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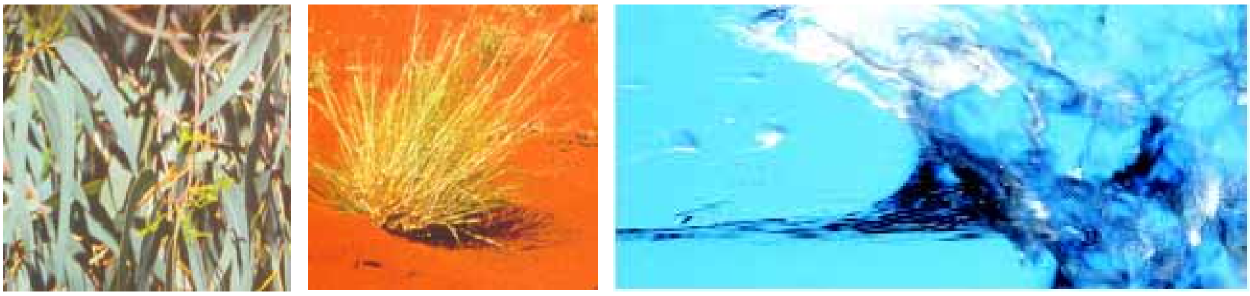

Defining sources of groundwater for the Blackhill Springs, Lower Marne River, South Australia

GLENN A HARRINGTON

Report DWLBC 2004/20

Government
of South Australia

River Murray
Catchment Water
Management Board
A healthy catchment – sustainable uses

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Disclaimer

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 organisims 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 atresses 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

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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	$^{o}/_{oo}$
CFC	=	Chlorofluorocarbon *(parts per trillion volume)*	pptv
$\delta^{18}O$	=	Oxygen isotope composition	$^{o}/_{oo}$
^{14}C	=	Carbon-14 isotope *(percent modern Carbon)*	pmC
Ppm	=	Parts per million	
Ppb	=	Parts per billion	

EXECUTIVE SUMMARY

The Research & Investigations Group of DWLBC Knowledge & Information Division was contracted by the River Murray Catchment Water Management Board (RMCWMB) in early 2003 to determine the source(s) of groundwater to the Blackhill Springs on the Lower Marne River, and identify any potential risks to the long-term health of the permanent pools they support.

The permanent pools once appeared within several hundred metres downstream of the Blackhill township. However, the location of the first pool has gradually migrated further downstream over the last 10 – 20 years, and in 2003 it was located near Christian Reserve, more than 2 kilometres downstream of Blackhill. The pools support healthy populations of native River Blackfish amongst other native aquatic species, however their future existence appears threatened as pools continue to dry up.

Until now, very little was known about the source of groundwater to the springs, and hence their long-term sustainability. This was in part due to a paucity of reliable, long-term groundwater level and surface flow monitoring data for this particular reach of the Marne River. Nevertheless, the methodology employed in the current study was such that historical data was not essential. Run-of-river sampling from numerous surface water points was carried out for subsequent chemical and isotopic analyses during November 2003. Several groundwater samples were also taken from the shallow Quaternary and deeper, regional Tertiary aquifers for laboratory analysis.

Salinity, stable isotope compositions, major ion chemistry and radioactive isotope (radon and carbon-14) concentrations of the water samples were interpreted simultaneously to develop a conceptual model of groundwater – surface water interactions at Blackhill Springs. The data indicate that the source for the permanent pools in this area is primarily the regional Murray Group limestone aquifer. This aquifer is recharged further upstream by infiltration of surface flows out of the Mount Lofty Ranges, and then discharges downstream of Blackhill township due to an impermeable basement high. Groundwater contributions from the Quaternary alluvial aquifers to the Marne River may be locally important for several months to a year after significant recharge events. Recent years of below average annual rainfall, combined with reduced frequency of low to median flows out of the Mount Lofty Ranges caused by unregulated damming, has meant that both the regional and alluvial aquifers have not been recharged and are declining rapidly. As the slope of the regional water table behind the basement high continues to fall, the position of the first pool moves downstream and pool depths downstream also decrease.

This study has highlighted the urgent need to improve the existing groundwater and surface water monitoring networks in the catchment and further investigate (i) how, where and at what rate, the regional aquifers are being recharged from surface flow now that it has been significantly affected by damming in the upper catchment, and (ii) the temporal responses of stream flows from the springs to groundwater level changes upstream.

1 INTRODUCTION

Background

Lower reaches of the Marne River below Blackhill have contained groundwater-fed permanent pools of water for several hundred years providing an ideal habitat for the native River Blackfish (*Gadopsis marmoratus*, cover photo). This section of the river is also lined with River Red Gum (*Eucalyptus camaldulensis)* vegetation which, due to low average annual rainfall and infrequent surface flow events, is dependent upon the shallow groundwater. There is growing concern regarding the future health of these ecosystems, as surface water levels have declined to the extent that Blackfish populations have now contracted to a few remaining pools, and many of the River Red Gums are suffering water stress (Tucker, 2001). The salinity of remaining pools is also on the rise, which may eventually wipe-out the Blackfish and other aquatic species.

Whether these trends in pool water levels and salinity are due to six out of the last ten years having below average annual rainfall (Fig. 1), a change in the flow regime of the river due to uncontrolled damming in the upper headwaters of the catchment, or declining groundwater resources is unknown. In fact, very little is known about the hydrological processes that control the levels and quality of these springs.

Hydrogeological Setting

Lower reaches of the Marne River traverse the western margin of the Murray Basin between Cambrai at the edge of the Mount Lofty Ranges and Wongulla on the River Murray. The main regional aquifer in the Murray Basin sedimentary sequence west of the River Murray is the Murray Group Limestone. Deeper Tertiary formations that are collectively termed the Renmark Group Confined Aquifer are essentially absent from this part of the basin due to the presence of basement highs (Fig. 2). The basement rocks become shallower in a southerly direction (Barnett, 1989) and actually outcrop in the Marne River bed.

Observation wells are located throughout the catchment (Fig. 3) presenting a range of different depth intervals and aquifers for routine monitoring. Barnett et al. (2001) provided a brief overview of aquifer characteristics and monitoring trends, as well as predicted results from modelling various groundwater recharge/use scenarios. Of particular interest to the current study, they found a close correlation between groundwater level (i.e. recharge) and annual streamflow out of the Mount Lofty Ranges. They also suggested that the regional water table had dropped by as much as 3 m around Kongolia over the last 3 years as a result of no recharge by streamflow in this period.

A reconnaissance trip by staff from RMCWMB and DWLBC in May 2003 identified four (apparently) different hydrogeological environments along the “gaining” reaches of the Marne River (essentially downstream of Blackhill, Fig. 3). These are:

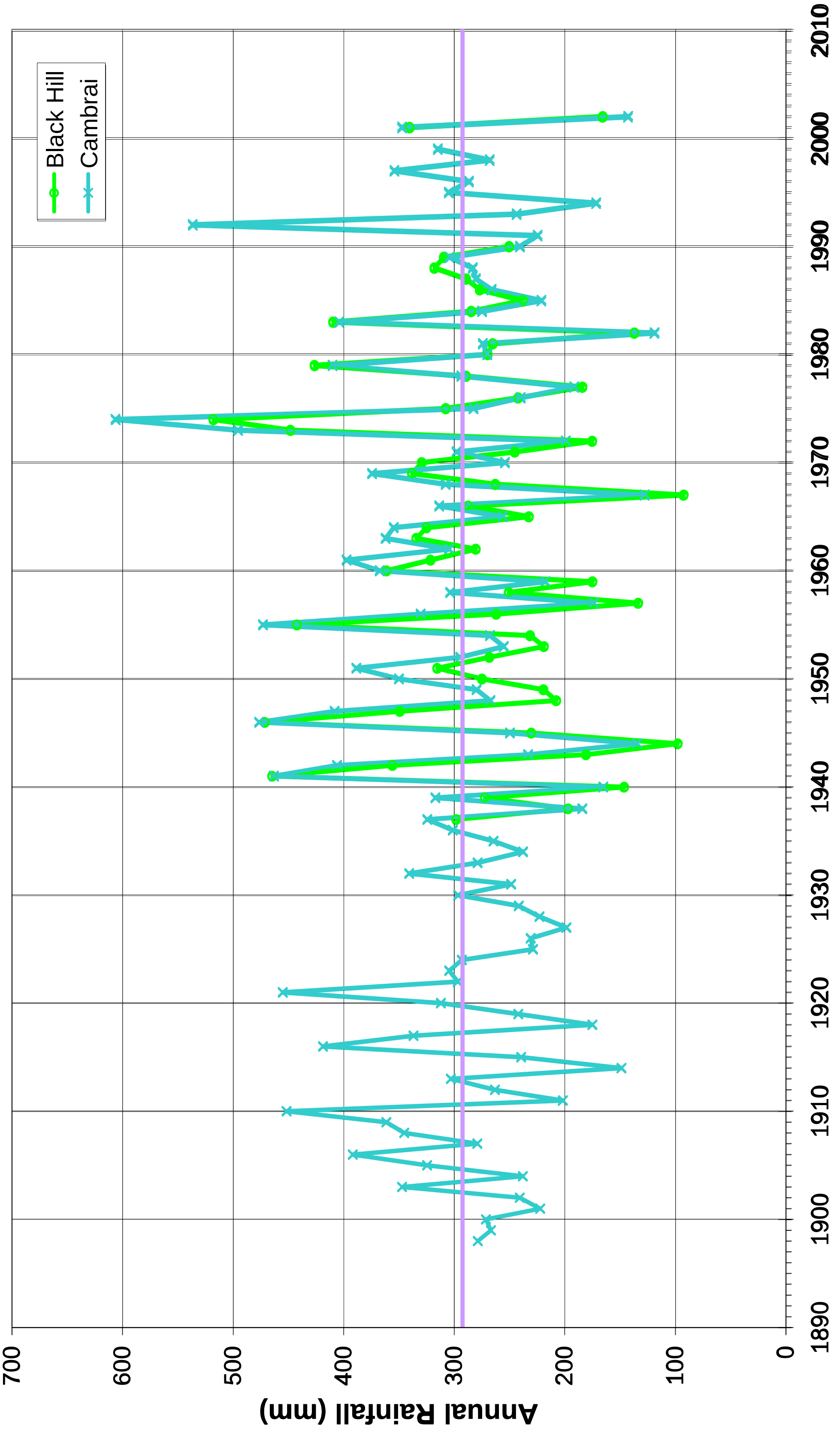

Figure 1. Annual rainfall for Black Hill and Cambrai. Purple line represents long-term mean annual rainfall of 295 mm/yr (104 years).

