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Vertical groundwater recharge to the Tertiary confined sand aquifer, South East, South Australia

Keith Brown, Andrew Love and Glenn Harrington

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Groundwater Assessment
Resource Assessment Division

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Report DWR 2001/002

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of South Australia

Department for
Water Resources

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Cover photo — aerial view of Blue Lake, Mount Gambier (PIRSA photo 045174).

FOREWORD

South Australia’s water resources are fundamental to the economic and social wellbeing of the State. Water resources are an integral part of our natural resources. In pristine or undeveloped situations, the condition of water resources reflects the equilibrium between rainfall, vegetation and other physical parameters. Development of surface and groundwater resources changes the natural balance and causes degradation. If degradation is small, and the resource retains its utility, the community may assess these changes as being acceptable. However, significant stress will impact on the ability of a resource to continue to meet the needs of users and the environment. Degradation may also be very gradual and take some years to become apparent, imparting a false sense of security.

Management of water resources requires a sound understanding of key factors such as physical extent (quantity), quality, availability, and constraints to development. The role of the Resource Assessment Division of the Department for Water Resources is to maintain an effective knowledge base on the State’s water resources, including environmental and other factors likely to influence sustainable use and development, and to provide timely and relevant management advice.

Bryan Harris
Director, Resource Assessment Division
Department for Water Resources

ABBREVIATIONS

General

^{14}C	carbon isotope
AHD	Australian height datum
Br	bromide
Ca	calcium
CFC	chlorofluorocarbon
CFC-11	$CFCl_3$
CFC-12	CF_2Cl_2
d	day
Ec	electrical conductivity
Eh	redox potential
HCO_3	bicarbonate
K	potassium
Log K	transmissivity
Mg	magnesium
MGA	map grid of Australia
Na	sodium
PDP	Pee Dee Belemnite
pH	measure of acidity
pmc	percent modern carbon
RSWL	reduced standing water level
S	sulphur
SMOW	standard mean ocean water
TDS	total dissolved solids
TLA	(unconfined) Tertiary limestone aquifer
TCSA	Tertiary confined sand aquifer

Measurement

Most units of measurement used in this volume are those of the International System of Units (SI) and are not included in this glossary. Units outside the SI which have been authorised for use within Australia’s metric system, and units having general application are given.

‰	parts per mil (per thousand)
°C	degree Celcius (the Celcius temperature)
Bq	becquerel (activity (radioactive))
pptv	parts per trillion volume

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Vertical groundwater recharge to the Tertiary confined sand aquifer, South East, South Australia

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ABSTRACT

Groundwater in the South East region of South Australia flows mainly through two major aquifer systems; a regionally unconfined aquifer and an underlying confined aquifer. The two aquifers are separated by a low-permeability confining bed (or aquitard). Determining the degree of hydraulic connectivity between the two major flow systems, and the mechanisms that control groundwater flow through the aquitard, are important in the assessment of the water resource of both aquifer systems, and ultimately in maintaining these resources at a sustainable level.

This report details the results of a study into vertical groundwater recharge in a known recharge area to the confined aquifer. At two sites, a series of multi-piezometer wells were constructed; the first site was located about 10 km east of Nangwarry (referred to here on as the Nangwarry site), the other about 5 km east of Tarpeena (referred to here on as the Tarpeena site). At each site a profile of groundwater flow between the aquifers was created using hydrochemical, isotopic and hydraulic information. A conceptualised model of recharge to the confined aquifer was generated using these results in conjunction with regional data.

It is inferred from carbon-14 and chlorofluorocarbon data, that recharge to the aquifer at the Nangwarry and Tarpeena sites is occurring via preferential flow (fractures, faults or sinkholes), rather than via porous media flow through the regional aquitard. Expansion of softwood, and more recently hardwood, forestry plantations may significantly impact on vertical recharge to the confined aquifer of these sites. Regional mapping of carbon-14 suggests that the recharge to the confined aquifer may occur in relatively small, localised areas, possibly controlled by preferential flow.

INTRODUCTION

In the South East region of South Australia groundwater is the main source of water. With the exception of the Glenelg River, there are no extensive supplies of good quality surface flow. Groundwater is primarily used for irrigation, but is also used for industrial and stock use and for supplying municipal water to a number of towns located in the area. Groundwater flows through two major systems, an upper unconfined aquifer and a deeper confined aquifer.

Critical to the management of a water resource is a sound understanding of the mechanisms involved, and the rate at which the groundwater system receives recharge. If an aquifer is to be maintained at a sustainable level there should be a balance between output (natural discharge and extraction) and input (recharge). The confined aquifer may be approaching or exceeding this limit. Well hydrographs in the main artesian area exhibit seasonal changes in head in excess of 14 m. More importantly, there has been a long-term decline in potentiometric head in this area, reflecting the sensitivity of a confined aquifer system to external stresses such as extraction. A decline in the potentiometric head in both the confined aquifer and the overlying unconfined aquifer in non-irrigation areas since the end of 1992 is of particular concern. While the is most likely associated with a period of below-average annual rainfall, the possibility exists that forestry expansion may also be contributing to a reduction in vertical recharge to the confined aquifer.

Much of the groundwater in the confined aquifer has an age in excess of 25 000 years (Love et al., 1993) and is in pristine condition (<700 mg/L of total dissolved solids (TDS)). Previous recharge estimation studies in the South East have tended to focus on the overlying unconfined aquifer (Holmes and Colville, 1970a, b; Colville and Holmes, 1972; Allison and Hughes, 1978; Leaney and Herczeg, 1995). Very little work has been undertaken into estimating recharge to a confined aquifer overlain by an aquitard. The exceptions being solute modelling undertaken by Love et al., (1993, 1994, 1995) and a compartmental mixing-cell model by Harrington et al. (1999).

Objectives

The main objectives were to:

- examine the hydraulic relationship between the two aquifer systems and the aquitard
- estimate recharge rates to the confined aquifer
- determine the spatial extent of confined aquifer recharge areas.

At two sites, nests of wells were drilled and completed at various intervals through the unconfined aquifer, aquitard, and confined aquifer. Hydraulic measurements, isotopic and hydrochemical data, including carbon–14 (^{14}C), chlorofluorocarbon (CFC), δ^2H, δ^{18}O and major ion chemistry, were used to construct a conceptual model of vertical recharge processes to the confined aquifer.

Recharge areas to the confined aquifer were broadly defined. Potential for vertical recharge to the aquifer exists at any point where the unconfined head is higher than the confined head, i.e. where the vertical head gradient is downwards. This downward head gradient occurs over a substantial part of the eastern portion of the South East. However, results from previous work by Love et al. (1993) suggest that, in this eastern portion, there were only a few areas where groundwater in the confined aquifer contained relatively modern radiocarbon activities. If it is assumed the presence of modern radiocarbon reflects modern recharge, this would mean the recharge area is much smaller than the vertical head gradient data would indicate. This has serious implications for determining the water budget of the resource. One of these perceived recharge areas is undergoing forestry expansion. To map potential recharge areas for the confined aquifer, additional ^{14}C sampling was carried out, and synthesised with existing data.

Background

HYDROGEOLOGY

Geologically, the study area encompasses most of the Gambier Embayment of the Otway Basin. Basement highs outcrop in the northwest and southeast of the study area. In the northwest, the basement high is the Padthaway Ridge, and in the east, it is the Dundas Plateau. Both of these basement highs consist of early Palaeozoic igneous rock and metasediments that are considered to act as hydraulic basement (Fig. 1).

Groundwater flows through two major aquifer systems, an upper unconfined Tertiary limestone aquifer (TLA), and a deeper Tertiary confined sand aquifer (TCSA). The two aquifers are separated by the lower Tertiary confining bed which consists mainly of low-permeability marls and black carbonaceous clays, including the upper carbonaceous clay unit of the confined aquifer (Fig. 2).

The regionally extensive unconfined aquifer consists mainly of calcareous sandstone and limestone deposited from the latter part of the Tertiary through to the Quaternary, and incorporates the Gambier Limestone, Bridgewater, and Padthaway Formations. The confined aquifer consists of non-calcareous quartz sands, interbedded with dark-brown carbonaceous clays. Together these units make up the Dilwyn Formation and were deposited during the early part of the Tertiary.

The confined aquifer is a multi-aquifer groundwater system, but for management purposes, is treated regionally as one aquifer. Lack of data means there is little real understanding of the hydraulic interconnection between these subaquifers. Most wells only penetrate into the uppermost sand unit of the aquifer for economic reasons, but a number of deeper petroleum wells provide valuable stratigraphic information.

Lateral flow, for both the unconfined and confined aquifer systems, is from the topographic high of the Dundas Plateau. From there, the groundwater flows radially westward and southward to the coast, and northwards to the Murray River. The potentiometric surface of the confined aquifer is shown in Figure 3. The velocity that groundwater flows through each aquifer varies depending on local hydrogeological characteristics. Higher rates of groundwater flow are most evident in the unconfined aquifer where a secondary porosity has developed.

There are only a few areas where the confined aquifer is exposed at the surface. Vertical recharge to the aquifer is therefore generally via downward leakage from the overlying unconfined aquifer. The downward head gradient allows for the potential for recharge to the confined aquifer in the eastern portion of the study area. In the west and south of the study area however, the head gradient is reversed and hence

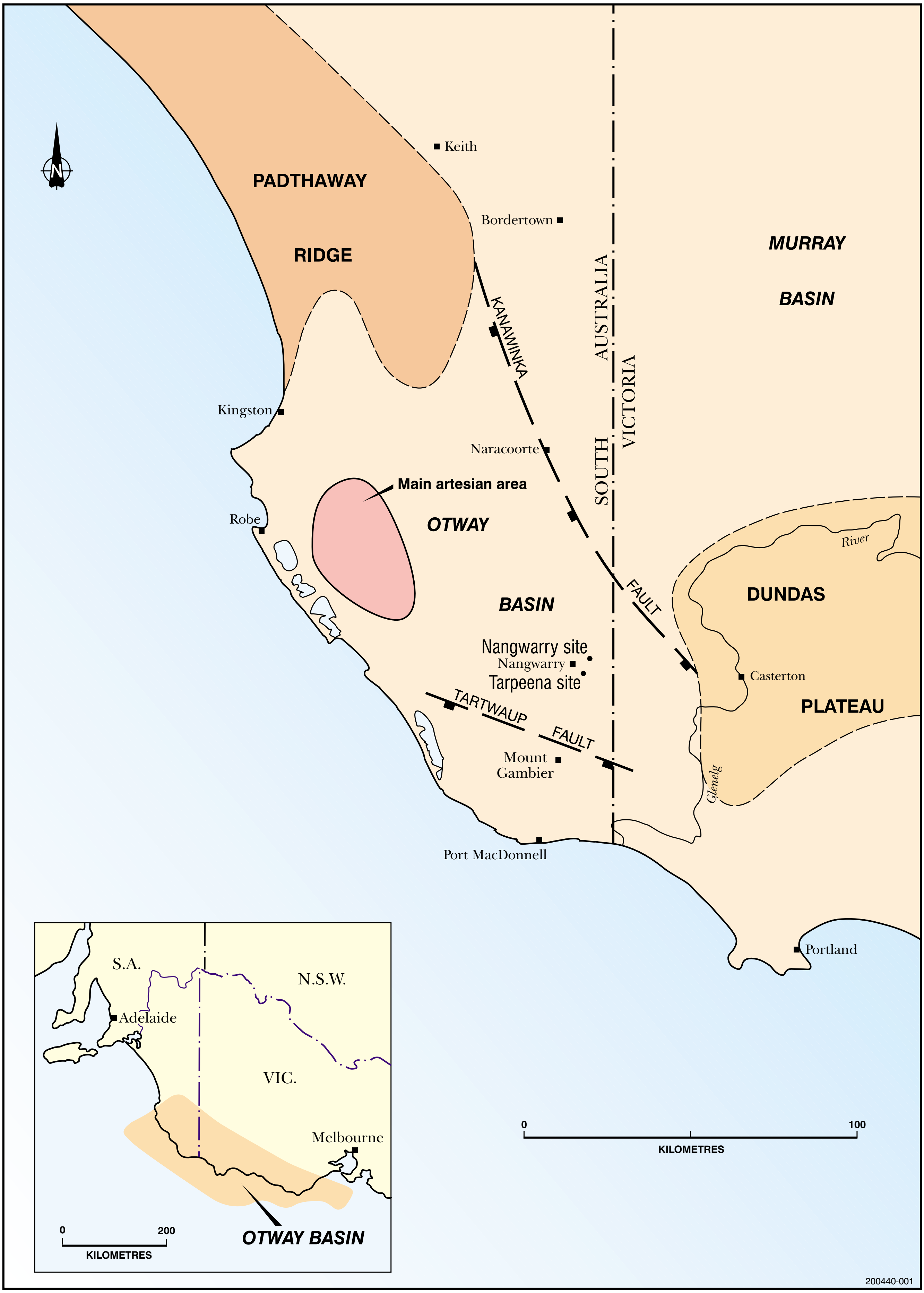
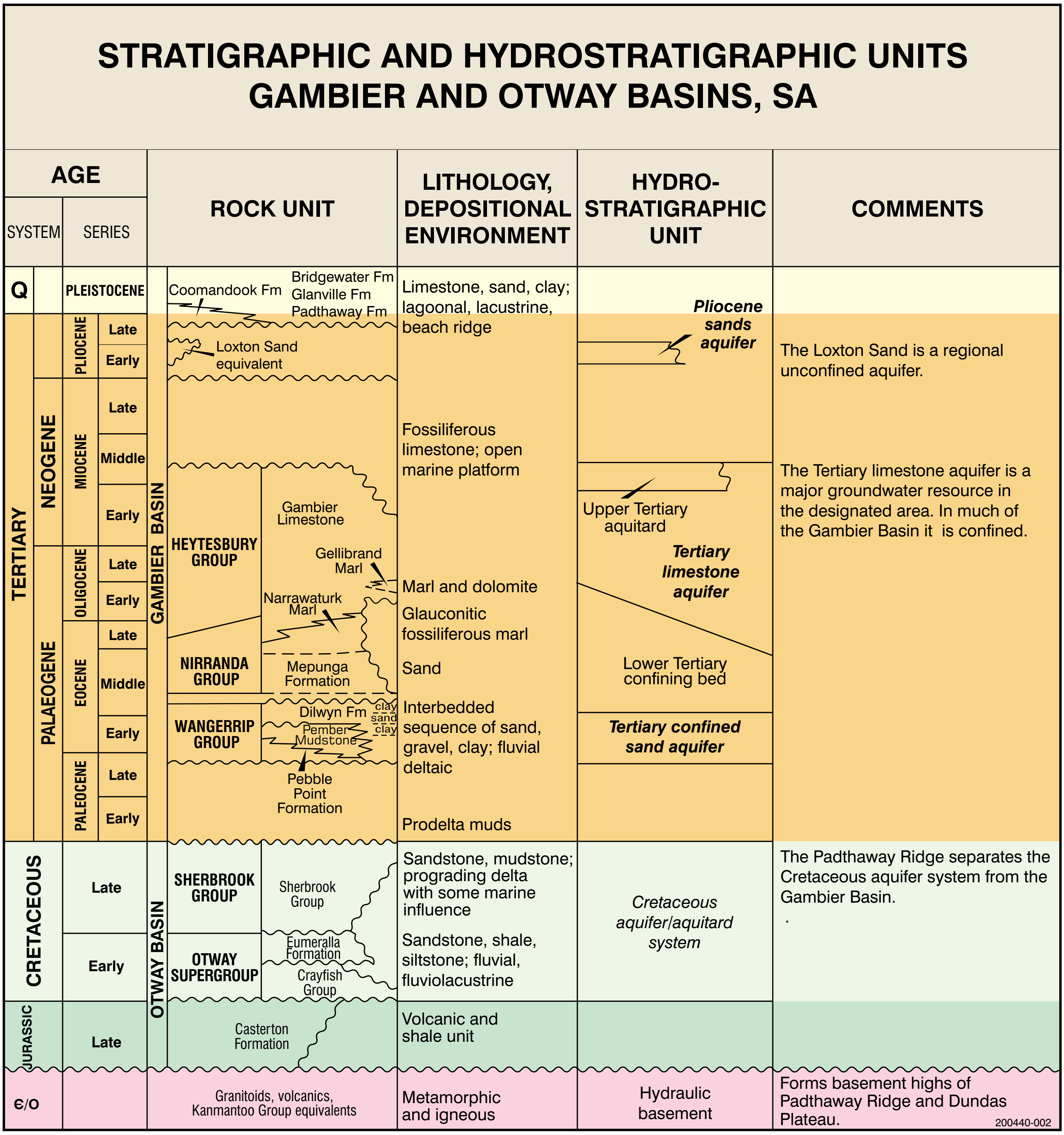


Figure 1 Geological provinces of the South East showing the location of study sites.



