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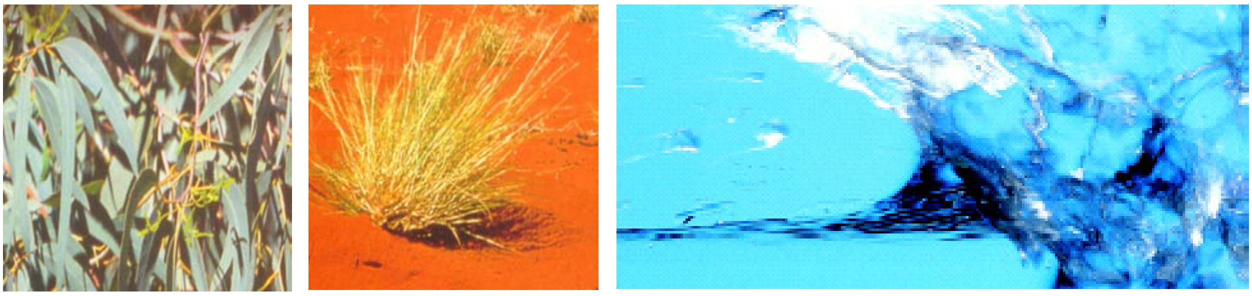

Groundwater contributions to stream flow along the Willunga Fault, McLaren Vale, South Australia

Keith G Brown

Report DWLBC 2004/21

Government
of South Australia

Groundwater Assessment 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

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

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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

In September 2003 a field survey showed that there were 22 streams flowing from valleys located in the western Mount Lofty Ranges onto the coastal plain of the Willunga Basin. The total outflow from the streams was estimated to be close to 250 L/s (21.6 ML/d) with approximately 40% of the flow coming from one stream, Kangarilla Creek. A second survey undertaken in March 2004 determined that only five of the original 22 streams were still flowing. Total flow was estimated to be less than 18 L/s (1.55 ML/d), with no flow occurring in Kangarilla Creek.

Analyses of salinity and isotope samples taken from streamflows and groundwater wells during the September and March surveys were used in conjunction with hydraulic information to develop conceptual models to better understand the processes that control spring flow to the streams, and to determine the relative contributions of groundwater and run-off from rainfall to stream flow.

Mechanisms for groundwater discharge to a stream

Groundwater discharges to the streams in two ways. The first is via a point source where groundwater enters a stream from a readily identifiable source such as a spring. The second is non-point source (diffuse) groundwater discharge whereby there is a noticeable increase in flow over a section of stream that was not associated with an observable point source.

Two conceptual models were developed to explain point source discharge from a spring in the McLaren Vale PWA:

- The first model describes spring flow that was observed on the hill slopes and banks that border a number of the streams. They are generally seasonally active with the flow controlled primarily by the annual rise and fall of the groundwater table.
- The second model describes those springs located in the stream channels where a vertical displacement in the stream bed, possibly a physiographic expression of the Willunga Fault coincides with an observed increase in stream flow.

From this study, non-point source discharge is considered to contribute significantly to overall stream flow.

Quantification of groundwater contributions to streamflow

A conceptual model was also developed to firstly describe the observed isotopic and hydrochemical composition of the stream samples and to thereby estimate the relative proportions of groundwater and non-groundwater (dam water derived from precipitation) to stream flow.

At the headwaters of most streams are large in-stream dams (usually they are the largest of a number of dams located along its length). For example both the two main tributaries of Kangarilla Creek have very large dams at their respective headwaters. Significant rainfall had occurred three days prior to the September sampling, subsequently most of

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the dams were full and overflowing when the streams were sampled. Evaporation of the dam water changes the stable isotope composition such that it is isotopically different from that of groundwater. As water flows out of each dam and along each stream it mixes with groundwater entering the stream as base flow. The relative proportions of each can be estimated by applying a mass balance calculation to the relative stable isotope concentrations of the water molecule from each water sample.

In September 2003 the groundwater contribution at the outflow to the plain from Kangarilla Creek was estimated to be 55 to 65% (Deuterium and Oxygen-18 mass balance) of the total stream flow. The remaining 35 to 45% of the total flow is inferred to have originated from dams recharged by the recent precipitation. In Willunga Creek about 90% of the stream flow was originally groundwater.

The difference in the relative contributions of surface water and groundwater between Willunga and Kangarilla creeks is attributed to the large dams situated at the head of the tributaries and the significantly higher number of dams located along Kangarilla Creek compared to Willunga Creek. Ratios of groundwater to non-groundwater in the other flowing streams ranged from approximately 50:50 to 90:10.

