Environmental tracers to constrain conseptual hydraulic models in the Loxton-Bookpurong region

DWLBC Report 2005/25

Government of South Australia

Department of Water, Land and Biodiversity Conservation

The Department of Water, Land and Biodiversity Conservation

Environmental tracers to constrain conceptual hydraulic models in the Loxton–Bookpurnong region

Nikki Harrington, Julianne James-Smith and Andrew Love

Report DWLBC 2005/25

Government of South Australia

Knowledge and Information Division
Department of Water, Land and Biodiversity Conservation
25 Grenfell Street, Adelaide
GPO Box 2834, Adelaide SA 5001

Telephone	+61 8 8463 6946
Fax	+61 8 8463 6999
Website	www.dwlbc.sa.gov.au

Disclaimer

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

Foreword

South Australia's natural resources are fundamental to the economic and social well-being of the State. One of the State's most precious natural resources, water is a basic requirement of all living organisms and is one of the essential elements ensuring biological diversity of life at all levels. In pristine or undeveloped situations, the condition of water resources reflects the equilibrium between, rainfall, vegetation and other physical parameters. Development of these resources changes the natural balance and may cause 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 the resource to continue to meet the needs of users and the environment. Understanding the cause and effect relationship between the various stresses imposed on the natural resources is paramount to developing effective management strategies. Reports of investigations into the availability and quality of water supplies throughout the State aim to build upon the existing knowledge base enabling the community to make informed decisions concerning the future management of the natural resources thus ensuring conservation of biological diversity.

Bryan Harris

Director, Knowledge and Information Division

Department of Water, Land and Biodiversity Conservation

CONTENTS

LIST OF TABLES

LIST OF FIGURES

SI UNITS COMMONLY USED WITHIN TEXT

Name of unit	Symbol	Definition in terms of other metric units	
Millimetre	mm	10^{-3} m	length
Metre	m		length
Kilometre	km	10^{3} m	length
Hectare	ha	10^{4} m^{2}	area
Microlitre	µL	10^{-9} m^{3}	volume
Millilitre	mL	10^{-6} m^{3}	volume
Litre	L	10^{-3} m^{3}	volume
Kilolitre	kL	1 m^{3}	volume
Megalitre	ML	10^{3} m^{3}	volume
Gigalitres	GL	10^{6} m^{3}	volume
Microgram	µg	10^{-6} g	mass
Milligram	mg	10^{-3} g	mass
Gram	g		mass
Kilogram	kg	10^{3} g	Mass

Abbreviations Commonly Used Within Text

Abbreviation		Name	Units of measure
TDS	=	Total Dissolved Solids *(milligrams per litre)*	mg/L
EC	=	Electrical Conductivity *(micro Siemens per centimetre)*	µS/cm
PH	=	Acidity	
δD	=	Hydrogen isotope composition	°/oo
CFC	=	Chlorofluorocarbon *(parts per trillion volume)*	pptv
$\delta^{18}O$	=	Oxygen isotope composition	°/oo
^{14}C	=	Carbon-14 isotope *(percent modern Carbon)*	pmC
Ppm	=	Parts per million	
Ppb	=	Parts per billion	

EXECUTIVE SUMMARY

The clearance of native vegetation and its replacement with irrigated crops adjacent to the River Murray has had a deleterious impact on the health of the river. These anthropogenic activities have resulted in an increase in the amount of salt entering the River Murray compared with natural pre-European settlement discharge conditions. It is estimated that 200 tonnes of salt enter the river each day between Bookpurnong and Loxton. In response to this, the Department of Water, Land and Biodiversity Conservation (DWLBC) is undertaking a multi-disciplinary investigation to develop both a concept and construction design for a Salt Interception Scheme (SIS) along this reach of the river.

This report presents results from the hydrochemical and environmental isotope component of the investigation. The environmental tracer approach was adopted due to the complexity of the groundwater flow system in the Bookpurnong-Loxton region including the potential for inter-aquifer mixing. In such situations, conventional hydraulic techniques applied in isolation are limited, and groundwater geochemical and isotopic data can provide valuable information to improve confidence in and help to constrain the conceptual model of the groundwater flow system.

Groundwater samples were collected from observation and production bores located along three transects on the eastern side of the River Murray. The three transects were oriented approximately in the direction of groundwater flow towards the river. Samples were also collected from a series of wells on the floodplain adjacent the river. Sampled bores were screened in the unconfined Loxton Sands / Monoman Formation aquifers and in the confined Murray Group aquifers (Pata, Glenforslan and Upper Mannum Formations). At some locations, samples of perched groundwater in the Woorinen Formation were also collected. Nests of bores, screened in all of the major aquifers were available for sampling at many of the locations. Groundwater samples were analysed for their major ion compositions (Cl, HCO_3, SO_4, Na, K, Ca, Mg) and concentrations of various trace elements (Br, Si, Al, Cd, Fe, Mn, Se, Sr and NO_3), as well as the stable isotope of the water molecule ($\delta^{18}O$ and $\delta^{2}H$) and $^{87}Sr/^{86}Sr$ ratios. Selected samples were also analysed for their ^{14}C, $\delta^{13}C$ and $\delta^{34}S$ compositions.

A combined tracer approach was used due to the similarity in the major ion compositions of groundwater in the different aquifers. Furthermore, different tracers were likely to be useful in identifying different processes in different parts of the system. For example, $\delta^{18}O$ and $\delta^{2}H$ can be useful in distinguishing between different recharge conditions and hence different water types, ^{14}C can be used to calculate groundwater residence times and to identify mixing between "old" groundwater and comparatively "young" groundwater. $\delta^{13}C$ can be used to identify many geochemical reactions that can affect ^{14}C signatures, as well as those of other tracers. The $^{87}Sr/^{86}Sr$ signature of a groundwater sample is strongly influenced by the mineralogy of the aquifer through which it flows and, hence, can differ markedly between silicate and carbonate aquifers, for example. $\delta^{34}S$ has been used successfully in the identification of inter-aquifer mixing in the Murray Basin (Dogramaci, 1998).

Using both naturally occurring environmental tracer and hydraulic data, a conceptual model of groundwater and solute movement at Loxton was developed. This involved identifying the chemical and isotopic signatures of potential groundwater mixing end -

members and applying simple mixing equations to determine inter-aquifer mixing ratios. The groundwater end-members that were identified and the origins of their salinity are:

- Regional Renmark Group groundwater, with a TDS of 3000–5000 mg/L. The Renmark Group groundwaters are palaeowaters, having recharged more than 30 kyr ago under a wetter climate than today.
- Regional Murray Group groundwater, with a TDS of 19 700–27 000 mg/L. This comparatively high TDS groundwater is diluted in the vicinity of the River Murray by upward leakage of lower TDS groundwater from the underlying Renmark Group aquifer system.
- Regional Lower Loxton Sands groundwater, with a TDS of 73 000 mg/L. Lateral flow of this groundwater into the floodplain Monoman Formation is responsible for the highest TDS concentrations observed in the latter aquifer, adjacent the River Murray.
- Regional Upper Loxton Sands groundwater, with a TDS of 36 000 mg/L. Although the TDS concentration of this groundwater is lower than that of the Lower Loxton Sands, lateral inflow of this groundwater is also responsible for high TDS concentrations in the Monoman Formation adjacent the River Murray, to the north of Loxton.
- Irrigation drainage water, with a TDS of <6500 mg/L. River water with a salinity of approximately 200 mg/L has undergone some evapotranspiration and mixed with higher salinity groundwater in the Loxton Sands and Monoman Formation.

In our conceptualisation of the system, the following processes were found to be important controls on the distribution of TDS concentrations in groundwater in the Loxton - Bookpurnong region:

- Upward leakage of comparatively fresh groundwater from the Renmark Group aquifer system, which causes the observed TDS distributions in the Glenforslan and Mannum Formations, and in the Pata Formation near the River Murray. This process therefore has a large influence over the TDS concentrations of groundwater discharging into the floodplain Monoman Formation and ultimately the River Murray. This is particularly important south of Thiele's Sandbar, where upward leakage from the Murray Group has been found to be a significant groundwater source to the Monoman Formation.
- Downward leakage of comparatively fresh irrigation drainage water (TDS <6 500 mg/L), which has replaced high salinity native groundwater (TDS ≈ 36 000 mg/L) in the Upper Loxton Sands aquifer below the Loxton Irrigation district. Leakage of this irrigation water through the Blanchetown Clay aquitard in this region has probably been facilitated by numerous drainage bore holes in that area and has caused a groundwater mound in the Upper Loxton Sands, centred around the LHO3 series of bores to the north east of the Loxton township. A similar process has also resulted in large amounts of irrigation drainage water to be present in the Loxton Sands to the east of bore LHO8, adjacent Westbrook's Floodplain, where it was calculated the groundwater was 100% irrigation water (modified by evaporation and reaction with aquifer minerals).
- Lateral movement of irrigation drainage water through the Upper Loxton Sands results in the discharge of lower TDS groundwater onto the floodplain to the south of Loxton, at bores LFO1A and LFO7A (n.b. any historical discharge from the Upper Loxton Sands would have had a much higher TDS concentration). The process is still in a transient state to the north of Loxton, with Upper Loxton Sands groundwater at bore LHO8 consisting of 100% irrigation drainage water, but native Upper Loxton Sands groundwater is still being discharged to the floodplain further along the flowpath.
- Downward leakage of high TDS groundwater occurs from the Lower Loxton Sands into the Pata Formation near the centre of the Loxton Irrigation Mound. It is estimated that

this has resulted in Pata Formation groundwater compositions in that region that comprise up to 35% groundwater from the Lower Loxton Sands. Simple calculations based on Darcy's law suggest that, if this downward leakage has occurred as a result of the irrigation mound, a vertical hydraulic conductivity of at least 2 x 10^{-3} m/day is implied for the Lower Loxton Clay / Bookpurnong Beds aquitard.

Groundwater flowing into the floodplain Monoman Formation can be derived from a mixture of upward leakage from the Murray Group aquifer system and lateral flow from the Loxton Sands aquifer. The latter may provide groundwater inflow with a native Lower Loxton Sands signature, an irrigation water signature or a mixture of water types. The relative importance of these sources varies along the River as follows:

- Groundwater in the floodplain Monoman Formation at Thiele's Sandbar (LFO6A) and south of this is derived from a combination of upward leakage from the Murray Group aquifers and lateral flow from the Loxton Sands.
- The exception to this is at LFO1A, located within the Loxton Caravan Park, where lateral flow of irrigation water from the Loxton Sands aquifer is the major source of groundwater to the Monoman Formation. This results in low TDS groundwater in the floodplain aquifer to the south of Loxton.
- Groundwater in the Monoman Formation at Thiele's Sandbar, has a comparatively high TDS (26 000 mg/L) despite the upward leakage of low TDS groundwater from the underlying Murray Group aquifers. The reason for this is that groundwater flowing in laterally from the Loxton Sands aquifer has a high TDS regional signature (TDS = 36 000–73 000 mg/L).
- In the area of Westbrook's Floodplain (i.e. bores LFO2A and LFO3A), lateral flow from the Loxton Sands aquifers dominates groundwater inflows to the floodplain Monoman Formation. At LFO2A, this inflow comprises a mixture of irrigation water and native Upper Loxton Sands groundwater. At LFO3A, irrigation water is not flowing into the Monoman Formation, rather a mixture of native Upper and Lower Loxton Sands groundwater results in high TDS groundwater on the floodplain.

The results of this hydrochemical and isotopic study can be used to refine and hence increase confidence in the current hydrogeological conceptualisation for the Loxton and Bookpurnong areas. Groundwater geochemical and isotopic signatures are the cumulative result of hydraulic processes that are very difficult to measure. For example, this study has provided independent evidence of upward and downward leakage between aquifers, whereas existing hydraulic models can only identify areas where there is a potential for movement between aquifers based on a measured static head. Difficulties with the collection of adequate hydraulic data for input into complex groundwater flow models can result in incorrect or inadequate conceptualisation of the system. For example, aquifer properties used in existing hydraulic models are often determined by aquifer pumping tests. These tests only provide local scale aquifer parameters and scaling these up over large areas can over-simplifiy a complex system. Additionally, the interpretation of results from a hydraulic model alone requires an awareness of the non-uniqueness of such a model. Model output that is based on an incorrect conceptual model can easily be matched with field data by varying the most poorly understood aquifer properties to obtain a match. Although hydrogeological models are useful tools for understanding complex systems, the environmental tracers provide an independent means by which to check the validity of the conceptual model and refine it in order to improve the confidence in model predictions.

1 INTRODUCTION AND OBJECTIVES

The degradation of natural ecosystems is a negative side effect of irrigation development. These effects are most pronounced in areas associated with a long history of irrigation. In the Loxton-Bookpurnong irrigation area, increased salt loads to the floodplains and River Murray are having a deleterious impact on the natural ecosystems with 25% of the riparian ecosystem being affected by increased salt loads and a further 15–25% threatened (AWE, 2003a, DWR, 2001).

Numerous studies assessing current and future impacts of the Loxton - Bookpurnong irrigation district on riparian health have been conducted (PPK, 1998; Bone and Davies, 2002; Holland, 2002) with the major findings showing an increase in the groundwater (and salt) discharge onto the floodplain, resulting from irrigation, and a reduced flood frequency (AWE, 2003a). As part of the strategy to reduce the negative impacts of irrigation development, a number of salt interception schemes with wells located on both the highland and floodplain areas is proposed to intercept the highly saline groundwater, lower floodplain water tables and reduce the impact of saline water on floodplain vegetation and the River Murray.

A number of hydrogeological investigations have been carried out to date for the Loxton-Bookpurnong area, which has increased our understanding of the complex hydrogeological system underlying these areas. A large range of hydraulic models now exists for estimating groundwater and solute fluxes through the Loxton/Bookpurnong Irrigation Districts. These include relatively simple analytical cross-sectional models (e.g. Narayan et al., 1993; Jolly et al., 1998; Holland, 2002), highly complex spatial numerical models (Armstrong et al., 1999; South Australian Steering Committee on Salt Interception, 2003) and analytical models implemented spatially within Geographical Information System (GIS) frameworks (Overton et al., 2003). As well as determining present groundwater flow conditions and salt loads, many of these are also intended as predictive tools for determining the effects of future irrigation development and management options on floodplain vegetation health and solute fluxes to the River Murray.

The models have been developed based on hydrogeological, water level and salinity data from an extensive observation well network in the Loxton and Bookpurnong areas. However, despite the unusually comprehensive dataset, the limitations inherent in any modelling exercise still apply, i.e.:

- Models are simplified representations of natural systems, and their ability to represent complexity in these systems is limited by the amount of real data that is available. In the absence of real data, aquifer properties and boundary conditions are usually assumed to be uniform between data points. In reality, such parameters can vary greatly and sometimes unpredictably within small distances, dramatically affecting groundwater flow patterns.
- Results of groundwater flow models can be made to agree with real data (e.g. measured hydraulic heads, groundwater salinities and salt loads) by varying any number of parameters, usually those that are less well understood (e.g. aquifer properties), within acceptable ranges and still maintaining the assumption of homogeneity. The fact that a model can replicate small sets of observation data does not mean that it is a good representation of the real system and will be able to make accurate predictions over large time scales into the future.

For these reasons, although hydrogeological models are useful tools for understanding complex systems, independent methods for constraining the conceptual models on which they are based and improving confidence in their predictions are increasingly being sought. Environmental tracers (naturally occurring elements in groundwater) can provide such a method. The hydrochemical and isotopic signatures of groundwater are cumulative records of its history, and hence their interpretation can be powerful tools in testing and developing conceptual models.

The objectives of this study are to:

- Develop a conceptual model for groundwater flow and solute transport in the Loxton-Bookpurnong region using a combination of chemical, isotopic and hydraulic approaches.
- Determine the relative contributions of (a) horizontal groundwater flow from the Loxton Sands aquifer and (b) upward leakage from the Murray Group aquifers to the salt load in the floodplain at selected locations along the River Murray.

The results of this study will be used to compare, test, and potentially constrain, existing conceptual models of groundwater flow and salt fluxes in these regions.

2 STUDY AREA

2.1 Introduction

The irrigation districts of Loxton and Bookpurnong are located on the eastern side of the River Murray between 25 and 5 km south of Berri (Fig. 1). The irrigation districts support crops predominantly of citrus and grapes, and cover areas of 3400 and 1500 ha (AWE, 2003a) respectively. It is estimated that 36 540 ML/a of water is used for irrigation at Loxton and 8359 ML/a at Bookpurnong, and from this irrigation, approximately 9000 ML of water is added to the groundwater mound each year in the Loxton irrigation district and 1375 ML per annum in the Bookpurnong irrigation area (AWE, 1999; AWE, 2003a). One negative impact of this irrigation is increased salt loads to the adjacent floodplains and the River Murray, with salt loads in the order of 200 t/d identified in this reach by run of river surveys (AWE, 2003a).

2.2 Hydrogeology

The two principal aquifers targeted for salt interception within the Loxton - Bookpurnong area are the Loxton Sands in the highland area and Monoman Formation in the floodplains adjacent to the River Murray. The Loxton Sands forms a regionally extensive unconfined aquifer into which the channel of the ancestral River Murray was incised. Within this channel, the Monoman Formation and the overlying Coonambidgal Formation were deposited, and it is within this sequence that the channel of the modern River Murray is incised. The river is a sink for regional groundwater within the Loxton – Bookpurnong area. A number of geological cross sections have been produced to display the relationship between the various geological units (Figs 2, 3, 4 and 5). The location of these sections A-A’, B-B’, C-C’ and D-D’ are shown in Figure 1.

The characteristics of each hydrogeological unit (Table 1) in the Loxton-Bookpurnong area are discussed in order of increasing depth below ground surface in the following sections. A large portion of the following is sourced from Hill et al. (2005).

2.2.1 COONAMBIDGAL FORMATION

The Coonambidgal Formation aquitard occurs ubiquitously across the floodplain and comprises clay and silts deposited during periods of episodic flooding. It is commonly 4–5 m thick in the middle of floodplains, but can vary in thickness from 1–11 m, with the greater thicknesses observed at the break in slope between the floodplain and highland.

2.2.2 MONOMAN FORMATION

The Monoman Formation unconfined aquifer is the primary target for salt interception on the floodplain, when the Loxton Sands cannot be targeted on the highland. The Monoman Formation consists of relatively clean, fine to coarse-grained, fluvial sands deposited as point bar sands within a wide floodplain. This formation occasionally comprises minor clay and silt layers, and occasional lignite bands towards the base of section. The Monoman

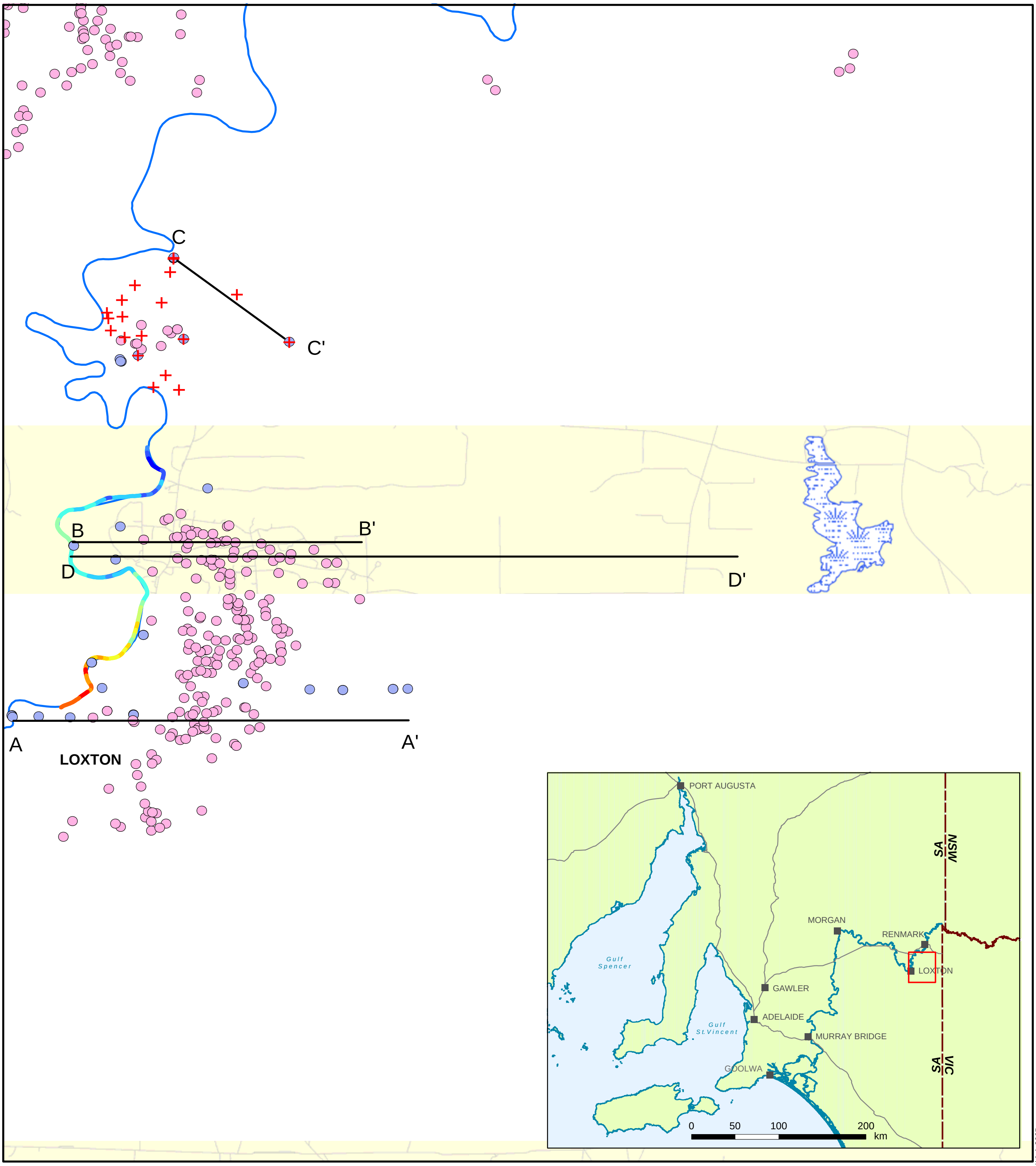


Figure 1.
Loxton - Bookpurnong Site Map

River Surface Salinity Sept 03
420-380 uS/cm

Drainage Wells

Sampled Wells July/Aug 03

Water Quality vs Depth Profiles Sept 03

Noora Saline Groundwater Disposal Complex

N

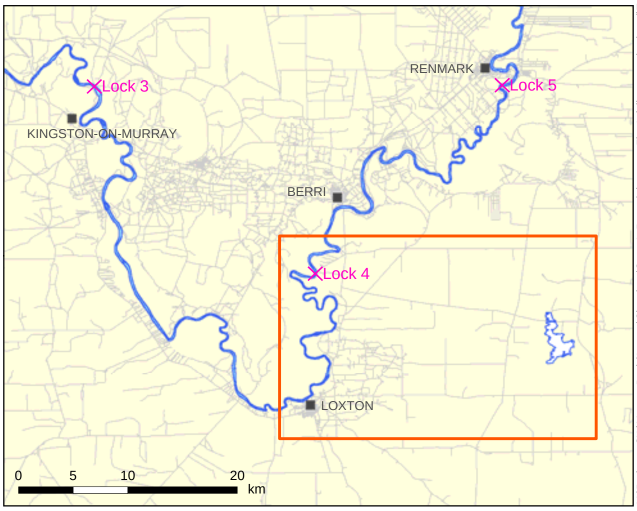
0 1.25 2.5 5 km

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

Date: July 2005

Geocentric Datum of Australia 1994
MGA Zone 54 Transverse Mercator

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



M:\Projects_GW\Murray_Basin\Loxton\Chemistry\Stage1_Report\site_map_Fig_1_julianne_revised.mxd\TanJ01\July2005

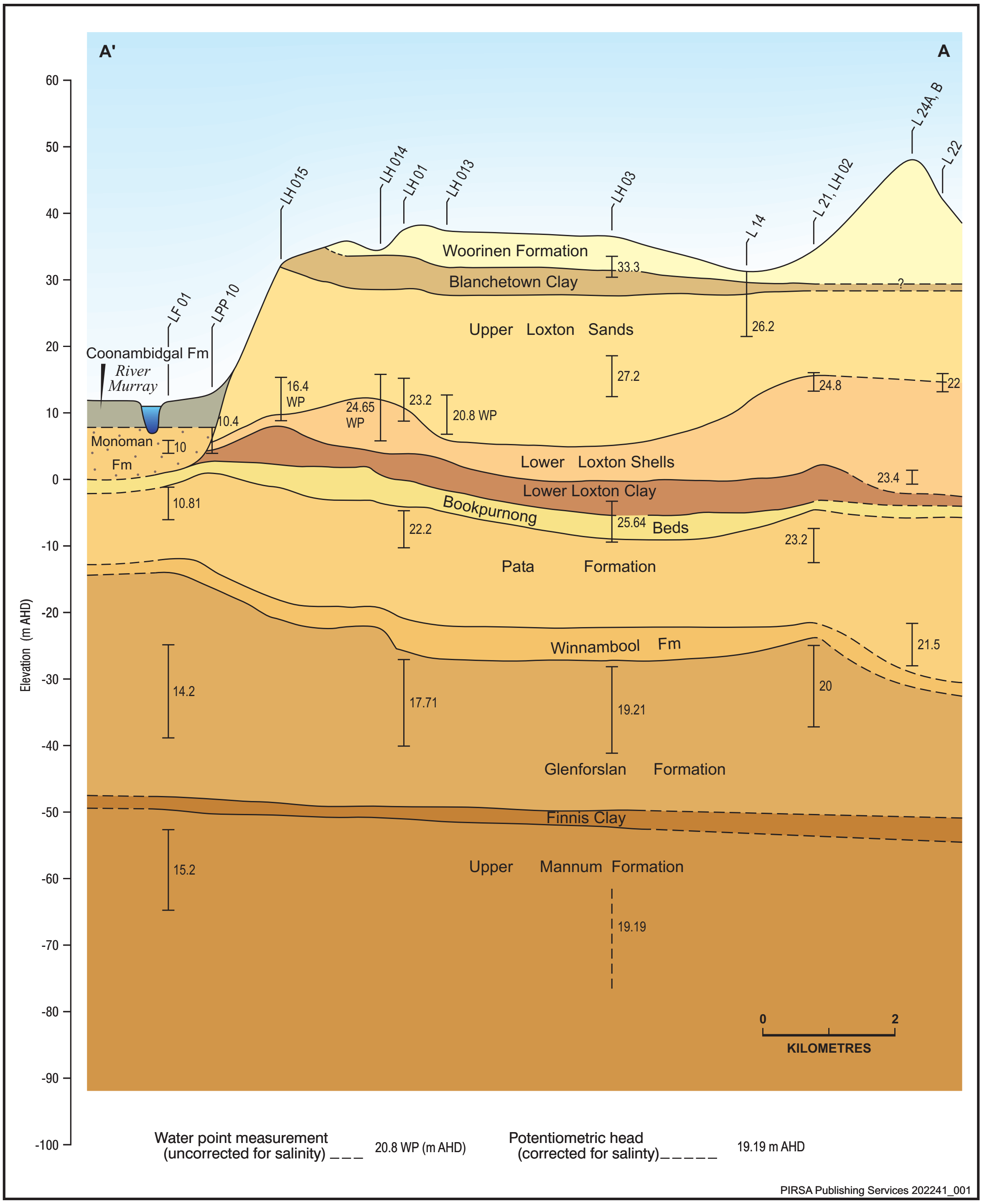


Figure 2. Geological cross-section AA'. See Figure 1 for cross-section location.

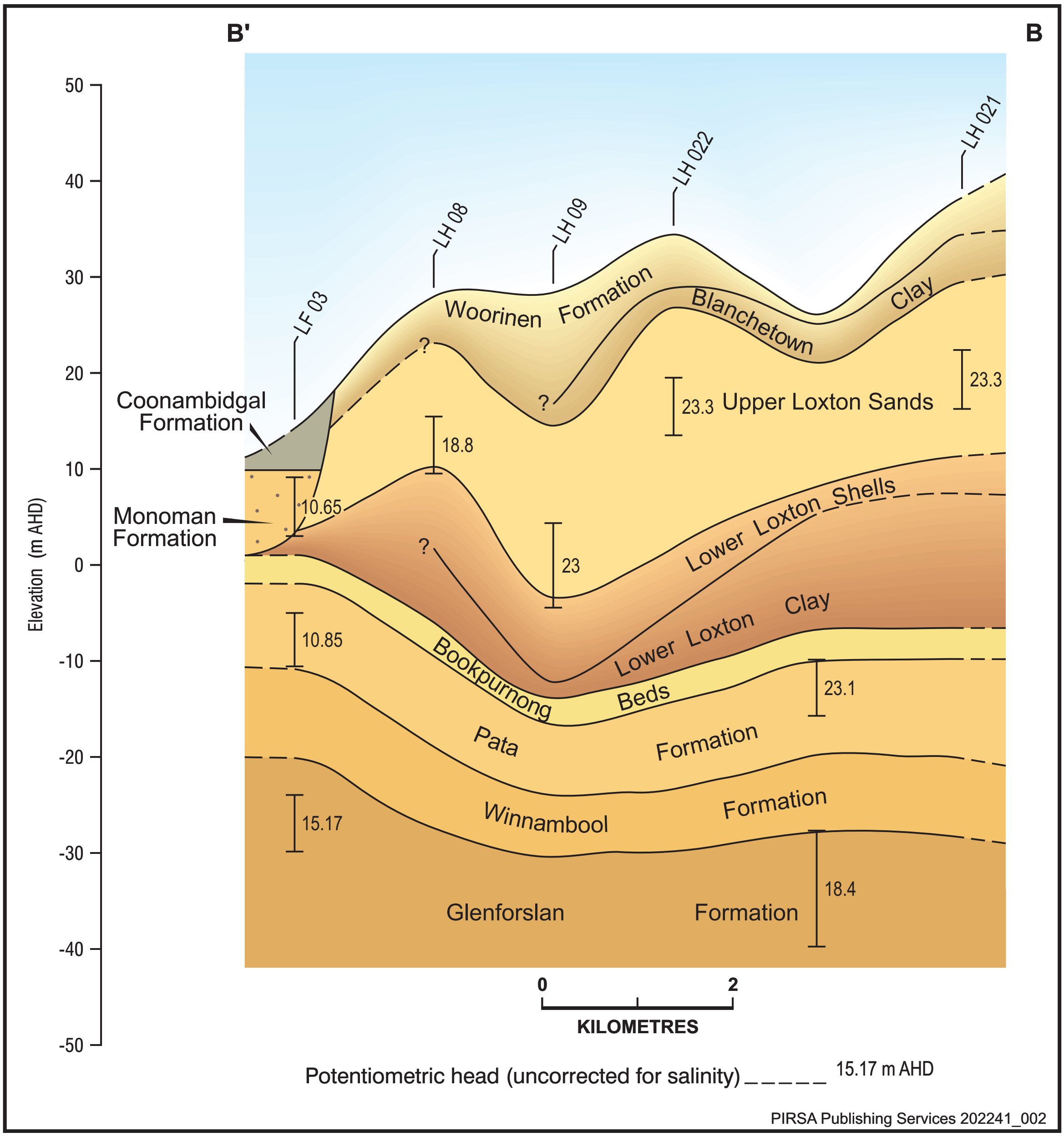


Figure 3. Geological cross-section BB'. See Figure 1 for cross-section location.

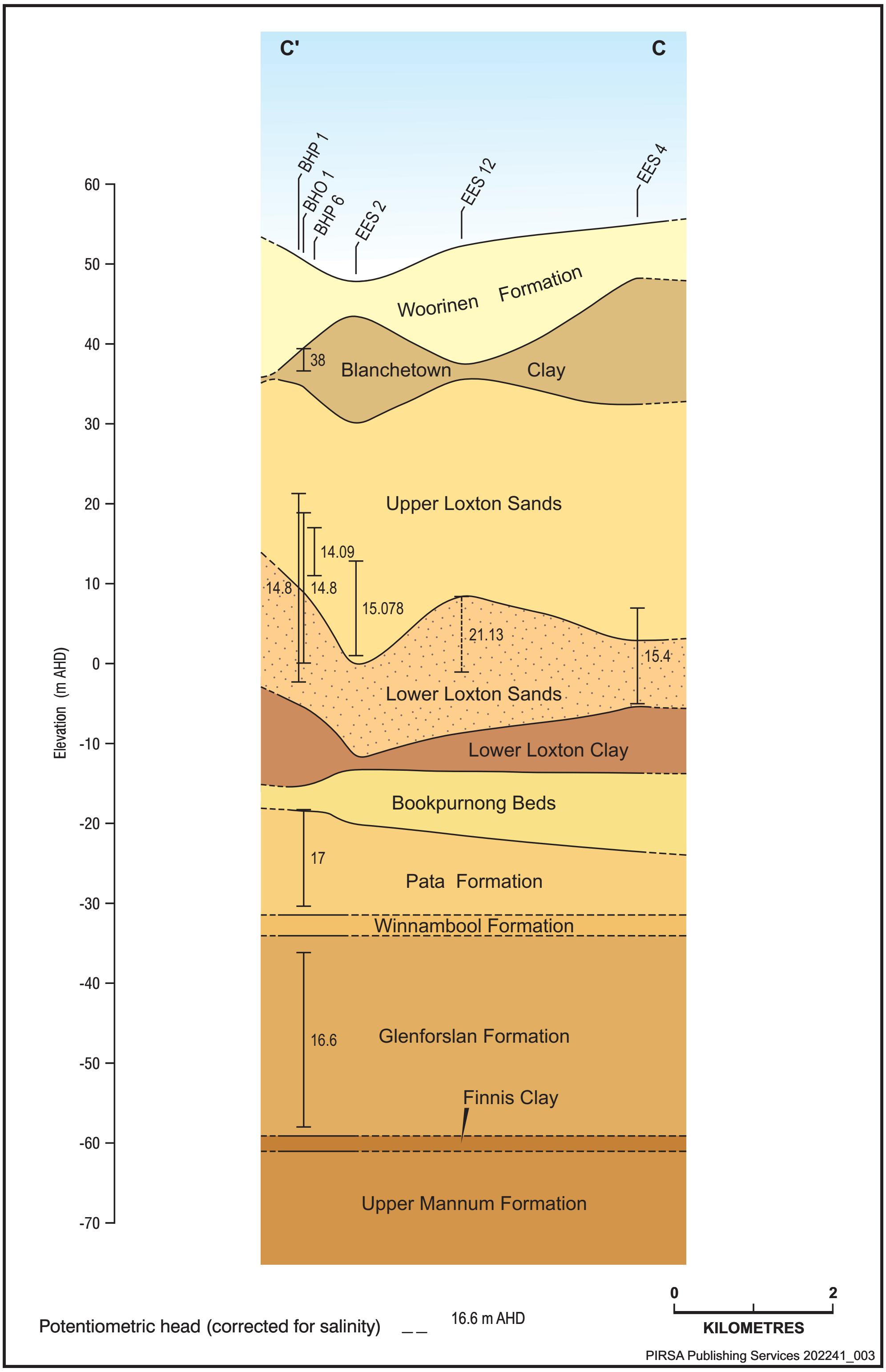


Figure 4. Geological cross-section CC’. See Figure 1 for cross-section location.

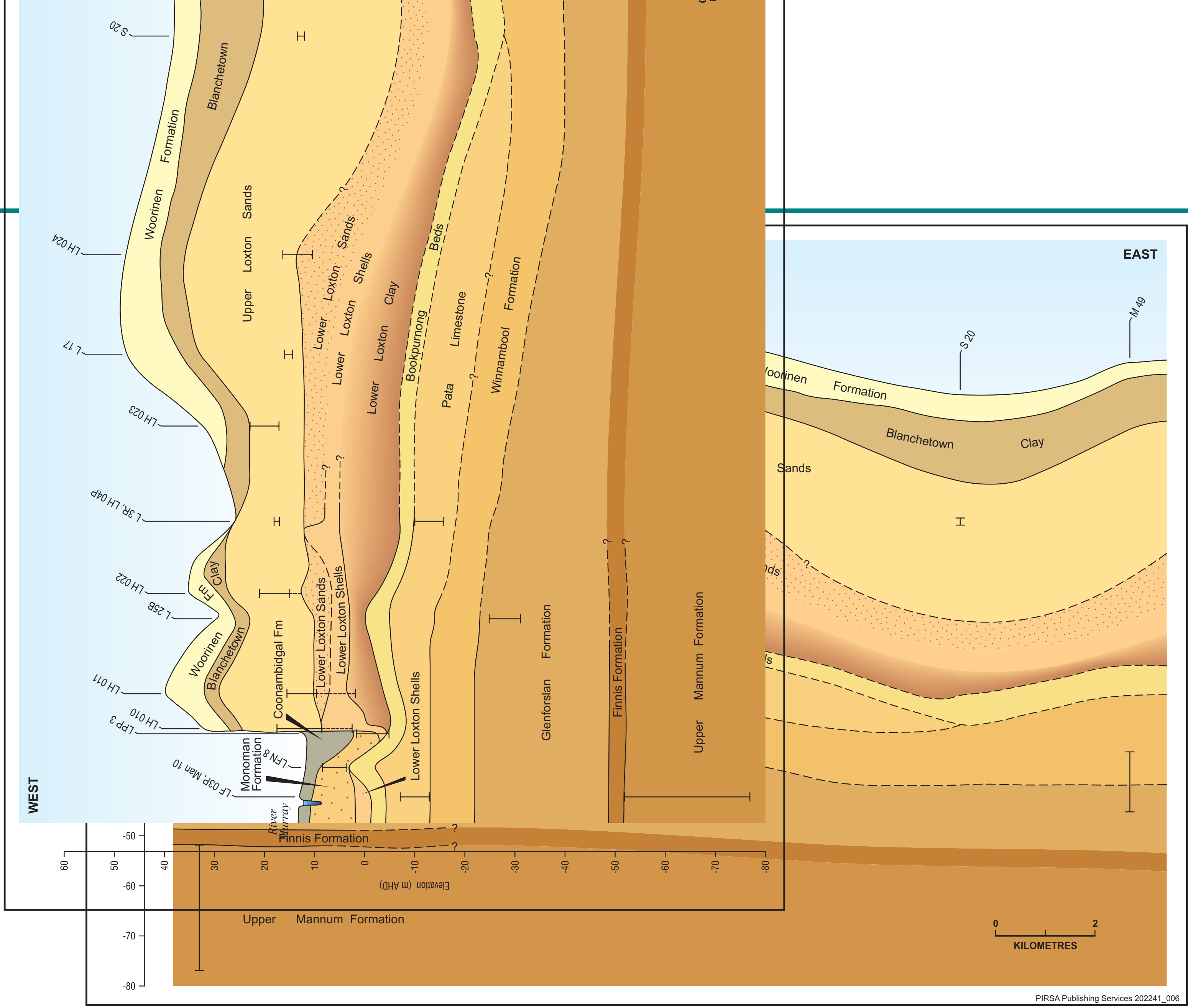


Figure 5. Geological cross-section DD'. See Figure 1 for cross-section location.

Formation is commonly 4–10 m thick and is thin to absent at the break in slope. However, it can reach a thickness of 25 m in deep incised channels within the meander belt.

Table 1. Hydrogeological units of the Loxton – Bookpurnong area.

