TECHNICAL REPORT

IMPROVED ESTIMATES OF GROUNDWATER RECHARGE IN SOUTH EAST SOUTH AUSTRALIA

2011/15

Government of South Australia
Department for Water

IMPROVED ESTIMATES OF GROUNDWATER RECHARGE IN SOUTH EAST SOUTH AUSTRALIA

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FOREWORD

South Australia's Department for Water leads the management of our most valuable resource—water.

Water is fundamental to our health, our way of life and our environment. It underpins growth in population and our economy—and these are critical to South Australia's future prosperity.

High quality science and monitoring of our State's natural water resources is central to the work that we do. This will ensure we have a better understanding of our surface and groundwater resources so that there is sustainable allocation of water between communities, industry and the environment.

Department for Water scientific and technical staff continue to expand their knowledge of our water resources through undertaking investigations, technical reviews and resource modelling.

Scott Ashby
CHIEF EXECUTIVE
DEPARTMENT FOR WATER

ACKNOWLEDGEMENTS

The work detailed in this report would not have been possible without the help of several people, whom the author would like to take this opportunity to thank. From DWLBC, project staff including Iain Marshall, Glenn Harrington and Paul O'Connor. Also, for technical help and assistance with the drilling program, George MacKenzie, Saad Mustafa, Jeff Lawson and Colleen Bernie. The author also acknowledges the input provided by David Maschmedt with regards to soil classifications, Daniel Wohling for assistance in interpreting soil water chloride profiles, Fred Leaney (CSIRO) for help with various technical issues and for reviewing a draft of this report, as well as Nikki Harrington, who also reviewed the first draft.

The author would also like to thank all land owners who provided DWLBC access to their land to install piezometers and conduct this research. Your support and cooperation was very much appreciated.

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EXECUTIVE SUMMARY

This report documents work undertaken as part of the Resource Sustainability component of the South East National Water Initiative project. Specifically, it relates to Sub Program 1.1 of this project, concerned with improving estimates of groundwater recharge rates in the South East of South Australia.

Presented herein is all the relevant documentation referred to in previous Project Progress Reports, augmented with the final Project milestone requirements, including:

- a literature review of available methods for estimating groundwater recharge rates to unconfined and confined aquifers (including a summary of the most suitable methods for this project)
- the methodology used to select 24 research sites for estimating unconfined aquifer recharge across the region
- details of site establishment (piezometer installation and instrumentation) and monitoring programs
- results of laboratory testing of groundwater samples and soil core samples
- interpretation/modelling of laboratory results to estimate recharge rates
- summary of recharge estimates including maps of adopted sub-catchment scale recharge rates.

Recharge estimates from this study range from 2–195 mm/y across the South East, with higher rates in the Lower South East, and lower rates in the more arid Upper South East. Rates in the Lower South East are, in some cases, lower than those previously adopted, whereas rates in the Upper South East are generally similar to those previously adopted.

It is recommended that the new recharge research sites established in this study are monitored on an ongoing basis, in order to further refine the estimates given in this report, and provide up-to-date estimates into the future.

1. INTRODUCTION

1.1. BACKGROUND OF STUDY

The groundwater resources of the South East are important for South Australia. These resources support a wide array of industry, predominantly wine, wool, meat, dairy, forestry and timber, fishing and aquaculture, vegetables and seed production. Furthermore, groundwater is the primary source of water for town supply throughout the region. There are signs of groundwater resource stress in the region.

One of the key knowledge gaps identified is reliable estimates of groundwater recharge rates over the region. The existing management principle of 'Permissible Annual Volumes' (PAVs) of groundwater extraction from the region states that groundwater allocation should not exceed mean annual vertical recharge to groundwater in each management area. Furthermore, in order for resource sustainability to be maintained, discharge (including extraction) from the groundwater system should not exceed recharge. Recharge is therefore a crucial component of the water balance and obtaining better estimates of recharge throughout the region is important for achieving sustainable development of the groundwater resource.

1.2. OBJECTIVES

As part of the South East National Water Initiative Project, the Department of Water, Land and Biodiversity Conservation (DWLBC) submitted a project proposal to the National Water Commission titled 'Integrated Water Resource Management in the South East of South Australia'. The key knowledge gaps related to resource sustainability were identified in this report, and plans to address these knowledge gaps were separated into a series of Sub Programs. Sub Program 1 is titled 'Resource Sustainability' and its stated objective is to *'Establish a robust understanding of the sustainable yield of the water resource systems and the constraints to development.'* The main objective of Project 1.1 of the Resource Sustainability Sub Program relates to *'improving the accuracy of spatially distributed recharge across the region.'*

The progress of Project 1.1 has been reported on in previous Milestone reports. To summarise, the first outputs of the project were a literature review on available methods for estimating groundwater recharge and the identification of up to 24 new research sites for estimating groundwater recharge to the regional unconfined aquifer. Subsequent reporting detailed the establishment of these new research sites, including piezometer installation. This Final Project Report will document the above outputs and also include point estimates of groundwater recharge at these research sites and adopted sub-catchment scale recharge rates.

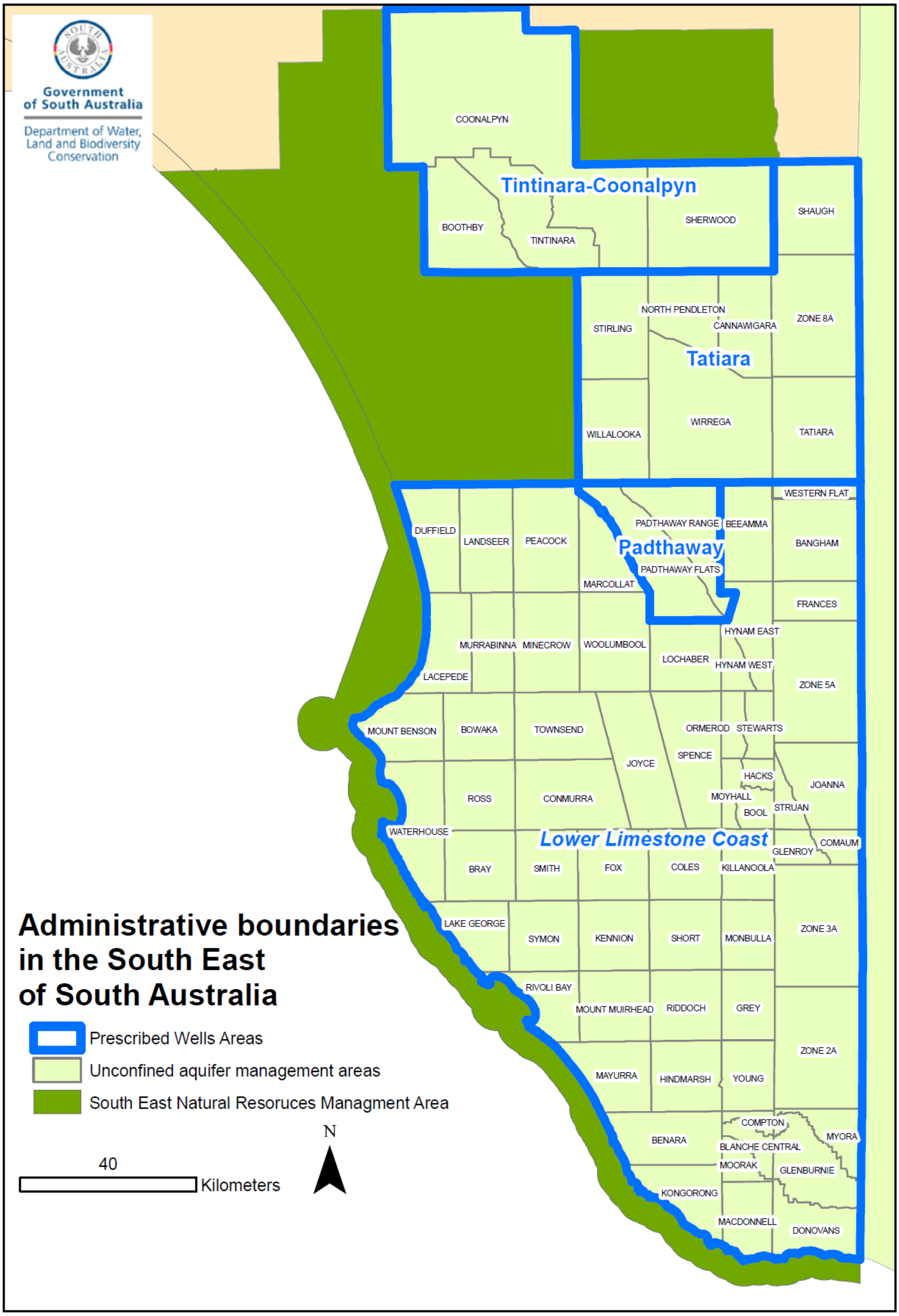

Figure 1. **South East Natural Resources Management Region, showing Prescribed Wells Areas and Unconfined Aquifer Management Areas**

2. LITERATURE REVIEW

2.1. DEFINITIONS OF RECHARGE

Before continuing, it is necessary to define some key terms important to this report. *Recharge* may be defined as replenishment of groundwater via infiltration or percolation of water to an aquifer. There are different ways in which groundwater may be recharged, the key processes being (Lerner et al 1990):

(1) Direct/diffuse recharge: vertical percolation of water through the unsaturated zone, which, if in excess of soil moisture deficits, may reach the water table.
(2) Indirect recharge: movement of water through the beds of surface-water bodies towards the water table.
(3) Localised/point source recharge: recharge which results from the concentration of water at the surface around depressions, joints, cracks, or in the South East sinkholes, runaway holes or other karst features.

In reality, recharge usually occurs via a combination of processes such as diffuse recharge via unsaturated flow or a saturated front (piston flow); preferential flow through root channels, cracks or fractures; or preferential flow as a result of unstable wetting fronts and changes in soil properties within the soil matrix (e.g. a change between clay and sand sediments).

Although many methods exist for estimating groundwater recharge rates, some methods are better suited to certain geographic and geomorphological settings than others. For example, Scanlon et al (2002) separate recharge estimation techniques into three broad classes based on where data is obtained for the estimate. These are (1) surface water, (2) unsaturated zone and (3) saturated zone. Considering that there are few significant surface water reservoirs in the South East region, and many of those that do exist contain some component of groundwater discharge (e.g. Blue Lake), a review of techniques based on surface water measurements is not necessary. Instead, this review will focus on studies that have previously been conducted in the region, discussing the methods that have been successfully used in the past. This will be followed by a weighing up of the benefits and limitations of each technique, accompanied by a discussion of possible new techniques that could be used as part of this study.

2.2. BACKGROUND TO STUDY AREA

The study area encompasses the entire South East Natural Resources Management Region (approximately 28 120 km^2, Figure 1). The climate is typically characterised by hot dry summers and cool wet winters. Mean annual rainfall varies across the region, ranging from approximately 460 mm/y at Keith to 700 mm/y at Mount Gambier. Potential evapotranspiration ranges from 1400 mm/y in the south to 1800 mm/y in the north.

Geologically, the region is comprised of two major basins, the Murray Basin in the north and the Otway Basin in the south (Figure 2). Both structures are characterised by an upper Tertiary limestone aquifer—the Gambier Limestone in the Otway Basin and the Murray Group Limestone in the Murray Basin. Both formations are separated from an underlying confined sand aquifer (Dilwyn Formation in Gambier and Renmark Group in Murray) by a clay aquitard. Overlying the Tertiary limestone aquifer throughout much of the region is a series of north-west trending Quaternary beach-dune ridge systems, separated by a series of inter-dunal corridors.

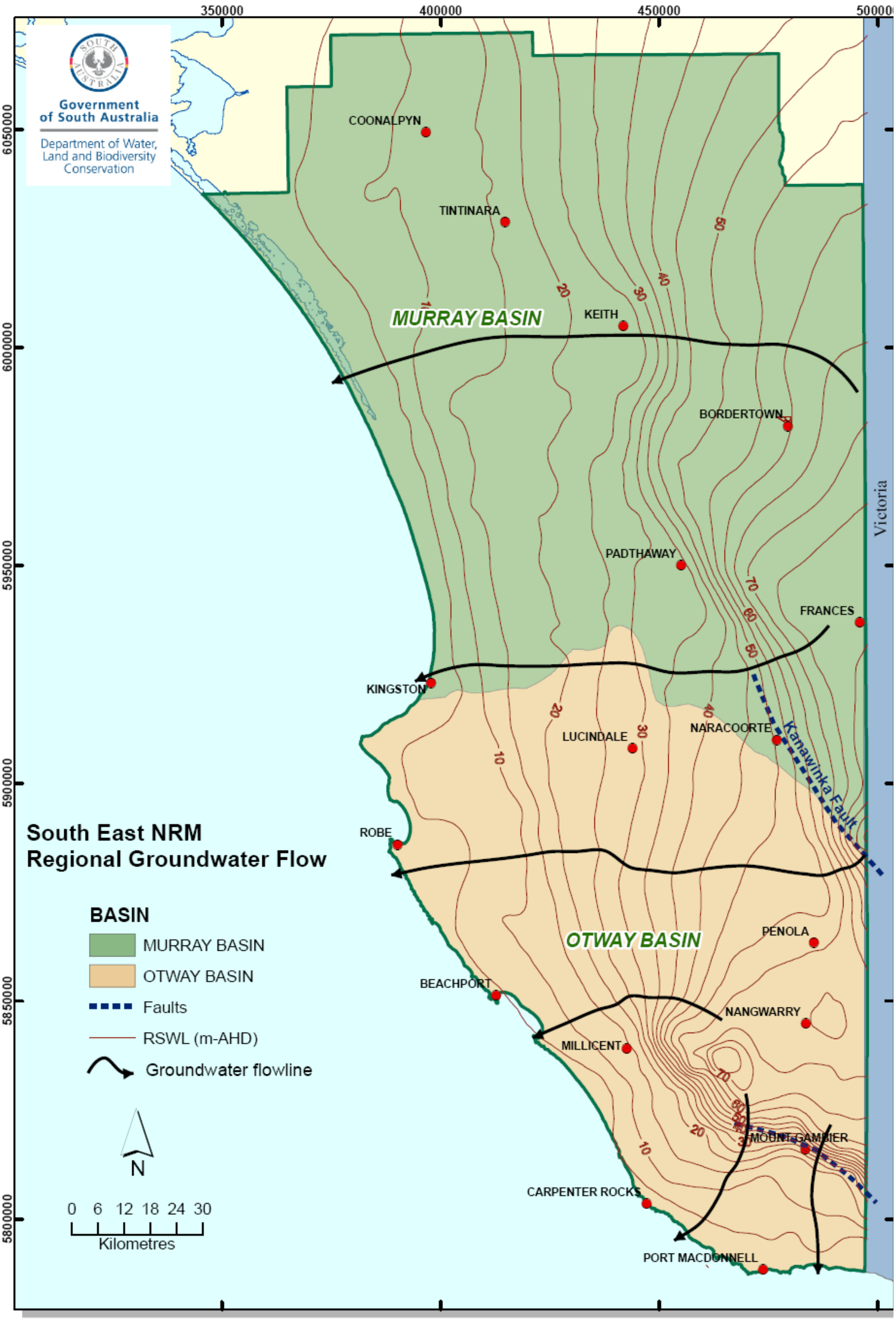

Figure 2. Hydrogeologic basins and regional groundwater flow pattern in the unconfined limestone aquifer in the South East of South Australia

The Tertiary limestone aquifers are the source of most groundwater extraction in the region. Regional groundwater flow is to the west (towards the coastline) for much of the area and to the south to south-west in the southern half of the Otway Basin (again, towards the coast) (Figure 2). Love et al. (1993) presented a conceptual model of the groundwater flow system in the Gambier Embayment, including a summary of regional recharge patterns. Based on hydraulic and hydrochemical measurements along two transects parallel to the groundwater flow direction in the north and south of the area, Love et al. (1993) describe a system where flow in the unconfined aquifer is dominated by local recharge and discharge, rather than recharge in one end of the basin and lateral flow through the rest of the basin. In the north of the area, there is a general pattern of recharge associated with topographic highs (Bridgewater Formation) and discharge in inter-dunal lows (Padthaway Formation). Local recharge patterns exist in the south of the area as well. However, the topography is flatter with less developed beach-dune sequences in the south, resulting in the local groundwater flow cells not being as deeply developed as in the north.

The underlying confined Dilwyn aquifer is dominated by lateral regional flow. Love et al. (1993) identify two possible areas where recharge to the confined aquifer is likely to occur. The first is in the north of the area, to the west of the Kanawinka Fault (between Naracoorte and Lucindale), where hydraulic data suggests there is downward leakage from the deeper part of the Gambier Limestone to the confined system. The other region corresponds to the area identified by Colville and Holmes (1972) around Nangwarry, where the unconfined and confined aquifers are close to the surface. The unconfined aquifer is characterised by a 'sink' in the water table in this region, whilst the confined aquifer is characterised by a groundwater mound. These features provide strong evidence for recharge to the confined aquifer in this region. Further work by Brown et al. (2001) in the Nangwarry area confirmed this, with recharge likely to be occurring via leakage through faults.

2.3. *RECHARGE IN THE SOUTH EAST*

2.3.1. OVERVIEW OF RECHARGE ESTIMATIONS AND METHODS FOR THE UNCONFINED AQUIFER IN SOUTH EAST SA

The importance of the groundwater resources in the South East has been recognised for a long time. Much of the area has been prescribed under the *Natural Resources Management (NRM) Act 2004*, and Water Allocation Plans have been developed. In the South East, water allocation policies have typically been based on estimates of groundwater recharge, with a proportion of recharge allocated for use. Consequently, many recharge studies have taken place throughout the region over the past four decades. The varying studies have employed a wide range of techniques to quantify recharge rates. This section of the report presents a summary of these studies to elucidate what is currently known about recharge in the region, while at the same time detailing the methods used to give some understanding of what is required for each method and how successful they have proven in the past.

2.3.1.1. Recharge under forest and pasture, Lower Limestone Coast

Holmes and Colville (1970[A]) used lysimeters to look at grassland hydrology near Mingbool, north of Mount Gambier (Lower Limestone Coast (LLC) PWA). Lysimeters are essentially containers filled with soil, buried in the site being investigated, but isolated from the surrounding soil so that the components of the water balance can be measured. The soil may be disturbed or undisturbed, and may have vegetation cover or be bare. Lysimeters are designed so that drainage may be collected and measured, and a recharge rate determined from this (Scanlon et al. 2002). Holmes and Colville (1970[A]) state measurements made using lysimeters from 1961 to 1965 gave a mean recharge rate of 63 mm/y. The authors then attempted to quantify recharge over the entire region. This was done by dividing the lower South East of SA (area south of Keith) into seven regions where precipitation and evaporation could be measured on a monthly basis. The amount of recharge was calculated as the amount of precipitation that exceeded evaporation above a measured soil water deficit (175 mm, obtained from lysimeters). Using this approach, only three regions were identified as 'recharge areas', with recharge rates ranging from 29 mm/y to 85 mm/y.

In a study conducted at around the same time, Holmes and Colville (1970[B]) looked at recharge under forest plantations in Penola Forest Reserve and Mount Gambier Forest Reserve (LLC PWA). Based on measurements of soil water content with depth under the forests, it was estimated that no recharge took place under the forest sites during the study period (1963–66); however, the potential for recharge under one forest site (where the depth to water was 7 m) existed if rainfall was to exceed 700 mm between May and September. Under a different forest site where the watertable was much deeper (40 m), it was estimated that *'even more'* rain would be required to recharge groundwater.

In addition to these methods, the authors performed statistical analysis on watertable observations in forested areas north of Mount Gambier around the same time, to see if estimated recharge patterns were the same using a different technique (Colville and Holmes 1972). They concluded that some recharge actually does occur under forests (between 19 mm/y and 73 mm/y for 1963–65) as well as grasslands, contradicting the results of their previous work. Colville and Holmes also identified the presence of a 'sink' area near Nangwarry, where recharge to the lower confined aquifer was likely to occur.

Allison and Hughes (1972) further looked at recharge under forest and pasture grassland near Nangwarry using tritium as an environmental tracer, in an attempt to *'solve the impasse'* of different recharge models under forest presented by Holmes and Colville (1970) and Colville and Holmes (1972). Tritium (^3H) is a radioactive isotope of hydrogen with a half-life of 12.32 years. The tritium that falls in precipitation can occur in the atmosphere as a result of two processes: (1) the natural interaction of cosmic radiation and ^{15}N in the upper atmosphere, and (2) fallout from thermonuclear explosions. The fallout from nuclear weapons testing (up to 1963) produced atmospheric tritium concentrations much higher than natural levels. However, the cessation of testing since that date, coupled with natural radioactive decay, has led to an exponential decrease in atmospheric tritium back towards natural levels (Allison et al. 1971). At the time of their study, however, Allison and Hughes (1972) stated that levels of tritium in precipitation were reasonably high, and therefore tritium should be found in the soil water beneath the plant root zone if significant recharge was occurring.

They found that tritium concentrations in soil at the top of the water table under forest plantations were much lower than those found under pasture, suggesting little soil water flux to this depth. One exception was a forest site, which was considered anomalous because the soil profile was almost entirely coarse sand (this, however, does highlight how local recharge is strongly influenced by soil type). They also found that mean tritium concentrations at the top of the watertable fluctuated seasonally under pasture, from a higher concentration in October—at the peak of the recharge period (Colville and Holmes 1972)—to a lower concentration in February (when seasonal recharge was presumably completed). However, mean tritium concentrations under forest showed no seasonal fluctuation, and the authors conclude that 'virtually no recharge' occurs under forest plantations.

2.3.1.2. Recharge over Naracoorte Ranges and Padthaway Flats

Allison and Hughes' research on recharge in the South East with tritium continued in a study on recharge estimation in the Padthaway PWA, just west of the Naracoorte Ranges (1975). Tritium concentrations of groundwater were measured beneath the Naracoorte Ranges and then up to 25 km to the west (approximately following the groundwater flow gradient). This data was then used in a compartmental mixing-cell model to estimate recharge from the Ranges and local recharge over the adjacent plain.

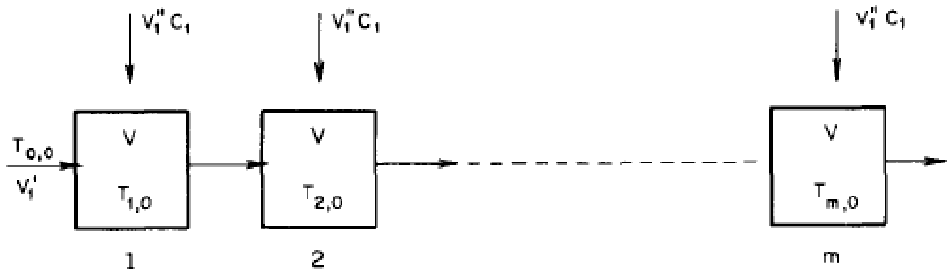

Figure 3. Conceptual model for compartmental mixing-cell model (Allison and Hughes 1975)

The mixing-cell model approach is essentially a type of inverse modelling, which estimates fluxes such as recharge and groundwater flow as a means of interpreting tracer data (Harrington et al. 1999). The aquifer is divided into a series of cells assumed to be perfectly mixed, and linear equations can be solved to estimate tracer concentrations in each cell. Figure 3 conceptualises this process, where each cell has a volume (V) and a tritium concentration ($T_{m,0}$), which is determined by inputs from lateral flow and local recharge. Volumetric fluxes (such as recharge and flow-through) can be altered until the tracer data predicted by the model matches that measured in the field. The best fit for the tritium data obtained by Allison and Hughes gave a recharge rate over the plain of 27 mm/y, with an estimated ±15% error range. Flow from the Naracoorte Ranges was estimated to be 780 m^3/y per metre length of the range with ±30% uncertainty.

2.3.1.3. Recharge under representative land units around Mount Gambier

Another study by Allison and Hughes (1978) looked at recharge under nine different soil types (all with dryland or pasture/cropping land use) in a study area surrounding Mount Gambier radially by approximately 20–30 km, using tritium and chloride. Each land unit was considered to be relatively homogeneous in terms of soil and hydrologic properties and therefore, representative of a type of recharge zone. Based upon their earlier work, recharge under forest units was considered to be negligible. Furthermore, coastal swamps were considered groundwater discharge zones with no net recharge. The concentration of tritium and chloride, and the volumetric water content with depth was collected from soil cores.

In most soil core samples, a peak in tritium concentration could be identified, which corresponded to a 1964–65 peak in tritium concentration in rainfall in southern Australia. Therefore, all tritium in the soil profile above this peak has been added since 1965. Sampling in 1975, Allison and Hughes calculated the total quantity of tritium added to the soil since 1965 (*T*) as:

$$T = \int_o^d T_z \theta_z dz \qquad \text{Equation (1)}$$

where T_z is the tritium concentration at depth *z* beneath the soil surface, θ_z is the water content at depth *z*, and *d* is the depth of the tritium peak beneath the surface. If recharge occurs every year, then the total amount of tritium that would have been added allowing for radioactive decay (T_u) is:

$$T_u = \sum_{n=1}^{10} W_n T_i(n) \exp(n\lambda) \qquad \text{Equation (2)}$$

where W_n is a weighting function accounting for year to year variation in recharge, $T_i(n)$ is the incoming tritium concentration *n* years from the time of sampling, and λ the radioactive decay constant of tritium. Mean annual recharge was calculated by T/T_u.

Recharge was also determined by estimating the total amount of water in the soil profile in March (driest time of year) between the 1965 peak tritium level and the surface, and dividing this by the number of years between 1965 and the time of sampling. For sites where sampling took place beneath the 1965 tritium peak, the year in which the soil water at the bottom of the profile fell as rain was estimated from its tritium concentration.

The technique for estimating recharge from chloride is known as the chloride mass balance. It is based on the principle that the amount of chloride coming into the soil via precipitation is equal to the amount of chloride leaving the root zone as recharge:

$$PC_P = RC_R \qquad \text{Equation (3)}$$

where *P* is annual rainfall with chloride concentration C_P, and *R* the recharge rate with chloride concentration C_R (measured as the chloride concentration in either soil solution beneath the root zone, or groundwater at the top of the watertable). Rearranging, the recharge rate *R* can be solved via:

$$R = \frac{C_P P}{C_R} \qquad \text{Equation (4)}$$

The main assumption made in this equation is that the system is in steady state. The steady state assumption is less likely to be valid if there is a change in land use. It also assumes that the only chloride input to soil is via rainfall, and that there is no surface runoff. Input of chloride via irrigation can be incorporated into this method, provided details about the irrigation routine and chemistry of irrigation water are known. It should also be noted that, being a point estimate of recharge, the chloride mass balance might give an underestimate of recharge by not accounting for preferential flow.

For their sampling sites, Allison and Hughes (1978) calculated the mean annual chloride concentration of rainfall (in meq/l)[1] using an empirical relationship between chloride fallout and distance from the coast derived by Hutton (1976), viz.:

$$C_P = \frac{0.99}{\sqrt[4]{d} - 0.23} \qquad \text{Equation (5)}$$

where *d* is distance from the coast (km) in the direction from which most of the oceanic chloride is likely to come. Ideally, in such a study, details of meteoric chloride input would be obtained through direct measurement (preferably over a long term).

Comparing the tritium and chloride techniques outlined above, Allison and Hughes (1978) reported good positive correlation between recharge estimates (Figure 4). A summary of Allison and Hughes' (1978) calculated mean annual recharge rates for different representative soil types is given in Table 1. To obtain a total amount of recharge for the area, these estimates were multiplied by the surface area of each land unit. This gave a total annual recharge to the unconfined aquifer in the study area of 2.4 x 10^8 m^3/y for tritium and 2.3 x 10^8 m^3/y for chloride data. These estimates compare well with estimates of groundwater discharge from the area—via subsurface flow from the coastline (based on values given by Waterhouse (1977)), urban and irrigation use, discharge via springs and evapotranspiration (based on values given by Allison (1975))—of 2.6 x 10^8 m^3/y. The authors also identify a knowledge gap in noting that no quantification of leakage between the Gambier Limestone and the lower Dilwyn Formation was included in the study, neglecting a possible source of either recharge to or discharge from the unconfined aquifer.

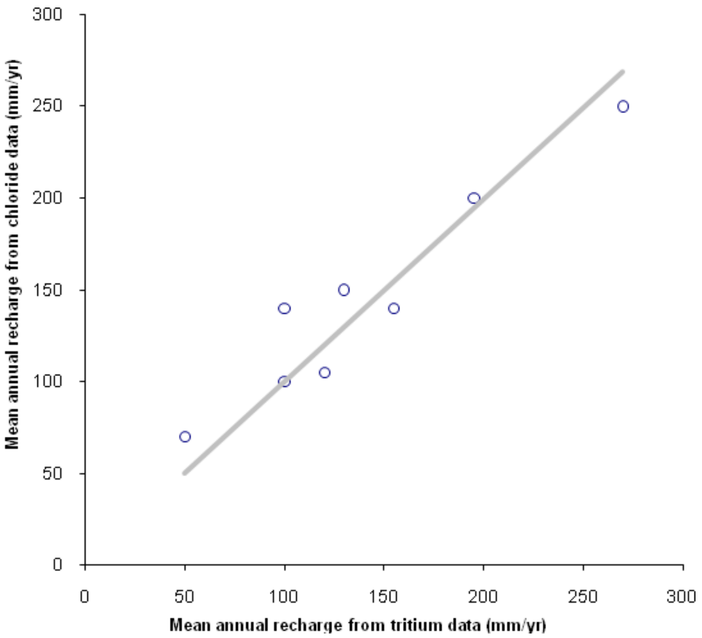

Figure 4. Correlation between mean annual recharge estimates made using tritium technique and chloride technique (Allison and Hughes 1978)

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[1] Chloride concentration may be expressed in the more readily used units of mg/L via: $C_p = 35.45\left(\frac{0.99}{\sqrt[4]{d} - 0.23}\right)$ from Walker (1998).

Hydrologic unit	Area (km^2)	Mean annual recharge (mm)	
		Chloride	Tritium
Sand over heavy clay	157	70	50
Volcanic soils	21	100	100
Sand over sandy clay	52	140	100
Sand over thin sandy clay over limestone	49	105	120
Terra rossa over limestone	60	150	130
Thin sandy loam over limestone	281	140	155
Aeolianite	380	200	195
Skeletal soils	330	250	270

Table 1. Summary of recharge estimates for different soil types (all dryland land use) using the chloride and tritium techniques

2.3.1.4. Recharge following a change in land use, Naracoorte Ranges

Walker et al. (1990) also used environmental tracers to look at recharge in the Naracoorte Ranges, an area that was cleared of native vegetation some 40–60 years prior to the study. Because of the deep watertable in this area (generally > 20 m), and the semi-arid climates (rainfall 450–650 mm/y), most other techniques for recharge estimation were considered inadequate. A number of holes were drilled in the area to obtain soil core samples that were analysed for water content, chloride concentration of soil water, and matric suction.

Walker et al. (1990) give the same theory behind the chloride mass balance as Allison and Hughes (1978) for steady state conditions (Equation 3). However, working on land that was cleared of vegetation, Walker et al. (1990) developed a mass balance involving both chloride and water for transient conditions (i.e. the recharge rate has changed due to land clearance and not yet reached steady state). The increase in drainage through the root zone after land clearing results in a pressure front, which moves down towards the watertable. This causes a downward displacement of saline soil water (referred to as the *chloride front*) as the pressure front moves through. When the pressure front reaches the watertable, recharge is increased. If sufficient recharge to establish a new steady state has not occurred (i.e. pressure front has not yet reached the water table), the amount of water that has drained below the root zone (deep drainage—*D*) is given by:

$$D = \int_{z_{cf}^{0}}^{z_{cf}^{n}} \theta dz + \int_{z_r}^{z_{cf}^{0}} \delta\theta dz + \left[\int_0^{z_r} \delta\theta dz\right]\left(\frac{C_n}{C_d}\right) \qquad \text{Equation (6)}$$

where z^n_{cf} and z^0_{cf} are chloride front depths (m) under new and old land use respectively, C_n and C_d are the chloride concentrations under new and original steady state conditions, and $\delta\theta$ is the difference in volumetric water content under old and new land uses.

Deep drainage rates estimated using this method at sites near Tatiara (Tatiara PWA), Binnum, and Joanna (LLC PWA) ranged from 0–6 mm/y for four sites and 12 mm/y and 80 mm/y for two other sites. The relatively low rates reflected the poor drainage of the soils the study was conducted on (shallow sand overlying heavy clay). The rate of 80 mm/y for one site corresponded with a shallow watertable of only 2 m depth.

Cook et al. (1994) looked at chloride and chlorine-36 concentrations to estimate recharge at the same sites, in a continuation of the work conducted by Walker et al. (1990). Chlorine-36 is a radioactive isotope of chloride with a half-life of 301 000 ±4000 years. Like tritium, it occurs naturally in low concentrations, but atmospheric levels were greatly increased as a result of nuclear weapons testing in the 1950s and 1960s (Phillips 2000). Therefore, peak chlorine-36 levels in the unsaturated zone may be observed (provided they have not been 'flushed' away) associated with this. The volume of water in the soil profile above the peak level is assumed to equal the total soil water flux since the time of peak atmospheric fallout. This is divided by the number of years since the peak fallout to give a recharge rate. Using the chloride mass balance, Cook et al. (1994) reported deep drainage rates of 7 mm/y, 2.5 mm/y, and 8.5 mm/y for sites around Tatiara, Binnum, and Joanna respectively. For chlorine-36, the estimated rates were 8 mm/y, 9 mm/y, and 9 mm/y for sites around Tatiara, Binnum, and Joanna respectively.

It is important to re-emphasise that deep drainage, estimated from the above method, refers to the rate of movement of water below the root zone after a change in land use. It does not necessarily equal recharge (movement of water through the unsaturated zone to the watertable), until the pressure front created by land clearance reaches the watertable. Whatever recharge may be occurring is likely to be less than the rate of deep drainage until this time. A provisional recharge rate may be estimated from deep drainage, though, by dividing deep drainage by the number of years since the land under investigation was cleared of native vegetation (equation 7, where *t* = time since land clearance). This can lead to errors, because it assumes that deep drainage is zero at the time of clearing, and increases linearly with time—when in reality there may be a large initial increase in deep drainage (Walker et al. (1991).

$$R = \frac{D}{t} \qquad \text{Equation (7)}$$

2.3.1.5. Recharge around Border Designated Area

Stadter (1989) made estimates of recharge using multiple methods along the South Australian – Victorian border, from north of Bordertown to south of Naracoorte (Border Designated Area). In areas west and south-west of the Kanawinka escarpment, recharge was estimated by comparing changes in groundwater levels from 1975 to 1987 to 'excess precipitation' (precipitation minus evaporation and soil moisture storage). A plot of water level change vs excess precipitation showed good positive correlation (Figure 5), and the value of excess precipitation, which corresponded to no change in groundwater storage given as the amount of water available for recharge and soil moisture storage. Expected values of soil moisture were subtracted from the total excess precipitation to give recharge values of 75–120 mm/y.

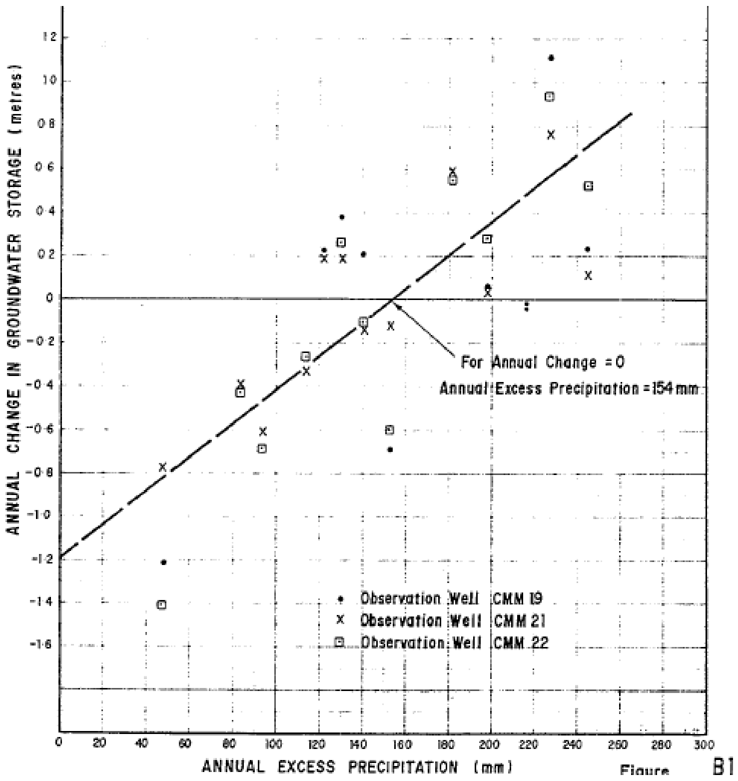

Figure 5. Change in groundwater storage vs excess precipitation, showing 154 mm available for recharge and soil moisture storage (Stadter 1989)

Stadter (1989) used Darcy's Law to calculate recharge, by looking at the change in lateral throughflow in the aquifer. The flow rate (*Q*) in the aquifer is given by:

$$Q = TiL \qquad \text{Equation (8)}$$

where *T* is transmissivity, *i* the hydraulic gradient, and *L* the width of the flow path, and changes in lateral throughflow are equivalent to recharge received by the aquifer. This assumes that the aquifer is homogeneous and there is no turbulent flow. This method was applied to the region around and south of Naracoorte, and yielded recharge rates of 17–40 mm/y.

The watertable fluctuation (WTF) method was also used by Stadter (1989) to estimate recharge. This method involves looking at the annual rise in watertable for individual bores, and multiplying this value by the specific yield of the aquifer (a mean value of 0.1 for the unconfined aquifer was used by Stadter (1989), based on aquifer tests). This approach gave recharge rates around the Naracoorte area of 10–83 mm/y (mean 39 mm/y), decreasing northwards towards Bordertown (mean 15 mm/y). Stadter's 1989 estimates using these physical techniques gave higher estimates than those of Walker et al. (1990) for the same areas. This is probably because of the underestimate of values given by the chloride mass balance (used by Walker) not accounting for preferential flow and spatial variability.

Herczeg and Leaney (1993) looked at recharge to the unconfined limestone aquifer under the Naracoorte Ranges using a suite of chemical and isotopic techniques. They divided their study area (north of Bordertown in Tatiara PWA to south of Naracoorte in LLC PWA, encompassing much of the

Border Designated Area) into three recharge zones based on soil type, extent of irrigation, and surface drainage patterns. As well as looking at diffuse recharge through the soil zone, they also looked at point-source recharge through swamps and sinkholes. Chloride concentration in soil water with depth was used to estimate recharge for several soil types and recharge through an ephemeral swamp. The method used followed that of Allison and Hughes (1978) under steady state conditions (Equation 4). However, under conditions where land clearance had increased the flux of water (and chloride) through the unsaturated zone, the method used followed that of Walker et al. (1990, Equations 6 and 7). Applying the chloride mass balance technique to a swamp, Herczeg and Leaney (1993) modified the chloride input parameters to allow for inflow from streams contributing to the swamp. Herczeg and Leaney (1993) also used water isotopes (oxygen-18 and deuterium) to fingerprint potential recharge sources for groundwater (i.e. direct input of precipitation to groundwater via sinkholes, or infiltration through the unsaturated zone with associated evaporation signature), and carbon-14 (^{14}C) and carbon-13 (^{13}C) concentrations of TIC (Total Inorganic Carbon) in groundwater to determine areas of enhanced recharge.

Herczeg and Leaney found that diffuse recharge was the main source of recharge in the area (with rates of around 4 mm/y for clay soils and 30 mm/y for sandy soils), but that on the whole, recharge to the unconfined aquifer was relatively low in the region. Point-source recharge was found to be relatively insignificant, accounting for only about 10% of total recharge. Areas where regional groundwater displayed a higher ^{14}C concentration and depleted ^{13}C composition were indicative of enhanced recharge, as the higher ^{14}C suggests recent contact with modern biogenic CO_2. Areas with lower ^{14}C and more enriched ^{13}C were indicative of older regional groundwater, in relative equilibrium with aquifer carbonate minerals. The maximum and minimum values of measured ^{14}C and ^{13}C became end members on a mixing line (Figure 6) that most of the regional groundwater samples fell on. Using these end members, the groundwater samples could be partitioned into components of enhanced recharge (*E*) and lateral groundwater flow (*L*). The fraction obtained from enhanced vertical recharge was calculated via:

(from ^{14}C) $$E = \frac{^{14}C_{gw}}{76} - 0.26 \qquad \text{Equation (9)}$$

(from ^{13}C) $$E = \frac{^{13}C_{gw}}{10.6} - 0.21 \qquad \text{Equation (10)}$$

From these equations, the fractions of groundwater obtained from enhanced vertical recharge ranged from 0.3 to 1.0 from Equation (9), and 0.6 to 1.0 from Equation (10) for zones 2 and 3, whereas zone 1 gave fractions of *E* ranging from 0 to 0.2 and 0 to 0.5 for Equation (9) and (10) respectively.