Climate, land use change and irrigation activity

Climate, land use change, and groundwater extraction can all impact on spring flow and therefore stream flow. To some degree all of these processes are occurring in the McLaren Vale PWA. However, it could not be established from this study whether the reduction in the number of flowing streams between September 2003 and March 2004 surveys is a regular occurrence or a modern phenomenon related to one or more of these processes.

There is an urgent need to investigate and quantify the relative affect these three processes are having on stream flows to the Plain. An investigation that quantifies the behaviour of the Willunga Fault in relation to the movement of groundwater from the Fractured Rock Aquifer to the deeper aquifers that lie beneath the sedimentary plain is also recommended.

1 INTRODUCTION

Background

Surface water in the form of streams outflows from steep narrow valleys cut into the uplifted Mount Lofty Ranges onto the low lying coastal plain of the Willunga Basin. Riparian zones that surround the streams are well established and provide an ecological habitat supporting a diversity of plant and animal life. Flows from the streams are also a source of recharge to the sedimentary aquifers that underlie the plain.

The origin of the water in the streams are considered to be predominantly groundwater sourced from springs or seeps located in the valleys and surface run-off derived from rainfall. The Department of Water, Land and Biodiversity Conservation (DWLBC), funded by the Onkaparinga Catchment Water Management Board (OCWMB), undertook an investigation to assess the relative contributions of groundwater and surface run-off to stream flows along the margin of the Willunga Basin and the Mount Lofty Ranges, as generally delineated by the Willunga Fault.

Approach

Field surveys were undertaken in September 2003 and March 2004 by staff from DWLBC; streams were inspected, and sampled for salinity, pH, temperature, stable isotopes and radon. Two streams, Kangarilla and Willunga creeks, were examined in closer detail because they are by far the largest contributors of flow to the plain.

Objectives

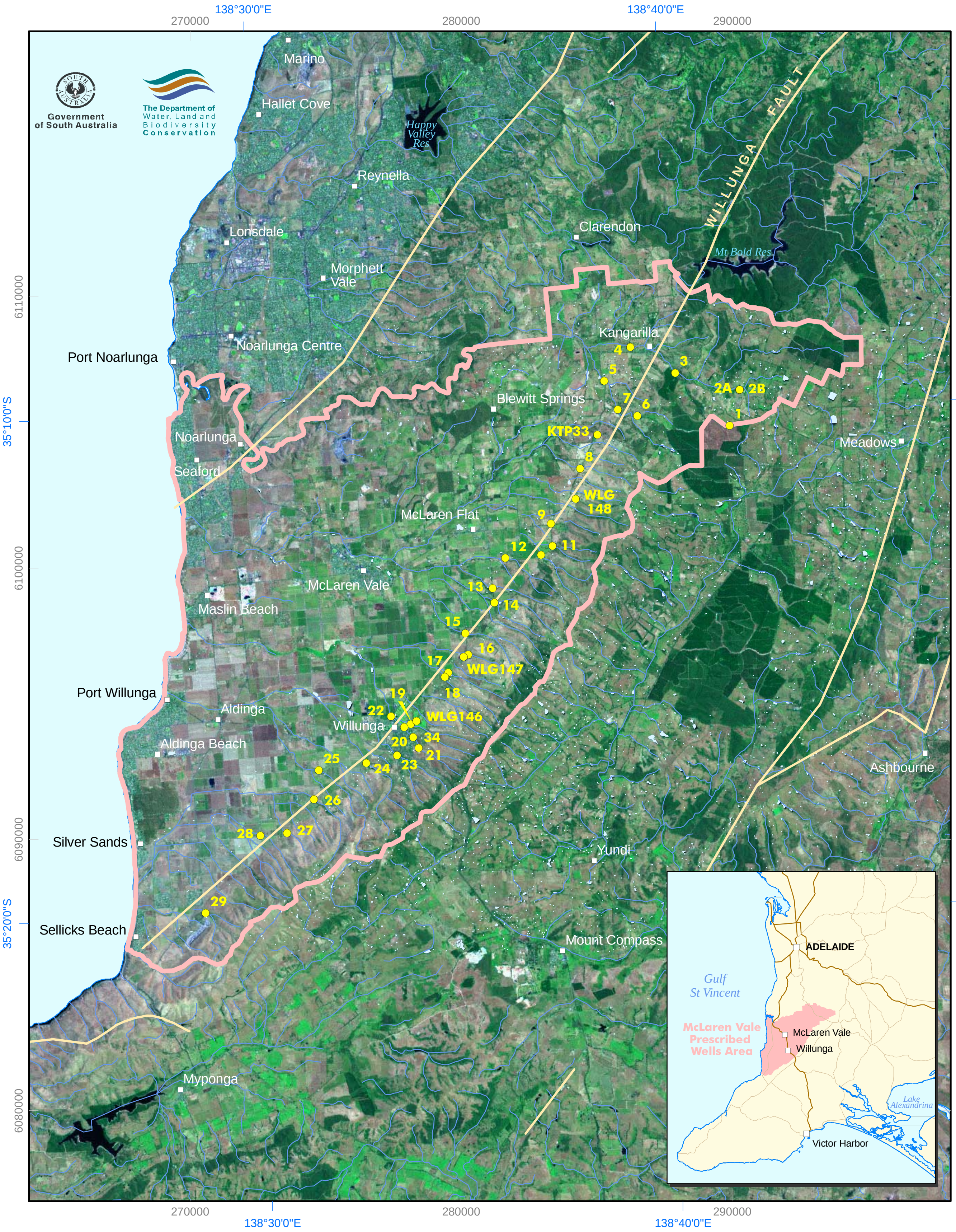
The main objectives of the project were to:

- Increase the understanding of surface water-groundwater interaction in the area.
- Quantify the contribution of groundwater to stream flow.
- Locate the source of stream flow in the form of springs and or seeps.
- Determine the number of streams that flow onto the coastal plain and estimate flow.

Study Area

LANDFORM, GEOLOGY, RAINFALL

The McLaren Vale Prescribed Wells Area (PWA) can be divided into two distinct landforms; a relatively flat low lying coastal plain juxtaposed against a steep mountain range which forms part of the Mount Lofty Ranges. Separating these two landforms is the predominantly northeast-southwest trending Willunga Fault (Fig. 1).



0 5 10 Kilometres

Datum GDA 94 – Projection MGA Zone 54

▭ McLaren Vale Prescribed Wells Area

● 11 Sample sites and number

— Fault

GROUNDWATER CONTRIBUTIONS TO STREAM FLOW ALONG THE WILLUNG FAULT – McLAREN VALE, SOUTH AUSTRALIA

LOCATION PLAN

Figure 1

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The sediments that underlie the plain are approximately (~)250 metres thick and were deposited into a small to medium-sized basin that formed from about 50 million years ago. The Ranges consist of uplifted metamorphosed sediments that vary in age from ~500–1000 million years.

Average annual rainfall at Willunga township is ~650 mm. Rainfall generally increases from west to east on this part of the Peninsula, and highlights the close relationship between rainfall intensity and topography (Fig. 2, source Bureau of Meteorology website, 2004).

Monthly rainfall, plotted as cumulative deviation from the mean for the Willunga, McLaren Vale, and Mount Bold gauging stations, are shown on Figure 3 and are located on Figure 4. The three gauging stations with the longest records, Willunga, McLaren Vale and Mount Bold, show a similar trend until the end of 1974 (a positive slope on the graph indicates above average rainfall, a negative slope means below average rainfall). Post 1974, both Willunga and McLaren Vale show below average rainfall while Mount Bold has above average rainfall.

