 4.5. Major ion/Cl ratio profiles sampled at the Eden Valley investigation site, September–November 2005. The dashed line is the major ion/Cl ratio for seawater. The average watertable depth was 2 m below ground for November 2005 when sampling was completed.

The isotopic signatures of groundwater samples from the Eden Valley investigation site plot to the left of the mean weighted rainfall for Adelaide (δ^2H = -4.7‰ and δ^{18}O = -26.3‰) and along the meteoric water line (based on local Adelaide rainfall events; Fig. 4.6). Waters plotting along the MWL and below the weighted average rainfall (more depleted signature) are indicative of seasonal recharge of autumn and winter rainfall events, and/or altitude effects. Altitude is a temperature-related effect and results in reducing both δ^{18}O (~0.15–0.5‰ per 100 m) and δ^2H (~1–4‰ per 100 m) values (Clark & Fritz 1997). The elevation difference between Adelaide and Eden Valley is 400–500 m and therefore the depleted groundwater isotopic values can be attributed to altitude effects. However, observations of higher rainfall and increased watertable elevations during autumn and winter in the UMRC provide evidence of seasonal recharge effects. Cooler rainfall would result in lower groundwater isotopic values compared to the values of average rainfall in Adelaide.

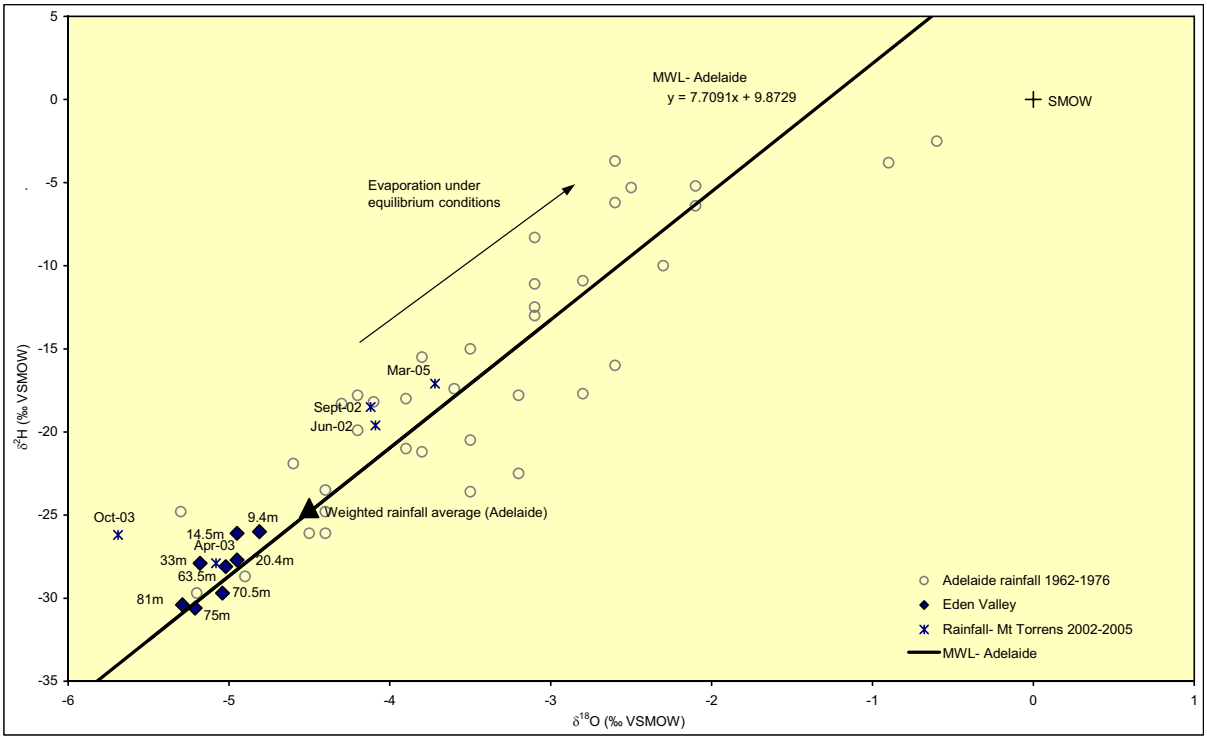

Figure 4.6. Isotopes δ^2H and $\delta^{18}O$ of the groundwater samples collected at the Eden Valley investigation site, September–November 2005, and rainfall samples collected at Mount Torrens stream gauging station 2002–05. The MWL for Adelaide is δ^2H = 7.7 $\delta^{18}O$ + 9.6. The mean weighted rainfall for Adelaide is δ^2H = -6.3‰$_{VSMOW}$ and $\delta^{18}O$ = -4.6‰$_{VSMOW}$. SMOW is standard mean ocean water.

Rainfall samples collected from the Mount Torrens gauging station (nearest representative rainfall samples to Marne River Catchment) between June 2002 and March 2005 have isotopic signatures that fall next to the MWL. The sample collected in October 2003 has a slightly more enriched signature suggesting that was subjected to secondary evaporation prior to collection.

4.2.2 CARBON-14 AND CHLOROFLUOROCARBONS

CFC-12 concentrations decrease with depth and are at or below detection limit (<25 pg/kg) at depths greater than 63.5 m (Fig. 4.7). This implies that circulation of modern water (less than 40 years old) extends no greater than ~63.5 m depth. The high ^{14}C (>70 pmC) present at depths less than 63.5 m is due to a thermonuclear component released from atomic testing into the atmosphere during the 1950s and 1960s. The thermonuclear component supports the presence of post-1960 CFC-12 concentrations at the equivalent piezometer depths and hence circulation of modern water.

The hydrochemistry data highlighted that the four deepest piezometers had elevated concentrations of calcium and sulphate ions from an additional source. This is likely to have influenced the ^{14}C activities from these groundwater samples, and as a result the estimated age of the water cannot be used as an absolute value in a quantitative manner. However, the results are still useful in understanding processes occurring in the deeper part of the aquifer system and providing a minimum recharge estimate.