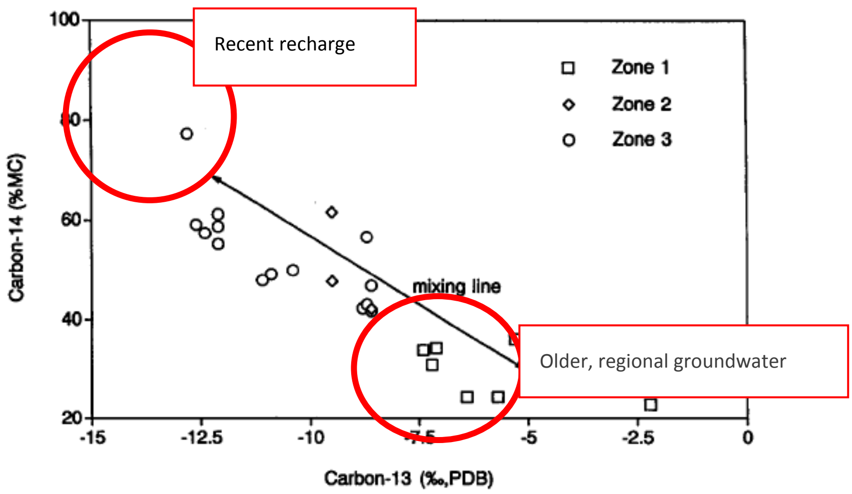

Figure 6. Mixing line for regional groundwater samples: higher ^{14}C and more depleted ^{13}C suggest recent recharge, while lower ^{14}C and more enriched ^{13}C suggest an older, regional signature

De Silva (1994) looked at recharge in the region east of Naracoorte in the Border Designated Area, using the watertable fluctuation (WTF) method. De Silva looked at the mean annual water level rise between 1970 and 1992 for fluctuations, and used a specific yield of 0.1 for the unconfined aquifer. The region was then divided into 'relatively homogeneous' zones based on soil type, land use and topography, to establish areas of like recharge characteristics. The recharge rates calculated using this method (10–45 mm/y for clayey soils where the water table is deeper than 5 m, and 20–60 mm/y for sandy soils) were actually higher than those calculated by Herczeg and Leaney (1993). This again highlights how the chloride mass balance technique may provide an underestimate of recharge by not accounting for preferential flow.

2.3.1.6. Recharge under cleared and irrigated land, Tintinara

Leaney et al. (1999) and Leaney (2000) used the chloride front displacement method to estimate deep drainage rates under cleared land, and the chloride mass balance method for recharge estimates under irrigated land north and east of Tintinara (Tintinara–Coonalpyn PWA). For the cleared land, the chloride front displacement method gave drainage rates ranging from 14 to > 90 mm/y. At the irrigated sites, estimates ranged from 18–420 mm/y, with the lower recharge rates corresponding to higher clay content in the soil profile.

2.3.1.7. Padthaway Salt Accession Study

As part of the Padthaway Salt Accession Study, van den Akker et al. (2006) developed models of salt accession processes in the Naracoorte Ranges, an important part of which was determining recharge rates for the area. In this study, a relationship between soil type and recharge was used as a tool for spatially extrapolating a one-dimensional model of increased recharge and saline soil water flushing following an increase in drainage (a consequence of land clearing). Estimates of recharge were made using the chloride mass balance and front displacement techniques (with additional input of chloride from irrigation considered), and using a one-dimensional model of solute and water flux through the unsaturated zone (LEACHM—Leaching Estimation and Chemistry Model). The LEACHM model uses the Richards Equation and convective-dispersion equations to simulate water and solute flux, based on several input parameters, amongst them:

- soil physical properties (particle size, bulk density and matric potential)
- daily precipitation/irrigation data
- total weekly evapotranspiration
- mean weekly air temperature
- mean weekly amplitude of air temperature
- vegetation information (e.g. for vines' canopy growth, rooting depth, date of maturity and harvest).

Van den Akker et al. (2006) also used the water balance technique. This is a simple equation where drainage (*D*) is solved as the residual of a water balance in the soil zone:

$$D = (P + I) - (ET + \Delta S) \qquad \text{Equation (11)}$$

where *P* is precipitation, *I* refers to the irrigation input component, *ET* to evaporation losses, and ΔS to the change in stored soil water. Data for *P* and *ET* was obtained from CSIRO and the Bureau of Meteorology. The change in soil moisture was measured on a fortnightly to monthly basis using a neutron moisture meter.

Where measurements of ΔS were not made directly, van den Akker et al. (2006) calculated a soil water balance on a daily basis using theoretical values for available soil moisture storage using the Penman-Grindley method. Penman-Grindley models express recharge as a function of precipitation (and irrigation) and evaporation, and recharge may only occur when the soil moisture deficit (SMD = (crop wilting point) x (crop root depth)) is zero. Further discussion of the Penman-Grindley method, with appropriate references, can be found in van den Akker et al. (2006).

Wohling et al. (2006) describe in further detail the methodology used in the Padthaway Salt Accession Study to spatially extrapolate recharge values. Once again, the chloride front displacement method was used, where a change in land use has led to an increase in drainage and hence recharge rates, and the amount of water that has drained below the root zone is given by Equations (6) and (7) from Walker et al. (1990). In order to spatially extrapolate estimates of recharge from point measurements to a regional scale, Wohling et al. (2006) adapted a relationship between the clay content (*C*) of soil and post-clearing drainage rates (*D*) developed by Leaney et al. (2004), where:

$$D = 10^{(-0.035 * C + 2.23)} \qquad \text{Equation (12)}$$

in mm/y. Wohling et al. (2006) then used a one-dimensional model to estimate recharge rates with time since clearing, based on the models by Leaney et al. (2004) and Cook et al. (2004). These studies use equations that assume a log normal distribution of recharge rate around a mean recharge rate, defined by μ and σ both parameters related to the variation coefficient. The method of Cook et al. (2004) calculates water content (θ_w) as a function of mean final drainage rate and the maximum hydraulic conductivity (K_{max}) for different soil types. Two soil layers may be included in the model, and the different soils are assigned parameters (θ_m^a, θ_0^a, θ_m^b, θ_o^b, K_m) where θ_0^a and θ_o^b are residual water content for no recharge for the soil layers *a* and *b*, and K_m is the reference value of hydraulic conductivity at a water content of θ_m^a and θ_m^b. Recharge with time (*t*) since clearing is then given by:

$$R(t) = 0.5e^{\mu+\frac{\sigma^2}{2}}\left(1 - erf\left(\frac{\ln\left(L/t^2\right) - \mu - \sigma^2}{\sigma\sqrt{2}}\right)\right) \qquad \text{Equation (13)}$$

Data for this study was collected along two transects (following the groundwater flow path), with research sites covering various land use types, including native vegetation, cleared dryland agriculture and irrigated lucerne. Soil core samples were collected at each site. Estimates of recharge from the chloride front displacement method ranged from 2.5 mm/y to 35 mm/y. At some sites, the 'centre of mass' of historical salt store had already flushed to the watertable, therefore 'minimum' recharge rates of > 13 mm/y to > 49 mm/y were estimated. For spatial extrapolation, the study area was separated into seven soil land units (SLUs), each with an average clay content. The clay contents were used to calculate drainage rates for each SLU using Equation (12). Based on this spatial map of drainage, clay content, the associated soil physical properties, and depth to water, the recharge rate as a function of time since clearing was used to create a spatial map of recharge using Equation (13). The salt flux associated with this change in recharge rate was also determined by Wohling et al. (2006); however, details of this will not be described here.

2.3.1.8. Recharge estimates as part of land use impacts investigation

Mustafa et al. (2006) investigated the impact of forestry plantations on water quality and quantity in the Lower South East, part of which involved estimating recharge rates under different land uses. Two study areas were looked at, one area around Nangwarry (Zone 2A) and also the Bakers Range area (Short management area). Recharge estimates were made using the watertable fluctuation method, chloride mass balance, and a water balance approach similar to that previously mentioned, but modified somewhat to accommodate the land type being studied. Mustafa et al. give the drainage rate (Q_{wt}) as:

$$Q_{wt} = P - I - T - E - \left(S_c - S_p\right) \qquad \text{Equation (14)}$$

where *P* is total precipitation, *T* represents uptake of water through plants (and associated transpiration), *E* is measured or estimated evaporation from the soil surface, and S_C and S_P represent the 'current' and 'previous' volumetric water content of the soil profile respectively. Using these approaches, recharge under native vegetation was estimated to be approximately 8 mm/y, while estimates under cleared land (pasture) ranged from 40 to 375 mm/y (average 200 mm/y). Data was also collected under blue gum and pine tree plantations; however, the authors assumed no recharge was occurring under these land covers (due to the amount of chloride concentrated in the unsaturated zone as a result of plant water uptake), and instead focused on estimating the amount of soil water/groundwater being taken up by the plantations.

2.3.1.9. Regional recharge estimation for evaluation of resource condition

The most recent review of the groundwater resource condition in the South East was conducted in 2006 (Brown et al. 2006). This involved a review of total available recharge (TAR) for each different management area in the region, in order to revise figures of permissible annual volumes (PAVs) of groundwater extraction. The watertable fluctuation method (WTF) was used to estimate recharge over much of the region (approximately 50% of management areas). In areas where the watertable fluctuation method was used, the specific yield of the unconfined aquifer was set as 0.1 again, considered to be 'conservative and representative of limestone aquifers'. In some areas, however, the WTF method was inadequate, either because the watertable was too deep for any fluctuation to occur, or because other factors masked the seasonal fluctuation. In these areas, estimates of recharge obtained in previous studies were used (e.g. Allison and Hughes 1978). Recharge rates obtained from these methods ranged from 15 mm/y to 200 mm/y (Figure 7).

Figure 7 shows that recharge rates calculated by Brown et al. (2006) are optimum rates, in that they assume the land is covered completely by unimproved pasture. To obtain a more accurate figure of regional recharge for resource management purposes, land under lakes and native forest was subtracted from the total area (the assumption being no recharge occurs under these features), to give a net land area over which recharge may occur, allowing for calculation of TAR. A nominal figure of 10% of this TAR was subtracted from the total to allow for the requirements of groundwater-dependent ecosystems. The use of groundwater resources by forestry plantations was also considered in assessing the condition of the resource, with adopted figures of 83% reduction in recharge under softwood and 77% reduction under hardwood forestry.

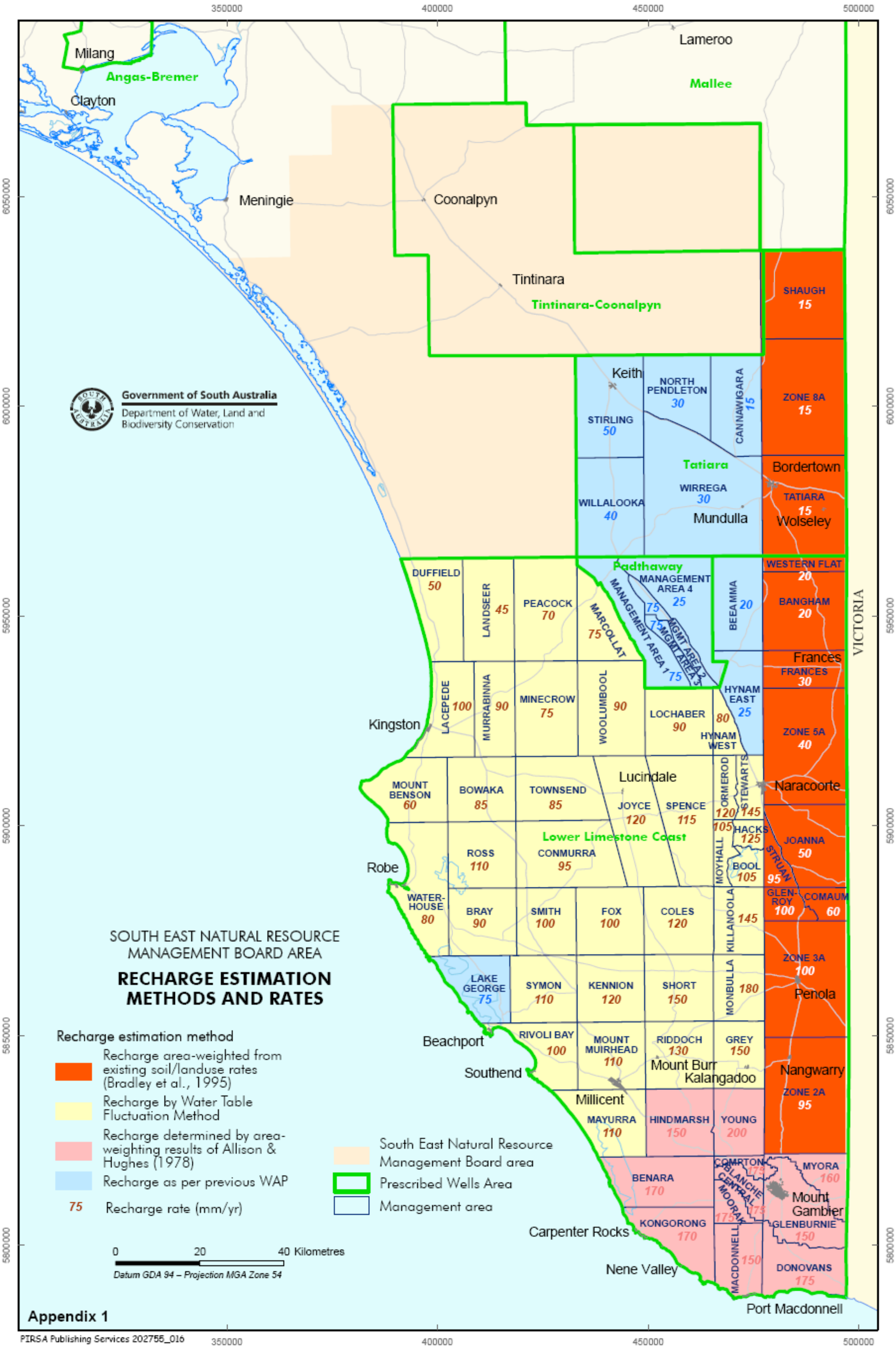

Figure 7. **Recharge rates for individual management areas obtained from different methods (taken from Brown et al. 2006)**

2.3.2. OVERVIEW OF RECHARGE ESTIMATIONS AND METHODS FOR THE CONFINED AQUIFER IN SOUTH EAST SA

The unconfined Gambier Limestone and confined Dilwyn Formation are separated by an aquitard throughout the region. The Dilwyn Formation rarely outcrops in the region (Love et al. 1993), therefore it is presumed there is some hydraulic connection between the two aquifers, which allows for recharge to the Dilwyn Formation from the Gambier Limestone. The potential for recharge to the Dilwyn Formation from the Gambier Limestone is thought to exist east of the 'zero-head difference contour' (Figure 8), a boundary inferred from hydraulic data which marks the change in hydraulic gradient between the two aquifers. To the east, the pressure head is higher in the Gambier Limestone than the Dilwyn Formation, accommodating conditions for downward flux.

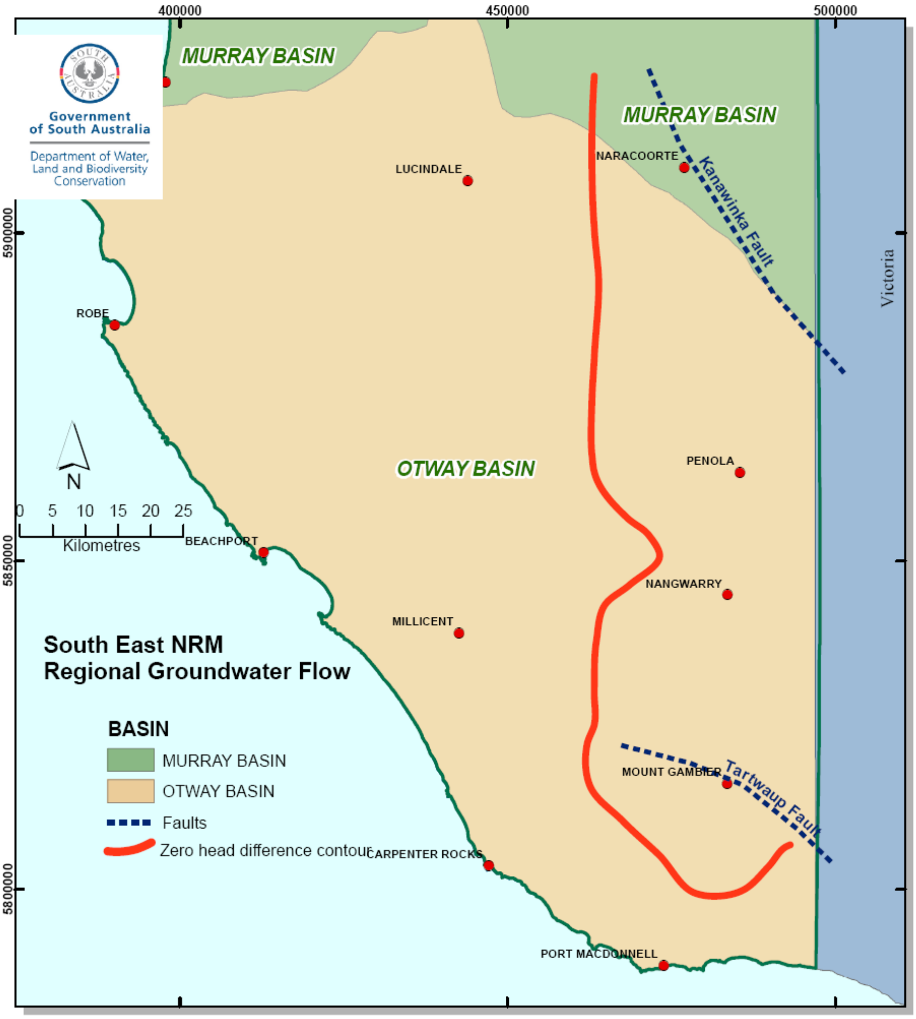

Figure 8. Approximate location of the zero-head difference: leakage from the unconfined to confined may occur to the east and north-east (after Harrington et al. 1999)

2.3.2.1. Modelling solute movement through confining layer

Love et al. (1996) investigated the transport of water and solutes through the aquitard that separates the two aquifers. Core samples were obtained from the confining bed and analysed for permeability, porosity, and ion chemistry and stable isotope composition of pore water. A one-dimensional advection/diffusion model was applied to the chloride and water isotope data to determine the change in concentrations in the aquitard with time due to advection (i.e. pressure-driven flux or groundwater flow) and diffusion (flux along a concentration gradient). The results showed that while diffusion was the dominant transport process in the aquitard at one site, and advection and diffusion were equally important in two other sites, overall there is little transport via diffuse leakage between the two aquifers through the aquitard. Love et al. (1996) concluded by hypothesising that recharge to (or discharge from) the Dilwyn Formation must occur via preferential flow, possibly through faults, which are numerous in the region.

2.3.2.2. Hydraulic and hydrochemical investigation, Nangwarry and Tarpeena

Brown et al. (2001) looked at recharge to the confined Dilwyn Formation at two sites previously identified as likely recharge areas (in Love et al. 1993; Colville and Holmes 1972) both east of the zero-head difference. Two sites, one east of Tarpeena and another east of Nangwarry, were instrumented with a series of multi-piezometer wells screened at different depths in the unconfined and confined aquifers. Groundwater samples were collected for carbon-14, carbon-13, chlorofluorocarbons (CFCs), stable isotopes of water, radon-222 and electrical conductivity (EC). Hydraulic head measurements in the unconfined aquifer were 16 m higher than the levels in the top of the confined aquifer at the Tarpeena site, and 13.5 m higher at the Nangwarry site. This showed a definite potential for downward flux of water from the unconfined aquifer to the confined aquifer.

Carbon-14 concentrations of groundwater were relatively similar in ‘recent age’ in the unconfined and confined aquifers; however, concentrations in the confining layer separating the two were much ‘older’. This age difference showed that diffuse recharge from the unconfined to the confined aquifer through confining layer was not likely to be occurring at these sites, supporting the hypothesis of Love et al. (1996).

Chlorofluorocarbons (CFCs) were used by Brown et al. (2001) to determine ‘ages’ of the groundwater (and hence the time of recharge). CFCs are synthetic organic compounds, produced for industrial and commercial purposes. In the past, three types of CFCs have been used for dating groundwater, CFC-11 ($CFCl_3$), CFC-12 (CF_2Cl_2), and CFC-113 ($C_2F_3Cl_3$), although Brown et al. only used CFC-11 and CFC-12. The atmospheric concentration of CFCs is relatively uniform over large areas and shows little spatial variation. Consequently the atmospheric input of CFCs to groundwater can be deduced with high precision (Cook and Herczeg 1998). CFC ages are determined by converting the CFC concentration in groundwater to equivalent atmospheric concentrations using known gas solubility values and assuming the temperature of recharge water (16 ^{o}C for Brown et al. 2001). These concentrations are then compared with known historic atmospheric concentrations to determine the approximate age of groundwater.

CFC results gave groundwater ages of 1970 at the Tarpeena site, and 1965 at the Nangwarry site. Similar groundwater ages, estimated from CFCs, were found in both the confined and unconfined aquifers, supporting the results from Carbon-14. Stable isotope data for the Tarpeena site suggests recharge occurred under similar climatic conditions to contemporary times in both the unconfined and upper portion of the confined aquifer. However, the bottom ‘sub-aquifer’ of the Dilwyn Formation shows some enrichment in $\delta^{18}O$ and $\delta^{2}H$, suggesting some degree of evaporation prior to recharge (and hence different recharge conditions).

2.3.3. FURTHER TECHNIQUES FOR ESTIMATING RECHARGE

2.3.3.1. Tritium/Helium-3 and recharge rates based on age dating

The use of tritium (^3H) alone in recharge studies has been mentioned already. However, due to radioactive decay, the previously discussed 1964–65 peak levels of tritium are difficult to distinguish from current tritium concentrations in rainfall in the Southern Hemisphere. This has resulted in a general replacement of the tritium technique with the tritium/helium-3 ($^3H/^3He$) method (Scanlon et al. 2002). Helium-3 is produced via the radioactive decay of tritium, and the ratio of tritium to helium-3 can be used to quantify the extent of radioactive decay of tritium, and thus estimate the residence time of groundwater (up to 40 years). Measuring both the tritium and helium-3 concentration of groundwater, a sample's age (t) can be estimated via:

$$t = \lambda^{-1} \ln\left(\frac{^3He^*}{^3H} + 1 \right) \qquad \text{Equation (15)}$$

where $^3He^*$ denotes helium-3 derived from tritium decay only (tritiogenic helium-3), not from other sources like the atmosphere, nuclear reactions in subsurface, or helium of mantle origin (Solomon and Cook 2000).

While the age of a groundwater sample gives an approximate time of recharge, it does not give a recharge rate. In order to determine recharge rate from age data (e.g. tritium/helium-3, CFCs), some assumptions about the aquifer under investigation are needed:

- Recharge is constant across the aquifer.
- The aquifer is of constant thickness and underlain by an impermeable layer.

If recharge is constant, then the groundwater age (t) sampled at depth (z) below the water table can be given by:

$$t = \frac{h\varepsilon}{R} \ln\left(\frac{h}{h - z} \right) \qquad \text{Equation (16)}$$

where h is aquifer thickness and ε is porosity. If the groundwater sample is taken at a discrete depth, then recharge can be estimated by rearranging Equation (16):

$$R = \frac{h\varepsilon}{t} \ln\left(\frac{h}{h - z} \right) \qquad \text{Equation (17)}$$

If the sampling takes place close to the watertable, however, the recharge rate may be expressed by:

$$R = \frac{z\varepsilon}{t} \qquad \text{Equation (18)}$$

These equations highlight that when performing a recharge study, and sampling for age tracers like tritium or CFCs, knowing the depth of sampling, or where exactly the piezometer is screened is important. Short screen intervals, which sample water from a discrete depth, are recommended for such studies (Cook and Herczeg 1998). Solomon et al. (1995) used the tritium-helium relationship to derive recharge rates to a shallow unconfined aquifer of glacial origin in Cape Cod, Massachusetts, ranging from 700 mm/y to 1150 mm/y.

Further tracers may be used to date relatively young (< 50 years old) groundwater, such as ^{85}Kr (a radioactive isotope of krypton, see Cook and Solomon (1997)) and sulphur hexafluoride (SF_6, see Goody et al. 2006). However, due to the current ease of analysis, the focus in this report is on CFCs.

2.3.3.2. Darcy's Law

Darcy's Law has been used to estimate recharge in the unsaturated zone in many studies in arid–semiarid conditions. Recharge is calculated via:

$$R = -K(\theta)\frac{dH}{dz} = -K(\theta)\frac{d}{dz}(h+z)$$
$$= -K(\theta)\left(\frac{dh}{dz}+1\right) \qquad \text{Equation (19)}$$

where *K(θ)* is hydraulic conductivity at water content *θ*, *H* is total head, *h* is matric pressure head and *z* is elevation. Accurate estimates of recharge based on this method rely heavily upon accurate estimates of conductivity (*K*) and head gradient (*dh/dz*). While precise estimates of conductivity may be made, the potential for errors in measurement means there is a lower limit of recharge estimation of approximately 20 mm/y using this method (Scanlon et al. 2002). Therefore, it is not the ideal technique for regions with lower recharge rates.

2.3.3.3. Zero flux plane

The zero flux plane (ZFP) can be defined as a boundary where no vertical water flux in the soil column takes place. Above the ZFP, flow is upwards via evapotranspiration, and below the ZFP it is downwards (Drainage). Recharge can be estimated based on changes in soil water content below the ZFP. This requires measurement of water contents at sufficient intervals down to the depth where recharge occurs (i.e. where downward movement occurs towards the watertable). This method can provide very accurate estimates of recharge; however, it is quite labour-intensive. Multiple tensiometers are needed to measure soil moisture content, and frequent measurements are required. Automated data collection systems can be set up; however, they can be expensive (Bond 1998). Furthermore, this technique cannot be applied in conditions where water fluxes are downward in the entire profile, because a water front moving down through the profile may mask the ZFP (Scanlon et al. 2002).

2.3.3.4. Applied tracers

The use of tracers already present in the groundwater system has been discussed; however, tracers may be introduced specifically to estimate recharge rates. Tracers (e.g. bromide, ^{3}H, visible dyes) are applied as a pulse at the surface or at some depth in the unsaturated zone. The movement of the tracer with time is determined by drilling test holes for sampling, and the recharge rate given by:

$$R = v\theta = \frac{\Delta z}{\Delta t}\theta \qquad \text{Equation (20)}$$

where v is velocity of the tracer movement (estimated from the sample holes), Δz is the depth of the tracer peak, Δt is the time between sampling and tracer application, and θ is volumetric water content (Scanlon et al. 2002). While accurate estimates of recharge may be made using applied tracers, there are also some limitations to the technique. There may be problems getting permission to apply tracers (e.g. tritium) and vadose zone processes such as sorption and plant uptake may alter the tracer concentration.

2.3.3.5. Stable isotopes of water

Stable isotopes of water (oxygen-18 and deuterium) may be used to estimate recharge rates in areas where the isotopic signature of rainfall changes over the year and significant recharge occurs during both summer and winter (Barnes and Allison 1988). If this is the case, the signature of isotopes in the unsaturated zone should show a cyclic pattern with depth. Each ‘cycle’ may be taken as an annual amount of recharge, and this amount quantified by integrating the water content over the cycle interval. Considering the climate in the South East, which is characterised by dry summers, this method is not suitable. However, analysis of stable isotopes in pore water may provide useful details on the climatic conditions under which recharge occurred.

2.3.3.6. Catchment scale modelling

Many recharge studies, like the present study, are concerned with estimating recharge rates for the purposes of natural resources management over large spatial scales. Approaches to this type of catchment scale recharge estimation have been developed which usually involve the separation of catchments into land units that are similar in recharge patterns (Hatton 1998). One-dimensional water balance models may then be applied to these land units in order to determine recharge maps for the catchment (two- or three-dimensional models may also be used where appropriate).

2.3.3.7. Electromagnetic induction methods

The need for up-scaling of point recharge estimates has already been discussed, along with a summary of projects where this has been attempted (Wohling et al. 2006), and given the context of this regional study, it is a desired outcome. One method of interpolating recharge characteristics in between point measurements is the use of electromagnetic induction (EM). EM is able to provide information about soil profile apparent electrical conductivity (*ECa*) over large spatial scales. *ECa* does not show purely soil water flux, but is a function of a number of factors, including soil texture, salt and water content, and clay mineralogy. However, provided EM data undergoes calibration or ground truthing with site observations, reliable data about factors such as clay content in the upper parts of the soil profile—and hence recharge—may be obtained from EM surveys (Cook and Williams 1998).

2.4. SUMMARY AND RECOMMENDATIONS

Tables 2 and 3 present a summary of the main techniques discussed in this review, sorted by author. The suitability of each technique for this particular study is commented upon. As can be seen, a number of techniques seem attractive for this study. These include techniques based on hydrochemistry (chloride methods) and age dating (CFCs), those based on hydrogeologic and meteorological data (WTF, Darcy's Law calculations) and modelling (up-scaling from point estimates). Furthermore, a number of techniques have identified themselves as not suitable for this study (lysimeters, tritium on its own, applied tracers, zero flux plane method etc.).

Having a wide variety of possible techniques is useful. Scanlon et al. (2002), for example, recommend a wide variety of techniques be employed in recharge studies in order to increase confidence in estimates. Ultimately, the selection of techniques will rely upon the selection of field sites. With regards to the SENRM Region, a basic conceptual understanding of recharge in the region (a further result of this review) helps in this aspect. For example, a number of physical and geomorphologic factors have been identified as having a significant influence on recharge, among them:

- Soil type: Increasing clay content (particularly within the top 2 m of the soil surface) in the unsaturated zone results in a decrease in drainage and hence recharge.
- Land use: For example, little or no recharge is reported to occur under forested land, whereas high rates occur under cleared land used for pasture.
- Depth to water: Some techniques apply more to shallower watertables (e.g. watertable fluctuation method), while other techniques may be useful where the watertable is deeper (e.g. chloride methods).
- Climate: The amount of precipitation that falls annually ultimately controls how much water will be available for recharge.

Obviously, a number of different combinations of the above factors exist, hence successful identification of the main physical and geomorphological land units in the region is useful for site selection. Choosing the most representative land units for the region will help in up-scaling point estimates of recharge and therefore improves estimates of regional recharge. Once the most representative land units for the region have been chosen, the appropriate methods can be applied based on background information on the particular study area. In the South East, the choice of recharge estimation techniques should be dictated largely by depth to water. For this project, in sites where the watertable is within 10 m of the surface, recommended methods are:

- water table fluctuation
- chloride mass balance/front displacement
- age dating with CFCs.

Where the watertable is more than 10 m below the surface, the recommended methods are:

- chloride front displacement
- possibly chloride mass balance (if soil coring reveals flushed profile)
- age dating with CFCs.

Techniques for estimating recharge to the confined aquifer in the region have been discussed; however, no real 'recharge rates' exist for the confined aquifer. This is because recharge to the confined aquifer is believed to occur via leakage from the unconfined aquifer through faults and fractures. These processes are not well-understood and improving knowledge on the influence of structural features like faults on groundwater flow in the region is the subject of Sub Program 1.3 of the South East National Water Initiative Project.

Study	Technique(s) used	Land type	Comments regarding current study
Holmes and Colville (1970)	Lysimeters	Dryland and forestry	Not suitable, instrument settling in period is beyond project timelines.
Allison and Hughes (1972)	Tritium (age dating)	Forestry	Age dating would be suitable for this study, though perhaps not with tritium due to decay of 'peak' levels.
Allison and Hughes (1975)	Mixing cell modelling	Dryland	Not suitable for this project; however, data collected in this project could help calibrate regional groundwater model at a later stage.
Allison and Hughes (1978)	Chloride mass balance and age dating (tritium)	Various (Lower South East)	Very suitable, both methods have relatively simple data requirements, and results seem to correlate well (validating both methods), and are applicable to varied site conditions. Again, an age dating analyte (such as CFCs) could be used in place of tritium for reasons mentioned above.
Walker et al. (1990)	Chloride front displacement	Various (Naracoorte Ranges)	Suitable for areas with considerable depth to water (> 10–15 m) where chloride may not have been flushed since land clearing.
Cook et al. (1994)	Chlorine-36 (age dating)	Various (Naracoorte Ranges)	Again, age dating would be suitable, although other analytes would be favourable over chlorine-36.
Stadter (1989)	Watertable fluctuation and Darcy's Law calculations	Various (Border designated area)	Both suitable techniques, although WTF method only valid in areas where the watertable is within 10–15 m of surface.
Herczeg & Leaney (1993)	Carbon isotopes	Various (Naracoorte Ranges)	Not suitable for estimating recharge rates, more for looking at areas of enhanced recharge on a regional scale.
van den Akker et al. (2006)	Water balance techniques and soil water flux modelling	Various (Padthaway)	Requires detailed data on microclimate at research site and soil physical parameters, therefore not suitable for this study (looking at 24 sites over large spatial scale).

Table 2. Summary of recharge estimation techniques previously used in the South East of South Australia

Technique	Reference	Comments regarding current study
Age dating with other analytes (tritium/helium-3 and CFCs, SF_6)	Scanlon et al. (2002)	Both suitable, although tritium/helium-3 expensive to analyse for and may have to be sent overseas for analysis. SF_6 not available to have commercially analysed. CFCs can be analysed locally, and therefore are more satisfactory for working within project budgets and timelines.
Zero-flux plane	Scanlon et al. (2002)	Not suitable considering data and monitoring requirements.
Applied tracers	Scanlon et al. (2002)	Not suitable for this study considering the time it may take tracer to move through unsaturated zone.
Stable isotopes of water	Barnes and Allison (1988)	Not suitable for estimating recharge rates for the South East because of climate.
Electromagnetic induction methods	Cook and Williams (1998)	Not necessarily suitable for this study looking at site by site recharge over a large spatial scale. May provide useful information and help in up-scaling at a later stage.

Table 3. Summary of recharge estimation techniques where there are no published rates for the South East of South Australia

3. METHODOLOGY

3.1. SITE SELECTION

3.1.1. GEOSTATISTICAL ANALYSIS

As mentioned in Section 2.4, for this type of regional recharge investigation, research sites should be selected based on what soil, climate and land use types are broadly representative of the larger study area. In order to determine this, geostatistical analysis was employed. ArcMap GIS software was used to find intersections between land use types and soil types in the South East. Land use spatial data from 1999 to 2003 published by DWLBC (2006) was used to define six major land use types for the study area (Figure 9):

- Dryland pasture agriculture
- Native vegetation
- Softwood forestry
- Hardwood forestry
- Irrigation
- Other (roads, urban areas etc.).

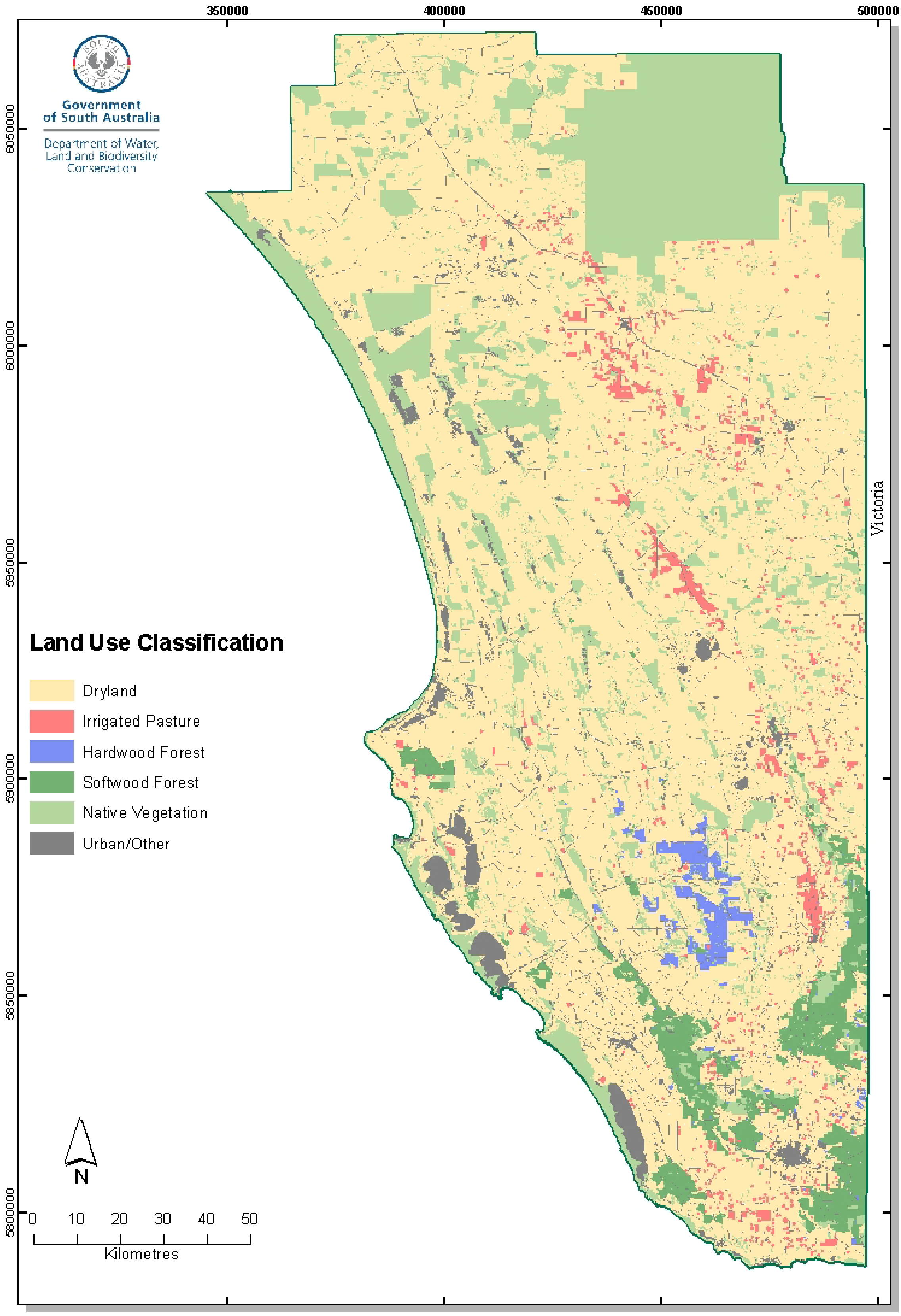

Figure 9. Land use types in the South East of South Australia (based on 2003 land use mapping)

Land and Soil Spatial Data for Southern Australia, published by DWLBC, was then used to look at soil types in the South East. As a result of the abundance of soil types in the region, a grouping of the 61 recognised soil types into seven categories of 'like recharge potential', by staff from DWLBC's Soil and Land Information team, was used for analysis in this project (Figure 10). The seven categories are:

- High
- High to Moderate
- Moderate to High
- Moderate
- Moderate to Low
- Low to Moderate
- Low

High indicates there is a high potential for water to percolate through the particular soil profile into underlying strata and recharge groundwater (for example, a deep sand profile). Likewise, Low indicates there is a low potential for water to percolate through the soil profile. Classifications are subjective and relative, and are influenced by profile thickness and underlying material (D Maschmedt [DWLBC] 2007, pers. comm., 6 February 2008). Full details of these classifications are given in Appendix A.

It is worth pointing out that these categories are based on soil descriptions that apply to the top 2 m of the soil profile. This is important to bear in mind when looking at soil types listed in section 4 (Results). For example, 'Thick sand over clay' means there is 0.5 m or more sand overlying clay in the top 2 m.