HYDROLOGY AND HYDROGEOLOGY

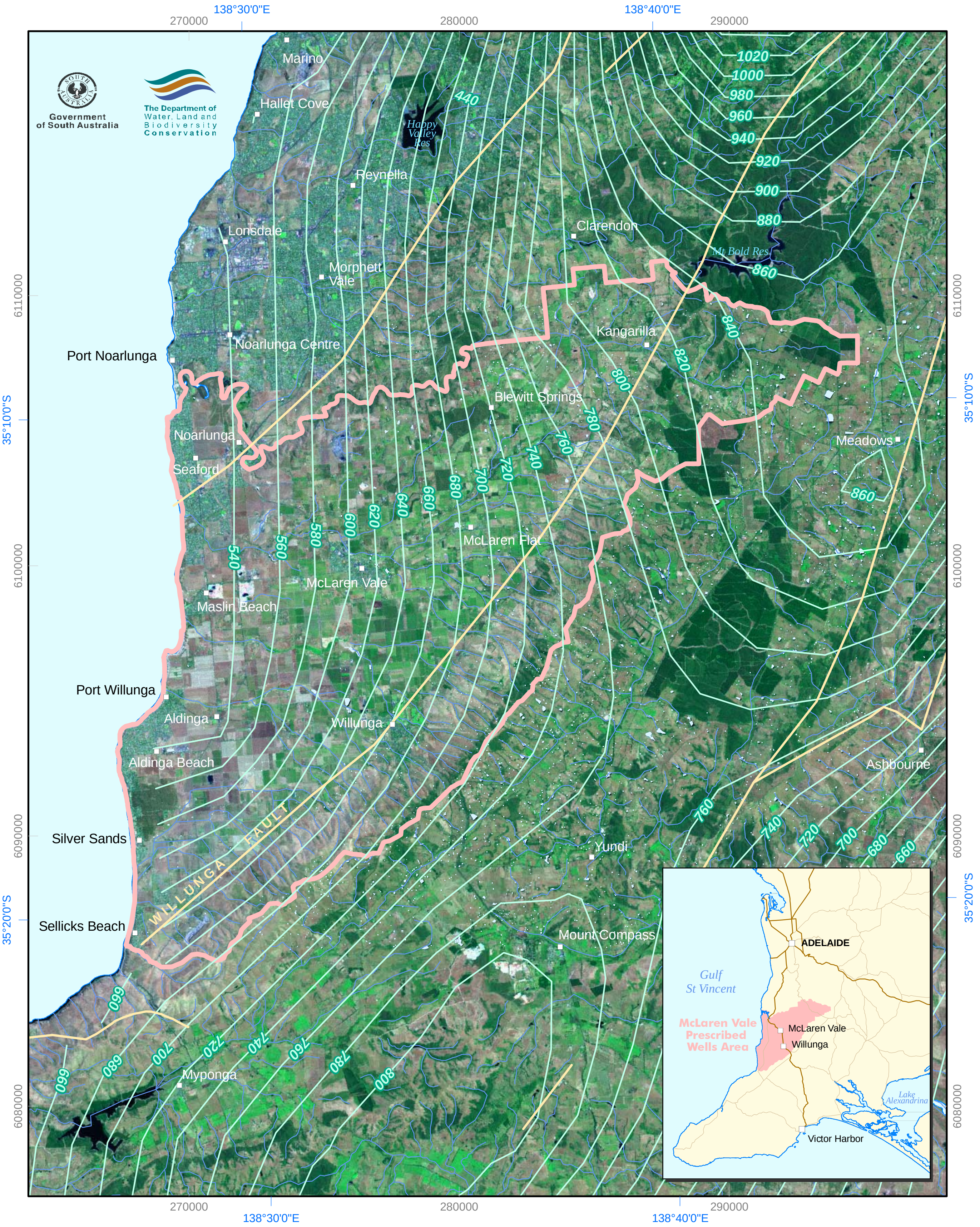
The natural movement of both surface and groundwater is generally westward from the elevated range, across the sedimentary plain to the sea. The old metasediments of the Mount Lofty Ranges are considered to be the main recharge source for the deeper sedimentary aquifers located beneath the plain and is collectively referred to as the Fractured Rock Aquifer. Groundwater flow in this type of aquifer is primarily through faults or fractures in the rock that do not necessarily follow the regional hydraulic flow direction.

The sediments beneath the plain have been sub-divided into a number of aquifers and aquitards and form a complex interconnected porous media flow system (Sereda and Martin, 2001).

The Willunga Fault represents the boundary between the Fractured Rock Aquifer and the sedimentary aquifers of the basin. This fault is commonly drawn as a single line on geological maps but it is more likely that it is a series of slumped faulted blocks that run sub-parallel to the basin axis. The movement of groundwater over the fault(s) and therefore the degree of interconnectivity between the fractured rock and the younger sedimentary aquifers is poorly understood.

Groundwater, springs and stream flow

The small narrow valleys are part of the Mount Lofty Ranges and were probably formed through natural erosion processes contemporaneously with the uplift of the Ranges. Each valley forms a small surface water catchment that receives local rainfall, that then enters the groundwater system as direct recharge or flows over the ground surface (as run-off) to be collected in streams (and dams) that have formed at the floor of each catchment.