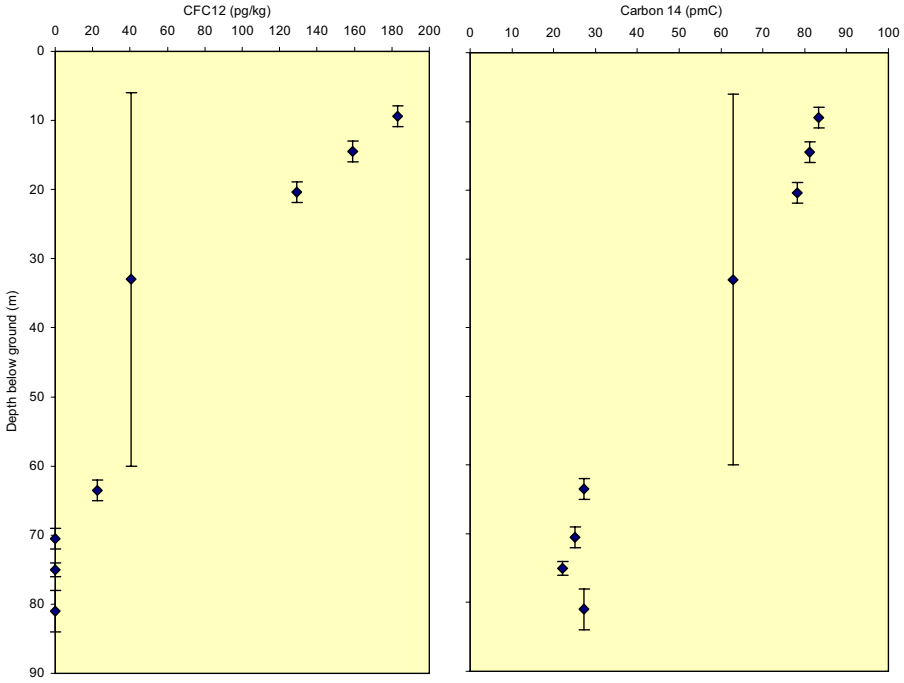

Figure 4.7. CFC-12 and carbon-14 profiles from the nested piezometer at the Eden Valley investigation site. The average watertable depth was 2 m below ground for November 2005 when sampling was completed. The error bars represent the length of screen of the piezometer from which the sample was taken.

The CFC-12 concentration and ^{14}C activities represent relative groundwater ages. The step-like decrease between 20.4–63.5 m depth depicts an abrupt increase in age of the groundwater. The age gradient shows that there is fairly rapid circulation of groundwater above 20.4 m and a gradual decrease in water movement with increasing depth. The step-like decrease coincides with the trends observed in the chemistry and isotopic data (Fig. 4.2), which correspond to a change in the lithology.

4.3 VERTICAL FLOW RATES AND AQUIFER RECHARGE

4.3.1 CARBON-14 AND CHLOROFLUOROCARBONS

Using equation 3.6, the equivalent fracture aperture ($2b$), obtained from the shallow piezometers located in the regolith and weathered fractured rock, is equal to 360 μm with a groundwater velocity through the fractures of 40 m/d. A mean fracture spacing of $2B$, equal to 0.21 m, and a bulk hydraulic conductivity of K equal to 14 m/d was applied according to outcrop measurements and single-well aquifer tests, respectively. Values of matrix diffusion coefficient (D) and matrix porosity (θ_m) were assumed to be equal to 10^{-4} m^2/y and equal to 0.02, respectively.

The average bulk hydraulic conductivity is 0.03 m/d determined from aquifer tests conducted on the piezometers located in the unweathered fractured rock. Assuming a fracture spacing of 0.21 m then the fracture aperture is 49 μm, significantly smaller than the spacing measured in the upper lithology. Subsequently, the flow velocity through the fracture would be 0.7 m/d.

The values of the matrix diffusion coefficient and matrix porosity are the same as those used in the investigation by Love et al. (2002) in the Clare Valley where the targeted geology type was the Saddleworth Formation. This formation is dominated by siltstone, shale and dolomite, and has similar characteristics to the Kanmantoo Group found at the Eden Valley site.

Figure 4.8 shows the apparent CFC-12 and ^{14}C uncorrected age of the groundwater at the Eden Valley investigation site. The vertical CFC-12 age gradient in the upper flow system (first three piezometers) is 0.61 y/m (7 y/11.5 m). Using the results from the aquifer tests in the shallow piezometers, together with outcrop measurements, the average vertical flow rate (V_w) in the fracture is 11 m/y and the aquifer recharge rate (Q_v) is 16 mm/y. Values of matrix diffusion coefficient (D) and matrix porosity (θ_m) were assumed to be equal to 10^{-4} m^2/y and 0.02, respectively. Given that there is a ^{14}C thermonuclear component (>75 pmC) in the upper three piezometers, it can be inferred that the vertical ^{14}C groundwater age gradient over ~20 m depth is 2.5 y/m (50 y/20 m). Assuming the same physical characteristics of the aquifer, the average vertical flow rate in the fracture is 6 m/y and the aquifer recharge rate is 9 mm/y.

The vertical ^{14}C gradient in the deeper aquifer system (Fig. 4.8) is ~152 y/m (1747 y/11.5 m). Assuming the same fracture spacing, $2B$ equal to 0.21 m, a fracture aperture of 49 μm, D equal to 10^{-4} m^2/y and θ_m equal to 0.02, the average vertical flow rate (V_w) in the fracture is 0.32 m/y and the aquifer leakage rate (Q_v) is 0.14 mm/y. These values are significantly lower than those determined in the upper system.