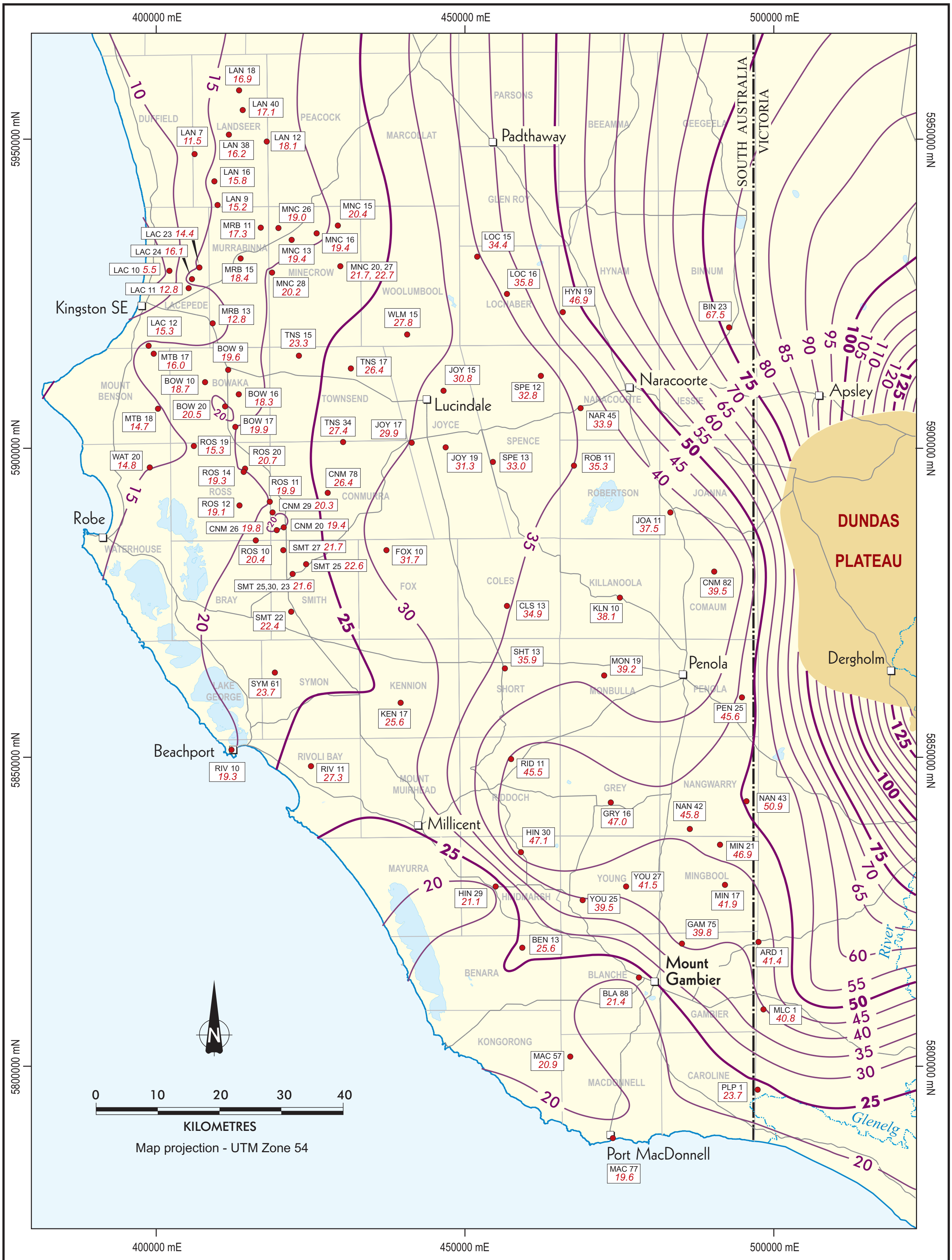
The Loxton Sand is a regional unconfined aquifer.

The Tertiary limestone aquifer is a major groundwater resource in the designated area. In much of the Gambier Basin it is confined.

The Padthaway Ridge separates the Cretaceous aquifer system from the Gambier Basin.

Forms basement highs of Padthaway Ridge and Dundas Plateau.

Figure 2



Observation well number and potentiometric level (m - AHD) ● BEN 13 25.6

Potentiometric surface contour (m - AHD) 35

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POTENTIOMETRIC SURFACE OF CONFINED AQUIFER September 1997

GeoTech Graphics 381-1639

Figure 3

there is the potential for discharge from the confined aquifer into the unconfined aquifer. The point where the heads in each aquifer are equal is commonly termed the zero head difference. In Figure 4, a schematic cross-section of the head distribution is presented.

There are a number of major faults in the area. The two most prominent are the northwest trending Kanawinka Fault and the west–northwest trending Tartwaup Fault (Fig. 1). The potentiometric surface of both aquifers indicate a significant steepening of slope immediately up-gradient of each fault. While the effect faulting has had on groundwater flow can be inferred from the head gradients from both aquifers, the mechanisms responsible for this effect are poorly understood.

Spatially the salinity of groundwater in the unconfined aquifer varies considerably. This variation is considered to be a result of localised recharge distribution, land use, soil type and time since the clearing of native vegetation. Rising salinity trends are evident in intensely irrigated areas, such as Padthaway, where irrigation activity has resulted in recycling of the slow moving groundwater. Increasing salinity trends are also evident in non-irrigation areas, and is a result of land clearance by early European settlers which allowed substantially higher rainfall recharge volumes to access the aquifer. This in-turn has remobilised salts stored in the soil profile and unsaturated zone which have subsequently percolated down into the aquifer.

While most of the groundwater in the confined aquifer has a low salinity (<700 mg/L TDS), there are areas where the salinity is >1500 mg/L TDS. Love et al. (1994) used modelled groundwater ^{14}C ages and the stable hydrogen and oxygen isotopes $^{2}H/^{1}H$ and $^{18}O/^{16}O$, to infer that most of the low-salinity groundwater was probably recharged during the last glacial period. During this period, the effect of lowering mean sea level by ~120 m would have moved the zero head difference ~50 km east of its present position; no vertical recharge could occur in this area at that time as the head in the confined aquifer is higher than the unconfined aquifer west of the zero head difference. At the end of the last glacial period mean sea level rose and the zero head difference moved to its current position thereby allowing vertical recharge to the confined aquifer.

CLIMATE

The climate of the South East varies from hot, dry summers to cool, wet winters. Annual rainfall ranges from >800 mm in the south to about 450 mm in the north. Potential evaporation increases from about 1400 mm in the south to about 1800 mm in the north. Figure 5 presents the cumulative deviation of annual rainfall from the mean annual rainfall at the Tarpeena (Pleasant Park) rain gauge station. The pattern of rainfall reflected in the graph is typical of data from rain gauge stations located throughout the South East, all of which show a decline in total annual rainfall since the end of 1992. The location of the Tarpeena rain gauge station is shown in Figure 6.

EXTRACTION AND BORE HYDROGRAPHS

Total groundwater extraction from the confined aquifer for irrigation use during the 1996–97 season was estimated to be ~22 500 ML/yr (data source: Department for Environment, Heritage and Aboriginal Affairs, 1998); groundwater is allocated on crop type and area and does not include irrigation losses. Total use including irrigation losses, town water supplies and losses to the unconfined aquifer from

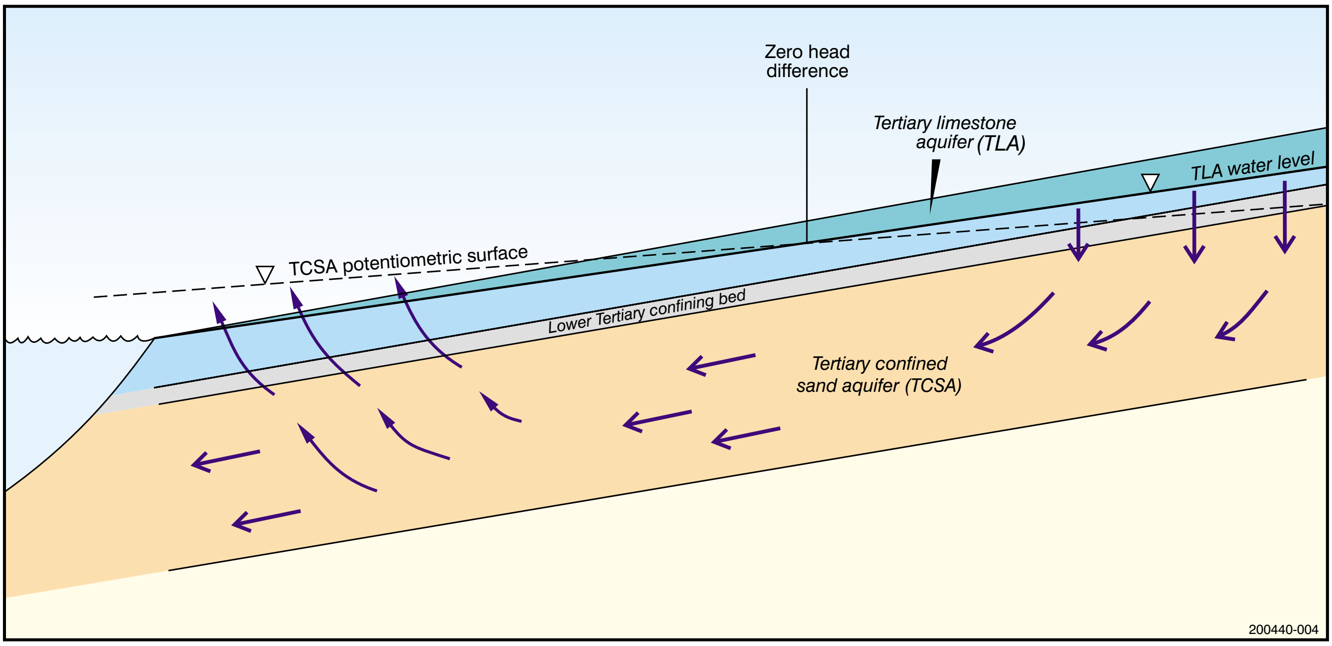


Figure 4 Schematic cross-section of groundwater flow in the South East.

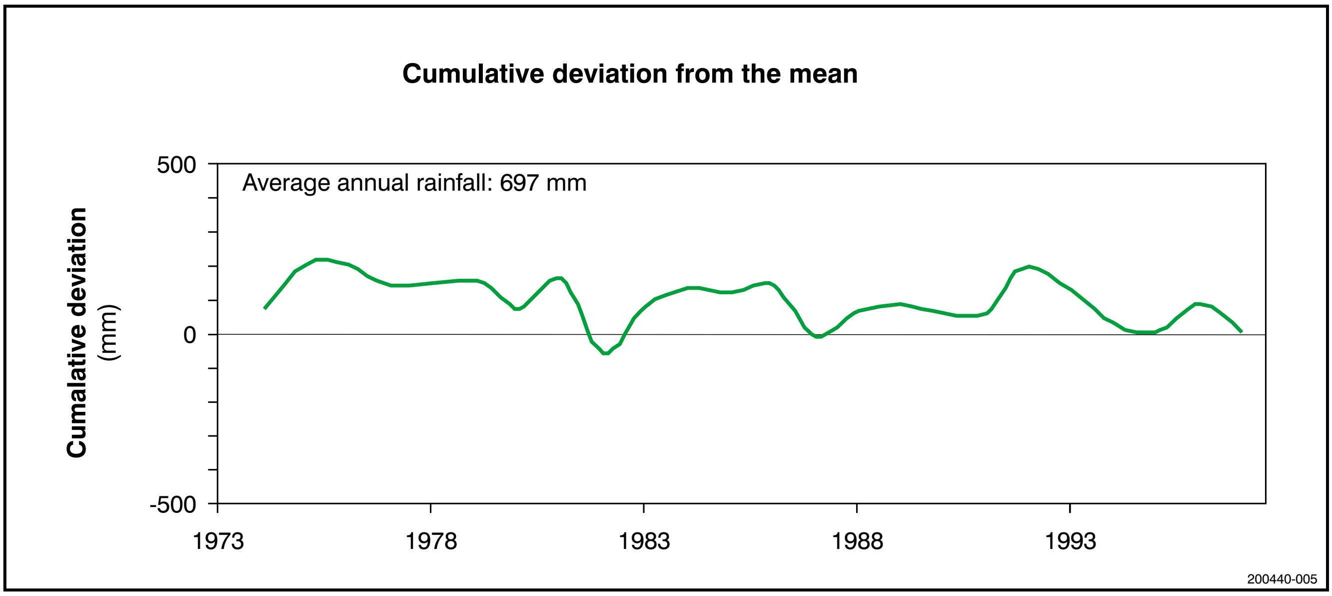
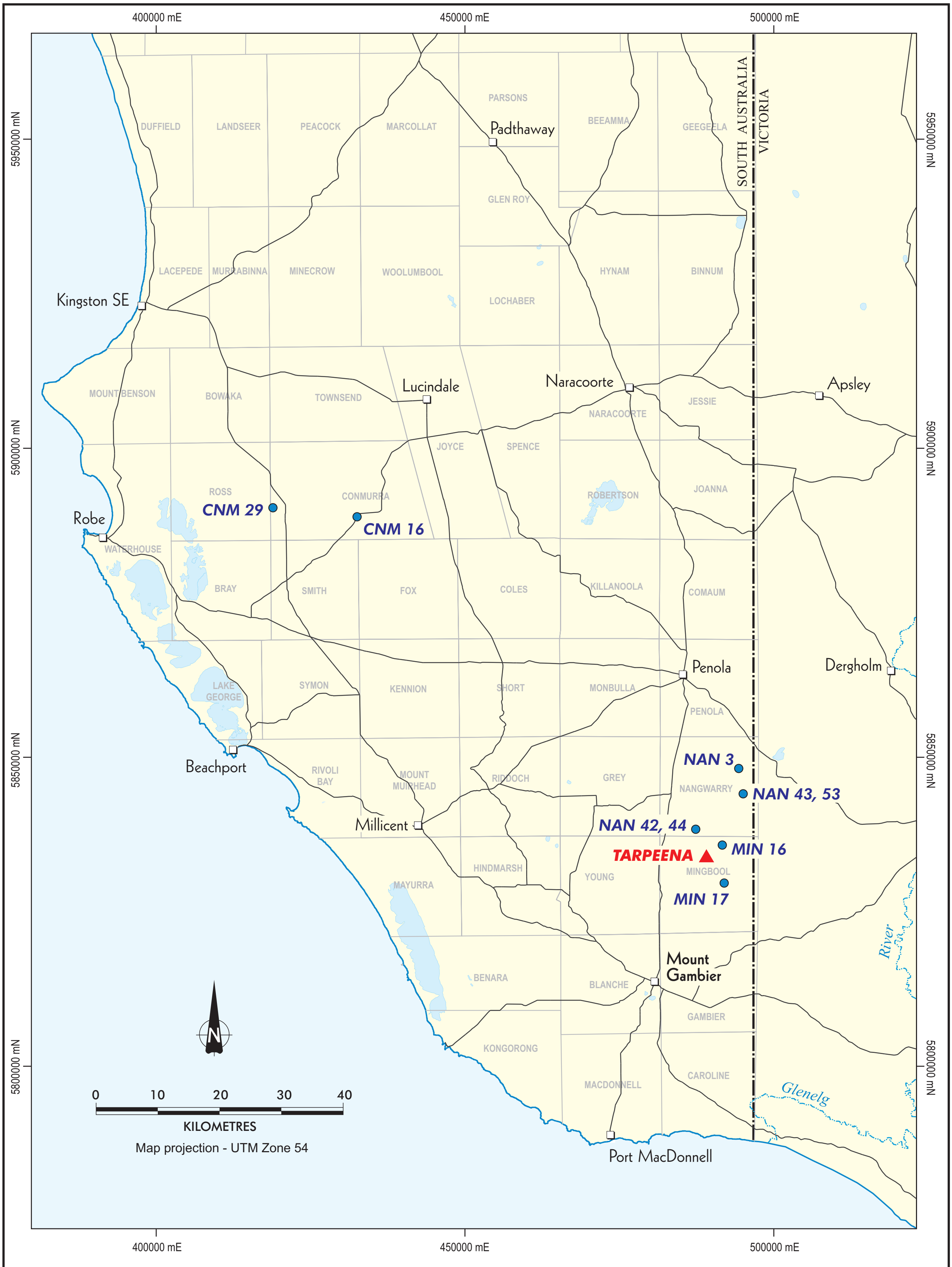


Figure 5 Annual rainfall at Tarpeena (Pleasant Park) in the South East.



Hydrograph observation well location and number _ _ _ _ _ _ _ _ _ **MIN 16** ●

Tarpeena rainfall gauge site _ _ _ _ _ ▲

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LOCATION OF HYDROGRAPH and RAINFALL GAUGE STATION

PIRSA 200440_006

GeoTech Graphics 381-1640

Figure 6

poorly completed wells is estimated to be in the range of 30 000 – 35 000 ML/yr. Further work needs to be urgently undertaken to refine these values, including installation of metering devices and rehabilitation of leaky wells.

An extensive network of salinity and water level monitoring wells exists for both the unconfined and confined aquifers. Representative hydrographs from a number of these wells are presented in Figure 7. Observation well CNM 29 reveals the long-term effects that seasonal extraction and leaking wells in the main artesian area have had on the head distribution in the confined aquifer. Water levels in the unconfined aquifer in the same area (observation well CNM 16) show similar declines, and probably reflect below average annual rainfall since 1992. Long-term hydrographs from the Nangwarry–Tarpeena area for both the unconfined aquifer (observation well NAN 3) and confined aquifer (observation well MIN 17) show a similar short-term decline. At each of the investigation sites, hydrographs for both the unconfined and confined aquifers display this same recent trend. The strong dependence of watertable elevations on rainfall is exhibited in Figure 8 where trends in rainfall at Tarpeena correlate well with water levels in nearby observation well NAN 3.

The hydrograph for observation well MIN 16 (Fig. 9) shows the water-level response in the unconfined aquifer beneath a forested area ~10 km east of Tarpeena. The rise in watertable elevation between 1983 and 1992 most likely reflects enhanced recharge that resulted from the removal of forest by the Ash Wednesday bush fires of February 1983. The overall decline in water level since the end of 1992 is attributed to below average annual rainfall and reforestation in the area. Water levels in an adjacent observation well MIN 21 in the confined aquifer exhibit similar trends to the hydrograph for the unconfined aquifer, although seasonal head variations are more pronounced in the latter. The rise and decline in water levels in the confined aquifer is attributed to an increase and subsequent decrease in overburden pressure associated with the increase and decrease in recharge rates over the same period.