0 5 10 Kilometres

Datum GDA 94 – Projection MGA Zone 54

▭ McLaren Vale Prescribed Wells Area

— Fault

— Rainfall isohyte (mm/yr)

GROUNDWATER CONTRIBUTIONS TO STREAM FLOW ALONG THE WILLUNG FAULT – McLAREN VALE, SOUTH AUSTRALIA

RAINFALL

Figure 2

PIRSA Publications 202420_004

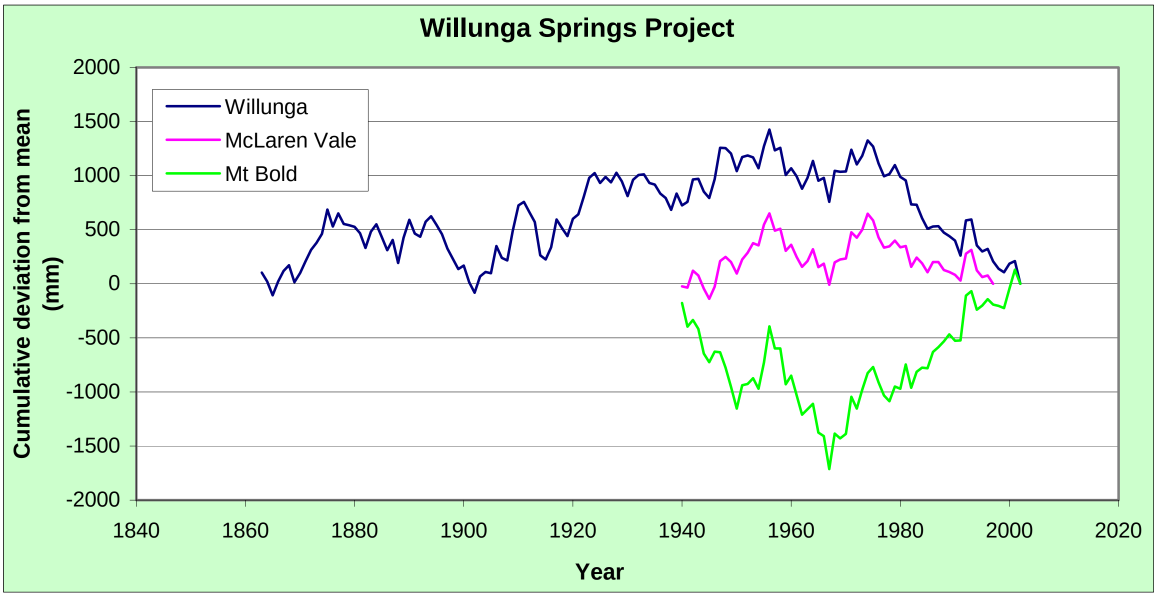


Figure 3. **Plot of cumulative deviation of mean rainfall for Willunga, McLaren Vale, and Mount Bold rainfall gauging stations**

▭ McLaren Vale Prescribed Wells Area

— Fault

☆ Rain gauge site

● Stream flow station

Figure 4

GROUNDWATER CONTRIBUTIONS TO STREAM FLOW ALONG THE WILLUNG FAULT – McLAREN VALE, SOUTH AUSTRALIA

RAINFALL GAUGING AND STREAM FLOW STATIONS

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Each valley has a dominant stream or channel, however significant inflows from smaller tributary valleys located along the reaches of the main channel can also contribute significantly to stream flow. In recent times dams have been constructed on most of the streams.

Stream flow is a mixture of water from two main sources; surface water run-off from rainfall, and groundwater base flow. Groundwater enters into stream flow via two mechanisms; at a discrete location (point source) or over a larger area (non-point source or diffuse recharge). Point source locations are generally springs that are situated above the level of the streams and are readily observed. Non-point source recharge occurs when there is an increase in stream flow without an observable point source. This occurs for example where the stream channel intercepts the groundwater table at or below the level of the top of the stream. Figure 5 schematically represents the surface water run-off and groundwater flow contributions to stream flow.

The only previously available stream flow data relevant to this study was taken from a gauging station located on one of the tributaries to Kangarilla Creek. Measurements were taken from the end of 1972 to the beginning of 1983. Figure 6 shows the daily maximum and minimum flow rates over the recorded period from this site. The data shows that the stream flowed almost entirely during the months May to November with negligible flows recorded between December and April.

Groundwater use in 2003 for the McLaren Vale area is plotted on Figure 7. Most of the irrigation activity is located on the plain with only a few irrigation wells located east of the Willunga Fault in the Fractured Rock Aquifer. However, while extraction from the fractured rock aquifer wells may be small relative to overall extraction, the hydraulic properties of this aquifer type make it sensitive to groundwater extraction.

Salinity, pH and temperature

The specific electrical conductivity measured in μS/cm and corrected to 25°C was used to show the bulk salinity content of each water sample. Acidity (as pH) and the temperature of the water were also recorded at the time of sampling and used in collaboration with the other measured parameters to delineate groundwater contributions to stream flow.