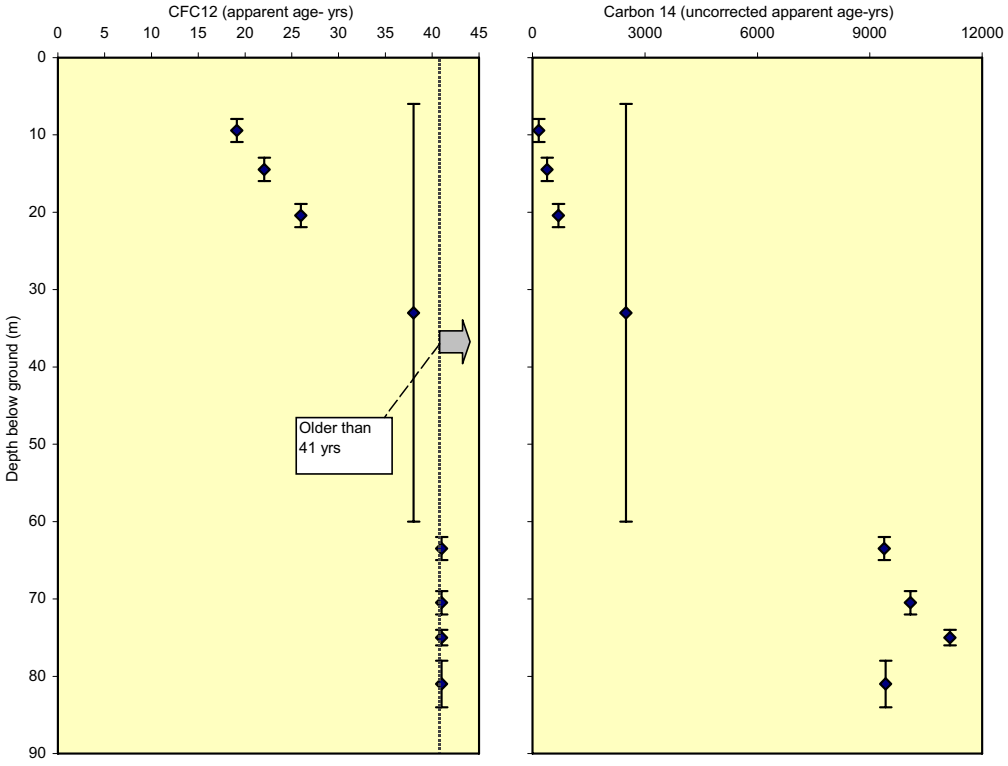

Figure 4.8. Apparent age (CFC-12 and ^{14}C) profiles from the nested piezometer at the Eden Valley investigation site, September–November 2005. The average watertable depth was 2 m below ground for November 2005 when sampling was completed. The error bars represent the length of screen of the piezometer from which the sample was taken.

The accuracy of these estimates depends largely on the estimated fracture spacing, matrix porosity and matrix diffusion coefficient and, to a lesser extent, the hydraulic conductivity (Cook & Simmons 2000).

If the aquifer system at the Eden Valley site is considered to be representative of a homogenous unconfined sedimentary aquifer then, using equation 3.2, the average recharge rate determined from the measured CFC-12 concentrations in the upper three piezometers would be ~27 mm/y, if a porosity value of 0.05% is assumed.

Figure 4.9 compares the measured CFC-12 concentrations with results from an equivalent porous media model for recharge rates of 10, 20, 35, 50 and 70 mm/y. The samples collected from the three piezometers in the upper aquifer system plot between the 10–35 mm modelled recharge rates, whilst the mixed sample from the slotted 8 inch casing plots between the 35–50 mm modelled recharge rates.

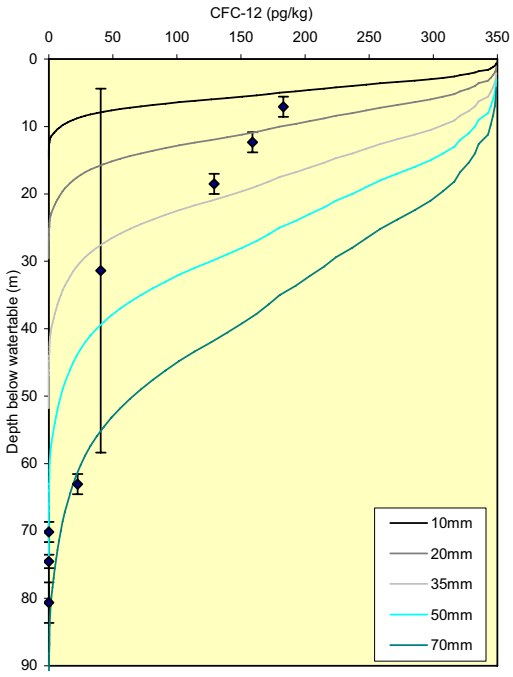

Figure 4.9. Comparison of measured CFC-12 concentrations from the Eden Valley investigation site with results from an equivalent porous media recharge model below the watertable. The error bars represent the length of screen of the piezometer from which the sample was taken.

4.3.2 CHLORIDE MASS BALANCE

Figure 4.10 shows the recharge estimates according to the CMB method across the UMRC. Annual precipitation values nearest to the bore locations were extracted from an interpolation of rainfall isohyet data produced by the Bureau of Meteorology. Precipitation ranged from 700 mm/y on the higher western margin of the catchment to 400 mm/y on the lower eastern margin, near the Palmer Fault, where it continues to decrease out into the Murray Basin. The chloride concentration in rainfall is assumed to be 5.6 mg/L according to measured chloride concentrations from collected rainfall at the Mount Torrens stream gauging station (2002–05), and an annual runoff rate equal to 10% of precipitation. Chloride concentrations