FIELD SITE AND METHODS

The two investigation sites were selected on the basis of shallow depth to the confined aquifer, previously identified regions of high ^{14}C activity (Love, 1993) and a downward hydraulic gradient between the unconfined and confined aquifers. As discussed previously, the Nangwarry–Tarpeena area was considered to provide significant recharge to the confined aquifer. Much of this area is now covered in softwood pine plantations and to a lesser extent blue gum forest. Aware of the effect these plantations have had on recharge, and water levels in the unconfined aquifer, the investigation sites were positioned as far as feasibly possible away from the forested areas.

Well construction details

The Tarpeena site is located about 5 km east of Tarpeena township. There are 10 wells at this site; four in the unconfined aquifer, one in the aquitard, and five in the confined aquifer (Fig. 10) and screen completion intervals are provided in Table 1. The four piezometers in the unconfined aquifer were completed using 50 mm diameter PVC. Each target interval was slotted and gravel packed. The slotted intervals were separated by cement isolation plugs. The well in the confining aquitard was completed using 125 mm diameter steel casing and a 2 m long, 0.35 mm slotted

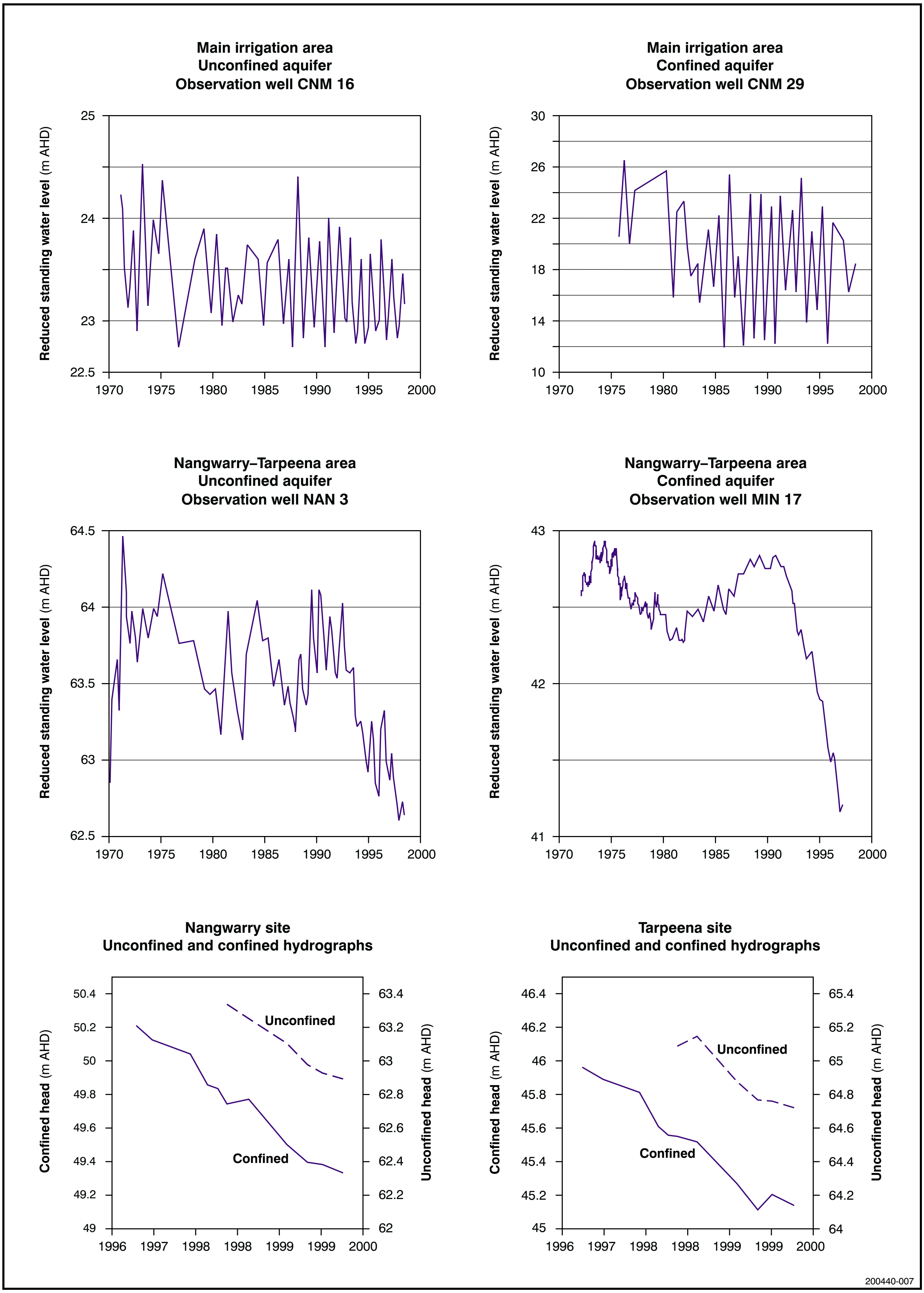


Figure 7 Well hydrographs for the main irrigation, Nangwarry and Tarpeena areas.

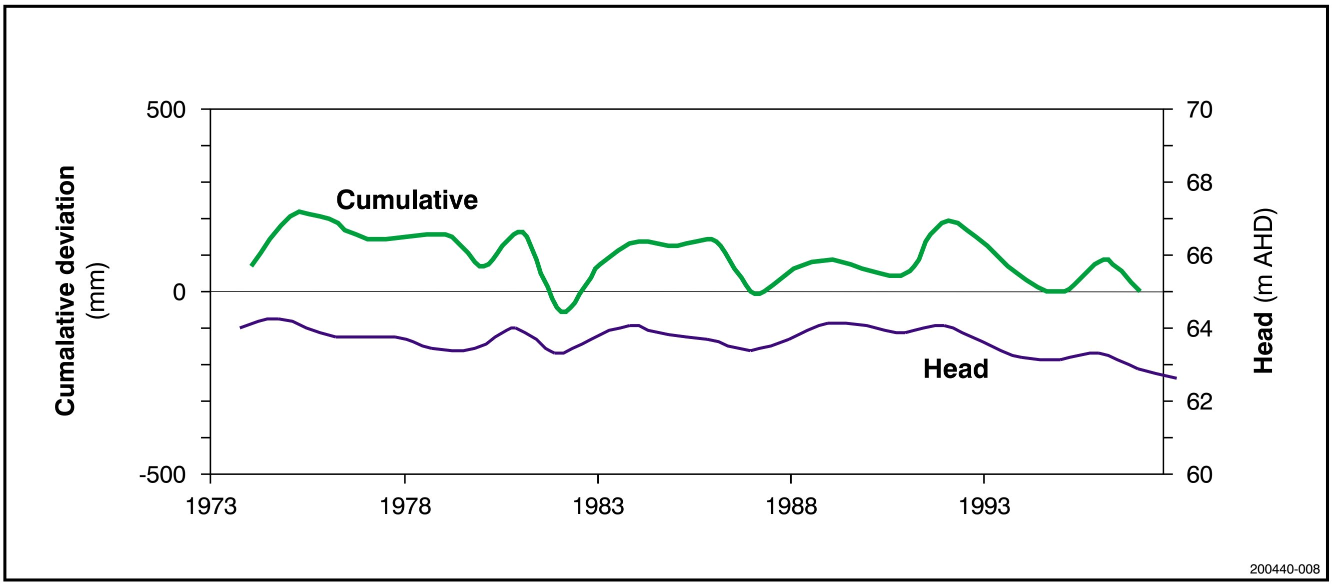


Figure 8 Comparison of cumulative rainfall and water-level trends at Tarpeena NAN 3.

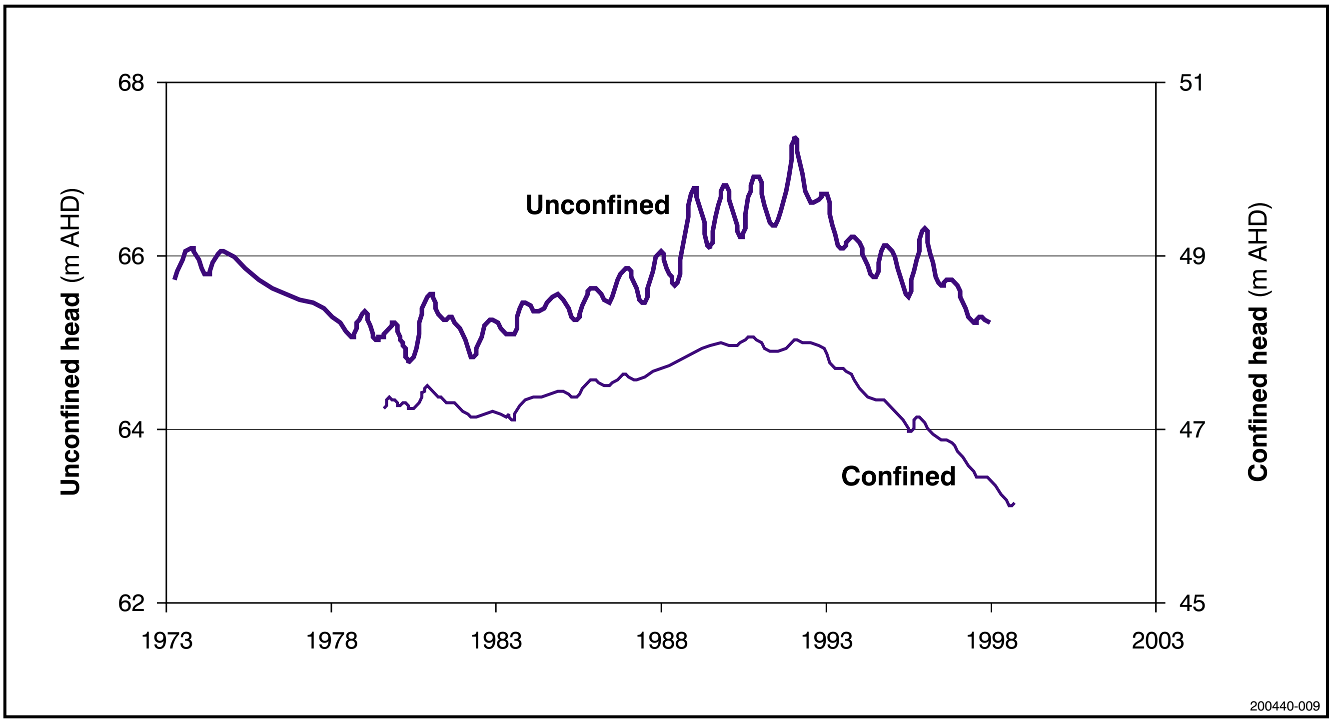
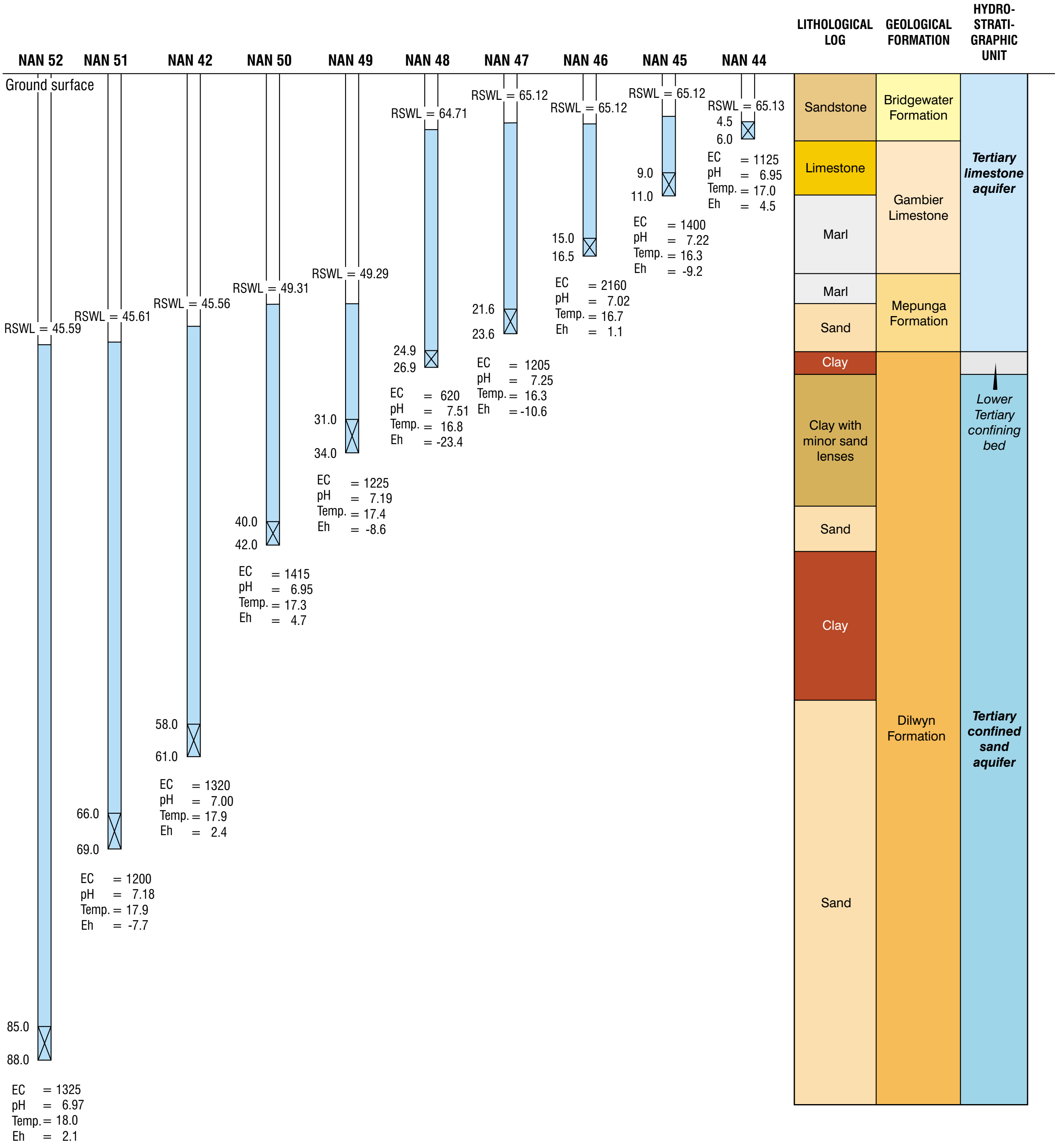


Figure 9 Comparison of long-term unconfined (MIN 16) and confined (MIN 21) hydrographs.

SOUTH EAST CONFINED AQUIFER INVESTIGATIONS
HYDROGEOLOGICAL SECTION
TARPEENA SITE



NOTE:
NAN 44 observation well
RSWL, reduced standing water level (m)
Water levels were taken on 20.4.98
EC, electrical conductivity (µmhos/cm at 25°C)
pH measure of acidity
Temperature (°C)
Eh, redox potential (mV)

200440-010

Figure 10

stainless steel screen located between 24.9 and 26.9 m below ground surface. The initial confined aquifer piezometers was completed between 58 and 61 m using 125 mm diameter PVC with an in-line 1 mm slot size stainless steel screen. The remaining four confined aquifer wells were completed using 50 mm diameter PVC casing. Each piezometer was slotted, gravel packed over each target interval and separated by cement plugs using a similar procedure to the unconfined aquifer wells.

The Nangwarry site is located 10 km east of the township of Nangwarry and is approximately 10 km up-gradient of the Tarpeena site. There are a total of six wells at this site; four of the wells were completed in the unconfined aquifer, one in the aquitard, and one in the uppermost sand unit of the confined aquifer. The four wells in the unconfined aquifer were completed as a nest of piezometers using the same method as per the Tarpeena site (Fig. 11, Table 1). The depth to the confining clay was located 53 m below surface and was just over 4 m thick. A 2 m long, stainless steel screen, with 0.35 mm slots was positioned in the aquitard between 53.6 and 55.6 m below ground surface. The confined aquifer well was originally drilled to 93 m but was completed with 125 mm diameter PVC using a stainless steel screen with 1 mm slot size in the first sand interval of the Dilwyn Formation between 61.5 and 64.5 m.

Local hydrogeology

The watertable in the unconfined aquifer slopes from the Nangwarry site towards the Tarpeena site (slope is from west to east) which is opposite to the direction of regional flow, reflecting a possible localised recharge mound in this area. The confined aquifer potentiometric surface slopes from east to west (from the Nangwarry site to the Tarpeena site) consistent with the regional flow pattern. Results from the drilling show the depth to the confined aquifer shallows down hydraulic gradient from ~50 m to the confining bed at the Nangwarry site to ~25 m at the Tarpeena site.

The geology of the Dilwyn Formation at the Nangwarry site is typical of the interbedded sequence of brown clays and quartz sands that characterise the formation. The five sand units encountered possibly represent separate subaquifers in the confined aquifer system.

Field and analytical techniques

Prior to sampling each of the piezometers were pumped so that at least three well volumes were removed. Electrical conductivity (Ec), pH, temperature and redox potential (Eh) were monitored and allowed to stabilise before sampling was undertaken. During the sampling process all of the wells were pump tested to determine hydraulic conductivity using standard techniques. A summary of pumping details is presented in Table 2.