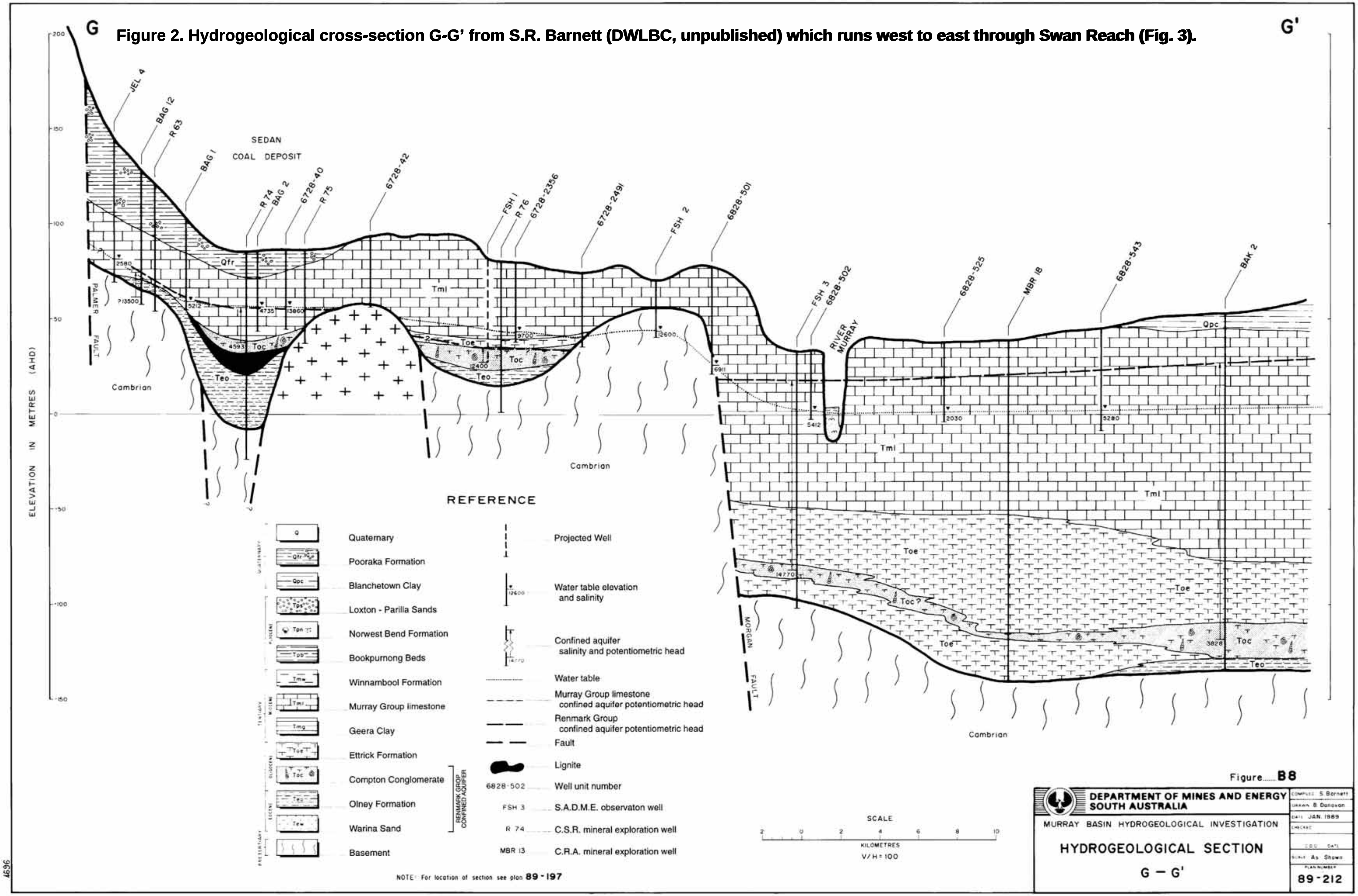

Figure 2. Hydrogeological cross-section G-G' from S.R. Barnett (DWLBC, unpublished) which runs west to east through Swan Reach (Fig. 3).

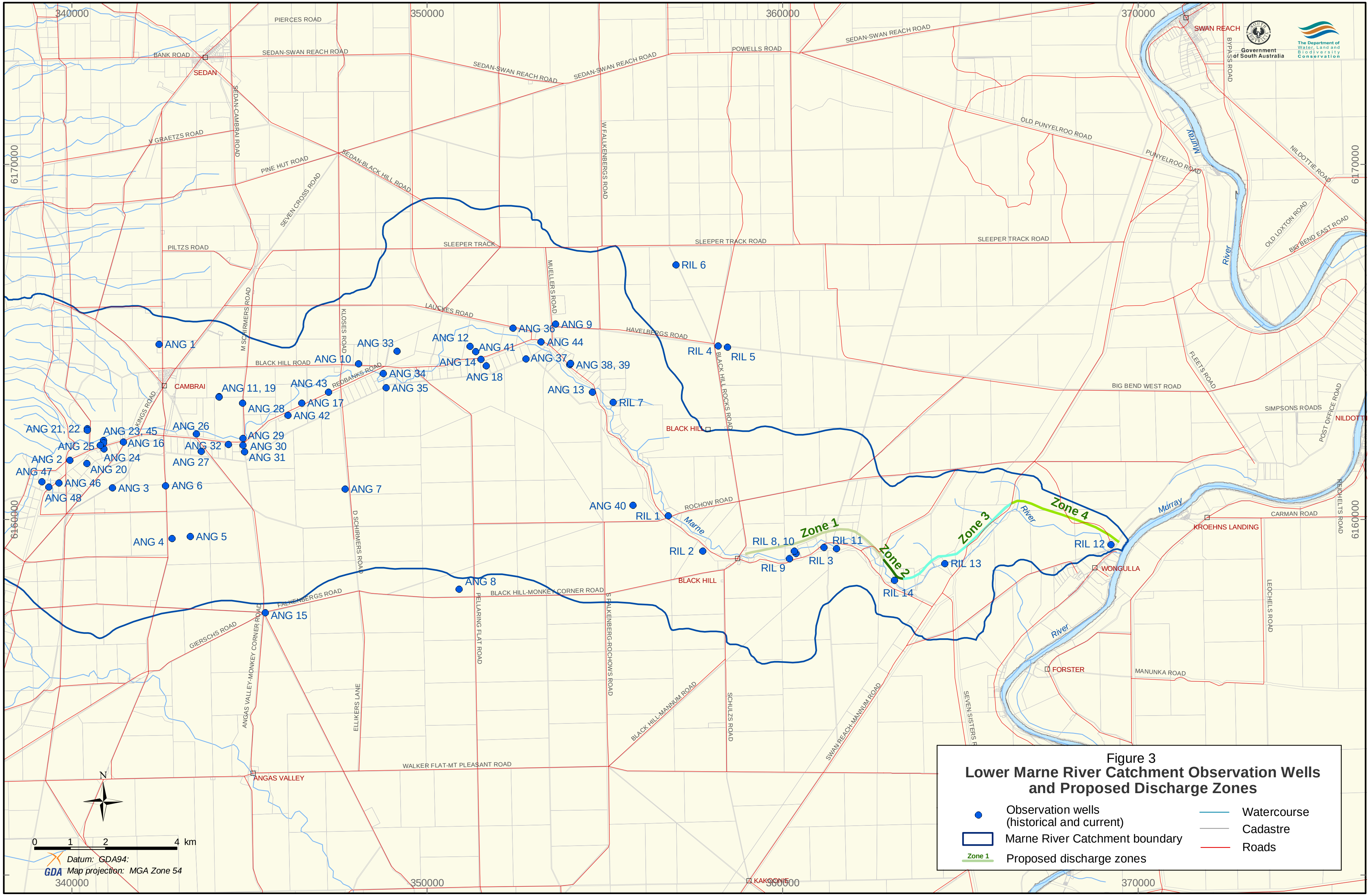

Figure 3
Lower Marne River Catchment Observation Wells and Proposed Discharge Zones

Zone 1: Blackhill to Gatt's property (Parcel D40534 A3), including Christian's Reserve:

- Often broad alluvial valley incised into Quaternary Blanchetown Clay and Tertiary Morgan Limestone (Murray Group); includes reddish-brown, sandy, Mallee-vegetated dunes and minor scarps of recent calcrete and Tertiary Morgan Limestone (Plate 1).
- Groundwater inputs to the Marne River may occur via discharge from the regional, water table aquifer, or bordering alluvial aquifers that are recharged during times of high surface flows in the river, or perched karst aquifers with short groundwater residence times.

Zone 2: Gatt's and Hammer's properties (Parcels D40534 A3 and A1):

- Location of geologic basement high consisting of Cambrian igneous and meta-sedimentary rocks (Kanmantoo Group) (Plate 2).
- Groundwater may be forced to lap onto this relatively impermeable structure, thereby discharging into the Marne River. Whether this groundwater is coming from shallow, local aquifers or deeper, more regional systems is unknown.

Zone 3: Basement high to bend where Marne River deviates (east) from Mannum - Swan Reach Road towards Wongulla.

- Narrower, alluvial valley incised through Tertiary sediments (Norwest Bend Formation and Morgan Limestone). Numerous short tributaries would flow into the Marne River from the bordering steep topography after intense rainfall events.
- Groundwater discharge may occur from the local Tertiary aquifers.

Zone 4: Bend on Mannum – Swan Reach Road to Wongulla (mouth).

- Narrow alluvial valley bounded by 35 metre-high cliffs of Tertiary limestone and sandstone. Lowest reaches choked by fine, clayey sediments that were deposited during the flood event of 1992 (pers. comm. K. Muller, RMCWMB, 2003).
- Groundwater-surface water interactions in this reach are unknown.

Scope and Objectives of the Study

The primary objectives of this study are (i) to determine the source of water for Blackhill Springs and (ii) to identify natural and anthropogenic mechanisms that are likely to impact on spring water levels and/or salinity.

In order to achieve these objectives, the project is divided into two parts. The first and most significant part is presented in this report and addresses issues such as:

- determining the relative contributions of each of the proposed sources of groundwater discharging to zone 1;
- determining the spatial variability and origin of groundwater discharge in zones 2/3.
- identify the likely impacts of climatic variation, upstream changes to the surface water flow regime and groundwater abstraction for irrigation on each of the proposed discharge mechanisms.