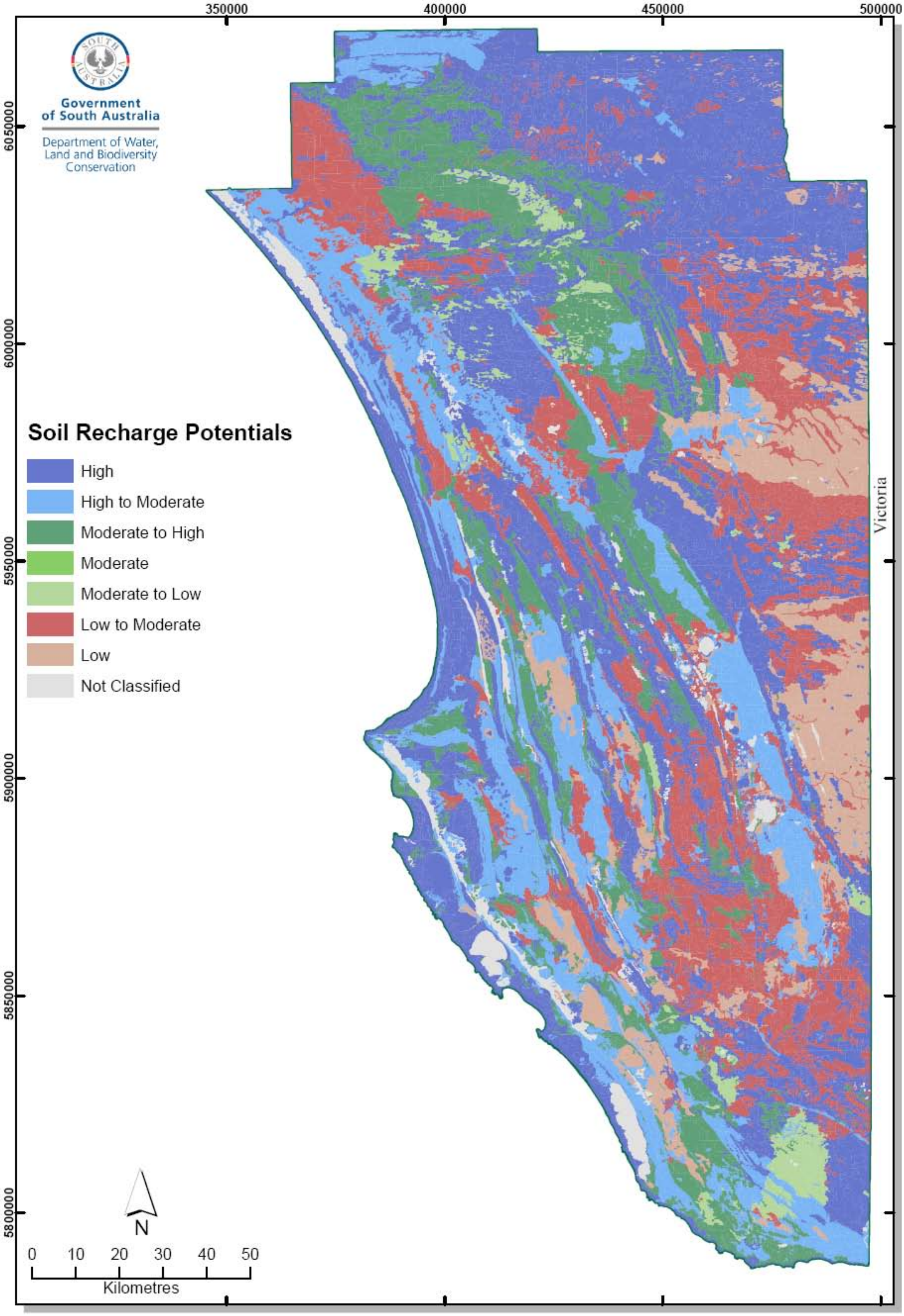

Figure 10. Soil recharge potentials in the South East of South Australia

The intersection of these two spatial data sets produced 42 GIS layers, each with a particular land use and soil recharge potential. To incorporate the influence of climate type on site selection, five climatic zones for the SENRM Region were defined. Gridded average annual rainfall and areal actual evapotranspiration data were obtained from the Bureau of Meteorology (BoM) and re-gridded using ArcMap software to obtain two datasets with coincident data points. The re-gridded evapotranspiration data was subtracted from the rainfall data using ArcMap to produce a third gridded data set (referred to herein as ‘Rain-AAET’). The Rain-AAET grid was contoured using ArcMap using Kriging interpolation and contour intervals were selected using the Jenks Natural Break methodology within ArcMap. This contoured Rain-AAET grid was examined and features deemed to represent artefacts of data processing were deleted or adjusted as judged appropriate (Marshall 2007). The five climate zones delineated as described above are shown in Figure 11.

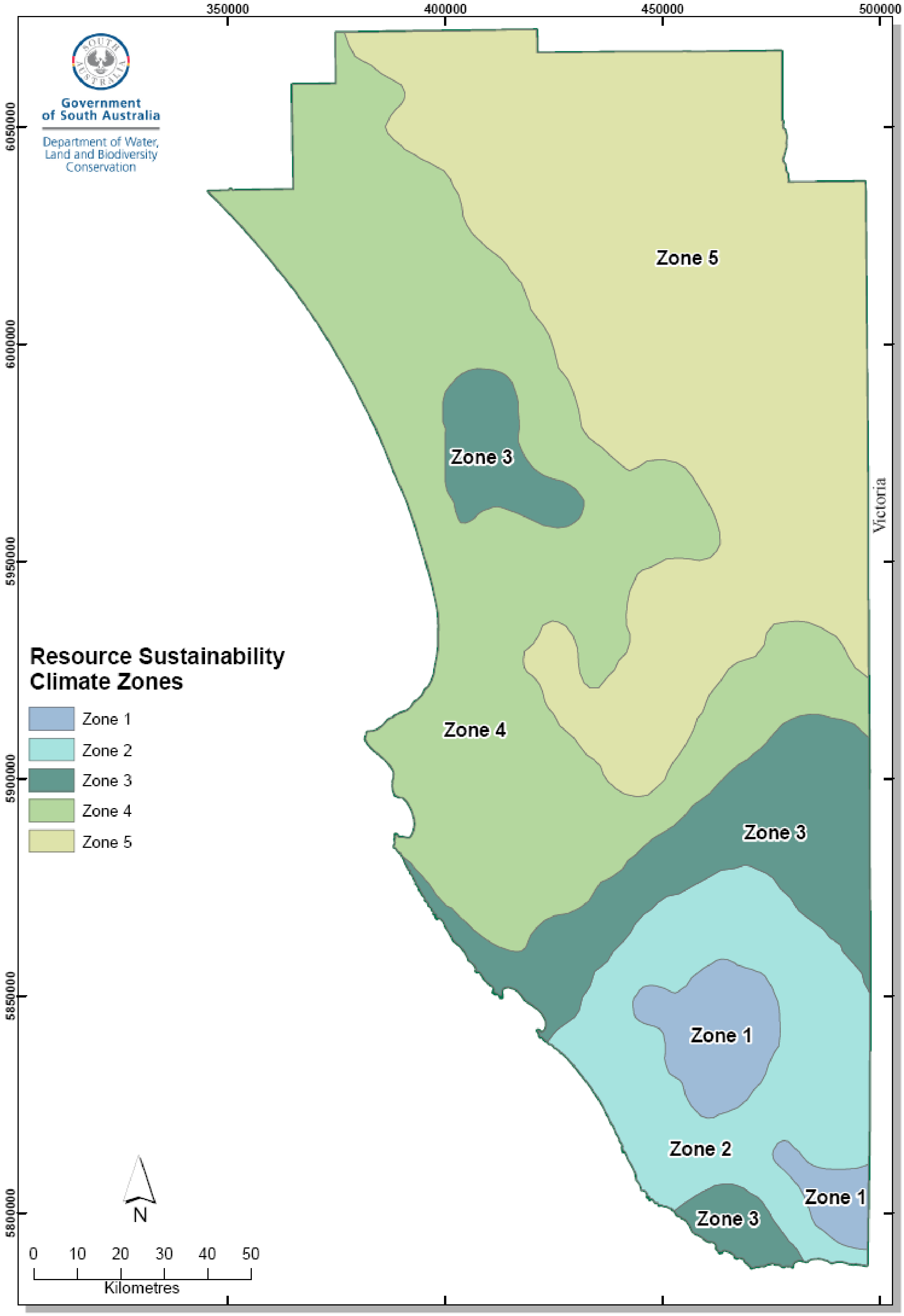

Figure 11. Climate Zones developed for South East of South Australia

Within each climate zone, the proportions of land possessing each land use and soil recharge potential combination were ranked in order of area. The four greatest (in terms of area) land use, soil recharge potential combinations in each climate zone were identified as geographic units considered broadly representative of the SENRM Region. Within these highest ranking combinations, the dominant soil type for the soil recharge potential group was identified, and site selection further targeted based on this. Combinations where the land use was either irrigation, water bodies or urban/other were not considered for site selection. The purpose of this study was to look at recharge from rainfall alone, hence areas where recharge estimation may be affected by pumping, returns to groundwater from irrigation or urban runoff were avoided.

This geostatistical selection process identified 20 possible research sites. A further four sites were chosen based on issues specifically related to the SENRM Region, including:

- two sites to investigate recharge in the vicinity of significant groundwater dependant ecosystems (Piccaninnie Ponds and Pick Swamp)
- recharge under hardwood forestry
- recharge processes in stranded beach-dune systems, following the work of Love et al. (1993) mentioned in Section 2.2 of this report.

3.1.2. SITE RECONNAISSANCE

Following the selection of potential recharge research sites as described above, detailed site reconnaissance was carried out in order to confirm soil type and land use conditions. This process involved hand augering at potential sites to a depth of ~1.5–2 m to confirm soil type and liaising with landholders (both public and private) in order to gain access to land to establish research sites. The location of research sites in representative areas (for example, actually in paddocks for dryland land use) was considered more favourable to locating sites in locations such as roadside verges, due to uncertainty as to what influence excess runoff from roads might have on recharge rate estimation.

Site ID	Easting*	Northing*	Selection criteria	Climate Zone	Soil recharge potential	Soil type	Land use	Comments
RS001A01			Geostatistical	1	Low–Moderate	Thick sand over clay	Dryland	New research site not established, existing wells used
RS002A01	472665	5831330	Geostatistical	1	High	Wet highly leached sand	Dryland	
RS003A01	491990	5799209	Geostatistical	1	High	Highly leached sand	Softwood forestry	
RS004A01	445692	5848192	Geostatistical	1	High–Moderate	Shallow sandy loam on calcrete	Softwood forestry	
RS005A01			Geostatistical	2	Low–Moderate	Thick sand over clay	Dryland	New research site not established, existing wells used
RS006A01	485267	5794566	Geostatistical	2	High–Moderate	Shallow sandy loam on calcrete	Dryland	
RS007A01	483630	5822787	Geostatistical	2	High	Highly leached sand	Dryland	
RS008A01	435133	5846924	Geostatistical	2	Low	Gradational dark clay loam	Dryland	
RS009A01	441923	5864539	Geostatistical	3	High–Moderate	Shallow dark clay loam on limestone	Dryland	
RS010A01	496336	5893349	Geostatistical	3	Low	Sandy loam over poorly structured clay	Dryland	
RS011A01	433613	5861181	Geostatistical	3	Low–Moderate	Thick sand over clay	Dryland	
RS012A01	417555	5980125	Geostatistical	3	High	Bleached siliceous sand	Dryland	
RS013A01	387442	6025105	Geostatistical	4	High	Bleached siliceous sand	Dryland	
RS013A02	387354	6025218	Geostatistical	4	High	Bleached siliceous sand	Dryland	
RS013A03	377297	6017664	Geostatistical	4	High	Bleached siliceous sand	Dryland	
RS014A01	413599	5874802	Geostatistical	4	High–Moderate	Shallow calcareous loam on calcrete	Dryland	
RS015A01	382340	6035511	Geostatistical	4	Low–Moderate	Thick sand over clay	Dryland	
RS016A01	421400	5943760	Geostatistical	4	Moderate–High	Shallow sand over clay on calcrete	Dryland	
RS017A01	487736	5952882	Geostatistical	5	High	Bleached siliceous sand	Dryland	
RS018A01	454036	6024985	Geostatistical	5	High	Bleached siliceous sand	Native vegetation	
RS019A01	488946	5954225	Geostatistical	5	Low–Moderate	Sand over poorly structured clay	Dryland	
RS020A01	452376	5920591	Geostatistical	5	Moderate–High	Shallow sand over clay on calcrete	Dryland	
RS021A01	491371	5790118	Other (see comments)	2	High–Moderate	Shallow sandy loam on limestone	Dryland	Upgradient of Pick Swamp
RS022A01	495031	5788904	Other (see comments)	2	High–Moderate	Shallow sandy loam on limestone	Dryland	Adjacent to Piccaninnie Ponds, existing well used
RS023A01	421740	5943924	Other (see comments)	4	High–Moderate	Shallow red loam on limestone	Dryland	Top of dune in Avenue Range
RS023A02	421691	5943900	Other (see comments)	4	High–Moderate	Shallow red loam on limestone	Dryland	Mid-point of dune in Avenue Range
RS023A03	421584	5943851	Other (see comments)	4	High–Moderate	Shallow red loam on limestone	Dryland	Base of dune in Avenue Range
RS024A01	455261	5883501	Other (see comments)	3			Hardwood forestry	Significant hardwood plantation

Table 4. Details for recharge research sites (*GDA 1994 MGA Zone 54)

The final location of all recharge research sites, along with their particular soil type, land use and climate zone combination is pictured in Figure 12 and site characteristics are summarised in Table 4. There are 27 sites listed in total. Two sites created from geostatistical modelling (RS001A01 and RS005A01) were not established as new research sites. A great deal of effort was directed towards finding a location for these sites; however, the presence of irrigation, significant drains and other features that may affect recharge estimation, in all desirable locations, meant an appropriate location for each site could not be found. In order to estimate recharge rates for these geostatistical combinations, Obswell data were used to find wells on the correct soil and land use combination and the watertable fluctuation method applied to the data from these wells to give a recharge estimate. Chloride samples were also taken from these wells and recharge estimated from the chloride mass balance. Details are given in the Results section. Site RS022A01 also utilised existing infrastructure. A monitoring well adjacent to Piccaninnie Ponds was identified early in the study as useful for the purposes of examining recharge processes near this significant groundwater-dependent ecosystem.

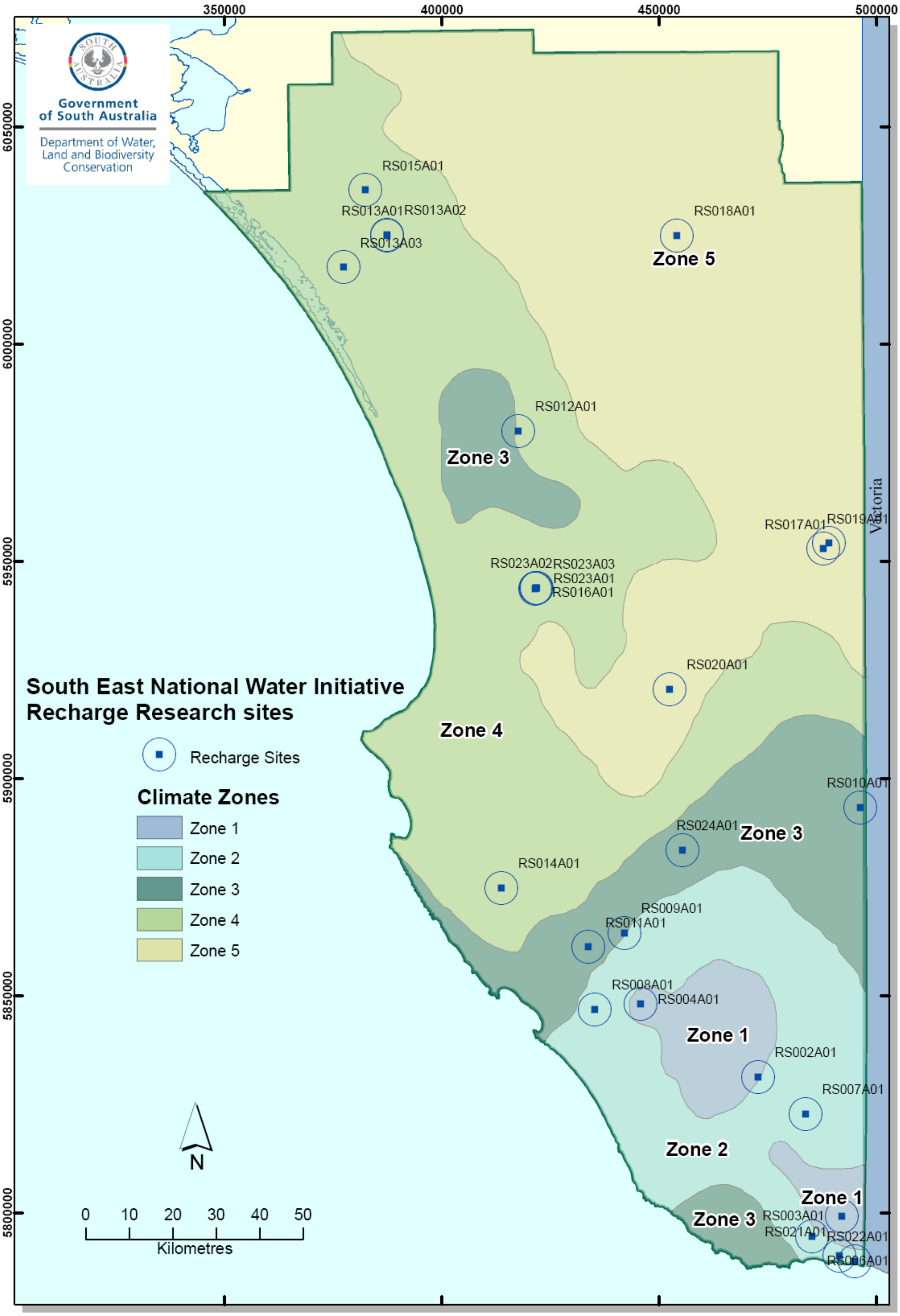

Figure 12. Location of new recharge research sites

Three sites were established to look at recharge processes in a dune system in the Avenue Range (RS023A01, RS023A02, RS023A03), with one site located on top of the dune, one midway down the dune, and one at the base of the dune. These sites were further complemented by the location of a geostatistically selected site on the adjacent flat (RS016A01). Two sites were established on a dryland paddock with high recharge potential in Climate Zone 4 (RS013A01, RS013A02), one site consisting of a series of piezometers to measure water chemistry and monitor water levels, the other consisting of a soil core to the watertable on a dunal rise nearby. A third core (RS013A03) was collected on the same soil/land type 12 km south. Overall, 25 new research sites were established and these were complemented by an additional three sites utilising existing infrastructure.

3.2. FIELD AND ANALYTICAL METHODS

In October and November of 2007 and late February of 2008, approximately 60 investigation holes were drilled at research sites across the entire SENRM Region by Drilling Solutions (Adelaide-based company), using an Investigator drill rig. At sites where there was a significant soil profile and depth to water, soil core samples were obtained using hollow flight augers and split tube core barrels on a wire line recovery. Core samples were collected at 0.5 m intervals from 1 m down to the watertable. In some instances, coring was suspended before reaching the watertable for various reasons (such as refusal with augers on rock, poor core recovery or equipment failure). Soil core samples were placed in 500 mL glass jars and sealed with metal lids wrapped with electrical tape immediately to prevent any evaporation of soil moisture. Soil cores were analysed for soil water chloride concentration and gravimetric water content by CSIRO Land and Water, Adelaide. All soil core results are given in Appendix D.

Piezometer installations were designed to cater to the recommended methods in section 2.4 of this report. Chiefly, at sites where the watertable was within approximately 10–15 m of the surface, one piezometer was installed with a 6 m length of screen straddling the watertable (1 m screen above the watertable, 5 m screen below). The aim of this installation was to measure fluctuations in the watertable, the 6 m screen length allowing for rise or decline in groundwater levels. A further two piezometers were installed in the top few metres of the watertable, completed with short screen intervals (0.5–2 m) for the purpose of sampling the top of the watertable for CFCs and chloride concentration. At sites with a greater depth to water, there were generally only two piezometers installed with short (1–2m) screens, and a soil core collected to look at chloride profiles in the unsaturated zone. Geological logs and piezometer completions are given in Appendix B.

Sites established in dryland paddocks with livestock present were secured by erecting mesh fencing material around piezometer standpipes (Figure 13). This also allowed for instrumentation of these sites with rain gauges. Rainfall collectors were also installed at the majority of sites for the purpose of collecting data on chloride concentration in rainfall. The design of these instruments was a slightly modified version of that described by Hutton and Leslie (1958).

Figure 13. RS015A01 on completion

All piezometers were developed prior to sampling by removing at least four to five times the volume of water added to the well during drilling, or until physical parameters of the water being purged from the piezometer (EC, pH, temperature) had stabilised and water being pumped from the piezometer became clear and silt- or sand-free. Piezometers were then purged prior to sampling using a 12 V submersible pump. As the volume of most piezometers was quite low (as low as 1.5 L in some cases), they were usually purged of more than three to five times the well volume (sometimes up to 20–30 times the well volume). Samples for major ion analysis where collected in plastic sample bottles, kept cool and sent off for laboratory analysis within one to two days of sampling.

Samples for CFC analysis were collected using a stainless steel gas bailer. The bailer was connected via nylon tubing to ultra-high purity nitrogen gas. The gas was used to pressurise the bailer, before the bailer was lowered to the desired sampling depth in each piezometer. The pressure in the bailer from the nitrogen was then released, allowing water to flow into the bailer, before it was re-pressurised and brought back to surface. At surface the sample from the gas bailer was used to fill glass sample bottles, which were allowed to overflow into a glass cup, effectively submersing the sample bottles. Metal lids were then screwed onto the sample bottles underwater, and the sample bottles checked for air bubbles. Any samples found to contain air bubbles were disregarded, and samples re-taken. CFC-11 and CFC-12 were analysed by gas chromatography at CSIRO Land and Water in Adelaide. CFC samples were collected in triplicate and analysed in duplicate. Where the two samples analysed were not in agreement, the third was analysed.

3.3. RECHARGE RATES

For the majority of sites in this study, both the chloride mass balance and CFC methods were used to estimate recharge rates. As discussed in Section 2, the chloride mass balance method requires information on chloride concentration in rainfall and average annual rainfall rates. Rainfall rates used in these calculations are taken from the gridded rainfall data used to delineate climate zones (as described in Section 3.1.1). Data on chloride concentration in rainfall from 2004 to 2006 exists for Mount Gambier (S Mustafa, unpublished data), Keith (Wohling 2008), and Padthaway (van den Akker, 2006). As Figure 14 shows, most of the data from the South East falls below the line established by Hutton (1976), and after personal communication with Fred Leaney, it was decided to use the average of all measured data as chloride input from rainfall, which is 11 mg/L (pers. comm. Fred Leaney, CSIRO).

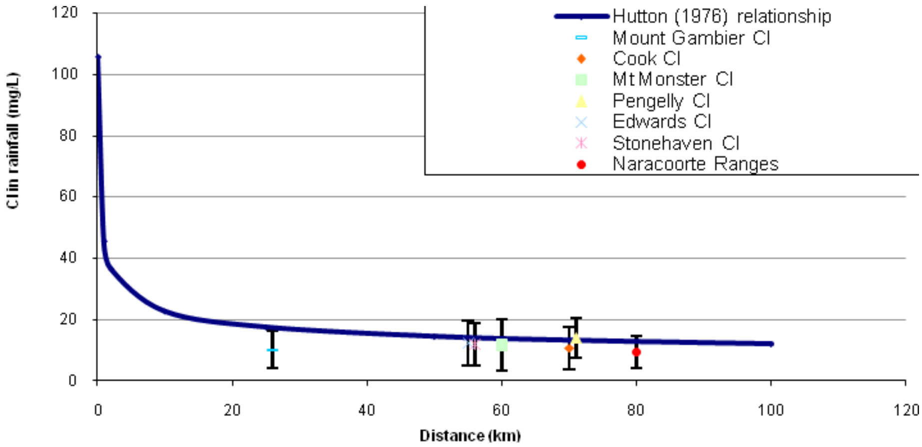

Figure 14. Hutton (1976) relationship between rainfall chloride concentration and distance from the coast, and existing South East data

The chloride mass balance also requires data on the chloride concentration of recharge water, which may be taken from soil water below the root zone, or groundwater close to the top of the watertable. Where possible in this study, soil water chloride concentrations are used to estimate recharge rates. The preference for soil water chloride concentration over groundwater chloride concentration is because of the uncertainty in origin of water sampled below the watertable. Figure 15 (after Cook and Solomon 1997) describes this concept—if recharge is constant over an aquifer area, then the age profile will also be constant. Therefore, water sampled below the watertable may not be representative of local vertical recharge, but rather a spatial and temporal average recharge rate. This will be especially true in areas where the horizontal groundwater flow rate exceeds the vertical recharge rate. The chloride concentration in soil water beneath the root zone, however, is a representation of vertical movement through the unsaturated zone towards the watertable, and therefore more representative of local recharge.

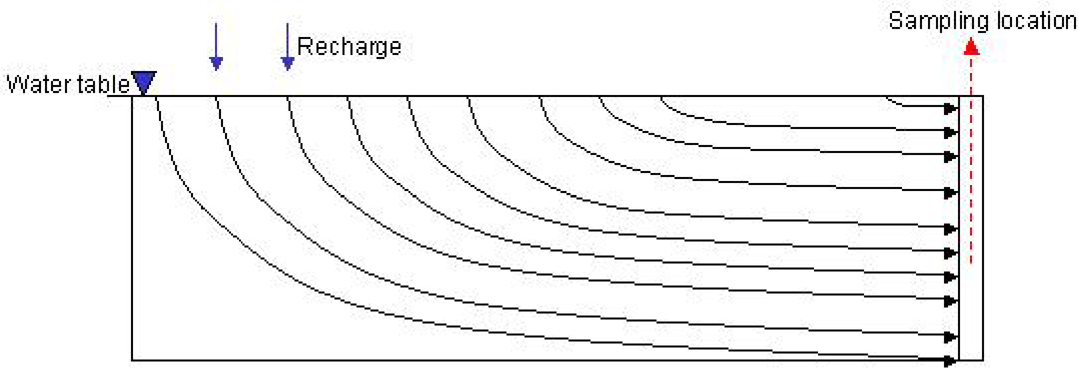

Figure 15. Conceptual model of groundwater flow net in a generic aquifer with constant recharge over the area, and purely advective transport (after Cook and Solomon 1997)

For the CFC method, data required (as well as the groundwater age) includes the depth beneath the watertable at which the groundwater sample was taken, and the porosity of the soil profile through which water has recharged. In all cases, a porosity of 30% was assumed. While the gas bailer was used to sample CFCs at discrete depths, there is still some uncertainty as to where exactly the water sampled has come from. In order to deal with this uncertainty, two recharge rates are given in each case for the CFC method:

- One estimate gives the lower limit of recharge, which assumes that water collected by the gas bailer came from the top of the screened section of aquifer.
- The other estimate gives an upper limit of recharge, which assumes the water collected by the gas bailer came from the bottom of the screened section of aquifer.

Given that most of the piezometers sampled for CFCs had relatively short screen sections (1 m), this recharge rate range is reasonably well-constrained. However, at some sites, the only well that could be sampled had a longer screen, which gave a larger recharge rate range. It should also be noted that for all calculations of recharge rates, the results from CFC-12 alone were used, as CFC-11 is more prone to degradation (see Cook and Solomon 1997).

CFC samples taken below the watertable may present the same problems with interpreting recharge estimates as those described in Figure 15. If a sample is taken too far below the watertable, it may not reflect local recharge. However, if a sample is taken too close to the watertable, it may give an estimated age that is not entirely accurate, as the water at the saturated-unsaturated zone interface may be in equilibrium with the unsaturated zone with respect to CFC concentration. For further discussion of these issues on a site by site basis, see Results.

In cases where the watertable fluctuation method was used on existing observation well records, seasonal differences in water level were multiplied by a specific yield of 0.1, following the recommendations of Brown et al. (2006). It is however acknowledged that specific yield in the limestone aquifer may vary considerably, and this presents a limitation in the approach.

4. RESULTS AND DISCUSSION

The results section is presented on a site by site basis, in order to more easily compare recharge estimations made by various methods at each site. A table of all groundwater chemistry results and all recharge estimates can be found in Appendix C.

4.1. RECHARGE ESTIMATES AT INDIVIDUAL SITES

4.1.1. RS001A01

Climate Zone: One
Soil recharge potential: Low to Moderate
Soil type: Thick sand over clay
Land use: Dryland

As mentioned in the Methods section, a new research site could not be found for the soil recharge potential, climate zone and land use type represented by RS001A01. In order to obtain a recharge estimate for this combination, existing groundwater observation wells, which were located on land units with the same soil/land use combinations, were sampled for chloride and recharge estimated from the chloride mass balance method. Long-term groundwater levels were also analysed and recharge estimated using the watertable fluctuation method. Piezometers selected for RS001A01 were YOU032, RID010. Recharge rates for the various methods are presented in Table 5.

Method	Recharge (mm/y)	
	YOU032	RID010
Watertable fluctuation	74	58
Chloride mass balance	48	17
CFC method	45	13 to 58

Table 5. Recharge rates for RS001A01, given by existing Obswells

4.1.2. RS002A01

Climate Zone: One
Soil recharge potential: High
Soil type: Wet highly leached sand
Land use: Dryland

RS002A01 was located on a grazed dryland paddock approximately 18 km north-west of Mount Gambier. One piezometer screened from 4.26 m to 5.26 m below ground level (herein BGL) was sampled for CFCs and major ion chemistry, and soil cores were collected to 3.5 m (where water was cut). The depth to water at the time of sampling was 3.45 m-BGL. The average soil water chloride concentration below 2 m was 66.3 mg/L (Figure 16), which gave a recharge rate of 127 mm/y (assuming precipitation of 765 mm/y and chloride in rainfall of 11 mg/L). This estimate is lower than the previous adopted recharge rates for the area of 200 mm/y.

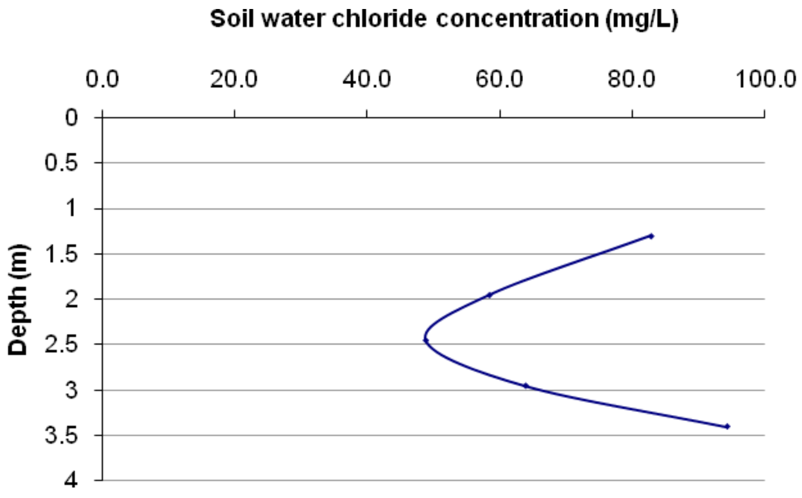

Figure 16. Soil water chloride concentration with depth for RS002A01

CFC-12 concentrations in groundwater at this site gave an apparent age of 29 years (recharge date of 1979). Using the top and bottom of the piezometer screen as the depth below the watertable from which the sample was taken and assuming a porosity of 30%, this gives a recharge rate range of 8–19 mm/y. These samples were collected 0.80–1.80 m below the watertable, so there is some uncertainty as to whether this is reflective of the local recharge rate or recharge from somewhere upgradient. Given the higher recharge rate from chloride, the latter argument seems more valid. Also, recharge estimated from an existing Obswell (YOU016, 1 km west of RS002A01) from the watertable fluctuation method is 234 mm/y. At the time of writing, there is not a sufficient record of water levels at RS002A01 to estimate recharge from the watertable fluctuation method. However, one piezometer at this site has been equipped with a data logger for future monitoring.

4.1.3. RS003A01

Climate Zone: One
Soil recharge potential: High
Soil type: Highly leached sand
Land use: Softwood forestry

RS003A01 was established in a softwood plantation (*Pinus radiata*) in Myora Forest, 18 km south-east of Mount Gambier, planted in 1984. Drilling took place approximately 5 m into a stand of trees just off an access track (Figure 17). Two piezometers were installed into the top of the watertable, which was cut at approximately 27 m below ground level while drilling. A soil core was also collected to 12 m, where there was poor core recovery through limestone.

Figure 17. Drilling of RS003A01, Myora Forest, December 2007

The soil core from RS003A01_MW001 (Figure 18) shows an expected profile of high chloride concentration (2500 mg/L) in the top 2–5 m, a result of plant uptake of soil water and concentration of chloride. Below that, the chloride concentration decreases to a relatively constant concentration of ~70–80 mg/L. The high concentration of chloride in the root zone suggests little or no water is passing through as recharge and renders the chloride mass balance invalid.

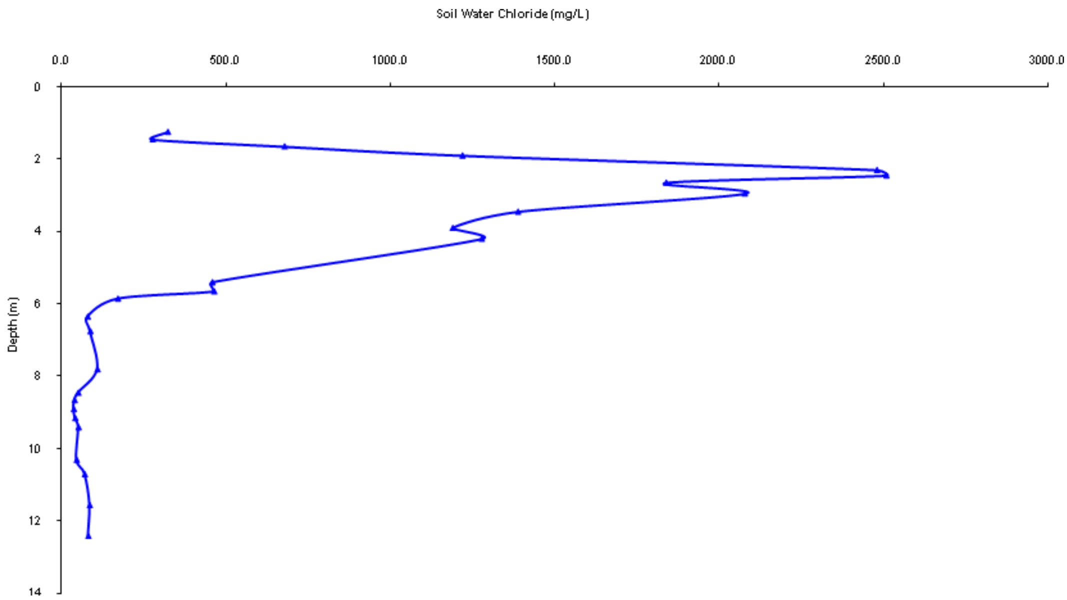

Figure 18. Soil water chloride (mg/L) with depth for RS003A01_MW001

The CFC-12 concentration in groundwater equated to a groundwater age of 1992. Based on the depth of sampling and an assumed porosity of 30%, estimated recharge rates from CFCs range from 25–53 mm/y.

These estimates are higher than expected from previous research—Holmes and Colville (1970[B]) and Allison and Hughes (1972) both report no recharge under forest plantations.

Hydrograph analysis of CAR042 (Figure 19), approximately 4 km north of RS003A01 in the same forest plantation with the same soil recharge potential, shows a steady decrease in groundwater levels from 1993 to the present time (Figure 18). This suggests that there is little to no recharge occurring under the forest, and the lower recharge estimate from the CFC method is the most accurate for this site. Also, given the previously adopted recharge rate for the area (Donovans management area) is 175 mm/y, and Brown et al. (2006) report a recharge reduction of 83% under softwood plantations, the lower CFC estimate of 25 mm/y corresponds well to a rate of 30 mm/y (given by reducing 175 mm/y by 83%). It is also worth noting that numerous sinkholes, some of which are open to the watertable, are present in the Myora Forest (such as Hells Hole), therefore recharge is likely to occur primarily through these features, with no recharge occurring under plantations.

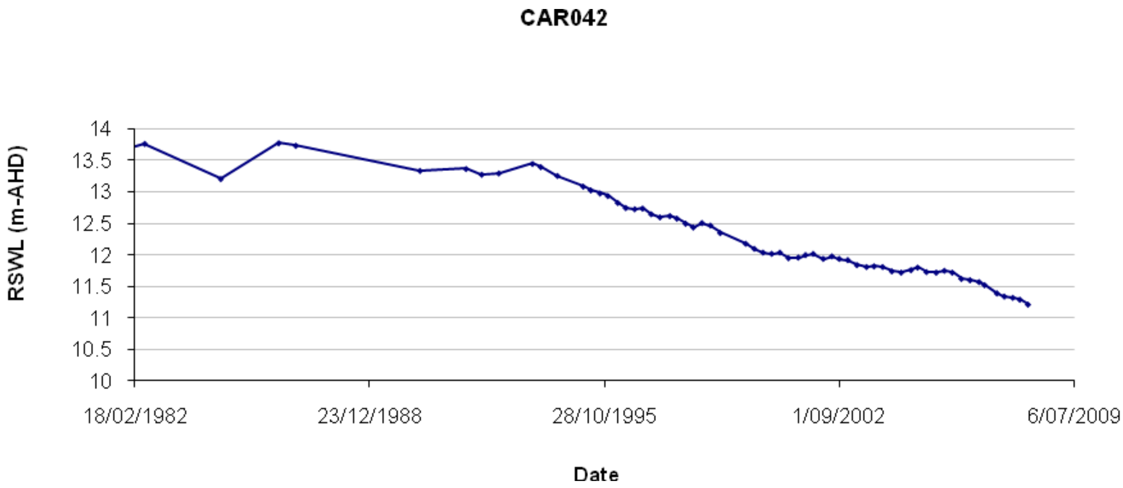

Figure 19. **Hydrograph for observation well CAR042**

4.1.4. RS004A01

Climate Zone: One
Soil recharge potential: High to Moderate
Soil type: Shallow sandy loam on calcrete
Land use: Softwood forestry

RS004A01 was established in a softwood forest plantation (*Pinus radiata*) 9 km north-east of Millicent, planted in 1992. One piezometer was installed between tree rows off an access track. Unfortunately, a soil core could not be collected at this site, as there was only approximately 0.5 m of soil over calcrete and sandstone (see Appendix B for geological log). The depth to water at sampling was 18.56 m, and groundwater samples were collected from the screened section of aquifer (23.7–26.7 m). CFC-12 concentrations were quite low (24 pg/kg) and consequently, groundwater age was estimated to be at least 43 years (> 1965). Unfortunately, the CFC dating technique cannot provide a more accurate date for samples with such low concentrations, therefore 43 years should be considered the youngest possible groundwater age. In reality, the groundwater age could be much older. Therefore, over the sampled interval the estimated recharge rate range is < 36–56 mm/y.

As with RS003A01, these estimates exceed expected recharge rates under softwood plantations, and the fact that no soil core could be collected limits interpretation. However, given what was observed at RS003A01 and what has previously been shown about soil water chloride accumulation under softwood plantations (Mustafa et al. 2006), it is reasonable to assume that there would also be significant chloride concentration in the soil zone beneath RS004A01 (hence the chloride mass balance has not been used here). Also, given that the water samples were collected between 5.14 m and 8.14 m below the watertable, these estimated rates can be assumed to be more representative of recharge from somewhere upgradient, rather than local recharge.

The previously adopted recharge rate for this area (Mount Muirhead management area) of 110 mm/y gives recharge under softwood forestry of 19 mm/y (allowing for 83% reduction in recharge). Therefore, the lower recharge rate from the CFC method of < 36 mm/y can be considered the most reliable estimate for this site. This is probably more reflective of recharge from somewhere upgradient. A data logger has been installed in the piezometer at this site, which will give more insight into recharge at this site into the future.

4.1.5. RS005A01

Climate Zone: Two
Soil recharge potential: Low to Moderate
Soil type: Thick sand over clay
Land use: Dryland

As with RS001A01, no new site was established for the combination represented by RS005A01. Therefore, two observation wells with good hydrograph records were selected for watertable fluctuation analysis to make up for this. MON008 gave an average recharge rate of 160 mm/y, and MON017 (Figure 20) gave an average recharge rate over the period of observation of 128 mm/y.

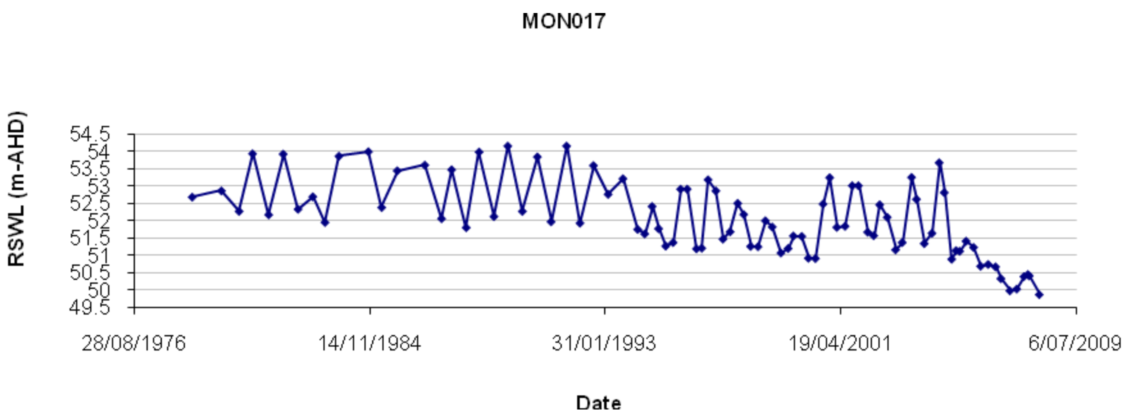

Figure 20. Hydrograph record for MON017

4.1.6. RS006A01

Climate Zone: Two
Soil recharge potential: High to Moderate
Soil type: Shallow sandy loam on calcrete

Land use: Dryland

RS006A01 was established on a dryland paddock approximately 20 km south of Mount Gambier. Major ion and CFC samples were collected from one of four piezometers installed on this site. The depth to water at sampling was 8.18 m-BGL and the sampled piezometer was screened from 9.85 m-BGL to 10.85 m-BGL. Chloride concentration measured in groundwater was 102 mg/L. Assuming a chloride concentration in rainfall of 11 mg/L and annual rainfall of 785 mm/y, the recharge rate from the chloride mass balance technique here is 85 mm/y. CFC-12 measurements give an apparent age of the groundwater at this site of 24 years (i.e. recharged in approximately 1984). This gives an upper estimate of 33 mm/y recharge and a lower estimate of 21 mm/y.