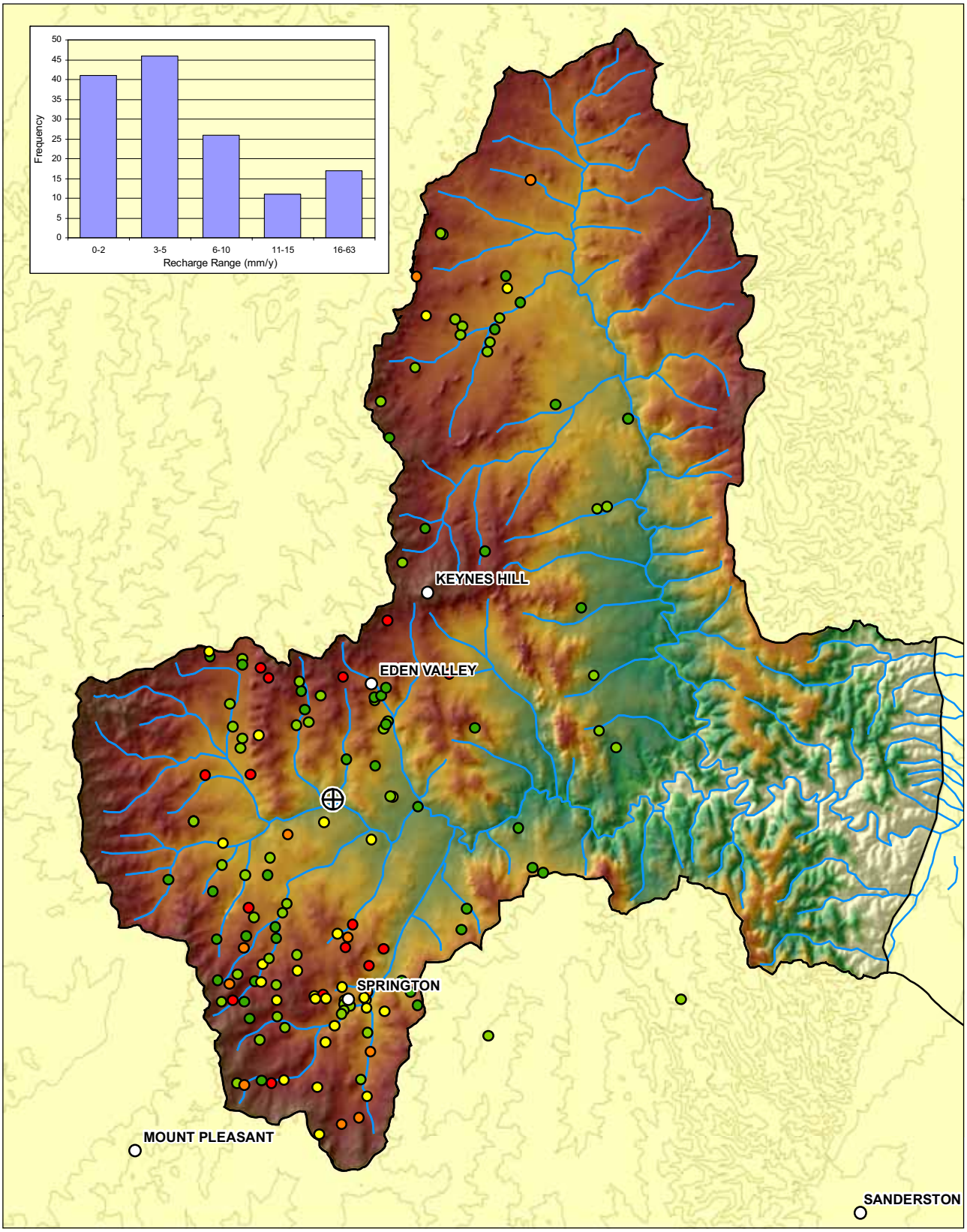

Figure 4.10 Upper Marne River Catchment Recharge Estimates (Chloride Mass Balance)

GW sample locations

Recharge estimate (mm/yr)

- 1 - 2
- 3 - 5
- 6 - 10
- 11 - 15
- 16 +

Marne catchment boundary

Eden Valley investigation site

Elevation (m ASL)

High : 540 metres

Low : 100 metres

Streams

Topographic contours (40m)

Town

0 2 4 6 km

N

Produced By: Mount Lofty Ranges Team
Knowledge and Information Division
Department of Water, Land and Biodiversity Conservation

Datum: Geocentric Datum of Australia 1994 (GDA 94).

Date: July 2007

© Government of South Australia, through the Department of Water, Land and Biodiversity Conservation 2007.
This work is Copyright. Apart from any use permitted under the Copyright Act 1968 (Cwlth), no part may be reproduced by any process without prior written permission obtained from the Department of Water, Land and Biodiversity Conservation. Requests and enquiries concerning reproduction and rights should be directed to the Chief Executive, Department of Water, Land and Biodiversity Conservation, GPO Box 2834, Adelaide SA 5001.

DISCLAIMER
The Department of Water, Land and Biodiversity Conservation, its employees and servants do not warrant or make any representation regarding the use, or results of use of the information contained herein as to its correctness, accuracy, currency or otherwise. The Department of Water, Land and Biodiversity Conservation, its employees and servants expressly disclaim all liability or responsibility to any person using the information or advice contained herein.

Government of South Australia
Department of Water, Land and Biodiversity Conservation

M:\Projects_GW\MtL_Lofty_Ranges\Marne 2006\Work_temp\Marne_Upper_Chloride.mxd July 2007 G. Green

measured from the bores throughout the catchment ranged from ~50–6500 mg/L, and were sampled as early as 1938. More than 60% of the recharge estimates were <5 mm/y, indicating that a very small proportion (0.7–1%) of rainfall recharges the aquifer system.

The recharge estimates according to the CMB method at the Eden Valley site ranged from ~9 mm/y in the upper system to 3 mm/y in the deeper aquifer flow system (Fig. 4.11). The chloride concentration in the deeper piezometers is more than triple the concentration in the shallow piezometers and hence recharge estimates are approximately one-third of those for the upper flow system.

The differences in recharge estimates between the shallow and deep aquifer system may reflect the effects of recent vegetation clearing on the equilibrium of chloride between the matrix and the fractures. Using equation 3.8, the approximate time taken for the chloride in the matrix to reach equilibrium with that of the fractures would be 220 years. This assumes an effective diffusion coefficient (D) of 10^{-4} m^2/y and fracture spacing ($2B$) of 0.21 m. This is greater than the length of time since clearing of native vegetation and hence would suggest that equilibrium has not yet been reached in the aquifer system. To highlight the importance of fracture spacing, if the fracture spacing were reduced to 0.1 m then the time to reach equilibrium would be 50 years.