Stable isotopes

The two elements that make up the water molecule, hydrogen and oxygen each have more than one isotopic state. They are generally used in hydrological studies in one of two ways, (1) to infer the climatic environment at the time when the water was deposited as rainfall, or (2) to determine the origin of water bodies such as the proportions of rainfall run-off and groundwater that make up flow in a stream (Coplen et al., 2000).

The latter method of using stable isotopes generally relies on a difference in isotopic signature between two end members (usually groundwater and rainfall). In this study however, rainfall and groundwater have a similar isotopic signature.

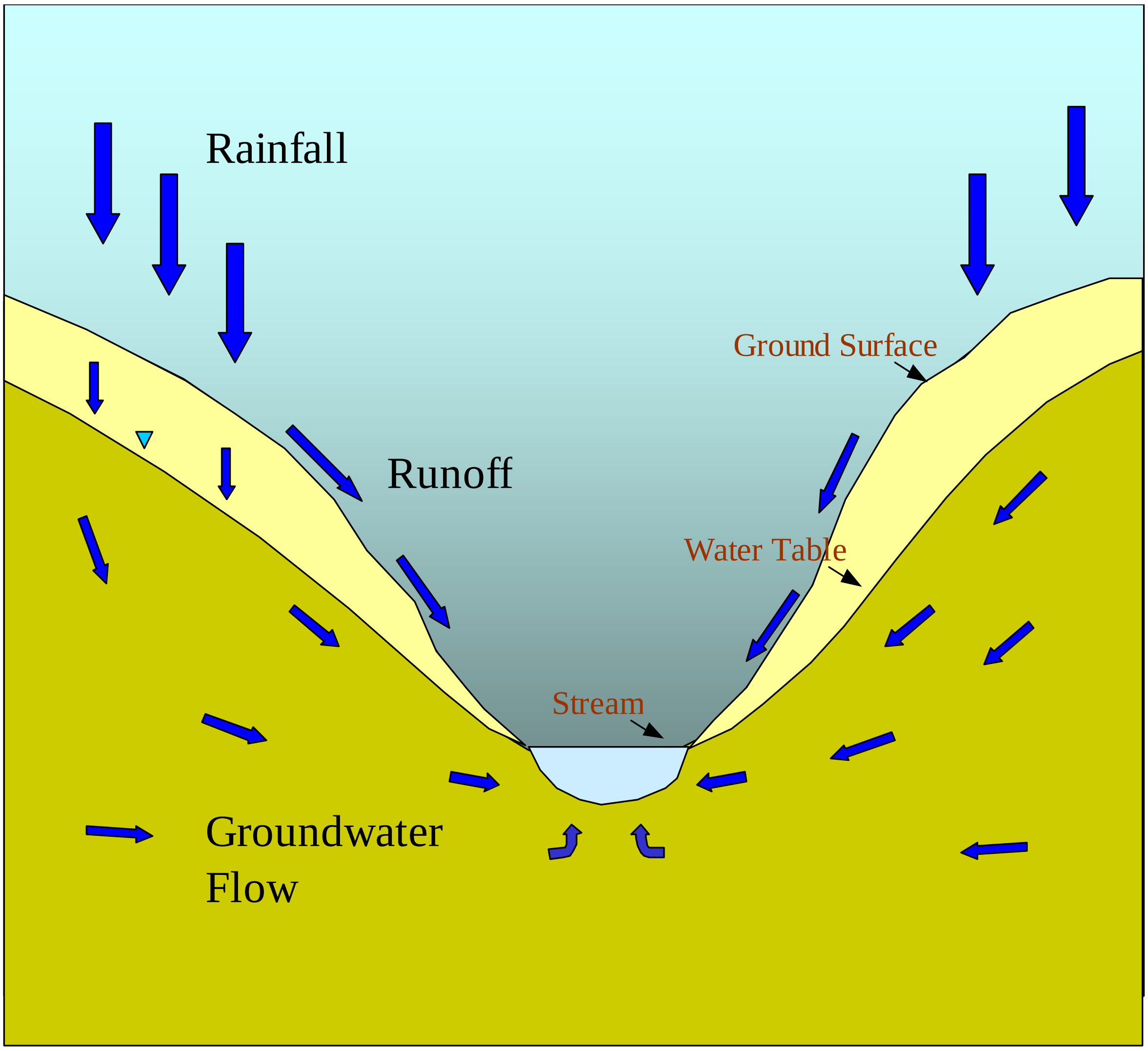


Figure 5. Schematic cross section of rainfall run-off and groundwater contributions to recharge