The second part of this project should be undertaken in mid-late 2004 (pending funding) and should include, but not be limited to monitoring temporal variations in the flow and quality of the identified discharge mechanisms in each of the zones.

Plate 1. Spring from outcrop of Morgan Limestone, Section 324 in Hundred of Ridley (Parcel D25716 A16).

Plate 2. Surface exposure of basement rocks (Heatherdale Shale) in Marne River, Parcel D40534 A1.

2 APPROACH

A review of historical rainfall, river flow and piezometric data was initially intended to highlight possible discharge mechanisms and their response to natural or anthropogenic change. However, the only continuous and reliable hydrologic data for this catchment is monthly rainfall at Cambrai (1897 – present) and Blackhill (1936 – 1990). The stream flow gauging station located upstream of Cambrai is effectively useless for the current investigation because the Marne River always loses flow to groundwater recharge across the plains. Most of the observation wells in the area around Blackhill are not ideal for monitoring groundwater-surface water interactions, especially the shallow piezometers in the alluvium which are completed at ground level with air holes and/or cracked casing that allows flood waters and overland flow to enter the aquifer.

Thorough investigation of the various discharge mechanisms consequently required the use of environmental tracers, as they can integrate hydrological processes over large spatial and temporal scales. The tracers adopted for this project were major ions, stable isotopes of the water molecule ($^{2}H/^{1}H$, $^{18}O/^{16}O$), chlorofluorocarbons (CFC-11, CFC-12) and the radioactive isotopes carbon-14 and radon-222.

Field measurements of Electrical Conductivity (EC), pH and temperature; and sampling for chemical and isotopic analyses were undertaken during November 2003. Samples were taken for major ions, radon and stable isotopes from eight surface water sites spanning the entire reach of surface flow (labelled GS# in Figs 4 – 6). Each site was assumed to be representative of the different hydrogeologic/geomorphologic zones. One of the surface water sites was also sampled from the bottom of a 1 m deep pool for CFC analysis (GS5, Plate 3). Spot values of EC were also obtained from three additional sites to fill-in large spatial distances between sampling sites (labelled SC#).

Four shallow piezometers in the Quaternary alluvium were sampled for field parameters (EC, pH and temperature) and laboratory analyses (major ions and stable isotopes) using a submersible Whale® pump (Plate 4). Due to low yields from most of these piezometers, only one could be sampled for radon (RIL014, also named GB2) and three for CFCs (RIL010, RIL011 and RIL013).

Groundwater samples from the regional limestone aquifer were obtained by pumping a domestic production bore (GB1) and collecting discharge from windmills (GB4 and GB5). The windmill samples were not analysed for CFCs due to potential air contamination.

Plate 3. Surface water sample site GS5 located just upstream of basement outcrop.

Plate 4. Piezometer RIL013 with 12V submersible Whale® pump.

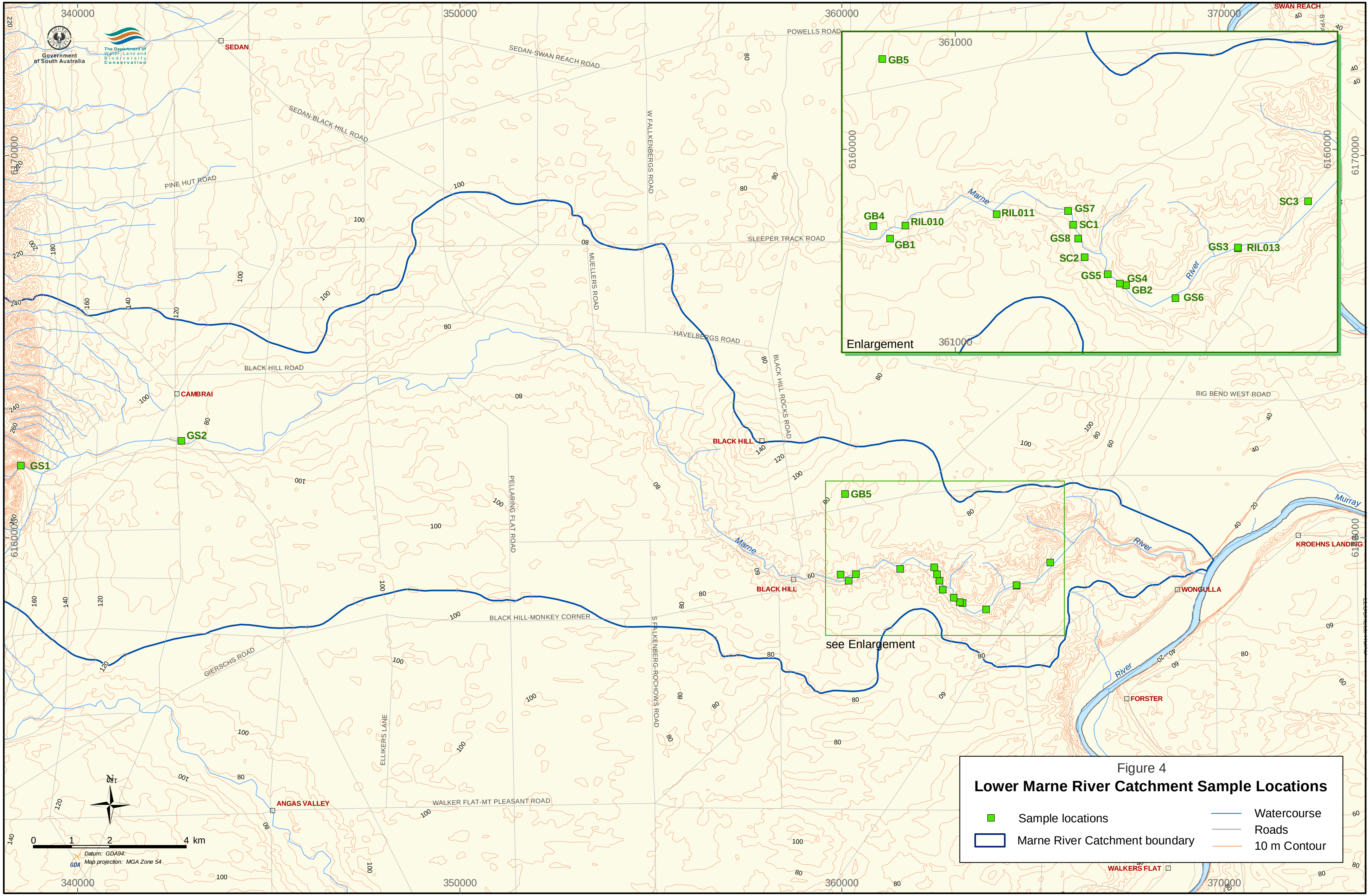

Figure 4

Lower Marne River Catchment Sample Locations

🟩	Sample locations	—	Watercourse
▭	Marne River Catchment boundary	—	Roads
		—	10 m Contour