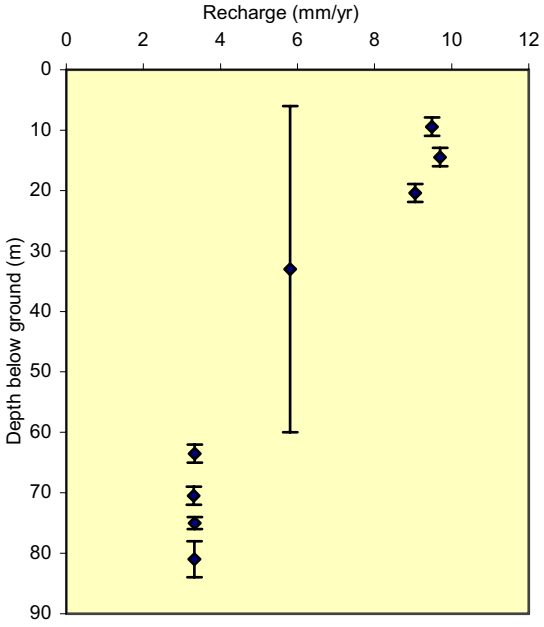

Figure 4.11. Vertical distribution of recharge estimates according to the CMB method at the Eden Valley investigation site. The error bars represent the length of screen of the piezometer from which the sample was taken.

4.4 HORIZONTAL FLOW RATES

4.4.1 RADON

In the piezometers at 14.5 and 20.4 m depth, the radon concentrations measured prior to purging (0.3–0.5 Bq/L) are similar to background concentrations, indicating that there is little water movement (Fig. 4.12). In the deeper piezometers (63.5–81 m depth), prior to purging

the radon concentrations are greater (12–66 Bq/L) during September 2005 and have significant vertical variation compared to the samples taken during March 2006 (6–16 Bq/L). The vertical variation in the deeper piezometers sampled during September 2005 are likely to be a result of extended pumping where the unpurged sample contains a mixture of water from the piezometer and from the aquifer.

After purging the piezometers, the radon concentrations increased significantly, representing water sampled directly from the aquifer. The radon concentrations increased from 0.5–65 Bq/L at 20.4 m and from 12–122 Bq/L at 75 m depth during September 2005. In March 2006 the radon concentrations increased from 16–212 Bq/L at 75 m depth. The increase in radon concentration in the deeper piezometers compared to the shallow piezometers most likely reflects a change in lithology from the regolith zone to the unweathered metasiltstone.

The ratio of unpurged to purged radon concentrations is 0.008 at 20.4 m and 0.1 at 75 m depth during September 2005. Using equation 3.9, the calculated horizontal flow rates were low to non-existent in the upper flow system, presumably a result of the well screens being located in heavy clay and mixed weathered material. Horizontal flow rates at 75 m depth varied from 1.1 to 0.8 m/y during September 2005 and March 2006, respectively. Given that these velocities refer to flow within the well, the corresponding horizontal flow within the aquifer would be 0.275 and 0.2 m/y, respectively. The higher flows calculated for the other deeper piezometers in September 2005 may represent a mixed sample induced by extended pumping and vertical mixing between piezometers (Fig. 4.12).

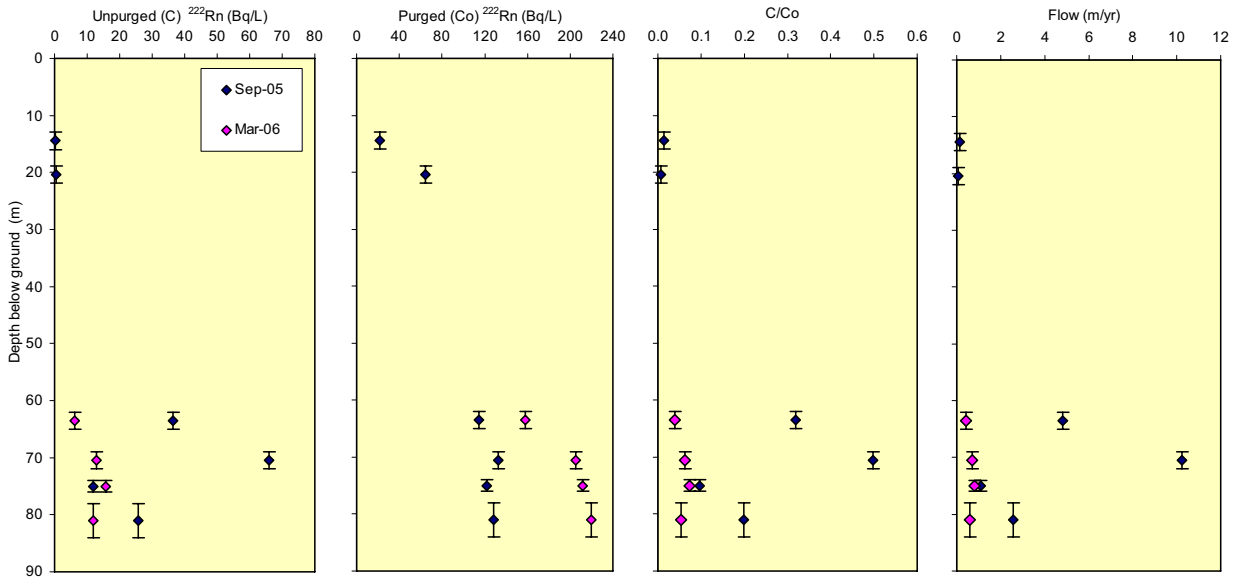

Figure 4.12. ^{222}Rn concentrations of unpurged and purged piezometers sampled during September 2005 and March 2006, ratio of unpurged (C)/purged (Co), and horizontal flow rates within the piezometers at the Eden Valley investigation site. Error bars show length of screen interval.

5. DISCUSSION

5.1 GROUNDWATER FLOW AND RECHARGE

At the Eden Valley investigation site there is an upper and deeper fractured rock groundwater flow system. The water composition in both systems indicates that water–rock interactions have occurred. Deuterium and $\delta^{18}O$ isotope ratios indicate that there has been some evaporation prior to recharge to the upper system, whereas the deeper FRA system shows little sign of evaporation and may represent older regional groundwater. Radon concentrations indicate that there is very little horizontal flow in the upper system whilst there was some horizontal movement in the unweathered deeper system at the time of sampling.

CFC-12 data collected from the upper flow system were used to estimate recharge using the vertical plate model, as it is most likely to represent recharge processes occurring in the last century when extensive vegetation clearing commenced in the area. A thermonuclear component in the ^{14}C concentrations confirmed recent recharge to the upper flow system. Uncorrected ^{14}C groundwater age gradients in the deeper FRA system were significantly greater than CFC-12 age gradients in the upper system and therefore produced a much lower vertical flow rate and hence vertical leakage estimate. This suggests that the vertical movement of water in the deeper fractured rock system is much slower than in the upper system, which may also be influenced to a greater extent by regional horizontal groundwater flow.