Hydrograph analysis of CAR040, a groundwater observation well 4 km east of RS006A01 on the same soil/land use combination gives an average recharge rate of 23 mm/y from the watertable fluctuation method, for the period 1999–2007 (period of best available records), which suggests that the estimate of recharge from the CFC method is perhaps more accurate for this site.

Figure 21. Drilling at RS006A01, November 2007

4.1.7. RS007A01

Climate Zone: Two
Soil recharge potential: High
Soil type: Highly leached sand
Land use: Dryland

RS007A01 is located in a dryland paddock located approximately 3 km east of Mount Gambier airport (also the location of the Mount Gambier BoM). A soil core was collected down to the watertable at RS007A01 (Figure 22), and it shows a flushed profile. Using the average soil water chloride concentration of 39 mg/L in the chloride mass balance (assuming precipitation of 691 mm/y and chloride in rainfall of 11 mg/L) gives a recharge rate of 195 mm/y.

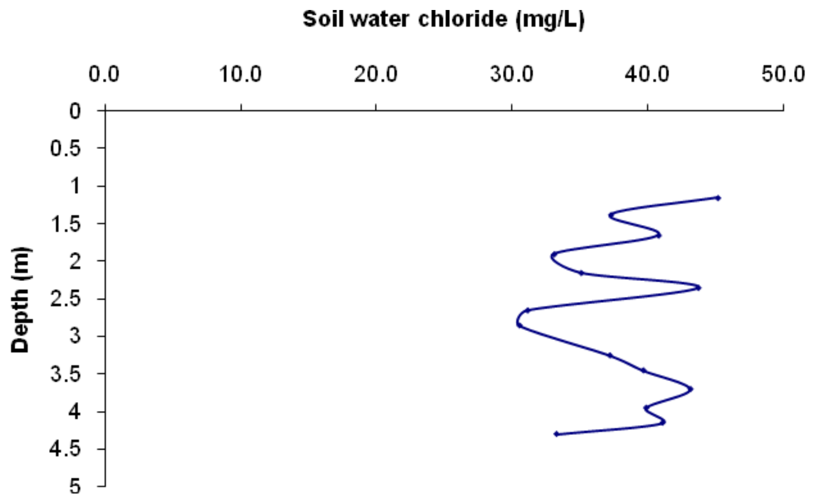

Figure 22. Soil water chloride (mg/L) with depth at RS007A01

CFC-12 concentration was measured in a bore screened 1.5 m below the watertable, and found to have an apparent age of 43 years (recharge date 1965). This gives a recharge rate range of 10–17 mm/y. As with site RS002A01 (located on a similar soil type 14 km north-west), the CFC method gives a significantly lower than expected recharge rate, and is probably more reflective of recharge further upgradient. It is worth noting that RS007A01 is located in the area of steep groundwater gradient north of Mount Gambier, therefore the horizontal groundwater flow rate is definitely greater than the vertical recharge rate. Also, given the previously adopted recharge rates for this area (90–160 mm/y, RS007A01 being on the border of the Nangwarry and Myora management areas), the rate given by the chloride mass balance is likely to be more reliable.

4.1.8. RS008A01

Climate Zone: Two
Soil recharge potential: Low
Soil type: Gradational dark clay loam
Land use: Dryland

RS008A01 was located on a dryland paddock 10 km north-west of Millicent. The soil type was classified as having a low recharge potential, and this is reflected in the estimated recharge rates. Samples for chloride and CFCs were collected from a piezometer screened within a metre of the watertable (located 2.72 m-BGL at the time of sampling). Chloride concentration was relatively high (899 mg/L). Using a rainfall chloride concentration of 11mg/L and rainfall of 730 mm/y, the estimated recharge rate was 9 mm/y. The groundwater age from CFC-12 was greater than 1965 (> 43 years old), which gave a lower recharge estimate of 5 mm/y and an upper estimate of 12 mm/y.

4.1.9. RS009A01

Climate Zone: Three
Soil recharge potential: High to Moderate
Soil type: Shallow dark clay loam on limestone

Land use: Dryland

RS009A01 was established on a dryland paddock 25 km north of Millicent. Chloride concentration in groundwater was found to be 324 mg/L, which (assuming chloride in rainfall of 11 mg/L, and annual rainfall of 691 mm/y) gives a recharge rate of 23 mm/y. CFC-12 concentration in groundwater measured at the same time was found to have an apparent age of 16 years (1992), which gives a recharge rate of 15 mm/y. Only one recharge rate for the CFC method is given here, as the depth to water was 0.19 m below the top of the watertable at this site at the time of sampling, so only the depth of the bottom of the piezometer screen below the watertable was used in estimating recharge.

4.1.10. RS010A01

Climate Zone: Three
Soil recharge potential: Low
Soil type: Sandy loam over poorly structured clay
Land use: Dryland

RS010A01 was established on a dryland paddock near Wrattonbully, 26 km south-east of Naracoorte. A soil core was collected to 9 m (Figure 23) when the core barrels broke, 6 m short of the watertable. It shows increasing chloride concentration with depth, suggesting the historic salt store has not yet been flushed and steady state conditions are invalid. However, there is insufficient data to apply the chloride front displacement method. Therefore, neither chloride method is applicable at this site.

CFC-12 samples in groundwater were found to have an apparent age of 27 years (1981), which gave recharge rates ranging from 3 mm/y to 14 mm/y, based on different assumed depths of sample collection. Both estimates are lower than the previously adopted rate for the area (Joanna management area) of 50 mm/y, which is thought to be due to the clayey soil type in the top 10 m of the profile (see Appendix B for geological log).

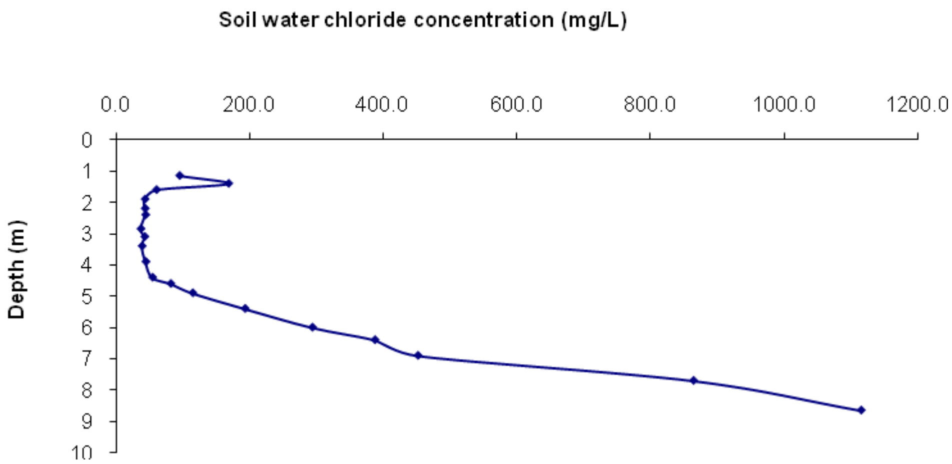

Figure 23. Soil water chloride profiles at site RS010A01

4.1.11. RS011A01

Climate Zone: Three
Soil recharge potential: Low to Moderate

Soil type: Thick sand over clay
Land use: Dryland

RS011A01 was located on a dryland paddock 25 km north-west of Millicent. Chloride in groundwater was found to be 254 mg/L, which gave a recharge rate of 30 mm/y, based on an assumed chloride in rainfall of 11 mg/L, and mean annual rainfall of 695 mm/y. CFC-12 concentration gave an apparent age of 17 years (1991), which gave a lower recharge rate of 49 mm/y and an upper recharge rate of 67 mm/y.

4.1.12. RS012A01

Climate Zone: Three
Soil recharge potential: High
Soil type: Bleached siliceous sand
Land use: Dryland

RS012A01 was established on a dryland paddock approximately 50 km north-west of Padthaway. Chloride concentration in groundwater was found to be 535 mg/L, which (assuming annual rainfall of 546 mm/y, and chloride in rainfall of 11 mg/L) gives a recharge rate of 11 mm/y. CFC-12 concentration was found to have an apparent age of 20 years (1988), which gave a recharge rate range of 5–50 mm/y (the larger range due to 3 m screen length).

4.1.13. RS013A01-RS013A03

Climate Zone: Four
Soil recharge potential: High
Soil type: Bleached siliceous sand
Land use: Dryland

RS013A01 was established in a dryland paddock 27 km west of Tintinara, in a slight inter-dunal flat. Chloride in groundwater was found to be 661 mg/L, which (assuming annual rainfall of 492 mm/y and chloride in rainfall of 11 mg/L) gives a recharge rate of 8 mm/y. CFC-12 concentrations displayed an apparent age of 32 years, which gave a lower and upper recharge rate of 5 mm/y and 14mm/y respectively.

RS013A02 consisted of a soil core on top of a dune with a deep sand profile, located in the same paddock as RS013A01, and approximately 10 m higher in elevation. The chloride profile in the unsaturated zone shows concentrations of ~150 mg/L near the surface, which decrease to 37 mg/L just above the watertable (Figure 24). This shows that the pre-clearance chloride store has been flushed, and that the watertable is now starting to be replenished with relatively fresh water. Taking the average soil water chloride concentration from 3 m-BGL to the watertable (~62 mg/L), mean annual rainfall of 466 mm/y and assuming a chloride input from rainfall of 11 mg/L, the chloride mass balance gives a recharge rate of 87 mm/y for this site.

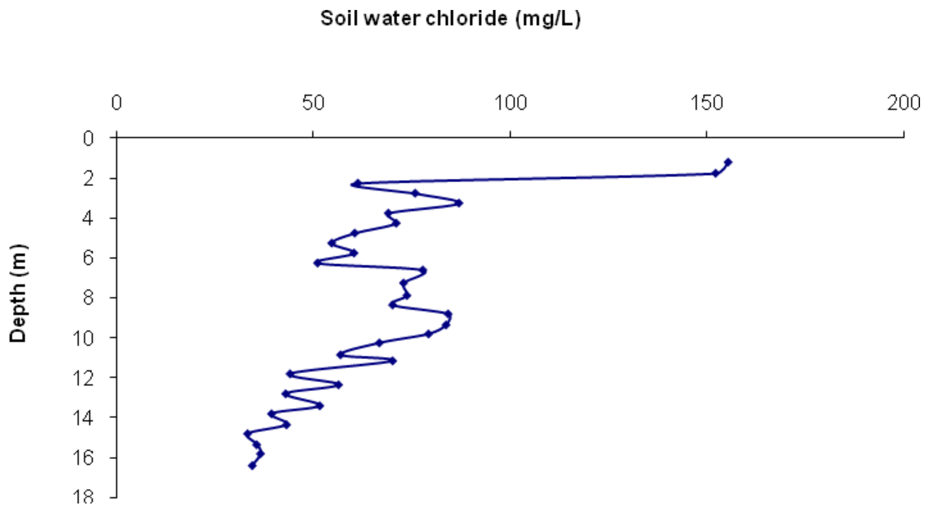

Figure 24. Soil water chloride profile for RS013A02

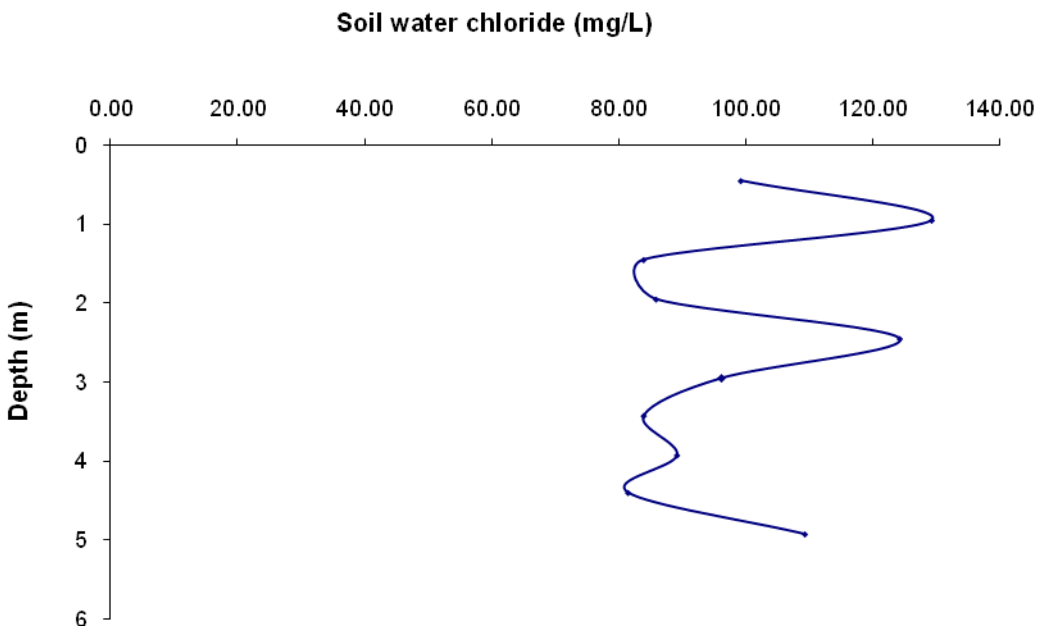

Figure 25. Soil water chloride profile for RS013A03

RS013A03 consisted of another soil core on the same soil type 12 km south-west of RS013A01. The core went to 5 m where the soil became saturated (Figure 25). Taking the average chloride concentration from 2 m-BGL to the top of the watertable (97 mg/L), annual precipitation of 510 mm/y, and chloride in rainfall of 11 mg/L, gives a recharge rate of 58 mm/y.

While the groundwater in this region is considered as a whole to be quite saline, and the recharge rate given for RS013A01 is quite low, the results from RS013A02–A03 show that some fresher water is starting to recharge the aquifer. The groundwater resource in this area is not prescribed, and generally only used for stock (often through groundwater access trenches or 'wedge holes'); however, these results have potential implications for future monitoring of groundwater levels and chemistry in this part of the South East.

4.1.14. RS014A01

Climate Zone: Four
Soil recharge potential: High to Moderate
Soil type: Shallow calcareous loam on calcrete
Land use: Dryland

RS014A01 was established on a dryland paddock approximately 25 km south-east of Robe. Given the chloride concentration in groundwater sampled 0.2 m below the watertable of 206 mg/L, chloride in precipitation of 11 mg/L, and annual precipitation of 660 mm/y, recharge is estimated to be 35 mm/y. CFC-12 concentration showed an apparent groundwater age of 28 years (1980), which gave lower and upper recharge rates of 2 mm/y and 13 mm/y respectively.

Analysis of observation well hydrographs from nearby on the same land unit type gave rates of 82 mm/y (BRA021 5 km north-west) to 100 mm/y (BRA020, 9 km north-east), suggesting that the hydrochemical methods may give an under-estimate of recharge. As with previous sites, ongoing monitoring of water levels at RS014A01 will determine if this is the case.

4.1.15. RS015A01

Climate Zone: Four
Soil recharge potential: Low to Moderate
Soil type: Thick sand over clay
Land use: Dryland

RS015A01 was established in a cropped dryland paddock 20 km south-west of Coonalpyn. A soil core was collected to 7 m (where water was cut, see Figure 26) and shows high chloride concentration (up to 787 mg/L) in the top 2 m, which freshens to ~60 mg/L to 5 m. Below 5 m, the concentration increases to the watertable, suggesting diffusion of chloride between the unsaturated zone and the watertable (groundwater chloride concentration measured here was 1540 mg/L). The higher concentrations in the top 2 m suggest the soil profile is not properly flushed, and therefore the chloride mass balance is not used here. CFC-12 concentrations gave an apparent age of 31 years (1977), which gave lower and upper recharge rates of 5 mm/y and 15 mm/y respectively.

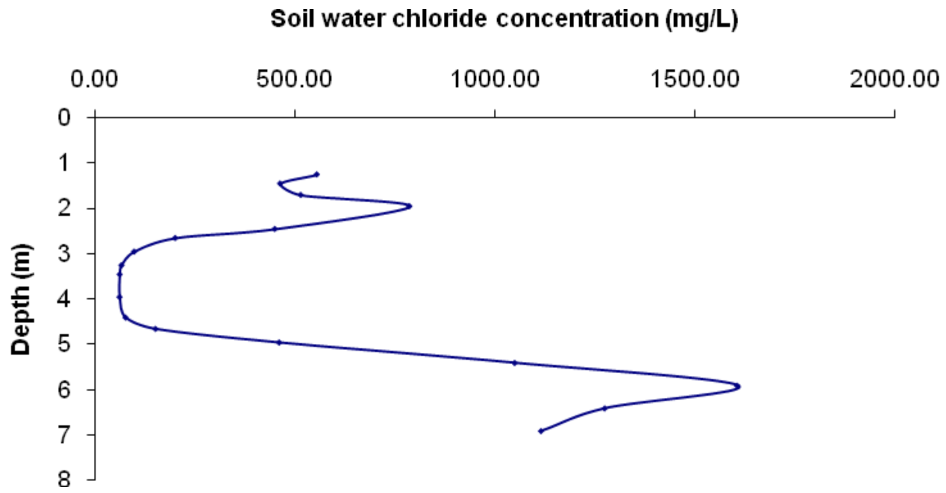

Figure 26. **Soil water chloride concentration with depth for RS015A01**

Figure 27. **Drilling at RS015A01, October 2007**

4.1.16. RS016A01

Climate Zone: Four
Soil recharge potential: Moderate to High
Soil type: Shallow sand over clay on calcrete
Land use: Dryland

RS016A01 was established in a dryland paddock 30 km north-east of Kingston SE, on an inter-dunal flat west of the Avenue Range. The site lies approximately 200 m west of the RS023A01-RS023A03 series of piezometers, which straddle the western side of the Range. Groundwater chloride concentration measured at the site was 1050 mg/L. Assuming annual average rainfall of 565 mm/y, and chloride concentration in rainfall of 11 mg/L, the estimated recharge rate from the chloride mass balance for this site is 6 mm/y. CFC-12 concentrations gave an apparent groundwater age of 26 years (recharge date of 1982). Unfortunately, the only piezometer that yielded enough water to sample at this site was the piezometer with the 6 m long screen. This means the recharge rate range from the CFC method is quite large—14 mm/y to 71 mm/y.

For the majority of sites so far, the chloride mass balance recharge estimate has been higher than that given by the CFC method. A possible explanation for the low estimate from chloride here is that RS016A01 is located in an inter-dunal flat, on the western side of the Avenue Range dune. In most years where average annual rainfall is exceeded, this area would be prone to surface water pooling (and possibly groundwater discharge, given the shallow depth to water). Hence, the water that has recharged the aquifer in this area would have undergone evaporation prior to infiltration, concentrating the amount of chloride in recharging water. For these reasons, the CFC method is thought to give a more accurate estimate of recharge. Analysis of the hydrograph from PEC051 (700 m south-east of RS016A01) from 1993 to the present (longest available record) gives a recharge rate of 37 mm/y, suggesting the range represented by the CFC method is more representative of the real recharge rate.

4.1.17. RS017A01

Climate Zone: Five
Soil recharge potential: High
Soil type: Bleached siliceous sand
Land use: Dryland

RS017A01 was established in a dryland paddock approximately 18 km north of Francis, on the same property as RS019A01. A soil core collected at RS017A01 revealed chloride concentration increasing with depth (> 200 mg/L below 10 m, see Figure 28), which suggests the profile is still being flushed of the historic salt store. As with RS010A01, however, coring was suspended approximately 8 m short of the watertable due to equipment failure. Therefore, there is insufficient data to apply the chloride front displacement method, and what data there is renders the steady state chloride mass balance inapplicable.

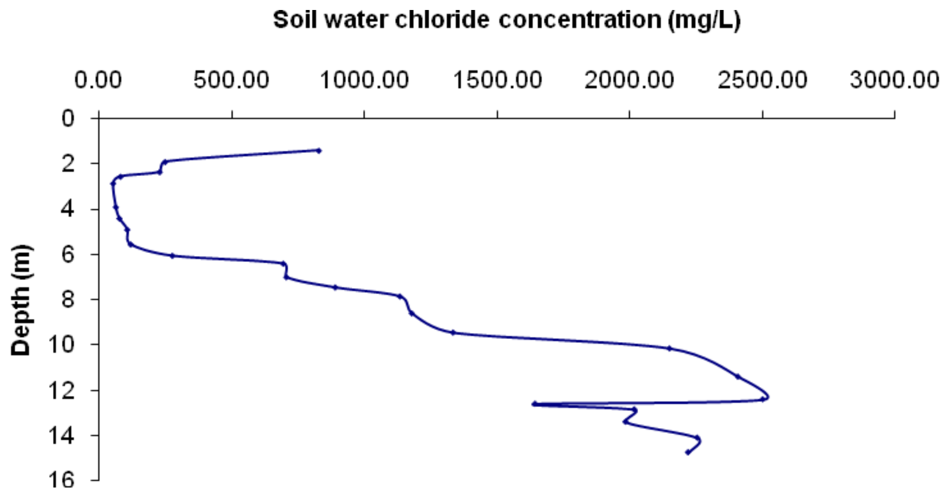

Figure 28. Soil water chloride concentration with depth at RS017A01.

CFC-12 concentrations showed an apparent groundwater age of 33 years (1975), which gave a recharge rate range of 2–20 mm/y. This is in relatively good agreement with the previously adopted recharge rate for this area of 20 mm/y (Bangham management area).

4.1.18. RS018A01

Climate Zone: Five
Soil recharge potential: High
Soil type: Bleached siliceous sand
Land use: Native vegetation

RS018A01 was located in Ngarkat Conservation Park, 25 km north-east of Keith. The Park consists of approximately 2700 km^2 of native mallee and heath vegetation over remnant coastal sand dunes. A soil core was collected to ~15 m (where coring was suspended due to core barrels being stuck in hole and water being added). Figure 29 shows high chloride concentration in this section of the unsaturated zone, a result of plant water uptake. Taking the average soil water chloride concentration from 3 m-BGL onwards (1448 mg/L) gives a recharge rate of 3 mm/y (assuming chloride in precipitation of 11mg/L and mean annual rainfall of 450 mm/y). This estimate agrees well with previous estimates of recharge under mallee vegetation in the Murray Basin of 0.06–14 mm/y (Allison et al. 1985).

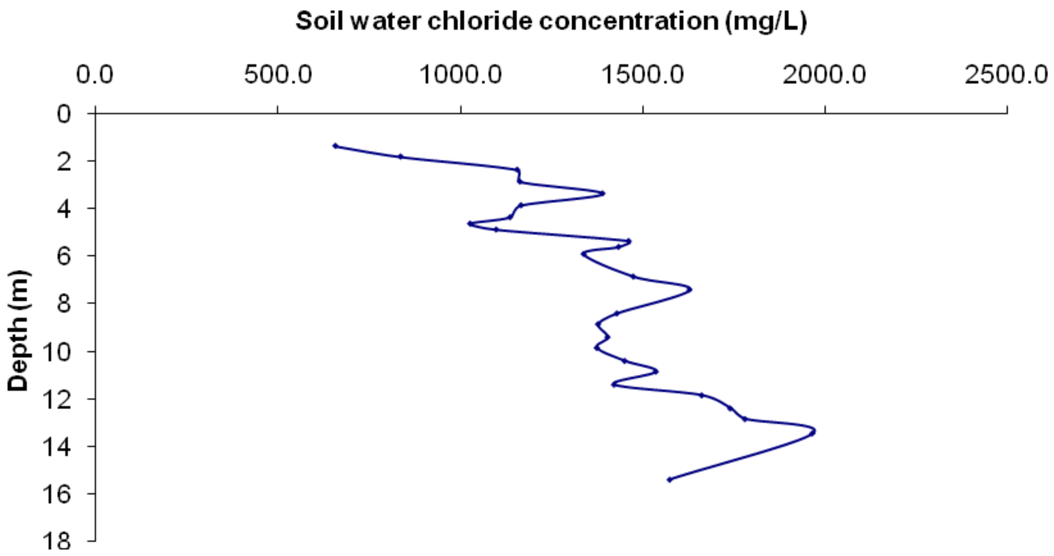

Figure 29. Soil water chloride concentration with depth for RS018A01

Figure 30. Drilling in Ngarkat Conservation Park, February 2008

4.1.19. RS019A01

Climate zone: Five
Soil recharge potential: Low to Moderate
Soil type: Sand over poorly structured clay
Land use: Dryland

Site RS019A01 was located on the same property as RS017A01; however, while RS017A01 was located on a slight dune rise with a deep sand profile, RS019A01 was located on a sand over clay type soil in a lower lying area. Two piezometers were installed at site RS019A01, and a soil core collected to 18.5 m. The soil water chloride profile shows a much higher chloride concentration through the unsaturated zone than site RS017A01 and site RS010A01 (both also in the Naracoorte Ranges). This, combined with the general bulging shape of the profile, suggests the historic salt load has not been significantly flushed since land clearing (Figure 31). In this case the chloride front displacement technique can be used.

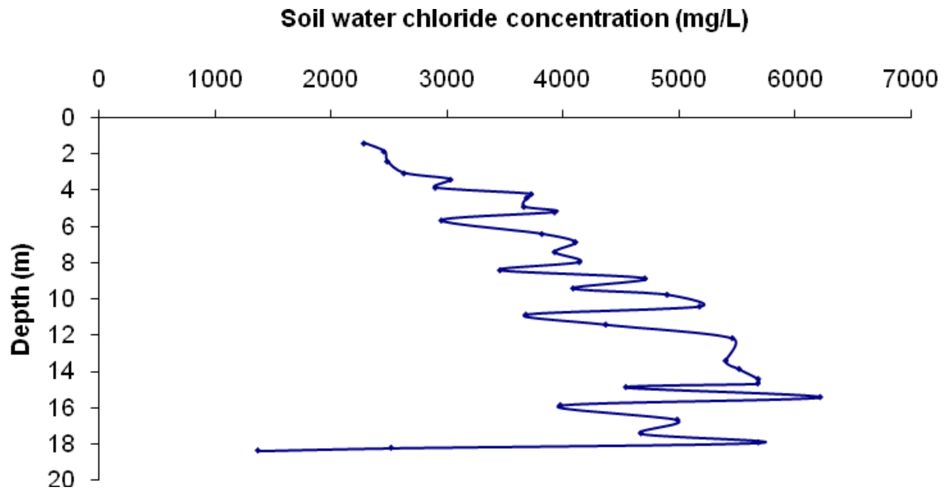

Figure 31. Soil water chloride concentration at RS019A01.

Two assumptions have been made in calculating the drainage rate using the chloride front displacement method here. The first assumption is that clearance of native vegetation at this site took place in 1960. This assumption is considered reasonable for the area, and has been used previously (Wohling et al. 2006). The second assumption regards the depth of the chloride front under original land use (z_{cf}^{0} in Equation 6). Typically, this is estimated based on the percent of clay content in the top 2 m of the soil profile, using an empirical relationship derived by Walker et al. (1991). Unfortunately, coring was not possible in the top metre of the profile at this site, and particle size analysis was not carried out. Therefore, two estimates of recharge using this method for RS019A01 are given:

- Deep drainage = 8 mm/y (assuming 10% clay in the top 2 m)
- Deep drainage = 14 mm/y (assuming 40% clay in the top 2 m)

As can be seen, 30% variation in assumed clay content does not drastically alter the deep drainage rate. Also, it compares well with the assigned recharge rate for the same management area (20 mm/yr, Brown et al. 2006). As mentioned earlier in the report, recharge is likely to be less than or equal to deep drainage calculated from this method under non-steady state conditions; however, this is still a good comparison.

CFC-12 data from one of the piezometers installed at RS019A01 gave an apparent groundwater age of 24 years (recharge date of 1984). This gives a recharge rate range of 5–30 mm/y for this site. There is an apparent discrepancy here; the chloride profile shows that the historical salt store, which would have begun being flushed towards the watertable upon clearance of native vegetation (assumed to be 48 years ago), has not yet reached the watertable. The presence of groundwater of half that age reiterates the idea that there is always uncertainty in using the CFC method to estimate local recharge (by taking samples from shallow groundwater). Even groundwater in the top metre of the aquifer is likely to be influenced by what has occurred (in terms of recharge) further upgradient.

These results show that the groundwater found at RS019A01 must have been recharged primarily via groundwater flowing from the east, and not through vertical infiltration of rainfall. This is in good agreement with previous work from the same area (Herczeg and Leaney 1993).

4.1.20. RS020A01

Climate Zone: Five
Soil recharge potential: Moderate to High
Soil type: Shallow sand over clay on calcrete
Land use: Dryland

RS020A01 was located on a dryland paddock in Lochaber, 14 km north-east of Lucindale. Groundwater sampled here was found to be quite saline (7680 mg/L), with a chloride concentration of 3210 mg/L. Assuming mean annual precipitation of 537 mm/y and chloride in rainfall of 11 mg/L, this gives a recharge rate of 2 mm/y. CFC-12 concentration gave an apparent groundwater age of 43 years (1965 recharge date), which gave a recharge rate of 8–16 mm/y.

4.1.21. RS021A01

Climate Zone: Two
Soil recharge potential: High to Moderate
Soil type: Shallow sandy loam on limestone
Land use: Dryland

RS021A01 was located in a dryland paddock approximately 250 m upgradient of Crescent Pond, a spring-fed pond that drains into Pick Swamp, a significant groundwater-dependent ecosystem in the region. The depth to water at sampling was only 2.42 m-BGL; however, due to the piezometers screened at shallow intervals being low yielding, samples for CFCs and chloride were only taken from a piezometer screened from 12.44 m-BGL to 13.44 m-BGL. The chloride concentration was 296 mg/L, and assuming chloride in rainfall is 11 mg/L, and average annual rainfall of 795 mm/y, the estimated recharge rate from this method is 30 mm/y. CFC-12 results showed the groundwater age to be older than 1965 (> 43 years old). Using this age, the recharge rate range was 67–73 mm/y. Given the proximity of this site to the coast, the chloride concentration in rainfall may be an under-estimate, hence the lower recharge rate given by the chloride mass balance.

4.1.22. RS022A01

Climate Zone: Two
Soil recharge potential: High to Moderate
Soil type: Shallow sandy loam on limestone
Land use: Dryland

RS022A01 utilised an existing observation well (CAR011) to investigate recharge processes close to Piccaninnie Ponds, another significant groundwater dependant ecosystem in the South East of South Australia. Hydrograph analysis from 1987 to the present (the best available record) showed consistent seasonal fluctuation in the watertable; however, the magnitude of this fluctuation was quite low, giving an average recharge rate of 5 mm/y. Groundwater sampled close to the watertable had a chloride concentration of 441 mg/L, which gave a recharge rate of 20 mm/y (based on chloride in precipitation of 11 mg/L and annual precipitation of 797 mm/y).

4.1.23. RS023A01-RS023A03

Climate Zone: Four
Soil recharge potential: High to Moderate
Soil type: Shallow red loam on limestone
Land use: Dryland

RS023A01, RS023A02 and RS023A03 were all located along a 170 m transect coming down the western side of the Avenue Range (Figure 32). The three sets of two wells were installed to investigate recharge processes through a remnant dune range. Groundwater chloride concentrations showed a progressively freshening trend down the dune, ranging from 832 mg/L at the top of the dune (RS023A01), 827 mg/L halfway down the dune (RS023A02) and 618 mg/L near the base (RS023A03). Using the same assumptions as RS016A01 (200 m to the west) gives recharge rates of 7 mm/y for RS023A01, 8 mm/y for RS023A02, and 10 mm/y for RS023A03.

CFC-12 concentrations in groundwater along the transect showed groundwater ages of 20 and 21 years for RS023A01 and RS023A02 respectively, giving recharge rates of 3–18 mm/y for RS023A01 and 14 mm/y for RS023A02. Groundwater measured at RS023A03 at the base of the dune had an apparent age of 18 years, giving a recharge rate of 13–30 mm/y. These results show that while recharge does occur through the dune itself, most of the recharge is focused at the base of the dune.

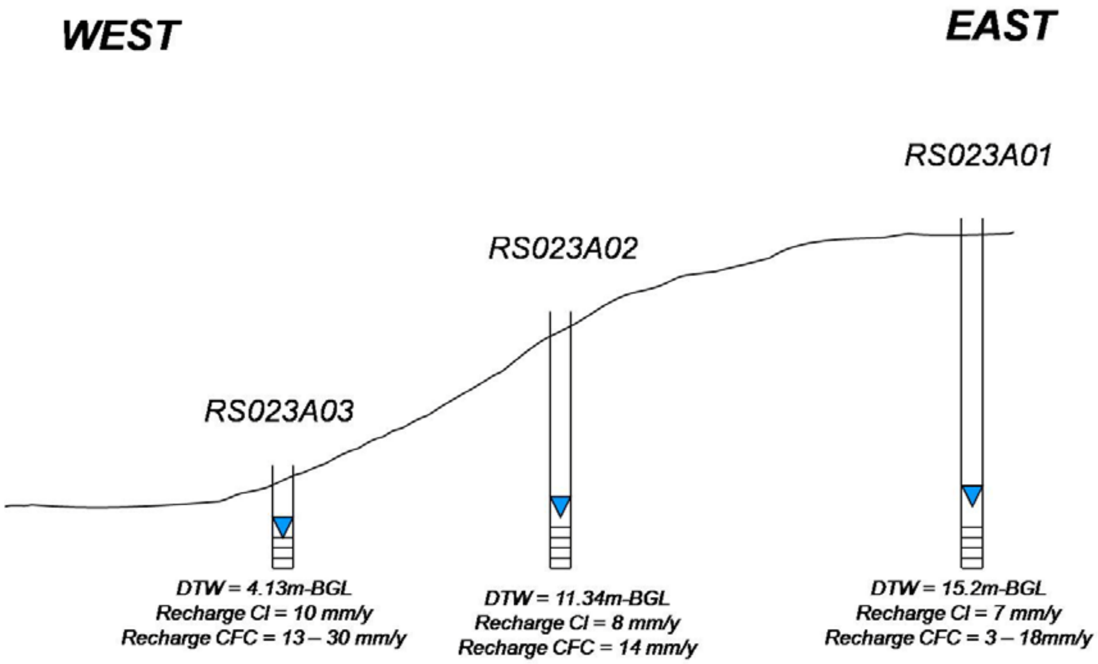

Figure 32. Schematic diagram of piezometer transect RS023A01–03

Figure 33. Drilling at RS023A02, Avenue Range, October 2007

4.1.24. RS024A01

Climate Zone: Three
Soil recharge potential: Moderate to High
Soil type: Shallow sand over clay on calcrete
Land use: Hardwood forestry

RS024A01 was located in a hardwood forestry plantation (*Eucalyptus globulus*), established in 2000, 36 km north-west of Penola. A soil core was collected to 5.5 m (Figure 34), and showed soil water chloride concentrations below the root zone of 418 mg/L. This gave a recharge rate of 16 mm/y (assuming mean annual rainfall of 629 mm/y and chloride in rainfall of 11 mg/L). CFC-12 concentrations in groundwater gave an apparent age of 43 years, which gave a recharge rate of 7 mm/y. This corresponds relatively well with estimates of recharge under hardwood forestry for this area. The adopted recharge rate for the area that RS024A01 is located in (Hundred of Coles) is 120 mm/y (Brown et al. 2006). Latcham et al. (2007) gave a recharge interception value for hardwood forestry of 78%, which for 120 mm/y recharge means recharge under hardwood forestry is 26 mm/y.

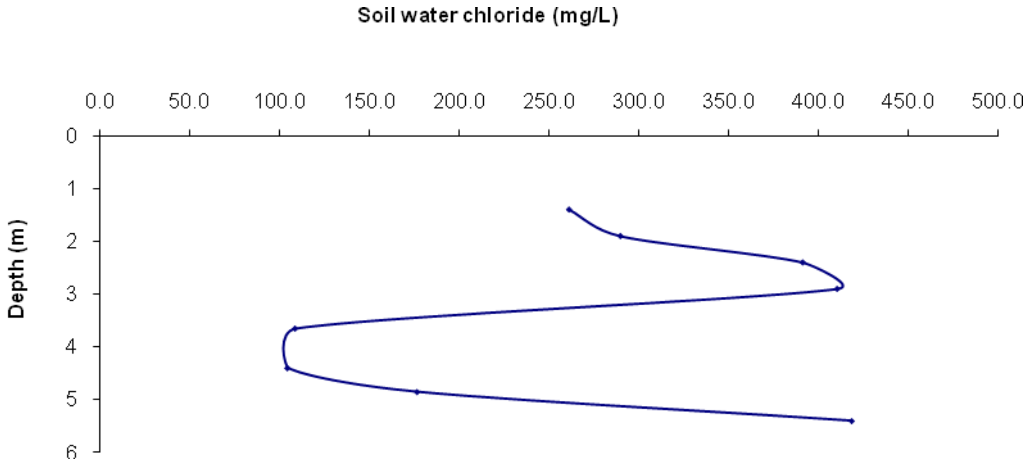

Figure 34. Soil water chloride concentration at RS024A01

5. SUMMARY

5.1. SUMMARY OF RECHARGE RATES—GEOSTATISTICAL SITES

5.1.1. CLIMATE ZONE 1

Figure 35 shows the spatial distribution of recharge rates for the different soil recharge potential/land use combinations for Climate Zone 1. Worth noting is the reported recharge rate for RS003A01 of 0–25 mm/y. As mentioned in the results section, soil core and Obswell data suggested no recharge was occurring in this area (under softwood plantation); however, CFC results gave a recharge rate range of 25–53 mm/y. These results from CFC data are thought to be a result of recharge somewhere upgradient, or recharge in the forest area through sinkholes. Therefore, Figure 35 reports a range from zero to the lower of the CFC rates, to recognise any recharge that may be occurring through sinkholes. This rate also agrees well with the current adopted recharge rate for the area under plantation (30 mm/y, given by reducing 175 mm/y by 83%).

Similar results were found at RS004A01, a softwood site north of Millicent. Unfortunately, no soil core could be collected. However, all existing research suggests that no recharge should be occurring in this area, but the CFC method gave a range of 36–56 mm/y. Therefore, a range of 0–36 mm/y has been given in Figure 35, to recognise any recharge that may be occurring through preferential flow in the area.

These results have also shown the discrepancy that can be given by recharge estimates based on the chloride mass balance and those based on CFC methods. RS002A01 had a recharge rate of 8–19 mm/y based on CFC samples taken below the watertable and 29 mm/y based on groundwater chloride concentrations. However, a rate of 127 mm/y was given by the chloride mass balance using soil water chloride concentrations. Watertable fluctuation estimates and existing data suggest the soil water chloride mass balance rate is more valid and that the groundwater chemistry methods have in this case given an underestimate of recharge. This is probably because the groundwater chemistry, even within the top 1–2 m of the watertable, is influenced by recharge and processes occurring upgradient (not just vertical recharge from directly above).