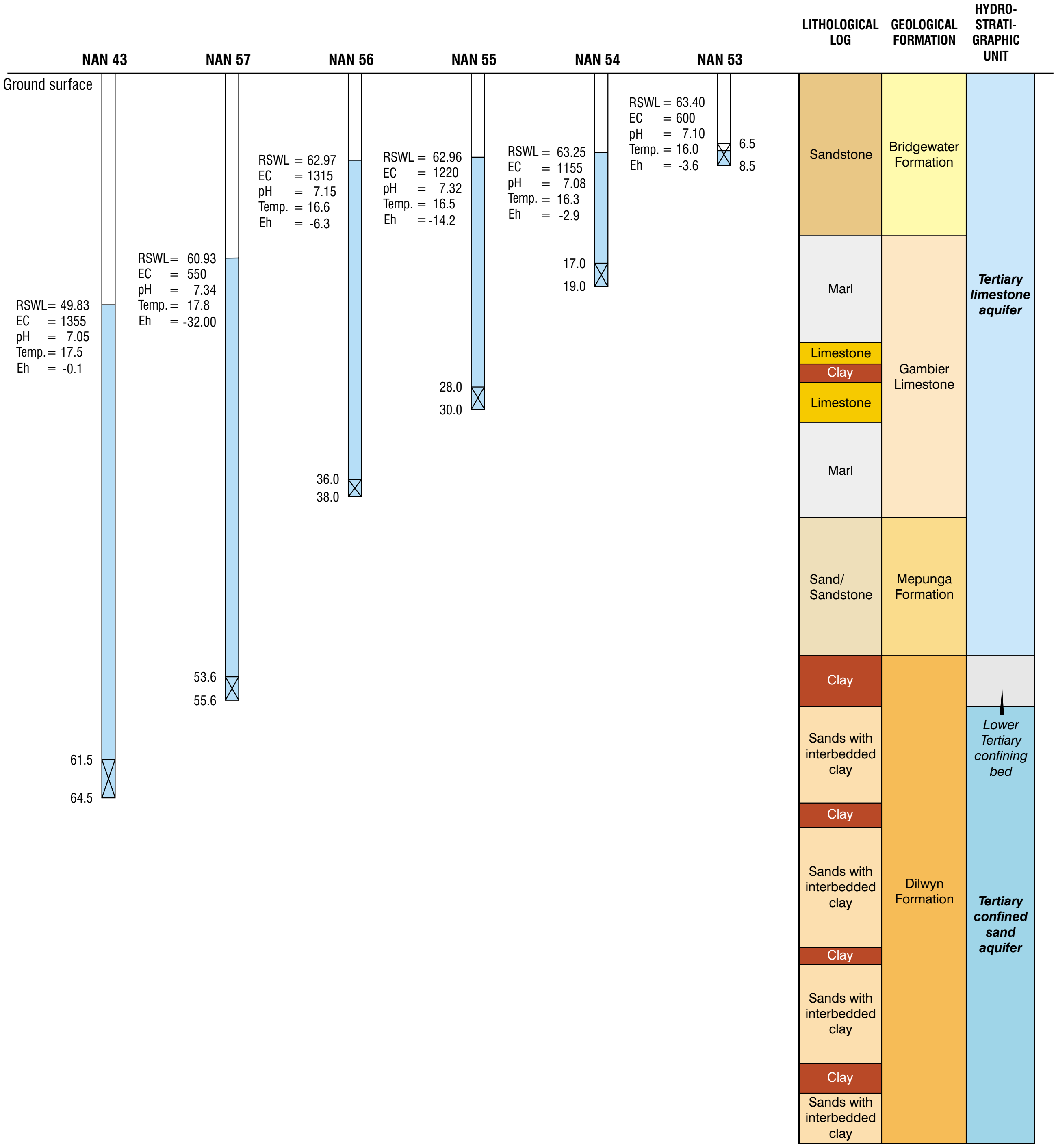
Chlorofluorocarbon sampling was undertaken using a stainless steel bailer connected to a nylon tube and pressurised with nitrogen gas. The bailer was lowered down to the depth of each screen, in each of the piezometers. The nitrogen was then released allowing water to flow into the bailer and tube. The bailer was repressurised and brought to the surface. Boro-silicate ampoules were then filled with the groundwater samples and sealed using an oxy-propane gas torch making sure

Table 1 Summary of well completion details, South East confined aquifer investigations

Observation well	Unit number	Permit number	Hundred	Section	MGA zone	Easting	Northing	Total depth (m)	Casing details		Screen details		Completion date
									Depth (m)	*Diameter* (mm)	*Interval* (m)	*Diameter* (mm)	
Nangwarry site													
NAN 53	7022–8525	42876	Nangwarry	Adj. 218	54	494970	5843872	8.5	0–6.5	50	6.5–8.5	50	12.12.97
NAN 54	7022–8524	42876	Nangwarry	Adj. 218	54	494970	5843872	19.0	0–17	50	17–19	50	12.12.97
NAN 55	7022–8523	42876	Nangwarry	Adj. 218	54	494970	5843872	30.0	0–28	50	28–30	50	12.12.97
NAN 56	7022–8522	42876	Nangwarry	Adj. 218	54	494970	5843872	38.0	0–36	50	36–38	50	12.12.97
NAN 57	7022–8479	42643	Nangwarry	Adj. 218	54	494995	5843876	55.6	0–53.4	125	53.6–55.6	100	12.11.97
NAN 43	7022–8326	39885	Nangwarry	Adj. 218	54	495000	5843875	93.0	0–61.5	125	61.5–64.5	125	09.02.97
Tarpeena site													
NAN 44	7022–8520	42862	Nangwarry	Adj. 77	54	487350	5837920	6.0	0–6	50	4.5–6	50	04.12.97
NAN 45	7022–8519	42862	Nangwarry	Adj. 77	54	487350	5837920	11.0	0–11	50	9–11	50	04.12.97
NAN 46	7022–8518	42862	Nangwarry	Adj. 77	54	487350	5837920	16.5	0–16.5	50	15–16.5	50	04.12.97
NAN 47	7022–8517	42862	Nangwarry	Adj. 77	54	487350	5837920	23.6	0–23.6	50	21.6–23.6	50	04.12.97
NAN 48	7022–8478	42642	Nangwarry	Adj. 77	54	487350	5837910	26.9	0–24.9	125	24.9–26.9	100	15.11.97
NAN 49	7022–8509	42653	Nangwarry	Adj. 77	54	487350	5837915	34.0	0–34	50	31–34	50	28.11.97
NAN 50	7022–8508	42653	Nangwarry	Adj. 77	54	487350	5837915	42.0	0–42	50	40–42	50	28.11.97
NAN 42	7022–8327	39886	Nangwarry	Adj. 77	54	487350	5837900	93.0	0–58	125	58–61	125	14.02.97
NAN 51	7022–8507	42653	Nangwarry	Adj. 77	54	487350	5837915	69.0	0–69	50	66–69	50	28.11.97
NAN 52	7022–8506	42653	Nangwarry	Adj. 77	54	487350	5837915	88.0	0–88	50	85–88	50	28.11.97

Note: because of casing failure a peizometer at the Nangwarry site set at 45–47 m was backfilled.

SOUTH EAST CONFINED AQUIFER INVESTIGATIONS
HYDROGEOLOGICAL SECTION
NANGWARRY SITE



NOTE:
NAN 44 observation well
RSWL, reduced standing water level (m)
Water levels were taken on 20.4.98
EC, electrical conductivity (μmhos/cm at 25°C)
pH measure of acidity
Temperature (°C)
Eh, redox potential (mV)

200440-011

Figure 11

through the whole process that there was no atmospheric contamination. CFC-11, and CFC-12 were analysed by gas chromatography (Busenberg and Plummer, 1992).

Carbon-14 was collected in 20 L containers and analysed by liquid scintillation counting of carbon dioxide adsorbed into a carbosorb–permafluor mixture (Leaney et al., 1994). Isotope ratio mass spectrometry was used to determine $^{13}C/^{12}C$ compositions and these are expressed in delta (δ) notation relative to the Pee Dee Belemnite standard.

An unpurged and purged water sample was taken from each of the piezometers for radon analysis. Unpurged samples were collected using a stainless steel gas bailer. Purged samples were obtained after pumping three bore volumes. Each sample was transferred to a low diffusion vial containing a mineral oil scintillant. Radon concentrations were measured by liquid scintillation counting (Herczeg et al., 1994).

Water samples were also collected in 25 mL glass vials for analysis of $^{2}H/^{1}H$ and $^{18}O/^{16}O$ compositions. Hydrogen isotope compositions were analysed by mass spectrometry after reducing water to H_2 gas over hot uranium metal (Dighton et al., 1997), while oxygen isotope compositions were analysed after equilibrating 1 mL of water with carbon dioxide gas at 25°C (Socki et al., 1992). Both hydrogen and oxygen isotope compositions are expressed in delta notation relative to the standard SMOW (standard mean ocean water). Major ion chemistry samples for each of the piezometers were collected in 1.25 L plastic bottles and analysed using standard laboratory techniques.

At each site, a number of 100 mm diameter cores were taken through low-permeability confining beds during the drilling operation. Sections of each core were taken and measured for vertical hydraulic conductivity using standard triaxial cell permeability tests. Samples of clay were also taken along each core and their pore water chloride concentrations analysed by potentiometric titration with silver nitrate on an Orion autotitrator.

RESULTS

The measured head gradient, isotope analyses results and chloride data, for each well, are presented in Table 3 and major ion chemistry in Table 4.

Head gradient

Hydraulic head decreases with depth at the Tarpeena site (Fig. 12). The head in the top piezometer in the unconfined aquifer is about 16 m higher than the head in the top piezometer in the confined aquifer. The measured heads from the five piezometers in the confined aquifer indicate that there are two subaquifers within the Dilwyn Formation at this site. The head difference between the upper two piezometers and the lower three piezometers in the aquifer is ~4 m. The two groups of piezometers are separated by a clay aquitard as observed in the lithological profile.

At Nangwarry the head also decreases with depth down the profile (Fig. 13). The difference in head between the watertable piezometer and the confined aquifer well is about 13.5 m.

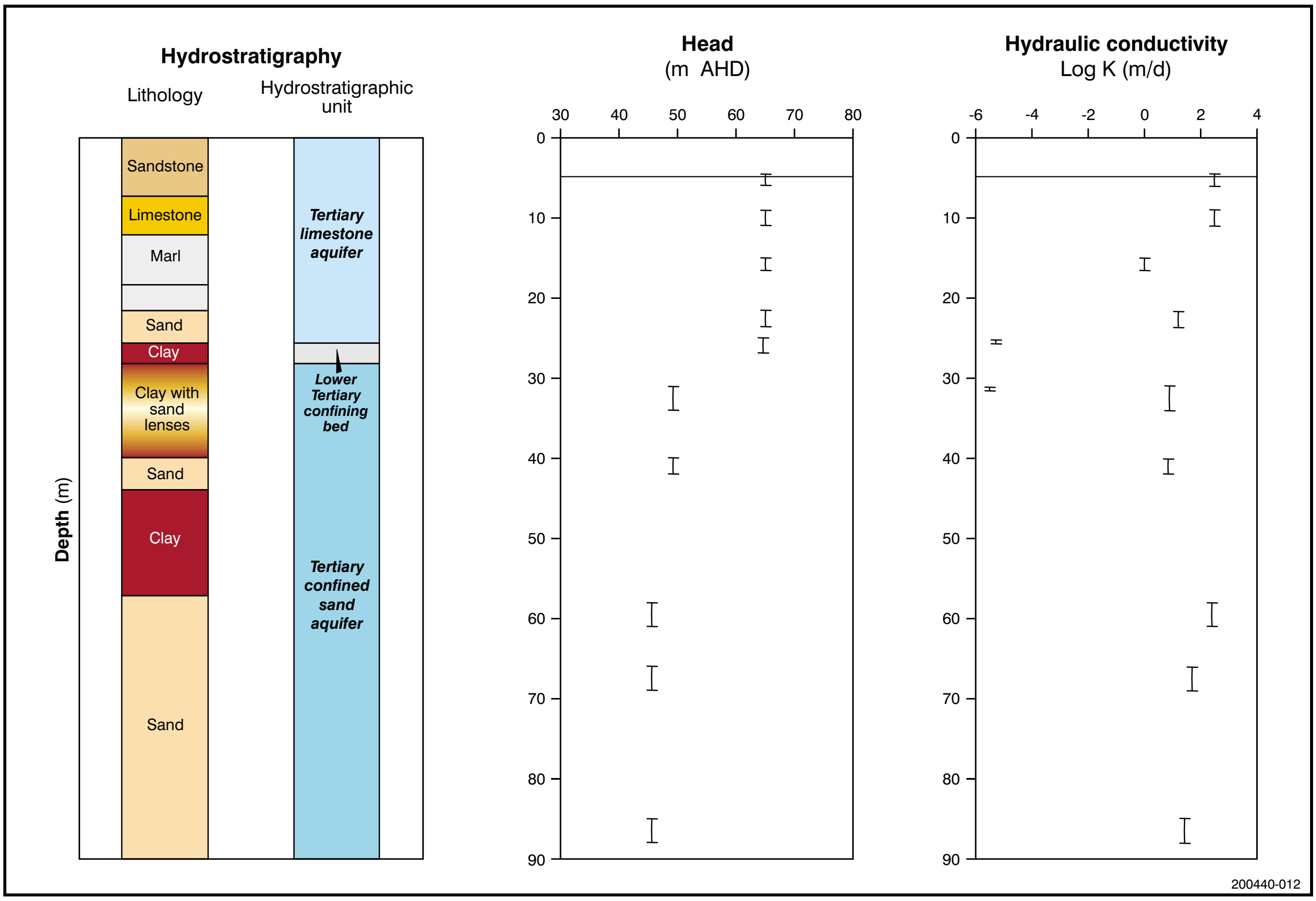


Figure 12 Hydrostratigraphy, head and hydraulic conductivity profiles, Tarpeena site.

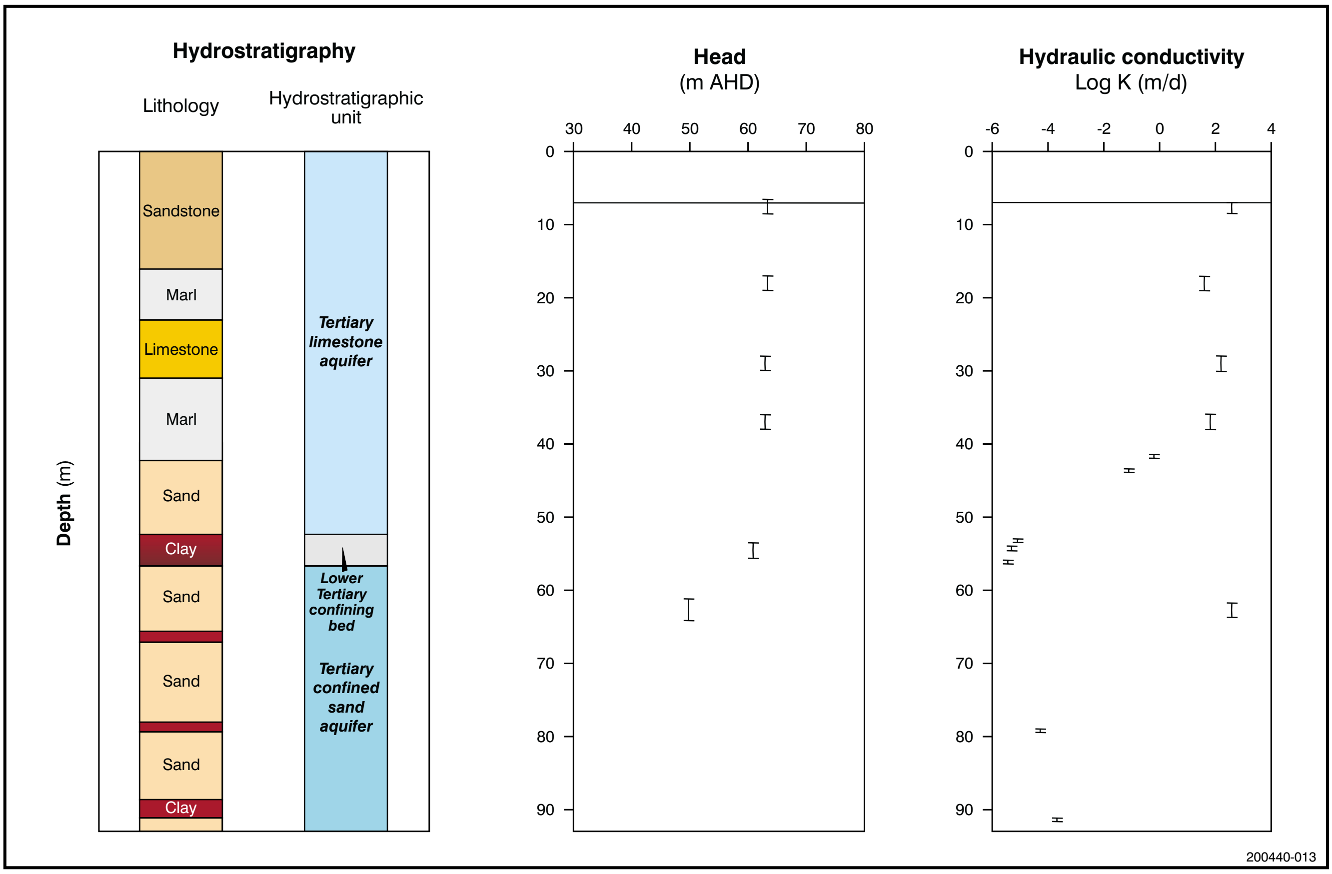


Figure 13 Hydrostratigraphy, head and hydraulic conductivity profiles, Nangwarry site.

There is, therefore, potential for downward leakage of groundwater from the unconfined aquifer to the confined aquifer at both sites.