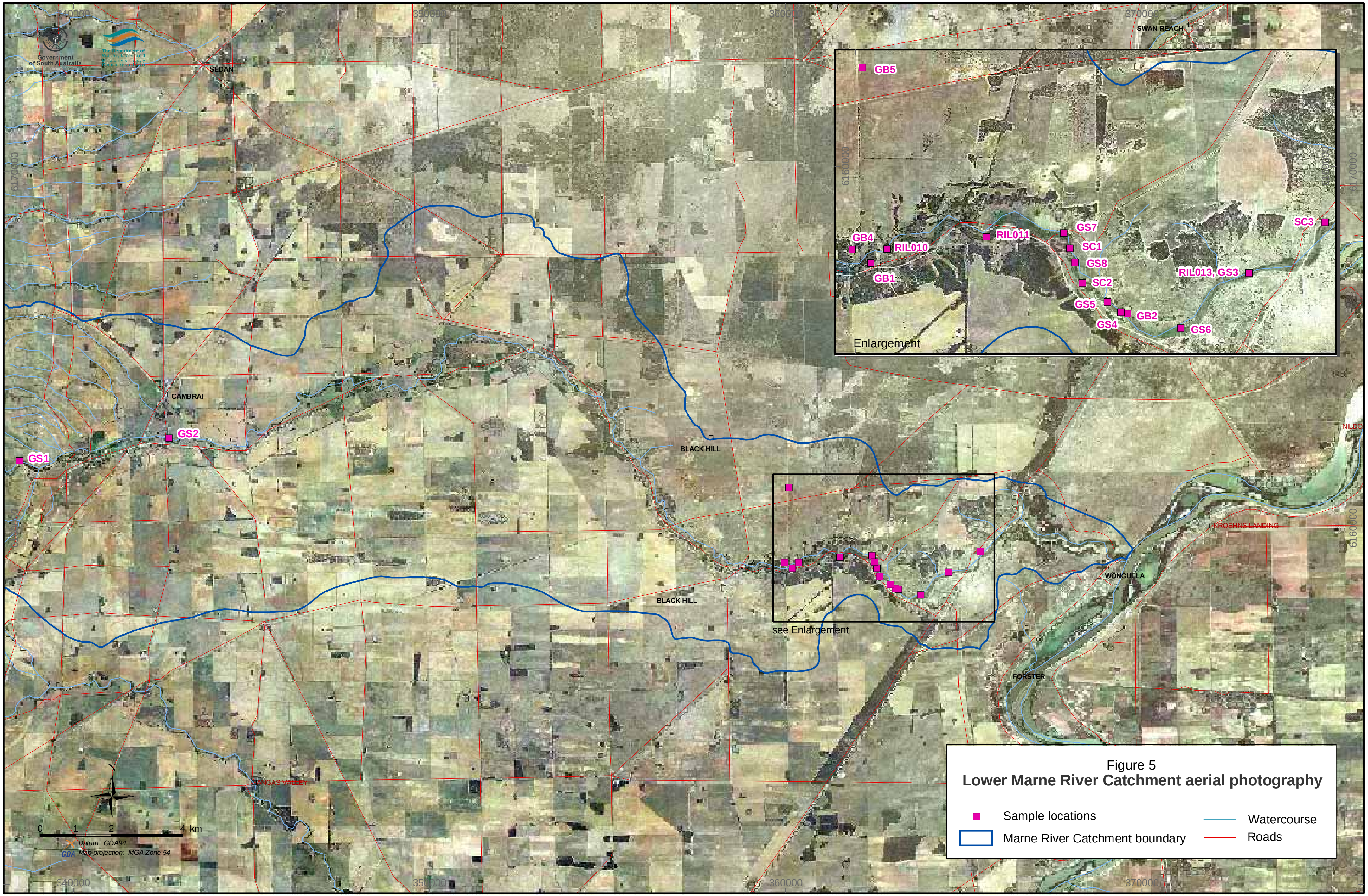

Figure 5
Lower Marne River Catchment aerial photography

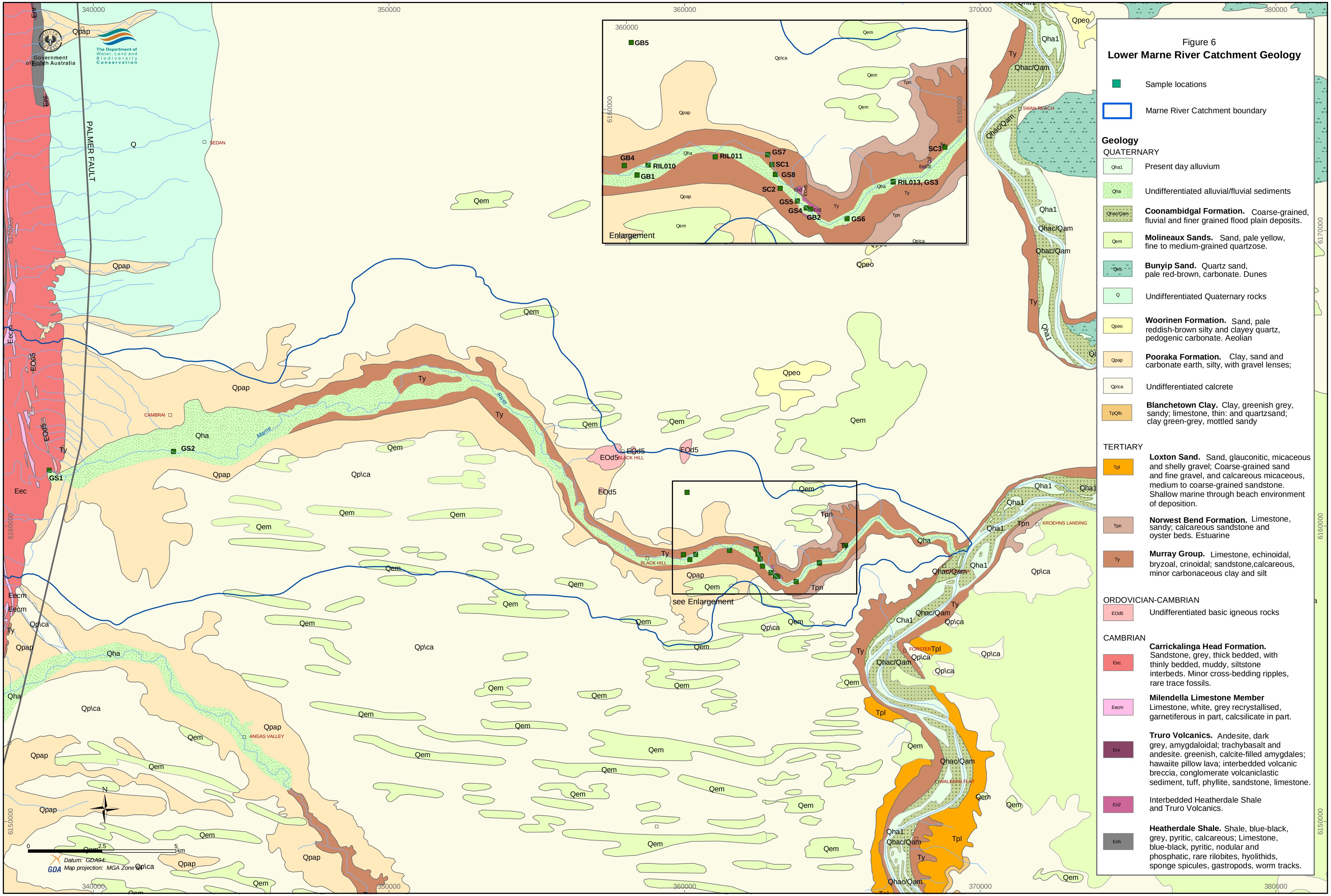

Figure 6
Lower Marne River Catchment Geology

3 CHEMICAL AND ISOTOPIC RESULTS

The Electrical Conductivity (EC) of surface water was generally lower than that of groundwater from the piezometers, but was higher than that of the regional groundwater (Fig. 7). EC increased between GS7 and SC1, then progressively decreased between GHS8, SC2 and GS5 before a slight increase at GS4. These trends indicate areas of groundwater discharge in the following three reaches:

i) between GS7 and SC1 – more saline than regional groundwater, probably shallow alluvial groundwater,

ii) between SC1 and GS5 – fresher than shallow alluvial groundwater, probably regional groundwater, and

iii) between GS5 and GS4 – more saline than regional groundwater, probably shallow alluvial groundwater.

The EC increased very gradually downstream of GS4, with a slightly steeper increase between the last two sites (GS3 and SC3). Flow was observed to be very dispersed and sluggish in this reach, thereby enhancing evaporative losses and increasing the salinity of the surface water.

The entire discharge zone inferred from the EC data was also revealed by radon concentrations increasing between GS7 and GS4 (Fig. 8). Because radon (^{222}Rn) is a radioactive gas produced naturally in all aquifers, any increase in radon concentration in surface water is indicative of groundwater discharge. Decreases in radon concentration occur by both degassing and radioactive decay (half life ~3.8 days). Radon concentrations decreased downstream of GS4 until GS6 then remained low to GS3, indicating no significant discharge downstream of GS4.

Stable isotope compositions of the surface water samples are comparable to those of groundwater from the shallow piezometers, but are more enriched in the heavier isotopes (i.e. ^{2}H and ^{18}O cf. ^{1}H and ^{16}O) than the regional groundwater samples (Fig. 9). All samples plot close to a linear trend, and the relatively high slope of 6.2 suggests they have been evaporated from a surface water body rather than a soil prior to recharge (Allison, 1982). This indicates that both the shallow, alluvial aquifer and deeper, regional aquifer are recharged from flood waters following intense rainfall events.

Figure 10 reveals a progressive depletion in oxygen isotope composition (i.e. δ^{18}O) down the River from a relatively enriched value of -4.17 ‰ at GS7 to -4.39 ‰ at SC1, -4.63 ‰ at GS8 and -4.82 ‰ at GS5. This trend supports the model proposed by the EC and radon data of mounting groundwater inputs from site GS7 to GS5. The source of this groundwater can only be from the relatively fresh, ^{18}O-depleted regional water table aquifer (Fig. 10). Whether the regional groundwater discharging here has been forced upwards to the surface from great depths by the basement rocks or is more locally recharged groundwater from the tertiary aquifers that border the river cannot be determined from the stable isotope data.

The slight increase in δ^{18}O between GS5 and GS4 corresponds to the small EC rise between these sites, and is attributed to an influx of groundwater from the relatively more

Table 1. Field, chemical and isotopic data for surface water and groundwater samples collected from the Lower Marne River in November 2003. Distance refers to the distance from the sample location along the main channel to the River Murray.

Sample ID	Location details	Sample Date	Easting	Northing	Distance	Q (est.)	SWL	TD	EC	pH	T	Alk	S	Ca	Mg	K	Na	HCO3	CO3	Cl	Br	Radon	CFC11	CFC12	Recharge date		δ^2H	$\delta^{18}O$
					(m)	(L/s)	(m)	(m)	(µS/cm)		(°C)						(mg/L)					(mBq/L)	(pg/kg)		CFC11	CFC12	(‰, SMOW)	(‰, SMOW)
Surface waters																												
GS3	Gardner's ford	05/11/2003	364565	6158753	6276				5120	7.77	17.8	20	63.3	216	127	18.1	916	453	8	1630	0.48	80.3					-23.9	-4.37
GS4	Hammer's ford	05/11/2003	363080	6158310	8144	8-10			5000	7.57	16.3	23	61.3	231	114	16.6	813	530	3	1570	0.33	5528.5					-27.1	-4.81
GS5	Gatt's ford	05/11/2003	362925	6158425	8337	8-10			4880	7.66	16.4	22	61.3	241	116	15.4	841	517	2	1420	0.52	3969.4	383	143.5	1984	1980	-26.8	-4.82
GS6	private ford	06/11/2003	363776	6158125	7338	10			5070	7.95	12.2	24	65	227	124	16	894	468	9	1460	0.43	91.1					-26.5	-4.7
GS7	Ford u/s Andrew's	06/11/2003	362421	6159224	9424	1.6			4470	7.7	14.5	25	49.3	230	98.8	13.1	792	470	9	1390	1.04	184.0					-22.6	-4.17
GS8	Andrew's pond #2	06/11/2003	362552	6158879	9036				5670	7.65	15.7	26	65.3	196	116	15.5	892	538	10	1750	4.34	2332.7					-25.1	-4.63
SC1	Andrew's pond #1	06/11/2003	362489	6159050	9220				6745	7.89		29	102	241	143	17.2	1330	512	10	2130	5.46						-23.2	-4.39
SC2	Gatz's - u/s GS5	06/11/2003	362635	6158644	8827				5220	7.74	17.4	27																
SC3	S/Reach Rd d/s GS3	06/11/2003	365450	6159348	5137	0			5800	7.4																		
Shallow piezometers																												
RIL010	Spring swamp	05/11/2003	360374	6159040	11825		1.07	1.97	4930	7.03			81.3	355	115	17.5	815	599	0	1490	0.73		52.5	88	1965	1974	-25.3	-4.81
RIL011	Christian Reserve	05/11/2003	361522	6159183	10507		1.58	2.26	14090	6.99			121	1140	386	38.4	1940	910	0	5110	14.1		90	109	1969	1976	-25.5	-4.61
RIL013	Gardner's piezo	05/11/2003	364565	6158763	6276		0.75	1.88	7630	7.28	12.8	42	81	263	320	32	1380	1370	8	2570	3.28						-23.1	-4.25
GB2 (RIL014)	Hammer's property	05/11/2003	363154	6158289	8076		0.44	1.03	9400	7.23	16.2	41	103	410	207	18	1820	879	0	2980	6.99	11950	91	139	1969	1980	-23.8	-4.48
Regional bores																												
GB1	Allsop's production well	04/11/2003	360182	6158874	12166				3150	6.62		21	16	141	31	6	227	309	0	565	1.59	18051	120.5	99	1970	1975	-28.2	-5.1
GB4	Windmill #1 (6728-2314)	06/11/2003	359968	6159033	12166		11.66		2950	7.14	20.5	22	25.1	164	46.7	9.1	354	405	0	793	1.36	2512					-26.8	-4.93
GB5	Windmill #2 (6728-0113)	06/11/2003	360085	6161143			24.8		5190	6.92	20.3	35	57.7	151	87.2	17.9	942	689	5	1530	0.66	8554					-27.5	-4.98