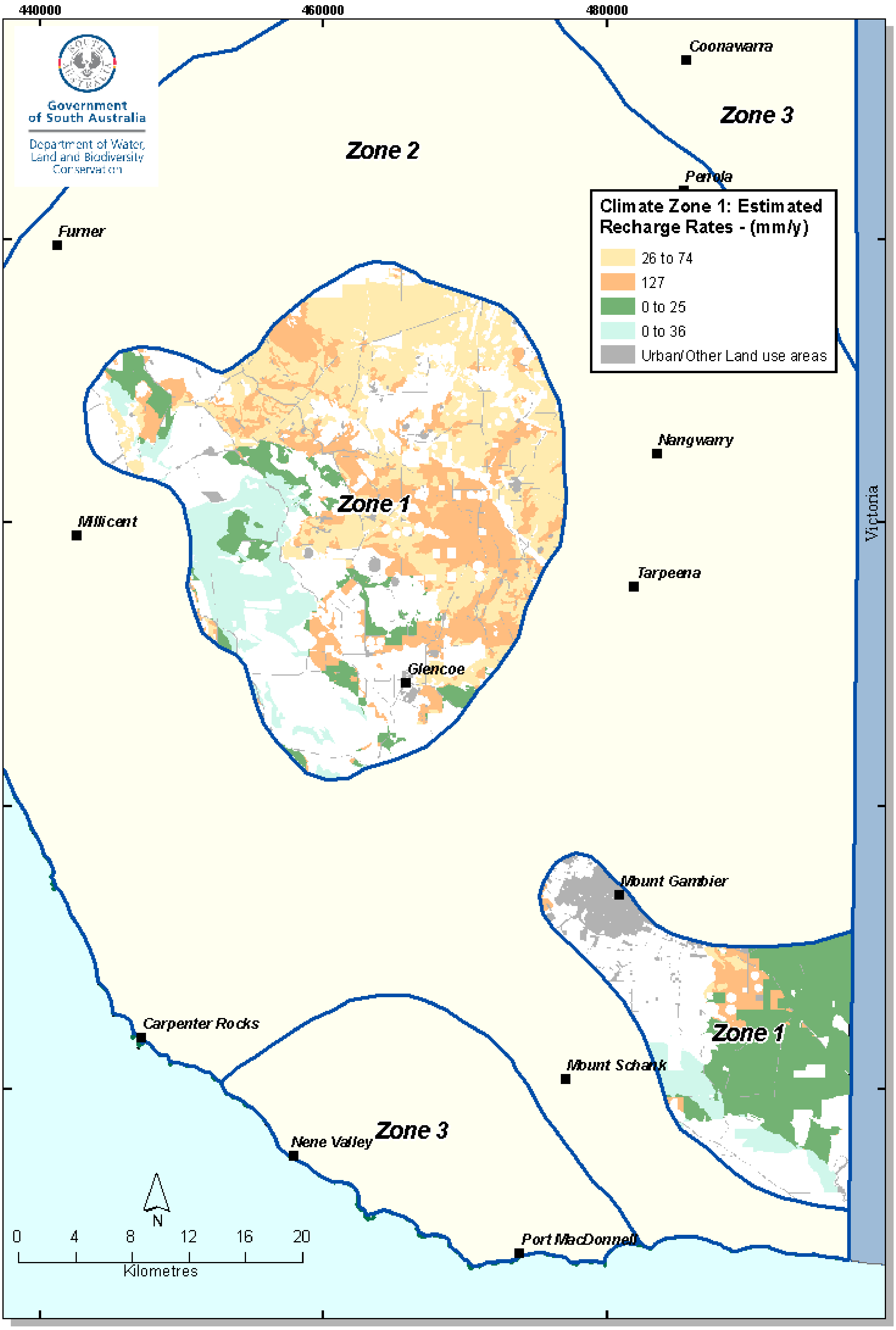

Figure 35. Estimated recharge rates for Climate Zone 1

5.1.2. CLIMATE ZONE 2

Figure 36 shows recharge rates for Climate Zone 2. As with Climate Zone 1, for dryland areas, some of the recharge rates given by the CFC method are underestimates compared to those given by the chloride mass balance (using soil water chloride—see results from RS007A01) and the chloride rates have been adopted for reasons discussed under Climate Zone 1.

As discussed earlier, RS005A01, for which a new research site could not be located, was assessed using existing observation wells and the watertable fluctuation method. One of the reasons a site could not be located for RS005A01 was the presence of extensive hardwood plantations in the area where the targeted soil type was largely found to occur (the Short and Coles management areas, west of Penola). Here arises a fault with the methodology used in this report. The Land Use data used in geostatistical analysis was for mapping done from 1999 to 2003 (published in 2006, DWLBC). This data was used because it was the most up-to-date available; however, numerous hardwood plantations have been established from 2000 to the present in these areas, on land previously classified as dryland pasture. This is why site RS024A01 was established in Climate Zone 2.

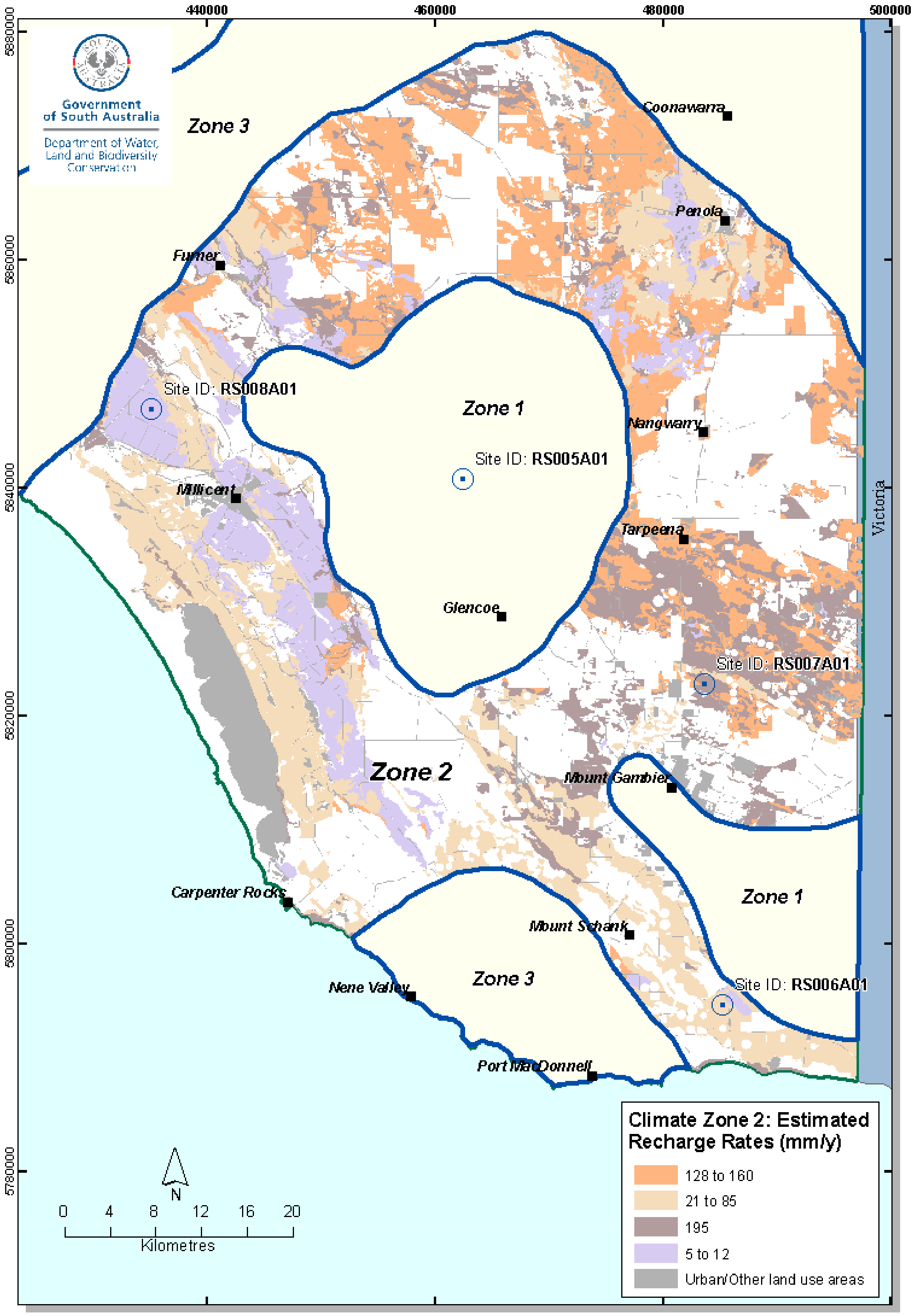

Figure 36. Estimated recharge rates for Climate Zone 2

5.1.3. CLIMATE ZONE 3

Figure 37 shows estimated recharge rates for Climate Zone 3. Some recharge rates are lower than previously estimated for some areas. For example, the currently adopted recharge rate for the area around RS009A01 and RS011A01 (Kennion management area) is 120 mm/y, higher than the estimates given in this study of 15–67 mm/y.

However, estimates are in good agreement with previous research done in other areas. For example, Walker et al. (1990) estimated recharge using chloride techniques in the vicinity of RS010A01 and reported rates ranging from 1.5 mm/y to 13 mm/y (they also reported one rate of 80 mm/y for a site with a depth to water of 2 m). These agree well with the estimates from RS010A01 of 3–14 mm/y.

Also, recently published estimates of recharge under dryland agriculture in management Zone 3A (around Penola) range from 20 mm/y to 50 mm/y (Harrington 2007). Estimates for dryland areas east of Penola show relatively similar figures (45–67 mm/y), even though the estimate for this area near Penola was taken from site RS011A01, approximately 60 km to the west.

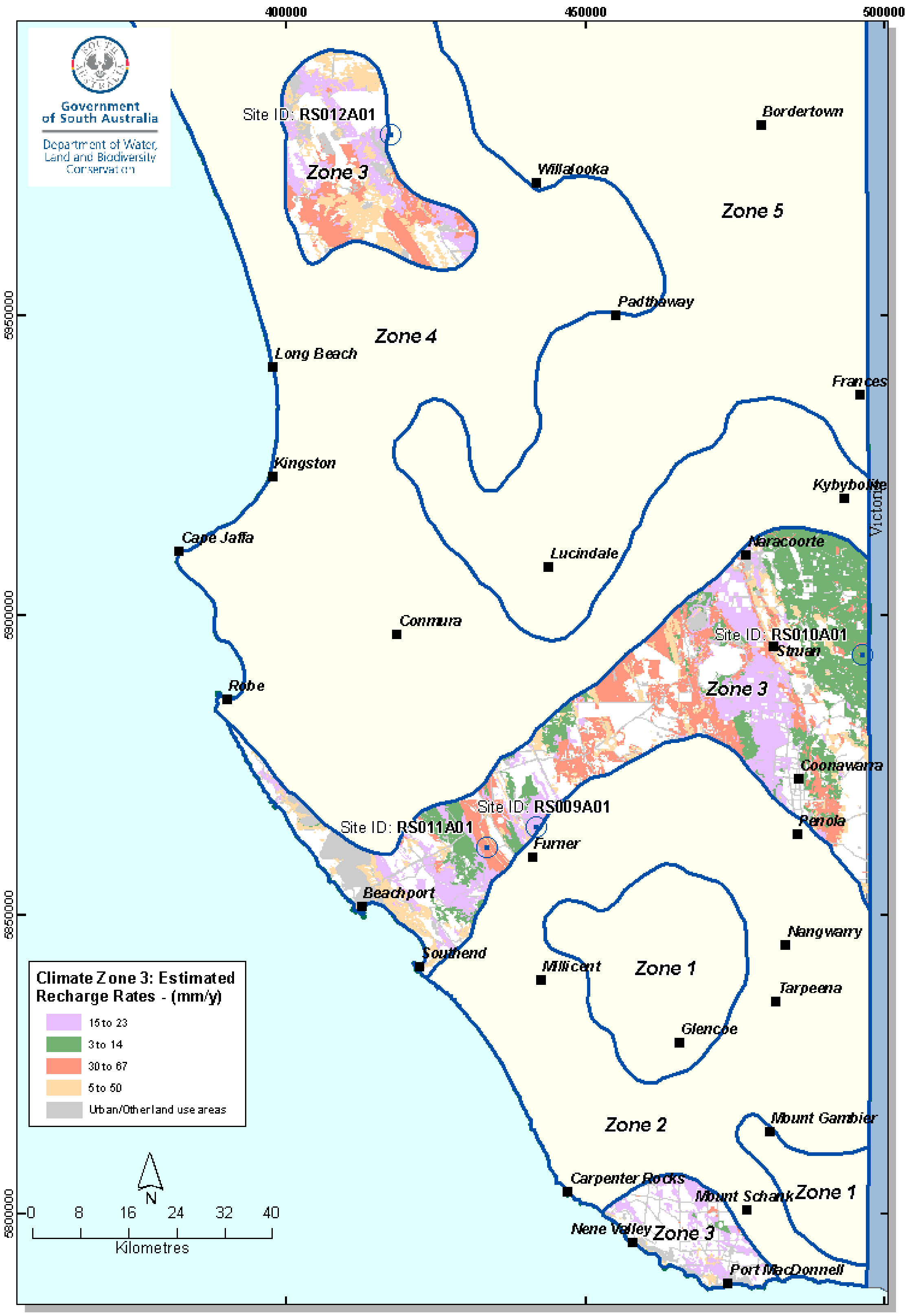

Figure 37. Estimated recharge rates for Climate Zone 3

5.1.4. CLIMATE ZONE 4

Figure 38 shows estimated recharge rates for Climate Zone 4. Recharge estimates are lower than those adopted by Brown et al. (2006) for the management areas they are located in (see Figure 7 for comparison). Hydrograph analysis for existing wells representing the same land unit as RS014A01 have displayed a recharge rate of 100 mm/y, suggesting estimates given in this study may again be underestimates. This may be because of the fact that shallow groundwater chemistry has been used for many estimates in this study and it has already been shown to give underestimates in some cases.

The reported rate in Figure 38 for the soil/land unit represented by RS013A sites is 5–87 mm/y. As discussed in the Results section, there is some discrepancy again between results given by groundwater chemistry (RS013A01) and those given by soil water chloride methods (RS013A02 and RS013A03). However, there seemed to be a significant enough difference between the two (i.e. shallow groundwater chloride concentrations at RS013A01 were > 600 mg/L higher than soil water concentrations at RS013A02) that it seemed appropriate to recognise this range of results in this report.

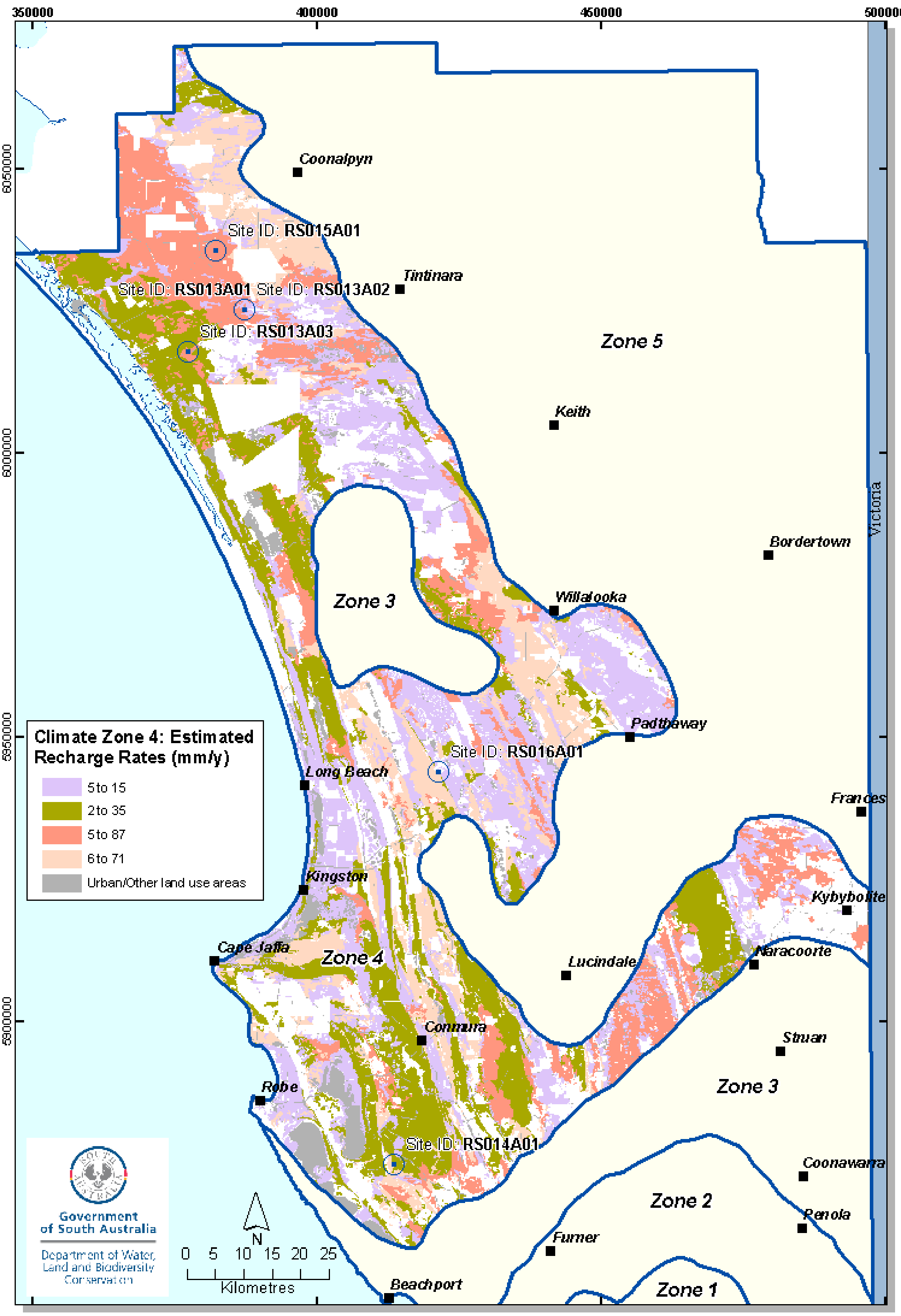

Figure 38. **Estimated recharge rates for Climate Zone 4**

5.1.5. CLIMATE ZONE 5

Figure 39 shows the recharge estimates for Climate Zone 5. These estimates are the lowest on average for the whole study area, representing the drier, more arid conditions in Climate Zone 5. Areas south of Padthaway have lower estimates than those adopted by Brown et al. (2006). However, estimates in other areas are generally in agreement with previous studies. For example, Herzceg and Leaney (1993) reported rates of 5–30 mm/y between Bordertown and Francis, which correlate well with the range of estimates for the same area given in this study. Likewise, previous estimates of recharge under native mallee vegetation in sandy soils give rates of between 0.06 mm/y and 14 mm/y (Allison et al. 1985), which agree well with the rate of 4 mm/y determined for Ngarkat Conservation Park in this study. The results from RS019A01 also show the importance of recharge from lateral throughflow in this region.

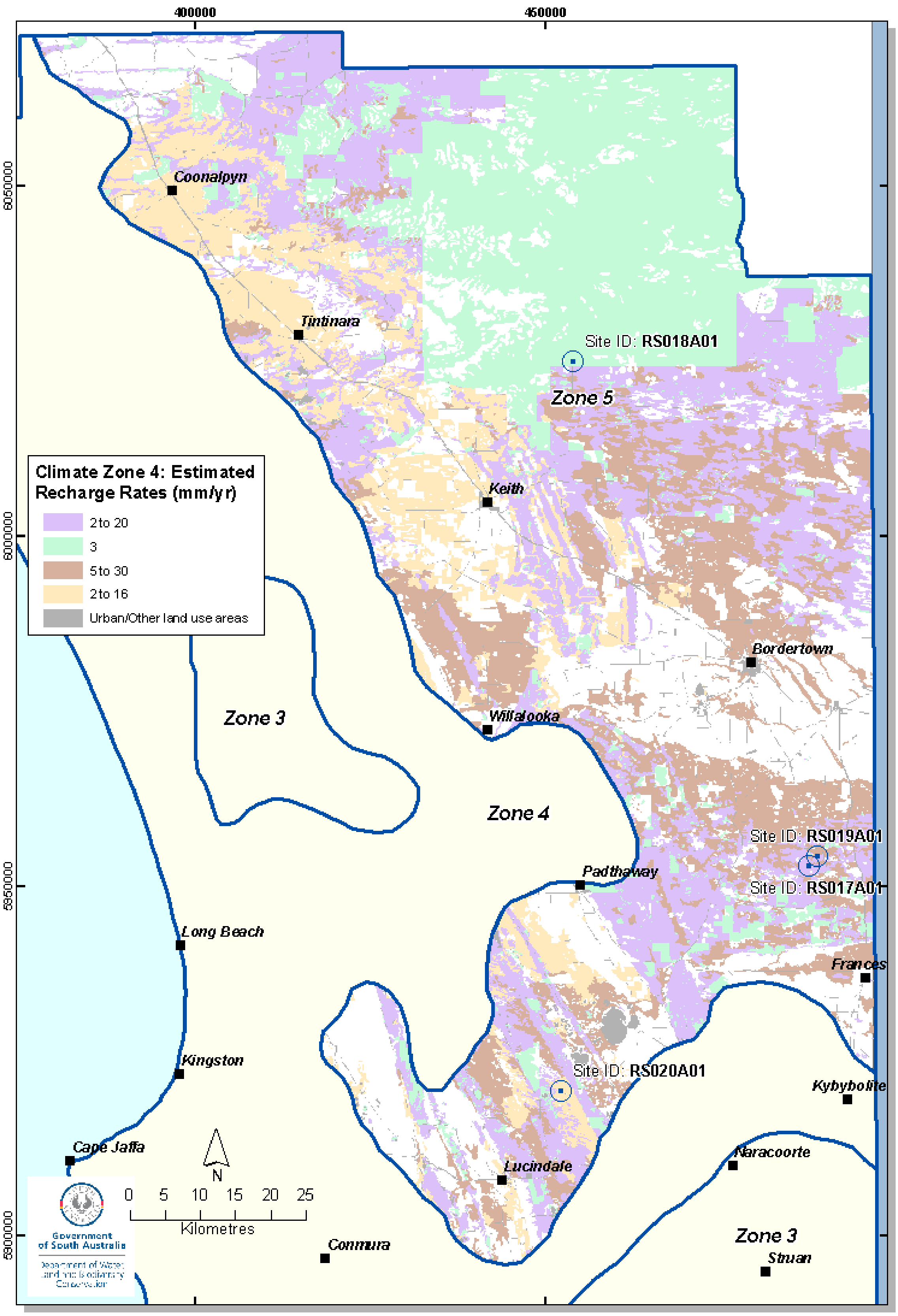

Figure 39. Estimated recharge rates for Climate Zone 5

5.2. COMPARISON OF TECHNIQUES

Figure 40 plots recharge estimates determined using the chloride mass balance method against average rates from the CFC method (average rate over the ranges reported in results). There is no distinct correlation between results from the two methods. While Allison and Hughes (1978) were able to find strong positive correlation between estimates based on chloride balances and age dating (using tritium, see Figure 5), that should not suggest that the results from this study are invalid. Both methods used by Allison and Hughes (1978) were based on soil coring techniques, whereas the methods in this study differed between those based on soil water data and those based on shallow groundwater chemistry. It also reflects the uncertainties in each method and shows that while the concentration of each tracer in groundwater is influenced by recharge rate, there are other controlling processes at play (e.g. the use of an assumed concentration of chloride in precipitation is considered a limitation in this study). Nevertheless, some sites show a reasonably good correlation between methods and agree well with previous research conducted on recharge in the South East.

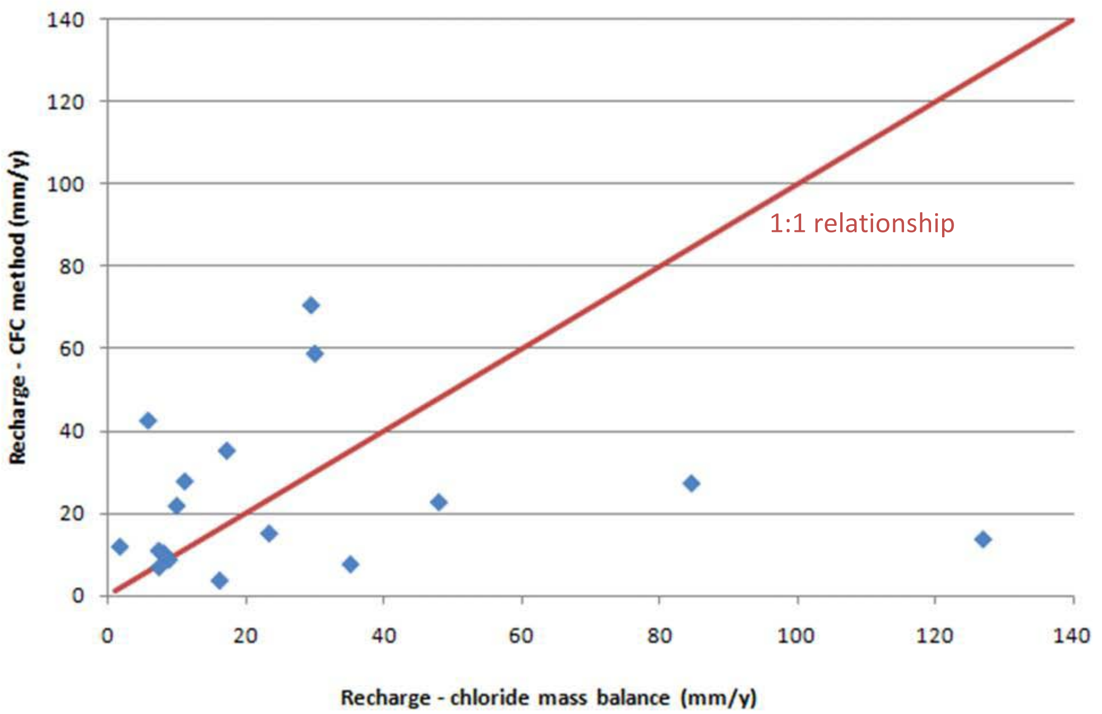

Figure 40. Correlation between recharge estimates determined from chloride mass balance and estimates determined from CFC dating.

Scanlon et al. (2002) state that recharge estimation is an iterative process, where estimates are refined as more data becomes available. These results show that ongoing data collection should be maintained as an extension of this project, in order to further refine recharge estimates (e.g. by measuring chloride concentrations in rainfall on an ongoing basis at specific sites and monitoring fluctuations in watertable levels at these sites).

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. CONCLUSIONS

The current study has improved our knowledge of recharge in the South East of South Australia by providing updated estimates of groundwater recharge for soil, land use and climate types considered broadly representative of the South East NRM Region. Some of the estimates are lower than those previously derived for similar areas. This could be either a result of the different methods used (chloride mass balance and CFC methods vs watertable fluctuation), or a reflection of change in climatic conditions in the South East. As has been shown in the results, watertable fluctuations in observation wells similar to research sites have given higher recharge estimates in some cases, meaning lower rates in this report may be a result of the methods used.

This report has also highlighted some of the uncertainties involved in estimating recharge. However, this should not be considered a negative outcome. As stated in the Summary, recharge estimation should be considered an iterative process, where estimates are updated as more data becomes available. This study has established 25 new recharge research sites, 23 of which have new piezometers installed, specifically designed to monitor fluctuations in the watertable (piezometers with 5–6 m long screens) as well as collect groundwater samples from the top of the watertable (piezometers with 1–2 m screens); therefore, ongoing monitoring should be maintained on these sites to enable recharge estimates to be continually updated.

6.2. RECOMMENDATIONS

The work completed as part of this study has identified a number of areas where further work can be done to build on the outcomes of this report. These include:

- Ongoing monitoring of water levels in piezometers at each of the research sites. At each site, data should be collected from the piezometers with the longest screened section of aquifer (maximum 6 m) and the piezometers incorporated into the observation well network in the region. Ongoing monitoring of these piezometers will provide important information for future management of the groundwater resources in the region and also help determine whether some of the rates given in this report are underestimates. This data will also help satisfy one of the key recommendations from the last review of the groundwater resource condition for the South East (Brown et al. 2006), as these new sites have been located in areas where there is little nearby influence from pumping/irrigation etc.

- Ongoing sampling of short screened wells for salinity levels. This will help improve the regional picture of salinity changes in the unconfined aquifer over time.

- Devices for collecting rainfall samples have also been installed at the majority of new sites. Samples from these should be collected on an ongoing basis to help refine estimates of recharge from the chloride mass balance in the region. This will also help satisfy one of the recommendations from Brown et al. (2006).

- Research sites should be revisited and re-sampled for chloride and CFCs in approximately five years' time, once a sufficient record of watertable fluctuations has been collected. This will provide an ongoing improvement of recharge estimates for the region, as well as helping determine whether current rates estimated from CFCs and chloride are underestimates.

- The recharge rates reported here should be considered as complimentary to those made in previous studies (eg. Brown et al., 2006), and ongoing estimates of recharge (eg. using the water table fluctuation method) should be made into the future.

APPENDICES

A. SOIL RECHARGE POTENTIAL CLASSIFICATION

The following soil classifications were provided by Mr. David Maschmedt of DWLBC.

Estimated recharge potential of South Australia's key agricultural soils

The soils categorised below are ranked according to estimated recharge potential, or more correctly, potential for water to percolate out of the profile and into underlying strata, including groundwater. Rankings are subjective and relative, and are influenced by variations in profile thickness and nature of material immediately below the soil profile. Indicative Australian Soil Classifications (Isbell 1996) are included.

Soil	Descriptive name	Typical Australian Soil Classification	Recharge class
A	Calcareous soils		
A1	Highly calcareous sandy loam	Supravescent Calcarosol; loamy	Mod–high
A2	Calcareous loam on rock	Paralithic Calcarosol; loamy	Mod
A3	Deep moderately calcareous loam	Calcic Calcarosol; loamy	Low
A4	Deep (rubbly) calcareous loam	Hypercalcic–Lithocalcic Calcarosol; loamy/loamy	Mod–high
A5	Rubbly calcareous loam on clay	Supracalcic–Lithocalcic Calcarosol; loamy/loamy with clayey substrate	Low
A6	Gradational calcareous clay loam	Hypercalcic Calcarosol; clay loamy/clayey	Low
A7	Calcareous clay loam on marl	Marly Calcarosol; clay loamy/clayey	Low
A8	Gypseous calcareous loam	Gypsic Calcarosol	Mod
B	Shallow soils on calcrete or limestone		
B1	Shallow highly calcareous sandy loam on calcrete	Shelly–Supravescent, Petrocalcic Calcarosol	High
B2	Shallow calcareous loam on calcrete	Petrocalcic Calcarosol	High–mod
B3	Shallow sandy loam on calcrete	Petrocalcic Tenosol–Red Kandosol	High–mod
B4	Shallow red loam on limestone	Petrocalcic, Red Dermosol	High–mod
B5	Shallow dark clay loam on limestone	Petrocalcic, Black Dermosol	High–mod
B6	Shallow loam over red-brown clay on calcrete	Petrocalcic, Red Chromosol	Mod–high
B7	Shallow sand over clay on calcrete	Petrocalcic, Brown Sodosol	Mod–high
B8	Shallow sand on calcrete	Petrocalcic, Bleached–Leptic Tenosol	High
B9	Shallow clay loam over brown or dark clay on calcrete	Petrocalcic, Brown Sodosol	Mod
C	Gradational soils with highly calcareous lower subsoils		
C1	Gradational red-brown sandy loam	Hypercalcic, Red Kandosol; loamy	Low–mod
C2	Gradational red-brown loam on rock	Hypercalcic, Red Dermosol; loamy	Mod
C3	Friable gradational red-brown clay loam	Hypercalcic, Red Dermosol; clay loamy	Low
C4	Hard gradational red-brown clay loam	Sodic, Red Dermosol; clay loamy	Low
C5	Gradational dark clay loam	Hypercalcic, Black Dermosol	Low
D	Hard red-brown texture contrast soils with highly calcareous lower subsoils		
D1	Loam over clay on rock	Hypercalcic, Red Chromosol; loamy	Mod
D2	Loam over red clay	Calcic, Red Chromosol; loamy	Low–mod
D3	Loam over poorly structured red clay	Calcic, Red Sodosol; loamy	Low
D4	Loam over pedaric red clay	Pedaric, Red Sodosol; loamy	Low
D5	Hard loamy sand over red clay	Hypercalcic, Red Sodosol–Chromosol; sandy	Low–mod
D6	Ironstone gravelly sandy loam over red clay	Ferric, Hypercalcic, Red Chromosol	Low

D7	Loam over poorly structured clay on rock	Hypercalcic, Red Sodosol; loamy	Low–mod
E	Cracking clay soils		
E1	Black cracking clay	Black Vertosol	Low
E2	Red cracking clay	Red Vertosol	Low
E3	Brown or grey cracking clay	Brown–Grey Vertosol	Low
Soil	Descriptive name	Typical Australian Soil Classification	Recharge class
F	Deep loamy texture contrast soils with brown or dark subsoils		
F1	Loam over brown or dark clay	Brown Chromosol; loamy	Low
F2	Sandy loam over poorly structured brown or dark clay	Brown Sodosol; loamy	Low
G	Sand over clay soils		
G1	Sand over sandy clay loam	Hypercalcic, Red Chromosol; sandy/clay loamy	Low–mod
G2	Bleached sand over sandy clay loam	Calcic, Brown Chromosol; sandy/clay loamy	Mod–low
G3	Thick sand over clay	Eutrophic, Brown Chromosol; sandy/clayey	Low–mod
G4	Sand over poorly structured clay	Calcic, Brown Sodosol; sandy/clayey	Low–mod
G5	Sand over acidic clay	Mesotrophic, Brown Kurosol; sandy/clayey	Low–mod
H	Deep sands		
H1	Carbonate sand	Shelly Rudosol	High
H2	Siliceous sand	Calcareous, Orthic Tenosol	High
H3	Bleached siliceous sand	Bleached–Orthic Tenosol	High
I	Highly leached sands		
I1	Highly leached sand	Aeric or Semi-Aquic Podosol	High
I2	Wet highly leached sand	Aquic Podosol	High
J	Ironstone soils		
J1	Ironstone soil with calcareous lower subsoil	Ferric, Calcic, Brown Chromosol	Low
J2	Ironstone soil	Ferric, Brown Kurosol	Low
J3	Shallow ironstone soil on ferricrete	Petroferric Tenosol	Mod–high
K	Moderately deep acidic soils on basement rock or deeply weathered rock		
K1	Acidic gradational loam on rock	Brown Dermosol	Mod
K2	Acidic loam over clay on rock	Brown–Red Kurosol	Mod
K3	Acidic sandy loam over red clay on rock	Red Chromosol–Sodosol	Mod
K4	Acidic sandy loam over brown or grey clay on rock	Brown Kurosol	Mod
K5	Acidic gradational sandy loam on rock	Brown Kandosol	Mod–high
L	Shallow soils on basement rock		
L1	Shallow soil on rock	Lithic Rudosol–Tenosol	High–mod
M	Deep uniform to gradational soils		
M1	Deep sandy loam	Brown–Red Kandosol or Orthic Tenosol; sandy	Mod–high
M2	Deep friable gradational clay loam	Red–Black Dermosol; clay loamy	Low–mod
M3	Deep gravelly soil	Clastic Rudosol	High
M4	Deep hard gradational sandy loam	Sodic, Eutrophic, Brown Kandosol; loamy/clayey	Low–mod
N	Wet soils		
N1	Peat	Organosol	Mod–high
N2	Saline soil	Salic Hydrosol	High
N3	Wet soil (non to moderately saline)	Redoxic Hydrosol	High
O	Volcanic ash soils		
O1	Volcanic ash soil	Andic Tenosol	Mod–low

Table 6. Soil recharge potentials for soil types used in this study

B. GEOLOGICAL LOGS AND PIEZOMETER COMPLETIONS AT EACH SITE

Table 7 shows details of piezometer completions at each site. Geological logs from the deepest hole at each site are also given. It can be assumed that the geology of shallower holes is the same of that of the deeper holes at individual sites.