Environmental tracers

CHLOROFLUOROCARBONS

CFC-11 ($CFCl_3$) and CFC-12 (CF_2Cl_2) results for both sites and their inferred modelled ages are presented in Table 3. The age of the samples as determined by converting the CFC concentration (CFC-12 was preferred because of its more conservative character) in picograms per kilogram (pg/kg) to equivalent atmospheric concentration (parts per trillion volume (pptv)) using known gas solubility relationships (Warner and Weiss, 1985) and assuming a recharge temperature of 16°C. This value was then compared to the atmospheric concentration curve to determine the sample age.

Table 2 Summary of pumping details 27.4.98 to 1.5.98, South East confined aquifer investigations

Observation well	**Piezo interval** (m)	**Electrical conductivity**	**pH**	**Temperature** (°C)	**Redox potential**	**Head** (m AHD)*	**Unit**
NAN 53	6.5–8.5	600	7.10	16.0	-3.6	63.40	Bridgewater
NAN 54	17.0–19.0	1155	7.08	16.3	-2.9	63.25	Gambier
NAN 55	28.0–30.0	1220	7.32	16.5	-14.2	62.96	Gambier
NAN 56	36.0–38.0	1315	7.15	16.6	-6.3	62.97	Gambier
NAN 57	53.6–55.6	550	7.34	17.8	-32	60.93	Dilwyn (clay)
NAN 43	61.5–64.5	1355	7.05	17.5	-0.1	49.83	Dilwyn (sand)
NAN 44	4.5–6.0	1125	6.95	17.0	4.5	65.13	Bridgewater
NAN 45	9.0–11.0	1400	7.22	16.3	-9.2	65.12	Gambier
NAN 46	15.0–16.5	2160	7.02	16.7	1.1	65.12	Gambier
NAN 47	21.6–23.6	1205	7.25	16.3	-10.6	65.12	Mepunga
NAN 48	24.9–26.9	620	7.51	16.8	-23.4	64.71	Dilwyn (clay)
NAN 49	31.0–34.0	1225	7.19	17.4	–8.6	49.29	Dilwyn (sand)
NAN 50	40.0–42.0	1415	6.95	17.3	4.7	49.31	Dilwyn (sand)
NAN 42	58.0–61.0	1320	7.00	17.9	2.4	45.56	Dilwyn (sand)
NAN 51	66.0–69.0	1200	7.18	17.9	-7.7	45.61	Dilwyn (sand)
NAN 52	85.0–88.0	1325	6.97	18.0	2.1	45.59	Dilwyn (sand)

* Water levels were taken on 20.4.98.

Table 3 Summary of isotopic results, South East confined aquifer investigations

Observation well	Screen interval	Reduced standing water level	Chloride	Radon-222			Chlorofluorocarbons						Radiocarbon		Stable isotopes	
				Unpurged C	*Purged Co*	*C/Co*	*Concentration* (pg/kg)		*Equivalent concentration* (pptv)		*Age* (year)		^{14}C	$\delta^{13}C$	$\delta^{2}H$	$\delta^{18}O$
	(m)	(m AHD)	(mg/L)	(Bq/L)	(Bq/L)		*CFC-11*	*CFC -12*	*CFC -11*	*CFC-12*	*CFC-11*	*CFC-12*	(pmc)	(‰, PDB)	(‰, SMOW)	
Nangwarry site																
NAN 53	6.5–8.5	63.404	23	1.3	3.5	0.37	50	34	20	59	1964	1965	72.8	-15.4	-17.2	-2.94
NAN 54	17.0–19.0	63.246	27	8.6	11.8	0.73	0	0	0	0	<1960	<1960	64.7	-14.7	-15.3	-2.66
NAN 55	28.0–30.0	62.962	127	0.5	14.1	0.04	0	0	0	0	<1960	<1960	56.8	-11.9	-24.3	-4.30
NAN 56	36.0–38.0	62.965	142	1.5	6.4	0.23	0	0	0	0	<1960	<1960	48.8	-11.9	-22.7	-3.93
NAN 57*	53.6–55.6	60.925	55	0.0	0.3	–	0	0	0	0	<1960	<1960	–	–	-21.9	-3.42
NAN 43	61.5–64.5	49.833	207	1.0	1.9	0.53	0	0	1	14	<1960	<1960	45.6	-12.6	-25.4	-4.49
Tarpeena site																
NAN 44	4.5–6.0	65.129	59	1.0	2.7	0.37	49	66	19	114	1964	1970	59.2	-12.0	-27.8	-5.09
NAN 45	9.0–11.0	65.122	100	3.2	3.9	0.82	24	22	10	37	1960	1961	73.8	-13.6	-27.4	-4.86
NAN 46	15.0–16.5	65.121	174	0.9	3.9	0.23	0	0	0	0	<1960	<1960	19.3	-8.4	-30.0	-5.00
NAN 47	21.6–23.6	65.121	155	2.9	6.8	0.43	0	0	0	0	<1960	<1960	14.1	-8.2	-29.2	-5.21
NAN 48	24.9–26.9	64.710	155	0.6	42.1	0.01	0	0	0	10	<1960	<1960	23.4	-9.2	-29.6	-5.19
NAN 49	31.0–34.0	49.286	185	2.0	5.1	0.39	16	11	6	19	<1960	1956	54.6	-12.5	-27.8	-4.97
NAN 50	40.0–42.0	49.306	197	0.9	2.5	0.36	23	19	9	33	1960	1960	57.4	-12.7	-24.7	-4.45
NAN 42	58.0–61.0	45.560	189	0.6	1.5	0.40	0	0	0	0	<1960	<1960	47.2	-12.0	-27.4	-4.48
NAN 51	66.0–69.0	45.607	185	0.4	1.6	0.25	0	0	0	0	<1960	<1960	46.6	-12.1	-23.9	-4.17
NAN 52[†]	85.0–88.0	45.589	203	0.3	1.6	0.19	–	–	–	–	–	–	47.3	-12.9	-22.9	-3.79

* insufficient sample for ^{14}C analysis

† contaminated sample

Table 4 Major ion chemistry, South East confined aquifer investigations

Observation well	Screen interval (m)	pH	Ion (mg/L)							
			Br	*Cl*	*HCO_3*	*Ca*	*K*	*Mg*	*Na*	*Total S*
Nangwarry site										
NAN 53	6.5–8.5	7.5	<0.2	23	348	40	2.7	6.5	22	4.6
NAN 54	17.0–19.0	7.6	<0.2	27	268	180	1.7	9.8	28	140.0
NAN 55	28.0–30.0	7.7	0.3	127	396	77	3.2	8.9	77	45.0
NAN 56	36.0–38.0	7.7	0.4	142	433	86	4.5	14.0	90	55.0
NAN 57	53.6–55.6	7.9	<0.4	55	250	70	1.6	8.7	47	2.7
NAN 43	61.5–64.5	7.5	0.5	207	464	87	3.0	13.0	130	8.1
Tarpeena site										
NAN 44	4.5–6.0	7.4	0.2	59	494	63	0.8	7.2	57	56.0
NAN 45	9.0–11.0	7.6	0.3	100	293	160	1.9	10.0	110	160.0
NAN 46	15.0–16.5	7.3	0.5	174	348	330	7.0	24.0	101	280.0
NAN 47	21.6–23.6	7.5	0.4	155	421	46	2.7	20.0	84	24.0
NAN 48	24.9–26.9	7.1	0.5	164	62	36	2.1	6.5	74	3.6
NAN 49	31.0–34.0	7.6	0.5	185	317	70	3.1	9.9	112	16.0
NAN 50	40.0–42.0	7.4	0.5	197	500	110	2.8	15.0	120	16.0
NAN 42	58.0–61.0	7.5	0.5	189	470	49	2.9	15.0	110	11.0
NAN 51	66.0–69.0	7.6	0.5	185	427	87	2.8	13.0	130	7.5
NAN 52	85.0–88.0	7.4	0.5	203	433	54	2.4	14.0	140	8.9

The age of the tracer is considered to be the period of time since the sample became isolated from the atmosphere (i.e. below the watertable). The CFC data indicates that the average recharge date (analysis date minus age) of water in the piezometer positioned at the watertable is 1970 at the Tarpeena site and 1965 at the Nangwarry site. Recharge to the unconfined aquifer is likely to have occurred at both sites since these dates because the groundwater samples represent mixtures of water from 1.5–2 m intervals.

RADIOCARBON

Carbon-14 activities at the Tarpeena site range from 14.1 to 73.8 percent modern carbon (pmc) and $\delta^{13}C$ values from -8.2 to -12.9‰ (Fig. 14). An apparent anomaly in the ^{14}C profile is the increase from 59.2 pmc in the top watertable piezometer to 73.8 pmc in the piezometer immediately below it. There are two possible explanations for this: the higher concentration represents an input of recharge water containing the bomb (high ^{14}C) pulse; or recharge is occurring by preferential flow from the top of the unconfined aquifer.

From the second piezometer the ^{14}C activity decreases with depth to background levels in the sample taken from the aquitard. This indicates that the pore water in the aquitard was recharged in excess of 25 000 years BP. Below the aquitard the ^{14}C activity is much higher in the confined aquifer: in the top subaquifer the two piezometers have a ^{14}C activity of 54.6 and 57.6 pmc; in the bottom subaquifer the three piezometers have a ^{14}C activity of 47.2, 46.6 and 47.3 pmc respectively.

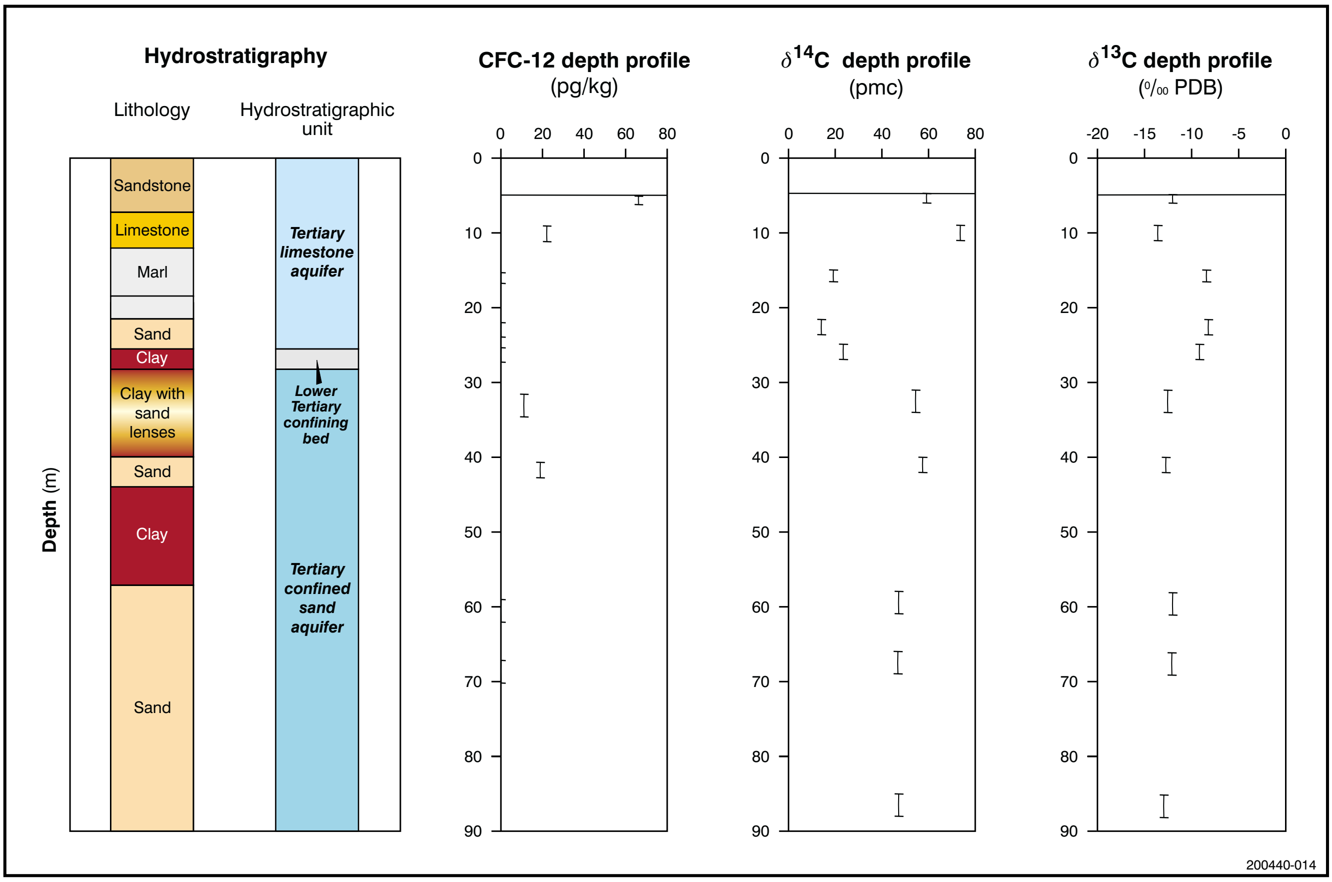


Figure 14 Hydrostratigraphy, CFC-12, δ^{14}C and δ^{13}C profiles, Tarpeena site.

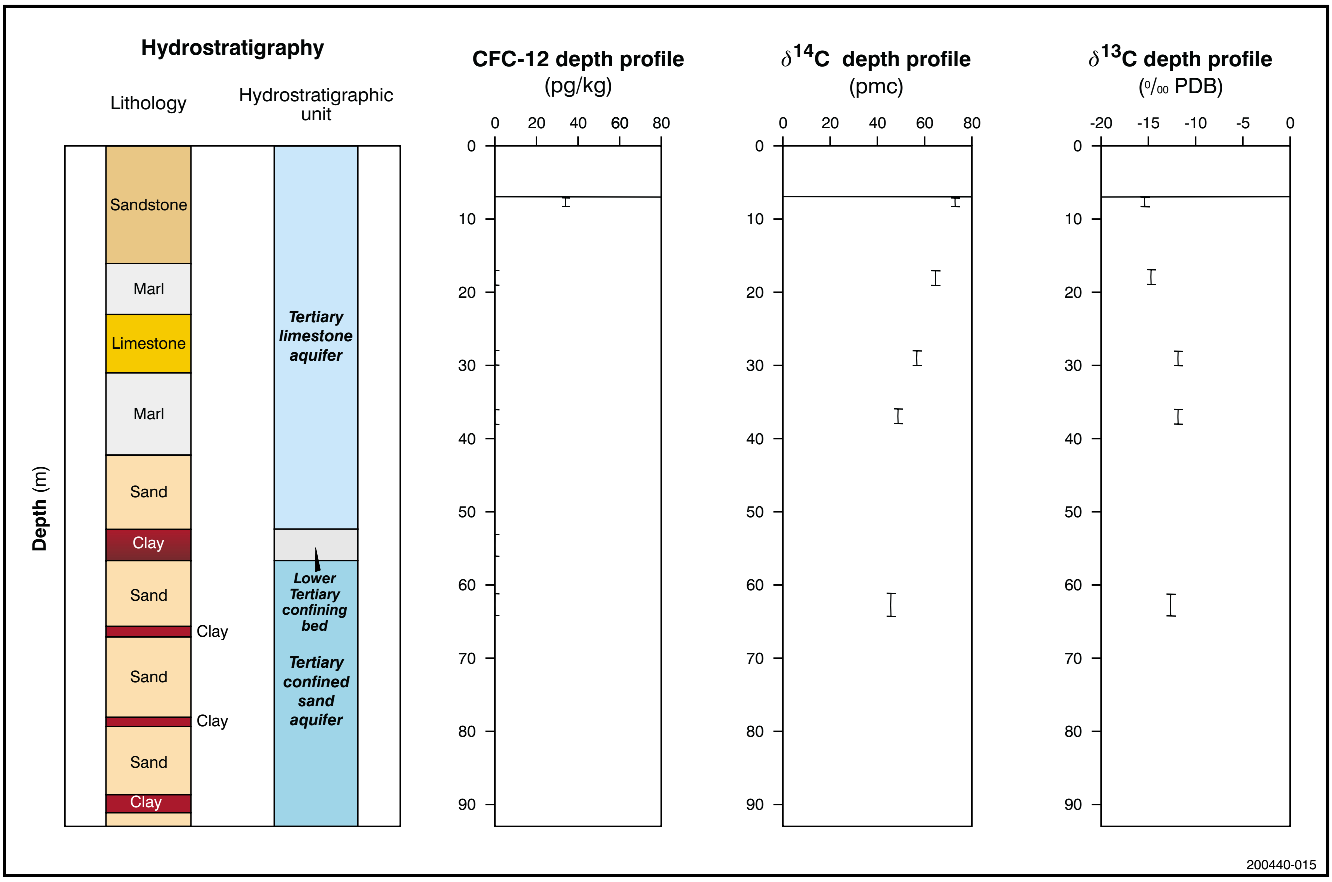


Figure 15 Hydrostratigraphy, CFC-12, δ^{14}C and δ^{13}C profiles, Nangwarry site.

At the Nangwarry site the ^{14}C activities range from 45 to 73 pmc (Fig. 15) and $\delta^{13}C$ values from -11.9 to -15.4‰. There is a general decline in ^{14}C activity with depth. Due to difficulties in obtaining a groundwater sample from the aquitard there is currently no data but further sampling, just completed, will provide this information.

The ^{14}C activity of groundwater in the confined aquifer at the Nangwarry site is 45.6 pmc. This is close to ^{14}C activities for the deeper subaquifer at the Tarpeena site (46.6 to 47.3 pmc). The $\delta^{13}C$ values for the confined aquifer range from -12.0 to -12.9‰. The one piezometer completed in the confined aquifer at Nangwarry has a $\delta^{13}C$ value of -12.6‰, which falls within this range. In the unconfined aquifer $\delta^{13}C$ ranges from -8.2 to -15.4‰ and at both sites there is general enrichment in $\delta^{13}C$ with depth.