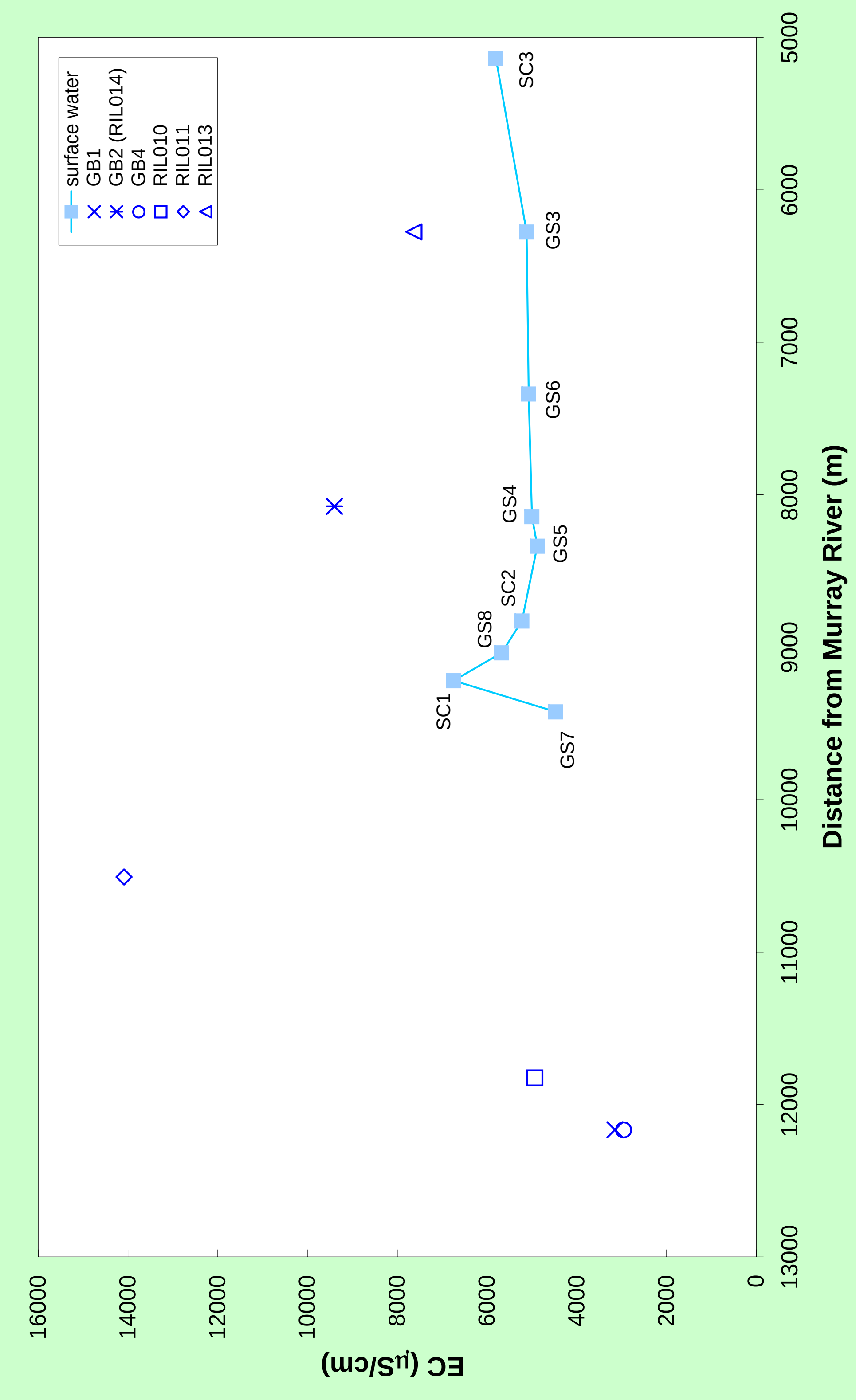

Figure 7. Electrical Conductivity (EC) versus distance from River Murray. Changes in surface water EC reflect inputs of groundwater. The slight rise in EC towards the end of the transect most likely also reflects concentration by evaporation in this sluggish section of the river.

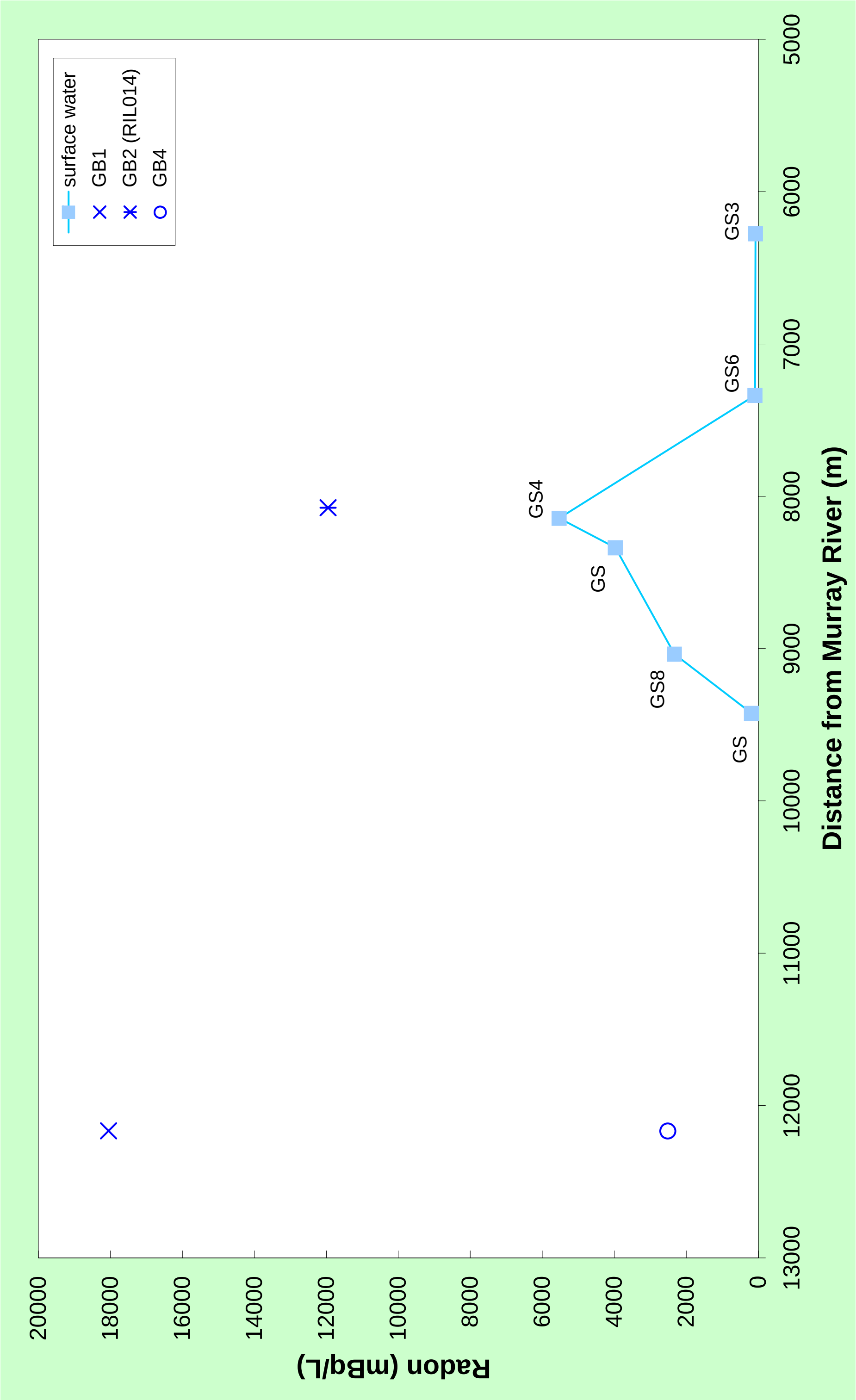

Figure 8. Radon concentration versus distance from River Murray. Radon is only produced sub-surface, so increases in radon concentration along the river indicate zones of active groundwater discharge. Decreases in radon concentration are due to little or no further groundwater inputs, plus loss of radon by degassing and radioactive decay.