Piezometer	Easting	Northing	Total depth (m-BGL)	Casing (m-BGL)	Screen interval (m-BGL)	Date of completion
RS002A01_MW001	472665	5831330	10	0 to 4	4 to 10	05/11/2007
RS002A01_MW002	472665	5831330	6.2	0 to 5.2	5.2 to 6.2	06/11/2007
RS002A01_MW003	472665	5831330	4.3	0 to 3.3	3.3 to 4.3	06/11/2007
RS002A01_MW004	472665	5831330	1	0 to 0.5	0.5 to 1	06/11/2007
RS002A01_MW005	472665	5831330	5.3	0 to 4.3	4.3 to 5.3	06/11/2007
RS003A01_MW001	491990	5799209	36	0 to 30.1	30.1 to 31.6	17/12/2007
RS003A01_MW002	491990	5799209	30	0 to 28.3	28.3 to 29.8	17/12/2007
RS004A01_MW001	445692	5848192	27.8	0 to 24	24 to 27	14/11/2007
RS006A01_MW001	485267	5794566	14	0 to 5.8	5.8 to 12.8	09/11/2007
RS006A01_MW002	485267	5794566	11	0 to 10	10 to 11	10/11/2007
RS006A01_MW003	485267	5794566	9.1	0 to 8.1	8.1 to 9.1	10/11/2007
RS006A01_MW004	485267	5794566	11	0 to 7	7 to 9.7	10/11/2007
RS007A01_MW001	483630	5822787	9.3	0 to 4.3	4.3 to 9.3	07/11/2007
RS007A01_MW002	483630	5822787	7	0 to 6	6 to 7	07/11/2007
RS007A01_MW003	483630	5822787	5.3	0 to 4.3	4.3 to 5.3	07/11/2007
RS007A01_MW004	483630	5822787	2	0 to 1.5	1.5 to 2	07/11/2007
RS008A01_MW001	435133	5846924	8.5	0 to 3.2	3.2 to 8.5	01/11/2007
RS008A01_MW002	435133	5846924	4.5	0 to 3.5	3.5 to 4.5	02/11/2007
RS008A01_MW003	435133	5846924	3	0 to 2.5	2.5 to 3	01/11/2007
RS008A01_MW004	435133	5846924	2.5	0 to 2	2 to 2.5	02/11/2007
RS009A01_MW001	441923	5864539	8	0 to 2	2 to 8	25/10/2007
RS009A01_MW002	441923	5864539	4.5	0 to 3.5	3.5 to 4.5	25/10/2007

RS009A01_MW003	441923	5864539	2.7	0 to 1.7	1.7 to 2.7	25/10/2007
RS010A01_MW001	496336	5893349	21.5	0 to 15.5	15.5 to 21.5	16/11/2007
RS010A01_MW002	496336	5893349	18	0 to 17	17 to 18	17/11/2007
RS010A01_MW003	496336	5893349	19.9	0 to 18.6	18.6 to 19.6	16/11/2007
RS011A01_MW001	433613	5861181	8.4	0 to 2.4	2.4 to 8.4	31/10/2007
RS011A01_MW002	433613	5861181	6.6	0 to 5.6	5.6 to 6.6	31/10/2007
RS011A01_MW003	433613	5861181	4.5	0 to 3.5	3.5 to 4.5	31/10/2007
RS012A01_MW001	417555	5980125	13	0 to 10	10 to 13	03/03/2008
RS013A01_MW001	387442	6025105	11	0 to 5	5 to 11	09/10/2007
RS013A01_MW002	387442	6025105	9.8	0 to 9.3	9.3 to 9.8	10/10/2007
RS013A01_MW003	387442	6025105	9	0 to 8	8 to 9	10/10/2007
RS014A01_MW001	413599	5874802	7.7	0 to 1.7	1.7 to 7.7	24/10/2007
RS014A01_MW002	413599	5874802	5.2	0 to 4.2	4.2 to 5.2	24/10/2007
RS014A01_MW003	413599	5874802	2.7	0 to 1.7	1.7 to 2.7	24/10/2007
RS015A01_MW001	382340	6035511	12.5	0 to 6.5	6.5 to 12.5	12/10/2007
RS015A01_MW002	382340	6035511	10.6	0 to 9.6	9.6 to 10.6	12/10/2007
RS015A01_MW003	382340	6035511	8.4	0 to 7.4	7.4 to 8.4	12/10/2007
RS016A01_MW001	421400	5943760	6.3	0 to 0.3	0.3 to 6.3	15/10/2007
RS016A01_MW002	421400	5943760	4.8	0 to 3.8	3.8 to 4.8	15/10/2007
RS016A01_MW003	421400	5943760	2.8	0 to 1.8	1.8 to 2.8	15/10/2007
RS016A01_MW004	421400	5943760	7	0 to 2	2 to 7	20/10/2007
RS017A01_MW001	487736	5952882	25.2	0 to 23.1	23.1 to 25.1	20/11/2007
RS017A01_MW002	487736	5952882	28	0 to 25.4	25.4 to 27.4	21/11/2007
RS017A01_MW003	487736	5952882	7	0 to 4.75	4.75 to 6.75	21/11/2007
RS018A01_MW001	454036	6024985	32.6	0 to 26.6	26.6 to 32.6	03/03/2008
RS019A01_MW001	488946	5954225	20.9	0 to 18.9	18.9 to 20.9	22/11/2007
RS019A01_MW002	488946	5954225	24	0 to 22	22 to 24	23/11/2007
RS020A01_MW001	452376	5920591	8	0 to 3.2	3.2 to 8	22/10/2007
RS020A01_MW002	452376	5920591	6.5	0 to 5.5	5.5 to 6.5	22/10/2007
RS020A01_MW003	452376	5920591	4.5	0 to 3.5	3.5 to 4.5	23/10/2007

RS020A01_MW004	452376	5920591	4.5	0 to 3.5	3.5 to 4.5	23/10/2007
RS021A01_MW001	491371	5790118	13	0 to 12	12 to 13	08/11/2007
RS021A01_MW002	491371	5790118	8	0 to 7	7 to 8	09/11/2007
RS021A01_MW003	491371	5790118	3.5	0 to 2.5	2.5 to 3.5	09/11/2007
RS023A01_MW001	421740	5943924	18	0 to 17	17 to 18	16/10/2007
RS023A01_MW002	421740	5943924	16.5	0 to 15.5	15.5 to 16.5	16/10/2007
RS023A02_MW001	421691	5943900	14.7	0 to 13.7	13.7 to 14.7	17/10/2007
RS023A02_MW002	421691	5943900	12.5	0 to 11.5	11.5 to 12.5	18/10/2007
RS023A03_MW001	421584	5943851	8.7	0 to 7.7	7.7 to 8.7	19/10/2007
RS023A03_MW002	421584	5943851	6.1	0 to 5.1	5.1 to 6.1	19/10/2007
RS024A01_MW001	455261	5883501	11	0 to 5	5 to 11	05/03/2008
RS024A01_MW002	455261	5883501	7	0 to 6	6 to 7	05/03/2008

Table 7. Piezometer completion details for all drill holes

South East National Water Initiative Project 1.1

Borehole ID: RS002A01_MW001
Date drilled: 05/11/07
Driller: Drilling Solutions
Logged by: CW & SM

Drilling method: Hollow augers
Bore diameter: 8"

Unit number: 7022-10485

Location: Dismal Swamp
Easting: 472665
Northing: 5831330

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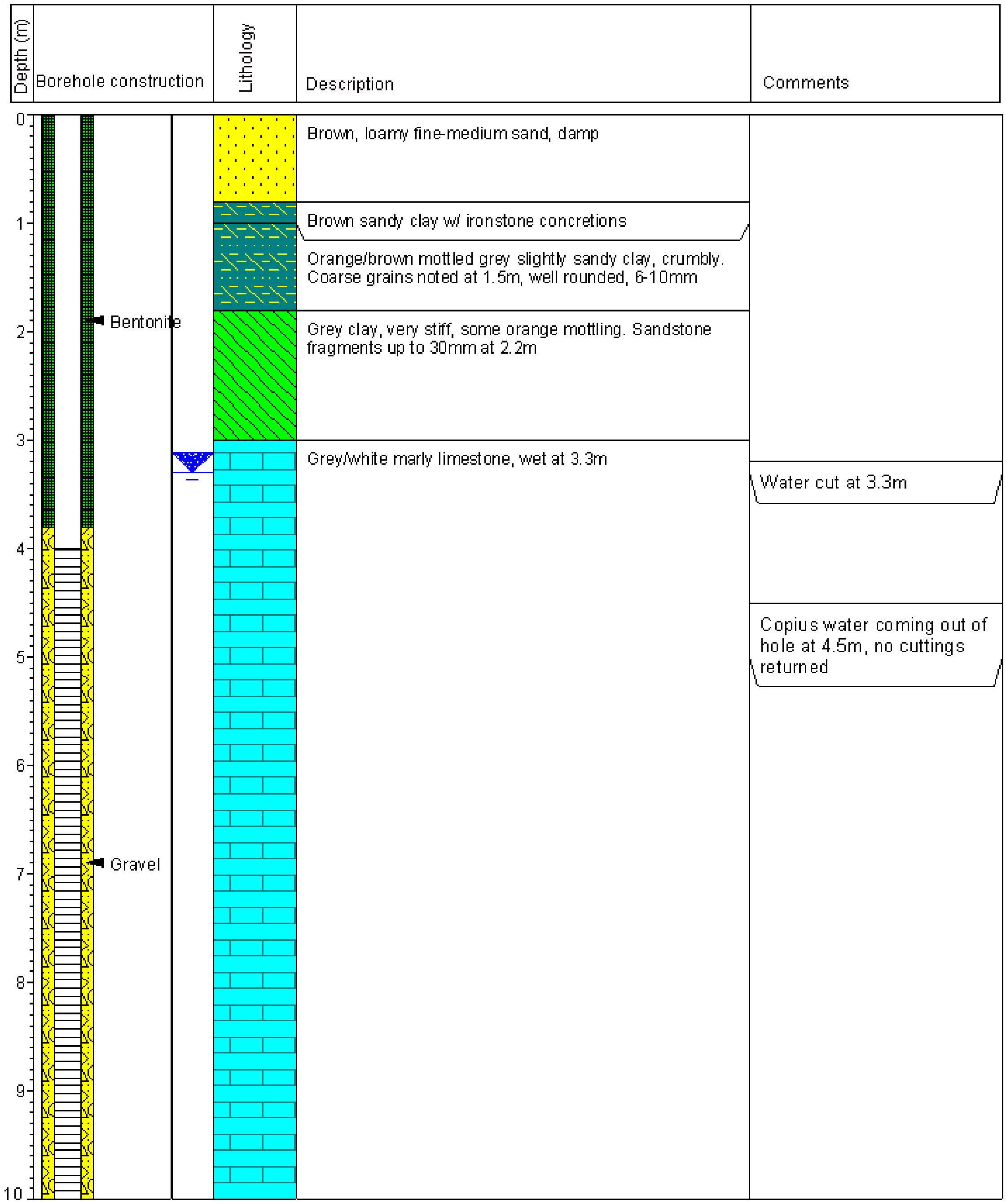

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

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South East National Water Initiative Project 1.1

Borehole ID: RS003A01_MW001
Date drilled: 12/11/07
Driller: Drilling Solutions
Logged by: CW & IM

Drilling method: Hollow augers
Bore diameter: 6"

Unit number: 702210490

Location: Caroline
Easting: 491990
Northing: 5799209

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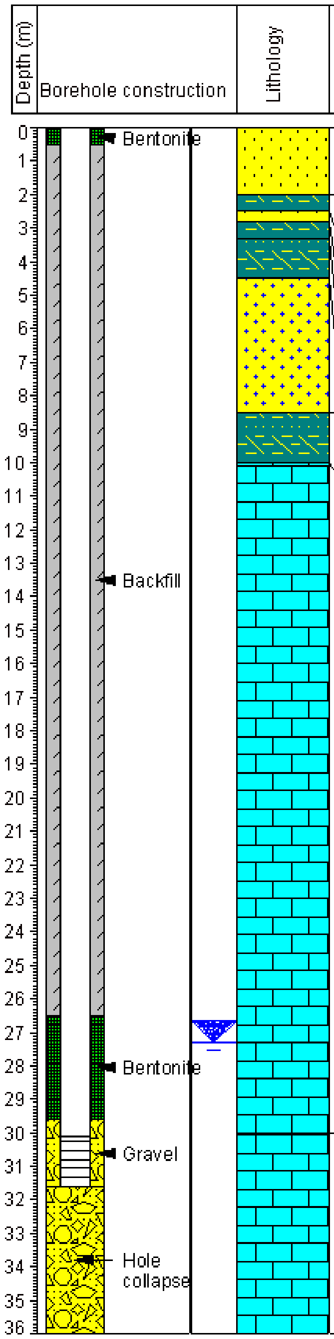

Description	Comments
Grey fine-medium sand, becomes brown at ~0.5m, changes to brown-orange 0.6-0.7m	
Quite clayey, 2-2.5m	Some charcoal fragments at 1.5m
Pale yellow sand	Charcoal fragments at 3m
Orange sandy clay	
Pale yellow sand w/ stiff, dry sandy clay horizons	
White fine-medium sandstone	
Grey/mottled orange stiff sandy clay w/ numerous bivalve shells	Oyster shell noted at 9.5m
White/cream limestone, numerous fossils in cuttings	Slightly damp at 10.6m
	Driller reports hard conditions 16-16.5m, yellowish/tan hard sandstone returned from this depth
	Cuttings not returned 19m onwards
	NOTE: Stopped drilling on 13/11/2007 @ 28m due to rig difficulties. Hole completed 17/12/2007 with 6" tricone
Dark cream fine-medium grained limestone with spary cement. Possible calcite veining, poor returns - possible cavity	

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

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South East National Water Initiative Project 1.1

Borehole ID: RS004A01_MW001
Date drilled: 14/11/07
Driller: Drilling Solutions
Logged by: IM

Drilling method: Hollow augers
Bore diameter: 6"

Unit number: 6922-4603

Location: Furner
Easting: 445692
Northing: 5848192

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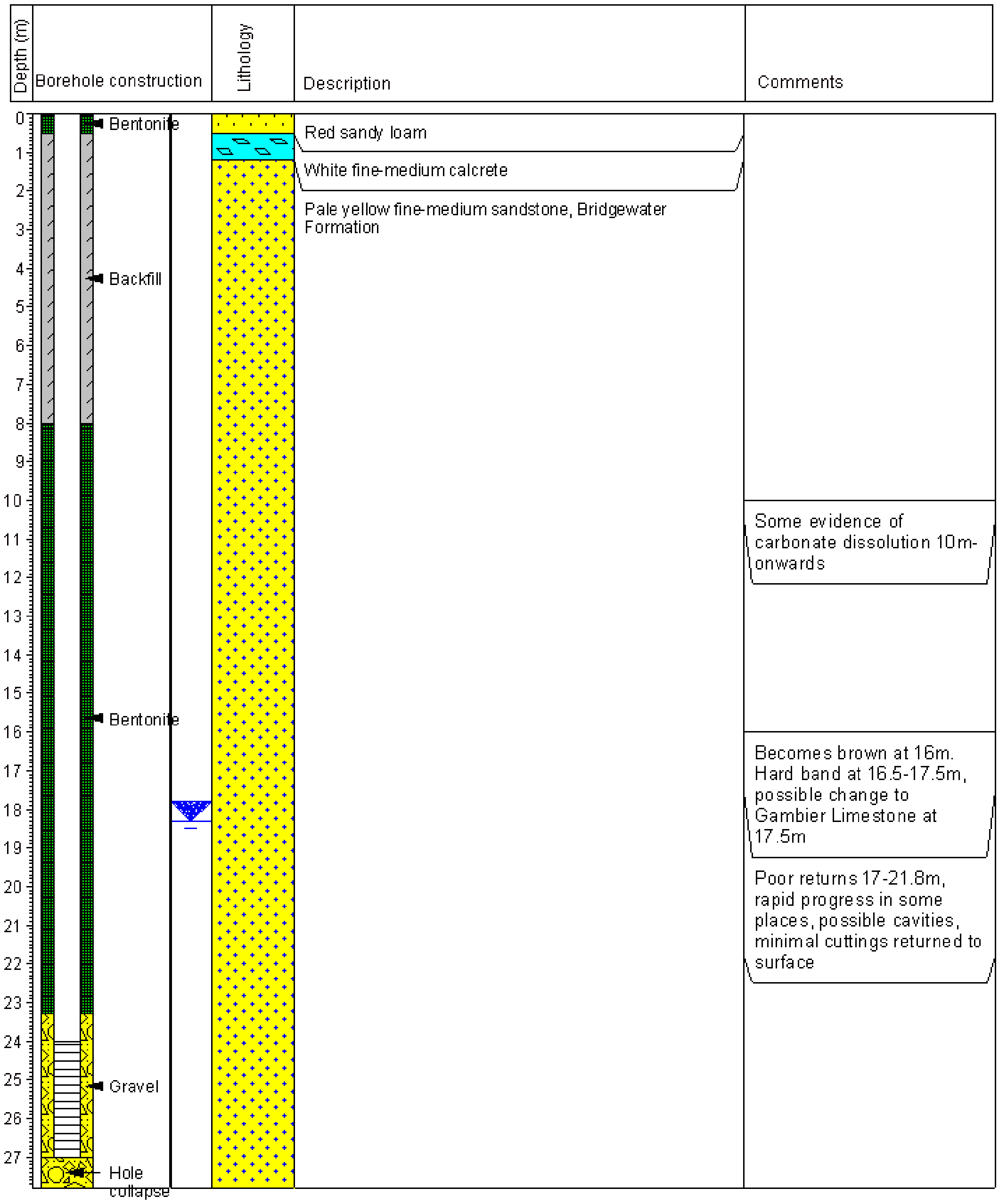

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

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South East National Water Initiative Project 1.1

Borehole ID: RS006A01_MW001
Date drilled: 09/11/07
Driller: Drilling Solutions
Logged by: CW & IM

Drilling method: Hollow augers
Bore diameter: 6"

Unit number: 7022-10493

Location: Greenpoint
Easting: 485267
Northing: 5794566

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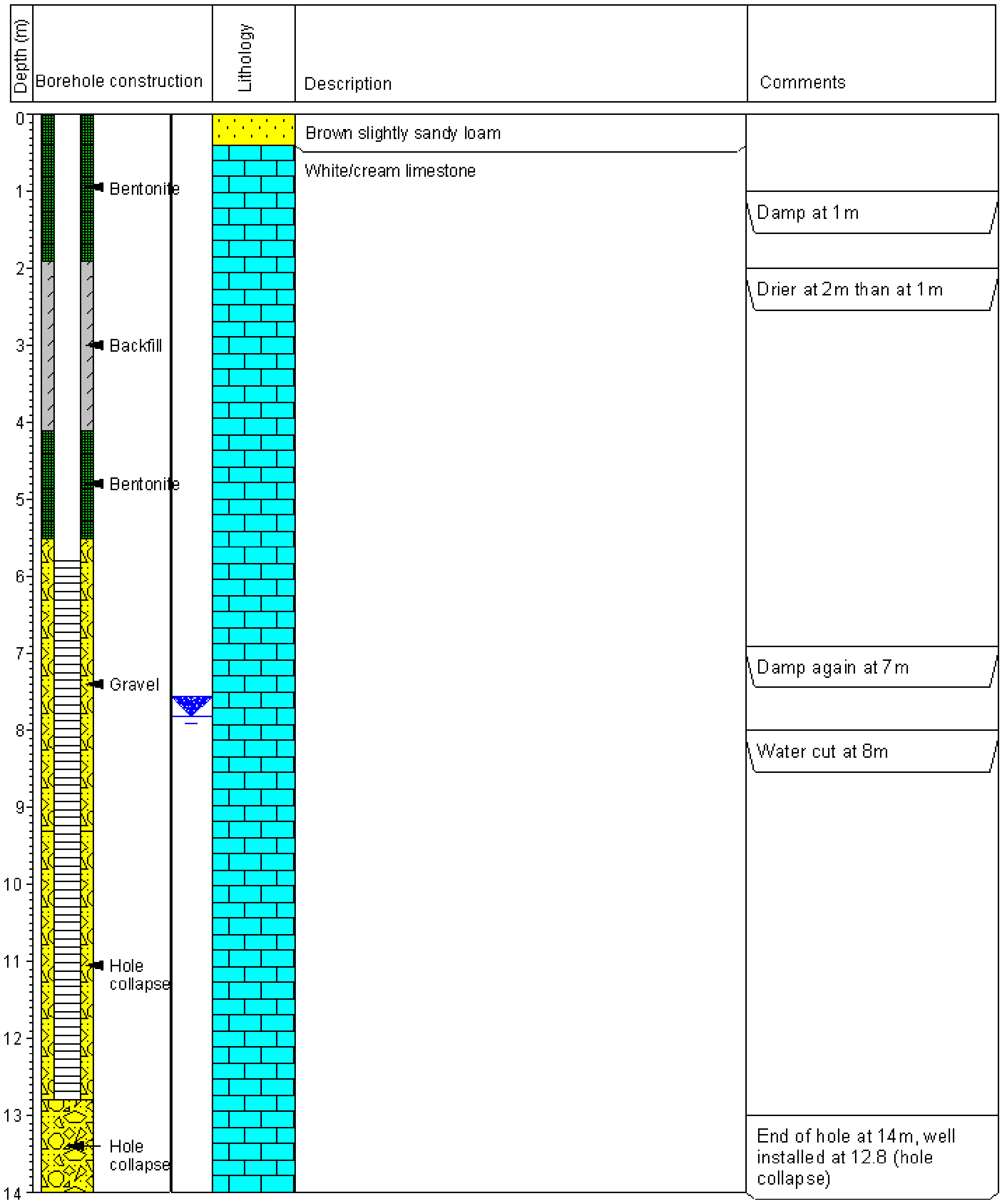

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

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South East National Water Initiative Project 1.1

Borehole ID: RS007A01_MW001
Date drilled: 07/11/07
Driller: Drilling Solutions
Logged by: CW & IM
Drilling method: Hollow augers
Bore diameter: 8"
Unit number: 7022-10496
Location: Peweena
Easting: 483630
Northing: 5822787

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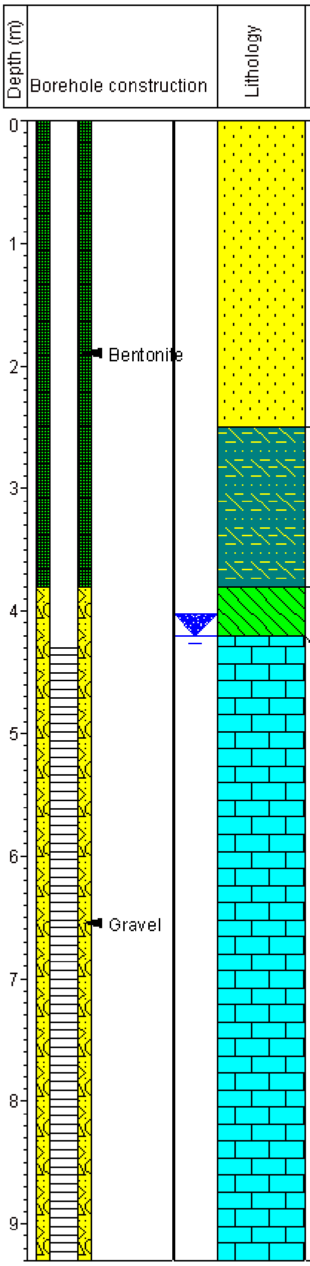

Description	Comments
Dark brown fine-medium sand. Becomes light brown-orange/red at 0.5m. Becomes yellow at 1m. Changes to off white/light brown at 1.75m	Ironstone concretions 1.25-1.5m
White clayey sand at 2.5m, clay content increases 2.3-3m. Quite stiff at 3m, slightly sandier at 3.5m	
Grey/mottled orange clay, firm to soft, damp, some carbonate fragments.	Water cut at 4.2m
Weathered fossiliferous limestone, wet.	No returns 5.5 to end of hole

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

Page: 1 **of:** 1

Department of Water Land & Biodiversity Conservation

South East National Water Initiative Project 1.1

Borehole ID: RS008A01_MW001
Date drilled: 01/11/07
Driller: Drilling Solutions
Logged by: CW & IM
Drilling method: Hollow augers
Bore diameter: 8"
Unit number: 6922-4604
Location: Millicent
Easting: 435133
Northing: 5846924

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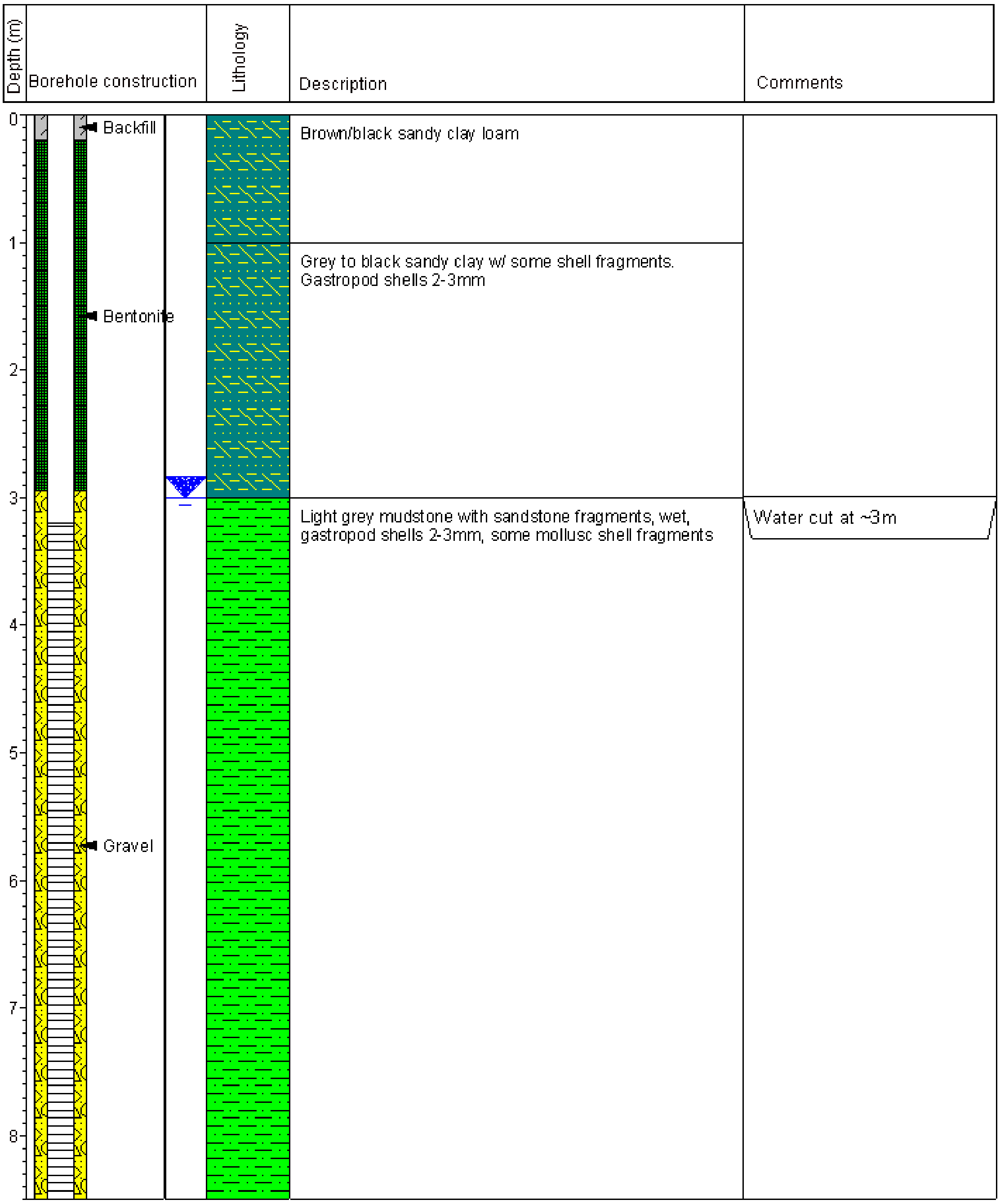

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

Page: 1 **of:** 1

Department of Water Land & Biodiversity Conservation

South East National Water Initiative Project 1.1

Borehole ID: RS009A01_MW001
Date drilled: 25/10/07
Driller: Drilling Solutions
Logged by: IM

Drilling method: Hollow augers
Bore diameter: 8"

Unit number: 6923-4520

Location: Furner
Easting: 441923
Northing: 5864539

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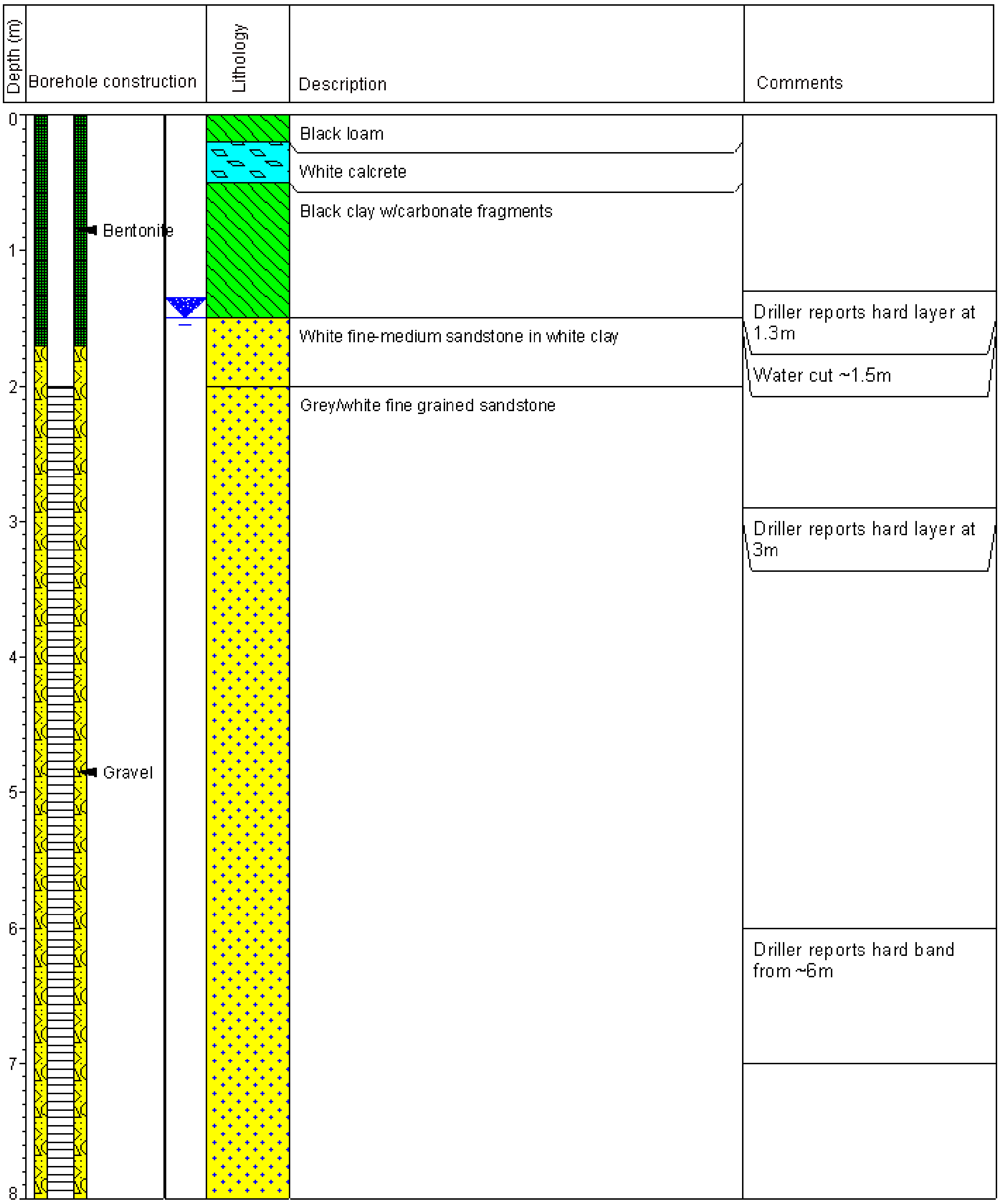

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

Page: 1 **of:** 1

Department of Water Land & Biodiversity Conservation

South East National Water Initiative Project 1.1

Borehole ID: RS010A01_MW001
Date drilled: 16/11/07
Driller: Drilling Solutions
Logged by: CW & IM

Drilling method: Hollow augers
Bore diameter: 6"

Unit number: 7023-6899

Location: Wrattonbully
Easting: 496336
Northing: 5893349

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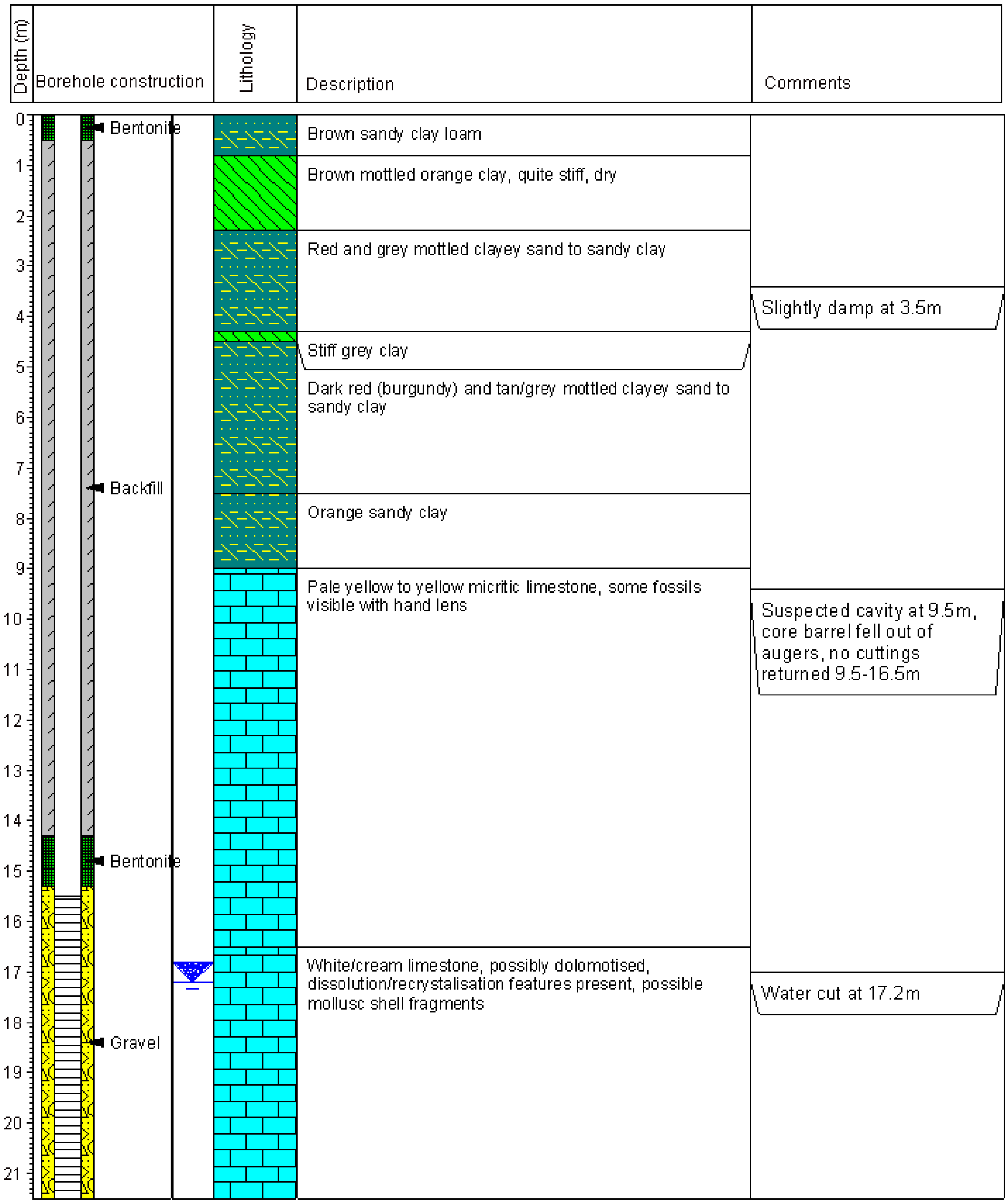

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

Page: 1 **of:** 1

Department of Water Land & Biodiversity Conservation

South East National Water Initiative Project 1.1

Borehole ID: RS011A01_MW001
Date drilled: 31/10/7
Driller: Drilling Solutions
Logged by: CW & SM

Drilling method: Hollow augers
Bore diameter: 8"

Unit number: 6923-4523

Location: Furner
Easting: 433613
Northing: 5861181

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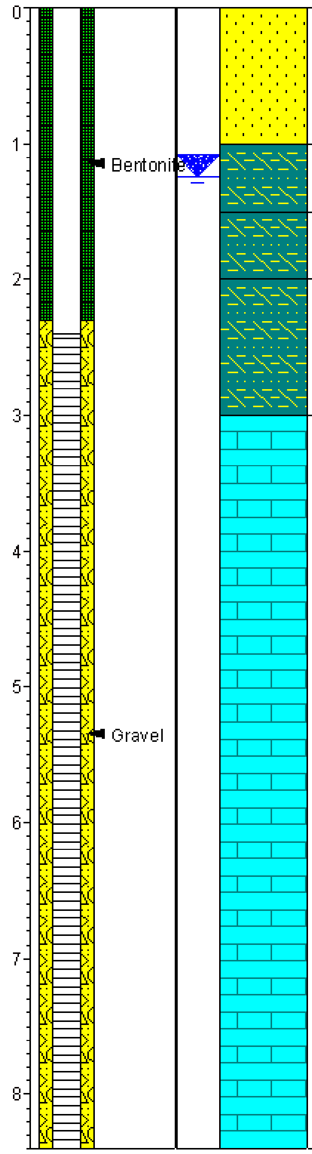

Description	Comments
Dark grey fine-medium sand, becomes pale grey at 0.8m	
Light brown fine-medium clayey sand with orange mottling	
Grey clayey sand, damp	
Brown orange sandy clay, slightly damp	
Grey clayey fine-medium sand, quite damp, marly. Shell fragments in cuttings from approximately 4m, wet cuttings	Water cut approx 3-4m. Depth to water on completion = 1.8m
	Driller reports slightly harder layer at 5m, not very thick or hard, very little cuttings returned 5m o end of hole

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

Page: 1 of: 1

Department of Water Land & Biodiversity Conservation

South East National Water Initiative Project 1.1

Borehole ID: RS012A01_MW001
Date drilled: 03/03/08
Driller: Drilling Solutions
Logged by: CW & GM

Drilling method: Hollow augers
Bore diameter: 6"

Unit number: 6925-3767

Location: Glenstrae
Easting: 417552
Northing: 5980111

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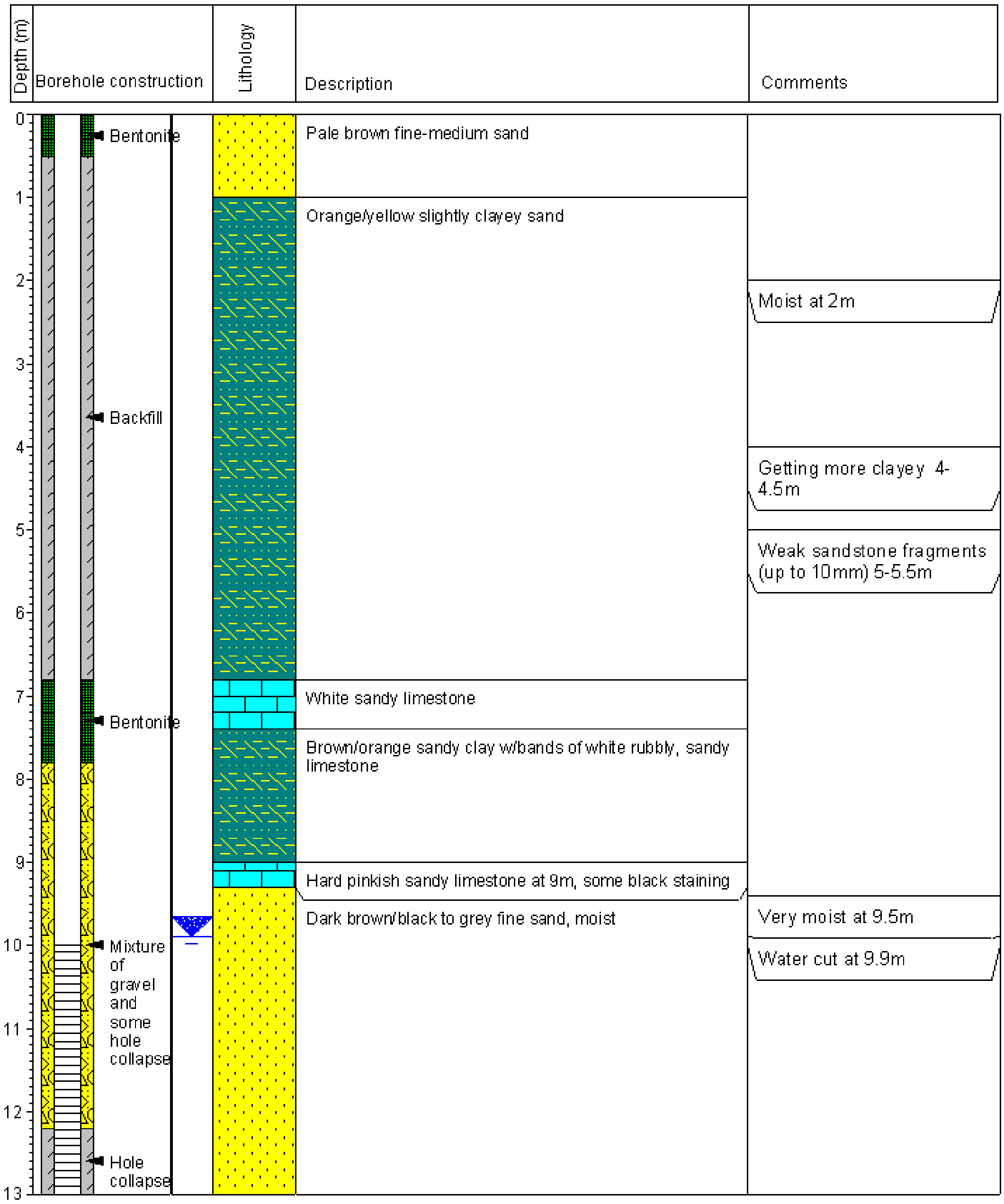

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

Page: 1 of: 1

Department of Water Land & Biodiversity Conservation

South East National Water Initiative Project 1.1

Borehole ID: RS013A01_MW001
Date drilled: 09/10/2007
Driller: Drilling Solutions
Logged by: CW

Drilling method: Hollow stem aug
Bore diameter: 6"

Location: Tintinara
Easting: 387442
Northing: 6025105

Unit number: 6826-1355

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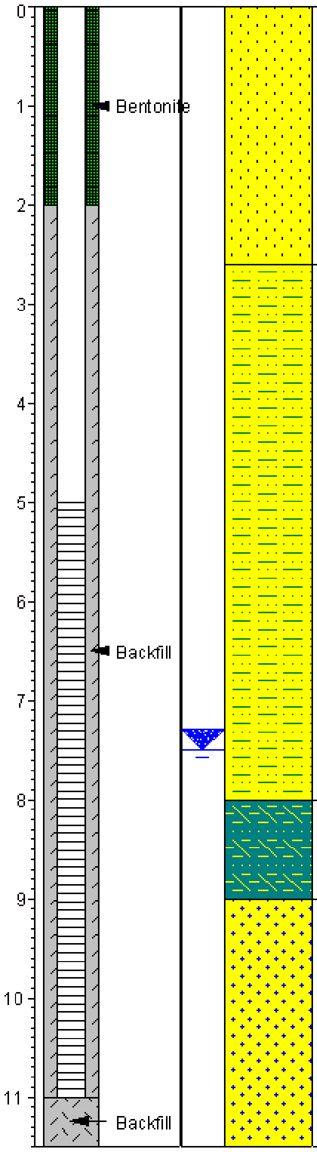

Description	Comments
Yellow fine-medium sand	
Dark yellow clayey sand, damp	Driller reports hard conditions 2.6-2.8
	Some calcereous concretions, less damp than at 3m
	Hard band encountered at 4.5m
	Becomes more orange at 6.5m
	Becomes paler at 7.1m
	Moist to wet 7-7.5
	Water cut at 7.5m
Interbedded grey clay and orange sand	
Light brown, fine-med grained sandstone	Hard from 10-10.4m
	Depth to water on completion = 6.63m (below

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

Page: 1 **of:** 2

Department of Water Land & Biodiversity Conservation

South East National Water Initiative Project 1.1

Borehole ID: RS013A02_SC001
Date drilled: 11/10/2007
Driller: Drilling Solutions
Logged by: CW & IM

Drilling method: Split spoon & aug
Bore diameter: 6"