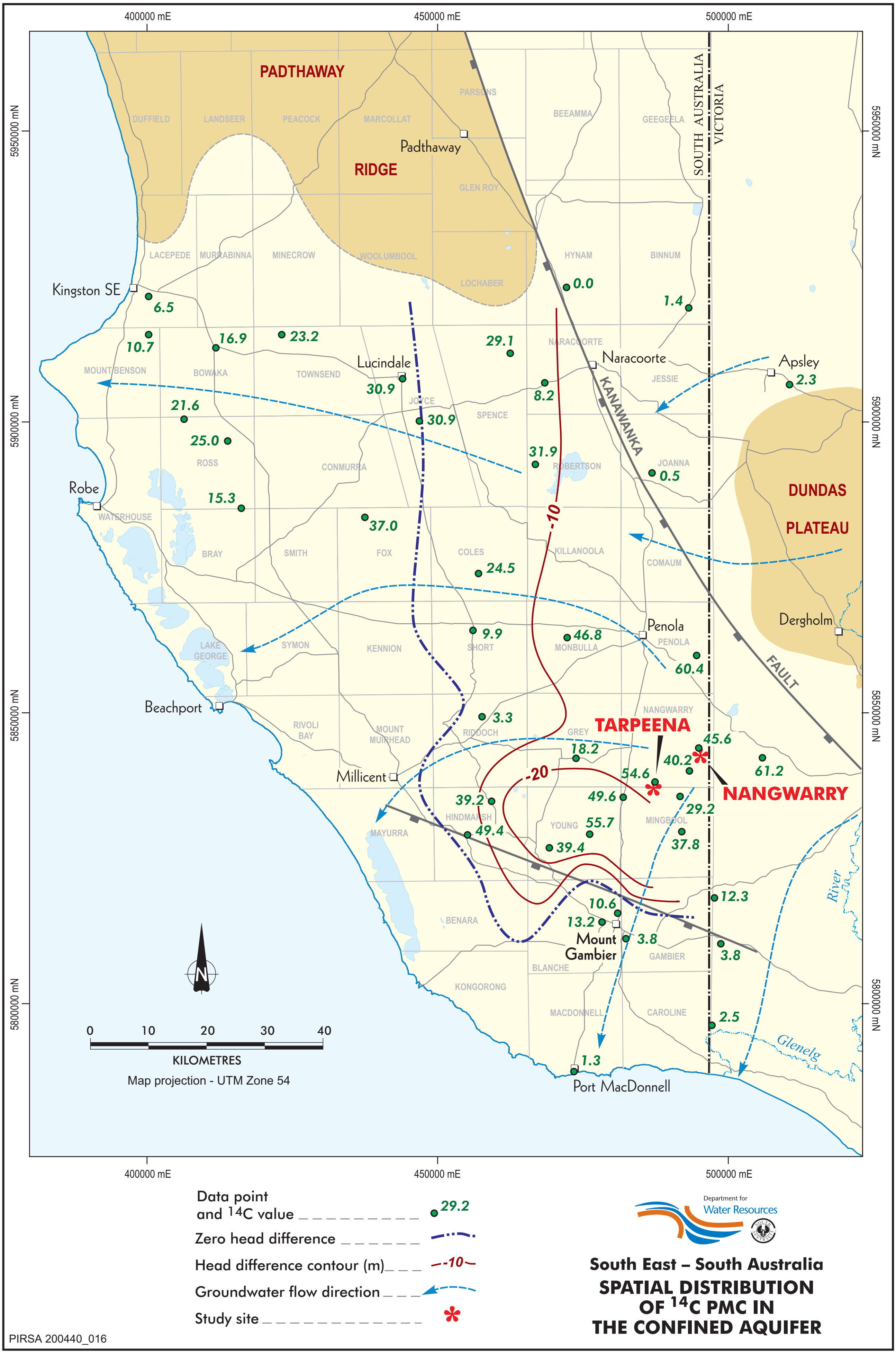
The spatial distribution of ^{14}C activity in the confined aquifer is shown in Figure 16. Most of the ^{14}C activities to the east of the zero head difference are <45 pmc. Assuming ^{14}C activity is a good proxy for relatively high recharge rates, this map indicates that recharge to the confined aquifer only occurs at several distinct locations, even though there is potential for recharge throughout the region to the east of the zero head difference. The two highest ^{14}C activities to the east of the zero head difference are in close proximity to the Kanawinka Fault, indicating possible contributions of recharge via preferential flow. To the east of the fault the ^{14}C activities are close to background levels, reflecting relatively low recharge rates in this area which is in agreement with previous modelling results (Love et al., 1994; Harrington et al., 1999). The ^{14}C activities and their respective locations are provided in Appendix 1.

Hydrogen and oxygen isotope profiles

The stable hydrogen and oxygen isotopic compositions of groundwater samples (expressed as $\delta^{2}H$ and $\delta^{18}O$, respectively) at each screen interval are plotted relative to the local meteoric water line (Love et al., 1994) for each site (Figs 17 and 18).

At the Tarpeena site the isotopic compositions of groundwater from the unconfined aquifer plot on or just below the local meteoric water line indicating that recharge has occurred under similar climatic conditions to modern times and that very little evaporation of rainfall occurred prior to recharge. The two piezometers in the upper subaquifer of the confined aquifer also plot very close to the local meteoric water line suggesting a similar recharge environment as the unconfined aquifer. However, the deeper of the two piezometers sampled is enriched in ^{2}H and ^{18}O relative to the overlying groundwater (Fig. 19). The three piezometers in the bottom subaquifer of the confined aquifer are also further enriched in ^{2}H and ^{18}O relative to the groundwater above them. They also fall to the right of the local meteoric water line indicating possible evaporation prior to recharge.

At the Nangwarry site there is no discernible pattern to the stable isotope chemistry (Fig. 20). This may be due in part to fewer sample points. The confined aquifer sample plots close to the local meteoric water line and has a similar isotopic composition to that of the upper subaquifer in the confined aquifer at the Tarpeena site. All of the samples plot near to or to the right of the local meteoric water line; the two top samples from the unconfined aquifer show the possible effects of evaporation prior to recharge.



South East – South Australia

SPATIAL DISTRIBUTION OF ^{14}C PMC IN THE CONFINED AQUIFER

GeoTech Graphics 381-1641

Figure 16

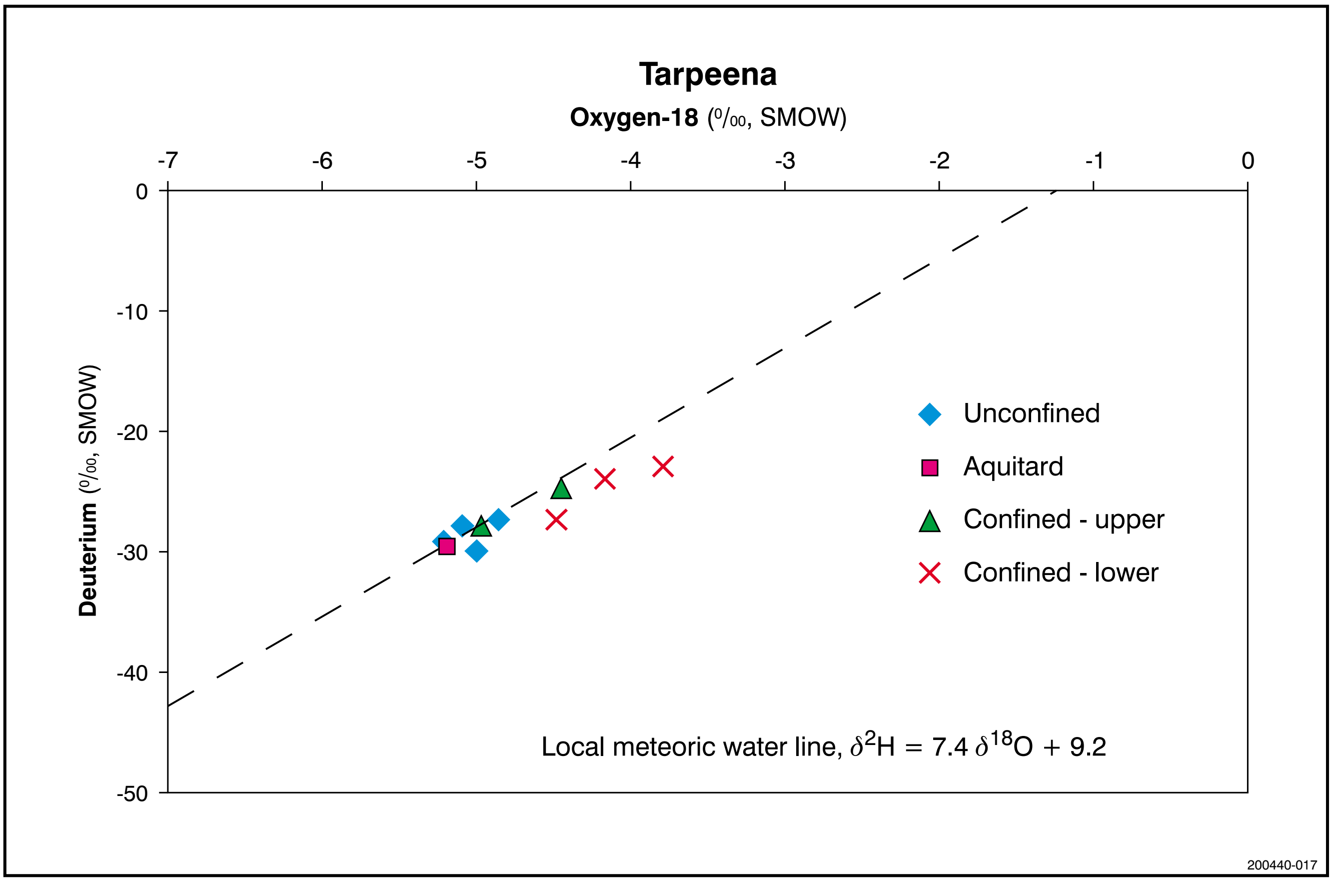


Figure 17 Stable isotopes, Tarpeena site.

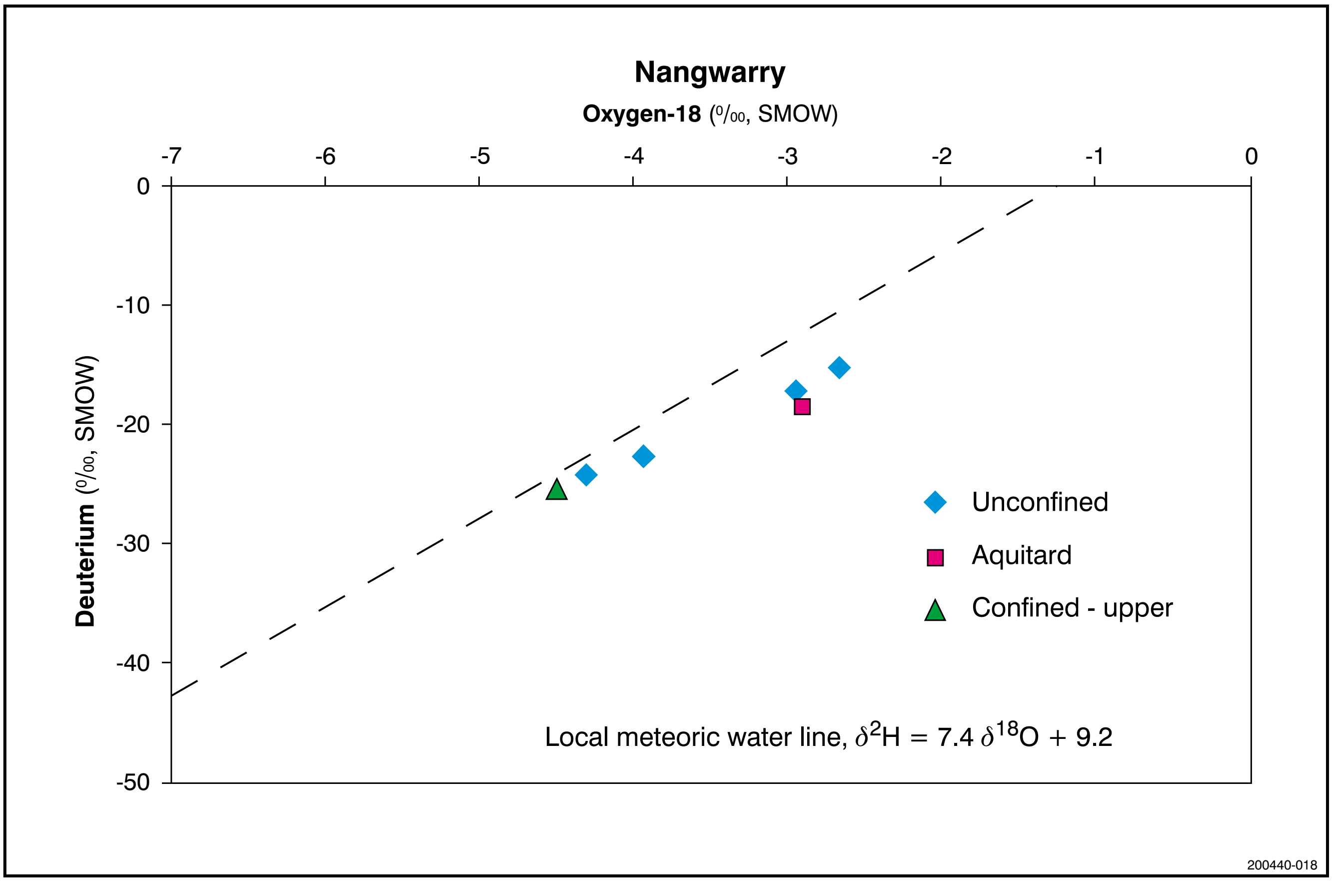


Figure 18 Stable isotopes, Nangwarry site.

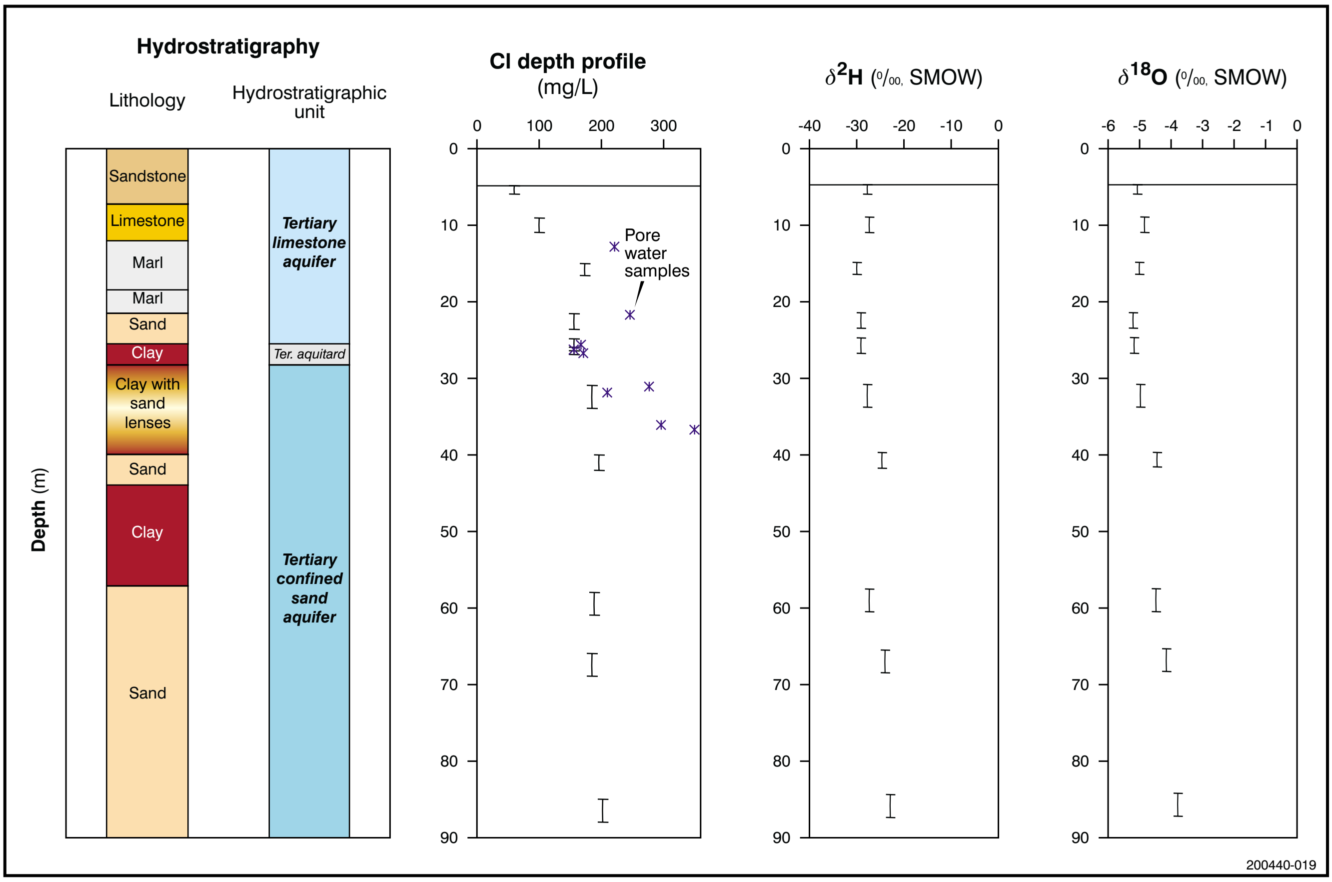


Figure 19 Hydrostratigraphy, chloride, δ^2H and δ^{18}O profiles, Tarpeena site.