Hydrogeological Unit		Aquifer / aquitard	Salinity range (mg/L)	Yield (L/s)
Coonambidgal Formation		Aquitard – clay	NA	NA
Monoman Formation		Aquifer semi-unconfined in river valley	5000–60 000	0.5–10
Loxton Sand		Aquifer unconfined to semi-unconfined on highland	5000–40 000	0.5–5
Lower Loxton Clay and Shells		Aquitard – clay, shells	NA	NA
Bookpurnong Formation		Aquitard – clay	NA	NA
Murray Group Limestone	Pata Formation	Aquifer (semi-confined upstream of river kilometre 486) limestone	10 000–30 000	0.5–1
	Winnambool Formation	Aquitard – marl	NA	NA
	Glenforslan Formation	Semi-confined aquifer limestone	5000–30 000	0.5–2
	Finniss Formation	Aquitard - marl	NA	NA
	Upper Mannum Formation	Confined aquifer limestone	3000–25 000	5–10
	Lower Mannum Formation	Confined aquifer limestone	NA	NA

The Monoman Formation is restricted to the River Murray valley and is in direct hydraulic communication with both the river and the adjacent Loxton Sands. In some instances, the Monoman Formation is in direct contact with Pata Formation where the Lower Loxton Clay and Shells and Bookpurnong Formation have been eroded by the ancestral Murray River channel. As a consequence of the depositional environment, the Monoman Formation is a highly variable aquifer with yields ranging from 0.5–10 L/s. This variability makes it difficult to predict likely yields across the floodplain, to the extent that production wells separated by 10 m can demonstrate contrasting specific yields.

The water table surface, corrected for density, for the Loxton Sands and Monoman Formation at May 2004 is given in Figure 6. The water table surface has been merged for these two units because of their hydraulic connection. A prominent groundwater mound trending northeast - southwest occurs in the Loxton Sands below the Loxton irrigation area, with a maximum height of >25 m AHD, and a smaller mound occurs in the Bookpurnong area (Fig. 6).

Groundwater heads are up to 2 m above river pool level (~10.0 m AHD) at the break of slope (Loxton Sands / Monoman Formation) on the eastern side of the River Murray (Fig. 6). On the western side of the river, groundwater heads are either close to or below river pool level with the exception of slightly elevated potentiometric heads (>10 m AHD) in the area of the Katarapko Island disposal basin to which irrigation drainage water from the Comprehensive Drainage System (CDS) network is pumped.

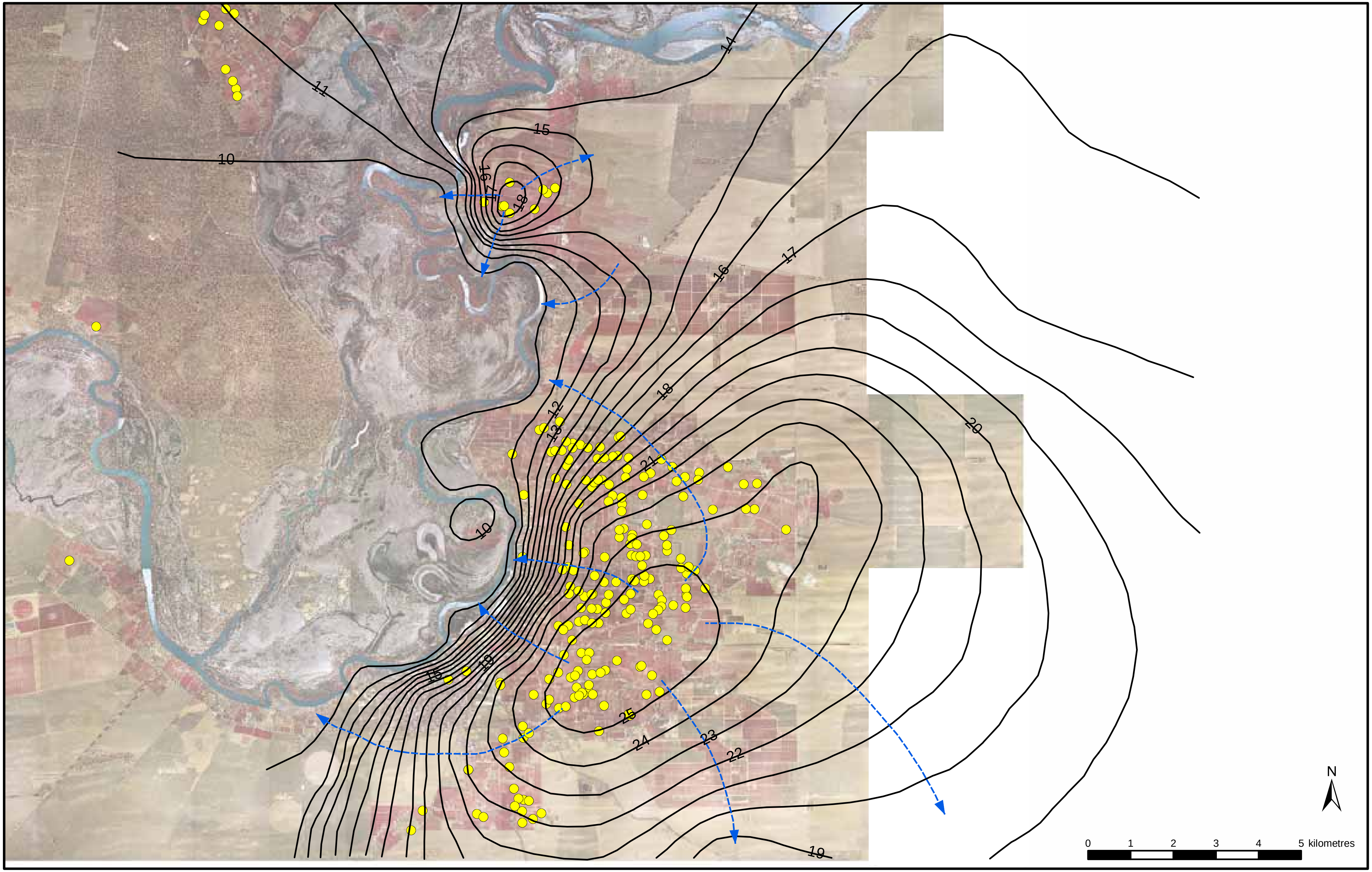


Figure 6. Density-Corrected Water Table Surfacefor the Unconfined Aquifer (Loxton Sands and Monoman Formation), May 2004.

Potentiometric Surface (mAHD)

Flow Line

Drainage Bore

The Department of Water, Land and Biodiversity Conservation

Government of South Australia

2.2.3 LOXTON SANDS

The Loxton Sands unconfined aquifer is the primary target for salt interception on the highland, yet is the most difficult interception target due to its unpredictable yield. In broad terms, the Loxton Sands represents an inverted aquifer, with the most permeable coarse grained and frequently unsaturated sands occurring at the top of the sequence and the least permeable fine sands (and occasional shell hash) at the base of the succession. These sands grade to a low permeability silty clay and shell facies towards the base, referred to in this report as the Lower Loxton Clay and Shells. This upward coarsening sequence represents a shift from offshore to nearshore and back beach/dune depositional environments, reflecting cyclic eustatic sea level drops resulting in progradational clastic packages.

Detailed sedimentological analysis, downhole geophysical logging and airborne electromagnetic (HEM) geophysical surveys (Hill et al. 2005) have helped to unravel the complexity of the Loxton Sands and provide some confidence for predicting suitable facies for salt interception at or below river pool level.

The key to predicting permeable sands is proximity to HEM derived strandlines (Fig. 7) that represent maximum thickness of the Loxton Sands during periods of eustatic stability. In general, there is an increased probability of better developed sands coincident and landward (i.e. to the northeast) of the strandline for distances up to 600 m, although more commonly 200–300 m. Fine to medium grained tidal channel deposits (often with shell hash at the base of the sequence) appear to occur within discrete zones parallel to strandlines and have been mapped over several kilometres in the Bookpurnong area.

The Loxton Sands have been targeted in the Loxton area for salt interception where no floodplain exists. However, the base of the fine sands and shell hash occurs close to river pool level and accordingly this has a significant impact on production well spacing in order to achieve effective salt interception. Although the Loxton Sands are commonly up to 25–30 m thick, the permeable basal shell hash and coarse sand unit at the base of the succession in the Loxton area is only 2 to 3 m thick. Yields up to 1.5 L/s have been observed in production wells completed in the basal shell hash facies. Elsewhere, yields vary from <0.5 L/s in fine grained sands up to 5 L/s in coarse grained facies in the Bookpurnong area in the area targeted for highland interception.

A contour map of groundwater salinity in the Loxton Sands and Monoman Formations shows a large plume of high TDS groundwater (approximately 60 000 mg/L) in the Loxton Sands aquifer to the east of Loxton (App. B). The source of salt to this groundwater may be the Noora Saline Groundwater Disposal Complex. Groundwater salinities then decrease towards the River Murray, with comparatively low TDS groundwater (≤ 20 000 mg/L) occurring below the Loxton and Bookpurnong irrigation districts (App. B, Fig. 8).

2.2.4 BOOKPURNONG FORMATION

The Bookpurnong Formation aquitard occurs between the Loxton Sands and the underlying Pata Formation. This formation consists of poorly consolidated plastic silts and shelly clays that are differentiated from the Lower Loxton Clays and Shells (grey in colour)

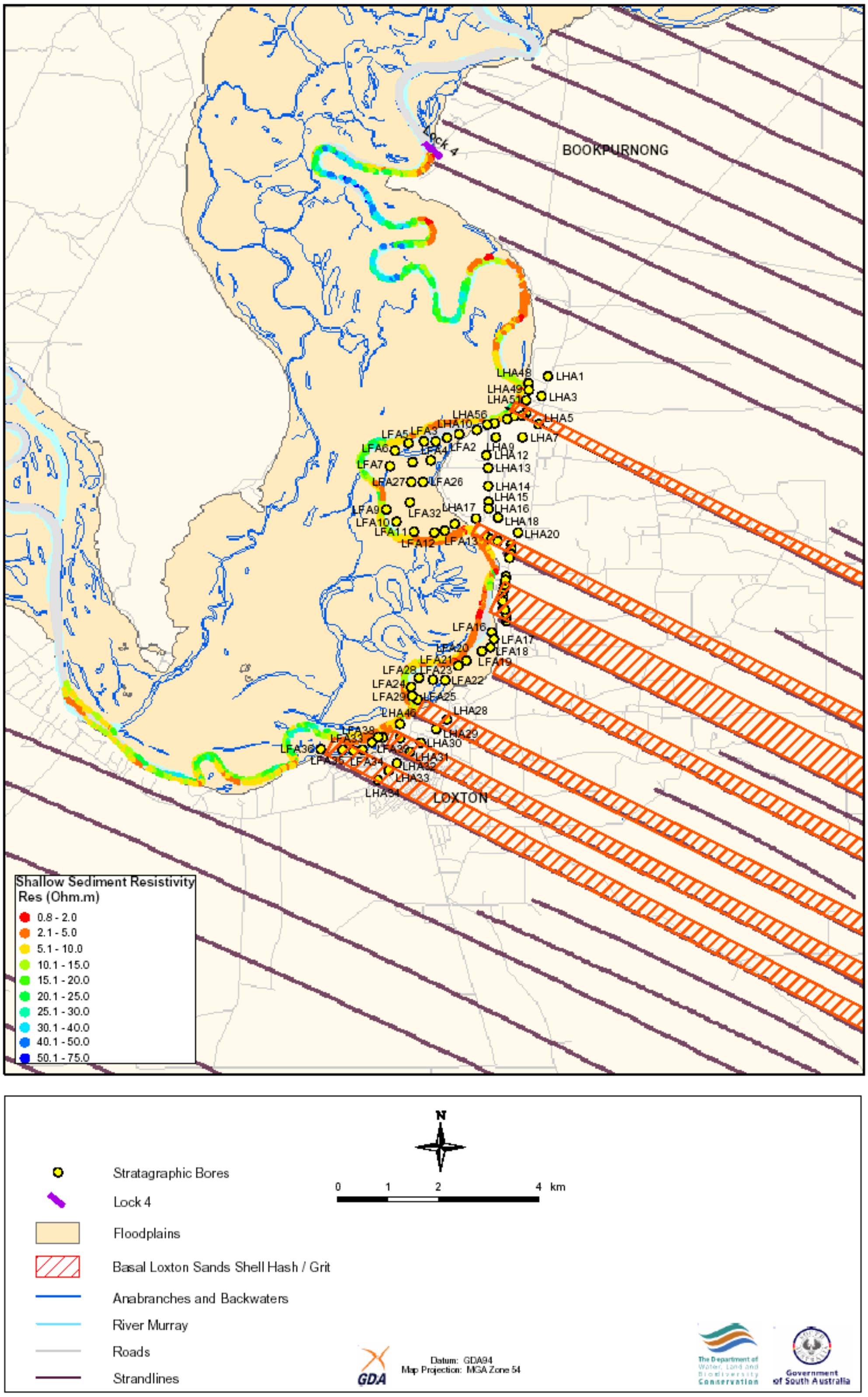


Figure 7. Conceptual depositional model – basal Loxton Sands permeability zones (Howles, Yan and Hill, 2004).

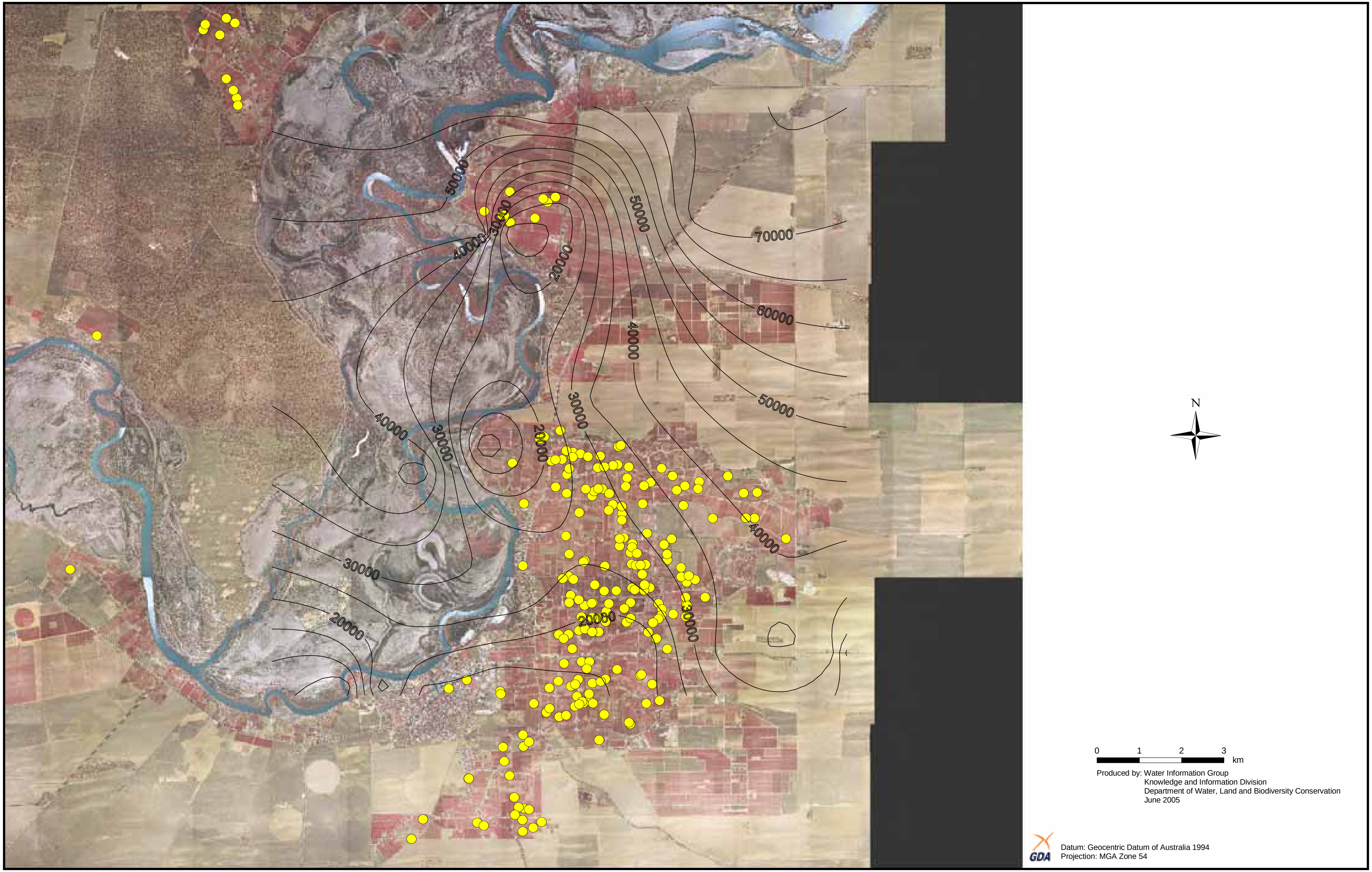


Figure 8. Groundwater TDS (mg/L) in the Unconfined Aquifer (Loxton Sands and Monoman Formation) (2003).

Isopycnal (mg/L)

Drainage bore

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

M:\Projects_GWMurray_Basin\Loxton\Chemistry\Stage1_Report\Unconfined_salinity_plot.mxd\June2005 on the basis of colour (light to dark khaki) and increased plasticity. The Bookpurnong Formation reaches a maximum thickness of 14 m in the Loxton area but is highly variable with no discernable trend observed. The Bookpurnong Formation is thin to occasionally absent on all floodplains in the Loxton area, more likely as a consequence of erosion, but possibly as a result of depositional thinning.

2.2.5 MURRAY GROUP LIMESTONE

Prior to recent subdivision of the Murray Group Limestone reported in Lukasik & James (1998), it was accepted that the Bookpurnong Formation was separated from the underlying Murray Group Limestone by the poorly consolidated to plastic marls of the Winnambool Formation. The recent work has resulted in a more detailed subdivision reflecting a change from predominantly fluvial environments of the Renmark Group to alternating deeper marine and shelf facies resulting in deposition of marl aquitards (Winambool Formation, Finnis Formation, Ettrick Formation), and limestone aquifers (Pata Formation, Glenforslan Formation, Upper and Lower Mannum Formations).

2.2.5.1 Pata Formation

The Pata Formation confined aquifer is a poorly consolidated bryozoal limestone with interbedded friable sand layers that occurs throughout the Loxton - Bookpurnong region. This formation outcrops to the south of Loxton where it is exposed at river level downstream from the Loxton Caravan Park, river kilometre 486 (and is dry 5 km to the west). The Pata Formation aquifer dips gently to the northeast to depths ~70 m (-25 m AHD) below ground surface at Bookpurnong. In the Loxton area, the formation commonly occurs 35–40 m below ground surface on the highland, but can occur as shallow as 10 m beneath the surface on the floodplains. It is typically in the range of 10–15 m in thickness with an observed thickening to the northeast. Although described as a limestone, the unit represents a poor aquifer due to the presence of marl. Aquifer testing of the aquifer by DWLBC at both floodplain and highland sites has returned yields of ~0.5–1 L/s.

The Loxton groundwater mound extends into the Pata Formation, where the potentiometric surface reaches an elevation of approximately 25 m AHD causing a steep hydraulic gradient towards the River Murray (Fig. 9). A positive (downward driving) head difference of approximately 1.5 m exists between the overlying Loxton Sands and the Pata Formation at the LHO3 nest of wells near the centre of the Loxton groundwater mound. This indicates a potential for downward groundwater leakage from the Loxton Sands to the Pata Formation at this location. Lesser hydraulic head differences occur elsewhere and, below Katarapko Island, hydraulic heads in the Pata Formation are either approximately equal to those in the overlying unconfined aquifer or slightly greater (up to 0.2 m), suggesting hydraulic connection between the two formations and the potential for a small amount of upward leakage at some locations. Groundwater salinities in the Pata Formation range from less than 10 000 mg/L on the floodplain south of Loxton up to 33 000 mg/L on the highland and on the floodplain north of Loxton (Fig. 10).

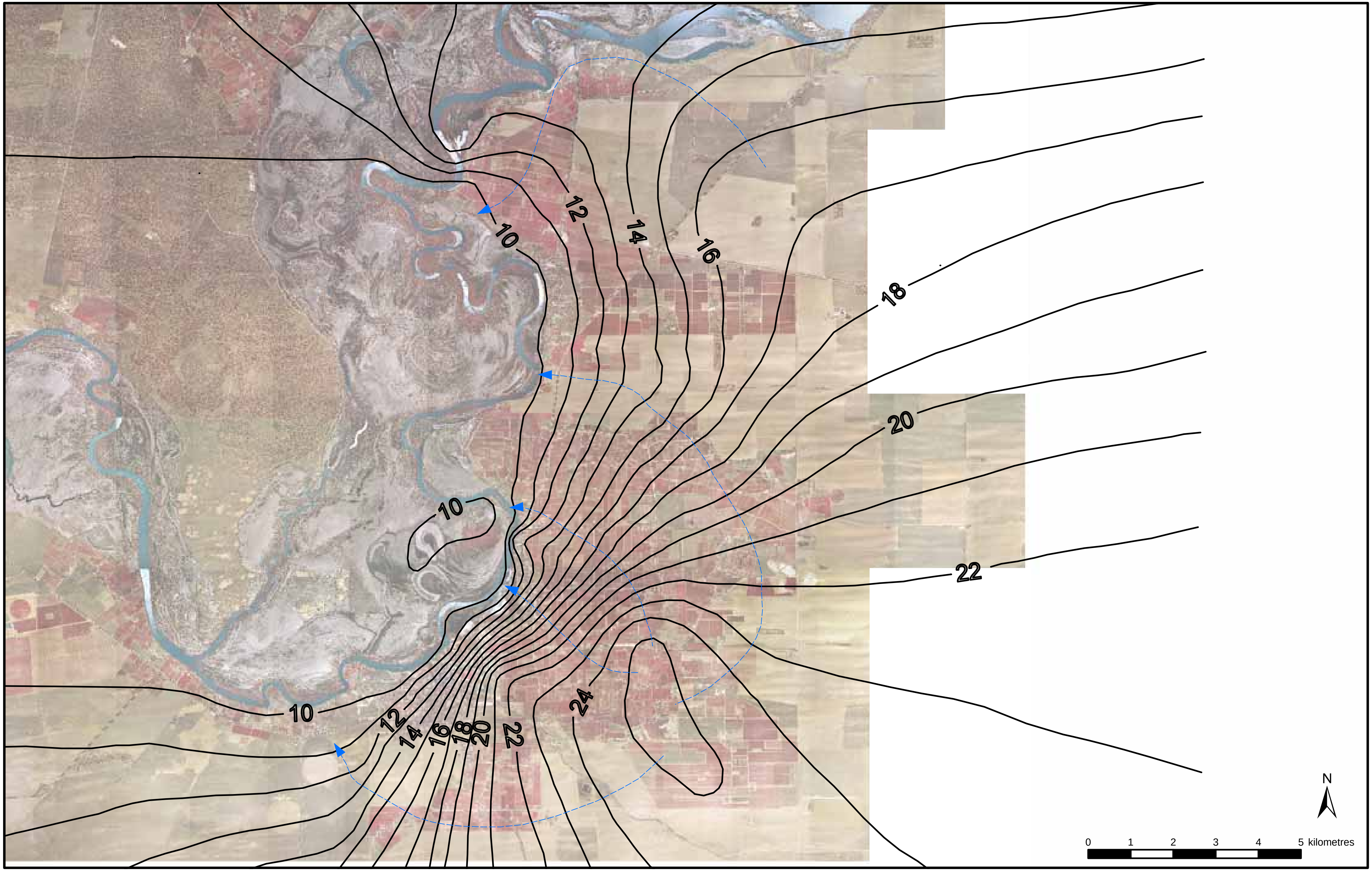


Figure 9. Density-Corrected Potentiometric Surface for the Pata Formation, May 2004.

Potentiometric Surface (mAHD)
Flow Line

The Department of Water, Land and Biodiversity Conservation

Government of South Australia

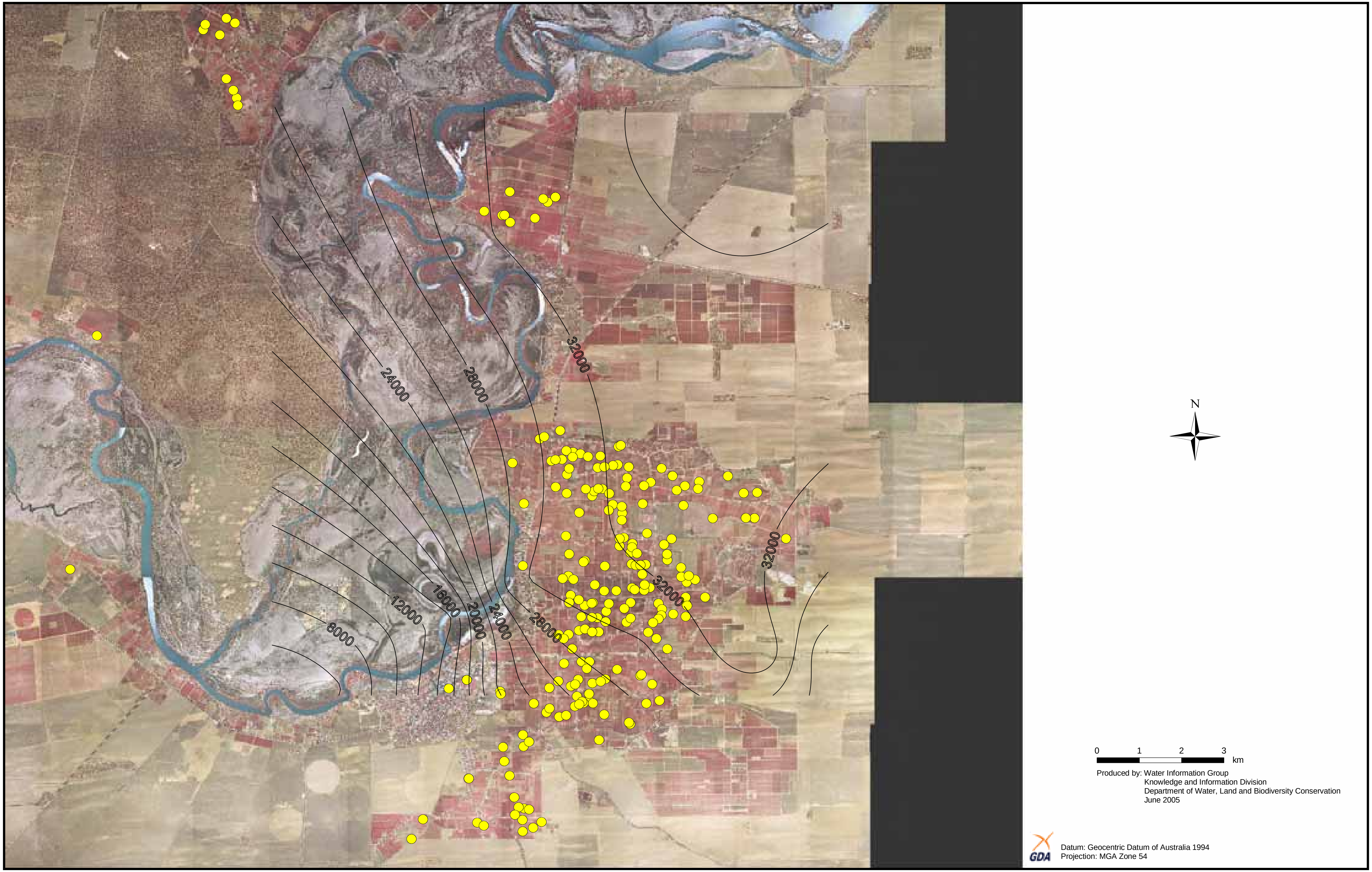


Figure 10. Groundwater TDS (mg/L) in the Pata Formation (2003).

Isopycnal (mg/L)
Drainage bore

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

M:\Projects_GW\Murray_Basin\Loxton\Chemistry\Stage1_Report\Pata_salinity_plot.mxd\June2005

2.2.5.2 Winnambool Formation

The Winnambool Formation aquitard comprises grey to pale green calcareous clay (marl) and silty clay. The unit dips to the northeast, consistent with the regional tilt. To the south of Loxton this formation occurs ~30 m below ground surface, deepening to as much as 85 m below ground surface at Bookpurnong. The Winnambool Formation varies in thickness from 3–15 m, with its depocentre located on Katarapko Island, and provides an effective aquitard between the Pata Formation and Glenforslan Formation.

2.2.5.3 Glenforslan Formation

The Glenforslan Formation confined aquifer is a grey sandy limestone that closely resembles the Pata Formation, with the exception that it contains occasional fine-grained, hard bands. Its thickness is consistently in the range 20–30 m, with the unit dipping to the northeast.

There are no groundwater mounds in the Glenforslan Formation, suggesting minimal hydraulic communication with the overlying aquifers (Fig. 11). However, a 6.4 m positive (downward driving) head difference exists between the overlying Pata Foramtion and the Glenforslan Formation at the centre of the groundwater mound (at the LHO3 nest of wells), suggesting a potential for downward groundwater leakage in this area. The distribution of groundwater salinity in the Glenforslan Formation generally follows that of the Pata Formation and ranges from 5000–30 000 mg/L (Fig. 12).

2.2.5.4 Finnis Formation

The Finniss Formation aquitard is a thin but spatially persistent grey to dark grey clay with thin sand layers and hard bands separating the Glenforslan Formation and Upper Mannum Formation. It has a maximum thickness of 4.5 m but is commonly 1–2 m in thickness.

2.2.5.5 Upper Mannum Formation

The Upper Mannum Formation confined aquifer has only been fully penetrated by a small number of wells in the area. This formation is 25 m thick at Bookpurnong and comprises highly fossiliferous calcarenitic and sandy limestone. The unit dips to the northeast, but is difficult to separate from the underlying Lower Mannum Formation in the Loxton region. Groundwater salinity in the Upper Mannum Formation ranges from approximately 10 000–27 000 mg/L.

2.2.5.6 Lower Mannum Formation

The Lower Mannum Formation confined aquifer has only been fully penetrated by a small number of wells in the area. This formation has a thickness up to 75 m at Bookpurnong and comprises hard, well compacted and moderately to well cemented gray limestone with some evidence of recrystallisation. There is an increase in fine carbonate sand towards the top of the unit.

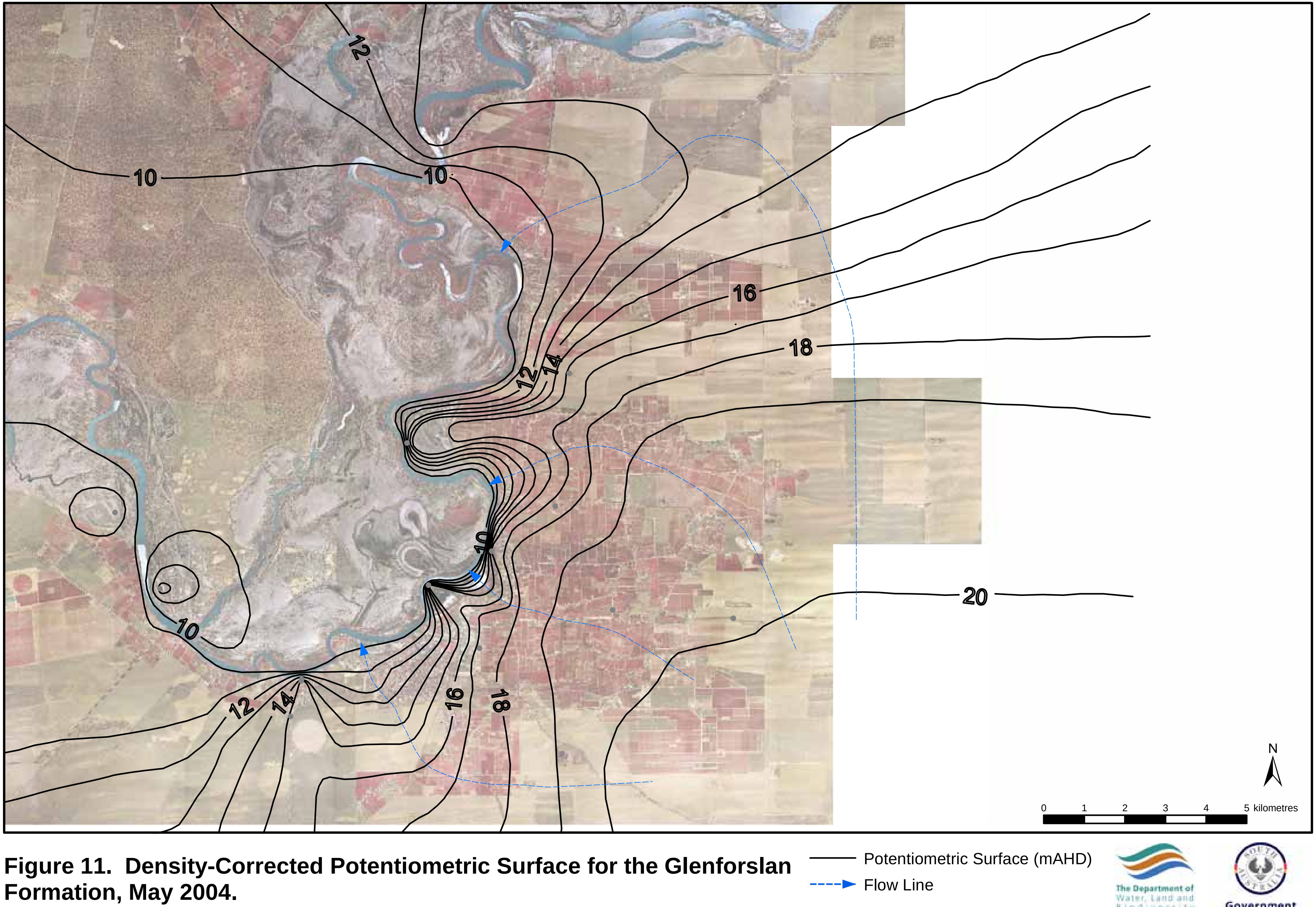


Figure 11. Density-Corrected Potentiometric Surface for the Glenforslan Formation, May 2004.

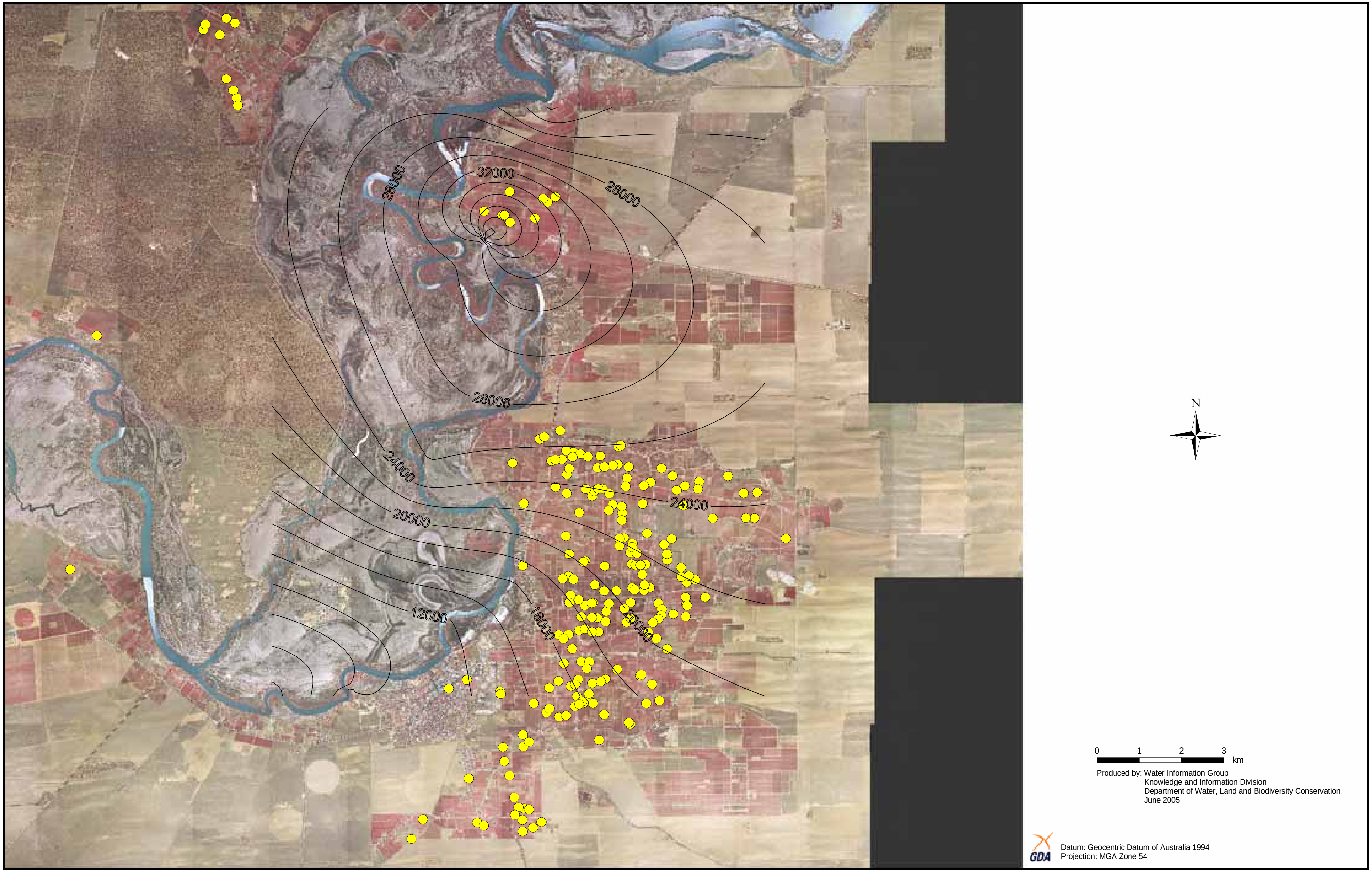


Figure 12. Groundwater TDS (mg/L) in the Glenforslan Formation (2003).

Isopycnal (mg/L)
Drainage bore

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

M:\Projects_GWMurray_Basin\Loxton\ChemistryStage1_Report\Glenforslan_salinity_plot.mxd\June2005

3 METHODOLOGY

3.1 Sampling and Analytical Methods

Groundwater samples from 56 wells in the Loxton Bookpurnong area were collected for analysis of their full chemical compositions (see Fig. 1 for well locations). This included major and trace ions, isotopic tracers including the stable isotopes of water ($\delta^{18}O$ and $\delta^{2}H$), stable and radioactive isotopes of carbon ($\delta^{13}C$ and ^{14}C), sulfur ($\delta^{34}S$) and strontium isotopes ($^{87}Sr/^{86}Sr$), metals and nutrients. Samples were collected during July and August 2003 prior to the commencement of the 2003/04 irrigation season.