Location: Tintinara
Easting: 387354
Northing: 6025218

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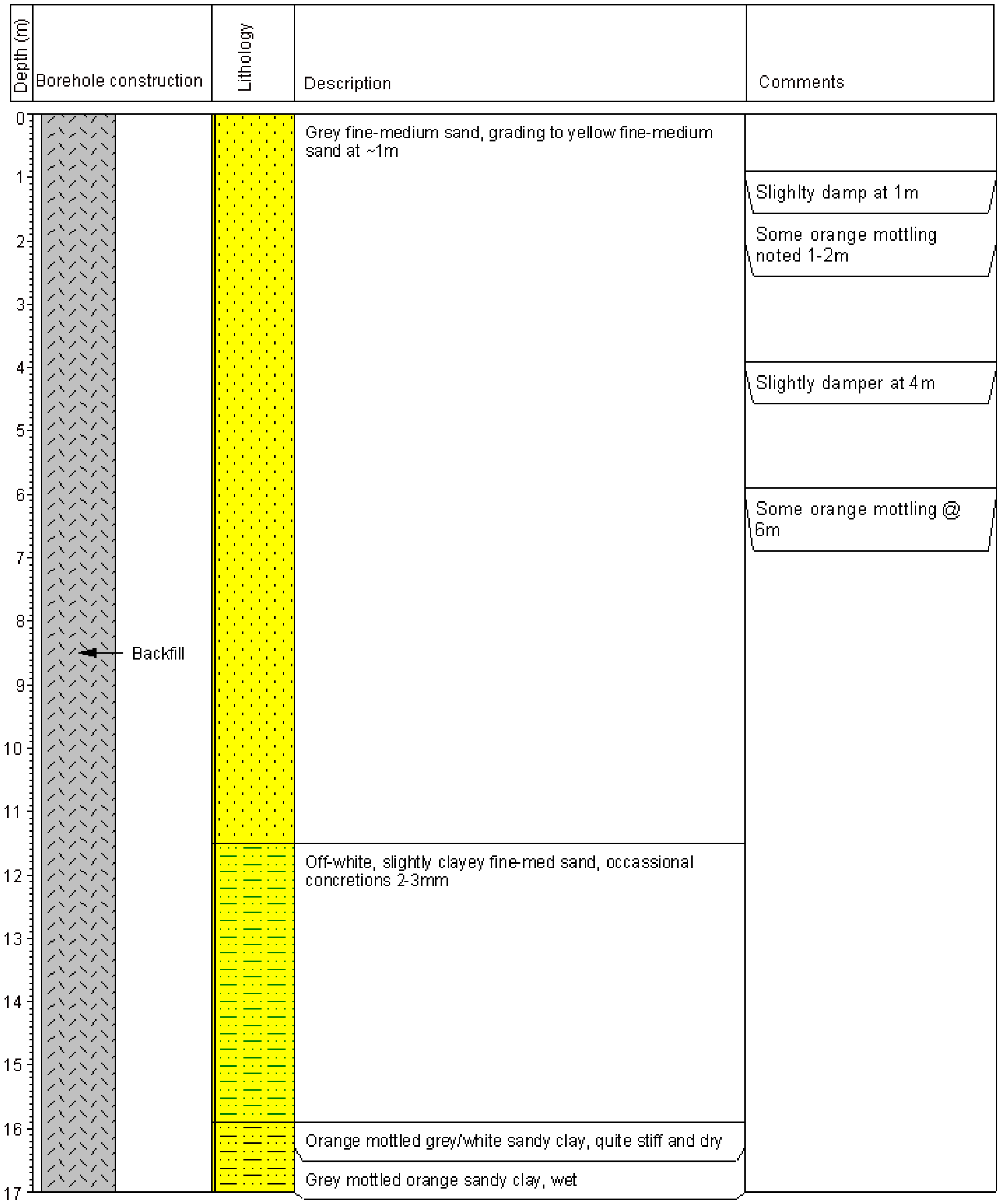

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

Page: 1 of: 1

Department of Water Land & Biodiversity Conservation

South East National Water Initiative Project 1.1

Borehole ID: RS014A01_MW001
Date drilled: 24/10/07
Driller: Drilling Solutions
Logged by: CW & IM

Drilling method: Hollow augers
Bore diameter: 8"

Unit number: 6923-4526

Location: East of Robe
Easting: 413599
Northing: 5874802

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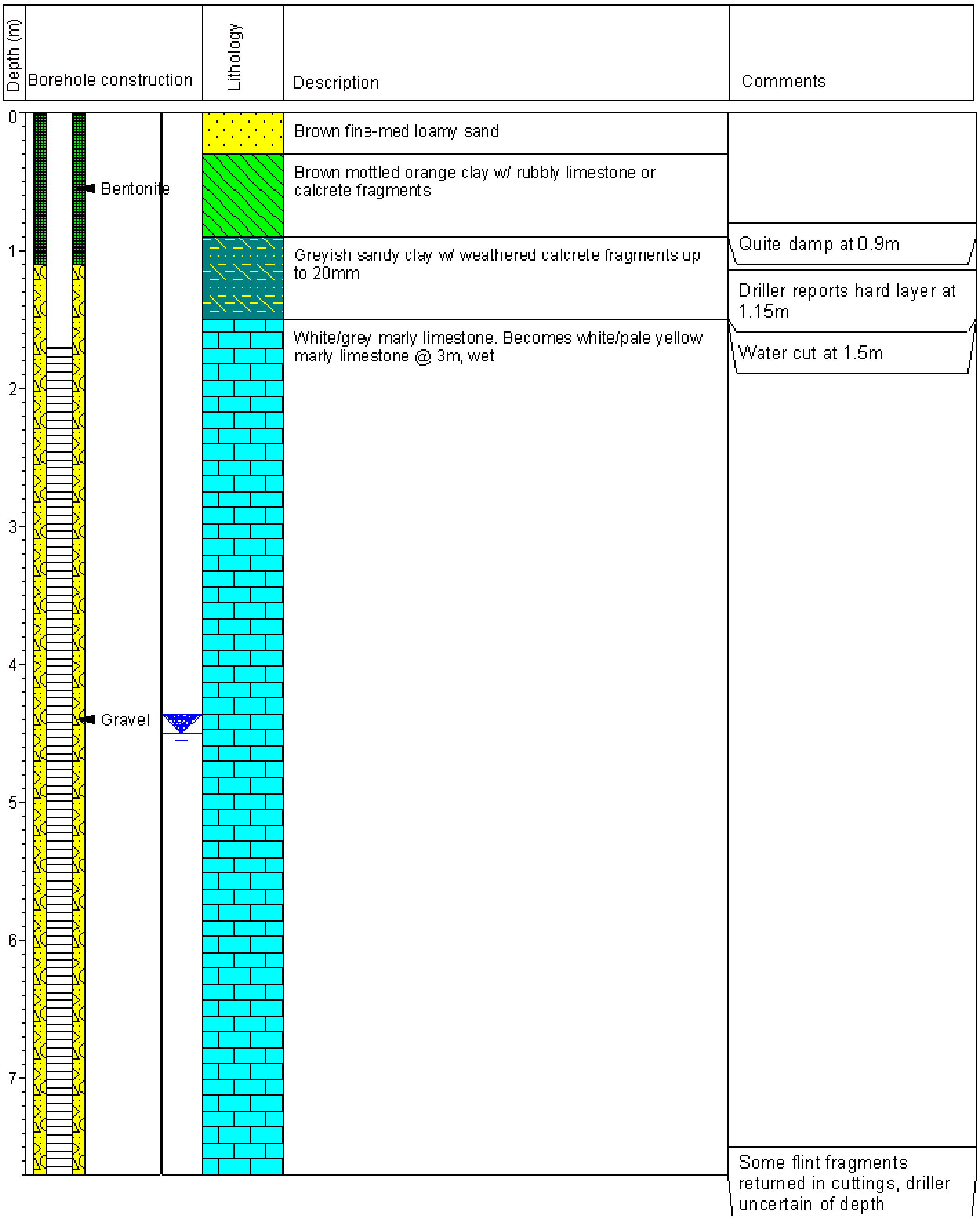

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

Page: 1 **of:** 2

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South East National Water Initiative Project 1.1

Borehole ID: RS015A01_MW001
Date drilled: 12/10/2007
Driller: Drilling Solutions
Logged by: CW

Drilling method: Hollow stem aug
Bore diameter: 6"

Location: Coonalpyn
Easting: 382340
Northing: 6035511

Unit number: 6826-1358

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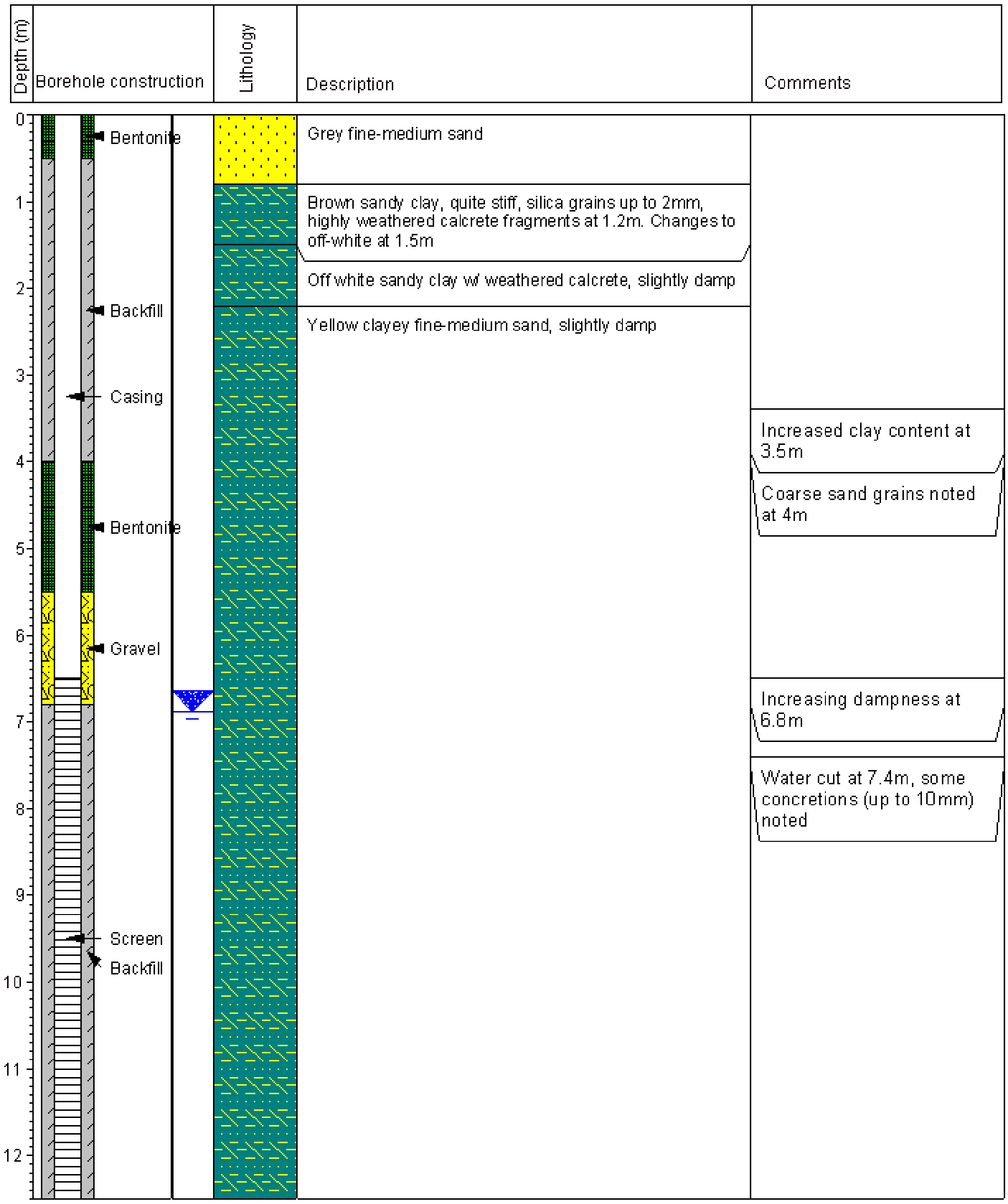

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

Page: 1 **of:** 1

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South East National Water Initiative Project 1.1

Borehole ID: RS016A01_MW001
Date drilled: 15/10/2007
Driller: Drilling Solutions
Logged by: CW & GM
Drilling method: Hollow augers
Bore diameter: 6"
Unit number: 6924-3993
Location: Avenue Range
Easting: 421400
Northing: 5943760

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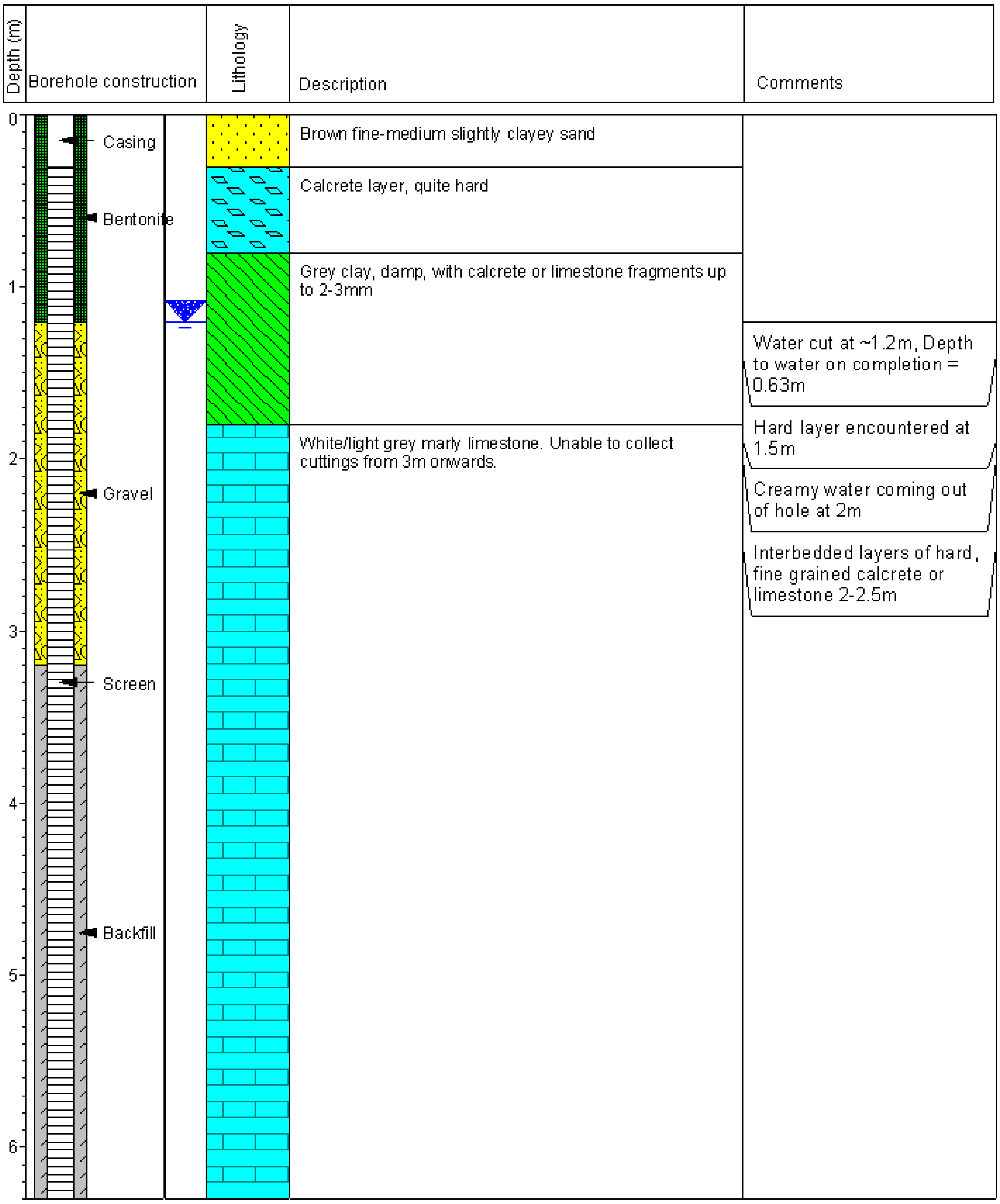

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

Page: 1 **of:** 1

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South East National Water Initiative Project 1.1

Borehole ID: RS017A01_MW001
Date drilled: 20/11/07
Driller: Drilling Solutions
Logged by: CW & IM

Drilling method: Hollow augers
Bore diameter: 6"

Location: Frances
Easting: 487736
Northing: 5952882

Unit number: 7024-5939

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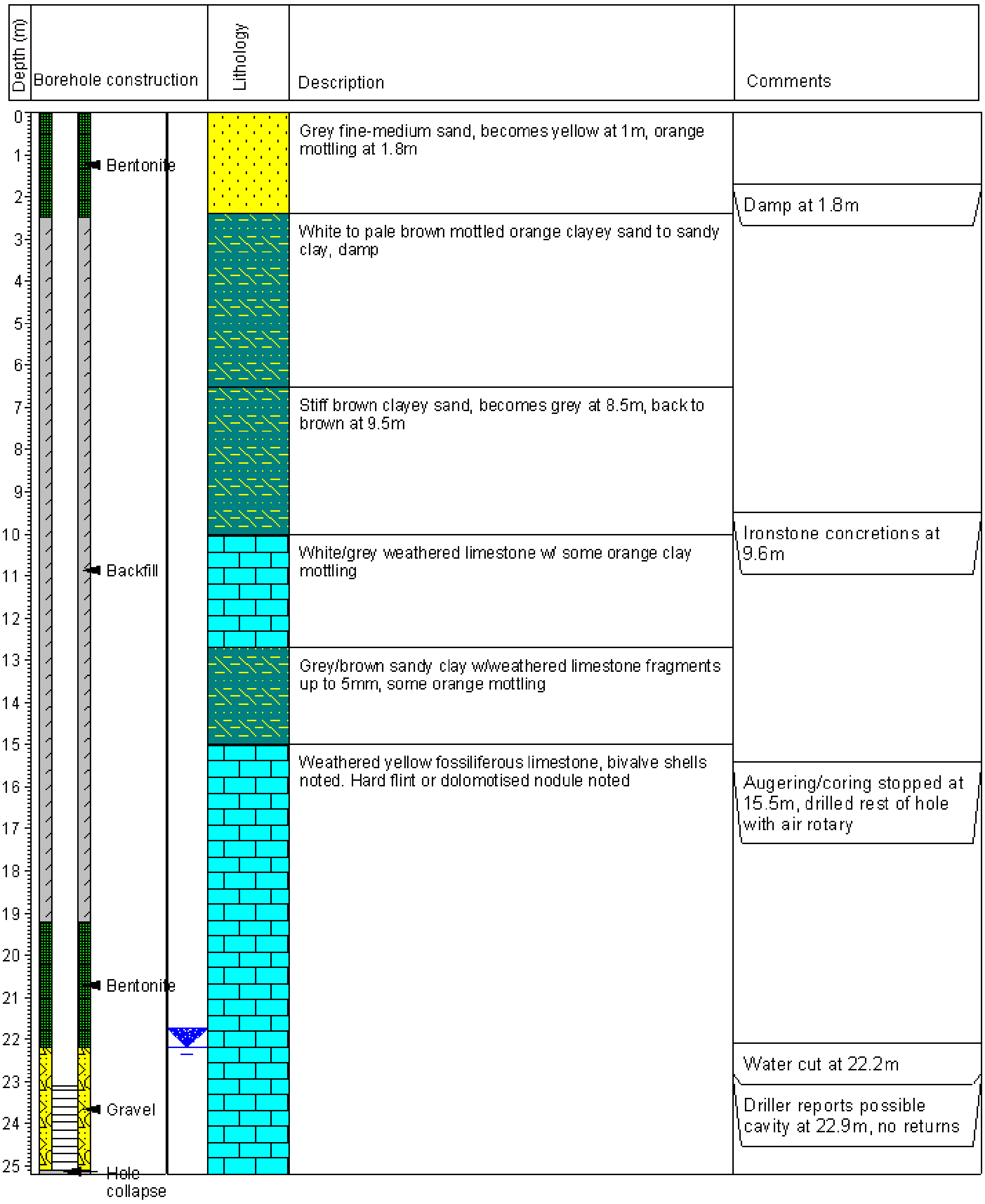

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

Page: 1 **of:** 1

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South East National Water Initiative Project 1.1

Borehole ID: RS018A01_MW001
Date drilled: 26/02/08
Driller: Drilling Solutions
Logged by: CW & GM

Drilling method: Hollow augers
Bore diameter: 6"

Unit number: 6926-765

Location: Ngarkat
Easting: 454481
Northing: 6025142

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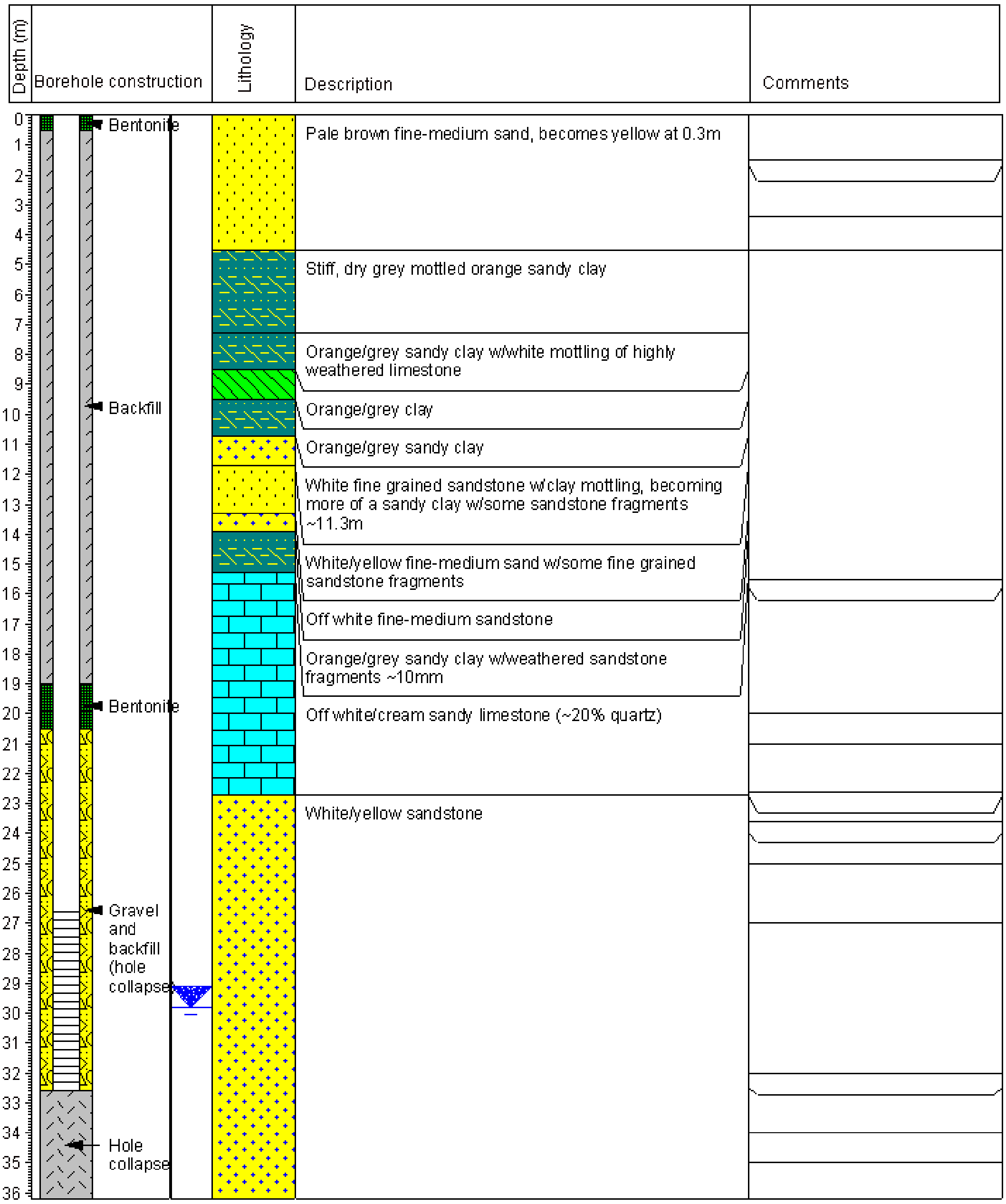

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

Page: 1 **of:** 1

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South East National Water Initiative Project 1.1

Borehole ID: RS019A01_MW001
Date drilled: 22/11/07
Driller: Drilling Solutions
Logged by: CW

Drilling method: Hollow augers
Bore diameter: 6"

Location: Frances
Easting: 488946
Northing: 5954225

Unit number: 7024-5942

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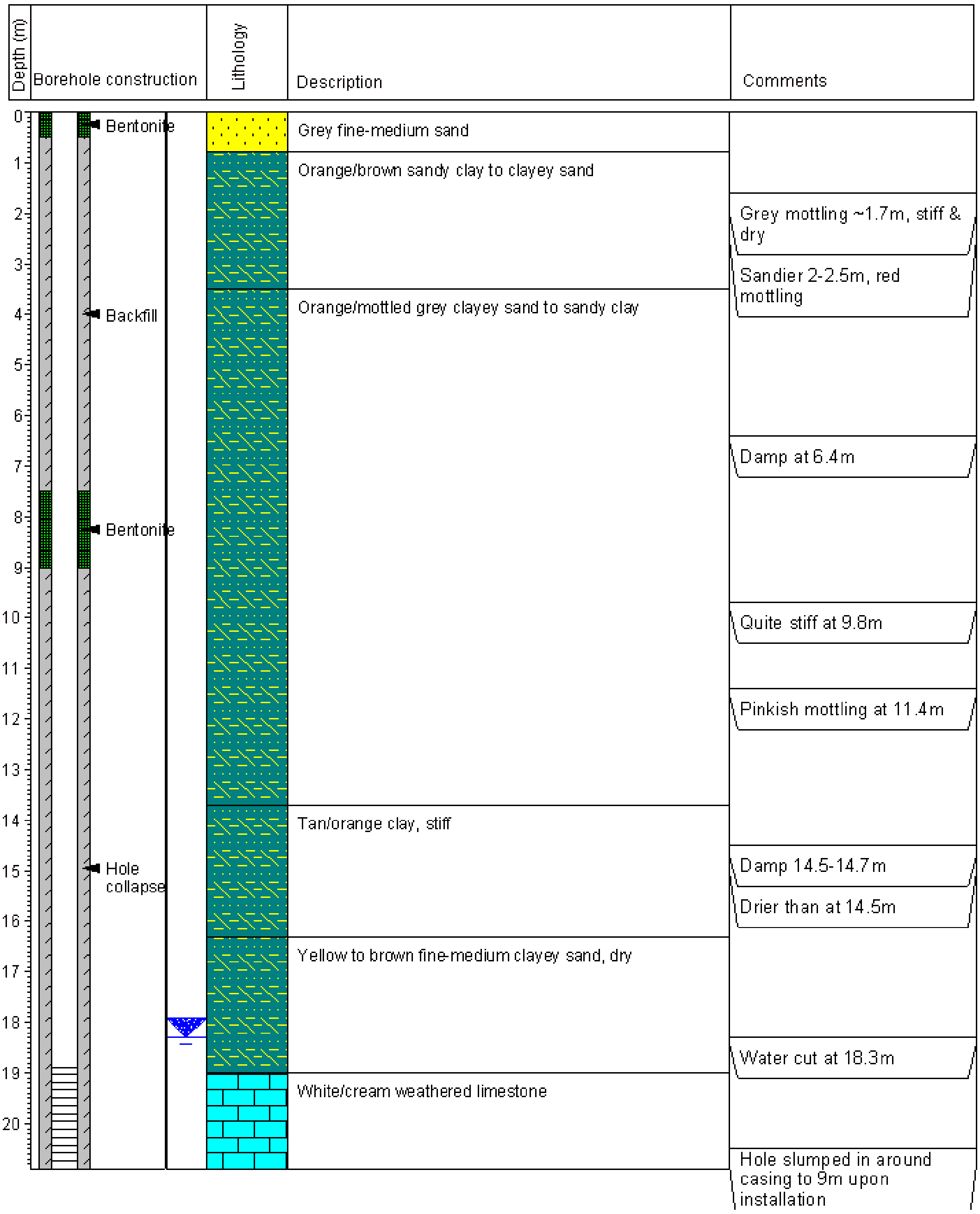

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

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South East National Water Initiative Project 1.1

Borehole ID: RS020A01_MW001
Date drilled: 22/10/07
Driller: Drilling Solutions
Logged by: CW & IM

Drilling method: Hollow augers
Bore diameter: 8"

Location: Lochaber
Easting: 452376
Northing: 5920591

Unit number: 6924-3997

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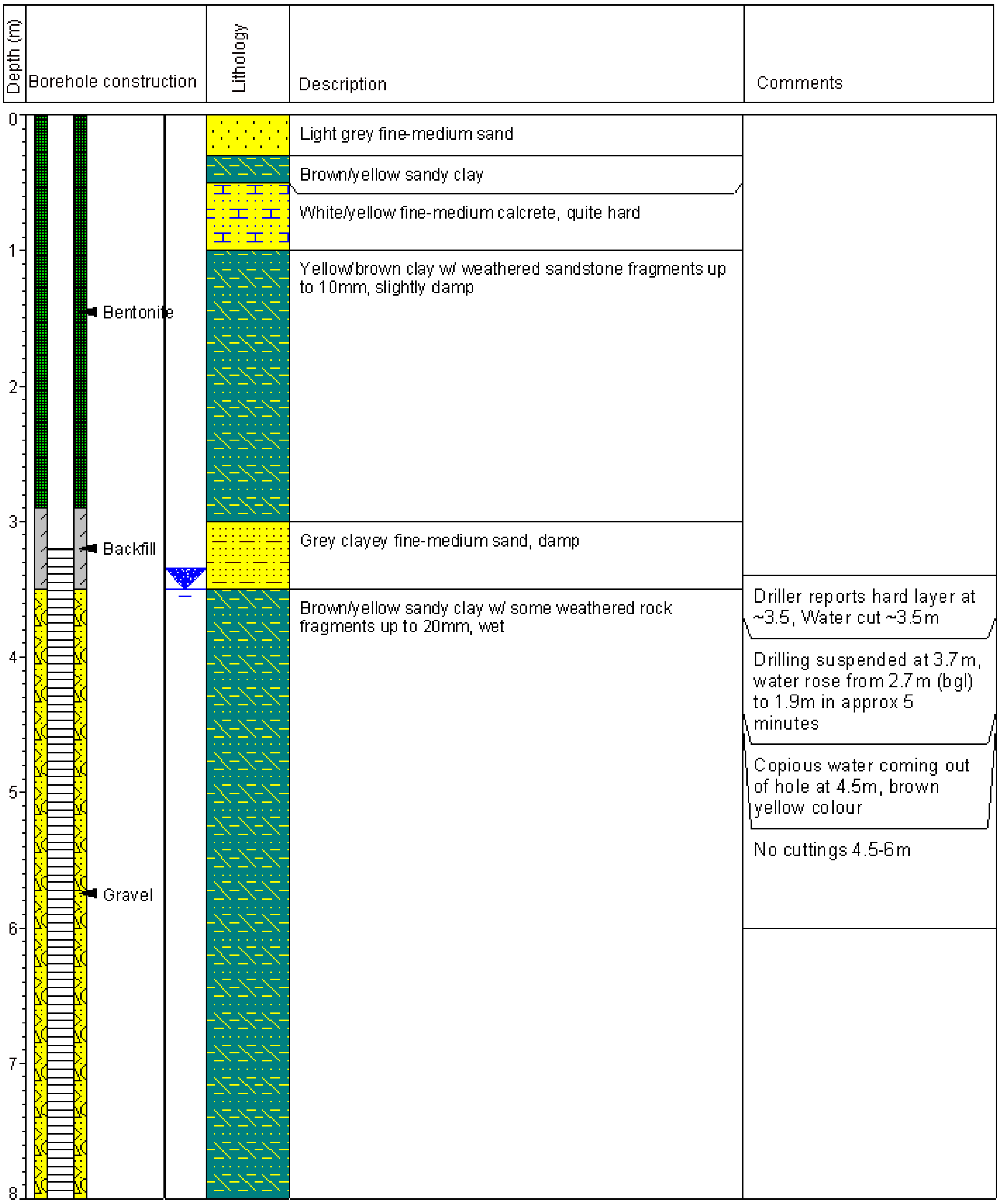

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

Page: 1 **of:** 1

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South East National Water Initiative Project 1.1

Borehole ID: RS021A01_MW001
Date drilled: 08/11/07
Driller: Drilling Solutions
Logged by: CW & IM

Drilling method: Hollow augers
Bore diameter: 8"

Unit number: 7021-3494

Location: Pick Swamp
Easting: 491371
Northing: 5790118

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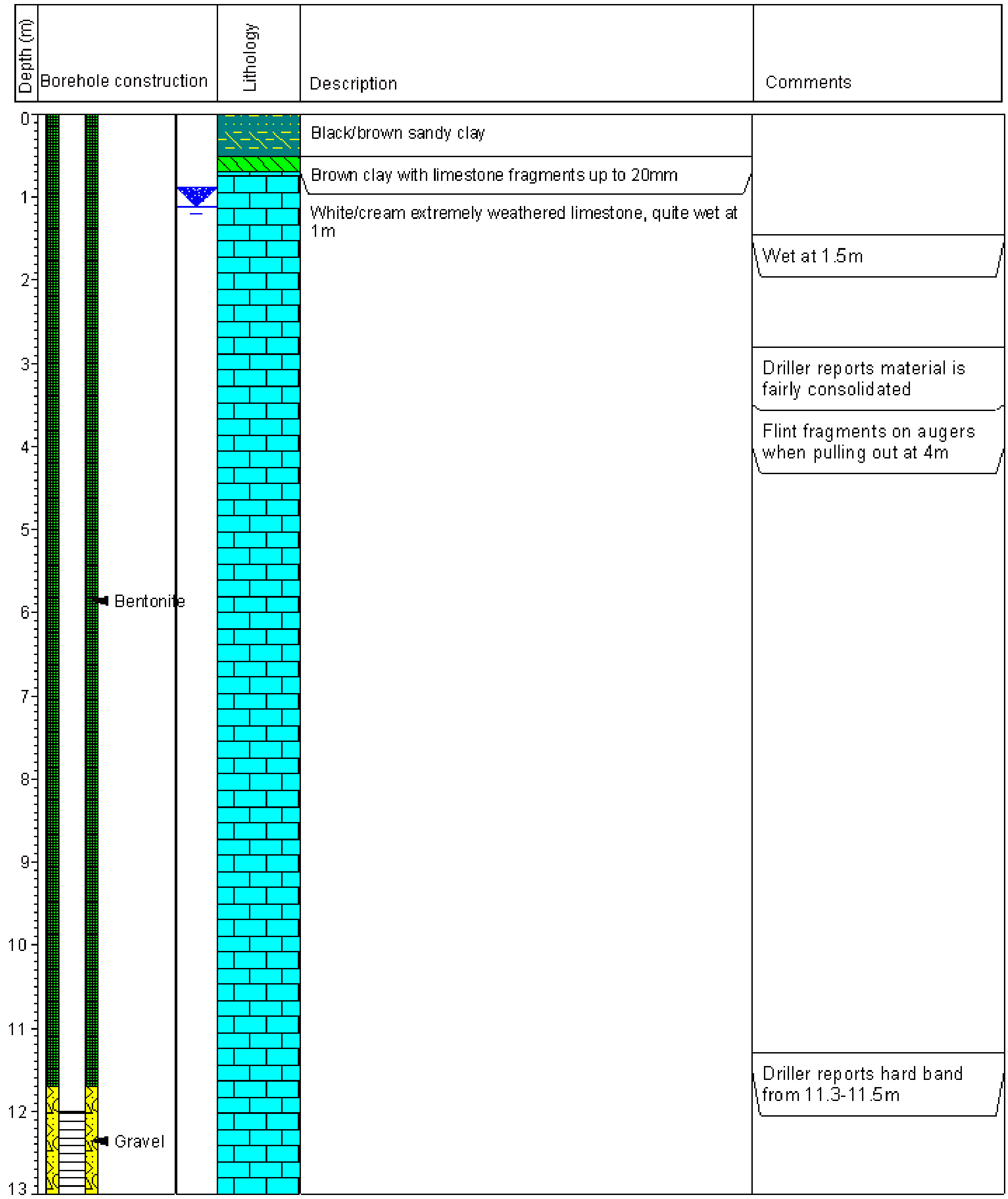

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

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South East National Water Initiative Project 1.1

Borehole ID: RS023A01_MW001
Date drilled: 16/10/2007
Driller: Drilling Solutions
Logged by: CW & IM
Drilling method: Hollow augers
Bore diameter: 6"
Unit number: 6924-4001
Location: Avenue Range
Easting: 421740
Northing: 5943924

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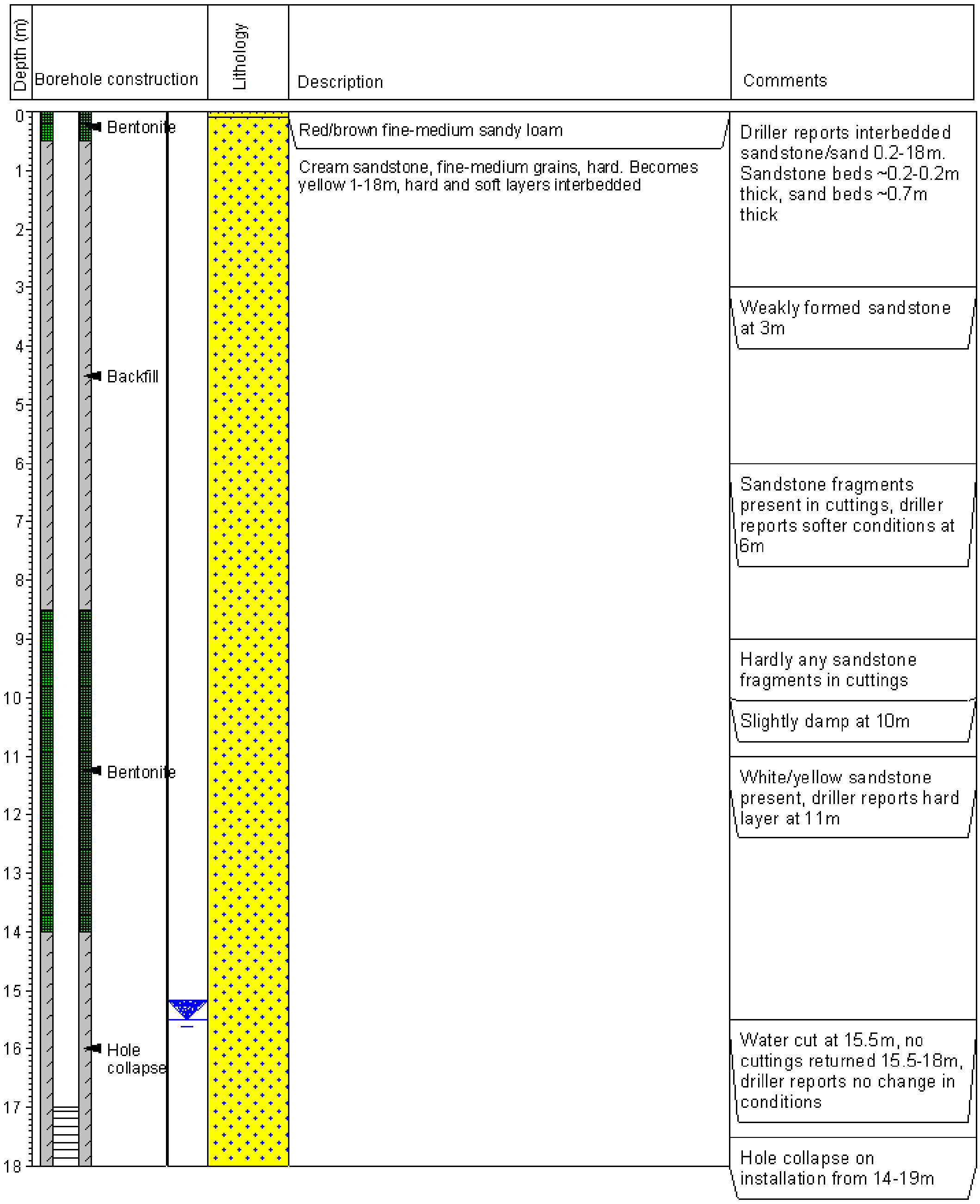

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

Page: 1 **of:** 1

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South East National Water Initiative Project 1.1

Borehole ID: RS023A02_MW001 **Drilling method:** Hollow augers **Location:** Avenue Range
Date drilled: 17/10/07 **Bore diameter:** 8" **Easting:** 421691
Driller: Drilling Solutions **Northing:** 5943900
Logged by: CW **Unit number:** 6924-4003