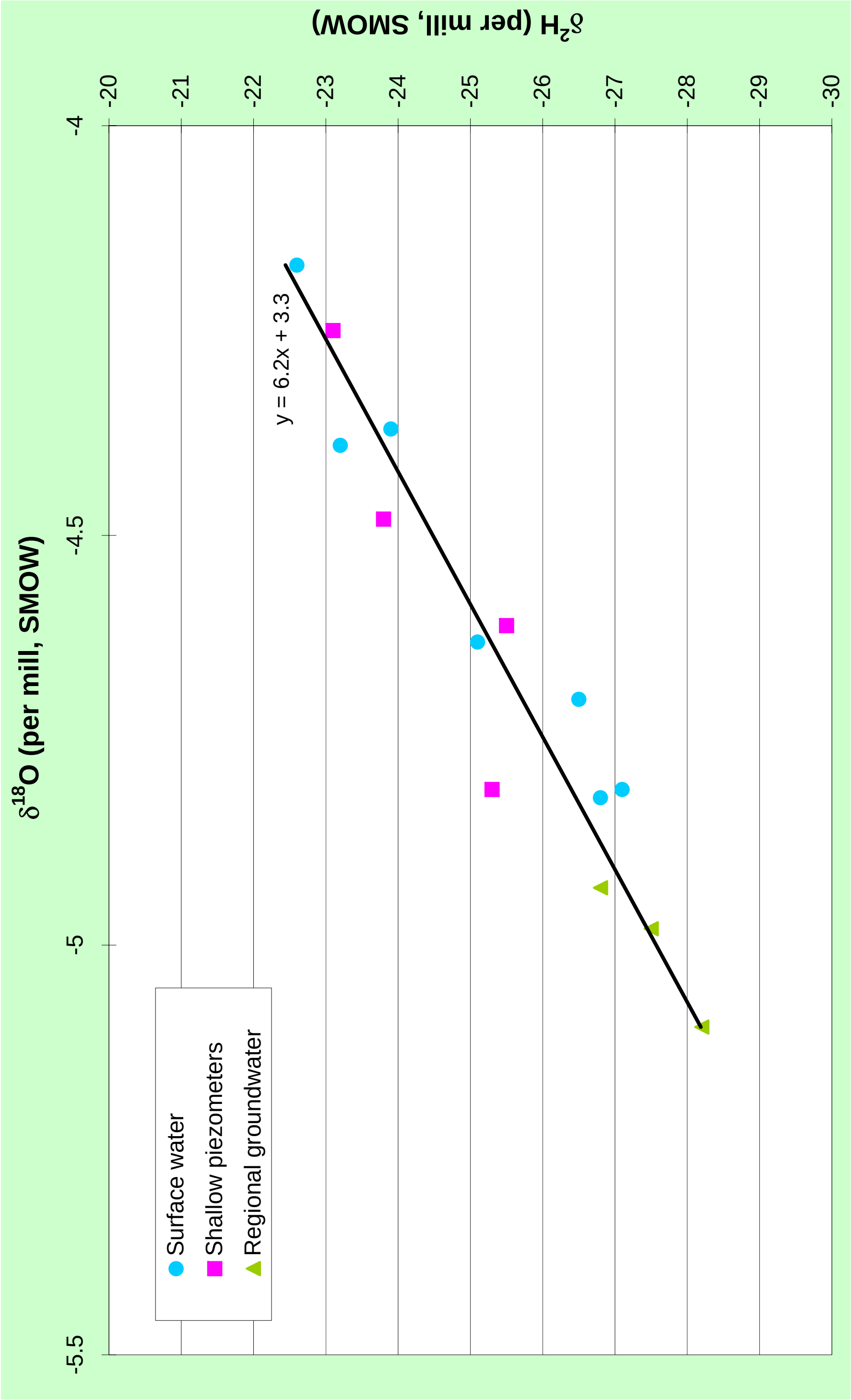

Figure 9. Stable hydrogen and oxygen isotope compositions of surface water and groundwater samples. Surface water (i.e. spring) samples have compositions which generally fall within the range of compositions measured in shallow piezometers and are more enriched in the heavier isotopes (i.e. ^{2}H and ^{18}O) when compared with deeper, regional groundwater samples. This indicates that the shallow, alluvial groundwater and surface water are evaporated versions of the deeper regional groundwater.

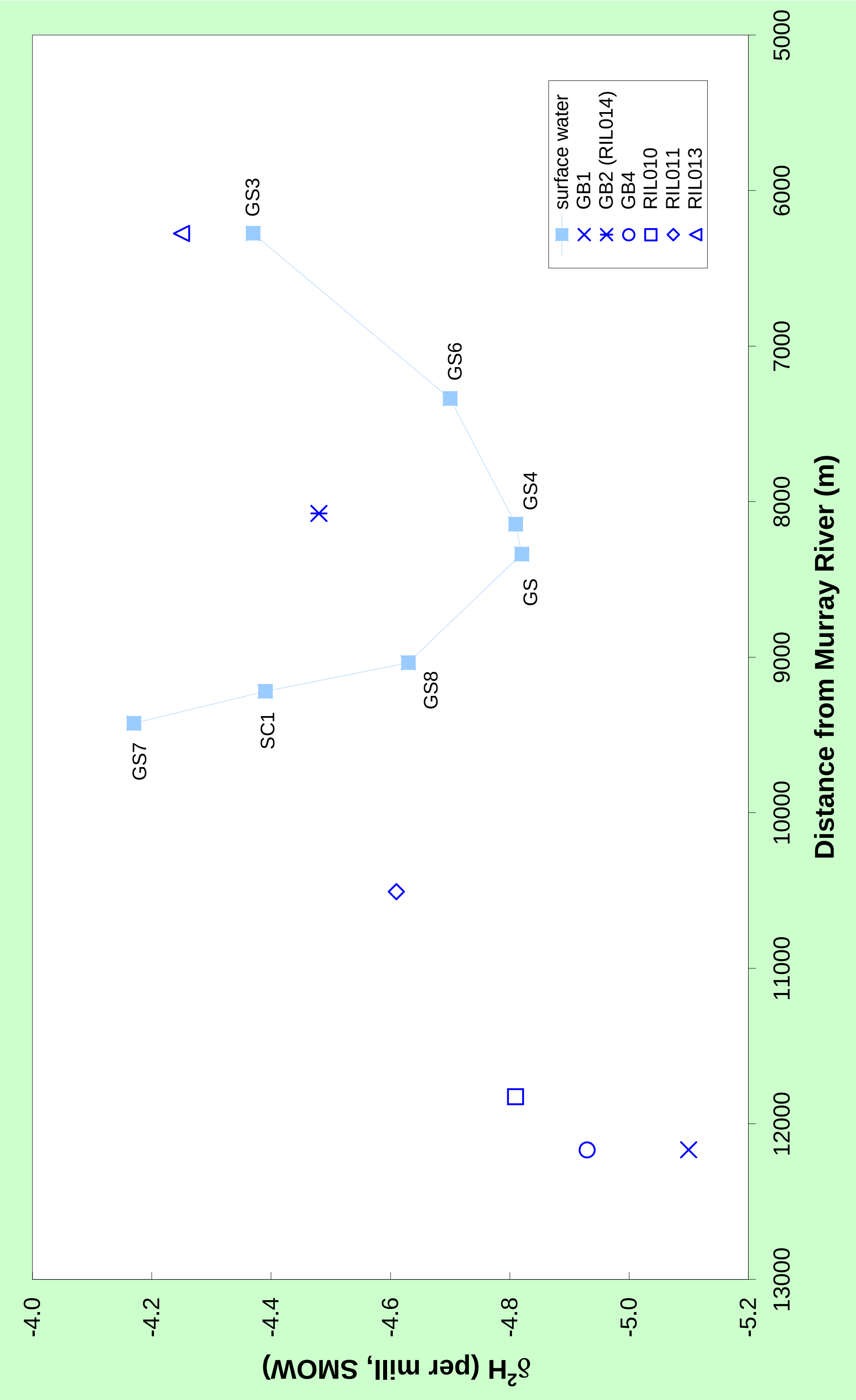

Figure 10. Stable hydrogen isotope composition versus distance from River Murray. Surface waters exhibit a gradual decline in δ^2H between the first emergence of surface water (GS7) and the location of the basement high (GS4) indicating discharge of the relatively ^2H-depleted regional groundwater in this zone.

saline (and ^{18}O enriched) alluvial aquifer near piezometer RIL014. Increases in the surface water $\delta^{18}O$ values from GS4 to GS6 then GS3 are most likely a result of evaporation causing preferential loss of the lighter isotope ^{16}O.

Groundwater chlorofluorocarbon concentrations (CFC-11 and CFC-12) were measured for several piezometers and one of the regional bores to provide estimates of groundwater ages. The date at which groundwater first enters the saturated zone, and is thereby isolated from the atmosphere, is termed the recharge date. Recharge dates have been determined from CFC-12 concentrations (more conservative than CFC-11) for all samples, including one surface water sample that was collected from the bottom of a 1 m deep pool at GS5, where flow appeared to be greater than anywhere else in the catchment (Fig. 11). A recharge date of 1980 was estimated for GS5 however this value should be regarded as an upper limit rather than the actual age because surface water samples are easily contaminated by CFCs in the atmosphere. Nevertheless, the data presented in Figure 11 suggests that the groundwater discharging at GS5 is at least 23 years old, which means that it is most likely sourced from shallow parts of the regional water table aquifer and/or the alluvial aquifer.

Further support for the discharging groundwater being sourced from recently recharged aquifers is provided in the radiocarbon (^{14}C) data. Samples from wells GB1 and GB4 (and GB5 although it is located over 2 km from the River) each returned ^{14}C values in the range 80 – 90 pmC which, in a calcareous aquifer, implies groundwater ages of less than about 200 years.

Major ion compositions of the surface water samples are all quite similar, especially when compared with the range of compositions obtained from shallow and regional groundwater samples (Fig. 12). The only groundwater sample that plots within the cluster of surface water samples on this plot is RIL014 – a shallow piezometer completed in the alluvial gravels towards the end of the zone where groundwater discharge was inferred from EC, radon and stable isotope data. This match in ionic compositions would normally indicate that groundwater of the type sampled from RIL014 is the sole source for discharge into the river. However, inspection of Na:HCO_3 ratios along the transect (Fig. 13) suggests that continual groundwater discharge along the River between GS7 and GS4 is coming from a source with relatively low Na:HCO_3 such as the regional aquifer, rather than RIL014 which has a higher Na:HCO_3 ratio.