Assuming that the chloride concentration is in equilibrium between the fractures and the matrix, then the CMB suggests that active modern recharge (post-vegetation clearing) has only reached the upper flow system (~20 m) and has not yet reached the deeper FRA system, which is dominated by much higher chloride concentrations. On a catchment scale, the CMB calculated from over 140 bores showed that the majority of estimates were <5 mm/y, which can be considered as a minimum recharge estimate due to the potential for additional sources of chloride.

It is a very difficult task to scale up estimates of recharge for the Eden Valley investigation site to a catchment scale, suitable for use in the WAP. Earlier investigations by Barnett et al. (2001) estimated a recharge rate on a catchment scale as 12–15 mm/y. One of the main problems with regional recharge estimates is the assumption that groundwater moves through the fractures and that they are interconnected over long distances. To what degree these fractures are continuous is relatively unknown. It is intended through further investigations to gain a greater understanding of the physical characteristics of the geology and improve on the reliability of estimates of the recharge component in the catchment water balance, and how it varies across the catchment.

6. CONCLUSIONS AND RECOMMENDATIONS

Hydrochemistry, isotopes and radiogenic tracer profiles from the Eden Valley investigation site in the UMRC have been used to identify an upper and deeper groundwater flow system. The upper flow system is characterised by a thin, 50 m thick regolith zone composed of sandy clay and weathered metamorphosed siltstone and sandstone. Geological fracture mapping, together with the aquifer test results and the CFC-12 vertical age profiling have shown that the average active recharge to the shallow system is 16 mm/y. The ^{14}C data and the CMB method produced an estimated recharge rate of ~9 mm/y. In comparison, a porous media model using the CFC-12 data showed the average recharge to be 27 mm/y. The horizontal flow was found to be very low in this system.

The deeper FRA system comprises unweathered metasandstone and metasiltstone units of greater than 50 m apparent thickness. The estimated leakage rate using the ^{14}C age is much lower at 0.14 mm/y, with a horizontal flow of ~1 m/y. In comparison, the CMB method determined a recharge rate of ~3 mm/y. Recharge to the deeper FRA system may not be entirely accurate due to the effects of regional horizontal flow and, additionally, equilibrium may not have been reached between the tracer concentrations in the fractures and matrix. The estimates of recharge are dependent on the measured fracture spacing, fracture aperture, diffusion coefficient and matrix porosity.

Assuming that only two-thirds of the available resource can be extracted, according to the CFC-12 recharge estimates of 16 mm/y, ~11 mm/y is available for allocation. The amount of water available to each user will need to be determined in accordance with the WAP.

6.1 FURTHER WORK

Further work to be conducted at the Eden Valley investigation site includes additional sampling from the piezometers to monitor any hydrochemical change since the previous sampling cycle, as well as additional pump tests and fracture mapping to quantify the physical characteristics of the aquifer system, which are used in the recharge models.

APPENDICES

A. CHEMISTRY RESULTS

					Field measurements								Laboratory analysis																
Location/ sample type	**Unit No.**	**Mid-screen from ground** (m)	**Sample ID**	**Collection date**	**DO** (ppm)	**Field EC** (µS/cm)	**pH**	**Redox** (mV)	**Temp** (oC)	**Field Alkalinity (HCO_3^-)** (mg/L)	**TDS (mg/L)**	**Lab pH**	**Ca^{2+}** (mg/L)	**Mg^{2+}** (mg/L)	**Na^+** (mg/L)	**K^+** (mg/L)	**SO_4^{2-}** (mg/L)	**Cl^-** (mg/L)	**Lab Alkalinity (HCO_3^-)** (mg/L)	**Br^-** (mg/L)	**NH_4-N** (mg/L)	**NO_x-N** (mg/L)	**Sr** (ug/L)	**$\delta^{18}0$** (‰ rel SMOW)	**δ^2H** (‰ rel SMOW)	**CFC-12** (pg/kg)	**CFC-12 apparent age** (y)	**^{14}C** (pmC)	**$\delta^{13}C$** (‰ PDB)
Eden Valley GW	6728-3630	9.4	E1	14/09/05	1.71	930	7.15	-171	17.4	310	906	7.5	54	56	171	4	33	266	321	0.43	0.10	5.86	225	-4.81	-26	183	19.13	83.4	-14.4
Eden Valley GW	6728-3629	14.5	E2	14/09/05	2.04	1403	7.23	-108	20.7	325	876	7.6	60	58	143	6	22	260	328	0.41	0.05	2.20	246	-4.95	-26.1	159	22.04	81.1	-14.5
Eden Valley GW	6728-3628	20.4	E3	15/09/05	2.20	1451	7.22	49	15.8	290	900	7.5	58	62	151	5	26	278	320	0.44	0.03	6.03	236	-4.95	-27.7	129	25.96	78.2	-14.0
Eden Valley GW	6728-3637	63.5	E4	22/09/05	-0.03	2780	7.62	-209	18.4	230	3294	7.6	449	53	505	17	1272	757	239	0.99	0.05	0.00	2631	-5.02	-28.1	22.5	41	27.3	-13.5
Eden Valley GW	6728-3636	70.5	E5	22/09/05	-0.25	3430	8.89	-296	18.5	250	2141	7.9	154	51	506	19	444	762	205	1.00	0.05	0.01	1402	-5.04	-29.7	<20	41	25.1	-14.2
Eden Valley GW	6728-3635	75.0	E6	27/10/05	-0.34	3770	8.29	-217	19.6	230	2513	7.8	291	50	487	18	743	756	165	2.08	0.11	<0.02	1259	-5.21	-30.6	<20	41	22.1	-12.8
Eden Valley GW	6728-3634	81.0	E7	03/11/05	-0.26	3730	8.66	-294	18.9	190	2630	8.1	327	50	486	18	888	758	101	2.10	0.31	<0.02	1625	-5.29	-30.4	<20	41	27.2	-13.3
Eden Valley GW	6728-3486	33.0	E8	03/11/05	1.03	1916	7.81	-52	17.7	310	1224	7.8	36	45	311	12	47	434	337	1.14	0.10	2.68	175	-5.18	-27.9	40.5	38	62.9	-13.7
Rainfall Mt Torrens				03/04/03														6						-5.08	-27.9				
Rainfall Mt Torrens				08/10/03														5						-5.69	-26.2				
Rainfall Mt Torrens				12/06/02																				-4.09	-19.6				
Rainfall Mt Torrens				25/09/02																				-4.12	-18.5				
Rainfall Mt Torrens				04/03/05														9						-3.72	-17.1				
Mean seawater											35139	8.2	412	1294	10760	399	2712	19350	145	67									