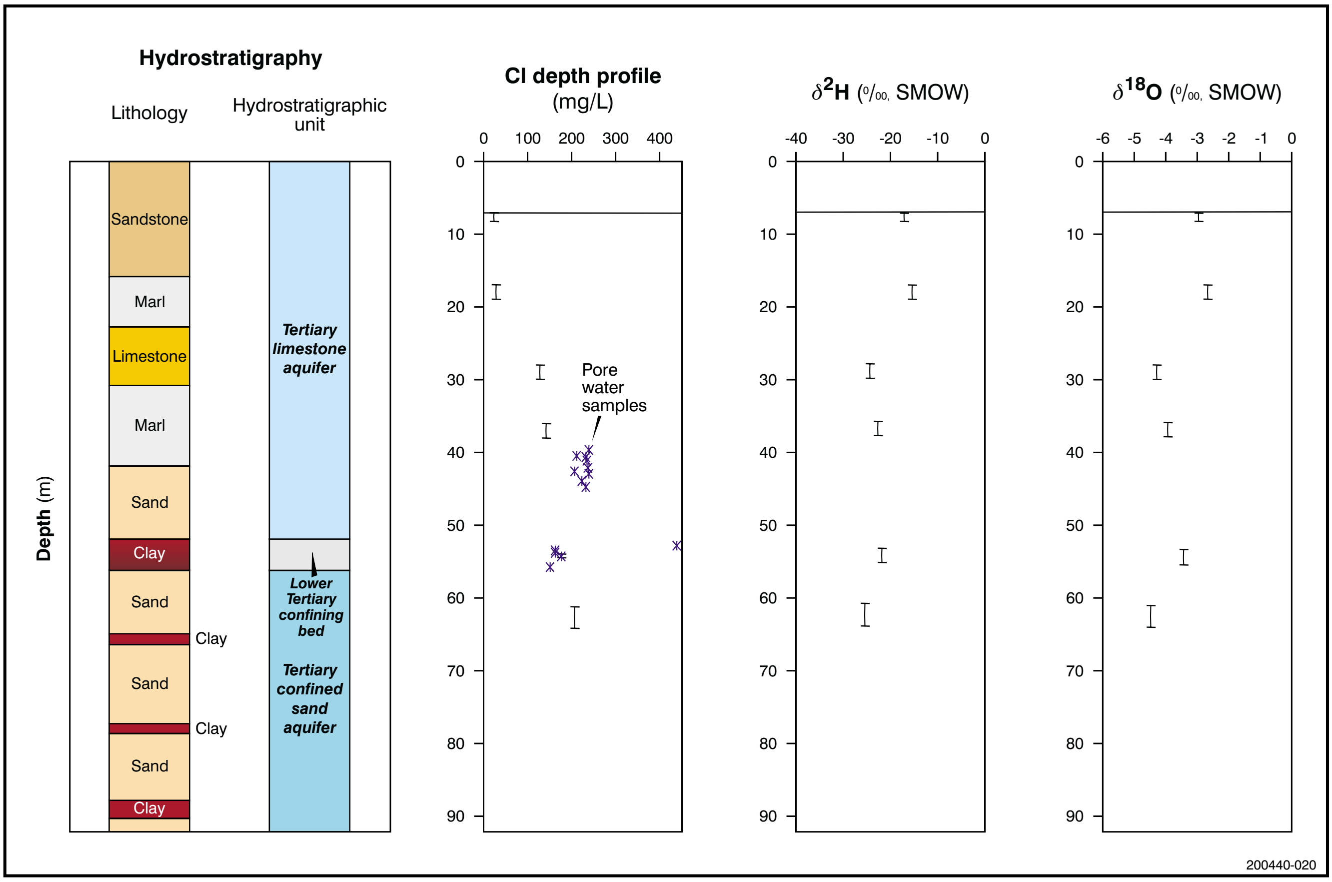


Figure 20 Hydrostratigraphic, chloride, δ^2H and δ^{18}O profiles, Nangwarry site.

Electrical conductivity and major ion chemistry

At the Tarpeena site the electrical conductivity of groundwater ranged from ~1125 to 2160 µS/cm in the unconfined aquifer and from 1200 to 1415 µS/cm (Fig. 10). Groundwater extracted from the aquitard had an electrical conductivity of 340 µS/cm (Fig. 10).

At the Nangwarry site, the electrical conductivity of groundwater in the unconfined aquifer ranged from ~600 to 1315 µS/cm and was measured at 1315 µS/cm immediately above the aquitard. The electrical conductivity of groundwater sampled from the aquitard was ~550 µS/cm and from the confined aquifer was ~1350 µS/cm.

The electrical conductivity of groundwater from the aquitard, is less than half that of the groundwater above and below it at both sites. At Nangwarry the electrical conductivity is about 200 µS/cm less than the groundwater in the unconfined and confined aquifers but there is some doubt as to whether it is a representative sample; further sampling is being undertaken.

The chloride ion behaves conservatively in most groundwater, that is, it does not participate in any hydrochemical reactions with other dissolved ions or with the surrounding rock minerals. Providing it is conservative, we can compare the concentrations of other ions relative to chloride to identify changes in the chemical composition of water since the time of recharge (e.g. via precipitation or weathering of minerals). Sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), bicarbonate (HCO_3) and bromide (Br) dissolved ion concentrations and total sulphur (S) from each sample interval were plotted against the chloride ion concentration (Figs 21 and 22).

The line on each graph represents the seawater dilution line for each ion. All rain that is derived by evaporation of sea water should have the same ion/Cl ratio as sea water when it reaches the ground surface. If groundwater compositions plot on these lines, the seawater ratio is preserved, and it is inferred that the ions are of marine origin and have behaved conservatively since recharge occurred.

The unconfined aquifer chemistry at both sites display a wide scatter for all the dissolved ions plotted, relative to the chloride ion. In contrast, the confined aquifer chemistry is distinctive and tightly grouped, and in comparison in between the two sites is lower for each dissolved ion concentration at the Nangwarry site. There is no major ion data for the aquitard at the Nangwarry site.

All groundwater samples are enriched in calcium and bicarbonate relative to chloride (i.e. they plot above the seawater ratio line). This indicates that these solutes have been added to the groundwater since deposition, most likely through a water/rock mineral interaction process. This enrichment is not unexpected given that the unconfined aquifer is largely made up of calcareous sandstone and limestone, both rich in calcium carbonate. Groundwaters in the South East are generally saturated with respect to calcite.

Groundwater of the confined aquifer tends to be enriched in sodium and depleted in potassium concentration relative to chloride. Dissolved magnesium data plots on the seawater dilution line suggesting the ion has behaved conservatively since passing below ground surface.

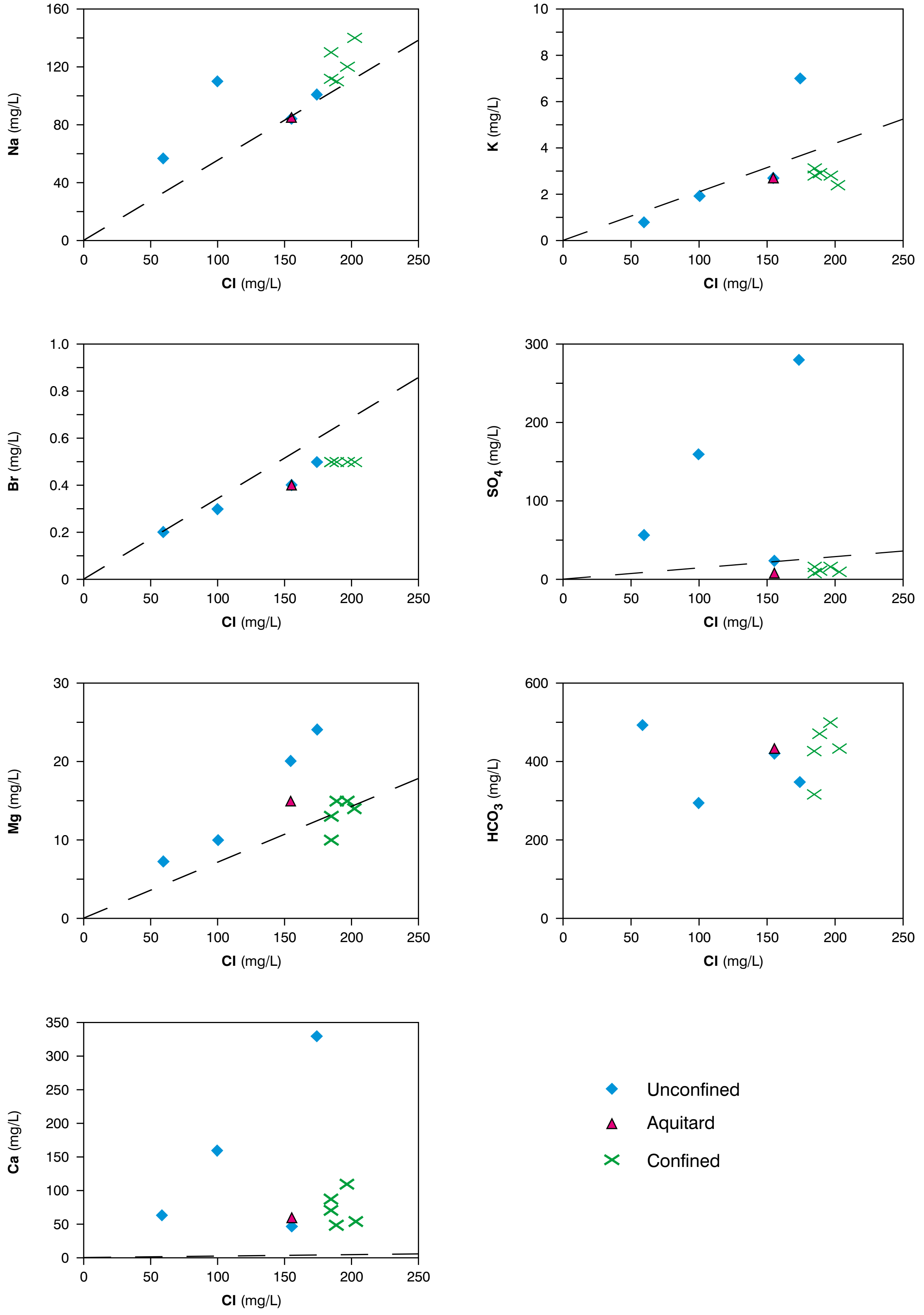


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Figure 21 Major ions against chloride, Tarpeena site.

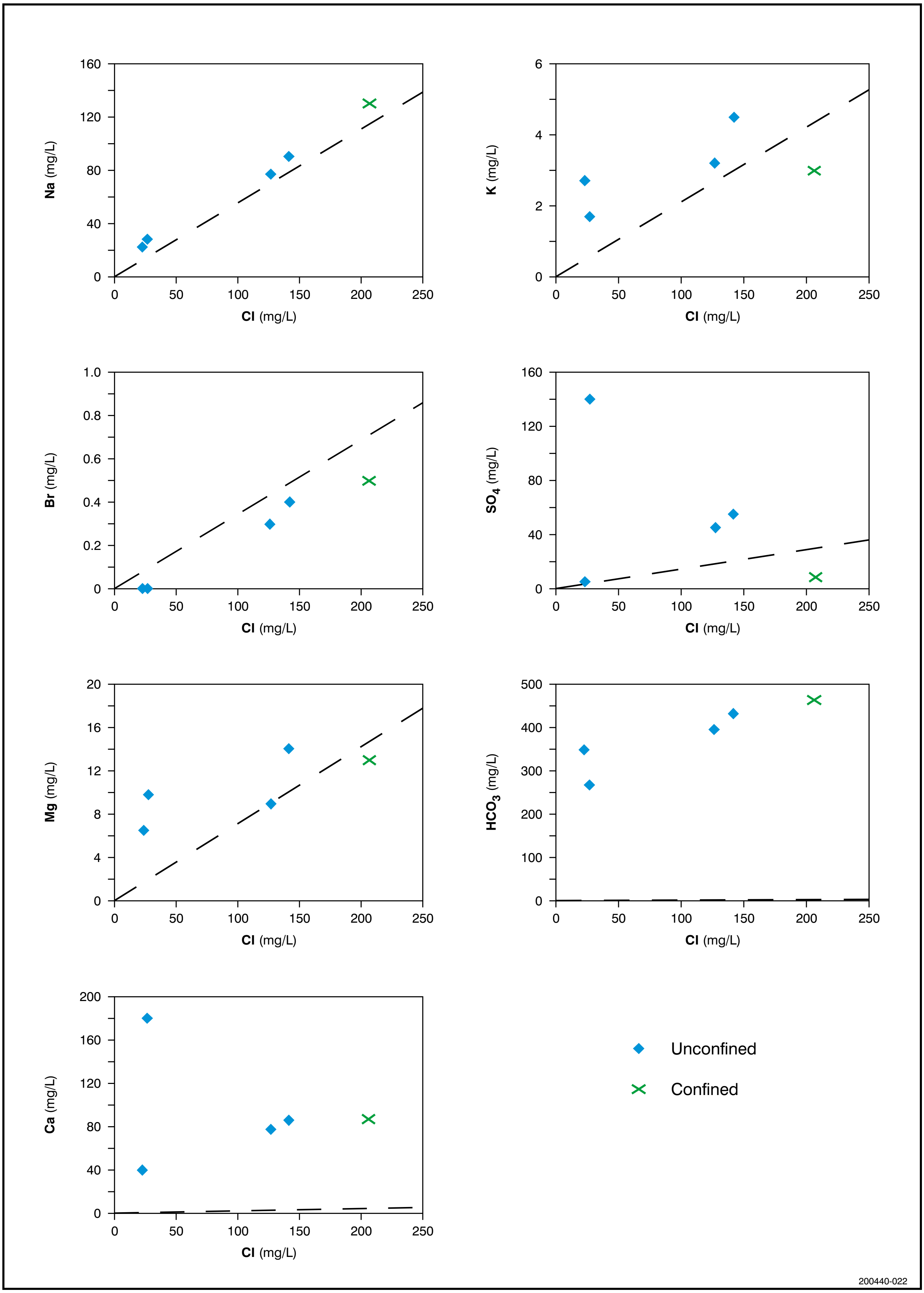

Figure 22 Major ions against chloride, Nangwarry site.

CHLORIDE PROFILE

The chloride profile for both the Tarpeena and Nangwarry sites is presented respectively in Figures 19 and 20. Chloride values at the watertable piezometer at each site are relatively low, 59 mg/L at the Tarpeena site and 23 mg/L at Nangwarry site. The low chloride concentrations coupled with reasonably high rainfall would suggest reasonably high recharge rates at both sites which contradicts CFC results.

In addition to obtaining chloride concentrations of the groundwater, chloride concentrations were also determined from pore water taken from drill core clay samples. In three screened intervals at the Tarpeena site there is both a groundwater sample and a pore water sample allowing a comparison between the two techniques (Fig. 19). In the aquitard there was good match in chloride concentration between analysis methods. The groundwater sample chloride measured 155 mg/L and the pore water chloride ranged from ~156 to 172 mg/L. In the first of the other screened intervals (21.6–23.6 m) the groundwater chloride concentration was 164 mg/L and the pore water chloride was 246 mg/L. The other screened interval, at 31–34 m, had a groundwater chloride concentration of 185 mg/L while the pore water concentration ranged from 209 to 277 mg/L. The difference, while small, is consistently higher in the pore water chloride taken from the clay samples.

At the Nangwarry site the groundwater sample chloride was 55 mg/L and the pore water chloride ranged from ~150 to 177 mg/L, which is in the same range as for the aquitard at the Tarpeena site.

Radon and hydraulic conductivity

The concentration of radon in groundwater has been successfully used in fractured rock aquifers to quantify the horizontal groundwater flow rate (Cook et al., 1999). At each screen interval the radon concentration was measured in the well prior to pumping (unpurged). This was then compared with a pumped (purged) sample representative of the aquifer radon concentration. A high ratio of unpurged/purged radon is indicative of high flow into the well.

Radon data (purged (C), unpurged (Co), and C/Co ratio) were plotted against depth for each site (Figs 23 and 24). C/Co ratios at both sites are typically quite low (< 0.5). Although a direct relationship between radon concentration and hydraulic conductivity was not possible, there was a general trend of high C/Co ratios and high hydraulic conductivities, and vice versa for low C/Co ratios.