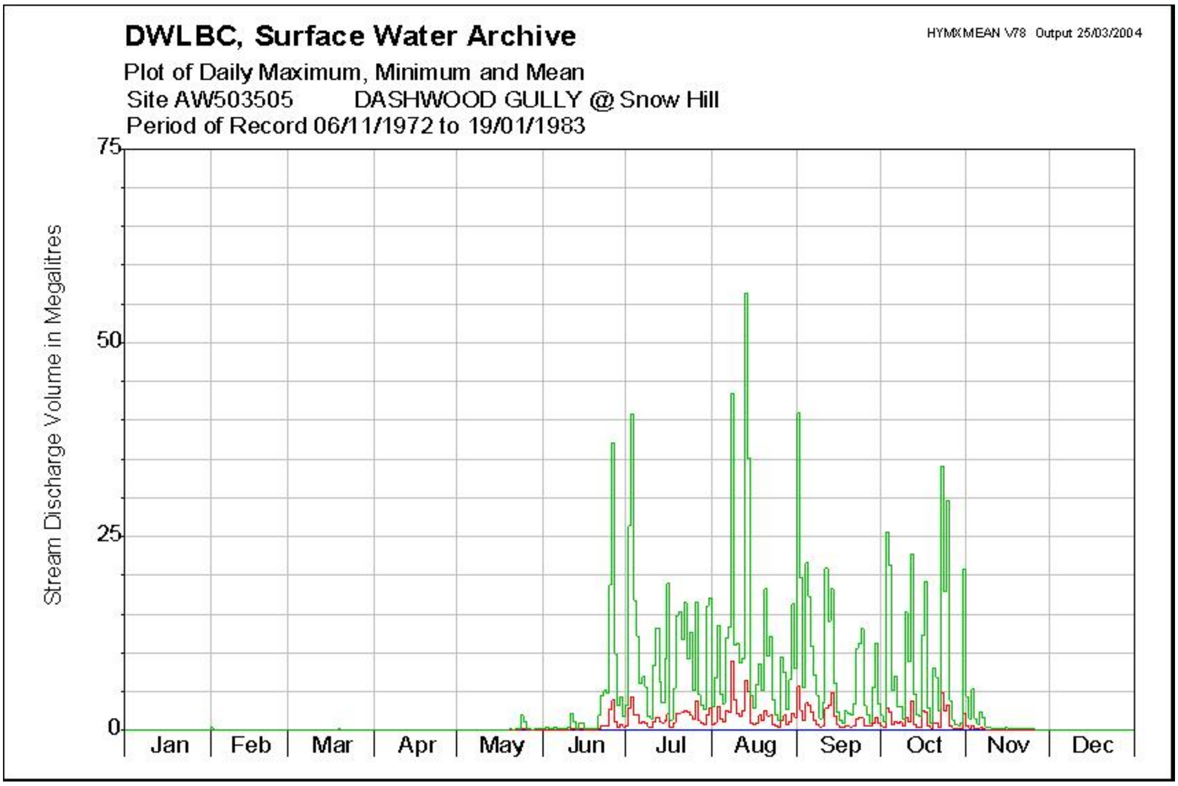
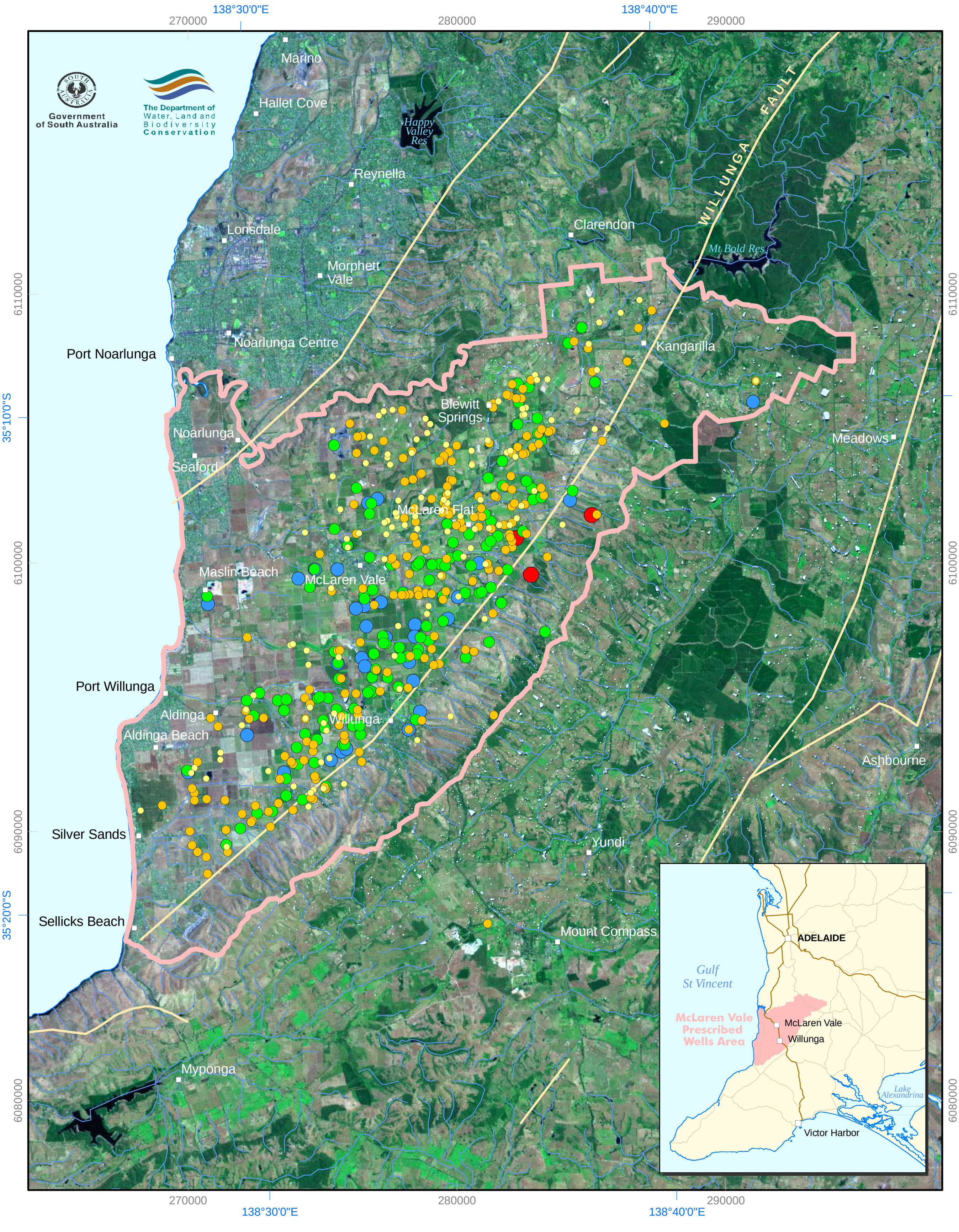