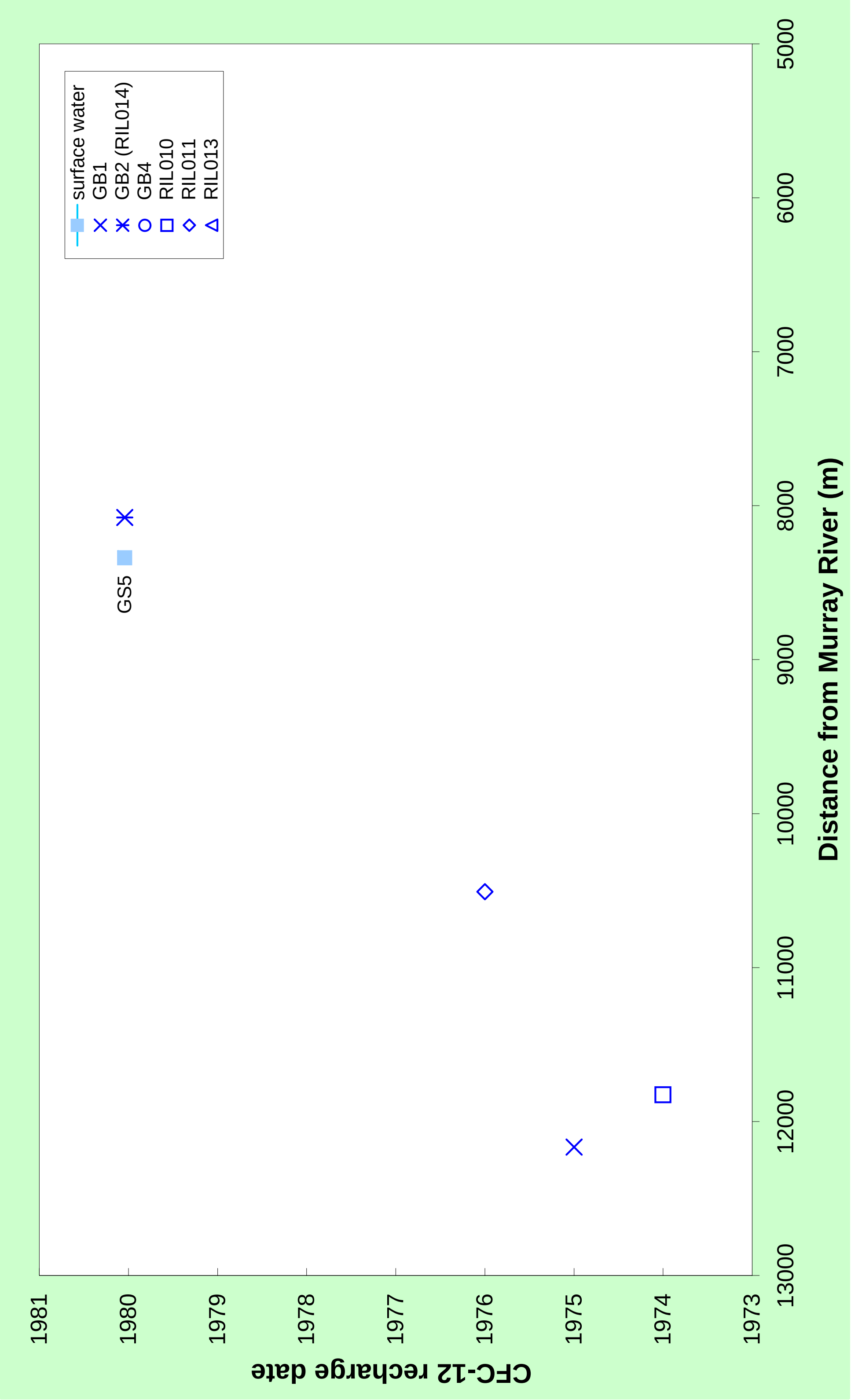

Figure 11. Recharge date for groundwater and surface water samples determined from CFC-12 concentrations. All groundwaters (shallow and regional) are less than 30 years old. Surface water sampled at site GS5 has a similar age to that of shallow groundwater in piezometer RIL014.

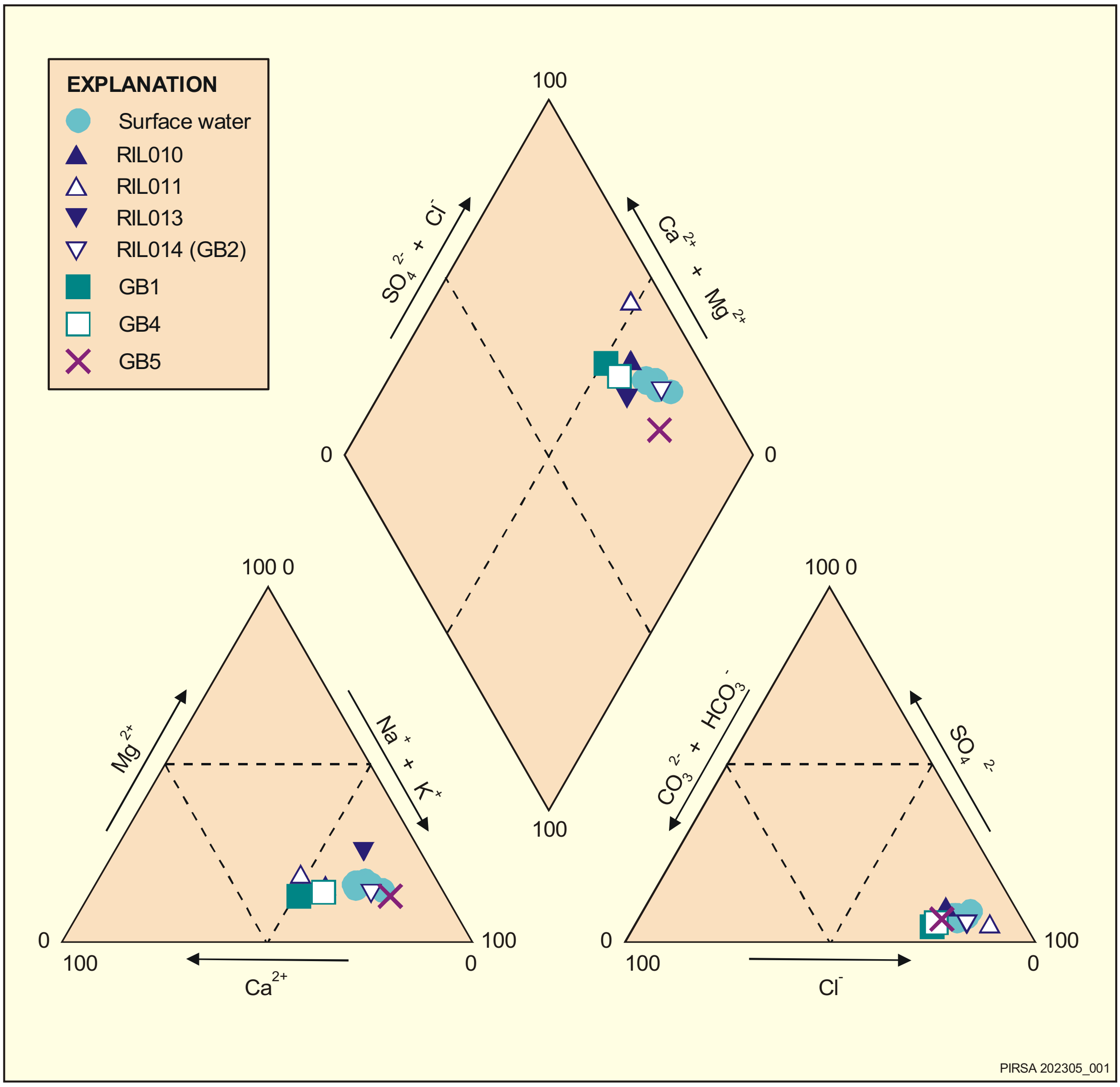

Figure 12. Piper diagram showing major ion compositions of surface water and groundwater samples. All surface water samples have similar compositions to that of shallow groundwater from RIL014.

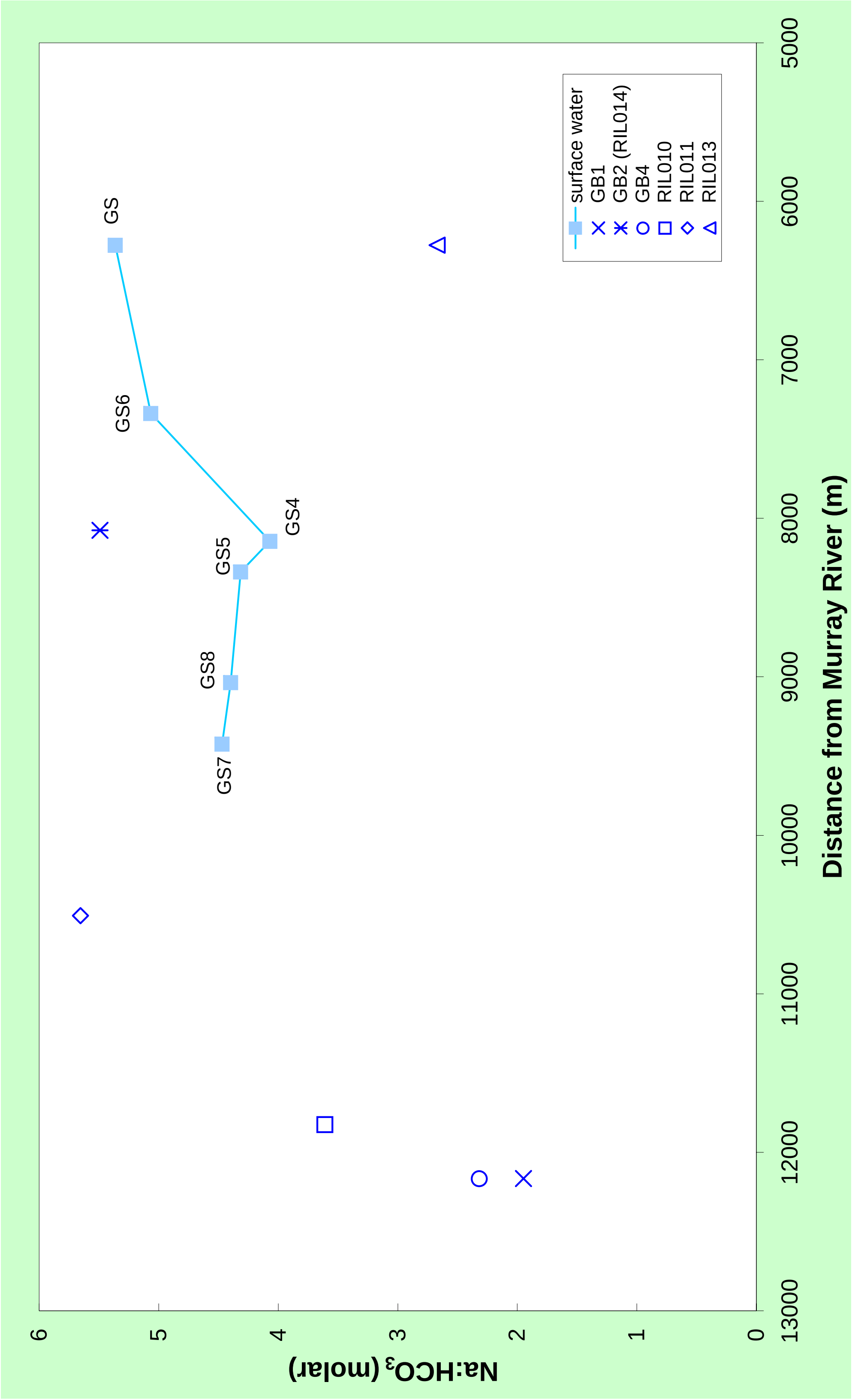

Figure 13. **Na:HCO$_3$ ratio versus distance from River Murray. Groundwater discharge between GS7 and GS4 is from a source with Na:HCO$_3$ less than that of RIL014, probably the regional groundwater (i.e. GB1 and GB4).**

4 DISCHARGE FLUXES

The stream flow rate at sites GS4 and GS5 was estimated to be in range 8 – 10 L/s at the time of sampling (November 2003). Applied over a whole year, these flow rates equate to a groundwater discharge flux of 250 – 315 ML/yr. In reality however, the groundwater discharge flux will vary from these values both on a daily and annual basis depending on the elevation and slope of the regional water table, and the importance of groundwater contributions from the Quaternary alluvial aquifers.