Groundwater samples were collected using either submersible pumps or, for artesian wells, taps on the wellhead. Because of low yields, samples were collected from wells BHO1W, LHO3W, L14 and L26A using a hand bailer lowered on a rope. All pumped and flowing samples were collected after a minimum of three bore volumes were purged from the well and the pH, redox potential (Eh), temperature (T), electrical conductivity (EC) and dissolved oxygen concentration (DO) of the removed groundwater had stabilised. Analyses of the groundwater samples for electrical conductivity (EC), pH, temperature, dissolved oxygen content and redox potential were carried out in the field using a portable TPS 90FLMV Temperature-pH-Salinity meter (T.P.S. Pty Ltd). Field measurements of alkalinity were made using a Hach® field titration kit, using 0.16 M H_2SO_4 to a pH 4.3 fixed end-point and reported as a HCO_3^- equivalent in mg/L. Samples that required filtering were filtered using an aluminium filter column to which 42 mm glass fibre pre-filters and Millipore 0.45 μm 47 mm MCE filter membranes were applied to the outlet. The column was pressurized with an air compressor to induce flow.

Samples collected for major cations, anions, Sr, B and Br were filtered and stored in 1.25 L plastic bottles. These bottles were kept on ice to ensure they were stored below 4°C and delivered to the Australian Water Quality Centre (AWQC) for standard laboratory analysis. Samples collected for metal analysis were filtered, acidified to pH <2 with nitric acid and stored in 0.5 L plastic bottles. Unfiltered samples for NO_3 + NO_2 and NH_3 analyses were collected in 0.5 L plastic bottles and stored on ice until they could be delivered to AWQC for analysis.

Samples for $\delta^{34}S$ analysis were filtered and stored in 2.25 L plastic bottles that were pre-rinsed with HCl. These samples were then acidified with HCl to pH <4. Groundwater samples collected for $^{87}Sr/^{86}Sr$ analysis were filtered, acidified to pH <2 and stored on ice in 125 ml plastic bottles (pre-rinsed with nitric acid). Unfiltered samples were collected for $\delta^{2}H$ and $\delta^{18}O$ analysis of H_2O in 30 ml McCartney bottles with rubber sealed screw top lids. These bottles were stored upside down ensuring there was no evaporation loss and delivered to CSIRO Land and Water Laboratory, Adelaide for analysis. $\delta^{2}H$ and $\delta^{18}O$ were analysed by H_2O reduction to H_2 (for $\delta^{2}H$) by hot Uranium (Dighton et al., 1997) and CO_2 equilibrium for $\delta^{18}O$ (Socki et al., 1992) respectively and expressed in per mil units relative to V-SMOW. Samples for ^{14}C analysis, were collected in 20 L plastic jerry cans that were pre-rinsed with 5% HCl and distilled water. Volumes of water required to contain a minimum of 2 g of carbon were calculated based on field alkalinity. To each 20 L of water collected for ^{14}C analysis, 600 ml of saturated $BaCl_2$ solution, 50 ml of saturated sodium hydroxide solution (or enough to raise the pH to >9.5) and 20 ml of MagnaFloc was added to form a heavy, white $BaCO_3/BaSO_4$ precipitate. The solution was allowed to stand for 24 hours and then decanted, with the remaining precipitate transferred to 5 L plastic containers (pre rinsed in 5% HCl and distilled water). ^{14}C was analysed by liquid scintillation counting after CO_2 adsorption into Carbsorb /Permafluor (Leaney et al 1994). $\delta^{13}C$ was analysed from an aliquot of CO_2 from the ^{14}C sample by standard techniques and expressed relative to the standard PDB.

3.2 Stable Isotope Notation

The stable isotopes of carbon, hydrogen, oxygen and sulfate are reported in the standard delta notation (δ), where:

$$\delta(‰) = \left[\frac{R_{sample}}{R_{standard}} - 1\right] x1000 \quad (1)$$

R_{sample} refers to the ratio of the heavy isotope to the light isotope ($^{13}C/^{12}C$, $^{18}O/^{16}O$, $^{2}H/^{1}H$ and $^{34}S/^{32}S$) in the sample and $R_{standard}$ is the ratio of an internationally accepted standard. The standards for deuterium and $\delta^{18}O$ are V-SMOW (Vienna Standard Mean Ocean Water. The $^{13}C/^{12}C$ ratio is expressed relative to standard PDB (*Bellemniteella americana* from the Cretaceous Pee Dee Formation, South Carolina). Isotope ratios of and $\delta^{34}S$ are reported as δ -values relative to standard meteoritic Canon Diablo Trolite (CDT).

3.3 Water Quality vs Depth Profiles

Vertical profiles of depth, temperature, pH and EC were measured using a YSI 600XL multi parameter water quality measurement and data collection system. The YSI 600XL consists of a series of water quality probes enclosed in a cylindrical PVC housing. After the water level in the well was measured, the YSI 600XL was lowered below the water table on a cable and water quality measurements were logged against depth below the water table at specified time intervals via a cable attached to a laptop at the surface. Water quality vs depth measurements were recorded at approximately 1 m depth intervals in a total of 21 wells in the Loxton – Bookpurnong region. Six of these wells were also part of the geochemistry and isotope sampling program (see Fig. 1 for locations of profiled wells).

3.4 Calculation of Equivalent Freshwater Heads

Due to large variations in the total dissolved solids concentrations of the groundwater in the Loxton – Bookpurnong region, it was necessary to correct measured hydraulic heads for density effects so that equivalent freshwater head can be used for the accurate calculation of hydraulic gradients (Fetter, 1994).

The empirical relationship between seawater density and salinity S, can be approximated by (1) (Maidment, 1993):

$$\rho_s = \rho_0 \quad + AS\ BS^{3/2} \ + CS^2 \qquad (2)$$

Where

ρ_s = density of water containing dissolved solids (kg m^{-3}):

A=8.24493 x 10^{-1} – 4.0899 x 10^{-3} T + 7.6438 x $10^{-5}T^2$ – 8.2467 X 10^{-7} T^3 + 5.3675 x 10^{-9} T^4

B = -5.724 x 10^{-3} + 1.0227 x 10^{-4}T – 1.6546 x 10^{-6} T^2

C = 4.8314 x 10^{-4}

T = temperature of groundwater (°C)

S = salinity in g/kg

Using Equation (2), the measured hydraulic head (h_s) can be converted to a fresh water head (h_f):

$$h_f = (\rho_s/\rho_f)\ h_s \qquad (3)$$

Where

ρ_f = density of pure water 1000 kg/m3

ρ_s = density of water containing dissolved solids (kg m^{-3})

3.5 Groundwater Mixing Ratios

In order to assess inter-aquifer leakage across leaky aquitards, groundwater mixing between defined end-members was calculated. The identification of the end-members used for this calculation is discussed in Section 5.1.2.1 below and the mixing calculations were carried out as follows:

$$xEM1 + (1-x)EM2 = M \qquad (4)$$

Where EM1 and EM2 represent the ion concentration, δ^2H or δ^{18}O signature of groundwater end members 1 and 2 respectively, M is the concentration or isotopic value of the mixture and x is the proportion of EM1 that has mixed with EM2.

This calculation assumes conservative mixing i.e no water rock interactions. Where the tracer being used to calculate mixing ratios is the isotopic signature of a species dissolved in water, both the concentration and isotopic signature of that species in each end-member must be taken into consideration by modifying equation (4) as follows:

$$xC_{EM1}S_{EM1} + (1-x)C_{EM2}S_{EM2} = C_M S_M \qquad (5)$$

Where C_{EM1}, C_{EM2} and C_M are the species concentrations in end members 1 and 2 and the mixture respectively and S_{EM1}, S_{EM2} and S_M are the isotopic signature of that dissolved species in end members 1 and 2 and the mixture respectively.

4 RESULTS

4.1 Groundwater Chemistry

Results of the major ion analyses of groundwater samples from the Loxton - Bookpurnong sampling program are shown in Table 2. Also included are field measurements of pH, EC, temperature, Eh and DO, as well as Br, Sr and Si concentrations. Figure 13 contains Schoeller Diagrams illustrating the typical groundwater chemical compositions in each aquifer in the Loxton and Bookpurnong regions, and the observed ranges in the major groundwater quality parameters for each of the aquifers sampled are summarised in Table 3 There is a large range of groundwater salinities in the Loxton – Bookpurnong area (Observed TDS = 840–77 400 mg/L) (Tables 2 and 3), and most of this groundwater is predominantly of a Na-Cl–(Mg)-(SO_4) type, as is common throughout the Murray Basin (Fig. 13; Herczeg et.al., 2001).

The groundwater samples were also analysed for concentrations of the dissolved trace elements aluminium, boron, cadmium, iron, manganese and selenium (Table 4) due to the observed precipitation of a white aluminium oxyhydroxide compound during pump tests of the highland production bore BHP1 at Bookpurnong (Australian Water Environments, 2002; Harrington, 2004) and the previously observed variability in dissolved metals concentrations, particularly cadmium and selenium (Australian Water Environments, 2003b). A preliminary analysis of the pre-existing groundwater chemistry database had identified variable dissolved aluminium concentrations throughout the Loxton Sands aquifer, with high dissolved aluminium concentrations often occurring in conjunction with high dissolved iron concentrations. Measured total aluminium concentrations in the Loxton Sands aquifer range from below detection to 265 mg/L. Likewise, measured total iron concentrations range between below detection and 592 mg/L. However, samples L14 and L26A were unfiltered samples, and the high concentrations in these samples may reflect metals bound to clay or colloidal particles rather than dissolved species. This was also the case for a Woorinen Formation sample, LHO3W, which had measured aluminium and iron concentrations of 2390 mg/L and 2690 mg/L respectively. With the exception of these, one sample in the Monoman Formation, three samples in the Loxton Sands and one in the Glenforslan Formation had aluminium concentrations above the aesthetic guideline for drinking water in Australia of 0.2 mg/L (NHMRC & ARMCANZ, 1996) (Table 4). A large number of samples from all of the aquifers had iron concentrations above the aesthetic guideline of 0.3 mg/L (Table 4).

Table 4 shows that almost all of the groundwater samples from the Loxton-Bookpurnong region had boron concentrations greater than the Australian drinking water guideline value for health of 0.3 mg/L. Boron concentrations ranged between less than 0.4 mg/L and 10.9 mg/L (Table 4). Cadmium concentrations in some of the groundwater samples were slightly greater than the drinking water guideline of 0.002 mg/L, with the highest measured concentration being 0.02 mg/L in the (unfiltered) Woorinen Formation sample LHO3W (Table 4). Manganese and selenium concentrations were generally below the health guideline values of 0.5 and 0.01 mg/L respectively. One exception was a manganese concentration of 5.5 mg/L measured in groundwater from the Monoman Formation well LFO6A at Thiele's sandbar.

Table 2. Details of wells sampled for groundwater chemistry and isotopic signatures from the Loxton and Bookpurnong regions and results of groundwater chemical analyses. (See Fig. 1 for well locations)

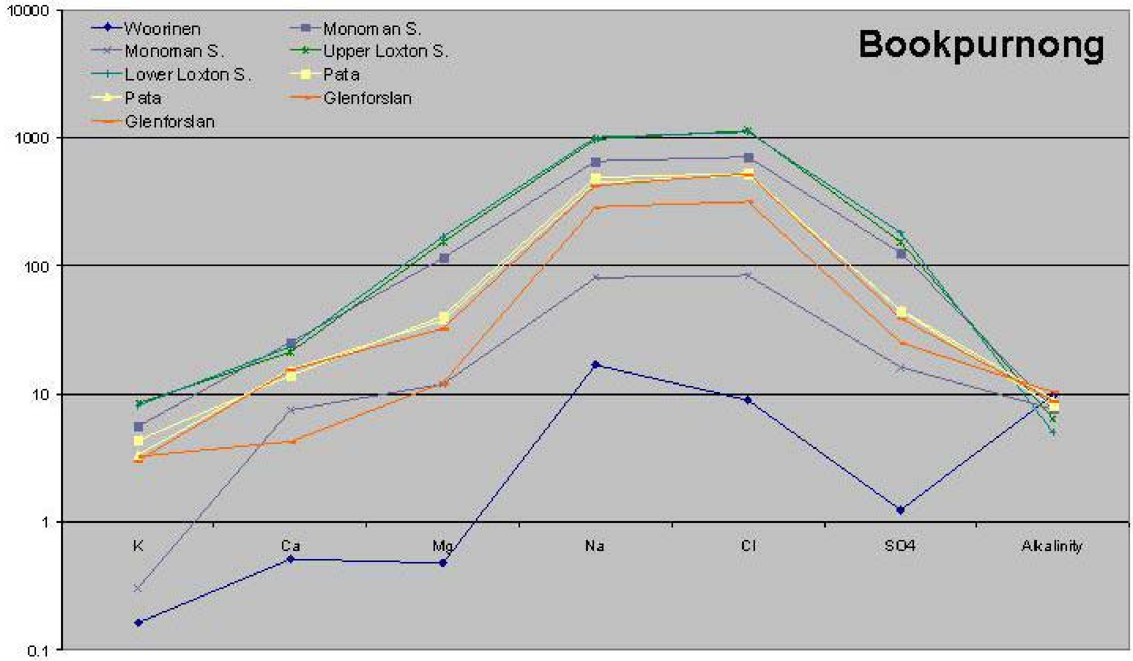
Bore Name	Easting	Northing	Loc	ground elev	RSWL	Sample Pt	pH	Temp	EC	Alk	TDS	Br	Ca	Mg	K	Na	Cl	SO4	NO3+NO2	NH3	Al	B	Fe	Mn	Sr	Sr	Si
				m AHD	m AHD			C	mS/cm	meq/L	(mg/L)	mEq/L							mmol/L (as N)		mmol/L				mEql/L	mmol/L	mg/L
Woorinen Formation																											
BHO1W	463205	6201439	Book	51.86	38.000	36.650	–	–	–	9.8	840	0.01	0.51	0.48	0.16	16.88	8.94	1.24	0.24	0.00	0.00	0.33	0.00	0.03	0.28	0.14	11
LHO3W	465287	6188747	Lox	36.36	32.967	30.777	–	–	–	–	9096	0.09	1.31	4.21	1.09	67.42	51.90	7.35	0.01	0.00	88.58	0.76	48.17	0.07	0.27	0.14	4
Monoman Formation																											
CF2	461601	6198422	Book	12.47	9.785	1.980	6.99	19.9	51.3	7.6	50782	0.90	25.40	115.20	5.60	661.16	710.81	127.00	0.00	0.03	0.01	0.32	0.06	0.00	0.66	0.33	12
CF1	461620	6198361	Book	12.47	10.500	-0.520	7.16	20.2	38.6	9.1	33729	0.66	16.67	70.44	3.81	419.75	487.97	83.49	0.00	0.01	0.00	0.31	0.05	0.00	0.36	0.18	12
LFO6A	460756	6189364	Lox	11.04	10.060	0.935	7.2	20.6	31.1	8.7	26026	0.48	24.80	46.16	1.31	297.09	369.51	75.99	0.00	0.32	0.00	0.21	0.30	0.10	0.36	0.18	17
LFO1A	458369	6187784	Lox	11.29	9.971	3.471	7.28	18.6	3.56	9.3	2087	0.04	4.73	6.39	0.00	25.01	28.49	4.50	0.00	0.17	0.00	0.00	0.07	0.03	0.05	0.02	25
LFO7A	456620	6187567	Lox	12.16	9.985	3.240	7.17	20.4	8.45	7.6	6275	0.12	7.49	11.93	0.30	81.34	84.34	16.26	0.00	0.27	0.00	0.08	0.23	0.05	0.08	0.04	21
LFO2A	462304	6190188	Lox	11.96	10.460	0.980	7.14	19.8	33.6	12.8	30091	0.66	8.73	42.21	4.81	394.52	406.17	88.27	0.00	0.02	0.00	1.01	0.03	0.00	0.32	0.16	14
LFO3A	460220	6192857	Lox	13.78	10.000	1.790	6.64	20.3	48.9	4.8	47489	0.99	67.87	89.69	1.97	582.87	755.94	71.83	0.00	0.02	0.00	0.17	0.14	0.01	1.00	0.50	20
LPP4	461474	6192439	Lox	11.15	10.219	-4.676	6.96	20	28	10.6	21378	0.51	18.11	40.57	2.34	274.03	307.45	65.17	0.00	0.12	0.00	0.57	0.05	0.01	0.39	0.20	30
LPP10	459177	6187758	Lox	12.20	10.163	2.828	6.79	20	31.9	8.3	27478	0.59	31.34	57.11	3.09	357.11	346.94	112.63	0.00	0.03	0.00	0.59	0.04	0.01	0.47	0.23	36
Loxton Sands																											
EES4	466662	6198941	Book	55.83	14.510	-8.435	6.62	23.5	77.5	6.4	73205	1.60	21.26	153.88	8.49	974.35	1145.19	154.27	0.00	0.03	0.00	0.36	0.05	0.01	0.35	0.17	13
BHP1	463204	6201432	Book	51.97	13.799	-1.536	6.43	22.4	64.3	5.4	60577	1.26	18.56	132.48	6.83	843.85	905.43	139.28	0.01	0.02	0.00	0.29	0.04	0.00	0.33	0.17	14
BHO1(ls)	463211	6201459	Book	51.72	19.924	-1.616	6.51	22.7	65.9	6.3	59875	1.26	20.01	136.60	7.19	809.05	894.15	147.59	0.00	0.02	0.01	0.28	0.08	0.01	0.36	0.18	15
IA3	463508	6199028	Book	55.03	15.540	7.630	6.5	24.3	21	2.4	17171	0.35	3.79	29.71	3.22	244.89	242.29	48.30	0.63	0.00	0.01	0.46	0.00	0.00	0.10	0.05	22
BKP1	462145	6198538	Book	–	–	-46.200	7.47	21.4	17.14	12.4	12942	0.23	4.11	22.71	1.64	185.30	178.83	39.14	0.10	0.00	0.00	0.31	0.01	0.00	0.10	0.05	11
BHP2	–	–	Book	27.97	13.897	–	7.55	21.8	24.8	3.9	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
BHP3	–	–	Book	–	–	–	7.65	20.6	14.71	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
LHO8	461614	6193426	Lox	27.30	18.174	-0.631	7.43	20.5	9.09	14.1	6176	0.10	2.36	5.64	1.04	98.74	71.36	24.57	0.47	0.00	0.00	0.57	0.00	0.00	0.04	0.02	17
L22	470200	6188581	Lox	41.85	21.520	13.060	6.74	21.8	31.4	11.4	23993	0.46	7.34	34.81	3.99	346.68	344.12	62.88	0.02	0.00	0.00	0.67	0.02	0.00	0.39	0.20	14
LHO15	460118	6187727	Lox	32.04	15.451	11.356	7.4	20.8	18.37	8.7	14488	0.27	9.18	24.69	2.86	196.61	194.63	50.18	1.14	0.00	0.00	0.34	0.00	0.00	0.06	0.03	18
L24A	469759	6188575	Lox	47.52	22.660	-0.970	6.59	24	47.8	15.4	39325	0.84	18.31	80.48	6.37	530.67	572.59	106.18	0.00	0.02	0.02	0.91	0.03	0.00	0.76	0.38	16
L14	467270	6188560	Lox	30.52	25.360	20.470	6.48	20.4	–	–	36785	0.80	12.28	64.84	5.68	491.52	502.08	101.39	0.00	0.13	9.82	0.84	10.60	0.01	0.49	0.25	13
L21	468258	6188540	Lox	33.50	24.040	12.820	6.99	20.4	46.6	13.7	39763	0.89	13.27	75.13	6.78	543.72	578.24	108.26	0.03	0.00	0.00	1.00	0.00	0.00	0.51	0.26	14
LHO3LS	465286	6188744	Lox	36.36	26.727	12.797	7.26	20.4	21.7	12.6	15798	0.31	5.29	23.95	2.66	223.14	214.09	52.47	0.32	0.00	0.00	0.70	0.00	0.00	0.18	0.09	12
LHO1LS	462013	6187808	Lox	36.70	22.930	8.390	7.12	21.6	16.18	11.9	11609	0.22	4.15	14.15	1.99	173.12	150.06	40.18	0.37	0.00	0.00	0.63	0.00	0.00	0.11	0.06	12
L26A	464221	6194564	Lox	44.91	19.063	13.813	9.65	18.2	–	–	36144	0.81	57.89	50.85	5.42	469.77	504.90	110.14	0.07	0.02	0.45	0.38	0.60	0.01	0.24	0.12	4
Pata Formation																											
BHO1P	463205	6201443	Book	51.76	15.357	-25.013	6.92	23.9	39.1	8	33407	0.77	13.92	40.73	4.35	491.52	533.10	44.76	0.00	0.19	0.00	0.24	0.00	0.00	0.64	0.32	18
CF9P	461633	6198359	Book	12.52	12.039	-20.871	6.69	20	39.3	9.1	31792	0.68	15.62	37.61	3.35	448.02	516.18	45.39	0.00	0.24	0.00	0.26	0.06	0.00	0.53	0.27	21
LFO6P	460760	6189363	Lox	11.04	10.125	-14.624	7.31	20.2	17.98	8.3	13176	0.25	6.99	16.79	1.54	174.86	203.93	30.40	0.00	0.17	0.00	0.28	0.01	0.00	0.17	0.08	28
L24B	469760	6188577	Lox	47.52	20.990	-28.290	6.83	25.1	33.8	10	26177	0.56	12.63	31.93	3.94	359.72	417.46	46.01	0.00	0.18	0.00	0.50	0.02	0.00	0.47	0.23	27
LHO3P	465287	6188746	Lox	36.37	24.954	-16.846	6.81	22.6	37.6	10.7	29719	0.66	12.58	41.31	4.76	411.49	442.84	73.28	0.00	0.10	0.00	0.64	0.03	0.00	0.46	0.23	15
LHO2P	468260	6188545	Lox	33.52	22.520	-12.870	6.72	22.8	41.2	13.5	33354	0.73	11.78	40.90	5.37	474.12	513.36	66.62	0.00	0.10	0.00	0.71	0.01	0.00	0.47	0.24	21
LHO1P	462010	6187805	Lox	36.61	21.750	-6.020	6.94	23.4	30.1	11.7	22528	0.51	8.73	27.81	3.68	332.76	324.38	54.96	0.00	0.07	0.00	0.47	0.02	0.00	0.24	0.12	21

Bore Name	Easting	Northing	Loc	ground elev	RSWL	Sample Pt	pH	Temp	EC	Alk	TDS	Br	Ca	Mg	K	Na	Cl	SO4	NO3+NO2	NH3	Al	B	Fe	Mn	Sr	Sr	Si
				m AHD	m AHD			C	mS/cm	meq/L	(mg/L)	mEq/L							mmol/L (as N)		mmol/L				mEql/L	mmol/L	mg/L
LFO1P	458375	6187787	Lox	11.29	10.720	-5.710	7.23	20.6	9.86	9.7	6147	0.14	2.73	8.06	1.10	95.69	89.13	10.95	0.00	0.12	0.00	0.19	0.01	0.00	0.10	0.05	45
LFO7P	456623	6187565	Lox	12.16	9.985	-3.950	6.79	20.6	6.75	8.8	4304	0.09	2.40	4.85	0.50	68.73	62.34	7.18	0.00	0.04	0.00	0.14	0.01	0.00	0.04	0.02	30
LFO2P	462303	6190190	Lox	11.96	11.520	-9.080	6.84	20	35.4	10.3	29443	0.73	12.78	43.61	4.42	401.48	442.84	71.62	0.00	0.13	0.00	0.62	0.03	0.00	0.53	0.26	21
LFO3P	460222	6192854	Lox	13.78	10.080	-12.390	6.58	20.9	38.6	6.6	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Glenforslan Formation																											
BHO1G	463205	6201441	Book	51.82	16.644	-59.336	8.44	25.4	25.2	10.4	19644	0.38	4.26	12.18	3.25	290.56	318.73	25.19	0.00	0.22	0.00	0.18	0.00	0.00	0.44	0.22	39
CF8	461639	6198349	Book	12.62	17.730	-44.300	6.63	21.2	39.8	8.9	31298	0.67	15.47	32.59	3.02	425.84	527.46	39.14	0.00	0.31	0.00	0.25	0.01	0.00	0.68	0.34	12
BKP8	461648	6198359	Book	12.60	10.776	2.966	7.02	19.8	45.2	7.8	44094	0.85	27.25	123.43	5.55	565.47	637.47	127.21	0.00	0.02	0.01	0.28	0.11	0.00	0.59	0.30	11
LFO6GF	460761	6189365	Lox	11.04	15.900	-30.200	7.21	19.9	16.62	–	11858	0.23	6.29	15.55	1.65	160.51	180.52	27.27	0.00	0.19	0.00	0.27	0.01	0.00	0.17	0.09	45
LHO2GF	468259	6188544	Lox	33.54	19.590	-37.610	6.75	23.9	29.2	9.9	20979	0.46	10.63	24.52	3.30	308.83	318.73	38.31	0.00	0.18	0.00	0.42	0.01	0.00	0.28	0.14	42
LHO3GF	465288	6188750	Lox	36.32	18.828	-40.742	6.82	24.3	27.1	9.3	19741	0.43	8.83	21.31	3.09	279.69	298.99	42.89	0.00	0.18	0.00	0.41	0.01	0.00	0.25	0.13	41
LHO1GF	462005	6187816	Lox	36.68	17.445	-40.605	6.89	24.5	18.05	9.4	13074	0.28	7.14	16.70	2.32	184.43	187.86	34.35	0.00	0.13	0.00	0.30	0.01	0.00	0.18	0.09	51
LFO1GF	458379	6187787	Lox	11.29	14.557	-37.843	7.18	20.7	10.51	9.7	6795	0.16	3.07	9.38	1.23	102.65	99.29	13.03	0.00	0.12	0.00	0.19	0.00	0.00	0.10	0.05	45
LFO7G	456624	6187556	Lox	12.16	14.330	-19.870	7.26	19.7	5.51	9	3272	0.08	1.87	5.16	0.74	51.76	46.54	5.16	0.00	0.06	0.00	0.15	0.01	0.00	0.04	0.02	44
LFO2G	462303	6190188	Lox	11.96	16.590	-29.110	6.87	20.5	22.2	8	15768	0.41	7.93	16.95	2.24	226.62	242.01	29.77	0.00	0.23	0.00	0.32	0.01	0.00	0.18	0.09	47
LFO3G	460218	6192857	Lox	13.78	15.170	-30.530	7.13	20.6	30.9	7.3	25697	0.63	13.42	9.79	3.56	374.95	420.28	32.69	0.00	0.26	0.00	0.18	0.01	0.00	0.39	0.20	6
LFP1	458395	6187740	Lox	11.29	15.051	-77.049	7.03	21.7	14.91	9.2	10491	0.23	5.09	14.65	1.60	148.33	151.75	26.65	0.00	0.17	0.00	0.25	0.01	0.00	0.18	0.09	46
Upper Mannum Formation																											
LHO3UMF	465287	6188743	Lox	36.20	18.854	-77.466	6.89	25.1	22.7	8.7	16306	0.37	8.58	17.36	2.27	230.54	252.17	31.44	0	0.22	0	0.33	0.00	0	0.19	0.10	39
Man12o	461068	6188605	Lox	34.49	16.569	-79.301	6.92	25.2	16.79	10.3	11209	0.26	6.74	14.48	1.71	164.42	159.09	27.69	0	0.17	0.00	0.27	0.01	0	0.21	0.10	45
LFO1UM	458379	6187789	Lox	11.29	15.022	-64.978	7.01	21	14.52	10.3	10318	0.23	4.64	14.89	1.66	151.81	146.11	25.61	0	0.16	0	0.26	0.01	0.00	0.15	0.08	48
LFO3UM	460224	6192852	Lox	–	–	-91.530	6.72	22.8	34.1	8.6	26929	0.67	15.42	32.17	3.04	394.52	417.46	43.93	–	0.22	–	0.33	0.03	–	0.53	0.27	42

Table 3. Observed ranges in groundwater EC, TDS and pH for the aquifers sampled in the Bookpurnong and Loxton regions.

Locality and Aquifer	No. of Samples	EC (mS/cm)	TDS (mg/L)[1]	pH
Bookpurnong				
Woorinen	1	–	840–9100	–
Monoman	2	38.6–51.3	33 700–50 800	7–7.2
Loxton Sands	7	14.7–77.5	13 600–77 400	6.4–7.7[2]
Pata Formation	2	39.1–39.3	32 500–34 100	6.7–6.9
Glenforslan Formation	3	25.2–45.3	20 000–46 100	6.6–8.4
Loxton				
Woorinen	1	–	9100	–
Monoman	7	3.6–51.3	2100–47 500	6.6–7.3
Loxton Sands	9	9.1–47.8	6600–41 500	6.5–7.4[3]
Pata Formation	9	6.7–41.2	4400–34 400	6.6–7.3
Glenforslan Formation	9	5.5–30.9	3400–26 200	6.8–7.3
Upper Mannum Formation	4	14.5–34.1	10 700–27 600	6.7–7

1 TDS calculated as sum of laboratory-measured ion concentrations.
2 A pH of 4.1 was measured in the highland bore, BHP1. This is suspected to be the result of geochemical reactions that occur in response to heavy pumping of the well, and not to be a natural condition of the aquifer (Harrington, 2004).
3 A pH of 9.65 measured at bore L26A was suspected to be due to the presence of remnant drilling mud, however, due to the shallow depth of the screen below SWL and low yield, this well could not be properly purged.



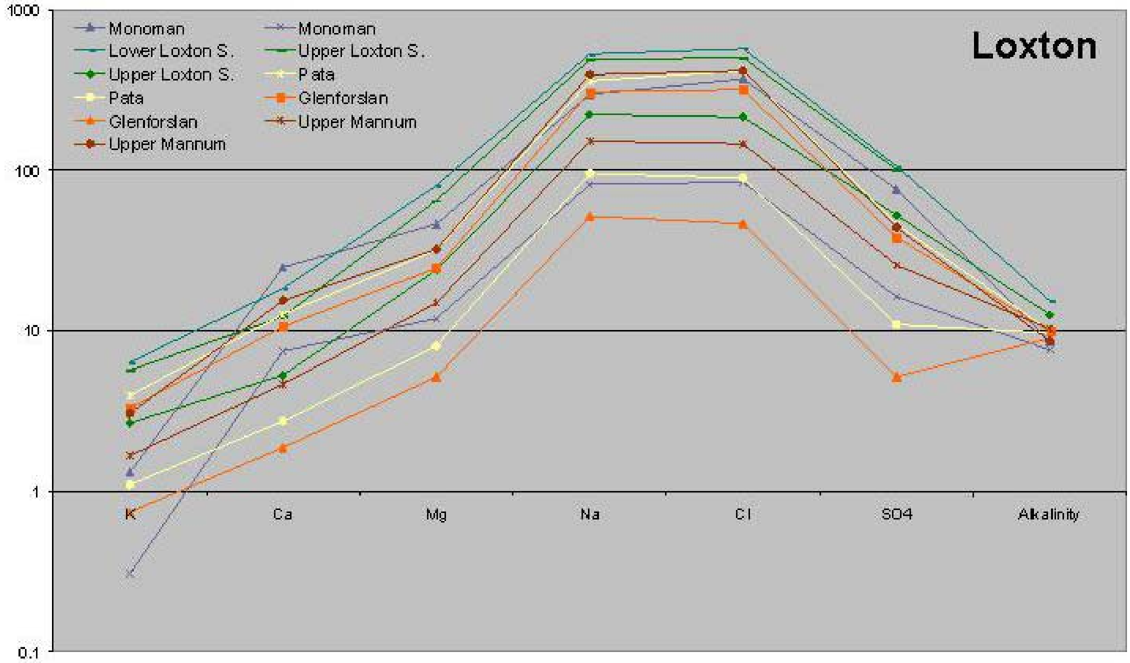


Figure 13. Schoeller diagrams showing representative groundwater compositions from each aquifer at Bookpurnong and Loxton.

Table 4. Metal concentrations in Loxton-Bookpurnong groundwater samples.

	Al (tot)	B	Cd (tot)	Fe (tot)	Mn (tot)	Se (tot)
	(mg/L)					
Guideline (Health)*		**0.3**	**0.002**		**0.5**	**0.01**
Guideline (Aesthetic)*	**0.2**			**0.3**	**0.1**	
Woorinen Formation						
BHO1W	<0.4	3.59	0.0068	<0.6	1.86	0.006
LHO3W	2390	8.2	0.02	2690	3.797	<0.3
Monoman Formation						
CF2	0.302	3.47	0.013	3.56	0.109	0.003
CF1	0.084	3.39	0.008	2.57	0.119	0.002
LFO6A	0.128	2.3	0.007	17	5.538	0.002
LFO1A	<0.2	<0.4	<0.005	3.79	1.535	<0.001
LFO7A	<0.2	0.844	0.013	13.1	2.714	0.003
LFO2A	<0.2	10.9	<0.005	1.51	0.017	0.004
LFO3A	<0.2	1.87	0.008	8.09	0.515	0.006
LPP4	<0.2	6.16	<0.005	2.64	0.356	0.002
LPP10	<0.2	6.43	<0.005	1.98	0.324	0.002
Loxton Sands						
EES4	0.121	3.87	0.007	2.89	0.802	0.009
BHP1	<0.2	3.09	0.006	2.49	0.194	0.005
BHO1(ls)	0.338	3.01	0.01	4.27	0.409	0.004
IA3	0.269	4.94	<0.005	<0.025	0.016	0.004
BKP1	0.049	3.35	<0.005	0.395	0.014	0.002
LHO8	0.042	6.2	<0.005	<0.025	0.009	0.007
L22	0.065	7.25	<0.005	0.964	0.01	0.014
LHO15	0.073	3.72	<0.005	<0.025	<0.005	0.004
L24A	0.515	9.8	0.008	1.58	0.06	0.001
L14	265	9.06	0.017	592	0.37	0.007
L21	<0.2	10.8	0.01	0.202	0.006	0.012
LHO3LS	<0.2	7.56	<0.005	0.192	0.179	0.062
LHO1LS	<0.2	6.78	<0.005	0.059	0.051	0.007
L26A	12.1	4.06	0.008	33.5	0.583	0.023
Pata Formation						
BHO1P	0.096	2.63	0.008	0.109	0.046	0.002
CF9P	0.094	2.82	0.012	3.2	0.074	0.003
LFO6P	0.052	3.01	<0.005	0.754	0.059	0.001
L24B	<0.2	5.4	0.007	1.01	0.008	<0.001
LHO3P	<0.2	6.94	0.008	1.74	0.009	<0.001
LHO2P	<0.2	7.65	0.006	0.741	<0.005	<0.001
LHO1P	0.069	5.04	<0.005	1.22	0.028	0.002
LFO1P	<0.2	2.02	<0.005	0.317	0.017	<0.001
LFO7P	<0.2	1.54	<0.005	0.45	0.04	<0.001
LFO2P	<0.2	6.67	<0.005	1.84	0.042	0.002

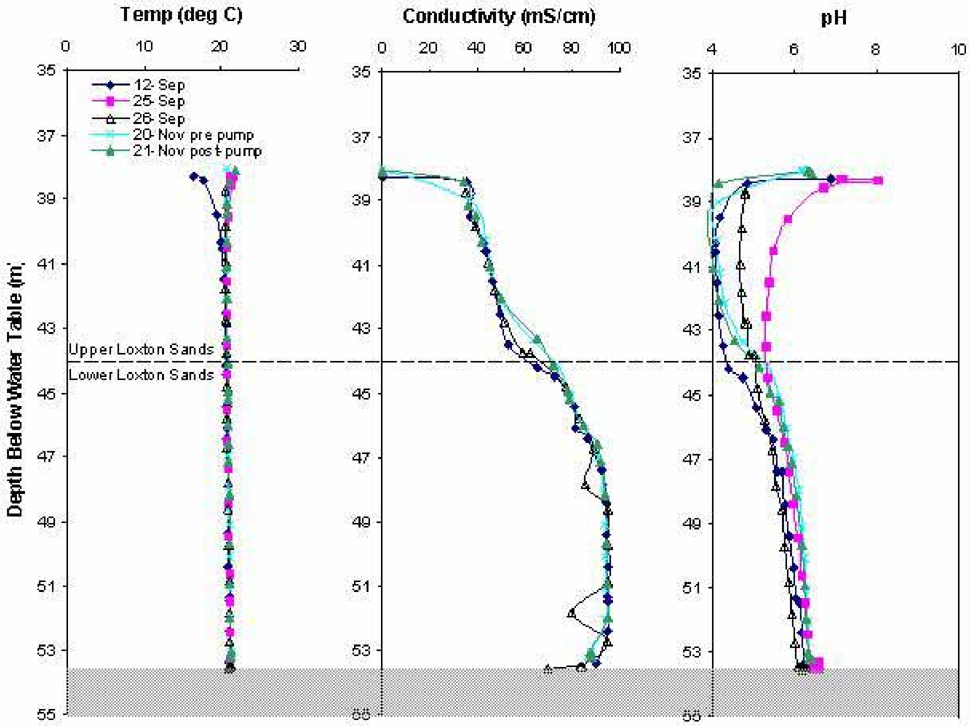
	Al (tot)	B	Cd (tot)	Fe (tot)	Mn (tot)	Se (tot)
	(mg/L)					
Glenforslan Formation						
BHO1G	0.032	1.91	<0.005	0.036	<0.005	0.004
CF8	0.064	2.67	0.014	0.809	<0.005	0.003
BKP8	0.243	2.98	0.013	6.26	0.18	0.004
LFO6GF	0.032	2.93	<0.005	0.53	0.011	0.001
LHO2GF	<0.2	4.54	<0.005	0.5	<0.005	<0.001
LHO3GF	<0.2	4.43	<0.005	0.334	<0.005	0.001
LHO1GF	0.066	3.19	<0.005	0.3	<0.005	0.003
LFO1GF	<0.2	2.1	<0.005	0.11	<0.005	<0.001
LFO7G	<0.2	1.57	<0.005	0.323	0.008	0.003
LFO2G	<0.2	3.44	<0.005	0.644	0.022	<0.001
LFO3G	<0.2	1.99	<0.005	0.554	0.014	0.004
LFP1	<0.2	2.74	<0.005	0.689	0.007	<0.001
Upper Mannum Formation						
LHO3UMF	<0.2	3.61	<0.005	0.22	<0.005	<0.001
Man12o	0.051	2.92	<0.005	0.44	<0.005	0.001
LFO1UM	<0.2	2.82	<0.005	0.643	0.01	<0.001
LFO3UM	<0.2	3.6	0.0053	1.94	0.007	0.002

* (NHMRC & ARMCANZ, 1996)
Yellow means >guideline value.
Red means >10 x guideline value

4.2 Groundwater Quality vs Depth Profiles in the Loxton Sands Aquifer

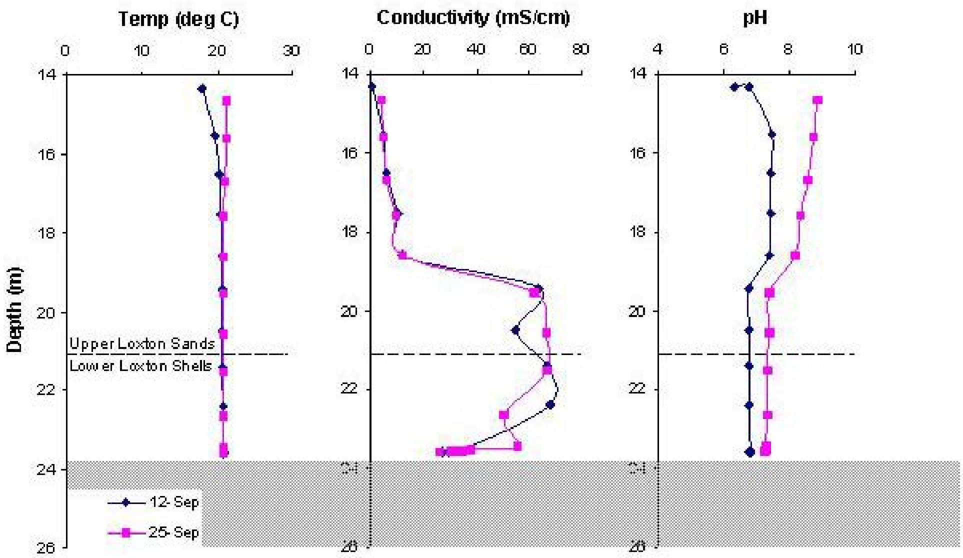
Groundwater quality (T, pH, EC) vs depth profiles were collected during September 2003 from a total of 20 wells screened in the Loxton Sands aquifer in the Loxton – Bookpurnong region (see Fig. 1 for well locations). The objective of this was to investigate variations in groundwater chemistry with depth in the Loxton Sands aquifer, particularly between the Upper Loxton Sands (ULS) and Lower Loxton Sands (LLS). Some representative profiles are shown in Figure 14(a-d) and all additional profiles are included as Appendix A. Water quality measurements start at the standing water level in the bore. Unshaded areas represent the screened interval, whereas shaded areas represent cased-off intervals.