Sample ID	**Radon unpurged date**	**Radon conc. (C) unpurged** (Bq/L)	**Radon error (C)** (Bq/L)	**Radon purged date**	**Radon conc. (Co) purged** (Bq/L)	**Radon error (Co)** (Bq/L)
E2	14-Sep-05	0.3	0.1	14-Sep-05	21.6	0.8
E3	14-Sep-05	0.5	0.1	15-Sep-05	64.7	2.2
E4	22-Sep-05	36.4	1.3	22-Sep-05	114.4	3.8
E5	22-Sep-05	66	2.2	22-Sep-05	132.6	4.4
E6	23-Sep-05	11.8	0.5	23-Sep-05	121.9	4.1
E7	23-Sep-05	25.6	0.9	23-Sep-05	128.6	4.3
E4	29-Mar-06	6.3	0.3	29-Mar-06	158	3.0
E5	29-Mar-06	12.9	0.5	29-Mar-06	205	4.0
E6	29-Mar-06	15.7	0.6	29-Mar-06	212	4.0
E7	29-Mar-06	12	0.5	29-Mar-06	220	4.0

B. LITHOLOGICAL LOG

The table below shows the lithological log for E3 (unit number 6728-3628) and is the same for the other two shallow piezometers E1 and E2.

Unit No.	Permit No	Drill date	Depth from (m)	Depth to (m)	Major lithology	Minor lithology	Description Eden Valley – Marne	Water cut (m)
6728-3628	PN106408	05/07/2005	0	0.5	Soil		Sand, moist, fine to medium grained, dark chocolate brown.	
			0.5	1	Soil		Sand, moist, fine to medium grained, dark brown tending to light brown with depth.	
			1	1.5	Sand	Clay	Clayey sand, moist, fine grained, light brown to brown, minor biotite–muscovite.	
			1.5	2	Sand	Clay	Clayey sand, moist, fine grained, red-brown, some biotite–muscovite, some metasandstone fragments.	
			2	2.5	Sand	Clay	Clayey sand, moist, fine grained, red-brown, significant biotite–muscovite, quartz-sandstone gravel inclusions (10–20 mm).	
			2.5	3.5	Sand	Clay	Clayey sand, moist, fine grained, light brown, minor biotite–muscovite, metasandstone fragments (0–0.5 mm).	
			3.5	5.5	Metasandstone		Weathered metasandstone, hard, tan, minor muscovite–biotite.	
			5.5	7.5	Metasandstone		Metasandstone, hard, tan, minor muscovite–biotite.	
			7.5	10.5	Metasandstone		Metasandstone, hard, tan, minor muscovite–biotite, iron staining.	
			10.5	12.5	Metasandstone		Metasandstone, hard, grey-black, minor muscovite–biotite.	
			12.5	16.5	Metasandstone		Metasandstone, hard, grey-black, dominant muscovite–biotite.	
			16.5	22	Metasandstone		Micaceous metasandstone, hard, grey-black.	~22

UNITS OF MEASUREMENT

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
microlitre	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

~	approximately equal to
δ^2H	hydrogen isotope composition
$\delta^{18}O$	oxygen isotope composition
^{14}C	carbon-14 isotope (percent modern carbon)
$\delta^{13}C$	dissolved inorganic carbon (DIC)
CFC	chlorofluorocarbon (parts per trillion volume)
EC	electrical conductivity (µS/cm)
pH	acidity
ppm	parts per million
ppb	parts per billion
TDS	total dissolved solids (mg/L)

GLOSSARY

Act (the) — In this document, refers to the *Natural Resources Management Act* (South Australia) *2004*.

Ambient — The background level of an environmental parameter (e.g. a background water quality such as salinity).

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 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 resource 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.

Artificial recharge — The process of artificially diverting water from the surface to an aquifer. Artificial recharge can reduce evaporation losses and increase aquifer yield. *(See natural recharge, aquifer.)*

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

Bore — *See well.*

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

Conjunctive use — The utilisation of more than one source of water to satisfy a single demand.

DWLBC — Department of Water, Land and Biodiversity Conservation. Government of South Australia.

EC — Abbreviation for electrical conductivity. 1 EC unit = 1 micro-Siemen per centimetre (µS/cm) measured at 25 degrees Celsius. Commonly used to indicate the salinity of water.

EMLR — Eastern Mount Lofty Ranges.

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

Floodplain — Of a watercourse means: (a) the floodplain (if any) of the watercourse identified in a catchment water management plan or a local water management plan; adopted under Part 7 of the *Water Resources Act 1997*; or (b) where paragraph (a) does not apply — the floodplain (if any) of the watercourse identified in a development plan under the *Development Act 1993*, or (c) where neither paragraph (a) nor paragraph (b) applies — the land adjoining the watercourse that is periodically subject to flooding from the watercourse.

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

Groundwater — *See underground water.*

Heavy metal — Any metal with a high atomic weight (usually, although not exclusively, greater than 100), for example mercury, lead and chromium. Heavy metals have a widespread industrial use, and many are released into the biosphere via air, water and solids pollution. Usually these metals are toxic at low concentrations to most plant and animal life.

Hydrogeology — The study of groundwater, which includes its occurrence, recharge and discharge processes and the properties of aquifers. *(See hydrology.)*

Hydrography — The discipline related to the measurement and recording of parameters associated with the hydrological cycle, both historic and real time.

Hydrology — The study of the characteristics, occurrence, movement and utilisation of water on and below the Earth's surface and within its atmosphere. *(See hydrogeology.)*

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.