5 PROPOSED CONCEPTUAL MODEL

The above results enable the development of a conceptual model for the various groundwater discharge mechanisms operating in this part of the Marne River. In summary, the chemical and isotopic data revealed the following properties for the main source(s) of groundwater discharge:

- recharge occurred from an open water body more than 23 years ago, but less than 100 – 200 years ago;
- EC is less than values measured in the alluvial aquifer
- (except possibly in the reach between GS7 and SC1);
- chemical composition is similar to that of groundwater in RIL014.

The following processes form the framework to the proposed conceptual model. Groundwater recharge of the regional Tertiary limestone aquifer occurs primarily by infiltration of river water between the Palmer Fault and Blackhill once the relatively impermeable Pooraka Formation becomes absent from the river bed (Fig. 6). The Quaternary and uppermost Tertiary aquifers are most likely recharged by the same process, but may also receive recharge from very intense rainfall events in the bordering sand dunes. Within several months to a year after the recharge events, most of the groundwater in these shallow aquifers will discharge into the River. For this reason, the shallow alluvial aquifers cannot be responsible for maintaining pool levels and flows throughout extended dry periods.

The regional aquifer discharges into the Marne River upstream of site GS4 when the water table is forced to flow over the impermeable geologic basement high (Fig. 14). The distance that this process extends upstream of GS4 is controlled by (a) the elevation of the basement high compared with that of the river channel (fixed), and (b) the slope of the regional water table (variable depending on recharge and pumping). The hydraulics of this groundwater discharge mechanism can be considered analogous to a swinging arm or door (the water table) pivoting on a hinge (the outcropping basement). Thus large fluctuations in the water table several kilometres upstream of the permanent pools will not be matched by large fluctuations in the water table near the pools, nor flow rates over the basement high. However, whilst lowering the regional water table around Blackhill will cause the most rapid decline in the length and flow of the pools, the long-term effects of groundwater over-exploitation further upstream are likely to be important and will depend on the location and magnitude of the irrigation development.

The chemical and stable isotopic compositions of the discharging groundwater evolve from those of the regional groundwater to something similar to that of RIL014 as a result of evaporative concentration (salts) and enrichment (stable isotopes) through the Quaternary sediments.

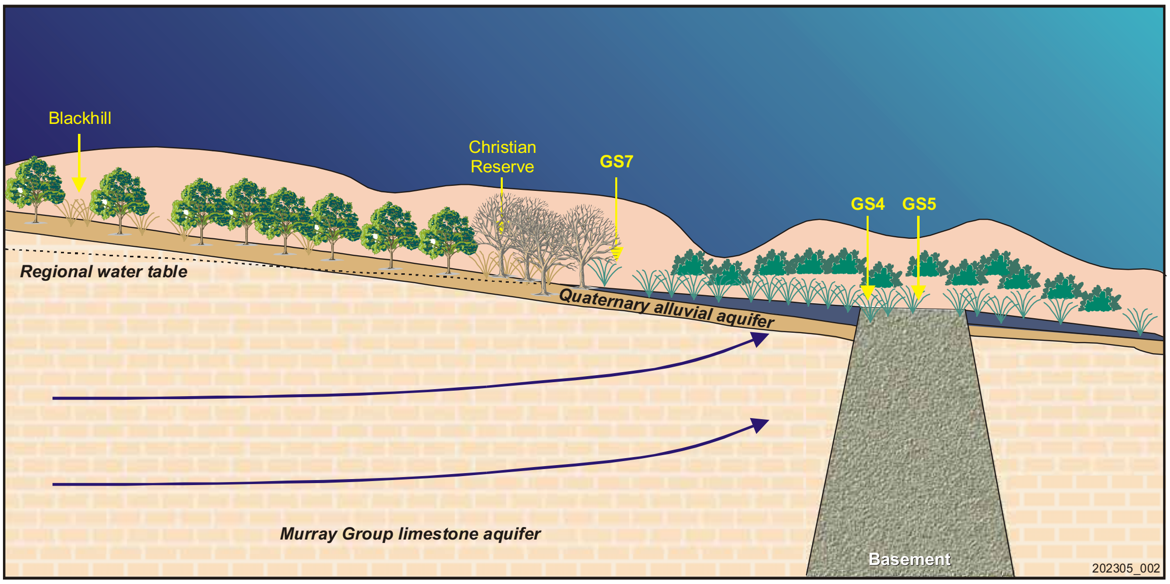

Figure 14. Schematic diagram of the proposed conceptual model for groundwater discharge into Blackhill Springs. Groundwater in both the shallow Quaternary and deeper Tertiary aquifers is recharged primarily by infiltration of floodwaters when flow in the Marne River is sufficient to cross the plains of the Murray Basin. The Quaternary aquifers may also be recharged through the adjoining sand dunes after intense rainfall events. Discharge from these shallow, local aquifers is likely to only be important for several months to possibly years after the recharge events. The most important process for maintaining spring water levels and flows is discharge from the regional limestone aquifer as it laps onto the impermeable basement high. Future exploitation of this groundwater resource, combined with reduced recharge rates due to upstream damming and climatic variability, will have detrimental impacts on the slope of the water table near Blackhill, and thus flows to the Springs.

6 CURRENT STATE OF THE SPRINGS AND IDENTIFICATION OF LONG TERM RISKS

Numerous sources of anecdotal evidence suggest that the location where the first permanent pool appears below Blackhill has moved downstream over the last decade (e.g., Elfriede Gitton, local resident, pers. comm. 2000). Visual support for this movement is provided by large stands of dead reeds (*Phragmites sp.*) between Blackhill and Christian Reserve (location of RIL011), and dead River Red Gums in Christian Reserve. We ascribe these observations to a significant reduction in annual recharge to the Quaternary and (to a lesser degree) Tertiary aquifers in this zone. The reasons for the reduction in recharge rate are likely to be numerous, but primarily they are (i) below average rainfall for the majority of the last 10 years (Fig. 1), and (ii) a reduction in the frequency and volume of surface flows possibly caused by uncontrolled damming in the headwaters of the catchment (Savadamuthu, 2002).

Barnett et al. (2001) reported that a permanent spring on Section 324, Hundred of Ridley (Parcel D25716 A16) had recently dried up. Inspection of this spring at the time of sampling (November 2003) revealed that it is sourced from the regional limestone aquifer and was still dry. The owners claim that it used to flow year-round until several years ago (pers. comm. Garner, November 2003). This cessation of spring flow has not occurred as a result of reduced recharge to the Quaternary aquifers, but instead reflects reduced recharge to the regional aquifer both within the surface water catchment to the north of the spring (shown in Barnett et al., 2001) and further up-gradient (i.e. west) of the spring. Increasing development of groundwater resources upstream may also be lowering the regional water table and thus reducing groundwater flow rates down-gradient.

The greatest risks to Blackhill Springs (i.e. the permanent pools) in their current form are natural processes and anthropogenic activities that will lower the regional water table. The most important of these are likely to be:

- further exploitation of the regional limestone aquifer upstream;
- extended periods of low rainfall throughout the catchment;
- further damming of surface water in the headwaters of the catchment.

7 CONCLUSIONS AND RECOMMENDATIONS

Conceptual Model

Chemical and isotopic data from surface water and groundwater samples collected around Blackhill Springs in November 2003 indicate that the source water for the permanent pools in this area is primarily the regional Murray Group limestone aquifer. This aquifer is recharged further upstream by infiltration of surface flows out of the Mount Lofty Ranges, and then discharges near Blackhill due to an impermeable basement high. Groundwater contributions from the Quaternary alluvial aquifers to the Marne River may be locally important for several months to a year after significant recharge events. Recent years of below average annual rainfall, combined with reduced frequency of low to median flows out of the Mount Lofty Ranges caused by unregulated damming, has meant that both the regional and alluvial aquifers have not been recharged and are declining.

Management

Current and future groundwater extractions from the regional limestone aquifer should be regulated and closely monitored to ensure that there is no long-term decline in the elevation and slope of the water table up-gradient of Blackhill. Given the impact that extensive damming in the headwaters of the catchment has had on reducing flows into the Lower Marne, any future applications to construct dams should be assessed very thoroughly.

Future Work

This investigation as well as earlier studies have revealed the complex and dynamic relationships between the surface water and groundwater resources of the Lower Marne River Catchment. However, each of these studies have only begun to unravel some of the processes occurring in the catchment. Suggested avenues for future work here should include:

- Rehabilitation and expansion of the existing groundwater monitoring network for water levels and salinity, particularly in the Blackhill area; continued monitoring of flows in the river above Blackhill with the existing gauges; possibly install a new stream flow gauge at the geologic basement high so that in future, flows rates there can be compared with water table elevations/slopes upstream.
- After several years of monitoring, developing a semi-quantitative (possibly numerical) model to determine, for example:
  - how much further reduction in stream pool lengths and levels could occur as a result of **current** groundwater development, and the associated timescales;
  - the likely impacts of **increased** groundwater development upstream, i.e. estimates of stream pool lengths/levels if water tables were to be lowered further than the current levels;
  - possible “trigger points” to avoid complete drying-up of the springs as a result of reducing water levels.

- Determining the mean annual recharge rate for the unconfined aquifer from infiltration of surface flows; this would provide a sustainable yield for the groundwater resource which could then be apportioned to (i) environmental water requirements (i.e. the springs), (ii) existing groundwater users, and (iii) possible future development. Such an investigation would most likely require estimation of the mean long-term recharge rate and then establishing how the surface flow regime has been changed as a result of damming in the past 10 – 20 years. This would enable the future frequency and magnitude of recharge events to be estimated.
- Investigation into the importance of recharge to the regional unconfined aquifer by lateral flow from the fractured-rock aquifers of the MLR, as proposed in earlier studies.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

Allison, G.B., 1982. The relationship between ^{18}O and Deuterium in water in sand columns undergoing evaporation. *J. Hydrol*. 55: 163-169.

Barnett, S.R., 1989. The hydrogeology of the Murray Basin in South Australia, with special reference to the alluvium of the River Murray floodplain. Flinders University (South Australia). M.Sc. thesis (unpublished).

Barnett, S.R., Zulfic, D. and Yan, W., 2001. Marne River Catchment Groundwater Assessment. SA Dept. for Water Resources, *Report DWR 2001/009*.

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

Tucker, A., 2001. Water use of *Eucalyptus camaldulensis* (River Red Gums) along the Marne River, Eastern Mt Lofty Ranges. Honours Thesis, School of Biological Sciences, Flinders University of South Australia.