Construction details were unknown for eight of the wells. However, for some of the remaining wells, it was known that blank casing had been installed at certain intervals below the standing water level (shaded intervals). Despite this, it was known that seven of the profiled wells (BHO1ls, BHP1, BHP2, BHP3, EES3, EES7 and EES8) were screened across both the ULS and LLS. Profiles from these wells showed that the EC in the LLS is generally between 30 and 70 mS/cm greater than in the ULS at any one point, with the exception of well EES8, where the difference was of the order of 6 mS/cm. There is usually a sharp transition between the two EC values at the ULS/LLS boundary. BHO1ls and BHP1, at Western's Highland in the Bookpurnong region, show an increase in groundwater pH across the ULS/LLS boundary, from 5 to 6 and 4 to 6 respectively. All other wells that were screened across the two sub-units showed a decrease in pH from



BHP1

Figure 14(a). Water quality versus depth profile from well BHP1, at Western's Highland in Bookpurnong. A series of profiles were collected at this well over time to show the change in chemistry of the Upper Loxton Sands groundwater with pumping, in relation to the formation of an aluminium hydroxide precipitate in the discharge water (Harrington, 2004).



BHP2

Figure 14(b). Water quality versus depth profile from Loxton Sands well BHP2, near Lock 4 in Bookpurnong.

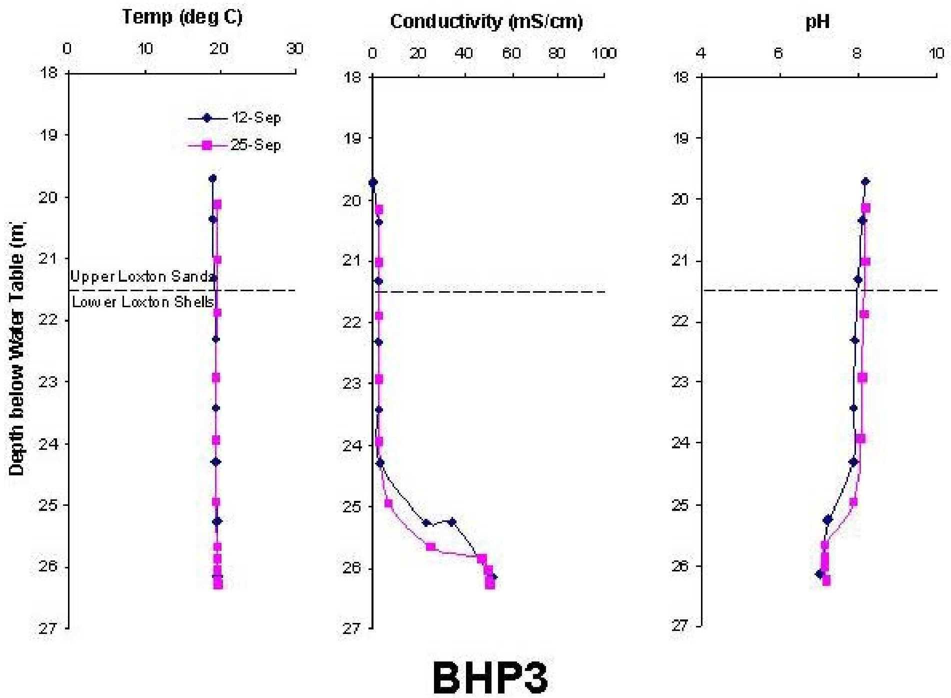


Figure 14(c). Water quality versus depth profile from Loxton Sands well BHP3, near Lock 4 in Bookpurnong.

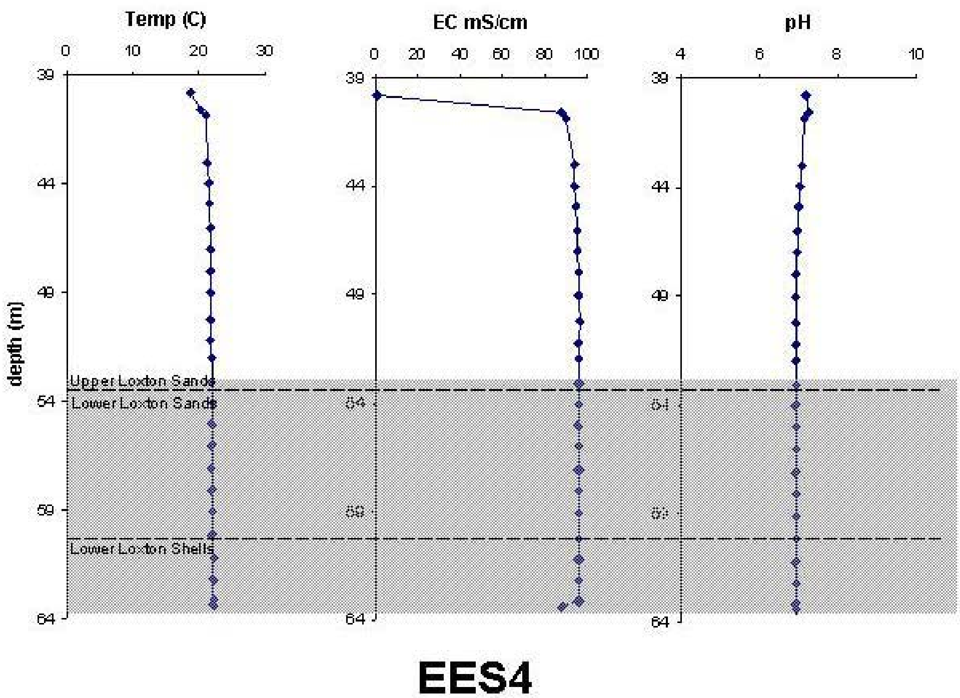


Figure 14(d). Water quality versus depth profile from Loxton Sands well EES4, in Bookpurnong.

approximately 7.8 to 6.8 across the ULS/LLS boundary. The exception of EES8, which decreased from pH 8.8 to 7.5.

Those wells that are only screened in the ULS and have an extensive sump generally show an increase in conductivity associated with the blank casing. This may be due to the development of density stratification within the sump.

4.3 The Stable Isotopes of the Water Molecule ($\delta^{18}O$ and $\delta^{2}H$)

Measured $\delta^{18}O$ and $\delta^{2}H$ values of the Loxton and Bookpurnong groundwater samples for the individual aquifers are shown in Table 5. The ranges of values observed in each aquifer in the Loxton and Bookpurnong regions are summarized in Table 6. The data are plotted on a $\delta^{2}H$ vs $\delta^{18}O$ in Figure 15, with the Adelaide Meteoric Water Line for reference. The effects of evaporation on recharging groundwater can be observed on such a diagram, on which rainfall samples generally plot along the Meteoric Water Line (MWL) and groundwater samples usually plot to the right of the MWL due to evaporation of rainfall under non-equilibrium conditions prior to recharge. The progressive evaporation of a water sample, with decreasing fraction of water remaining (*f*), follows an evaporation curve to the right of the MWL, which approximates a straight line. The slope of this line is a function of humidity, TDS, temperature and wind speed during evaporation, with humidity being by far the dominant influence (Gat, 1971, 1981; Gonfiantini, 1986).

$\delta^{2}H$ and $\delta^{18}O$ values of the groundwater samples from Bookpurnong range between -28.8‰ and -12.6 ‰ and -4.2‰ and -1.5‰ respectively, whilst observed $\delta^{2}H$ and $\delta^{18}O$ values of Loxton Sands groundwaters range between -38.7‰ and -15.5‰ and -5.9‰ and -2.0‰ respectively (Tables 5 and 6). Similarly to TDS, groundwater from the Bookpurnong region is generally more enriched in the heavy isotopes, ^{2}H and ^{18}O than that from the Loxton region.

4.4 Carbon Isotopes ($\delta^{13}C$ and ^{14}C)

Measured $\delta^{13}C$ and ^{14}C values of the Loxton and Bookpurnong groundwater samples are shown in Table 5. These are summarized for the individual aquifers in the region in Table 7 and the data are plotted on a ^{14}C vs $\delta^{13}C$ plot in Figure 16. The groundwaters at Loxton and Bookpurnong have a large range of $\delta^{13}C$ values (-14.5‰ to -2.1‰), indicating the occurrence of a range of processes involving the carbonate system. ^{14}C values are generally zero in the Murray Group aquifers, typical of old groundwater recharged >20 000 years ago. Groundwaters with ^{14}C values between 55 pMC and 90 pMC, typical of groundwater recharged between 5000 years ago and present, occur in the Monoman and Loxton Formations. Non-zero ^{14}C values were observed in a few Pata Formation groundwater samples, for example LHO2P, LHO1P, LFO6P and BHO1P (Table 5). The observed trend of increasing $\delta^{13}C$ with decreasing ^{14}C content is typically representative of carbonate mineral dissolution. The Loxton Sands groundwater ^{14}C values in the Bookpurnong region tend to be lower than those in the Loxton region.

Table 5. Isotopic signatures of groundwater samples collected from the Loxton and Bookpurnong regions. See Table 2 for well details and Figure 1 for well locations.

Bore Name	δ ^{18}O	δ ^{2}H	Deut excess	δ ^{13}C ‰ PDB	^{14}C pmC	^{87}Sr/^{86}Sr	δ ^{34}S ‰ CDT
Woorinen Formation							
BHO1W	-1.51	-12.6	-0.52	–	–	–	12.2
LHO3W	-2.04	-15.5	0.82	-10.7	85.7	–	23.1
Monoman Formation							
CF2	-3.61	-23.8	5.08	–	–	0.708978	12.6
CF1	-2.915	-25.2	-1.88	-8.6	84	0.709165	11.6
LFO6A	-4.39	-27.6	7.52	-12.4	51.2	0.709439	13
LFO1A	-2.6	-18.5	2.3	-14.5	92.6	0.709924	11.1
LFO7A	-3.59	-24	4.72	–	–	0.710219	–
LFO2A	-3.11	-24.6	0.28	–	–	0.709090	14.3
LFO3A	-3.44	-26	1.52	–	–	0.709712	–
LPP4	-3.21	-21.9	3.78	–	–	0.709237	5.9
LPP10	-3.89	-30.4	0.72	–	–	0.709440	-3.4
Loxton Sands							
EES4	-2.41	-22	-2.72	-8.2	32.4	0.709113	10.6
BHP1	-3.14	-25	0.12	-7.9	41.8	0.709097	10.7
BHO1(ls)	-3.14	-25.9	-0.78	-8.5	34.2	0.709091	11.2
IA3	-3.15	-23.9	1.3	–	–	0.709050	15
BKP1	-2.08	-17.3	-0.66	-7.8	52.6	0.708954	11.5
BHP2	–	–	–	–	–	–	–
BHP3	–	–	–	–	–	–	–
LHO8	-2.3	-18.4	0	-10.4	79.3	0.709111	5.1
L22	-3.14	-24	1.12	–	–	0.709088	12.3
LHO15	-2.98	-21.9	1.94	-10	95.5	0.709222	13.5
L24A	-3.67	-26.9	2.46	-8.8	53.9	0.709100	15.4
L14	-3.445	-26.9	0.66	–	–	–	15.1
L21	-3.67	-27	2.36	-7	90.5	0.709081	–
LHO3LS	-2.65	-21.5	-0.3	-11	82.6	0.709086	14.6
LHO1LS	-2.7	-17.2	4.4	-9.1	72.5	0.709093	12.7
L26A	-3.425	-28.3	-0.9	–	–	–	–
Pata Formation							
BHO1P	-3.77	-26.5	3.66	-2.1	3.1	0.708695	18.5
CF9P	-4.095	-28.2	4.56	-5.9	0	0.708726	17.2
LFO6P	-5.08	-30.8	9.84	-5.1	2.9	0.708915	21.6
L24B	-4.28	-29	5.24	-8	0	0.708948	19.5
LHO3P	-4.15	-28.4	4.8	-4.5	0	0.708993	–
LHO2P	-3.865	-28.6	2.32	-5.4	9.9	0.709608	13.2
LHO1P	-4.24	-29.9	4.02	-4.5	3.1	0.709015	14.6
LFO1P	-5.65	-35.1	10.1	-3.9	0	0.708822	18

Bore Name	$\delta^{18}O$	$\delta^{2}H$	Deut excess	$\delta^{13}C$ ‰ PDB	^{14}C pmC	$^{87}Sr/^{86}Sr$	$\delta^{34}S$ ‰ CDT
LFO7P	-5.51	-38.4	5.68	–	–	0.709567	14.8
LFO2P	-4.13	-28.7	4.34	–	–	0.708994	13.5
LFO3P	-4.155	-27.7	5.54	–	–	0.708953	22.6
Glenforslan Formation							
BHO1G	-3.88	-27	4.04	-5.2	4.1	0.708643	23.7
CF8	-4.18	-28.8	4.64	-7.4	0	0.708684	18.5
BKP8	-3.36	-26.65	0.23	–	–	0.709008	11.6
LFO6GF	-5.24	-32.9	9.02	-4.7	0	0.708819	22.4
LHO2GF	-4.63	-29.8	7.24	-6.9	0	0.708893	20.7
LHO3GF	-4.59	-31.4	5.32	-5.2	0	0.708926	18.8
LHO1GF	-5.16	-34.3	6.98	-3.1	0	0.708866	21.2
LFO1GF	-5.665	-35.9	9.42	-3.5	0	0.708780	17.8
LFO7G	-5.86	-38.7	8.18	–	–	0.709015	15.1
LFO2G	-5.16	-30.9	10.38	–	–	0.708863	–
LFO3G	-4.55	-29.6	6.8	–	–	0.708834	19.2
LFP1	-5.38	-34.1	8.94	–	–	0.708814	19.5
Upper Mannum Formation							
LHO3UMF	–	–	–	-7.6	0	0.708857	22.5
Man12o	-5.26	-33.9	8.18	–	–	0.708817	22.7
LFO1UM	-5.37	-35	7.96	-3.9	0	0.708813	–
LFO3UM	-4.93	-31.2	8.24	–	–	0.708796	18.8

Table 6. Observed ranges in groundwater $\delta^{18}O$ and $\delta^{2}H$ for the aquifers sampled in the Bookpurnong and Loxton regions.

Locality and Aquifer	No. of Samples	$\delta^{18}O$ (‰ V-SMOW)	$\delta^{2}H$ (‰ V-SMOW)
Bookpurnong			
Woorinen	1	-1.5	-12.6
Monoman	2	-3.6 – -2.9	-25.2 – -23.8
Loxton Sands	7	-3.2 – -2.1	-25.9 – -17.3
Pata Formation	2	-3.8 – -4.1	-28.2 – -26.5
Glenforslan Formation	3	-3.4 – -4.2	-28.8 – -26.7
Loxton			
Woorinen	1	-2.0	-15.5
Monoman	7	-4.4 – -2.6	-30.4 – -18.5
Loxton Sands	9	-3.7 – -2.3	-28.3 – -17.2
Pata Formation	9	-5.7 – -3.9	-38.4 – -28.4
Glenforslan Formation	9	-5.9 – -4.6	-38.7 – -26.7
Upper Mannum Formation	4	-5.4 – -4.9	-35.0 – -31.2

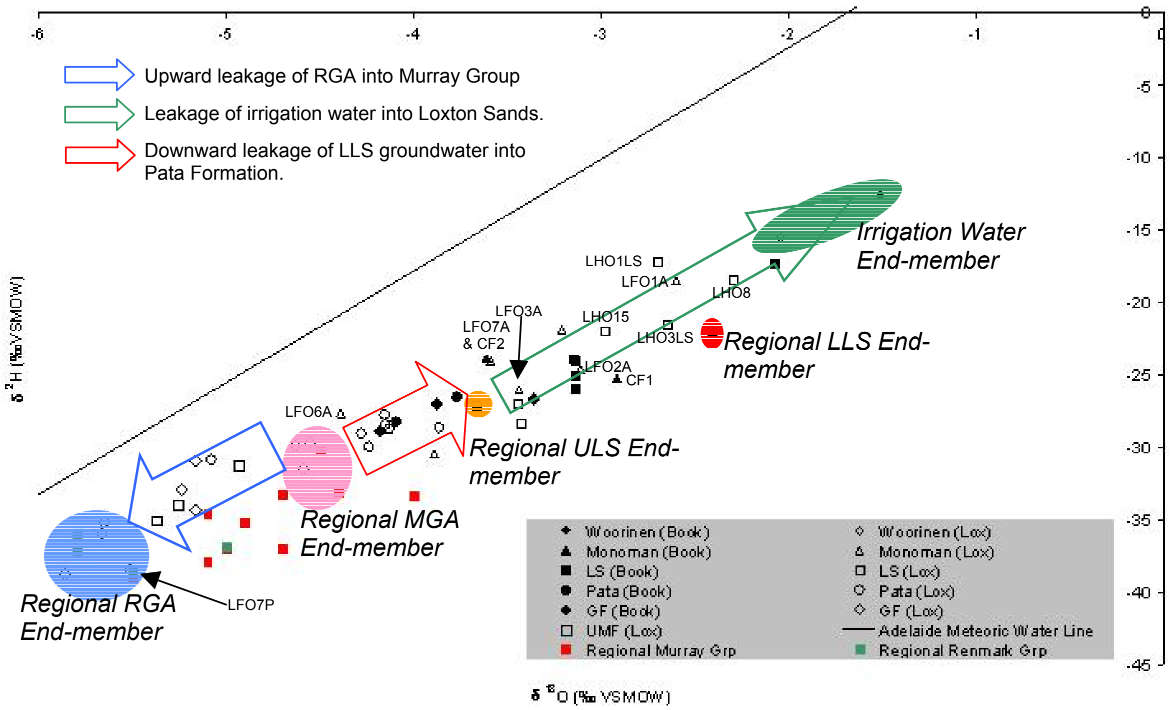


Figure 15. δ^2H vs δ^{18}O diagram for groundwater samples from the Loxton – Bookpurnong region, with the Meteoric Water Line for Adelaide shown for reference.

Table 7. Observed ranges in groundwater δ^{13}C and ^{14}C for the aquifers sampled in the Bookpurnong and Loxton regions.

Locality and Aquifer	No. of Samples	δ^{13}C (‰ V-PDB)	^{14}C (pmC)
Bookpurnong			
Woorinen	–	–	–
Monoman	1	-8.6	84
Loxton Sands	4	-8.5 – -7.8	32.4 – 52.6
Pata Formation	2	-5.9 – -2.1	0 – 3.1
Glenforslan Formation	2	-7.4 – -5.2	0 – 4.1
Loxton			
Woorinen	1	-10.7	85.7
Monoman	2	-12.4 – -14.5	51.2 – 92.6
Loxton Sands	6	-11 – -7	53.9 – 90.5
Pata Formation	6	-8 – -3.9	0 – -9.9
Glenforslan Formation	5	-6.9 – -3.1	–
Upper Mannum Formation	2	-7.6 – -3.9	–

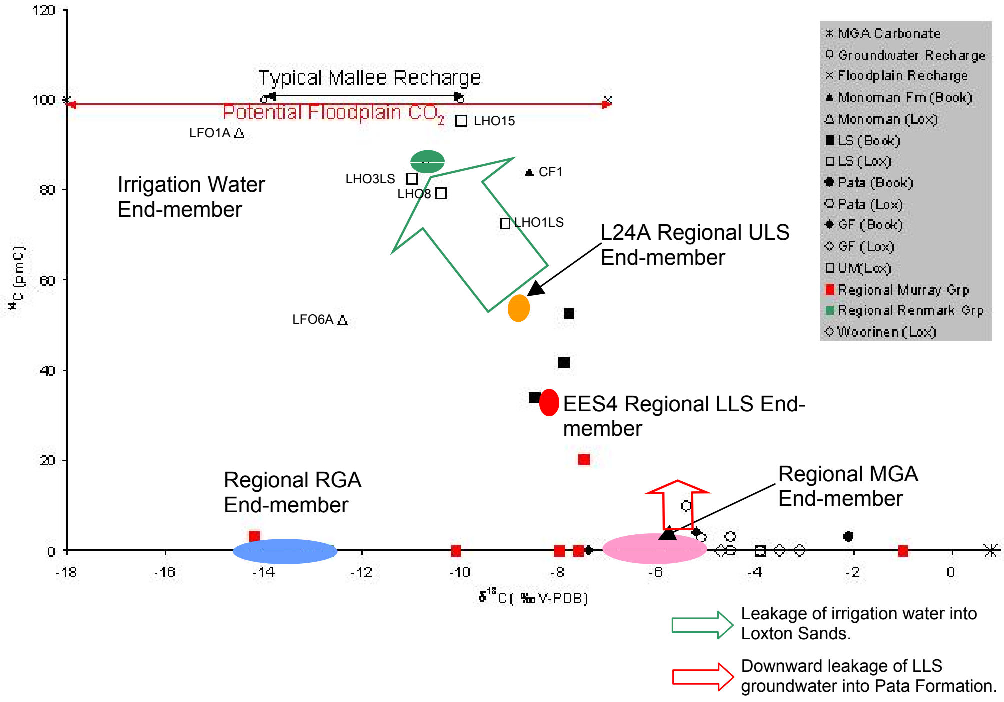


Figure 16. Plot of $^{14}C_{DIC}$ concentration versus $\delta^{13}C_{DIC}$ of groundwater samples collected from the Loxton (Lox) and Bookpurnong (Book) regions. The compositions of a typical Murray Group Aquifer carbonate (MGA Carbonate), typical recharge under mallee, potential floodplain CO_2 and some regional Murray Group and Renmark Group groundwaters (Dogramaci, 1998) are shown for reference. LS = Loxton Sands; GF = Glenforslan Formation; UMF = Upper Mannum Formation.

4.5 $^{87}Sr/^{86}Sr$

Measured Sr concentrations and $^{87}Sr/^{86}Sr$ ratios of the Loxton and Bookpurnong groundwater samples are shown in Table 5. These are summarized for the individual aquifers and regions in Table 8 and the data are plotted on a $^{87}Sr/^{86}Sr$ vs Sr/Ca diagram in Figure 17. Despite large variations in Sr concentration and Sr/Ca ratio, the Loxton Sands groundwaters have a constant $^{87}Sr/^{86}Sr$ ratio of approximately 0.7091, only slightly lower than the value for modern seawater. In contrast, groundwaters in the Murray Group aquifers have a range of $^{87}Sr/^{86}Sr$ values, between 0.70864 and 0.70961. The trend of increasing Sr/Ca with decreasing $^{87}Sr/^{86}Sr$ ratio, observed in the Murray Group aquifers, is consistent with the incongruent dissolution of carbonate minerals (Dogramaci, 1998; Dogramaci et al., 1998). Two samples from the Pata Formation, LHO2P and LFO7P, lie outside this trend, with high $^{87}Sr/^{86}Sr$ values closer to the theoretical value of 0.7097 for groundwater recharge in the Murray Basin (Dogramaci, 1998). Groundwater from the floodplain Monoman Formation has a range of $^{87}Sr/^{86}Sr$ ratios. For example, sample CF2, from Clarke's Floodplain at Bookpurnong has a ratio below that of the Loxton Sands groundwaters, whilst LFO2A, from the floodplain north of Loxton has a similar ratio to the Loxton Sands groundwaters and LFO6A and LPP10 adjacent Loxton have ratios closer to that of the theoretical Murray Basin recharge value.

Table 8. Observed ranges in groundwater Sr concentrations and $^{87}Sr/^{86}Sr$ ratios for the aquifers sampled in the Bookpurnong and Loxton regions.

Locality and Aquifer	No. of Samples	[Sr] (mEq/L)	$^{87}Sr/^{86}Sr$ (moles/moles)
Bookpurnong			
Woorinen	–	–	–
Monoman	2	0.363–0.655	0.70898–0.70917
Loxton Sands	5	0.099–0.357	0.70895–0.70911
Pata Formation	2	0.532–0.637	0.70870–0.70873
Glenforslan Formation	3	0.440–0.678	0.70864–0.70901
Loxton			
Woorinen	–	–	–
Monoman	7	0.050–1.000	0.70909–0.71022
Loxton Sands	7	0.039–0.764	0.70908–0.70922
Pata Formation	9	0.040–0.525	0.70882–0.70961
Glenforslan Formation	9	0.044–0.392	0.70878–0.70902
Upper Mannum Formation	4	0.154–0.533	0.70880–0.70886

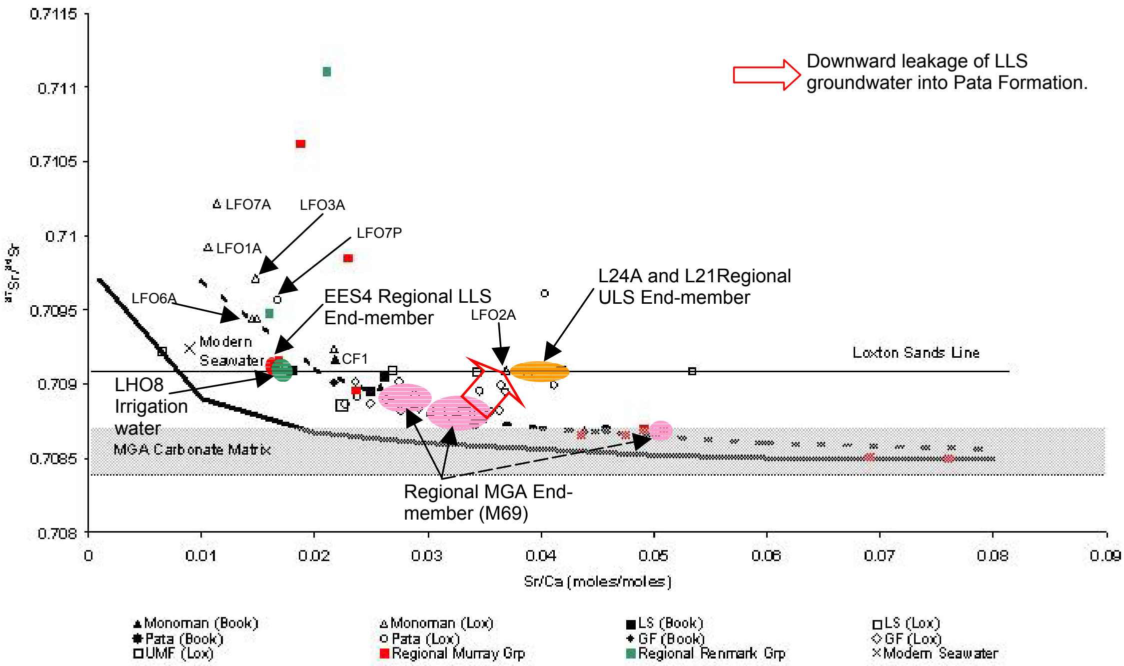
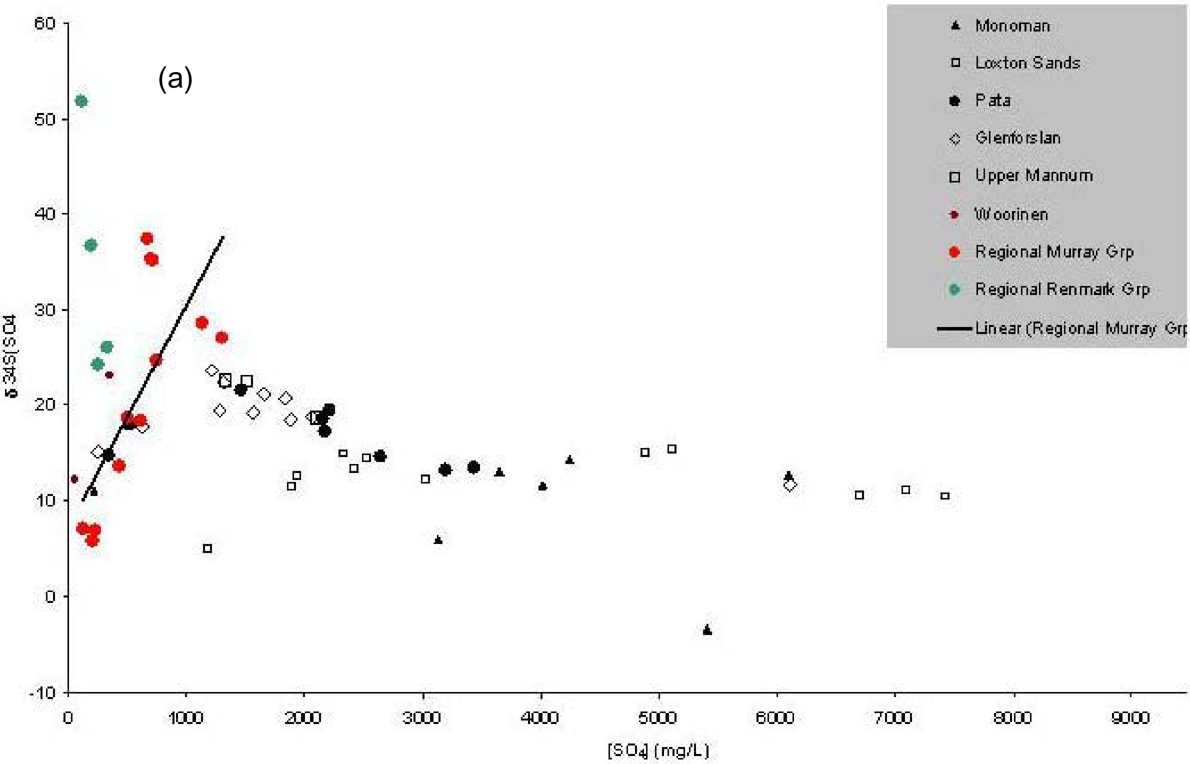


Figure 17. Plot of $^{87}Sr/^{86}Sr$ vs Sr/Ca of groundwater samples collected from the Loxton (Lox) and Bookpurnong (Book) regions. The range of $^{87}Sr/^{86}Sr$ ratios observed for Murray Group Limestone (Dogramaci, 1998) is shown as a shaded zone for reference and the compositions of modern seawater and some regional Renmark and Murray Group groundwaters (Dogramaci, 1998) are also shown for reference. LS = Loxton Sands; GF = Glenforslan Formation; UMF = Upper Mannum Formation. The solid and dashed curves represent the evolution of recharging groundwater along a groundwater flow path with incongruent dissolution of Murray Group carbonate minerals, for two starting Sr/Ca ratios (Dogramaci, 1998; Dogramaci & Herczeg, 2002).



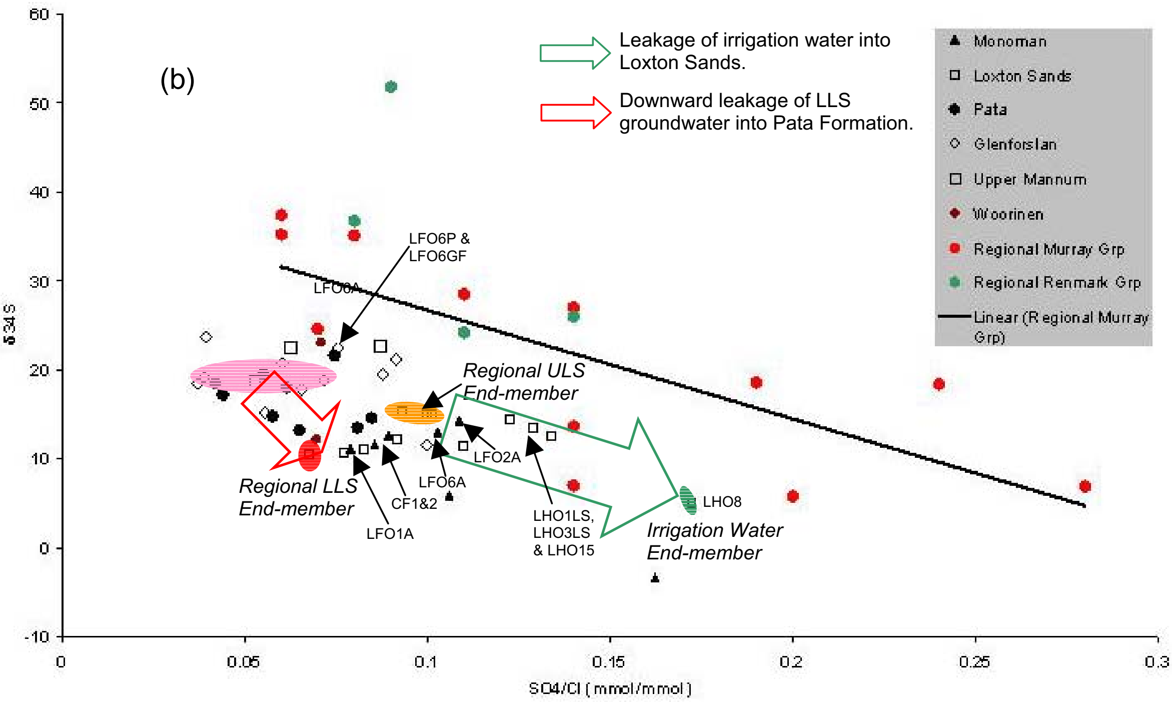


Figure 18. Plots of (a) $\delta^{34}S$ vs [SO_4^{2-}] and (b) $\delta^{34}S$ vs SO_4/Cl (mmol/mmol) of groundwater samples collected from the Loxton region. The compositions of regional Murray and Renmark Group groundwaters (Dogramaci, 1998) are also shown for reference.

5 DISCUSSION

5.1 Development of a Conceptual Groundwater Flow Model for the Loxton and Bookpurnong Regions Based on Chemistry, Isotope and Hydraulic Data

Both hydraulic and hydrogeochemical data were used to develop a model to infer groundwater movement. Present day water level distributions provide a “snapshot” of the hydraulics whereas chemistry and environmental isotopic signatures integrate processes over longer time scales. Vertical hydraulic gradients across aquitards imply the potential for groundwater fluxes across these aquitards. However, the actual magnitudes of such fluxes depend on the hydraulic conductivity of the aquitard, which is difficult to measure and can vary by several orders of magnitude over small distances. A large hydraulic gradient across an aquitard with an extremely low permeability may still only result in a negligible flux. Therefore, hydraulic data can be used to infer the potential for, and the direction of, flow, providing a guide for the interpretation of hydrochemical data. Hydrochemical data can then be used to confirm, via the identification of mixing between two aquifer water types, whether such a flux has occurred and its approximate magnitude.

5.1.1 POTENTIAL GROUNDWATER FLUXES DETERMINED FROM HYDRAULIC DATA

The fluid potential of a groundwater flow system can be determined empirically from observations of the hydraulic head distribution. The most common method of displaying the distribution of hydraulic head is to produce water table plots or potentiometric surfaces in plan view. As vertical fluxes between aquifers are as, if not more, important than horizontal fluxes within individual aquifers, in this report, we represent the distribution of fresh water hydraulic heads in cross-sectional view. This was achieved by plotting the observed hydraulic head at the elevation that the well is open to the aquifer in a similar manner to Love et al. (1993).

Equipotential lines plotted on Cross Sections AA’, BB’ and CC’ are shown in Figures 19, 20 and 21 respectively. Cross section AA’ lies approximately along a groundwater flow line through the Loxton Irrigation Mound. The vertical distribution of hydraulic heads along this cross-section indicates a potential for downward leakage of groundwater from the Loxton Sands aquifer into the Murray Group aquifers below the eastern half of the groundwater mound (Fig. 19). To the west, between the mound and the river, groundwater flow in the Loxton Sands is horizontal, towards the floodplain. This is also the case in the Murray Group aquifers, with the exception of directly below the floodplain, where the groundwater flow lines curve upwards. This suggests potential discharge of groundwater from the Murray Group aquifers into the River Murray in this region.

Equivalent freshwater heads plotted on Cross Section BB’ also show the potential for downward groundwater movement between aquifers under the highland to the east of the River Murray, and upward groundwater leakage from the Murray Group aquifers below the River (Fig. 20). The limited hydraulic data available along Cross Section CC’ in the Bookpurnong region suggests that the potential for vertical groundwater movement is predominantly downwards (Fig. 21). However, horizontal groundwater flow may dominate

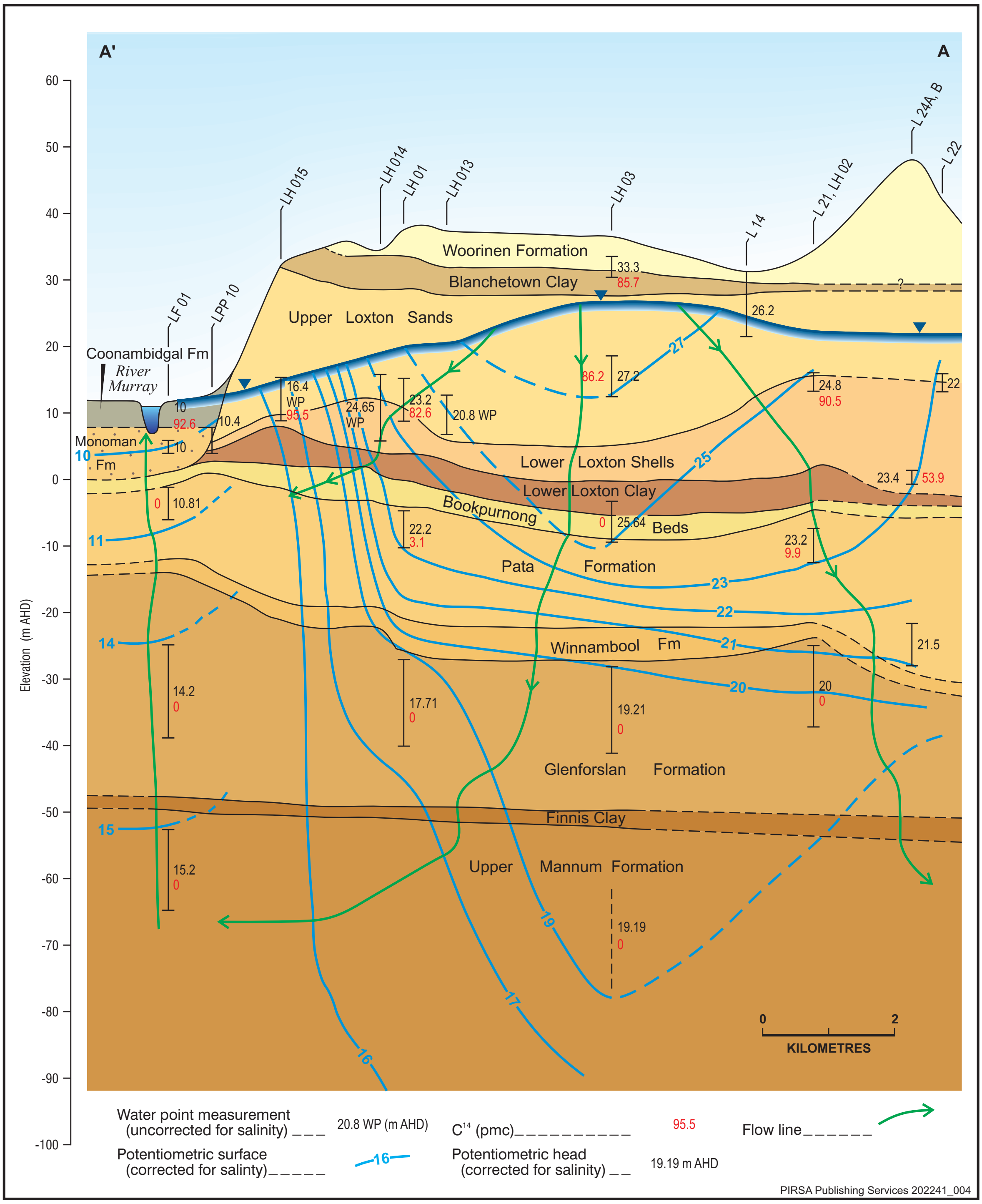


Figure 19. Cross-section AA' showing density-corrected equipotentials and flow lines. See Figure 1 for cross-section location.