GENERAL DISCUSSION OF RESULTS

Potential recharge area

Vertical recharge to the confined aquifer may be over a much smaller area than that inferred from a simple downward head gradient from the unconfined aquifer. On the basis of data collected during this investigation, it is concluded that: (1) recharge to the confined aquifer may be controlled and limited by faulting, fractures or sinkholes through the aquitard; (2) east of the Kanawinka Fault ^{14}C activities are at background levels which would suggest very little recharge is occurring to the confined aquifer in this area; and (3) one of the areas with a high ^{14}C concentration, and therefore an

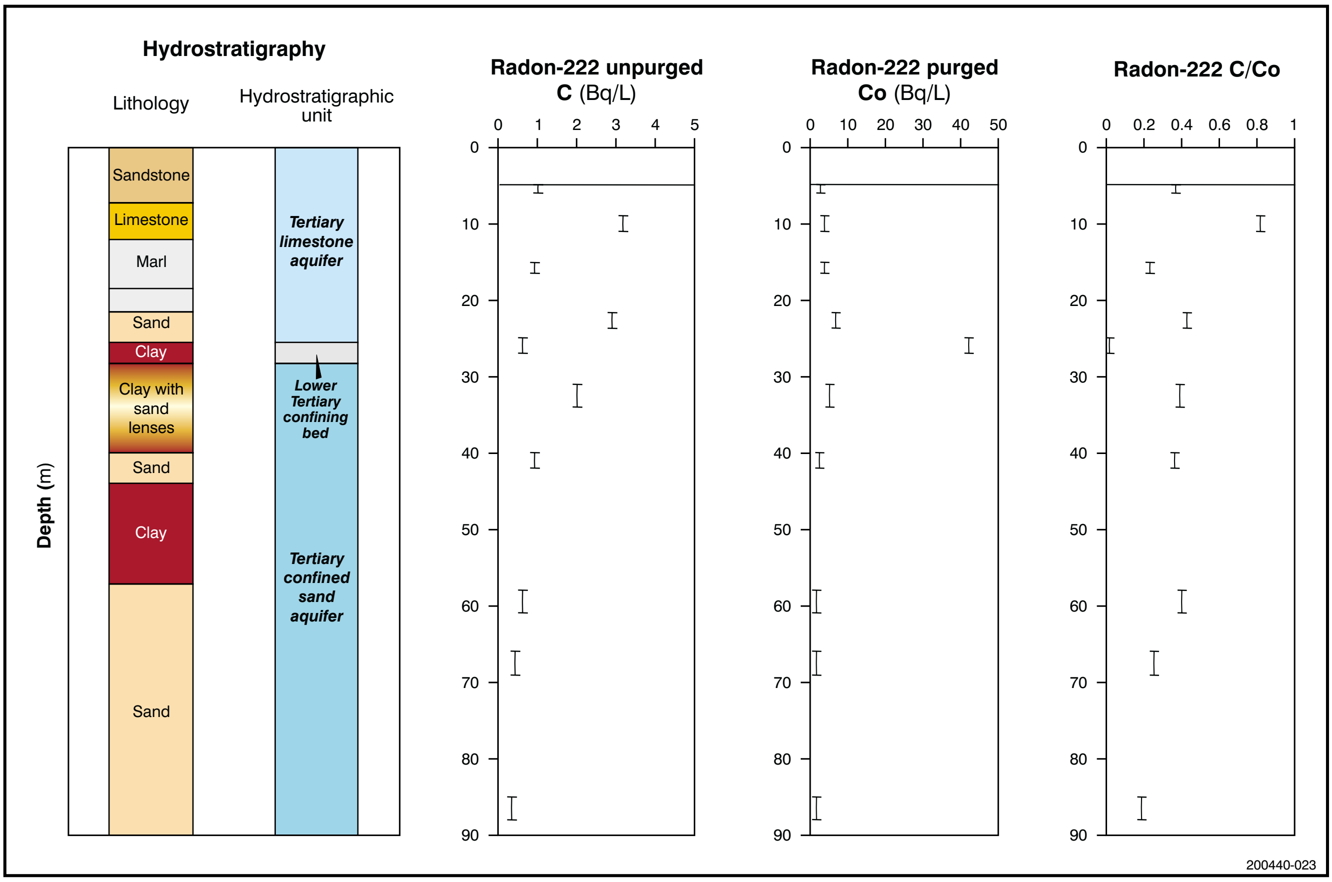

Figure 23 Hydrostratigraphy and radon (C, Co and C/Co) profiles, Tarpeena site.

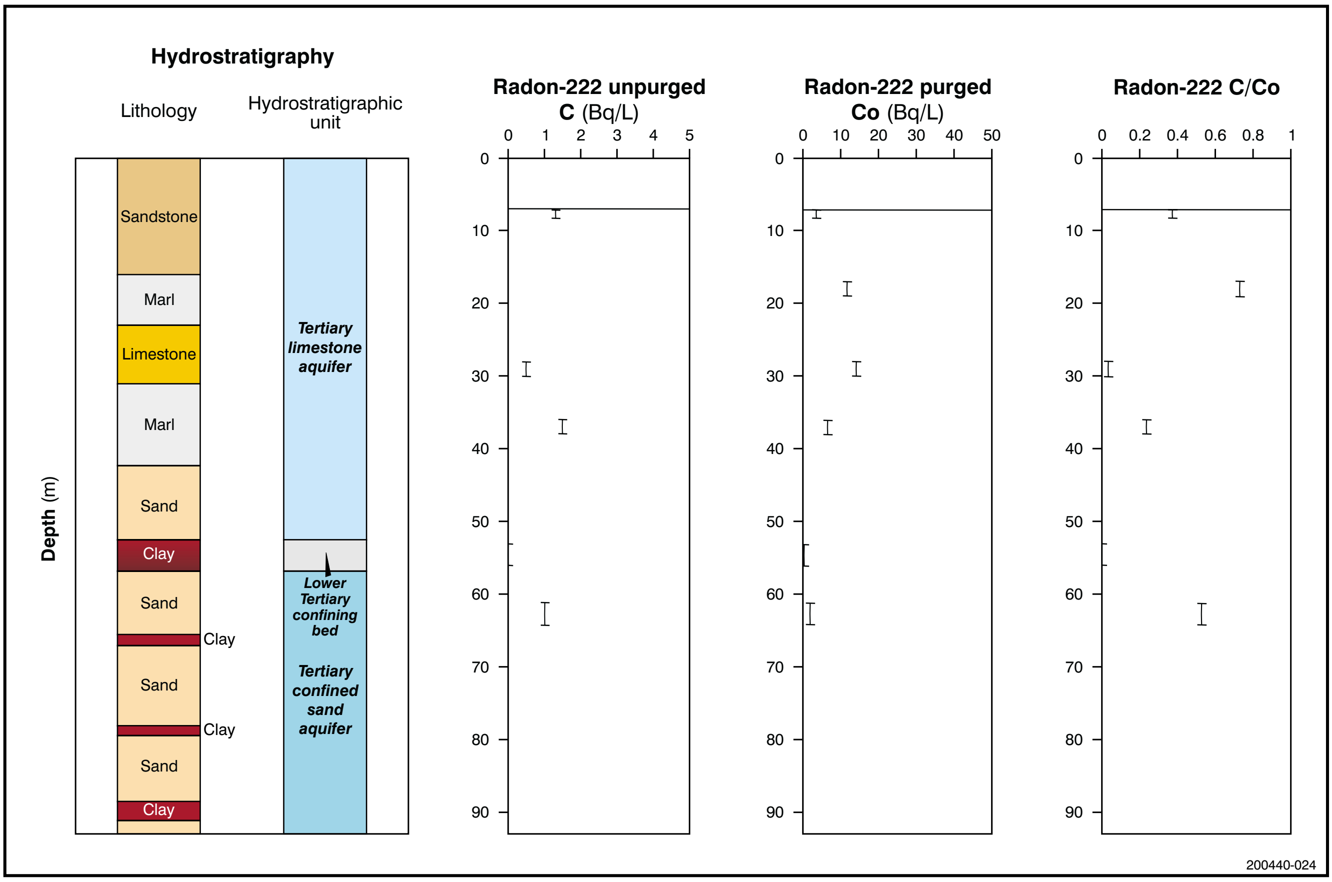

Figure 24 Hydrostratigraphy and radon (C, Co and C/Co) profiles, Nangwarry site.

inferred recharge area, is now covered by forestry. The presence of the forest will in effect preclude any further recharge to the confined aquifer occurring.

Recharge mechanisms

The ^{14}C profile at the Tarpeena site decreases from relatively high values of ~60 pmc near the watertable to <15 pmc through the underlying marl and clay aquitard. Higher groundwater ^{14}C concentrations in the confined aquifer suggest that vertical recharge from the unconfined aquifer is not by diffuse percolation through the aquitard. The CFC data show a similar trend; concentrations decrease to zero in the aquitard but increase in the upper subaquifer of the confined aquifer. If recharge is not occurring by a diffuse mechanism, then ^{14}C and CFC data cannot be used to estimate a recharge rate. The only semi-quantitative information that the ^{14}C and CFC concentrations provide is that the groundwater in the confined aquifer is younger than those in the aquitard and in the basal unit of the overlying unconfined aquifer.

If recharge to the confined aquifer is not diffuse, then conventional methods for estimating recharge, such as the Darcy equation and chloride mass balance are inappropriate. Moreover, the argument that it is the head difference between the two aquifers that is driving recharge, may not be valid for this system. The head difference could simply be a reflection of the very low-permeability of the clay aquitard. A large head difference between the two aquifers may reflect an area of relatively low recharge.

Based on the results from this study, flow through the aquitard into the confined aquifer is conceptualised as occurring via preferential flow paths such as fracture zones and corroborates the earlier work of Colville and Holmes (1972). They, however, suggested that the recharge to the aquifer occurred via sink holes. Extensive faulting occurs throughout the South East and has had a significant impact on lateral flow in both the unconfined and confined aquifers but its impact on vertical flow to this point had not been recognised. If relatively high conductivity zones are responsible for recharge to the confined aquifer, then they must extend vertically from the top of the unconfined aquifer into the confined system, in order to produce the observed ^{14}C and CFC profiles. The absence of, or fracture through, the aquitard alone would not produce the observed ^{14}C profiles. In such a scenario, the ^{14}C concentrations in the confined aquifer would be expected to be much lower than observed, as they would have to had mixed with low pmc ^{14}C groundwater in the overlying marl and aquitard.

Management implications

The estimated total water use from the confined aquifer is ~30 to 35 000 ML/yr and this mostly occurs west of the zero head difference in the main artesian area. If extraction is maintained at its current rate, the head will continue to decline in this area until a new equilibrium is established. However, the current extraction rate does not explain the disproportionate decline in head in areas outside the main irrigation area.

The observed recent decline in water levels from hydrographs in the unconfined aquifer is regional and is attributed to below-average annual rainfall over the last seven years. However, it is also likely that reforestation has resulted in a lowering of recharge rates and hence water levels in several areas of the region.

The head gradient, ^{14}C activity, CFC concentrations and geology of the profile at both sites show that there is a minimum of two discrete subaquifers within the confined aquifer. There has been very little research into deeper subaquifers within the confined aquifer but they may provide an important alternative source of groundwater.

It is concluded that while the confined aquifer has received recharge since the end of the last glaciation, vertical flow is not controlled by diffuse recharge through a porous medium, and hence the current rate of recharge could not be quantified. In some areas such as beneath forest the aquifer may be receiving no recharge at all. Based on ^{14}C information the recharge areas to the confined aquifer is spatially a lot smaller than previously recognised.

RECOMMENDATIONS

1. This study be ongoing and that a further review of the project be undertaken once the outstanding hydrochemical and isotopic data become available.

2. Implement a drilling program and geophysical survey to broaden the conceptual understanding of groundwater recharge to the confined aquifer in the Nangwarry–Tarpeena area with specific reference to determining if fracture flow or possibly karstic flow mechanisms are the preferred flow path medium to the aquifer.

3. Monitor both the confined and the unconfined aquifers for water level and water quality, including areas outside the main irrigation area, until the degree of hydraulic connection between the unconfined and confined aquifers is better understood.

4. Quantify the total extraction from the confined aquifer and restore leaking wells in the main irrigation area.

5. Adopt an alternative method of groundwater allocation using a volumetric approach. Under the current method, the unconfined and confined aquifers are managed as one system and it is assumed that any excess irrigation water applied percolates back down into the aquifer; this is not true for the confined aquifer.

6. Investigate the hydrogeology of the deeper subaquifers in the confined aquifer.

APPENDIX

SUMMARY OF ^{14}C ACTIVITIES, SOUTH EAST CONFINED AQUIFER INVESTIGATIONS

Observation well	**Unit number**	**MGA zone**	**Easting**	**Northing**	^{14}**C** (pmc)
HYN 19	7024–2712	54	466 376	5 922 115	0
ROB 11	7023–3736	54	466 843	5 892 710	31.9
PEN 25	7023–1827	54	494 624	5 859 914	60.4
MON 19	7023–3675	54	472 172	5 862 884	46.8
SHT 13	7023–3674	54	456 144	5 864 007	9.9
FOX 10	6923–3060	54	437 456	5 883 624	37
MTB 17	6824–1411	54	400 293	5 915 012	10.7
GRY 16	7022–0690	54	473 838	5 842 108	18.2
YOU 25	7022–4194	54	469 103	5 826 795	39.4
YOU 27	7022–4192	54	476 084	5 829 020	55.7
HIN 29	6922–0401	54	455 105	5 829 053	49.4
HIN 30	7022–3977	54	459 176	5 834 721	39.2
NAN 22	7022–5530	54	493 249	5 839 875	40.9
ROS 10	6923–1566	54	416 238	5 885 074	15.3
ROS 19	6823–0977	54	406 277	5 900 481	21.6
RID 11	7022–4190	54	457 678	5 849 283	3.3
CLS 13	7023–1849	54	457 185	5 873 969	24.5
ROS 20	6923–3610	54	413 997	5 896 712	25
	6924–2244	54	443 883	5 907 436	30.9
TNS 17	6924–1273	54	423 147	5 914 842	23.2
	6824–0470	54	400 377	5 921 520	6.5
BOW 9	6924–1045	54	411 855	5 912 640	16.9
SPE 13	7024–2711	54	462 484	5 911 786	29.1
	7022–1910	54	481 813	5 835 382	49.6
	7021–1347	54	473 457	5 788 209	1.3
	7022–2676	54	482 385	5 811 077	3.8
MIN 17	7022–1278	54	491 896	5 829 398	37.8
PLP 1	7022–3595	54	497 117	5 796 250	2.5
MIN 21	7022–4191	54	491 672	5 835 608	29.2
BLA 88	7022–2782	54	478 234	5 814 145	13.2
MLG 1	7022–3593	54	498 627	5 810 246	3.8
ARD 1	7022–3594	54	497 547	5 818 166	12.3
	7022–2927	54	480 853	5 815 483	10.6
NAG 1	7122–0039	54	505 867	5 842 337	61.2
NAN 49	7022–8509	54	487 350	5 837 900	54.6
NAN 43	7022–8326	54	495 000	5 843 875	45.6
NAR 45	7024–2713	54	468 507	5 906 645	8.2
MUR 1	6923–0002	54	510 784	5 906 355	2.3
JOY 19	6923–3676	54	446 899	5 900 096	30.9
BIN 23	7024–2786	54	493 057	5 919 461	1.4
NAR 62	7024–4128	54	476 805	5 907 703	0.5

REFERENCES

Allison, G.B. and Hughes, M.W., 1978. The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer. *Australian Journal of Soil Research,* 16:181–195.

Busenberg, E. and Plummer, L.N., 1992. Use of chlorofluorocarbons (CCl_3F and CCl_2F_2) as hydrologic tracers and age-dating tools: the alluvium and terrace system of central Oklahoma. *Water Resources Research,* 28:2257–2283.

Colville, J.S. and Holmes, J.W., 1972. Watertable fluctuations under forest and pasture in a karstic region of southern Australia. *Journal of Hydrology,* 17:61–80.

Cook, P.G., Love, A.J. and Dighton, J.C., 1999. Inferring ground water flow in fractured rock from dissolved radon. *Ground Water,* 37(4):606–610.

Dighton, J.C., Leaney, F.W.S., Herczeg, A.L., Allison, G.B. and Hughes, M.W., 1997. A rapid and robust method for the preparation of isotopically unaltered hydrogen gas from water for stable isotope mass spectrometry. *In: Sixth Australian – New Zealand Environmental Isotope Conference, Lower Hutt, New Zealand.*

Harrington, G.A., Walker, G.R., Love, A.J. and Narayan, K.A., 1999. A compartmental mixing-cell approach for the quantitative assessment of groundwater dynamics in the Otway Basin, South Australia. *Journal of Hydrology,* 214:49–63.

Herczeg, A.L., Dighton, J.C., Easterbrook, M.L. and Salomons, E., 1994. Measurement of radon-222 and radium-226 in groundwater by liquid scintillation counting. *In: Radon and radon progeny measurements in Australia.* Symposium, Canberra, February 1994, pp. 79–82.

Holmes, J.W. and Colville, J.S., 1970a. Grassland hydrology in a karstic region of South Australia. *Journal of Hydrology,* 10:38–58.

Holmes, J.W. and Colville, J.S., 1970b. Forest hydrology in a karstic region of southern Australia. *Journal of Hydrology,* 10:59–74.

Leaney, F.W., Herczeg, A.L. and Dighton, J.C., 1994. New developments for the direct CO_2 absorption method for radiocarbon analysis. *Quaternary Science Reviews* (Quaternary Geochronology), 13:171–178.

Leaney, F.W. and Herczeg, A.L., 1995. Regional recharge to a karst aquifer estimated from chemical and isotopic composition of diffuse and localised recharge, South Australia. *Journal of Hydrology,* 164:363–387.

Love, A., Herczeg, A.L., Armstrong, D., Stadter, F. and Mazor, E., 1993. Groundwater flow regime within the Gambier Embayment of the Otway Basin, Australia: evidence from hydraulics and hydrochemistry. *Journal of Hydrology,* 143:297–338.

Love, A., Herczeg, A.L., Leaney, F.W., Stadter, M.F., Dighton, J.C. and Armstrong, D., 1994. Groundwater residence time and palaeohydrology in the Otway Basin, South Australia: ^{2}H, ^{18}O and ^{14}C data. *Journal of Hydrology,* 153:157–187.

Love, A., Herczeg, A.L. and Walker, G., 1995. Transport of water and solutes across a regional aquitard inferred from porewater deuterium and chloride profiles Otway Basin, Australia. *In: Isotopes in water resources management*. Symposium, Vienna, March 1995. International Atomic Energy Agency, 1:73–86.

Socki, R.A., Karlsson, H.R. and Gibson, E.K. Jr., 1992. Extraction technique for the determination of oxygen-18 in water using pre-evacuated glass vials. *Analytical Chemistry,* 64:829–831.

Warner, M.J. and Weiss, R.F., 1985. Solubilities of chlorofluorocarbons 11 and 12 in water and seawater. *Deep Sea Resources,* 32:1485–1497.