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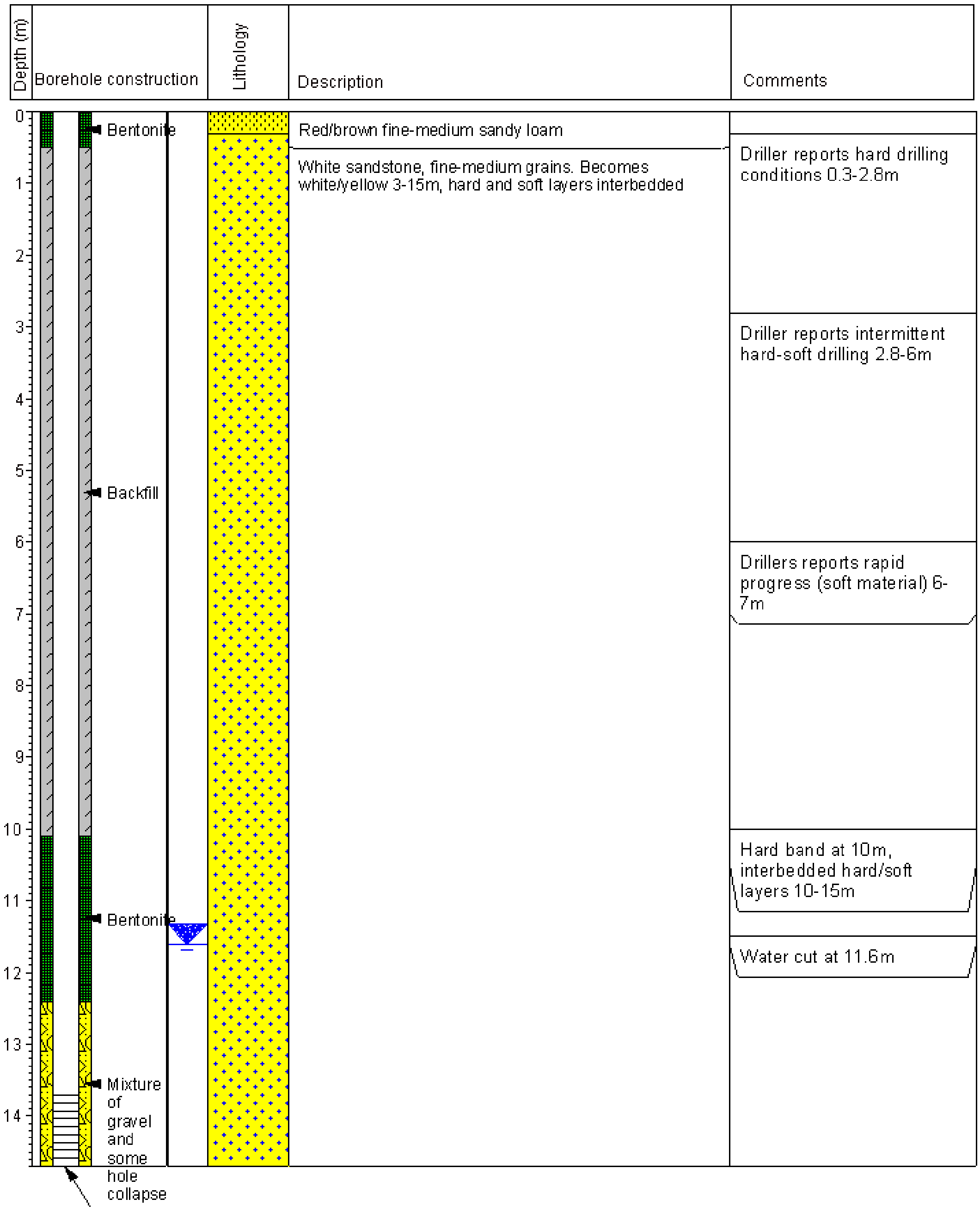

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

Page: 1 **of:** 2

Department of Water Land & Biodiversity Conservation

South East National Water Initiative Project 1.1

Borehole ID: RS023A03_MW001 **Drilling method:** Hollow augers **Location:** Avenue Range
Date drilled: 18/10/2007 **Bore diameter:** 8" **Easting:** 421584
Driller: Drilling Solutions **Northing:** 5943851
Logged by: CW **Unit number:** 6924-4005

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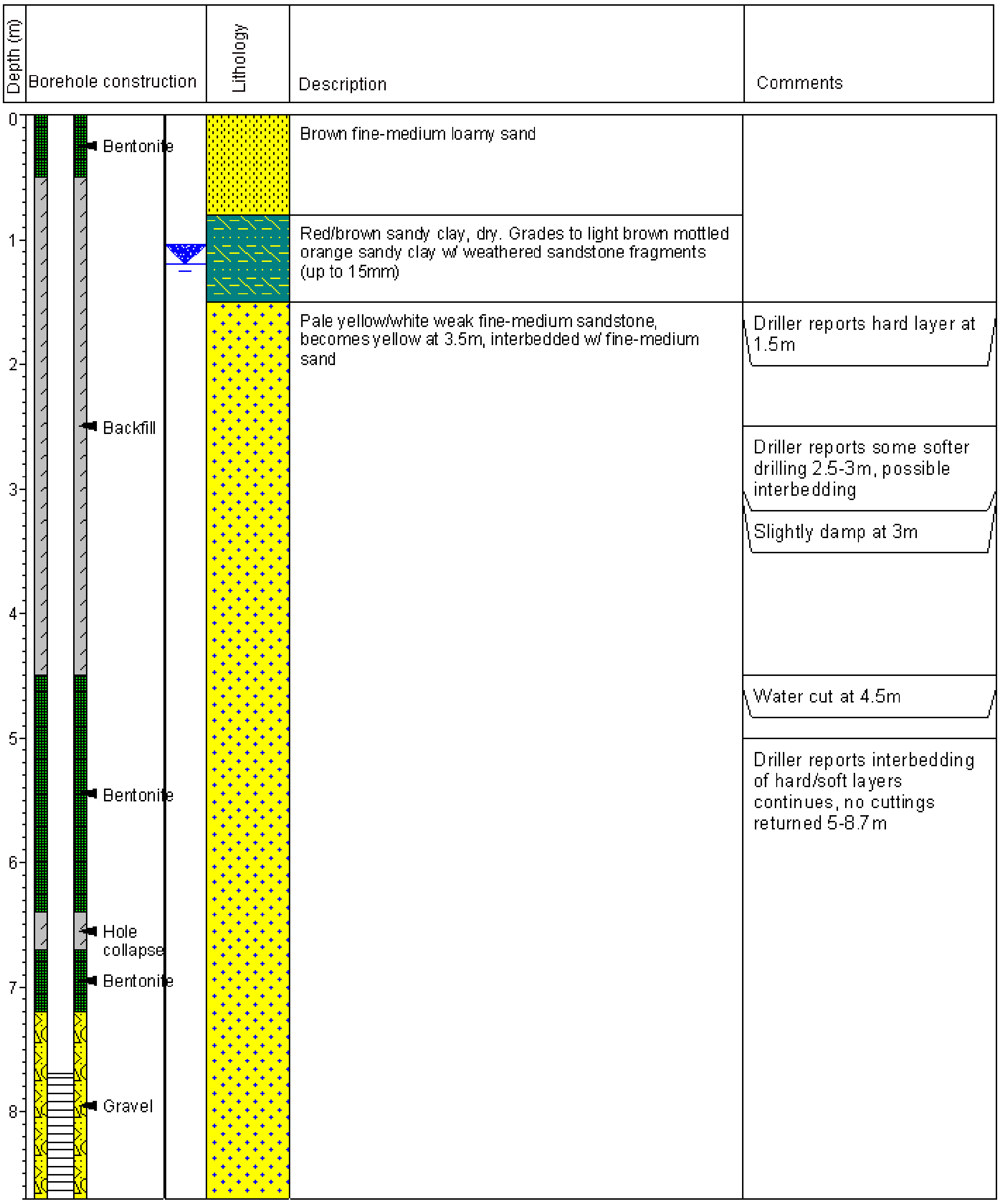

Casing/screen material: Class 18 PVC **Page:** 1 **of:** 1
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5 **Department of Water Land & Biodiversity Conservation**

South East National Water Initiative Project 1.1

Borehole ID: RS024A01_MW001
Date drilled: 05/03/07
Driller: Drilling Solutions
Logged by: CW & GM
Drilling method: Hollow augers
Bore diameter: 6"
Location: Coles
Easting: 455282
Northing: 5883482
Unit number: 6923-4529

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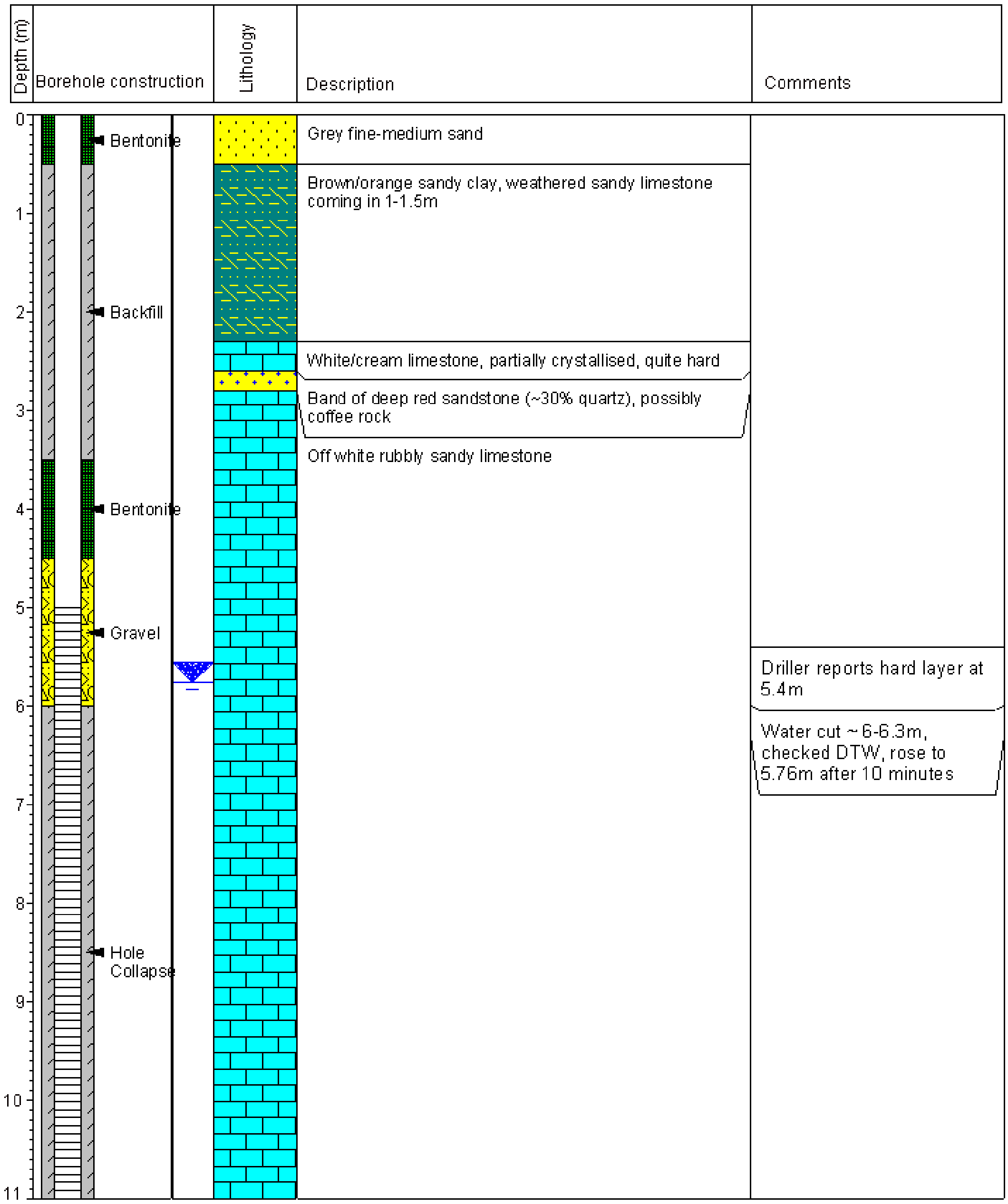

Casing/screen material: Class 18 PVC
Casing/screen diameter (mm): 50
Screen slot size (mm): 0.5

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Department of Water Land & Biodiversity Conservation

APPENDICES

C. GROUNDWATER CHEMISTRY AND RECHARGE RATE ESTIMATES

																					Chlorofluorcarbons			
Well details							Field parameters				Ionic concentrations (mg/L)										Concentration (pg/kg)		Apparent Age (y)	
Well_ID	E	N	Date sampled	Total Depth (m)	Screen interval (m)	DTW (m)	EC (uS/cm)	pH	Temp (C)	DO (mg/L)	TDS	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	HCO_3^-	SO_4^{2-}	NO_3^-	SiO_2	CFC 11	CFC 12	CFC 11	CFC 12
RS002A01_MW005	472665	5831330	29/02/2008	5.26 (BGL)	4.26 to 5.26 (BGL)	3.45 (BGL)	1481	7.69	13.3	6.59	904	227	<1	81	21	250	247	97	0.039	17.3	109	140	1969	1979
RS003A01_MW002	491990	5799209	04/04/2008	29.77 (BGL)	28.27 to 29.77 (BGL)	26.96 (BGL)	948	7.9	14		542	68	2	69	38	108	303	15	1.6	12	578	270	1990	1992
RS004A01_MW001	445692	5848192	21/02/2008	26.7 (BGL)	23.7 to 26.7 (BGL)	18.56 (BGL)	1213	7.05	14.4	1.72	892	104	3	105	26	165	378	46	1.29	25.8	32	24	<1965	<1965
RS006A01_MW004	485267	5794566	07/02/2008	10.85 (BGL)	9.85 to 10.85 (BGL)	8.18 (BGL)	896	7.73	14.6	6.6	638	68	4	114	10	102	220	32	10.6	7	422.5	190	1983	1984
RS007A01_MW003	483630	5822787	29/02/2008	5.17 (BGL)	4.17 to 5.17 (BGL)	4.37 (BGL)	337	7.72	15.4	0.85	340	40	2	52	7	91	60	29	2.1	5.2				
RS007A01_MW002	483630	5822787	15/04/2008	6.83 (BGL)	5.83 to 6.83 (BGL)	4.46 (BGL)	725	7.74	14.2												26	36	<1965	1965
RS008A01_MW002	435133	5846924	21/02/2008	4.45 (BGL)	3.45 to 4.45 (BGL)	2.72 (BGL)	4360	7.23	16	1.96	3020	517	17	268	131	899	466	620	<0.010	81.2	11	59	<1965	1965
RS009A01_MW003	441923	5864539	01/04/2008	2.68 (BGL)	1.68 to 2.68 (BGL)	1.87 (BGL)	1636	7.54	17.8	6.5	1090	175	4	88	40	324	285	35	7.79	13.1	384	260	1982	1992
RS010A01_MW002	496336	5893349	31/03/2008	18 (BGL)	17 to 18 (BGL)	16.76 (BGL)	3230	7.35	17.3	9.92	2050	538	10	67	52	688	550	107	7.97	28.3	234	155	1975	1981
RS011A01_MW002	433613	5861181	01/04/2008	6.41 (BGL)	5.41 to 6.41 (BGL)	2.59 (BGL)	1436	7.57	16.8	8.95	894	149	2	100	29	254	330	43	3.71	12.3	300	236	1979	1991
RS012A01_MW001	417555	5980125	26/03/2008	12.77 (BGL)	10 to 13 (BGL)	9.66 (BGL)	2710	7.92	17.5		1740	453	20	48	38	535	354	226	3.54	35.1	407	215	1984	1988
RS013A01_MW003	387442	6025105	26/03/2008	9.22 (BGL)	8.22 to 9.22 (BGL)	7.64 (BGL)	3140	8.32	16.3	7.92	1970	489	31	17	13	661	424	185	1.29	31.2	110	123	1969	1976
RS014A01_MW003	413599	5874802	19/03/2008	2.57 (BGL)	1.57 to 2.57 (BGL)	1.37 (BGL)	1309	7.44	17.7		904	114	4	108	22	206	245	50	16.9	12.2	160	158	1972	1980
RS015A01_MW003	382340	6035511	26/03/2008	8.3 (BGL)	7.3 to 8.3 (BGL)	6.77 (BGL)	7870	7.81	17.3	2.16	4960	1570	69	31	84	1540	1380	224	2.64	25.1	73	118	1967	1977
RS016A01_MW004	421400	5943760	27/03/2008	7.16 (BGL)	2.16 to 7.16 (BGL)	0.99 (BGL)	4210	7.44	17.4	2.4	2510	618	21	80	71	1050	192	150	2.69	14.8	194	160	1974	1982
RS017A01_MW001	487736	5952882	18/03/2008	24.33 (BGL)	22.33 to 24.33 (BGL)	22.14 (BGL)	1923	7.25	17.3	10.23	1210	208	7	139	41	389	430	41	0.433	21.8	108	113	1969	1975
RS018A01_MW001	454036	6024985	16/04/2008	31.62 (BGL)	26.6 to 32.6 (BGL)	28.83 (BGL)	1899	7.77	16.7	4.15	1730	244	9	71	46	417	214	60	0.289	26.7				
RS019A01_MW001	488946	5954225	18/03/2008	20.86 (BGL)	18.86 to 20.86 (BGL)	18.49 (BGL)	1945	7.04	17.1	11.62	1250	197	6	141	39	400	360	41	0.341	22.7	222	183	1974	1984
RS020A01_MW004	452376	5920591	08/04/2008	4.23 (BGL)	3.23 to 4.23 (BGL)	2.09 (BGL)	11970	7.4	19.1	6.85	7680	2230	59	89	227	3210	739	614	<0.010	27.7	27	32	<1965	1965
RS021A01_MW001	491371	5790118	07/02/2008	13.44 (TOC)	12.44 to 13.44 (TOC)	2.42 (TOC)	1666	7.19	14.5	1.68	1140	164	4	171	28	296	321	42	0.615	36.8	12.5	6	<1965	<1965
RS022A01 (CAR011)	495031	5788904	30/04/2008	146 (BGL)	Unknown	0.64 (TOC)	2208	7.6	13.9		1370	291	16	78	58	441	277	66	1.72	15.2				
RS023A01_MW002	421740	5943924	27/03/2008	16.42 (BGL)	15.42 to 16.42 (BGL)	15.2 (BGL)	3460	7.22	16.1	6.57	2130	496	16	84	60	832	385	109	3.94	15.4	349	213	1981	1988
RS023A02_MW002	421691	5943900	27/03/2008	12.29 (BGL)	11.29 to 12.29 (BGL)	11.34 (BGL)	3400	7.61	16.8	6.67	2140	501	16	87	61	827	398	111	4.19	14.9	350	208	1981	1987
RS023A03_MW002	421584	5943851	27/03/2008	5.93 (BGL)	4.93 to 5.93 (BGL)	4.13 (BGL)	2770	7.56	17.9	10.81	1720	374	11	89	47	618	339	93	9.67	15.1	384	231	1983	1990
RS024A01_MW002	455261	5883501	08/04/2008	6.86 (BGL)	5.86 to 6.86 (BGL)	5.85 (BGL)	1954	7.67	16.6		1200	222	4	103	37	425	304	40	<0.010	15.2	28	33	<1965	1965
RS001A01 (YOU032)	471297	5835790	23/04/2008	11.54 (TOC)	5 to 11 (BGL)	7.24 (BGL)	1368	6.87	16.3		810	164	1	113	19	179	407	36		18.6				
RS001A01 (RID010)	462498	5840732	24/04/2008	15.35 (TOC)	9.14 to 15.30 (TOC)	7.43 (TOC)	2410	6.7	14.7		1710	234	4	198	48	526	362	39		32.2				

BGL = Below ground level

Table 8. **Groundwater chemistry results from sampled piezometers at research sites**

Well_ID	E	N	Chloride Mass Balance Method					CFC method							
			Cl- in GW (mg/L)	Cl- in SW (mg/L)	Cl- in Precip (mg/L)	Precip (mm/y)	Recharge (mm/y)	CFC-12 (pg/kg)	Apparent Age (CFC-12)	Time (yrs)	Depth* (m)	Depth** (m)	Lower recharge ***(mm/y)	Upper recharge ****(mm/yr)	Avg R (CFC)
RS002A01_MW005	472665	5831330	250	66.3	11	765	127	140	1979	29	0.81	1.81	8	19	14
RS003A01_MW002	491990	5799209	Chloride mass balance not applicable					270	1992	16	1.31	2.81	25	53	39
RS004A01_MW001	445692	5848192	Chloride mass balance not applicable					24	<1965	43	5.14	8.14	36	57	46
RS006A01_MW004	485267	5794566	102		11	785	85	190	1984	24	1.67	2.67	21	33	27
RS007A01_MW003	483630	5822787	91	39	11	691	195								
RS007A01_MW002	483630	5822787						36	1965	43	1.37	2.37	10	17	13
RS008A01_MW002	435133	5846924	899		11	730	9	59	<1965	43	0.73	1.73	5	12	9
RS009A01_MW003	441923	5864539	324		11	691	23	260	1992	16	0	0.81	0	15	15
RS010A01_MW002	496336	5893349	Chloride mass balance not applicable					155	1981	27	0.24	1.24	3	14	8
RS011A01_MW002	433613	5861181	254		11	695	30	236	1991	17	2.82	3.82	50	67	59
RS012A01_MW001	417555	5980125	535		11	546	11	215	1988	20	0.34	3.34	5	50	28
RS013A01_MW003	387442	6025105	661		11	492	8	123	1976	32	0.58	1.58	5	15	10
RS013A02_SC002	387354	6025218		62	11	492	87								
RS013A03_SC001	377297	6017664		97	11	510	58								
RS014A01_MW003	413599	5874802	206		11	660	35	158	1980	28	0.2	1.2	2	13	8
RS015A01_MW003	382340	6035511	Chloride mass balance not applicable					118	1977	31	0.53	1.53	5	15	10
RS016A01_MW004	421400	5943760	1050		11	565	6	160	1982	26	1.17	6.17	14	71	42
RS017A01_MW001	487736	5952882	Chloride mass balance not applicable					113	1975	33	0.19	2.19	2	20	11
RS018A01_MW001	454036	6024985	438	1448	11	450	3								
RS019A01_MW001	488946	5954225	Recharge rate calculated from Chloride front displacement method				14	183	1984	24	0.37	2.37	5	30	17
RS020A01_MW004	452376	5920591	3210		11	537	2	32	1965	43	1.14	2.23	8	16	12
RS021A01_MW001	491371	5790118	296		11	795	30	6	<1965	43	9.58	10.58	67	74	70
RS023A01_MW002	421740	5943924	832		11	565	7	213	1988	20	0.22	1.22	3	18	11
RS023A02_MW002	421691	5943900	827		11	565	8	208	1987	21	0	0.95	0	14	7
RS023A03_MW002	421584	5943851	618		11	565	10	231	1990	18	0.8	1.8	13	30	22
RS024A01_MW002	455261	5883501	425		11	629	16	33	1965	43	0.01	1.01	0	7	4
RS001A01 (YOU032)	471352	5835726	179		11	782	48	343	1983	25	0	3.76	0	45	23
RS001A02 (RID010)	462498	5840730	526		11	828	17	79	1967	41	1.71	7.87	13	58	35
RS022A01 (CAR011)	495247	5788954	441		11	797	20	78	1967	41	CFC recharge rate not applicable (screen length not known)				

**** Depth of bottom of screen below watertable (m)**

***** Based on depth of top of screen**

****** Based on depth of bottom of screen**

Table 9. Recharge rates

D. SOIL CORE RESULTS

Sample ID	Depth (m-BGL)	Soil moisture content (g/g)	Soil water Cl- (mg/L)
RS013A02_SC002	1.0-1.4	0.030	155.32
RS013A02_SC002	1.5-2.0	0.032	152.12
RS013A02_SC002	2.0-2.5	0.049	61.22
RS013A02_SC002	2.5-3.0	0.045	75.78
RS013A02_SC002	3.0-3.5	0.035	86.89
RS013A02_SC002	3.5-4.0	0.034	68.95
RS013A02_SC002	4.0-4.5	0.032	70.98
RS013A02_SC002	4.5-5.0	0.034	60.46
RS013A02_SC002	5.0-5.5	0.035	54.58
RS013A02_SC002	5.5-6.0	0.037	60.25
RS013A02_SC002	6.0-6.5	0.040	50.98
RS013A02_SC002	6.5-7.0	0.026	77.73
RS013A02_SC002	7.0-7.5	0.023	72.84
RS013A02_SC002	7.75-8.0	0.022	73.68
RS013A02_SC002	8.20-8.5	0.025	70.05
RS013A02_SC002	8.6-9.0	0.025	84.16
RS013A02_SC002	9.2-9.5	0.025	83.64
RS013A02_SC002	9.6-10.0	0.021	79.17
RS013A02_SC002	10.0-10.5	0.030	66.70
RS013A02_SC002	10.7-11.0	0.031	56.82
RS013A02_SC002	11.0-11.3	0.031	70.07
RS013A02_SC002	11.6-12.0	0.077	44.01
RS013A02_SC002	12.2-12.5	0.048	56.33
RS013A02_SC002	12.6-13.0	0.057	42.88
RS013A02_SC002	13.3-13.5	0.044	51.55
RS013A02_SC002	13.6-14.0	0.055	39.29
RS013A02_SC002	14.2-14.5	0.038	43.10
RS013A02_SC002	14.6-15.0	0.073	33.24
RS013A02_SC002	15.2-15.5	0.073	35.52
RS013A02_SC002	15.6-16.0	0.086	36.49
RS013A02_SC002	16.3-16.5	0.178	34.39
RS015A01_MW003	1.2-1.3	0.111	555.69
RS015A01_MW003	1.4-1.5	0.168	464.03
RS015A01_MW003	1.6-1.8	0.113	515.49
RS015A01_MW003	1.9-2.0	0.088	787.01
RS015A01_MW003	2.4-2.5	0.050	450.54
RS015A01_MW003	2.6-2.7	0.021	201.74
RS015A01_MW003	2.9-3.0	0.037	99.26
RS015A01_MW003	3.2-3.3	0.042	67.61
RS015A01_MW003	3.4-3.5	0.062	63.10
RS015A01_MW003	3.9-4.0	0.064	62.86
RS015A01_MW003	4.3-4.5	0.060	77.90
RS015A01_MW003	4.6-4.7	0.065	152.63
RS015A01_MW003	4.9-5.0	0.074	461.52
RS015A01_MW003	5.3-5.5	0.076	1050.16
RS015A01_MW003	5.8-6.0	0.087	1605.95
RS015A01_MW003	6.3-6.5	0.170	1274.99
RS015A01_MW003	6.8-7.0	0.238	1116.14

RS017A01_MW002	1.30-1.50	0.032	260.56
RS017A01_MW002	1.80-2.10	0.057	230.83
RS017A01_MW002	2.30-2.50	0.130	96.38
RS017A01_MW002	2.50-3.00	0.322	42.88
RS017A01_MW002	3.10-3.50	0.146	64.23
RS017A01_MW002	3.80-4.00	0.159	63.41
RS017A01_MW002	4.30-4.50	0.125	102.83
RS017A01_MW002	4.80-5.00	0.120	115.15
RS017A01_MW002	5.20-5.50	0.134	123.27
RS017A01_MW002	5.80-6.00	0.138	158.48
RS017A01_MW002	6.30-6.50	0.183	354.08
RS017A01_MW002	6.70-7.00	0.319	429.06
RS017A01_MW002	7.30-7.50	0.213	415.73
RS017A01_MW002	7.80-8.00	0.210	491.58
RS017A01_MW002	8.30-8.50	0.185	659.91
RS017A01_MW002	8.80-9.00	0.158	941.98
RS017A01_MW002	9.30-9.50	0.241	1104.55
RS017A01_MW002	9.70-10.00	0.367	1255.86
RS017A01_MW001	1.30-1.50	0.020	827.74
RS017A01_MW001	1.80-2.00	0.054	247.69
RS017A01_MW001	2.30-2.40	0.070	227.12
RS017A01_MW001	2.40-2.70	0.174	79.29
RS017A01_MW001	2.70-3.00	0.201	51.41
RS017A01_MW001	3.80-4.00	0.151	61.75
RS017A01_MW001	4.30-4.50	0.119	74.96
RS017A01_MW001	4.50-5.30	0.124	104.83
RS017A01_MW001	5.30-5.80	0.136	117.80
RS017A01_MW001	5.80-6.30	0.140	274.85
RS017A01_MW001	6.30-6.50	0.112	693.29
RS017A01_MW001	6.70-7.30	0.280	705.12
RS017A01_MW001	7.30-7.60	0.229	889.51
RS017A01_MW001	7.70-8.00	0.263	1133.46
RS017A01_MW001	8.40-8.80	0.144	1178.42
RS017A01_MW001	9.30-9.60	0.205	1334.12
RS017A01_MW001	9.80-10.50	0.140	2150.67
RS017A01_MW001	10.80-12.00	0.194	2408.50
RS017A01_MW001	12.30-12.50	0.145	2502.59
RS017A01_MW001	12.50-12.70	0.339	1643.60
RS017A01_MW001	12.70-13.00	0.346	2017.79
RS017A01_MW001	13.30-13.50	0.352	1984.61
RS017A01_MW001	13.70-14.50	0.172	2255.16
RS017A01_MW001	14.60-14.90	0.179	2220.59
RS019A01_MW001	1.30-1.50	0.074	2283.52
RS019A01_MW001	1.70-2.00	0.123	2455.47
RS019A01_MW001	2.30-2.50	0.073	2485.42
RS019A01_MW001	2.80-3.30	0.080	2628.74
RS019A01_MW001	3.30-3.50	0.061	3030.42
RS019A01_MW001	3.70-4.00	0.085	2899.44
RS019A01_MW001	4.10-4.30	0.066	3725.91
RS019A01_MW001	4.30-4.50	0.069	3688.52
RS019A01_MW001	4.80-5.00	0.069	3663.10
RS019A01_MW001	5.10-5.30	0.078	3926.86
RS019A01_MW001	5.30-6.00	0.370	2952.32

RS019A01_MW001	6.30-6.50	0.083	3818.18
RS019A01_MW001	6.70-7.00	0.118	4106.77
RS019A01_MW001	7.30-7.50	0.076	3927.91
RS019A01_MW001	7.80-8.10	0.083	4140.27
RS019A01_MW001	8.30-8.50	0.114	3456.92
RS019A01_MW001	8.70-9.00	0.111	4705.88
RS019A01_MW001	9.30-9.50	0.094	4087.68
RS019A01_MW001	9.70-9.80	0.093	4897.01
RS019A01_MW001	10.30-10.50	0.099	5176.56
RS019A01_MW001	10.70-11.00	0.088	3680.56
RS019A01_MW001	11.30-11.50	0.095	4368.45
RS019A01_MW001	11.80-12.50	0.139	5459.04
RS019A01_MW001	13.30-13.50	0.247	5402.00
RS019A01_MW001	13.70-14.00	0.473	5517.70
RS019A01_MW001	14.30-14.50	0.514	5682.28
RS019A01_MW001	14.60-14.70	0.386	5678.30
RS019A01_MW001	14.70-15.00	0.596	4542.18
RS019A01_MW001	15.30-15.50	0.620	6216.93
RS019A01_MW001	15.70-16.00	0.564	3977.04
RS019A01_MW001	16.30-17.00	0.157	4985.59
RS019A01_MW001	17.30-17.50	0.198	4672.60
RS019A01_MW001	17.80-18.00	0.160	5682.97
RS019A01_MW001	18.10-18.30	0.175	2518.84
RS019A01_MW001	18.30-18.40	0.266	1371.27
RS019A01_MW002	1.30-1.50	0.070	3054.99
RS019A01_MW002	1.70-2.00	0.096	2402.99
RS019A01_MW002	2.10-2.20	0.087	2141.32
RS019A01_MW002	2.30-2.50	0.070	2383.95
RS019A01_MW002	2.70-3.00	0.121	2535.77
RS019A01_MW002	3.30-3.70	0.107	3455.28
RS019A01_MW002	3.70-4.00	0.075	2610.04
RS019A01_MW002	4.30-4.50	0.062	3102.81
RS019A01_MW002	4.70-5.00	0.081	3276.17
RS019A01_MW002	5.30-5.50	0.080	3532.38
RS019A01_MW002	5.70-6.00	0.133	3875.84
RS019A01_MW002	6.30-6.50	0.103	3724.14
RS019A01_MW002	6.70-7.00	0.102	3949.34
RS019A01_MW002	7.40-7.50	0.095	3770.00
RS019A01_MW002	7.70-8.00	0.072	4218.65
RS019A01_MW002	8.40-8.50	0.079	4286.14
RS010A01_MW001	1.10-1.20	0.286	94.9
RS010A01_MW001	1.30-1.50	0.301	168.4
RS010A01_MW001	1.50-1.70	0.288	60.4
RS010A01_MW001	1.8-2.0	0.278	43.1
RS010A01_MW001	2.10-2.30	0.239	43.3
RS010A01_MW001	2.3-2.5	0.208	43.9
RS010A01_MW001	2.70-3.00	0.196	36.9
RS010A01_MW001	3.00-3.20	0.175	42.7
RS010A01_MW001	3.30-3.50	0.205	38.8
RS010A01_MW001	3.80-4.00	0.221	44.2
RS010A01_MW001	4.30-4.50	0.259	54.2
RS010A01_MW001	4.50-4.70	0.244	81.6
RS010A01_MW001	4.80-5.00	0.208	114.5

RS010A01_MW001	5.30-5.50	0.192	193.0
RS010A01_MW001	5.80-6.20	0.176	293.8
RS010A01_MW001	6.30-6.50	0.220	387.5
RS010A01_MW001	6.80-7.00	0.194	452.0
RS010A01_MW001	7.40-8.00	0.248	864.7
RS010A01_MW001	8.40-8.90	0.255	1116.1
RS003A01_MW001	1.20-1.30	0.059	323.1
RS003A01_MW001	1.40-1.50	0.060	276.8
RS003A01_MW001	1.60-1.70	0.059	678.3
RS003A01_MW001	1.80-2.00	0.081	1219.7
RS003A01_MW001	2.20-2.40	0.172	2481.2
RS003A01_MW001	2.40-2.50	0.098	2509.9
RS003A01_MW001	2.60-2.70	0.030	1839.7
RS003A01_MW001	2.9-3.0	0.066	2078.6
RS003A01_MW001	3.40-3.50	0.024	1388.7
RS003A01_MW001	3.80-4.00	0.054	1189.9
RS003A01_MW001	4.10-4.30	0.032	1278.5
RS003A01_MW001	5.30-5.50	0.018	458.5
RS003A01_MW001	5.60-5.70	0.020	464.0
RS003A01_MW001	5.80-5.90	0.022	171.0
RS003A01_MW001	6.30-6.40	0.039	79.3
RS003A01_MW001	6.70-6.80	0.034	87.3
RS003A01_MW001	7.70-7.90	0.032	109.0
RS003A01_MW001	8.40-8.50	0.087	50.7
RS003A01_MW001	8.60-8.70	0.210	39.5
RS003A01_MW001	8.80-9.00	0.190	37.1
RS003A01_MW001	9.10-9.20	0.198	41.3
RS003A01_MW001	9.3-9.5	0.183	51.3
RS003A01_MW001	10.20-10.40	0.159	45.7
RS003A01_MW001	10.60-10.80	0.058	70.6
RS003A01_MW001	11.50-11.60	0.060	85.7
RS003A01_MW001	11.50-11.60	0.077	81.0
RS002A01_MW001	1.20-1.40	0.276	82.7
RS002A01_MW001	1.90-2.00	0.289	58.4
RS002A01_MW001	2.40-2.50	0.356	48.8
RS002A01_MW001	2.90-3.00	0.274	63.8
RS002A01_MW001	3.30-3.50	0.263	94.2
RS007A01_MW001	1.10-1.20	0.070	45.2
RS007A01_MW001	1.25-1.50	0.047	37.3
RS007A01_MW001	1.60-1.70	0.047	40.8
RS007A01_MW001	1.80-2.00	0.060	33.1
RS007A01_MW001	2.10-2.20	0.060	35.1
RS007A01_MW001	2.30-2.40	0.056	43.7
RS007A01_MW001	2.60-2.70	0.164	31.1
RS007A01_MW001	2.80-2.90	0.264	30.5
RS007A01_MW001	3.20-3.30	0.193	37.2
RS007A01_MW001	3.40-3.50	0.198	39.6
RS007A01_MW001	3.60-3.80	0.222	43.1
RS007A01_MW001	3.90-4.00	0.532	39.9
RS007A01_MW001	4.10-4.20	0.269	41.1
RS007A01_MW001	4.20-4.40	0.334	33.2
RS013A03_SC001	0.4-0.5	0.055	99.19
RS013A03_SC001	0.9-1.0	0.050	129.28

RS013A03_SC001	1.4-1.5	0.055	83.88
RS013A03_SC001	1.9-2.0	0.068	85.85
RS013A03_SC001	2.4-2.5	0.132	124.24
RS013A03_SC001	2.9-3.0	0.042	96.15
RS013A03_SC001	3.35-3.5	0.050	83.91
RS013A03_SC001	3.85-4.0	0.046	89.15
RS013A03_SC001	4.3-4.5	0.047	81.43
RS013A03_SC001	4.85-5.0	0.210	109.31
RS018A01_MW001	1.20-1.50	0.033	656.2
RS018A01_MW001	1.60-2.00	0.026	835.1
RS018A01_MW001	2.20-2.50	0.016	1155.4
RS018A01_MW001	2.70-3.00	0.019	1162.5
RS018A01_MW001	3.20-3.50	0.012	1389.8
RS018A01_MW001	3.70-4.00	0.012	1166.0
RS018A01_MW001	4.20-4.50	0.007	1135.8
RS018A01_MW001	4.50-4.75	0.107	1025.9
RS018A01_MW001	4.75-5.00	0.198	1097.5
RS018A01_MW001	5.20-5.50	0.143	1461.0
RS018A01_MW001	5.50-5.70	0.144	1433.7
RS018A01_MW001	5.80-6.00	0.329	1337.8
RS018A01_MW001	6.70-7.00	0.275	1474.2
RS018A01_MW001	7.30-7.50	0.180	1628.7
RS018A01_MW001	8.30-8.50	0.193	1429.1
RS018A01_MW001	8.70-9.00	0.346	1377.4
RS018A01_MW001	9.30-9.50	0.334	1403.4
RS018A01_MW001	9.70-10.00	0.302	1374.0
RS018A01_MW001	10.30-10.50	0.443	1450.3
RS018A01_MW001	10.70-11.00	0.243	1536.0
RS018A01_MW001	11.30-11.50	0.244	1421.1
RS018A01_MW001	11.70-12.00	0.097	1662.0
RS018A01_MW001	12.30-12.50	0.077	1740.4
RS018A01_MW001	12.70-13.00	0.083	1780.8
RS018A01_MW001	13.30-13.50	0.075	1965.8
RS018A01_MW001	15.30-15.50	0.062	1574.2
RS012A01_MW001	1.20-1.50	0.055	191.8
RS012A01_MW001	1.70-2.00	0.068	79.7
RS012A01_MW001	2.20-2.50	0.081	58.7
RS012A01_MW001	2.70-3.00	0.079	51.2
RS012A01_MW001	3.20-3.50	0.074	61.2
RS012A01_MW001	3.70-4.00	0.077	43.2
RS012A01_MW001	4.20-4.50	0.097	44.5
RS012A01_MW001	4.70-5.00	0.094	45.9
RS012A01_MW001	5.30-5.50	0.105	55.1
RS012A01_MW001	5.70-6.00	0.097	49.8
RS012A01_MW001	6.30-6.50	0.096	43.2
RS012A01_MW001	6.60-6.80	0.098	63.8
RS012A01_MW001	6.80-7.00	0.070	67.7
RS012A01_MW001	7.20-7.40	0.100	58.1
RS012A01_MW001	7.40-7.50	0.164	59.3
RS012A01_MW001	7.80-8.00	0.119	81.4
RS012A01_MW001	8.20-8.40	0.080	65.6
RS012A01_MW001	8.70-9.00	0.154	64.4
RS012A01_MW001	9.40-9.80	0.207	71.7

RS024A01_MW001	1.30-1.50	0.281	261.3
RS024A01_MW001	1.80-2.00	0.171	289.9
RS024A01_MW001	2.30-2.50	0.148	391.3
RS024A01_MW001	2.80-3.00	0.044	410.5
RS024A01_MW001	3.30-4.00	0.051	108.9
RS024A01_MW001	4.30-4.50	0.066	104.6
RS024A01_MW001	4.70-5.00	0.070	176.7
RS024A01_MW001	5.30-5.50	0.121	418.6

Table 10. Soil water chloride and soil moisture content results for all soil cores collected

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

Shortened forms

~	approximately equal to
bgs	below ground surface
EC	electrical conductivity (µS/cm)
K	hydraulic conductivity (m/d)
pH	acidity
pMC	percent of modern carbon
ppb	parts per billion
ppm	parts per million
ppt	parts per trillion
w/v	weight in volume
w/w	weight in weight

GLOSSARY

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

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

Artesian — Under pressure such that when wells penetrate the aquifer water will rise to the ground surface without the need for pumping.

BoM — Bureau of Metrology, Australia.

Bore — *See well.*

^{14}C — Carbon-14 isotope (percent modern Carbon; pmC).

CFC — Chlorofluorocarbon; the unit is parts per trillion *(*ppt)

CMB — Chloride mass balance.

δD — Hydrogen isotope composition ($^{o}/_{oo}$).

DES — Drillhole Enquiry System. A database of groundwater wells in South Australia, compiled by DWLBC.

DO — Dissolved Oxygen.

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

EC — Electrical conductivity**.** 1 EC unit = 1 micro-Siemen per centimetre (µS/cm) measured at 25°C. Commonly used to indicate the salinity of water.

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

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

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

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

Groundwater — *See underground water.*

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

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

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

δ^{18}O — Oxygen isotope composition ($^{o}/_{oo}$).

Obswell — Observation Well Network.

Pasture — Grassland used for the production of grazing animals such as sheep and cattle.

PWA — Prescribed Wells Area.

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.)*

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

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

TDS —Total Dissolved Solids; the unit is milligrams per litre (mg/L).

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

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

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.

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