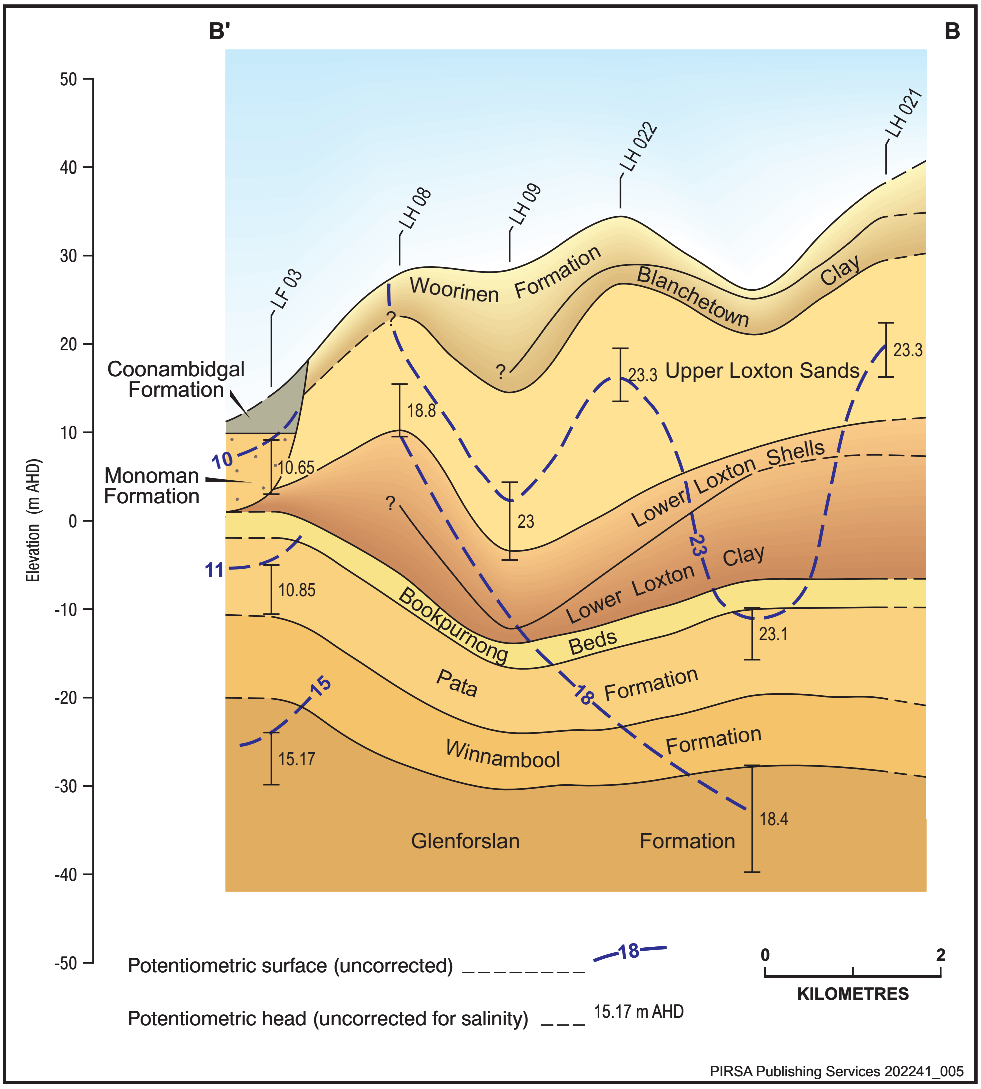


Figure 20. Cross-section BB' with uncorrected equipotentials.

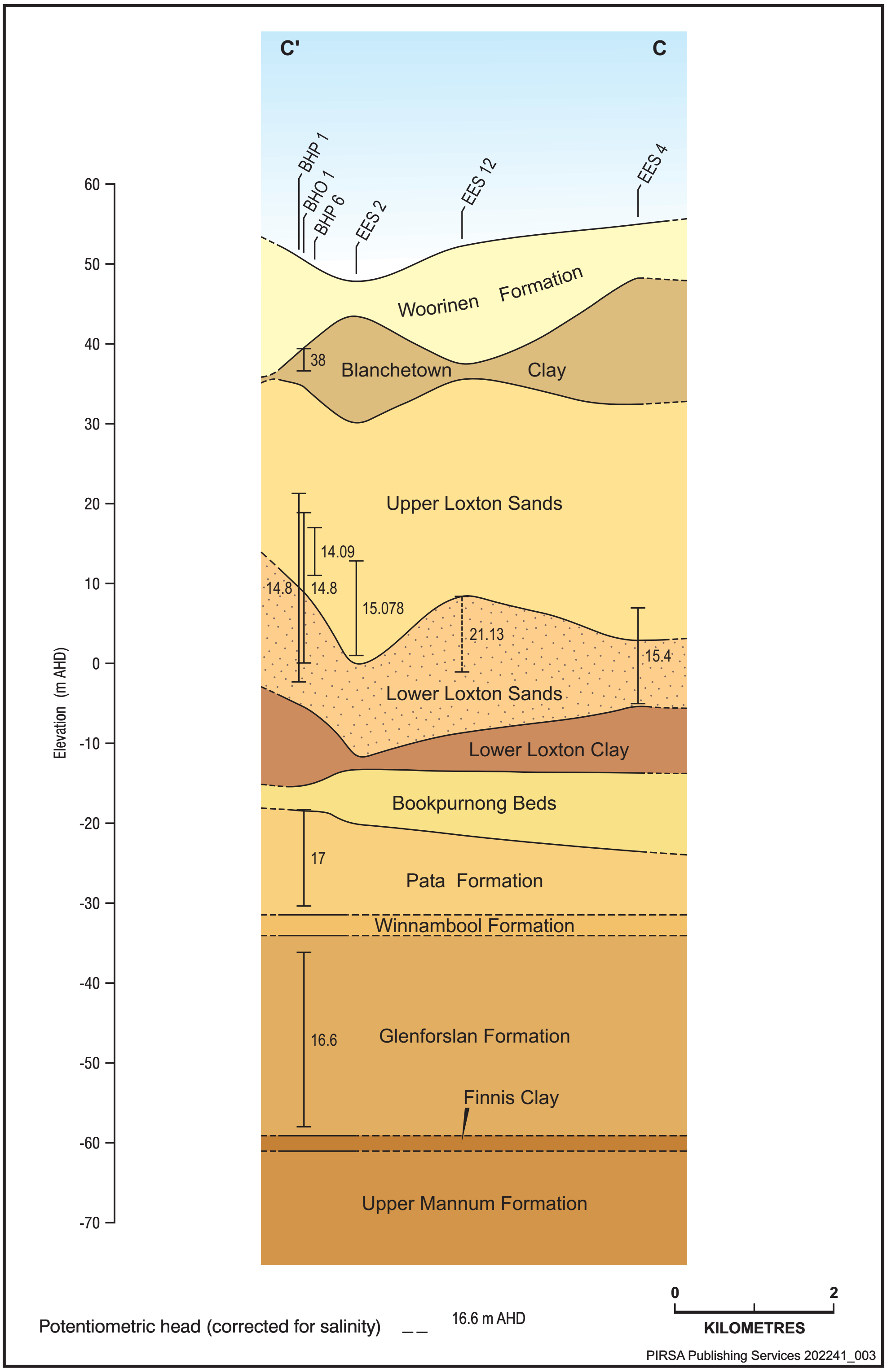


Figure 21. Cross-section CC' with uncorrected hydraulic heads.

groundwater movement in the Loxton Sands aquifer and provide groundwater discharge to the River.

5.1.2 HYDRAULIC PROCESSES AFFECTING GROUNDWATER CHEMISTRY AND ISOTOPIC COMPOSITIONS

5.1.2.1 Identification of the Geochemical End-Members

As described above, actual groundwater movement across aquitards can often be shown via the identification of mixing between two distinctive starting groundwater compositions (end-members). The groundwater geochemical end-members for mixing processes in the Loxton region were identified by AWE (2003) based on hydraulic models and salinity data to be:

- Regional groundwater in the Loxton Sands (LS) aquifer (TDS >40 000 mg/L).
- Regional groundwater in the Upper Mannum Formation (UMF) aquifer (TDS ≈ 3000 mg/L).
- High salinity groundwater in the floodplain Monoman Formation resulting from evaporation (TDS ≈ 40 000 mg/L).
- Irrigation drainage water (TDS = 1000–3000 mg/L).

The results of the groundwater chemistry investigation generally support these end-members. However, regional groundwater data suggests that Mannum Formation groundwater flowing into the Loxton area is comparatively saline, as is groundwater in the other two Murray Group aquifers, the Pata and Glenforslan Formations. Fresher groundwater is introduced to the Murray Group aquifers via upward leakage from the Renmark Group (Dogramaci, 1998). This is discussed in Section 5.1.2.2. The geochemical signatures of the groundwater end-members at Loxton are summarized in Table 10 and discussed individually below.

Table 10. Summary of the geochemical and isotopic signatures of the groundwater end-members at Loxton.

Groundwater End-member	TDS (mg/L)	$\delta^{18}O$ (‰ VSMOW)	$\delta^{2}H$ (‰ VSMOW)	$\delta^{13}C$ (‰ VPDB)	^{14}C (pmC)	$^{87}Sr/^{86}Sr$	$\delta^{34}S$ (‰ CTD)
Renmark Group	3000–5000	-5.5 – -5.8	-38.5 – -35.9	-12 – -15	0	0.70948–0.71092	24–52
Mannum Formation	27 000	-4.9	-31.2	NA	NA	0.70888	18.8
Glenforslan / Pata Formations	19 700–25 700	-4.6	-31.4 – -29.6	-5.2 – -6.9	0	0.70883–0.70893	18.8–20.7
Lower Loxton	73 000	-2.4	-22.0	-8.2	32.4	0.70911	10.6
Upper Loxton	36 200	-3.4	-26.9	-7 – -8.8	53.9–90.5	0.70908–0.7091	15.1
Irrigation Water	<6200	-2.3	-18.4	-10.4	79.3	0.70911	5.1

5.1.2.1.1 REGIONAL RENMARK GROUP GROUNDWATER

The geochemistry of and groundwater movement between the Murray Group (MGA) and Renmark Group (RGA) aquifers in the Murray Basin have been discussed by Dogramaci (1998), Dogramaci et al. (1998, 2001) and Dogramaci and Herczeg (2002). The study area and bores sampled for that work are shown in Figure 22. As the RGA is predominantly a silicate aquifer, whereas the MGA is predominantly carbonate, the groundwater geochemical signatures of these aquifers are quite different. The general regional hydrogeochemical characteristics of the RGA groundwaters were found to be (Dogramaci, 1998; Dogramaci et al., 2001):

- TDS generally increases from <1000 mg/L at the basin margin in the south-east of the study area to approximately 22 300 mg/L near the River Murray.
- Although groundwater TDS in the MGA and RGA vary over more that two orders of magnitude, TDS in the two aquifer systems generally correspond to each other at any one location.
- Groundwaters sampled from the RGA were all devoid of ^{14}C and those from Zone B (the northern part of the study area, around Loxton) generally had depleted $\delta^{13}C$ (-14.1‰ to –21.65‰).
- RGA groundwaters in Zone B have $^{87}Sr/^{86}Sr$ ratios ranging from 0.7108 to 0.7111, with Sr/Ca ratios >0.016.
- The RGA is a very reducing environment, with high $\delta^{34}S$ and $\delta^{18}O$ of sulphate compared with the MGA, which has signatures similar to atmospheric values. At any one location, the $\delta^{34}S$ of sulphate in the RGA is usually significantly higher than that in the overlying MGA aquifers.

As mentioned above, a major conclusion from the studies described above was that upward leakage of groundwater from the RGA plays a major role in the current distribution of TDS of the MGA in the northern and north-eastern part of the study area, including the area surrounding Loxton.

The geochemical signatures of the RGA groundwaters from bores R15, R16 and R17, which are the closest up-gradient bores to Loxton included in the above studies, are plotted on Figures 15, 16, 17 and 18 with the data from the current study. The geochemical signature of the RGA groundwater flowing into the Loxton area can therefore be characterized as follows:

- TDS = 3000 mg/L to 5000 mg/L, which is low compared with the groundwaters sampled from Loxton and Bookpurnong (Table 10).
- Low $\delta^{18}O$ and δ^2H values, lying at the low $\delta^{18}O$ and δ^2H end of the line formed by the Loxton and Bookpurnong data on a δ^2H vs $\delta^{18}O$ diagram (Table 10; Fig. 15).
- Very negative $\delta^{13}C$ values (-12‰ to –15‰) compared with the groundwater samples collected from Loxton and Bookpurnong. Only two samples, LFO1A and LFO6A, from the floodplain Monoman Formation at Loxton have similarly low $\delta^{13}C$ values. These have a ^{14}C value of 0 pmC (Table 10; Fig. 16).
- $^{87}Sr/^{86}Sr$ = 0.70948 (bore R14) to 0.71092 (bore R16) (Table 10). These values are higher than those for the majority of the groundwater samples collected during this study. When plotted on a $^{87}Sr/^{86}Sr$ vs Sr/Ca diagram (Fig. 17), bore R14 plots at the high $^{87}Sr/^{86}Sr$ end of a curve drawn for dissolution of the Murray Group aquifer

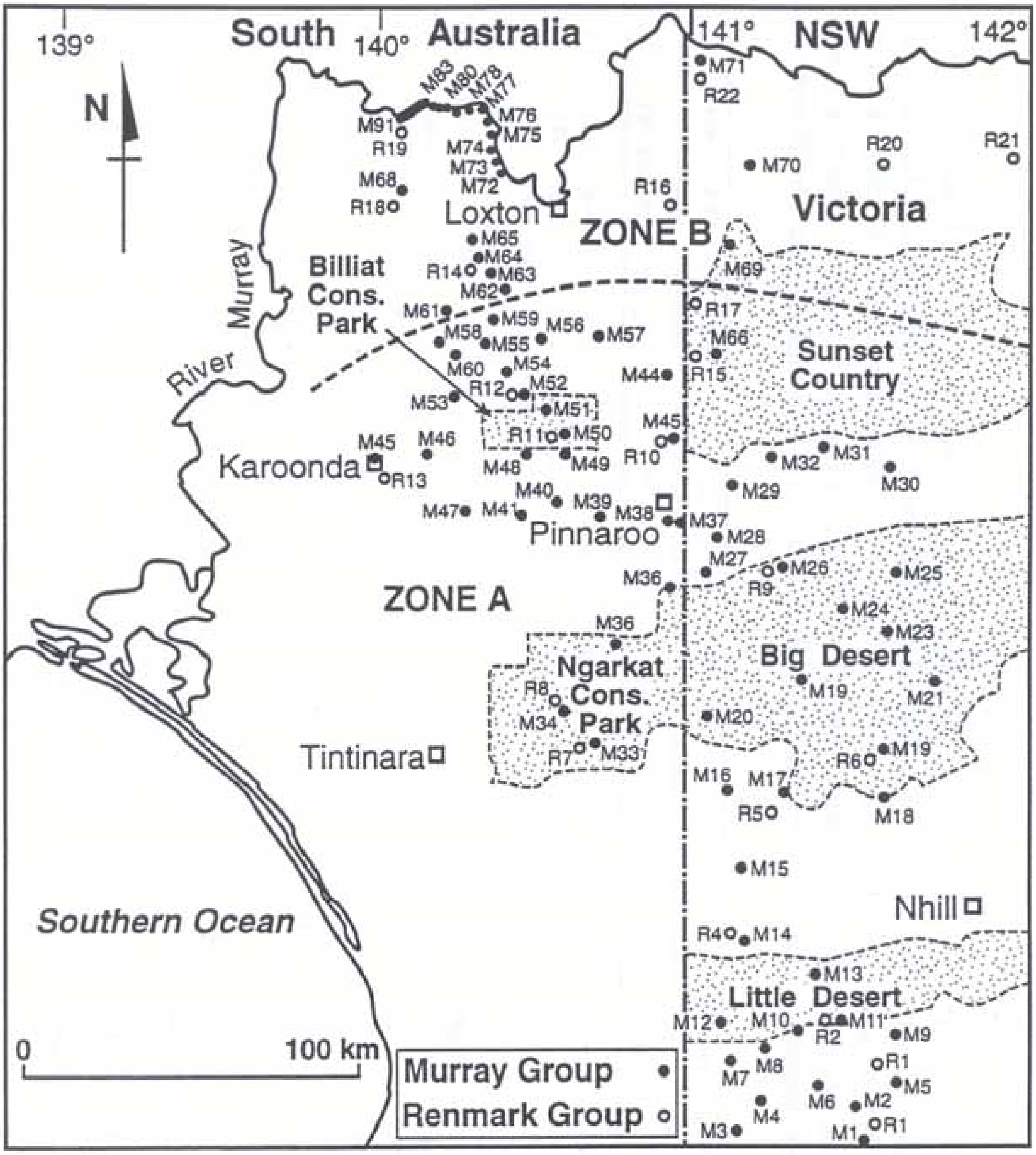


Figure 22. Study area and regional Murray Group and Renmark Group wells sampled by Dogramaci (1998), Dogramaci et al. (1998, 2001) and Dogramaci and Herczeg (2002). The water quality zones, Zone A and Zone B identified in that study are also shown for reference.

carbonate matrix by typical Murray Basin recharge waters (Dogramaci, 1998; Dogramaci & Herczeg, 2002). The sample from bore R16 has a much higher Sr/Ca ratio than any of the samples collected during this study.

- $\delta^{34}S$ = 24 ‰ to 52 ‰, which is higher than the value for seawater (15‰ to 21 ‰) and the values for the majority of Murray Group groundwaters throughout the Murray Basin due to the effects of bacterial sulphate reduction in the reducing RGA environment (Table 10; Fig. 18; Dogramaci, 1998; Dogramaci et al., 2001).

5.1.2.1.2 THE MURRAY GROUP AQUIFERS

Similarly to the Renmark Group (RGA) described above, Dogramaci (1998), Dogramaci et al. (1998, 2001) and Dogramaci and Herczeg (2002) also provide geochemical data for regional groundwater bores screened in the Murray Group aquifers in the region surrounding Loxton and Bookpurnong, and throughout the Murray Basin. The locations of these bores are shown on Figure 22 and the geochemical / isotopic signatures of those located closest to Loxton are shown on Figures 15–18. As none of the bores included in these studies were closer than approximately 30 km to Loxton, TDS data from additional bores, BKP 14 and BKP18 were obtained from the state government database, SAGeodata. It is unknown which unit of the Murray Group the regional MGA wells are screened in (Pata, Glenforslan or Upper Mannum Formations). Analysis of the regional MGA data identified two possible inflowing groundwater types, as follows:

1. Groundwater flowing in from the east, represented by bore M69 (see Fig. 22 for location) has:
   - A comparatively high TDS of approximately 18 000 mg/L (Dogramaci, 1998).
   - Comparatively high $\delta^{18}O$ and $\delta^{2}H$ values of –4 ‰ and –33 ‰ respectively (Fig. 15).
   - Unknown ^{14}C and $\delta^{13}C$ values (groundwater from this bore was not analysed for ^{14}C and $\delta^{13}C$).
   - Low $^{87}Sr/^{86}Sr$ and high Sr/Ca, plotting at the bottom right of a curve representing the dissolution of carbonate minerals in the MGA aquifer matrix (Fig. 17).
   - Comparatively high $\delta^{34}S$ of 27.0 ‰ (Fig. 18).
2. Groundwater flowing in from the south and south-east, represented by bores M56, M57, M66, BKP14 and BKP18 (see Fig. 22 for locations), with:
   - Comparatively low TDS of approximately 2000–4000 mg/L.
   - Low $\delta^{18}O$ and $\delta^{2}H$ values of approximately –6 ‰ to -5 ‰ and –43 ‰ to –38 ‰ respectively (Fig. 15).
   - $\delta^{13}C$ values between approximately –8 ‰ and –1 ‰, which are more positive than those of the RGA groundwaters and ^{14}C values of 0 pmC (Fig. 16).
   - $^{87}Sr/^{86}Sr$ between 0.70896 and 0.70916, close to or just above the value for modern seawater and the value of the majority of the Loxton Sands samples collected from the Loxton – Bookpurnong region (Fig. 17). On a plot of $^{87}Sr/^{86}Sr$ vs Sr/Ca, the regional MGA samples plot at the top left of the MGA dissolution curve.
   - Low $\delta^{34}S$ of approximately 6 ‰ to 7 ‰. This is at the low end of the range of values measured for the Loxton – Bookpurnong groundwaters (Fig. 18).

Due to the lack of data close to Loxton, but beyond the influence of any potential inter-aquifer leakage processes associated with the groundwater mound in that region, it is difficult to determine which of these two groundwater types (1 or 2) best represents that flowing into the Loxton Irrigation District. It is also unknown whether, on a regional scale, groundwater in the sub – units of the Murray Group (i.e the Pata, Glenforslan and Upper Mannum Formations) chemically differ from each other. Groundwater from bore BKP14, to the south-east of Loxton, has a TDS of 12 900 mg/L, which is intermediate to those of groundwater types (1) and (2) described above and, hence, may be a mixture of these, as may be the MGA groundwater flowing into Loxton.

MGA groundwaters sampled at the up-gradient margin of the Loxton Irrigation District (i.e. Pata Formation bores L24B, LHO2P and LHO3P and Glenforslan bores LHO2GF and LHO3GF) have slightly higher TDS concentrations than the higher TDS Group 1 regional groundwaters described above. This may be due to a small amount of downward leakage of saline groundwater from the overlying aquitards under the influence of the groundwater mound. The TDS of the Glenforslan Formation groundwaters, LHO2GF and LHO3GF (TDS = 21 000 mg/L) are identical to that of bore M71, located near the River Murray north of Loxton. On a δ^2H vs δ^{18}O plot, LHO2GF and LHO3GF, as well as another Glenforslan bore LFO3GF, plot close to regional Group 1 bore, M69 (Fig. 15). These groundwaters have δ^{13}C values of –6.9‰ and –5.2‰ repectively and ^{14}C values of 0 pmC, although carbon isotope analyses were not carried out on LFO3GF. The carbon isotope signature of the Group 1 regional end – member bore M69 is not available for comparison.

On the ^{87}Sr/^{86}Sr vs Sr/Ca diagram (Fig. 17), LHO2GF, LHO3GF and LFO3GF all plot slightly higher on the MGA carbonate dissolution curve than the regional bore M69, closer to the lower TDS regional bore, M66. They also have slightly lower δ^{34}S values, between 18.8 ‰ and 20.7 ‰, than M69, which has a value of 27.0. The Loxton – Bookpurnong δ^{34}S values are similar to that of atmospheric marine aerosol input, whilst the slightly higher value at M69, located on the northern border of Sunset Country, with its numerous groundwater discharge zones, may suggest some influence of upward leakage from the Renmark Group. Likewise, the high δ^{34}S value at bore M71 and its more negative δ^2H and δ^{18}O values are consistent with upward leakage from the Renmark Group.

Based on the above discussion, and in the absence of any Murray Group aquifer data close to Loxton but beyond the potential influence of the Loxton irrigation mound, the regional Murray Group (Pata and Glenforslan Formations) end-member flowing into the Loxton Irrigation District is thought to be best represented by groundwater from bores LHO2GF, LHO3GF and LFO3GF, with geochemical characteristics as summarized in Table 10. The four groundwater samples collected from the lower sub-unit of the Murray Group, the Mannum Formation, had a range of TDS concentrations, the highest of which was collected from bore LFO3umf (TDS = 26 900 mg/L), located below the floodplain north of Loxton. Although this TDS is slightly higher, this sample had similar δ^2H, δ^{18}O and δ^{34}S values to the Glenforslan Formation regional groundwater end-members, LHO2GF, LHO3GF and LFO3GF described above, suggesting that this may represent regional groundwater inflow in the Mannum Formation (Figs 15 and 18). LFO3umf also plots slightly further along the MGA carbonate dissolution curve on the ^{87}Sr/^{86}Sr vs Sr/Ca diagram than the regional Glenforslan samples, consistent with a greater degree of dissolution of aquifer carbonate material. Carbon isotope analyses were not carried out on this sample. The geochemical characteristics of the interpreted Mannum Formation end-member are hence summarized in Table 10.

5.1.2.1.3 LOXTON SANDS REGIONAL GROUNDWATER

Water quality versus depth profiles collected from Bookpurnong bores BHP1 and BHO1Is, both screened across intervals of the Upper and Lower Loxton Sands, showed a difference in EC (and hence TDS) between the two sub-units (Section 4.2; see Fig. 1 for bore locations). At this location, groundwater in the Upper Loxton Sands had an EC of 38–50 mS/cm (TDS ≈ 25 000–33 000 mg/L). Groundwater in the Lower Loxton Sands had an EC of 73–95 mS/cm (TDS ≈ 48 000–63 000 mg/L). Due to the lack of water quality versus depth data beyond the potential zone of influence of infiltrating irrigation water, it is currently uncertain whether the salinity stratification at this location is a natural phenomenon or a result of infiltrating irrigation water in the Upper Loxton sands aquifer. However, historical EC data from Loxton Sands observation wells that are located hydraulically up-gradient of the Loxton and Bookpurnong Irrigation Districts suggests that the lower EC groundwater is present in the aquifer on a regional scale. A review of geological logs is required to identify the interval of the aquifer (Upper or Lower Loxton Sands) that is represented by these data.

Due to its location approximately 4 km to the east of the centre of the Bookpurnong Irrigation Mound (Fig. 1), bore EES4 is expected to intersect groundwater in the Lower Loxton Sands aquifer that has a regional geochemical signature. This groundwater has the following geochemical characteristics (Tables 2 and 5):

- TDS = 73 000 mg/L. This was the highest TDS groundwater sample collected during this study and it is believed that the high salinity in the Loxton Sands in this region may be a result of leakage from the Noora groundwater discharge complex, located to the east of the study area (Fig. 1).
- $\delta^{18}O$ = -2.4 ‰ and $\delta^{2}H$ = -22 ‰ (Fig. 15). Despite its high salinity, this groundwater sample is not the most enriched in ^{18}O and ^{2}H. The most enriched groundwaters are those influenced by irrigation water (see Section 5.1.2.1.4 below).
- ^{14}C = 32.4 pmC and $\delta^{13}C$ = -8.2 ‰ (Fig. 16). This carbon isotope signature may reflect simple radioactive decay of ^{14}C in a closed groundwater system or may include some influence of carbonate mineral dissolution. This will be discussed in more detail in Section 6.1.2.3 below.
- $^{87}Sr/^{86}Sr$ = 0.70911. When plotted on a $^{87}Sr/^{86}Sr$ vs Sr/Ca diagram (Fig. 17), EES4 plots at the low Sr/Ca end of a horizontal line that can be drawn through the Loxton Sands data and appears to be quite diagnostic of this aquifer.
- $\delta^{34}S$ = 10.6 ‰, which is much lower than the value for seawater, probably due to some degree of sulfide mineral oxidation (Fig. 18).

The lower salinity (TDS = 36 200 mg/L) and slightly lower $\delta^{18}O$ (-3.4 ‰) and $\delta^{2}H$ (-27 ‰) of Upper Loxton Sands groundwater sample, L14, from the eastern (up-gradient) edge of the Loxton irrigation district may represent the regional Upper Loxton Sands groundwater signature for that region. Due to the low volume of groundwater that could be extracted from this well, carbon isotope and $^{87}Sr/^{86}Sr$ analyses could not be carried out. However, the TDS and $\delta^{18}O$ and $\delta^{2}H$ signatures of groundwater from wells L21 and L24A are almost identical to that of L14, possibly due to downward infiltration of groundwater from the Upper Loxton Sands into the lower permeability Lower Loxton Sands under the irrigation mound (see Section 6.1.2.3 below). The geochemical characteristics of these groundwater samples are:

- TDS ≈ 36 200 mg/L, which is lower than that of the Lower Loxton Sands groundwater at Bookpurnong (EES4), but is highest of the Loxton Sands groundwater samples from the main Loxton irrigation area.
- $\delta^{18}O$ = -3.4 ‰ and $\delta^{2}H$ = -26.9‰. This groundwater is the least enriched in ^{18}O and ^{2}H of all of the Loxton Sands groundwaters sampled (Fig. 15).
- ^{14}C = 53.9 pmC to 90.5 pmC and $\delta^{13}C$ = -8.8‰ to –7.0‰. The $\delta^{13}C$ of this groundwater is similar to that of the LLS groundwater at Bookpurnong (EES4), however the higher ^{14}C value is consistent with a younger groundwater age (Fig. 16).
- $^{87}Sr/^{86}Sr$ = 0.70908 to 0.7091, which is approximately the same as the Lower Loxton Sands at EES4. However, when plotted on a $^{87}Sr/^{86}Sr$ vs Sr/Ca diagram, L24A and L21 plot at the high Sr/Ca end of a horizontal line that can be drawn through the Loxton Sands data (Fig. 17). Hence, EES4 and L24A / L21 appear to represent low and high Sr/Ca ratio end-members for mixing between Lower and Upper Loxton Sands groundwater respectively (Fig. 17).
- $\delta^{34}S$ = 15.1 ‰, which is closer to the composition of seawater than the interpreted LLS end-member.

5.1.2.1.4 IRRIGATION DRAINAGE WATER

Irrigation drainage water, present in the Upper Loxton Sands below the Loxton irrigation mound, and as perched groundwater in the Woorinen Formation at LHO3 (below the Loxton mound) and BHO1W (Western's Highland), has a low salinity similar to some Pata and Glenforslan Formation groundwaters (Table 2), but is much more enriched in $\delta^{18}O$ and $\delta^{2}H$ (Fig. 15). This difference in stable isotope signatures may be the result of (a) different recharge environments, i.e. a source with a more enriched starting composition, or (b) a greater degree of evapotranspiration of the irrigation water. The geochemical signature of groundwater at LHO3W, which has one of the lowest TDS concentrations and highest $\delta^{18}O$ and $\delta^{2}H$ values of the groundwaters sampled during this study can be summarized as follows:

- TDS = 9100 mg/L
- $\delta^{18}O$ = -2.0‰ and $\delta^{2}H$ = -16‰.
- ^{14}C = 85.7 pmC and $\delta^{13}C$ = -10.7‰.

$^{87}Sr/^{86}Sr$ signatures of the Woorinen Formation samples were not analysed due to the low yields of these bores and the resulting difficulty in obtaining enough sample for these particular analyses. However, groundwater from the Loxton Sands bore LHO8, located to the north of Loxton, appears to consist predominantly of irrigation drainage water as it has a salinity and stable isotope signature similar to that of LHO3W. The geochemical and isotopic signatures of this groundwater are summarized in Table 10.

5.1.2.2 Upward Leakage of Renmark Group Groundwater

As mentioned previously, Dogramaci (1998) and Dogramaci et al. (2001) present evidence for significant upward leakage of groundwater from the Renmark Group aquifers to the Murray Group in the northern half of their study area shown in Figure 22, and in particular along the River Murray. In the vicinity of the Renmark Group bore R16, the closest available point to Loxton, there is a hydraulic head difference of approximately 15 m between the Renmark Group and Murray Group aquifers, indicating significant potential for upward leakage (Dogramaci et al., 2001). If the Murray Group and Renmark Group end-members for the Loxton region are characterized correctly above, the occurrence of lower TDS groundwater in the Mannum (LHO3umf, Man12o and LFO1umf), Glenforslan (LHO1GF, LFO1GF, LFO2GF, LFO6GF and LFO7GF) and Pata (LFO1P, LFO6P and LFO7P) Formations is likely to be due to upward leakage of comparatively fresh groundwater from the underlying Renmark Group.

Calculations of mixing fractions, for mixing between the Renmark Group end-member and the Mannum and Pata / Glenforslan Formation end-members defined above, have been carried out using the methodology described in Section 3.5. Being the closest upgradient points to Loxton at which information is available, an average of the signatures from the Renmark Group bores, R16 and R17 have been used to represent the end-member for that aquifer system. An average signature between LHO2GF, LHO3GF and LFO3GF has been used to represent the Pata / Glenforslan regional end-member and the signature of LFO3umf has been used to represent the regional Mannum Formation end-member. Chloride concentrations and $\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$, $^{87}Sr/^{86}Sr$ and $\delta^{34}S$ signatures were used for the calculations, the results of which are shown in Table 11.

Table 11. Calculated percentage RGA contribution to groundwater compositions in the Murray Group aquifers at Loxton. Note that the most conservative tracers ([Cl], $\delta^{18}O$ and $\delta^{2}H$) provide the most reliable estimates. The $\delta^{13}C$ signatures of the resultant groundwaters have been affected by dissolution of the carbonate MGA matrix by the intruding RGA groundwater. As yet unidentified processes have caused the mixing fractions calculated based on $\delta^{34}S$ signatures at LFO6P, LHO1GF, LFO6GF, LHO3umf and Man12o and $\delta^{2}H$ at LFO6P and LFO2GF to be lower than those calculated using the other tracers.

Result	[Cl]	$\delta^{18}O$	$\delta^{2}H$	$\delta^{13}C$	$^{87}Sr/^{86}Sr$	$\delta^{34}S$	Accepted range
Pata							
LFO1P	92	88	77	-	87	90	75-90
LFO6P	51	40	**8**	**-12**	59	**14**	40-60
LFO7P	100	76	131	-	112	105	75-100
Glenforslan							
LHO1GF	56	47	65	**-36**	55	**2.6**	50-65
LFO1GF	88	89	90	**-31**	88	84	85-90
LFO2GF	37	47	**10**	-	-	-	35-50
LFO6GF	59	54	42	**-17**	56	**22**	40-60
LFO7GF	100	100	135	-	110	109	100
Mannum							
LHO3umf	47	-	-	-	73	**17**	Approx 50
Man12o	73	40	51	-	70	**28**	40-70
LFO1umf	77	52	72	-	82	-	50-80

Although able to identify upward leakage from the Renmark Group, Dogramaci (1998) was unable to calculate the magnitude of that leakage using carbon isotopes, $^{87}Sr/^{86}Sr$ or $\delta^{34}S$ due to the chemical reactions that occurred during the mixing of the two water types. Similar reactions have complicated these tracer signatures in the resultant waters at Loxton. Dissolution of the carbonate aquifer matrix in the Murray Group aquifers has resulted in more positive $\delta^{13}C$ values in the resultant water, closer to the signature of the MGA carbonate matrix than either of the starting compositions (Fig. 16). This has resulted in negative values for the calculated percentage contribution from the RGA based on $\delta^{13}C$. There does not appear to have been a significant effect on the $^{87}Sr/^{86}Sr$ ratio of the resultant water by carbonate mineral dissolution.

For bores LFO6P, LFO6G, LHO1G, LHO3umf and Man12o, the mixing fractions calculated based on the $\delta^{34}S$ data are low compared with those based on the other tracers. This suggests that a geochemical process causing a lowering of the $\delta^{34}S$ (and SO_4/Cl) value occurs on mixing between the two water types at these locations. Likewise, bores LFO6P and LFO2GF have δ^2H values that place them slightly above the linear trend defined by the rest of the Loxton-Bookpurnong groundwater samples and closer to the meteoric water line on a δ^2H vs $\delta^{18}O$ diagram (Fig. 15). This causes low estimated percentage RGA contributions for these samples based on δ^2H compared with values calculated from the other tracers.

The ranges of values of percentage RGA contribution accepted from the calculations discussed above are shown in Table 11 and on Figure 23. The results suggest significant input of comparatively fresh groundwater from the RGA via upward leakage to the Mannum Formation at all locations along Transect AA' and that this progresses into the overlying Glenforslan and Pata Formation aquifers adjacent the River Murray. These estimates may be improved by obtaining a better understanding of the regional end-member signatures through sampling of MGA and RGA wells in the Loxton region that are beyond any potential influences of the Loxton Irrigation Mound and are not affected by upward leakage.

5.1.2.3 Downward Leakage of Irrigation Water Below the Loxton Mound

Preliminary interpretation of the groundwater hydrochemistry data from Loxton-Bookpurnong indicated the presence of irrigation drainage water throughout extensive areas of the Loxton Sands aquifer. The signatures of the Loxton Sands regional groundwater and irrigation water end-members are described in Sections 5.1.2.1.3 and 5.1.2.1.4. The presence of the irrigation water can be identified as a reduction in TDS and an increase in $\delta^{18}O$ and δ^2H values of the Loxton Sands groundwaters compared with the regional Loxton Sands end-members. Such groundwaters also have high ^{14}C concentrations compared with the regional groundwater, and in the Loxton area include LHO3LS, LHO1LS, L22, LHO8 and LHO15.