MLR — Mount Lofty Ranges.

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

Mount Lofty Ranges Watershed — The area prescribed by Schedule 1 of the regulations.

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

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

Permeability — A measure of the ease with which water flows through an aquifer or aquitard.

Potentiometric head — The potentiometric head or surface is the level to which water rises in a well due to water pressure in the aquifer.

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.

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

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.

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

Water allocation — (a) in respect of a water licence means the quantity of water that the licensee is entitled to take and use pursuant to the licence; (b) 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 plan (WAP) — A plan prepared by a CWMB or water resources planning committee and adopted by the Minister in accordance with Division 3 of Part 7 of the Act.

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.

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; and a lake through which water flows; and 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.

Well — (a) an opening in the ground excavated for the purpose of obtaining access to underground water; (b) an opening in the ground excavated for some other purpose but that gives access to underground water; (c) a natural opening in the ground that gives access to underground water.

REFERENCES

Barnett, SR, Zulfic, D & Yan, W 2001, *Marne River Catchment groundwater assessment*, Report DWR 2001/009, Department for Water Resources, Adelaide.

Clark ID & Fritz P 1997, *Environmental isotopes in hydrogeology*, Lewis Publishers, New York. p 328.

Cook, PG 2003, *A guide to regional groundwater flow in fractured rock aquifers*, CSIRO Land and Water, Australia.

Cook PG & Bohlke, J-K 1999, 'Determining timescales for groundwater flow and solute transport', in PG Cook & AL Herczeg (eds), *Environmental tracers in subsurface hydrology*, Kluwer Academic, Boston, London, pp.1–30.

Cook, PG, Love, AJ & Dighton, JC 1999, 'Inferring groundwater flow in fractured rock from dissolved radon,' *Groundwater*, 37(4), pp.606–610.

Cook, PG & Simmons, CT 2000, 'Using environmental tracers to constrain flow parameters in fractured rock aquifers: Clare Valley, South Australia', in B Faybishenko (ed.), *Dynamics of fluids in fractured rocks: Concepts and recent advances*, AGU Monograph, 122, pp.337–347.

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

Coplen, TB, Herczeg, AL & Barnes, CJ 1999, 'Isotope engineering using stable isotopes of the water molecule to solve practical problems', in PG Cook & AL Herczeg (eds), *Environmental tracers in subsurface hydrology*, Kluwer Academic, Boston, London, pp.79–110.

Dansgaard, W 1964, 'Stable isotopes in precipitation', *Tellus*, 16, pp.436–469.

Fetter, CW 2001, 'Cooper-Jacob straight line method', in *Applied Hydrogeology*, 4th edn, Prentice Hall, New Jersey, p.174.

Fontes, JC & Garnier, JM 1979, 'Determination of the initial ^{14}C activity of the total dissolved carbon: A review of the existing models and a new approach', *Water Resources Research*, 15, pp.399–413.

Gravestock, DI & Gatehouse, CG 1995, 'Early and Middle Palaeozoic', in JF Drexel & WV Preiss (eds), *The geology of South Australia, Vol. 2, The Phanerozoic*, Bulletin 54, Geological Survey, Adelaide.

Harrington, GA 2004, Hydrogeological investigations of the Mount Lofty Ranges, Progress report 4: Groundwater – surface water interactions in the Scott Creek, Marne River and Tookayerta Creek Catchments, Report DWLBC 2004/11, Department of Water, Land and Biodiversity Conservation, Adelaide.

Harrington, GA, James-Smith, JM, Wohling, D & Van Den Akker, J 2004, Hydrogeological investigations of the Mount Lofty Ranges, Progress report 5: Drilling phases 2.1 to 2.3: research and monitoring wells at Scott Creek, Balhannah, Willunga Fault, Lobethal, Eden Valley and Ashbourne, Report DWLBC 2004/04, Department of Water, Land and Biodiversity Conservation, Adelaide.

Herczeg, AL & Edmunds, WM 1999, 'Inorganic ions as tracers', in PG Cook & AL Herczeg (eds), *Environmental tracers in subsurface hydrology*, Kluwer Academic, Boston, London, pp.31–77.

REFERENCES

Love, AJ, Cook, PG, Harrington, GA & Simmons, CT 2002, *Groundwater flow in the Clare Valley*, Report DWR02/03/0002, Department for Water Resources, Adelaide.

Love, AJ, Simmons, CT, Cook, P, Harrington, GA, Herczeg, A & Halihan, T (in prep.), 'Estimating groundwater flow rates in fractured metasediments: Clare Valley, South Australia', International Association of Hydrogeologists SP Series.

Neretnieks, I 1981, 'Age dating of groundwater in fissured rock: Influence of water volumes in micropores'. *Water Resources Research*, 17(2), pp.421–422.

Nielsen, DM 1991, *Practical handbook of ground-water monitoring*, Lewis Publishers, New York.

Parkhurst, DL & Appelo, CAJ 1999, User's guide to PHREEQC (Version 2) — A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations, US Geological Survey Water Resources Investigations Report, 99-4259.

Pearson, FJ Jr & Hanshaw, BB 1970, 'Sources of dissolved carbonate species in groundwater and their effects on carbon_14 dating', in *Isotope Hydrology 1970*, IAEA, Vienna, pp.271-286.

Savadamuthu, K 2002, *Impact of farm dams on streamflow in the Upper Marne Catchment*, Report DWR 02/01/0003, Department for Water Resources, Adelaide.

Szabo, Z, Rice, DE, Plummer, LN, Busenberg, E, Drenkard, S & Schlosser, P 1996, 'Age dating of shallow groundwater with chlorofluorocarbons, tritium/helium 3, and flow path analysis, southern New Jersey coastal plain', *Water Resources Research*, 32(4), pp.1023–1038.

Tamers, MA 1967, 'Surface-water infiltration and groundwater movement in arid zones of Venezuela', in *Isotopes in Hydrology*, Proceedings of the IAEA Symposium in Vienna, 1966, pp.339–351.

Zulfic, D & Barnett, S 2003, *Eastern Mount Lofty Ranges groundwater assessment*, Report DWLBC 2003/25, Department of Water, Land and Biodiversity Conservation, Adelaide.