All of these wells predominantly screen the higher permeability Upper Loxton Sands, although L22 straddles the boundary between the Upper and Lower Loxton Sands. In the Bookpurnong region, groundwaters from bores BKP1 and IA3 may be influenced by irrigation drainage water, although the geochemical signatures are slightly ambiguous in relation to this in these cases. Using the geochemical signatures of the Upper Loxton

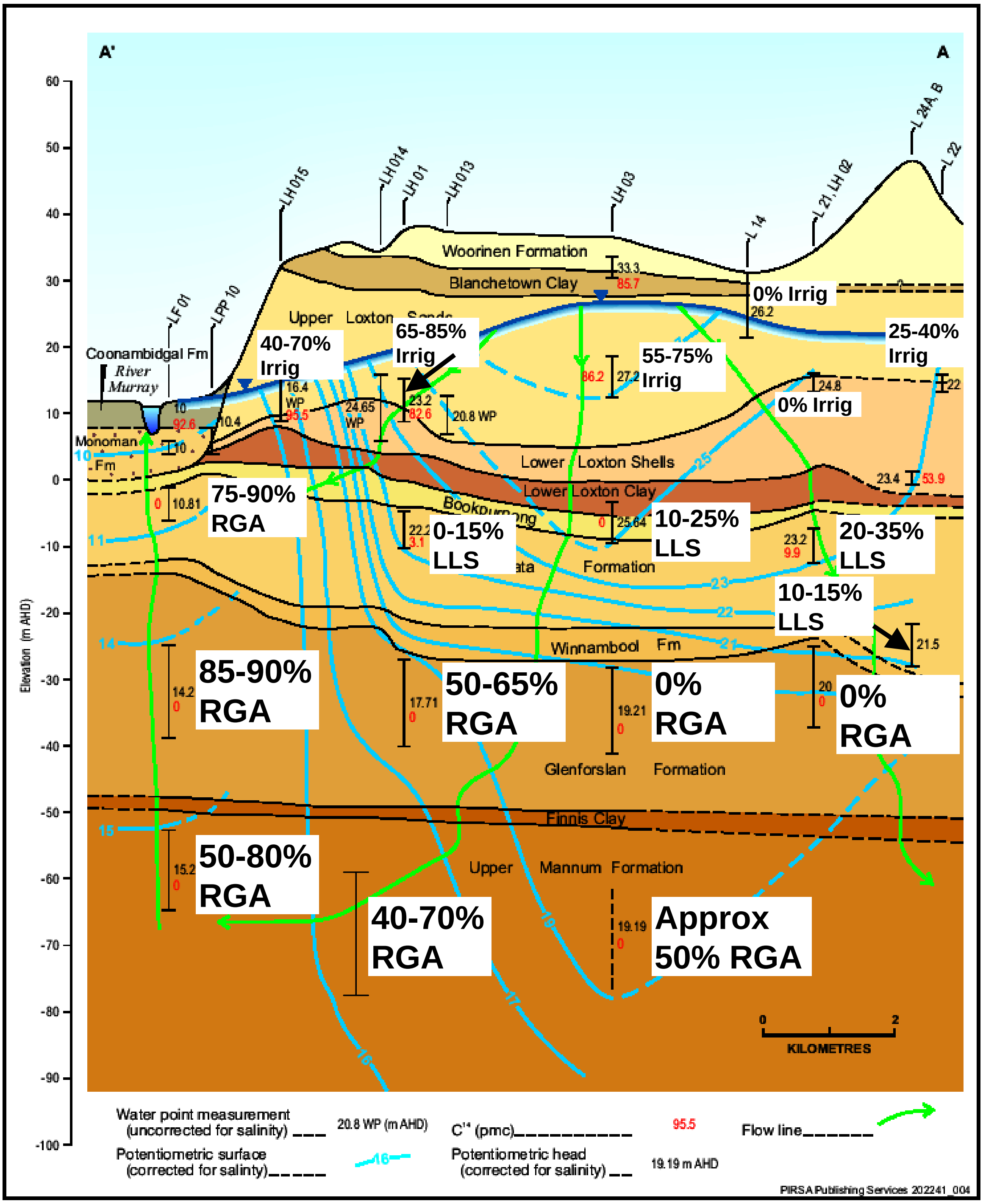


Figure 23. Conceptual model of proportional groundwater sources to the different aquifers along Cross-section AA' inferred from environmental tracer signatures.

Sands and irrigation water end-members defined in Sections 5.1.2.1.3 and 5.1.2.1.4, mixing fractions have been calculated for the full suite of environmental tracers (Table 12). These are represented spatially in Figure 24.

Table 12. Calculated percentage irrigation water contribution to groundwater compositions in the Loxton Sands aquifer at Loxton. Note that the most conservative tracers ([Cl], $\delta^{18}O$ and $\delta^{2}H$) provide the most reliable estimates. The $\delta^{13}C$ and ^{14}C signatures of the resultant groundwaters have been affected by dissolution of carbonate minerals in the aquifer by the intruding irrigation water. As yet undetermined processes appear to have influenced the $^{87}Sr/^{86}Sr$ signatures of the resultant groundwaters, causing an overestimation of the percentage contribution from irrigation water.

Bore ID	TDS	$\delta^{18}O$	$\delta^{2}H$	$\delta^{13}C$	^{14}C	$^{87}Sr/^{86}Sr$	$\delta^{34}S$	Accepted range
L22	41	27	34	–	–	41	**59**	25-40
LHO3LS	68	70	64	74	**-14**	76	54	55-75
LHO1LS	82	65	**114**	**-21**	**-278**	**88**	73	65-85
LHO15	72	41	59	**-88**	**-324**	**97**	61	40-70

The signature at bore L14 was used to represent regional Loxton Sands groundwater in the area, whilst the low TDS signature at bore LHO8 was used to represent irrigation water. Where carbon isotope and $^{87}Sr/^{86}Sr$ data was not available for bore L14, an average value for bores L24A and L21 was used, as the TDS, $\delta^{18}O$, $\delta^{2}H$ and $\delta^{34}S$ signatures of these samples were extremely similar to L14. Discrepancies in the results obtained from the carbon isotopes and $^{87}Sr/^{86}Sr$ may be explained by the occurrence of chemical reactions during the mixing process. For example, comparatively fresh irrigation water has the ability to dissolve carbonate minerals within the Loxton Sands aquifer, affecting the $\delta^{13}C$, ^{14}C and $^{87}Sr/^{86}Sr$ signatures of the resultant groundwater. The most reliable ranges of percentage contributions from irrigation water calculated from the TDS, $\delta^{18}O$ and $\delta^{2}H$ signatures are shown in Table 12 and on Figure 23.

5.1.2.4 Drainage Bores as a Mechanism for Downward Leakage of Irrigation Water Below the Loxton Mound

Figure 1 shows the locations of abandoned drainage bores at Loxton. The Loxton Sands bores that were identified in Section 5.1.2.3 to display an irrigation water signature were LHO3LS, LHO1LS, LHO8, LHO15 and L22 (see Fig. 1 for locations). The fact that the Loxton Irrigation Mound coincides with the highest density of drainage bores suggests that these bores could be the mechanism for transmitting large amounts of irrigation water into the Upper Loxton Sands at LHO3LS and LHO1LS. In this area, the Blanchetown Clay aquitard is approximately 5 m thick and would normally inhibit drainage from the Woorinen Formation into the Loxton Sands. There is no record of any drainage bores on the eastern margin of the mound, in the vicinity of piezometer L22, suggesting that preferential flow

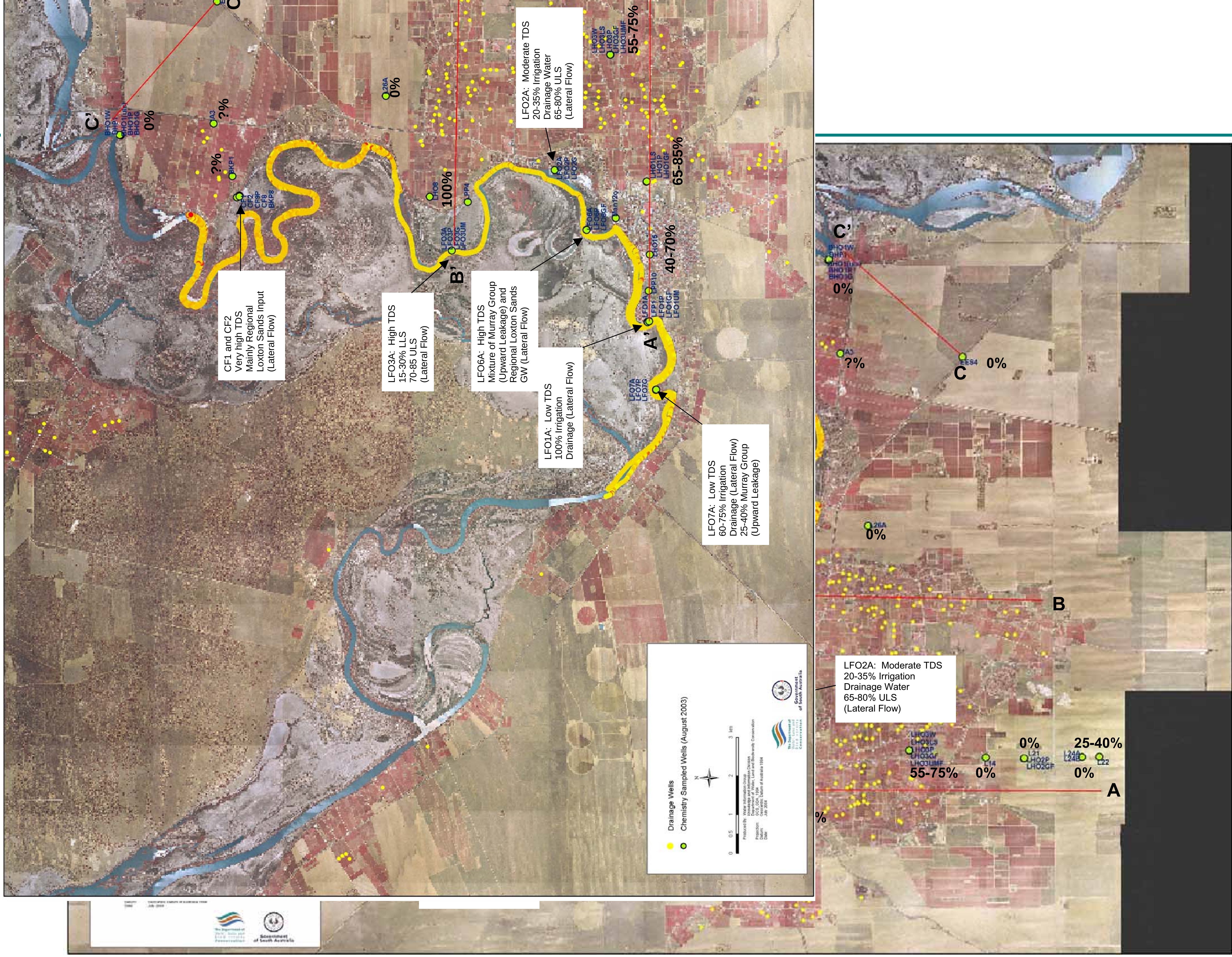


Figure 24. Map showing the spatial distribution of irrigation water (as %) in the Loxton Sands aquifer and the inferred sources of water and salt to the floodplain Monoman Formation along the River Murray.

down drainage holes is probably not the reason for the presence of irrigation water in the Loxton Sands aquifer at that location. Instead, the Blanchetown Clay is thin or absent in this region and any irrigation water that spreads laterally along the top of this aquitard may eventually drain into the Loxton Sands to the east of the mound in the vicinity of L22.

Groundwater at bore LHO8, located on the highland adjacent Westbrook's Floodplain, was also found to consist predominantly of irrigation drainage water. The reason for this may be the presence of two drainage wells, between 20 m and 30 m deep, directly up-gradient of this location. A simple calculation of travel time for lateral flow from the drainage wells to bore LHO8, based on Darcy's Law and assuming a horizontal hydraulic conductivity of 3 m/day and a porosity of 35% for the Upper Loxton Sands yields approximately 170 years. As this is of the same order of magnitude as the time since the drainage wells were installed and, since broad estimates of aquifer properties were used in the calculation, it is possible that they are responsible for the high proportion of irrigation drainage water present at LHO8. An alternative explanation is that the Blanchetown Clay may be thin or absent in the vicinity of LHO8, allowing the free movement of irrigation water into the Loxton Sands. Confirmation of the status of the Blanchetown Clay at this location is required to determine whether this is a viable explanation for the geochemical signature of LHO8.

5.1.2.5 Downward Leakage of Saline Groundwater From the Loxton Sands and Underlying Aquitards to the Murray Group Below the Loxton Irrigation Mound

The occurrence of higher TDS groundwater in the Pata Formation than the interpreted Murray Group end-member composition (Section 5.1.2.1.2), below the Loxton Irrigation Mound suggests downward leakage of saline water from the Loxton Sands and / or the Lower Loxton Clay / Bookpurnong Bed aquitard in that region. There is a downward hydraulic gradient in this area, indicating the potential for such a process to occur. Downward leakage at bores L24B, LHO2P, LHO3P and LHO1P (see Fig. 1 for locations) is also supported by higher $\delta^{18}O$ and $\delta^{2}H$ values (Fig. 15), non-zero ^{14}C values (Fig. 16) and $^{87}Sr/^{86}Sr$ ratios that lie between the curve and the line defined by the Murray Group and Loxton Sands data respectively (Fig. 17).

Percentage contributions of Lower Loxton Sands groundwater to the Pata Formation at sites L24B, LHO1P, LHO2P and LHO3P were calculated using the methodology described in Section 3.5 using the full suite of environmental tracers. The results are shown in Table 13 and on Figure 23.

Accession of salt from the high TDS Lower Loxton Sands aquifer and underlying aquitards to the Pata Formation has been identified in bores LHO3P, LHO2P and L24B, and possibly to a small degree at bore LHO1P. In order for drainage bores to be responsible for this salt accession, any drainage bores in the area would need to be at least approximately 40 m deep. There is no record of such deep drainage bores in the vicinity of LHO3 or to the east of this and hence this is probably not a viable explanation for the observed salinity increases.

Downward leakage induced by the presence of the groundwater mound in the Loxton Sands is another possible explanation for the observed TDS distribution in the Pata

Table 13. Calculated percentage Lower Loxton Sands contribution to groundwater compositions in the Pata Formation at Loxton. Note that the most conservative tracers ([Cl], $\delta^{18}O$ and $\delta^{2}H$) provide the most reliable estimates. The $\delta^{13}C$, ^{14}C and $^{87}Sr/^{86}Sr$ signatures of the resultant groundwaters have been affected by dissolution of the carbonate MGA matrix by the intruding RGA groundwater.

Result	[Cl]	$\delta^{18}O$	$\delta^{2}H$	$\delta^{13}C$	^{14}C	$^{87}Sr/^{86}Sr$	$\delta^{34}S$	Accepted range
L24B	9	14	16	**-390**	**0**	**386**	17	10-15
LHO1P	-3	16	5	**97**	17	**-171**	7	0-15
LHO2P	21	33	20	**-265**	**64**	**410**	15	20-35
LHO3P	12	20	23	**177**	**0**	**370**	–	10-25

Formation. As the groundwater mound probably built up fairly quickly in response to enhanced drainage of perched irrigation water from the Woorinen Formation into the Loxton Sands, the currently observed downward hydraulic gradient between the Loxton Sands and the Pata Formation would have existed virtually since the installation of the drainage wells. The permeability of the least permeable unit controls the hydraulic flux across an aquitard. The hydraulic head difference across the Lower Loxton Clay / Bookpurnong Beds at the centre of the Loxton Sands groundwater mound is approximately 0.5–1 m, resulting in a hydraulic gradient of approximately 0.06–0.1. The environmental tracer results suggest that groundwater from the Lower Loxton Sands has travelled across the 9 m aquitard in less than 50 years (i.e. the time since the drainage wells into the Loxton Sands have been in operation and the irrigation area has been fully developed. This suggests a hydraulic flux of at least 0.18 m/yr. According to Darcy's Law ($v = Ki/\phi$, where v = velocity [m/s], K = hydraulic conductivity [m/s], i = hydraulic gradient [m/m] and ϕ = porosity [m^3/m^3]), this implies a K/ϕ ratio of 1.8 m/yr. If a porosity of 40% is assumed, this results in a vertical hydraulic conductivity of *at least* 2×10^{-3} m/day, which is consistent with a silty clay.

5.2 Sources of Salt to the Floodplain Monoman Formation at Loxton

A number of complex geochemical processes can be expected to affect the signatures of groundwater in a floodplain environment, including evapotranspiration, dilution by stream water, groundwater discharge and biological processes caused by the large amounts of organic matter present in the floodplain sediments. Hence, the geochemical signatures of groundwater inputs to the floodplain can be masked by processes occurring within the floodplain itself. This has created ambiguity in the interpretation of the geochemical data in relation to groundwater sources to the floodplain at some locations. However, some conclusions that could be made are discussed in the following sections and shown on Figure 24.

5.2.1 SOUTH OF LOXTON: LFO1A AND LFO7A

Groundwater in the Monoman Formation bore LFO1A, screened 7.8 m below ground level and 6.5 m below the water table has a comparatively low TDS of 2100 mg/L, but enriched $\delta^{18}O$ and $\delta^{2}H$ signatures, suggesting that the low TDS is due to the presence of irrigation water rather than upward leakage of low TDS groundwater from the Murray Group and ultimately the Renmark Group aquifers (Table 2, Table 5, Fig. 15). The similarity in salinity and $\delta^{18}O$ and $\delta^{2}H$ signatures between LFO1A and the Upper Loxton Sands groundwater samples from LHO8, LHO15, LHO3LS and LHO1LS support this. LFO1A, as well as another floodplain sample from Thiele's Sandbar, LFO6A, has quite a negative $\delta^{13}C$ signature, causing them to plot to the left of the other groundwater samples from the Loxton and Bookpurnong regions on a ^{14}C vs $\delta^{13}C$ diagram (Fig. 16). These negative $\delta^{13}C$ signatures may be due to small amounts of biological degradation of organic matter. The ^{14}C signature of LFO1A is quite modern (92.6 pmC), similar to those of the Loxton Sands samples LHO15, LHO8, and LHO3LS, which contain large amounts of irrigation water. The radiogenic $^{87}Sr/^{86}Sr$ signature of LFO1A, which is higher than the Loxton Sands groundwaters and modern seawater, probably reflects the signature of the Monoman Formation aquifer minerals rather than the parent water. Hence, the strontium isotope signature of this sample cannot be used to determine its origin.

LFO1A has a similar $\delta^{34}S$ signature to the Upper Loxton Sands groundwater samples that have mixed with irrigation water, LHO3LS, LHO15 and LHO1LS, but a much lower SO_4/Cl ratio (Fig. 8). This low SO_4/Cl ratio may be due to sulphate reduction by organic matter in the Monoman Formation, which is supported by the comparatively reducing conditions (measured Eh = -195 mV), a low $\delta^{13}C$ and significant dissolved Fe concentration (3.79 mg/L) at this location. High dissolved Fe concentrations are a good indicator of reducing conditions in groundwater systems and Figure 25 shows a plot of SO_4/Cl vs Fe concentrations of the Loxton / Bookpurnong groundwater samples, which shows that the lower SO_4/Cl ratios in the Monoman and Loxton Sands formations generally correspond to higher Fe concentrations. Bacterial sulphate reduction usually results in an increase in $\delta^{34}S$ of the residual sulphate due to the preference for the lighter isotopes in the biological process. Therefore, if sulphate reduction is the reason for the low SO_4/Cl ratio, the parent water probably had a lower original $\delta^{34}S$ value, similarly to Upper Loxton Sands bore LHO8, which represents 100% mixing with irrigation water. A Lower Loxton Sands source is an alternative explanation for the SO_4/Cl and $\delta^{34}S$ values of LFO1A, as the two plot close together on Figure 18. However, the low TDS of LFO1A suggests that this is not the case and therefore it is believed that the main source of water and solutes to the floodplain at LFO1A is lateral flow of predominantly irrigation drainage water from the Upper Loxton Sands (Fig. 24).

Groundwater from the Monoman Formation bore, LFO7A, also located to the south of Loxton, has a similarly low TDS (6300 mg/L), although not quite as low as that of LFO1A. Likewise, the $\delta^{18}O$ and $\delta^{2}H$ signature of LFO7A is more enriched than the low TDS groundwaters in the underlying Murray Group aquifers, but not to the same degree as the groundwater at LFO1A. The $\delta^{18}O$ and $\delta^{2}H$ signature of LFO7A is similar to those of the regional Upper Loxton Sands end-members, L14, L24A and L21. However, the low TDS value of this sample suggests that this is not the source. Mixing between the underlying

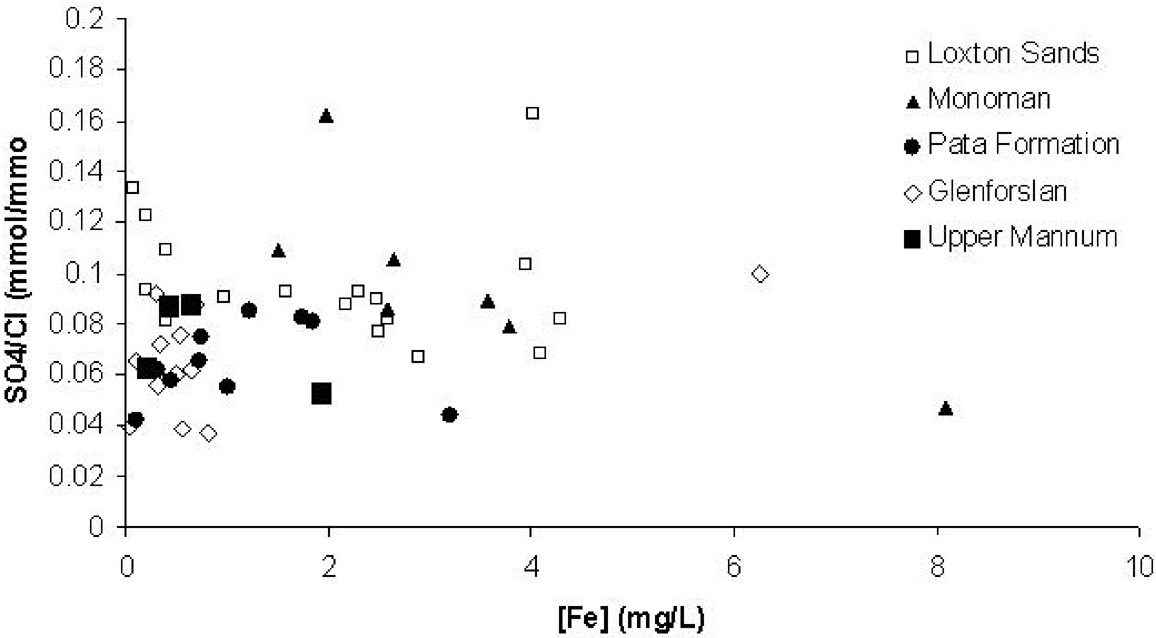


Figure 25. Plot of SO_4/Cl vs Fe concentrations of the Loxton / Bookpurnong groundwater samples.

low TDS Murray Group groundwaters (TDS = 4300 mg/L) and the similarly low TDS irrigation water (TDS ≈ 6200 mg/L) can explain the TDS concentration and $\delta^{18}O$ and $\delta^{2}H$ signature of LFO7A. Because of the similar TDS concentrations of the two end-members, mixing is difficult to distinguish based on this alone. However, if the $\delta^{18}O$ and $\delta^{2}H$ signatures of groundwater at bore LHO8 are taken to represent irrigation water inflow from the Upper Loxton Sands and those at LFO7P are taken to represent the underlying Murray Group groundwater, mixing calculations carried out according to Equation 5 in Section 3.5 suggest a 60–75% contribution from the Upper Loxton Sands aquifer and conversely 25–40% contribution from the underlying Murray Group (Fig. 24). Again, the $^{87}Sr/^{86}Sr$ ratio of the parent waters is masked by a high value probably in equilibrium with the Monoman Formation aquifer minerals, making this tracer of no use in identifying mixing processes. Carbon isotope and $\delta^{34}S$ analyses were not carried out on this sample.

5.2.2 THIELE'S SANDBAR: LFO6A

Groundwater in the Monoman Formation at Thiele's Sandbar, to the north of Loxton, is represented by groundwater from bore LFO6A, which is screened approximately 10 m below ground, with a standing water level of approximately 9 m. Groundwater at this location has a TDS concentration of 26 000 mg/L, considerably higher than that to the south of Loxton at LFO1A and LFO7A. LFO6A has lower $\delta^{18}O$ and $\delta^{2}H$ values than either of the Loxton Sands regional end-members and the irrigation water end-member, suggesting some input from the underlying Murray Group groundwaters, which have low $\delta^{18}O$ and $\delta^{2}H$ values (Fig. 15). The higher TDS, higher $\delta^{18}O$ and $\delta^{2}H$ end-member is more difficult to define based on TDS and $\delta^{18}O$ and $\delta^{2}H$ alone, as it may be native groundwater from either the Upper or lower Loxton Sands. The high TDS of LFO6A suggests that irrigation water does not play a major role in the groundwater chemical composition at LFO6A.

Figure 18 shows that LFO6A has a slightly higher $\delta^{34}S$ value than the Lower Loxton Sands end-member, plotting between this end-member and the signature of the underlying Murray Group groundwater (LFO6P and LFO6GF). However, it has a higher SO_4/Cl ratio than both these end-members. Dogramaci et al. (2001) found that a trend of increasing SO_4/Cl and decreasing $\delta^{34}S$ in the Murray Group groundwaters along regional groundwater flow paths through the Murray Basin was most likely to be due to the systematic accession and oxidation of biogenic sulphur ($\delta^{34}S$ = 0 ‰) from the unsaturated zone via recharge. Addition of biogenic sulphur in the floodplain environment is a possible explanation for the higher SO_4/Cl ratio of LFO6A compared with the Lower Loxton Sands end-member and the underlying Murray Group groundwater. Hence, mixing between these two compositions is still a possible explanation for the composition at LFO6A. Alternatively, LFO6A plots close to the Upper Loxton Sands regional end-member, suggesting that this may be the high TDS end-member for the mixing process. Calculations of mixing between (a) the underlying Murray Group groundwater and the Lower Loxton Sands end-member and (b) the Murray Group groundwater and the Upper Loxton Sands end-member were carried out for the full suite of tracers, following the methodology described in Section 3.5. The results are shown in Table 14 as the percentage contribution from upward leakage from the Murray Group.

Table 14. Calculated contribution of upward leakage from the underlying Murray Group aquifers to the groundwater composition in the Monoman Sands at LFO6A. Calculations were based on (a) mixing between Murray Group groundwaters (LFO6P) and regional groundwater from the Lower Loxton Sands (EES4) and (b) mixing between Murray Group groundwaters (LFO6P) and regional groundwater from the Upper Loxton Sands (L14).

	[Cl]	$\delta^{18}O$	$\delta^{2}H$	$\delta^{13}C$	^{14}C	$^{87}Sr/^{86}Sr$	$\delta^{34}S$
(a) Mixing with LLS	82	74	64	**-546**	**-130**	**-5**	66
(b) Mixing with ULS	44	58	**22**	**10**	59	41	62

Table 14 shows good agreement between the mixing calculation results using [Cl], $\delta^{18}O$, $\delta^{2}H$ and $\delta^{34}S$ for both scenarios (a) and (b). The calculations based on the carbon isotopes and $^{87}Sr/^{86}Sr$ ratios produced poor results for scenario (a), however these could be explained by the non-conservative nature of these tracers. On a ^{14}C vs $\delta^{13}C$ diagram, LFO6A plots to the left of the majority of the Loxton-Bookpurnong samples, with a $\delta^{13}C$ value of –12.4‰ (Fig. 16). Such a negative value suggests that some geochemical process on the floodplain, for example decay of organic matter, may have affected the carbon isotope signature of the sample. Likewise, LFO6A has a high $^{87}Sr/^{86}Sr$ value, similarly to LFO7A, LFO1A and LFO3A, which may be the result of reaching equilibrium with radiogenic minerals in the Monoman Formation, obscuring the signatures of the parent waters (Fig. 17). Based on the [Cl], $\delta^{18}O$, $\delta^{2}H$ and $\delta^{34}S$ signatures for scenario (a), a composition that comprises 65–85% upward leakage from the Murray Group and

15–35% lateral flow of irrigation water from the Upper Loxton Sands is reasonable for groundwater at LFO6A. For scenario (b), a mixture of 45–65% upward leakage from the Murray Group and 35–55% of regional (non-irrigation) water from the Upper Loxton Sands is suggested (Fig. 24).

5.2.3 NORTH OF THIELE'S SANDBAR: LFO2A

Moving further north from Loxton, the Monoman Sands groundwater to the north of Thiele's Sandbar is represented by bore LFO2A, which is screened 11 m below ground level and has a standing water level of approximately 9.5 m. Like LFO6A, the groundwater at this location has a high TDS concentration of 30 100 mg/L (Table 2). On the $\delta^{18}O$ vs $\delta^{2}H$ diagram, LFO2A plots between the Upper Loxton Sands and irrigation water end-members (Fig. 15). This is also the case on the $\delta^{34}S$ vs SO_4/Cl diagram (Fig. 18). Figure 17 shows that LFO2A has the same $^{87}Sr/^{86}Sr$ ratio as the Loxton Sands groundwaters. All of these results qualitatively support the lateral flow of irrigation water in the Upper Loxton Sands as the source of salt and water to the floodplain at LFO2A. Carbon isotope analyses were not carried out on this sample. The results of mixing calculations, using bore L14 as the Upper Loxton Sands end-member and LHO8 to represent irrigation water are shown in Table 15.

Table 15. Calculated contribution of irrigation water to the groundwater composition in the Monoman Sands at LFO2A. Calculations were based on mixing between Upper Loxton Sands groundwaters (L14) and irrigation water moving through the Upper Loxton Sands (LHO8).

	[Cl]	$\delta^{18}O$	$\delta^{2}H$	$\delta^{13}C$	^{14}C	$^{87}Sr/^{86}Sr$	$\delta^{34}S$
% Irrigation Water	22	30	27	–	–	37	19

Table 15 shows good agreement between the results of the mixing calculations using the different tracers, suggesting that the groundwater at LFO2A originates from irrigation water moving through the Upper Loxton Sands aquifer, with the percentage of irrigation water being between approximately 20% and 35% (Fig. 24).

5.2.4 WESTBROOK'S FLOODPLAIN: LFO3A

Groundwater in the Monoman Formation at Westbrook's Floodplain is sampled by bore LFO3A, which is screened 12 m below ground level, with a standing water level 8.2 m above this. The groundwater TDS at this location is 47 500 mg/L, the highest of the floodplain groundwaters sampled in the Loxton region, and similar to the Bookpurnong floodplain groundwater at bore CF2. The TDS and $\delta^{18}O$ and $\delta^{2}H$ signatures of LFO3A are consistent with it being derived from a mixture of Upper and Lower Loxton Sands regional groundwater. LFO3A has a high $^{87}Sr/^{86}Sr$ ratio, similarly to the other floodplain samples, LFO6A, LFO1A and LFO7A, once again probably due to interaction with radiogenic minerals in the Monoman Sands aquifer. Carbon isotope and $\delta^{34}S$ analyses were not carried out on the sample from LFO3A. The percentage of groundwater derived from the Lower Loxton Sands was calculated using the equations shown in Section 3.5, based on chloride concentrations and $\delta^{18}O$ and $\delta^{2}H$ values only. The results are shown in Table 16. These results suggest that groundwater on the floodplain at LFO3A is derived from lateral flow of a mixture of Upper and Lower Loxton Sands groundwater, with no influence from irrigation drainage water.

Table 16. Calculated percentage contribution of regional Lower Loxton Sands groundwater to the floodplain at LFO3A, for mixing between Upper and Lower Loxton Sands groundwater. No impact from irrigation water is implied.

	[Cl]	$\delta^{18}O$	$\delta^{2}H$
% Lower Loxton Sands	31	18	20

5.2.5 CLARKE'S FLOODPLAIN AT BOOKPURNONG: CF1 AND CF2

Groundwater in the Monoman Formation at Clarke's Floodplain is intersected by bores CF1 and CF2, which are screened 13 m and 10.5 m below ground level respectively (see Fig. 1 for locations). Groundwater at CF1 has a TDS concentration of 33 700 mg/L whilst that at CF2 has a TDS of 50 800 mg/L, the highest of the floodplain samples analysed during this study (Table 2). On a $\delta^{2}H$ vs $\delta^{18}O$ diagram (Fig. 15), CF2 plots close to the Upper Loxton Sands end-members, whilst CF1 plots between the Upper and Lower Loxton Sands end-members. CF1 has a comparatively modern ^{14}C signature of 84 pmC, ploting with the Upper Loxton Sands groundwaters that have mixed with irrigation water on a ^{14}C vs $\delta^{13}C$ diagram (Fig. 16). Carbon isotope analyses were not carried out on CF2. The $\delta^{34}S$ and SO4/Cl values of CF1 and CF2 cause them to plot on Figure 18(b) with the mixed Upper / Lower Loxton Sands samples from BHP1, BHO1LS and L22, although these signatures are also similar to some Murray Group samples. The $^{87}Sr/^{86}Sr$ ratio of the groundwater at CF1 is slightly higher than the common value shared by the majority of the Loxton Sands groundwaters sampled (Fig. 17). A more radiogenic $^{87}Sr/^{86}Sr$ signature than the parent groundwaters is common in the floodplain groundwater samples, probably due to interactions with more radiogenic minerals in the Monoman Formation. This masks any signature derived from the parent waters. The results discussed above qualitatively suggest a Loxton Sands origin for the groundwaters at CF1 and CF2. More data from the Bookpurnong region is required to investigate this further (Table 17).

5.3 Conceptual Model of Groundwater and Solute Movement at Loxton, Based on Environmental Tracer Results

The conceptual model for groundwater flow and solute movement in the Loxton area, based on the results of the environmental tracer study, as discussed above, is shown in Figures 23 and 24. The main features of this conceptual model are:

Compositions of Regional Groundwater Inflows:

- Regional groundwaters flowing into the Loxton area in the Upper and Lower Loxton Sands, Pata / Glenforslan Formations, Mannum Formations and Renmark Group formations have TDS concentrations as shown in Table 10.

The Importance of Upward Leakage from the Renmark Group:

- Upward leakage of comparatively fresh groundwater from the Renmark Group aquifer system causes the observed TDS distributions in the Glenforslan and Mannum Formations.
- Therefore, this has a large influence over the TDS of groundwater discharging into the Monoman Formation and ultimately the River Murray at some locations.
- For example, Murray Group groundwater to the south of Loxton, at bore LFO7, has a 100% Renmark Group signature, and groundwater in the overlying floodplain Monoman Formation at this location is derived from a mixture of this (via upward leakage) and irrigation drainage water flowing in laterally via the Loxton Sands. Likewise, at the Thiele's Sandbar bores, LFO6, to the north of Loxton, groundwater in the Murray Group aquifers has a signature that comprises 40–60% Renmark Group, and groundwater in the overlying Monoman Formation is derived from a mixture of this and lateral flow of native Loxton Sands groundwater.

Irrigation Drainage into the Upper Loxton Sands:

- Comparatively fresh irrigation drainage water (TDS <6000 mg/L) has replaced high salinity native groundwater (TDS $\approx$ 36 000 mg/L) in the Upper Loxton Sands aquifer below the Loxton Irrigation district.
- Leakage of the irrigation water through the Blanchetown Clay aquitard in this region has probably been enhanced by preferential flow along numerous drainage bore holes in this area.
- This process has caused a groundwater mound in the Upper Loxton Sands, centred around the LHO3 bores to the north east of the Loxton township.
- A similar process has apparently caused a 100% irrigation water signature to occur in the Upper Loxton Sands at bore LHO8.
- As is the case at LHO8 to the north of Loxton, groundwater moving through the Upper Loxton Sands along flow paths to the south of Loxton, and terminating at the floodplain at LFO1A and LFO7A comprises predominantly low TDS irrigation drainage water.

Downward Leakage into the Pata Formation Below the Loxton Mound:

- Downward leakage of high TDS groundwater from the Lower Loxton Sands has occurred near the centre of the Loxton Irrigation Mound, as observed at bores LHO1P, LHO2P, LHO3P and L24B.
- If this downward leakage has occurred as a result of the irrigation mound, a vertical hydraulic conductivity of at least 2 x 10^{-3} m/day is implied for the Lower Loxton Clay / Bookpurnong Beds aquitard.

Groundwater Inflows to the Floodplain:

- Groundwater in the floodplain Monoman Formation at Thiele's Sandbar (LFO6A) and south of this (LFO7A) is derived from a combination of upward leakage from the Murray Group aquifers and lateral flow from the Loxton Sands. At LFO7A, the inflow from the Loxton Sands aquifer is predominantly irrigation drainage water.

- The exception to this is at LFO1A, where lateral flow of irrigation water from the Loxton Sands aquifer is the major source of groundwater to the Monoman Formation. This results in low TDS groundwater in the floodplain aquifer to the south of Loxton.
- At Thiele's Sandbar, groundwater in the Monoman Formation has a comparatively high TDS (26 000 mg/L) despite the upward leakage of low TDS groundwater from the underlying Murray Group aquifers. The reason for this is that groundwater flowing in laterally from the Loxton Sands aquifer has a high TDS regional signature (TDS = 36 000 mg/L to 73 000 mg/L).
- North of Thiele's Sandbar (i.e. bores LFO2A and LFO3A), lateral flow from the Loxton Sands aquifers dominates groundwater inflows to the floodplain Monoman Formation. At LFO2A, this inflow comprises a mixture of irrigation water and native Upper Loxton Sands groundwater. At LFO3A, irrigation water is not flowing into the Monoman Formation, rather mixture of native Upper and Lower Loxton Sands groundwater results in high TDS groundwater on the floodplain.

5.4 Comparison of Results With Existing Conceptual Models

As there is currently no formal description of the existing conceptual model for groundwater flow and solute movement in the Loxton region, details have been obtained from the original Approval Submission (AWE, 2003a) and from examination of the boundary conditions and aquifer parameters used in the most current version of the numerical groundwater flow model. It is not our objective to present the entire conceptual model here, although a general description of the hydrogeological framework has been given in the introductory sections of this report. The reader is referred to other publications in relation to this project for further information on the results of the hydrogeological investigations. However, selected features of the conceptual model, as obtained from the Approval Submission and numerical model, are discussed below and compared with the relevant conclusions from the hydrochemistry and isotope study.

5.4.1 SALINITY DISTRIBUTIONS IN THE MURRAY GROUP AQUIFER

5.4.1.1 Existing Model

- The highest salinity water in the Upper Mannum Formation (>25 000 mg/L) occurs at Bookpurnong and decreases to <5000 mg/L to the south-west of Loxton (AWE, 2003a).
- Groundwater salinity in the Glenforslan Formation exhibits a similar pattern to that in the Upper Mannum Formation, decreasing in a south-westerly direction from 30 000 mg/L at Bookpurnong to <5000 mg/L south of Loxton. Bookpurnong is a regional high point for salinity in the Glenforslan Formation (AWE 2003a).
- Groundwater in the Pata Formation ranges between <10 000 mg/L and >30 000 mg/L. East of the Bookpurnong groundwater mound, groundwater TDS is greater than 50 000 mg/L. However, the salinity of 20 000 mg/L below the floodplain at Bookpurnong is believed to be a more regional signature (AWE 2003a).
- Groundwater salinities in the Pata Formation are generally lower than in the Monoman and Loxton Sands Formations, with the exception of below the irrigation mounds, where the opposite is true (AWE 2003a).

- The Pata Formation has groundwater salinities higher than the Glenforslan Formation to the south of Loxton whilst, to the north of Loxton, the salinities in the two aquifers are similar (AWE 2003a).
- Hydraulic head data suggest that the salinity distribution is due to a tongue of fresher water discharging to the river from the Mallee Proclaimed Wells Area (AWE 2003a).

5.4.1.2 Comparison With Results from This Study

The results of the groundwater chemistry and isotopic tracer study have identified that the observed salinity distribution in the Murray Group aquifers is due to the upward leakage of comparatively fresh groundwater from the Renmark Group aquifer system. This has not been considered in previous conceptual models. The higher TDS signatures observed at Bookpurnong are closest to the signature of regional groundwater Murray Group groundwater flowing into the area (Table 8). As observed at Bookpurnong, the salinities of regional groundwater in the Pata, Glenforslan and Mannum Formations are probably similar to each other. Closer to Loxton, where upward leakage from the Renmark Group is more significant, salinities vary between the aquifers, depending on the relative contribution from the Renmark Group. The calculated percentages of Renmark Group groundwater mixed with regional Murray Group groundwater at various locations around Loxton are shown in Table 11 and Figure 23.

5.4.2 GROUNDWATER QUALITY IN AND RECHARGE TO THE LOXTON SANDS AQUIFER

5.4.2.1 Existing Model

- The distribution of the Blanchetown Clay, which ranges from a clayey sand to a stiff clay, is patchy across the region (AWE 2003a).
- The pre-development salinity trend is for high salinity water near Bookpurnong, reducing southward. The high salinities to the north are believed to reflect salt inputs from the Noora Discharge Complex (AWE 2003a).
- The regional (older) pattern of high salinity has been overprinted in the Loxton Sands, by more recent, low salinity drainage water in the vicinity of the irrigation mounds. These low salinities are evident in the vicinity of recently decommissioned irrigation channel overflow areas and near the floodplain (AWE 2003a).
- The Loxton Sands groundwater salinity in the Bookpurnong area is reduced at some locations due to drainage of lower salinity perched water into the Upper Loxton Sands via drainage bores (AWE 2003a).
- Both groundwater mounds in the Loxton Sands aquifer are centred around the older, more established irrigation areas (AWE 2003a).

5.4.2.2 Comparison With Results from This Study

The results of this study agree with the model of a pattern of older higher salinity regional groundwater, overprinted by younger, lower salinity irrigation drainage water. Rather than having a regional end-member that decreases in salinity from north to south, we have adopted separate Upper and Lower Loxton Sands regional end-members that differ from each other in their salinities, but are spatially uniform. The Upper Loxton Sands has a TDS concentration of approximately 36 000 mg/L whilst the Lower Loxton Sands is much more saline, with a TDS concentration of approximately 73 000 mg/L (see Section 5.1.2.1.3). This conclusion was based on the water quality profiles collected in the Loxton Sands, which consistently showed a salinity stratification between the Upper and Lower Loxton Sands. However, further sampling of bores with screened intervals known to intersect the Upper and Lower Loxton Sands, further to the east and south-east of the study area has been proposed in order to increase confidence in these end-members.

This study has also found that the irrigation mound at Loxton is centred around the highest concentration of drainage bores into the Loxton Sands and identified this as a potential mechanism for enhanced movement of irrigation water into this aquifer, particularly where the Blanchetown Clay is quite thick. Percentage contributions of irrigation water to Loxton Sands groundwater compositions at discrete points have also been quantified and the distribution of comparatively fresh irrigation water better constrained (see Section 5.1.2.3).

5.4.3 THE GROUNDWATER MOUNDS AND DOWNWARD LEAKAGE ACROSS THE BOOXTON AQUITARD

5.4.3.1 Existing Model

- The Booxton Aquitard (combination of the Lower Loxton Shells, Lower Loxton Clay and Bookpurnong Beds) is thick and relatively low permeability at Bookpurnong, becoming thinner and increasingly leaky downstream of this (AWE 2003a).
- Downward hydraulic gradients occur beneath both the Loxton and Bookpurnong Irrigation Mounds (AWE 2003a).
- Downward leakage from the Loxton Sands to the Pata Formation is anticipated to occur more readily in the south of the study area, where the Booxton Aquitard is thin or absent (AWE 2003a).
- Groundwater mounds occur in the Pata Formation below both the Loxton Irrigation District, where the maximum head is approximately 15 m above river level, and the Bookpurnong Irrigation District, where the Booxton Aquitard is thick and of low permeability (AWE 2003a).
- There is a groundwater mound in the Glenforslan Formation below the Loxton Irrigation District, but not below the Bookpurnong Irrigation District, although gradients in this aquifer more closely reflect the regional hydraulic gradient (AWE 2003a).
- There is no groundwater mound in the Upper Mannum Formation and hydraulic heads reflect the regional north-westerly hydraulic gradient (AWE 2003a).

5.4.3.2 Comparison With Results from This Study

The carbon and strontium isotope data has strongly supported the conclusion that higher TDS groundwater in the Pata formation under the Loxton groundwater mound is due to downward leakage from the Lower Loxton Sands. The contribution of downward leakage from the Lower Loxton Sands to Pata Formation groundwater compositions has also been quantified at various locations (see Section 5.1.2.5). Rough calculations of the leakage rate, based on the broad assumption that leakage is a result of the groundwater mound and that the formation of the mound coincided with installation of the drainage bores and the peak in irrigation development (i.e. 1955), suggest a vertical hydraulic conductivity of at least 2 x 10^{-3} m/day, which corresponds well with that applied in the numerical groundwater model (2.38 x 10^{-3} m/d).

5.4.4 GROUNDWATER DISCHARGE TO THE FLOODPLAIN

5.4.4.1 Existing Model

UPWARD LEAKAGE

- Hydraulic heads in the Pata Formation below the floodplain are generally 0.5–1 m above river level and those in the Glenforslan Formation are approximately 4.5 m above river level (AWE 2003a). Upward hydraulic gradients across much of the floodplain suggest a discharging regional groundwater system (AWE 2003a).
- Steep gradients in the Pata Formation adjacent to the floodplain also indicate groundwater discharge to the Monoman Formation (AWE 2003a).
- The Bookpurnong Beds are approximately 4 m thick, where present, and consist predominantly of silty clay. This unit diminishes in thickness to the south-west of Loxton, becoming increasingly leaky, and is completely eroded downstream of Habel Landing (AWE 2003a). This would facilitate increased upward leakage from the Murray Group in the south of the study area.
- At Loxton, the Booxton Aquitard is completely absent and the Pata Formation is in direct contact with the base of the river bed and the alluvial aquifer (Monoman Formation) (AWE 2003a). Likewise, a similar hydraulic head in the Pata Formation to the river level at Thiele’s Flat suggests good connection between the Pata Formation and the Monoman Formation at this location (AWE 2003a).
- Upward leakage from the Pata Formation to the floodplain occurs just west of Loxton, and groundwater discharge from the Upper Mannum and Glenforslan Formations is occurring downstream of Pyap (AWE 2003a).

LATERAL INFLOW FROM THE LOXTON SANDS

- Where the mounds have spread to the boundary between the highland and the floodplain, there is a very steep hydraulic gradient towards the floodplain. Where there is limited hydraulic connection between the Loxton Sands and Monoman Formation aquifers, groundwater seeps occur at the break in slope (AWE 2003a).

RECHARGE AND RIVER DISCHARGE

- Hydraulic gradients in the Monoman Formation are relatively low and variable, but generally towards the river (AWE 2003a).
- Although changes in river level are reflected quickly by pressure changes in the Monoman Formation, the flow of low TDS water into the alluvium during high river levels is limited. Likewise, there is little vertical recharge to the Monoman Formation during periods of inundation due to the low permeability of the overlying Coonambidgal Formation (AWE 2003a).
- There is resistance to groundwater flow across the river / alluvium interface (AWE 2003a).

5.4.4.2 Additional Information Provided by This Study

The results of the hydrochemical and isotopic tracer investigation are generally in agreement with the conceptual model that upward leakage from the Murray Group aquifers to the floodplain increases from Bookpurnong to Loxton and to the south-west of Loxton. Additionally, the use of a multiple tracer approach has facilitated well-constrained estimates of the contribution of upward leakage relative to lateral flow from the Loxton Sands to groundwater compositions in the alluvial aquifer (Section 5.2). Even at locations where the Pata Formation is in direct connection with the Monoman Formation, for example, at Thiele's Flat (LFO6A), the contribution of groundwater from the Murray Group is less than 50% and lateral flow from the Loxton Sands represents a large proportion of the groundwater flow. The relative solute fluxes from each source is dependent on their individual TDS concentrations.

In addition to estimating the relative proportions of upward leakage and lateral flow into the alluvial aquifer, the environmental tracer investigation has allowed discrimination between the three potential Loxton Sands end-members, which are the regional (native) Upper and Lower Loxton Sands groundwaters and irrigation drainage water. The salt flux to the floodplain is highly dependent on the proportions of each of these end-members in the inflow water and, in some cases, for example where large spatial variations in groundwater TDS occur in the Loxton Sands, this is difficult to determine based on conventional hydraulic techniques alone.

5.4.5 TDS DISTRIBUTIONS ON THE FLOODPLAIN

5.4.5.1 Existing Model

- Groundwater salinity on the floodplain is quite variable, ranging from 20 000–50 000 mg/L, due to variable fluxes (from different sources) and evaporative concentration of salts (AWE 2003a).
- High salinities may also be due to retention of "native" groundwater in areas of poor lateral hydraulic conductivity (AWE 2003a).
- Bores very close to the river intersect low salinity groundwater (<5000 mg/L).
- At Loxton, high salinity groundwater is surrounded, on both sides and below, by lower salinity groundwater (AWE 2003a).

5.4.5.2 Additional Information Provided by This Study

The current study has identified that the observed range of groundwater salinities in the floodplain Monoman Formation is due to different contributions from upward leakage of low TDS Renmark Group groundwater and lateral flow of Loxton Sands groundwater. The latter may range from low salinity, if large amounts of irrigation drainage water are present, to high salinity, if the inflow is predominantly native Lower Loxton Sands groundwater. Estimated contributions from the different end-members at different points along the floodplain are given in Section 5.2.

No evidence of evaporative concentration of salts was identified as having influenced the compositions of groundwaters in the Monoman Formation at the locations sampled. However, the bores sampled on the floodplain are screened from approximately 6–15 m below their standing water levels and, and it is possible that evaporation may have influenced shallower groundwater concentrations. Likewise, there is no evidence for river water contributing to groundwater compositions at the locations sampled. Rather, low TDS groundwater signatures observed at LFO1A and LFO7A are consistent with combinations of the Renmark Group and irrigation drainage water end-members. This is in agreement with the section of the conceptual model discussed in Section 5.2.1. Sampling of Murray River water will help to confirm this.

5.4.6 INTER-AQUIFER LEAKAGE WITHIN THE MURRAY GROUP

5.4.6.1 Existing Model

- The bottom 4 m of the Winnambool Formation is a “tight” clay, becoming a silty calcareous clay above this. It is believed to be an effective aquitard (AWE 2003a).
- The Finniss Formation is a thin silty clay layer and is believed to be a leaky aquitard (AWE 2003a).
- Downward leakage from the Pata Formation to the Glenforslan Formation has lead to the formation of a groundwater mound in the Glenforslan Formation below the Loxton Irrigation District (AWE 2003a).
- Upward hydraulic gradients between the Glenforslan and Pata Formations occur across most of the river valley. The large hydraulic head differences here suggest that the Winnambool Formation is acting as an effective aquitard (AWE 2003a).
- Upward vertical gradients exist between the Upper Mannum and Glenforslan Formations, and head differences of less than 1 m suggest that the Finniss Formation is not as effective an aquitard as the Winnambool Formation (AWE 2003a).

5.4.6.2 Additional Information Provided by This Study

The results of this investigation suggest that, although the Winnambool Formation may behave as an effective aquitard during pump tests, upward leakage through both this formation and the Finniss Clay dominates groundwater flow below the river valley in the southern part of the study area (i.e. to the south of the LFO2 piezometer nest). In this area, groundwater salinities in the Murray Group and Monoman Sands aquifers are strongly influenced by the input of comparatively fresh groundwater from the Renmark Group aquifer system. The influence of this upward leakage in the Glenforslan Formation extends inland to the LHO1 nest of piezometers and, in the Upper Mannum Formation, at least as far inland as LHO3umf. The northern extent of this upward leakage process appears to be somewhere near the LFO2 nest of piezometers, where a Renmark Group signature is observed in the Glenforslan Formation, but not in the overlying Pata Formation. No influence of upward leakage from the Renmark Group is observed in the Murray Group bores at LFO3.

As the regional Pata and Glenforslan Formation end-members are not believed to differ significantly in the geochemical signatures, downward leakage between these two formations could not be identified through this study.

6 CONCLUSIONS AND RECOMMENDATIONS

This study has shown the following processes to be important controls on the distribution of TDS concentrations in groundwater in the Loxton – Bookpurnong region:

- Upward leakage of comparatively fresh groundwater from the Renmark Group aquifer system, which causes the observed TDS distributions in the Glenforslan and Mannum Formations, and in the Pata Formation near the River Murray. This process therefore has a large influence over the TDS concentrations of groundwater discharging into the floodplain Monoman Formation and ultimately the River Murray. This is particularly important south of Thiele's Sandbar, where upward leakage from the Murray Group has been found to be a significant groundwater source to the Monoman Formation.
- Downward leakage of comparatively fresh irrigation drainage water (TDS <6500 mg/L), which has replaced high salinity native groundwater (TDS ≈ 36 000 mg/L) in the Upper Loxton Sands aquifer below the Loxton Irrigation district. Leakage of this irrigation water through the Blanchetown Clay aquitard in this region has probably been facilitated by numerous drainage bore holes in that area and has caused a groundwater mound in the Upper Loxton Sands, centred around the LHO3 series of bores to the north east of the Loxton township. A similar process has also resulted in large amounts of irrigation drainage water to be present in the Loxton Sands to the east of bore LHO8, adjacent Westbrook's Floodplain, where it was calculated the groundwater was 100% irrigation water.
- Lateral movement of irrigation drainage water through the Upper Loxton Sands results in the discharge of lower TDS groundwater onto the floodplain to the south of Loxton, at bores LFO1A and LFO7A (n.b. any historical discharge from the Upper Loxton Sands would have had a much higher TDS concentration). The process is still in a transient state to the north of Loxton, with Upper Loxton Sands groundwater at bore LHO8 consisting of 100% irrigation drainage water, but native Upper Loxton Sands groundwater is still being discharged to the floodplain further along the flowpath.
- Downward leakage of high TDS groundwater occurs from the Lower Loxton Sands into the Pata Formation near the centre of the Loxton Irrigation Mound. It is estimated that this has resulted in Pata Formation groundwater compositions in that region that comprise up to 35% groundwater from the Lower Loxton Sands. Simple calculations based on Darcy's law suggest that, if this downward leakage has occurred as a result of the irrigation mound, a vertical hydraulic conductivity of at least 2×10^{-3} m/day is implied for the Lower Loxton Clay / Bookpurnong Beds aquitard.

Groundwater flowing into the floodplain Monoman Formation can be derived from a mixture of upward leakage from the Murray Group aquifer system and lateral flow from the Loxton Sands aquifer. The latter may provide groundwater inflow with a native Lower Loxton Sands signature, an irrigation water signature or a mixture of water types. The relative importance of these sources varies along the River as follows:

- Groundwater in the floodplain Monoman Formation at Thiele's Sandbar (LFO6) and south of this is derived from a combination of upward leakage from the Murray Group aquifers and lateral flow from the Loxton Sands.
- The exception to this is at LFO1A, located within the Loxton Caravan Park, where lateral flow of irrigation water from the Loxton Sands aquifer is the major source of groundwater to the Monoman Formation. This results in low TDS groundwater in the floodplain aquifer to the south of Loxton.

- Groundwater in the Monoman Formation at Thiele's Sandbar, has a comparatively high TDS (26 000 mg/L) despite the upward leakage of low TDS groundwater from the underlying Murray Group aquifers. The reason for this is that groundwater flowing in laterally from the Loxton Sands aquifer has a high TDS regional signature (TDS = 36 000–73 000 mg/L).
- In the area of Westbrook's Floodplain (i.e. bores LFO2A and LFO3A), lateral flow from the Loxton Sands aquifers dominates groundwater inflows to the floodplain Monoman Formation. At LFO2A, this inflow comprises a mixture of irrigation water and native Upper Loxton Sands groundwater. At LFO3A, irrigation water is not flowing into the Monoman Formation, rather mixture of native Upper and Lower Loxton Sands groundwater results in high TDS groundwater on the floodplain.

Additional work that would improve the confidence in the conclusions presented above includes:

- Sampling of Loxton Sands and Murray Group groundwater in the Loxton – Bookpurnong region, beyond the influence of the irrigation mound. This would improve the confidence in the regional end-members used in the above interpretation.
- Construction and sampling of a series of observation wells in the Renmark Group aquifers in the Loxton – Bookpurnong region in order to improve confidence in the regional Renmark Group end – member signature adopted in the above interpretation. Measurement of hydraulic heads in the Renmark Group aquifers is also required to confirm the potential for upward leakage from this aquifer in the Loxton – Bookpurnong region.
- Development of a two-dimensional cross-sectional groundwater flow and solute transport model for comparison between hydraulic data and conclusions based on the geochemistry data.

7 REFERENCES

Armstrong, D., Yan, W. and Barnett, S.R., 1999, Loxton Irrigation Area – Groundwater Modelling of Groundwater / River Interaction., Department of Primary Industries and Resources, Adelaide, South Australia.

AWE (Australian Water Environments), 1999, Bookpurnong and Lock 4 Preliminary Land and Water Management Plan., October, 1999.

AWE (Australian Water Environments), 2002, Bookpurnong - Lock 4 Environmental Enhancement Scheme, Hydrogeological Investigations. Prepared for Loxton to Bookpurnong Local Action Planning Committee, July 2002 to September 2002.

AWE (Australian Water Environments), 2003a, Bookpurnong and Loxton Salt Interception Schemes: Joint Works / State Action Approval Submission to the Murray-Darling Basin Commission High Level Inter-Jurisdictional Working Group on Salt Interception, February, 2003.

AWE (Australian Water Environments), 2003b, Bookpurnong to Lock 4 Environmental Association: Groundwater Chemical Analysis, Comparison of Metals in Groundwater (Draft Report)., July, 2003.

Bone, B. and Davies, G., 2002, Effects of irrigation on riparian vegetation in the South Australian Riverland., South Australian Department of Agriculture.

Dighton J. C., Leaney F. W., 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., 6th Australian-New Zealand Environmental Isotope Conference, Wellington New Zealand, 2-4 April, 1997.

Dogramaci, S.S., 1998, Isotopes of sulphur, oxygen, strontium and carbon in groundwater as tracers of mixing and geochemical processes, Murray Basin, Australia., PhD thesis, The Flinders University of South Australia.

Dogramaci, S.S., Herczeg, A.L. and Bone, Y., 1998, $^{87}Sr/^{86}Sr$ in groundwater as indicators of carbonate dissolution., Water-Rock Interaction, Arehart & Hulston (eds), Balkema, Rotterdam, ISBN 90 5410942 4.

Dogramaci, S.S., Herczeg, A.L., Schiff, S.L. and Bone, Y., 2001, Controls on delta ^{34}S and delta ^{18}O of dissolved sulfate in aquifers of the Murray Basin, Australia and their use as indicators of flow processes., *Appl. Geochem*., 16, 475-488.

Dogramaci, S.S. and Herczeg, A.L., 2002, Strontium and carbon isotope constraints on carbonate-solution interactions and inter-aquifer mixing in groundwaters of the semi-arid Murray Basin, Australia., *J. Hydrol*., 262:50-67.

DWR (Department of Water Resources, South Australia), 2001, South Australian River Murray Salinity Strategy 2001 – 2015., Department for Water Resources, Government of South Australia.

Fetter, C.W., 1994, Applied Hydrogeology, Prentice-Hall, Inc., New Jersey, 691 p.

Gat, J.R., 1971, Comments on the stable isotope method in regional groundwater investigations., Water Resour. Res., 7: 980-993.

Gat, J.R., 1981, Isotopic Fractionation., In: Stable Isotopes in Hydrology, Deuterium and Oxygen-18 in the Water Cycle., Technical Reports Series No. 210, IAEA, Vienna, pp 21-34.

Gonfiantini, R., 1986, Environmental Isotopes in Lake Studies. In: Fritz, P., Fontes, J-Ch. (Eds), Handbook of Environmental Isotope Geochemistry. Vol. 2. The Terrestrial Environment. Elsevier, Amsterdam, pp. 113-168.

Harrington, N.M., 2004, Investigation into the precipitation of Al-hydroxide during pumping of bores at Bookpurnong (Western's Highland Site) in relation to groundwater quality in the Loxton Sands Aquifer., Government of South Australia, Department of Water, Land and Biodiversity Conservation Report DWLBC 2004/40.

Herczeg, A.L., Dogramaci, S.S. and Leaney, F.W., 2001, Origin of dissolved salts in a large, semi-arid groundwater system: Murray Basin, Australia., Mar. Freshwater Res., 52, 41-52.

Hill, A.J., Rammers, N and Wilson, T.C., 2005. Loxton Salt Interception Scheme: Stage 1 Investigations - Geology and Geophysics. DWLBC Report 2005/19.

Holland, K., 2002, Black Box (Eucalyptus largiflorens) Tree Health and Groundwater Discharge on the Lower River Murray Floodplain: Linking Spatial and Temporal Scales., PhD thesis, The Flinders University of South Australia.

Howles, S., Yan, W. and Hill, A., 2004, Loxton Numerical Groundwater Model. DWLBC Report 2005/16.

Jolly, I.D., Narayan, K.A., Armstrong, D. and Walker, G.R., 1998, The impact of flooding on modelling salt transport processes to streams., *Environmental Modelling and Software*, 13: 87-104.

Krouse, H.R. and Mayer, B., 1999, Sulfur and oxygen isotopes in sulfate., In: Cook, P.G. and Herczeg, A.L. (Eds.), Environmental Tracers in Subsurface Hydrology. Kluwer, Boston, pp. 195-231 (Chapter 7).

Leaney, F.W., Herczeg, A.L. and Dighton, J.C., 1994, New developments for the direct CO2 absorption method for radiocarbon analysis., Quaternary Geochronology, Quaternary Science Reviews, 13: 171-178.

Love, A.J., 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., J. Hydrol., 143: 297-338.

Lukasik J.J. and James N.P, 1998, Lithostratigraphic revision and correlation of the Oligo-Miocene Murray Supergroup, western Murray Basin, South Australia. Aust. J. of Earth Sciences, 45:889 - 902.

Maidment, D. R. (Ed), 1993, Handbook of Hydrology., Mcgraw-Hill, Inc., New York.

Narayan, K.A., Jolly, I.D. and Walker, G.R., 1993, Predicting flood-driven water table fluctuations in a semi-arid floodplain of the River Murray using a simple analytical model., CSIRO Division of Water Resources, Divisional Report (93/2): 16p.

NHMRC (National Health and Medical Research Council) and ARMCANZ (Agriculture and Resource Management Council of Australia and New Zealand), 1996, National Water Quality Management Strategy Australian Drinking Water Guidelines – Summary, Commonwealth of Australia, ISBN 0 642 24462 6 ISSN 1038 7072.

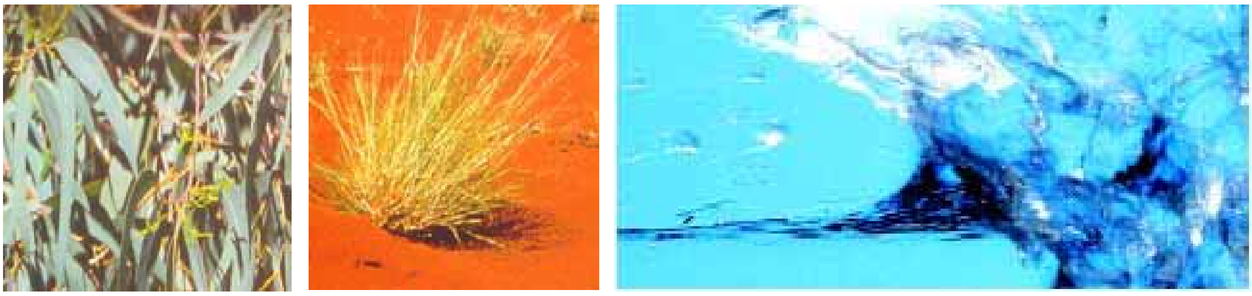
PPK, 1998, Assessment of the impact of the Loxton Irrigation District on floodplain health and implications for future options., PPK Environment and Infrastructure Report No. 27J121A 97-542.

Overton, I.C., Jolly, I.D., Holland, K. and Walker, G., 2003, The Floodplain Impacts Model (FIP): A Tool for Assisting the Assessment of the Impacts of Groundwater Inflows to the Floodplains of the Lower River Murray., Report prepared for the River Murray Catchment Water Management Board and the National Action Plan for Salinity and Water Quality by CSIRO Division of Land and Water.

Socki, R.A., Karlsson, H.R. and Gibson, E.K. Jr., 1992, Extraction techniques for the determination of oxygen-18 in water using preevacuated glass vials., *Anal. Chem*., 64: 829-831.

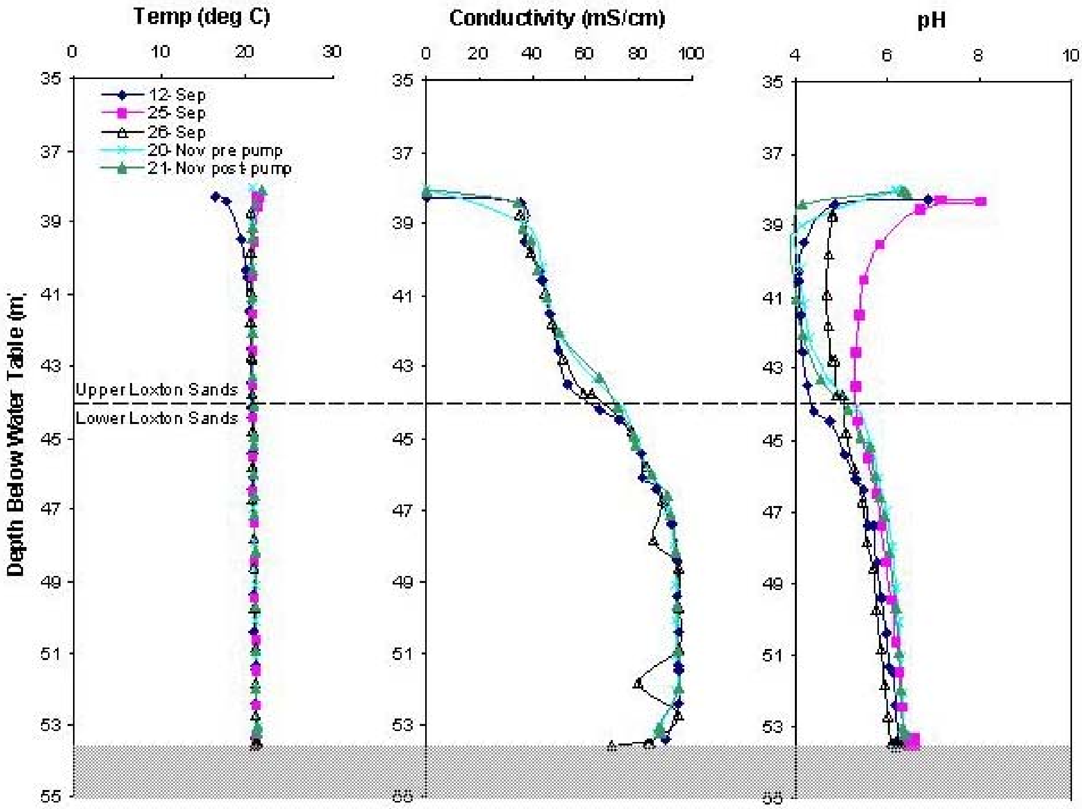
South Australian Steering Committee on Salt Interception, 2003, Bookpurnong and Loxton Salt Interception Schemes. Joint Works / State Action Approval Submission to the Murray-Darling Basin Commission High Level Inter-Jurisdictional Working Group on Salt Interception, February 2003.

APPENDIX A

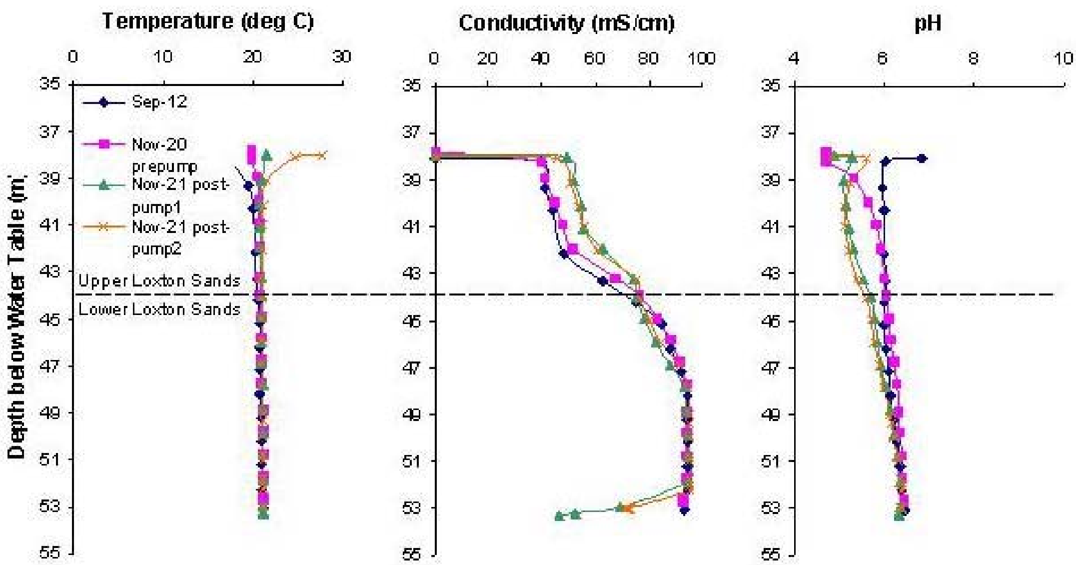


WATER QUALITY VS DEPTH PROFILES FROM THE LOXTON SANDS AQUIFER

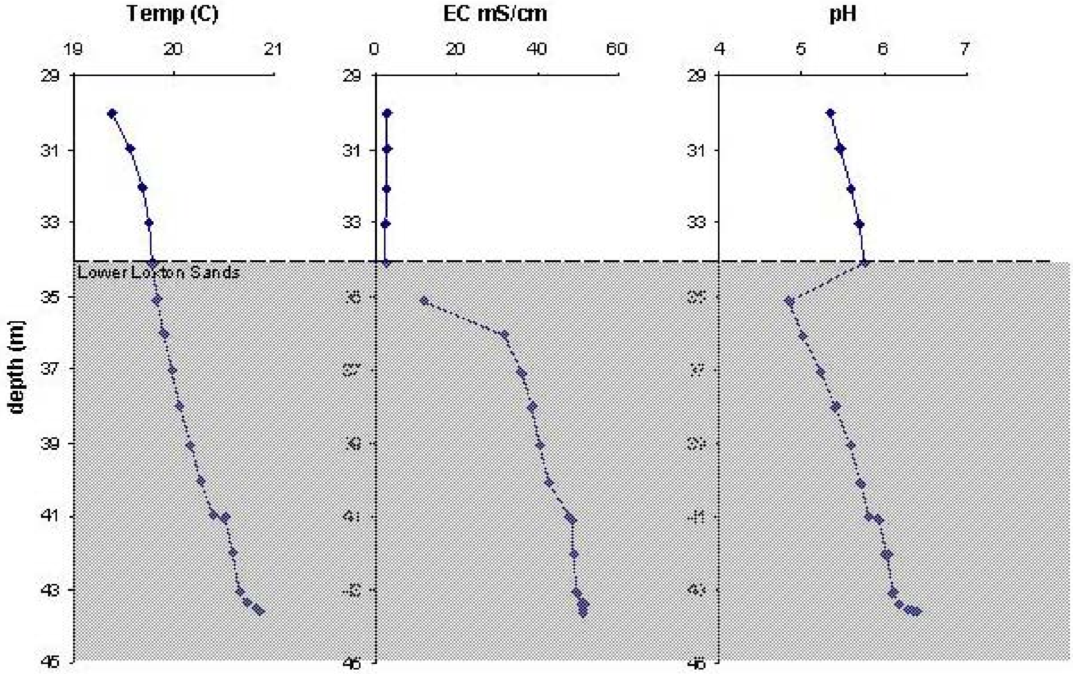
Water quality measurements were started at the standing water level in the bore. Unshaded areas represent the screened interval, whereas shaded areas represent cased-off intervals. Bore locations are shown on Figure 1.


Temp (deg C)
Conductivity (mS/cm)
pH
Depth Below Water Table (m)
12-Sep
25-Sep
26-Sep
20-Nov pre pump
21-Nov post pump
Upper Loxton Sands
Lower Loxton Sands

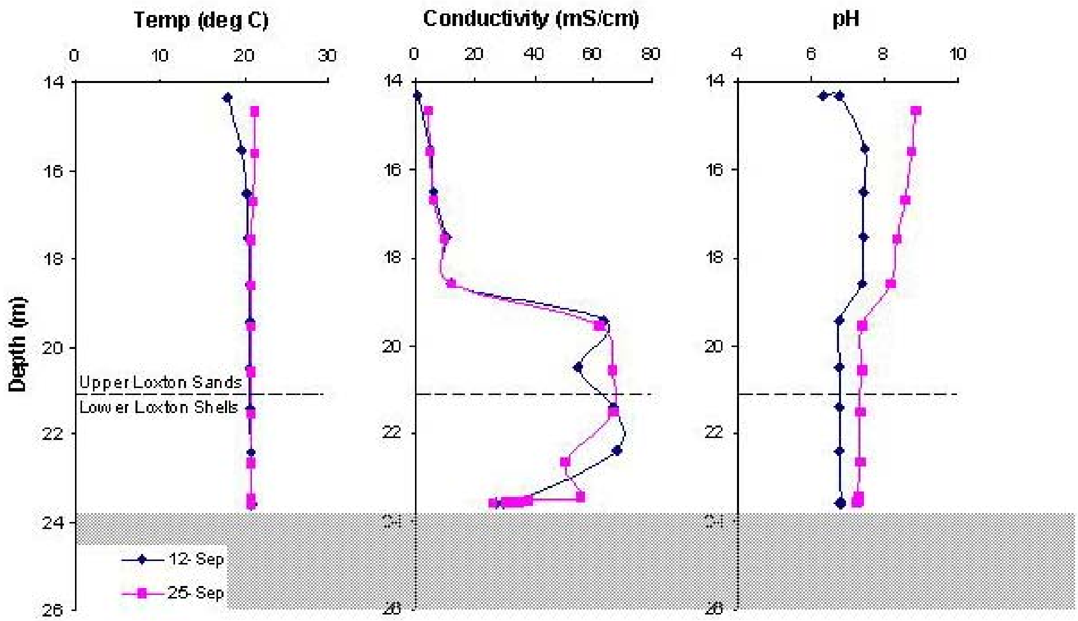
BHP1


Temperature (deg C)
Conductivity (mS/cm)
pH
Depth below Water Table (m)
Sep-12
Nov-20 prepump
Nov-21 post-pump1
Nov-21 post-pump2
Upper Loxton Sands
Lower Loxton Sands

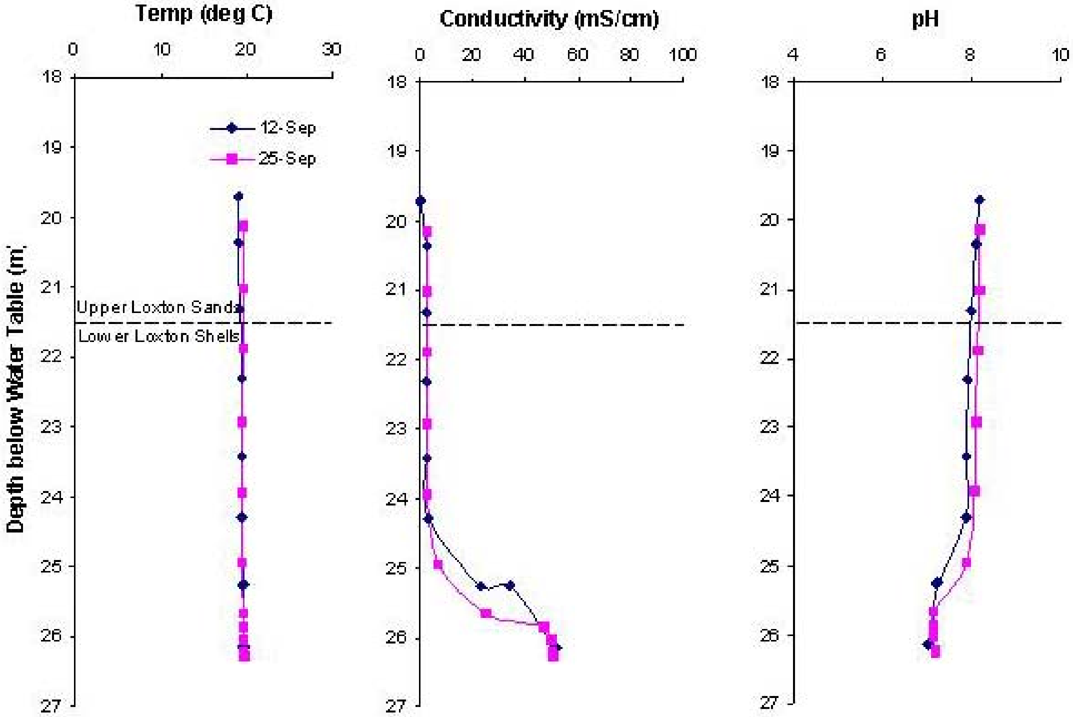
BHO1ls


Temp (C)
EC mS/cm
pH
depth (m)
Lower Loxton Sands

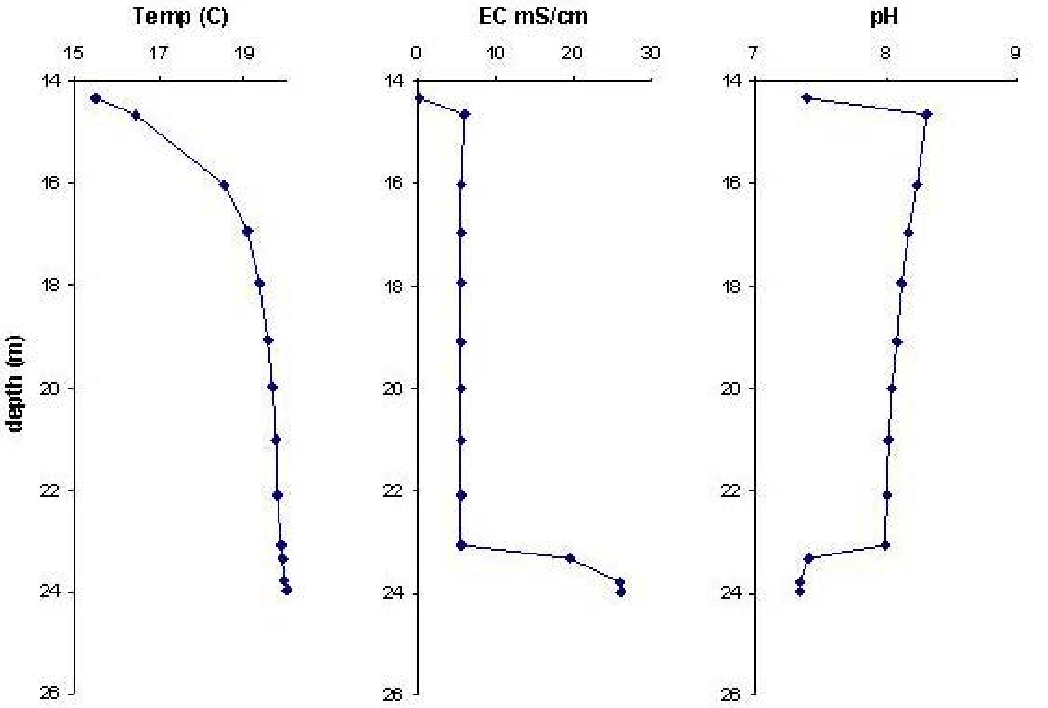
BHO4


Temp (deg C)
Conductivity (mS/cm)
pH
Depth (m)
Upper Loxton Sands
Lower Loxton Shells
12-Sep
25-Sep

BHP2

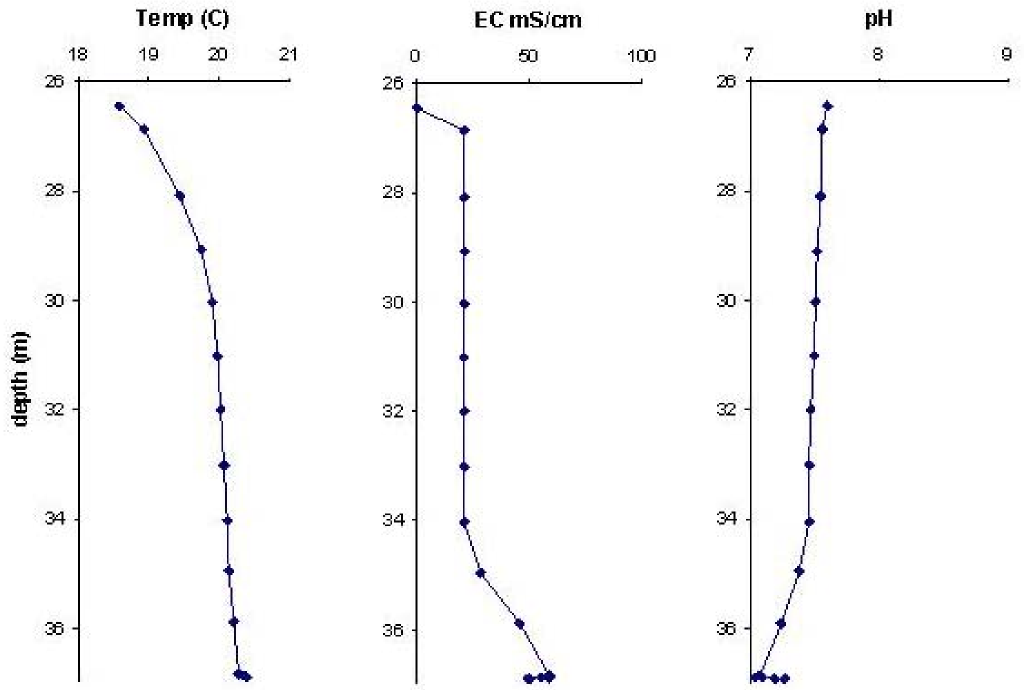


BHP3



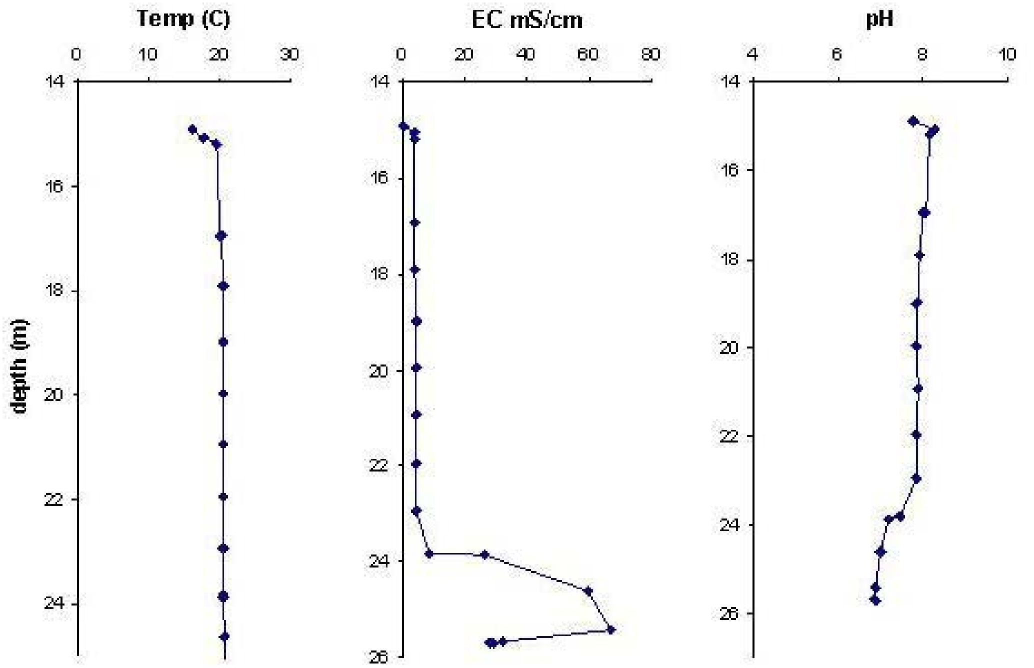
BKP1

*Construction and lithology unknown



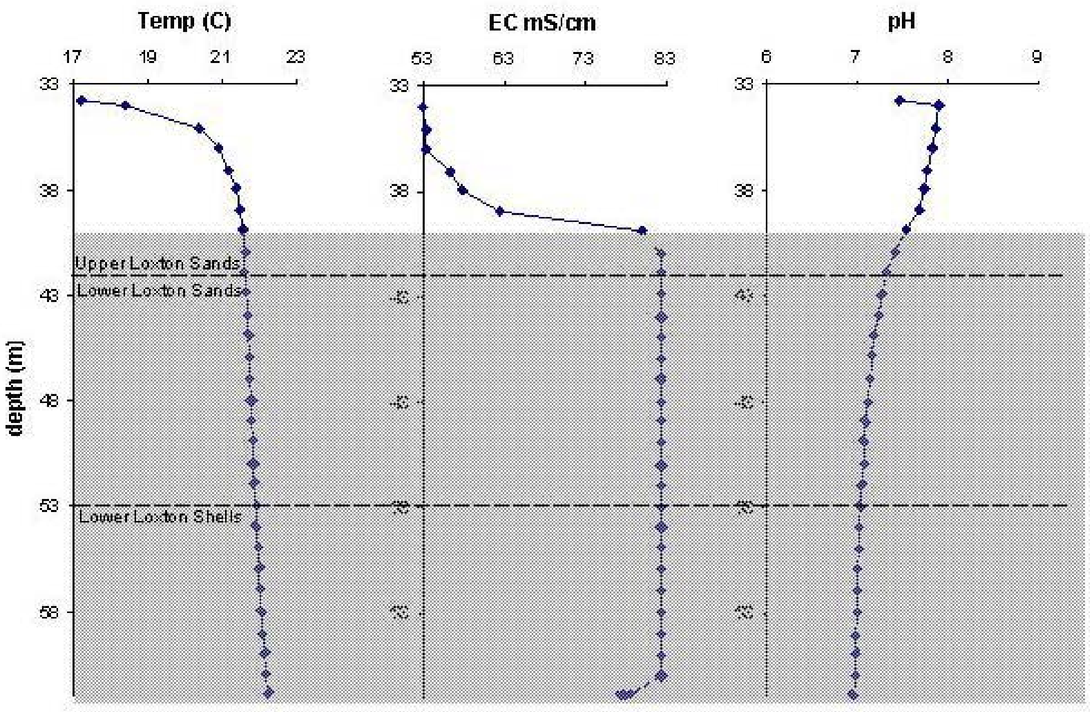
BKP2

*Construction and lithology unknown

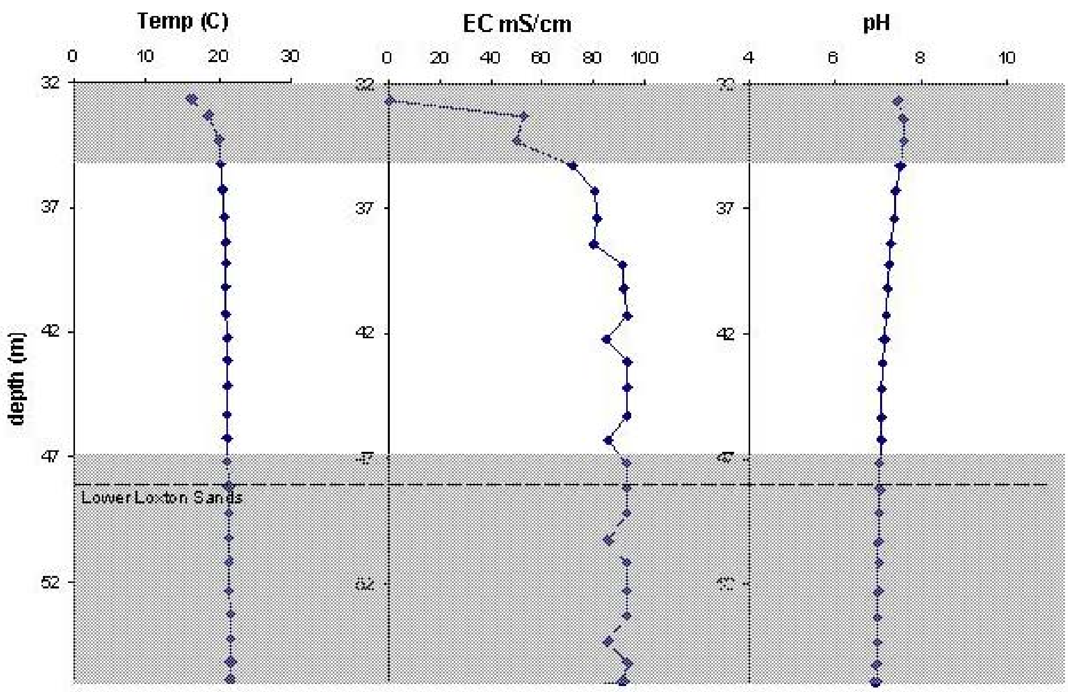


BKP5

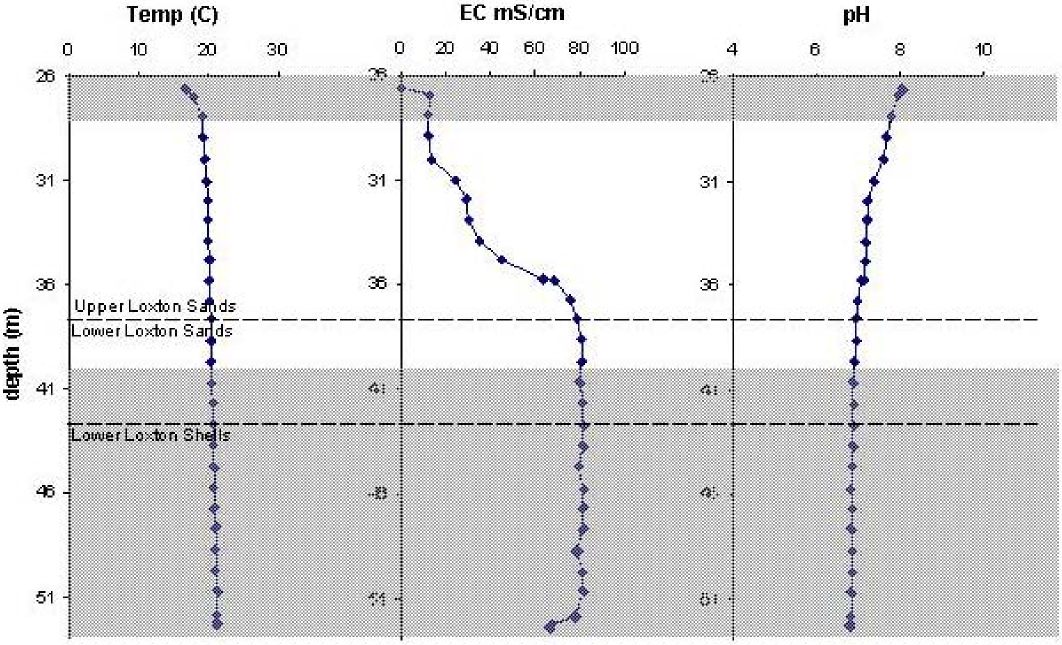
*Construction and lithology unknown


Temp (C)
EC mS/cm
pH
depth (m)
Upper Loxton Sands
Lower Loxton Sands
Lower Loxton Shells

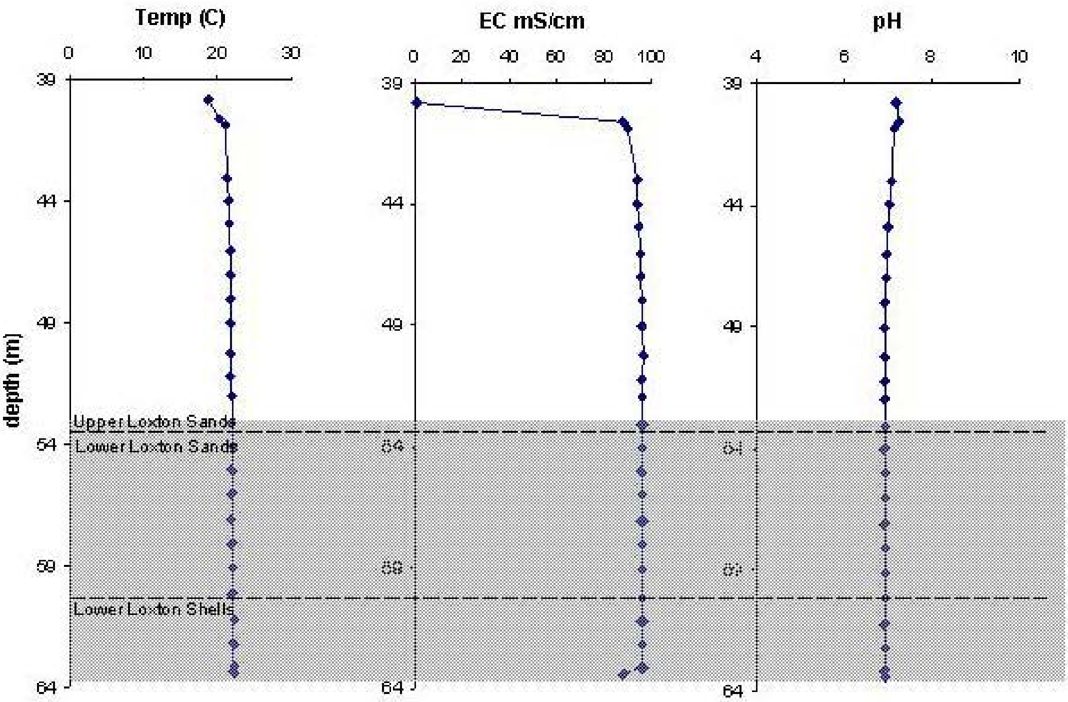
EES1


Temp (C)
EC mS/cm
pH
depth (m)
Lower Loxton Sands

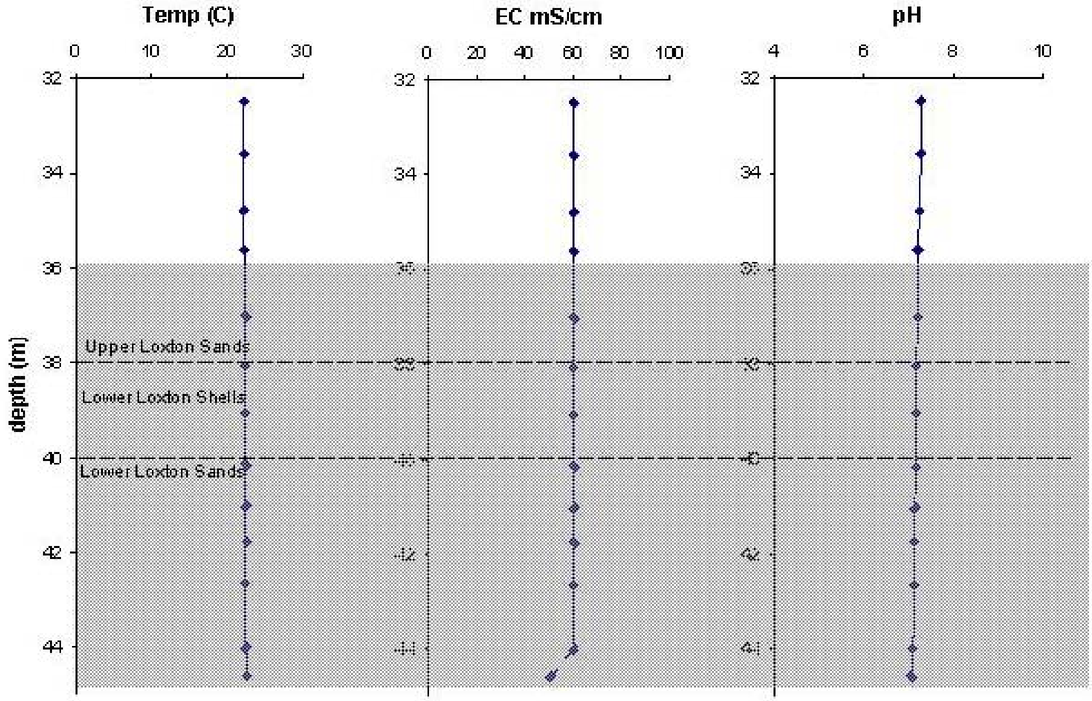
EES2


Temp (C)
EC mS/cm
pH
depth (m)
Upper Loxton Sands
Lower Loxton Sands
Lower Loxton Shells

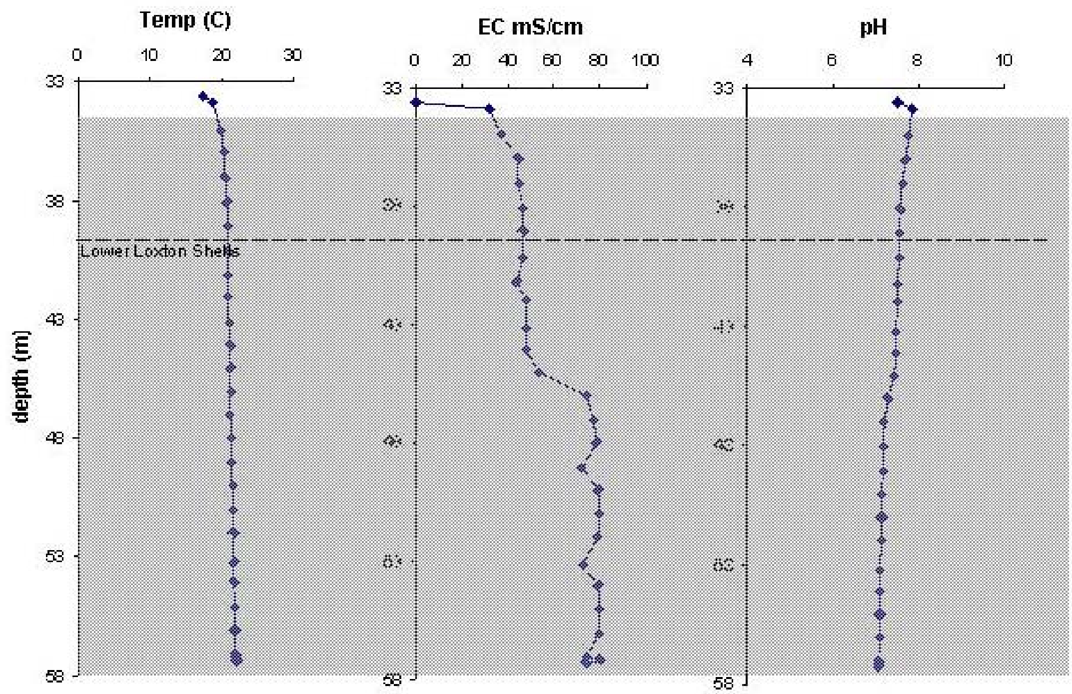
EES3


Temp (C)
EC mS/cm
pH
depth (m)
Upper Loxton Sands
Lower Loxton Sands
Lower Loxton Shells

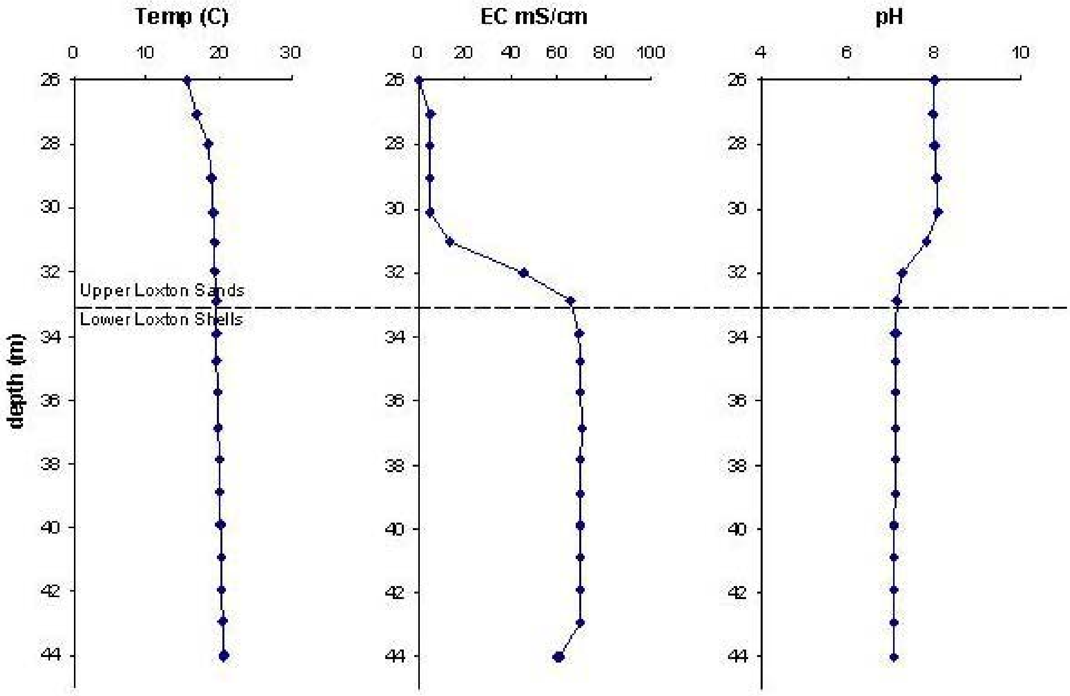
EES4


Temp (C)
EC mS/cm
pH
depth (m)
Upper Loxton Sands
Lower Loxton Shells
Lower Loxton Sands

EES5

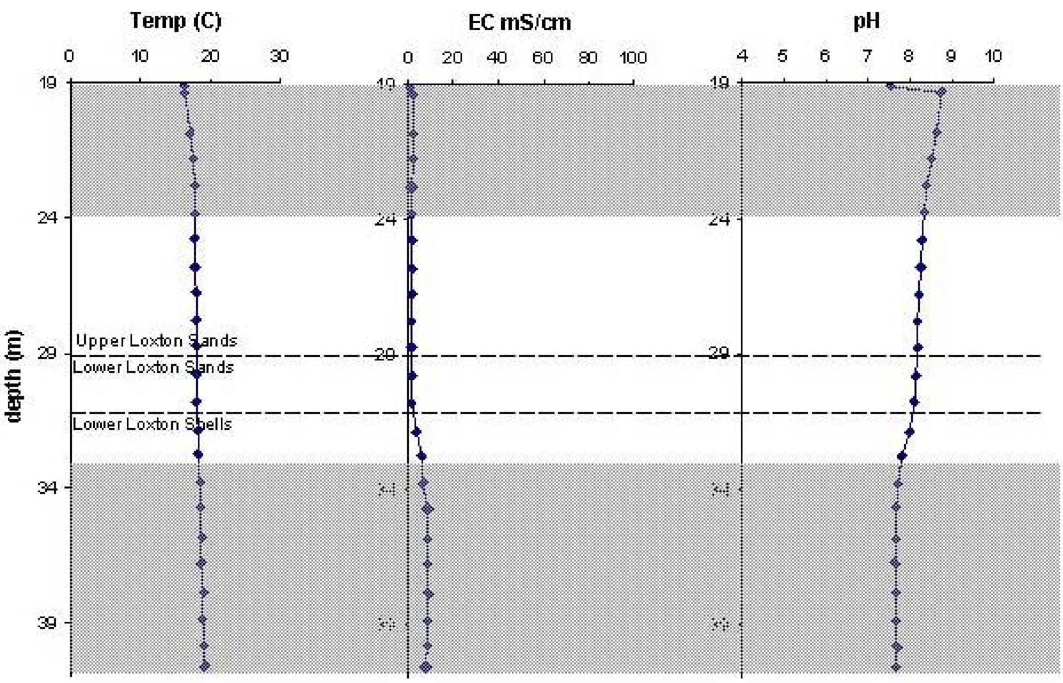

Temp (C)
EC mS/cm
pH
depth (m)
Lower Loxton Shells

EES6

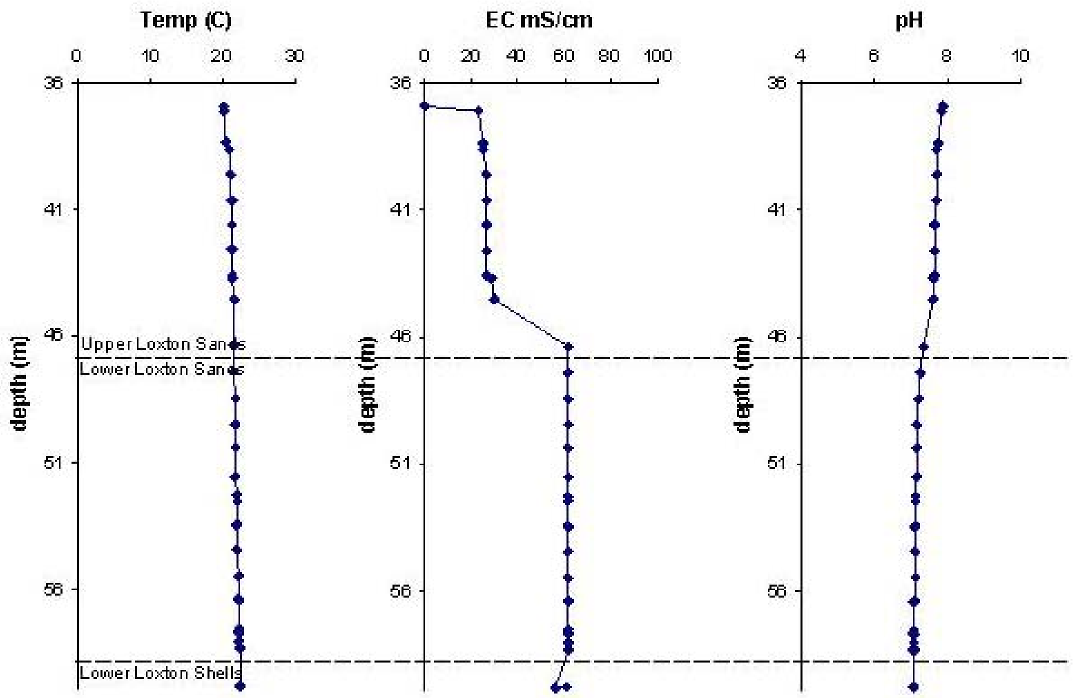


EES7

*Construction unknown

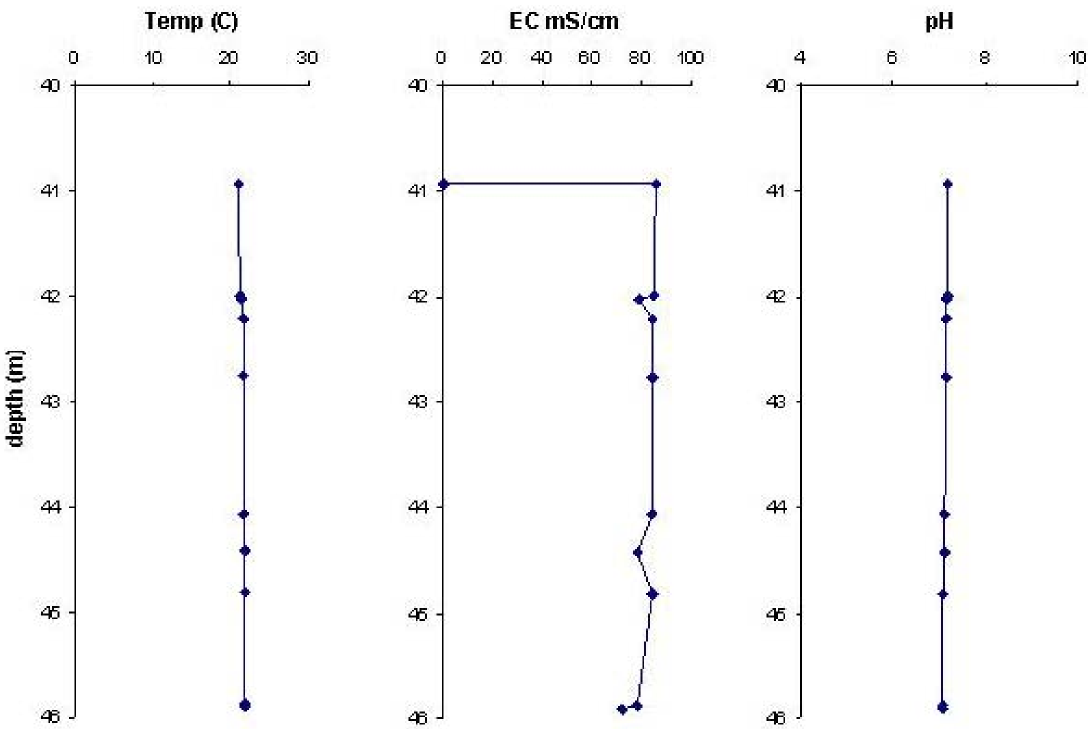


EES8



EES9

*Construction unknown



EES12

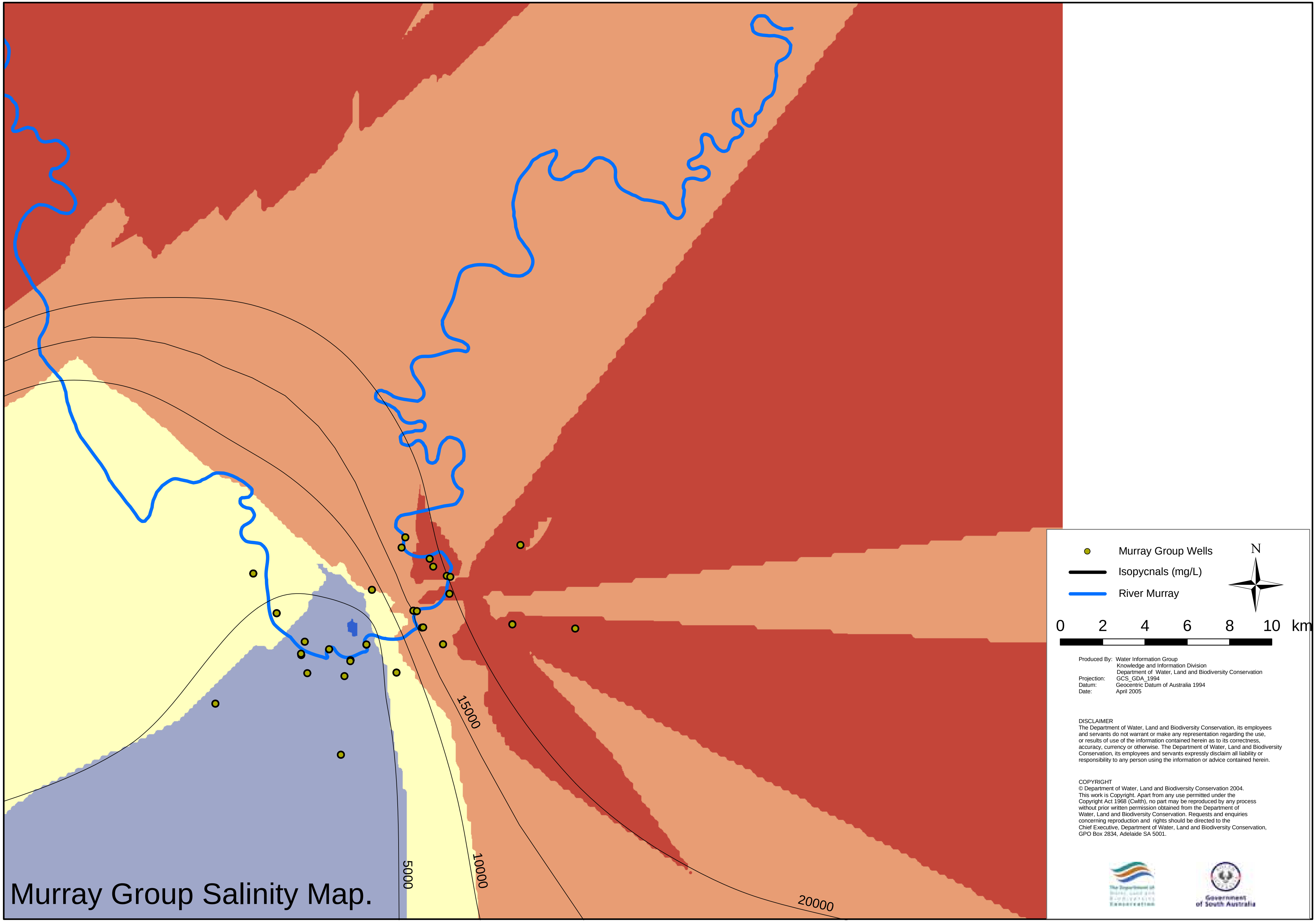
*Construction unknown

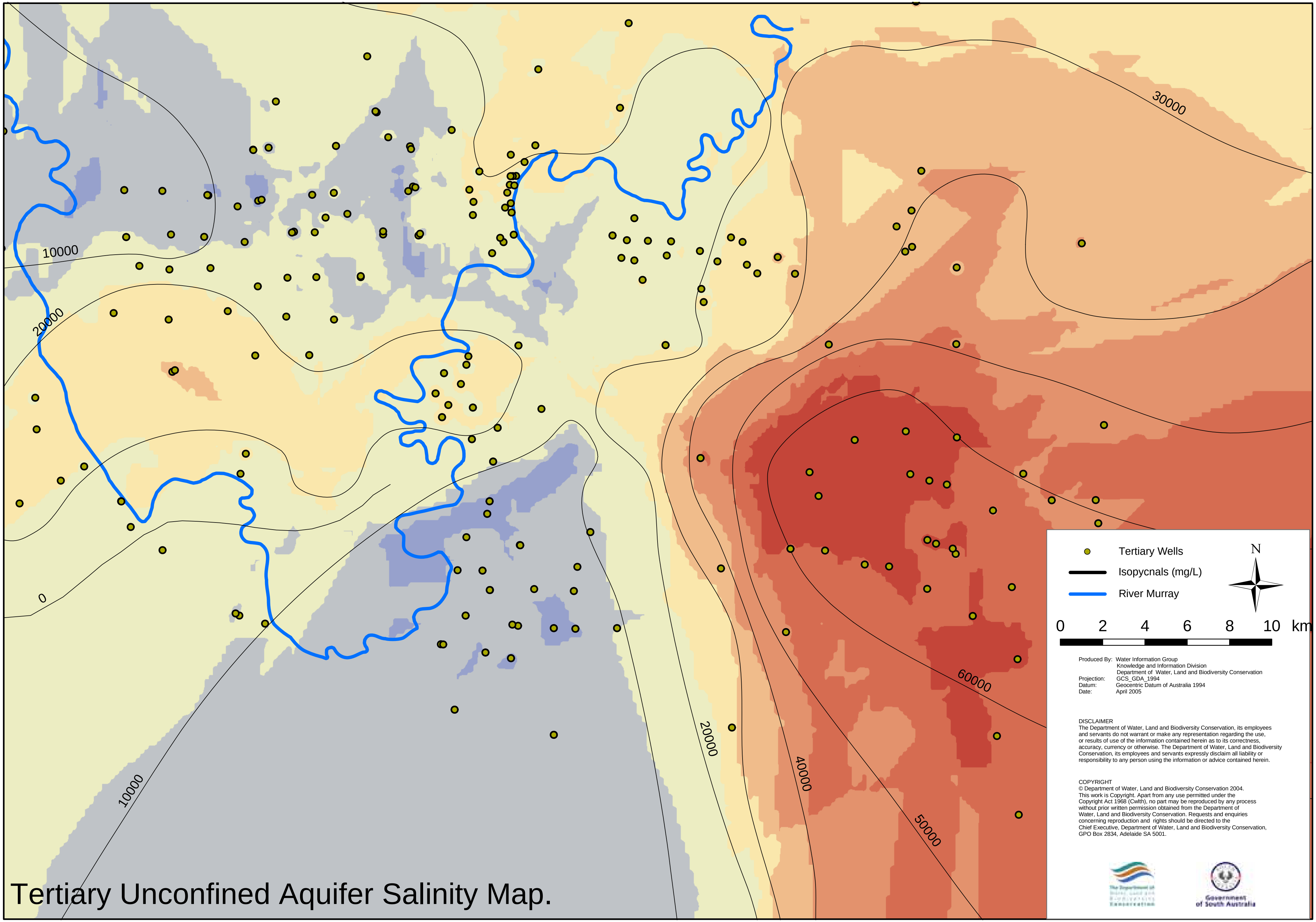
APPENDIX B



REGIONAL GROUNDWATER SALINITIES

The regional groundwater salinity maps included in this appendix have been constructed by converting measurements of electrical conductivity (EC) to estimates of total dissolved solids (TDS). Field meausurements of EC always provide only an approximate indication of TDS and can also be affected by a number of factors including whether the bore was purged properly prior to sampling and the level of maintenance and calibration of the EC probe used. The authors have no knowledge of the methodology used to collect the samples for EC measurement nor of the equipment used. Hence these salinity maps should be used as a general indication of the salinity trends in the aquifers only and not too much reliance should be placed upon the finer details.


Murray Group Wells
Isopycnals (mg/L)
River Murray
N
0 2 4 6 8 10 km
5000
10000
15000
20000
Produced By: Water Information Group
Knowledge and Information Division
Department of Water, Land and Biodiversity Conservation
Projection: GCS_GDA_1994
Datum: Geocentric Datum of Australia 1994
Date: April 2005
DISCLAIMER
The Department of Water, Land and Biodiversity Conservation, its employees and servants do not warrant or make any representation regarding the use, or results of use of the information contained herein as to its correctness, accuracy, currency or otherwise. The Department of Water, Land and Biodiversity Conservation, its employees and servants expressly disclaim all liability or responsibility to any person using the information or advice contained herein.
COPYRIGHT
© Department of Water, Land and Biodiversity Conservation 2004.
This work is Copyright. Apart from any use permitted under the Copyright Act 1968 (Cwlth), no part may be reproduced by any process without prior written permission obtained from the Department of Water, Land and Biodiversity Conservation. Requests and enquiries concerning reproduction and rights should be directed to the Chief Executive, Department of Water, Land and Biodiversity Conservation, GPO Box 2834, Adelaide SA 5001.
Government of South Australia
Murray Group Salinity Map.



Tertiary Unconfined Aquifer Salinity Map.

Produced By: Water Information Group
Knowledge and Information Division
Department of Water, Land and Biodiversity Conservation
Projection: GCS_GDA_1994
Datum: Geocentric Datum of Australia 1994
Date: April 2005