Figure 6. Daily maximum and minmum flow rates for stream gauging station



▭ McLaren Vale Prescribed Wells Area

— Fault

2003 Usage (ML)

●	0.0 to 2.5	●	25.1 to 50.0
●	2.6 to 10.0	●	50.1 to 80.0
●	10.1 to 25.0		

GROUNDWATER CONTRIBUTIONS TO
STREAM FLOW ALONG THE WILLUNG FAULT
– McLAREN VALE, SOUTH AUSTRALIA

2003 GROUNDWATER USAGE

Figure 7

PIRSA Publications 202420_006

Direct measurement of hydrogen and oxygen isotopes is difficult. Therefore, it is common to measure the ratio of the isotopes ($^{2}H/^{1}H$ for hydrogen and $^{18}O/^{16}O$ for oxygen). These are then compared to a standard with an exact known ratio of each isotope, the VSMOW standard (Vienna Standard Mean Ocean Water). This ratio is small and is therefore multiplied by 1000, and is signified by delta (δ) notation (i.e. $\delta^{18}O$ and $\delta^{2}H$) see below.

$$\sigma = \frac{R_{sample} - R_{s\tan dard}}{R_{s\tan dard}} \times 1000$$

R equals the isotope ratio, eg. $\frac{^{18}O}{^{16}O}$ or $\frac{^{2}H}{^{1}H}$

Radon-222

The radioactive isotope radon-222 (^{222}Rn) is a gas by-product from the natural decay of uranium-238 (^{238}U) that to some degree occurs in all rock types. Radon-222 has a short half-life (3.82 days) decaying to negligible concentrations within 30 days. When groundwater comes into contact with a uranium source, ^{222}Rn is dissolved into it. Assuming only a natural rock source, the presence of radon-222 in a water sample, taken from a stream, can therefore be used to infer the contribution of groundwater to surface water discharge. Samples with low or negligible radon concentrations could be considered to have come from a non-groundwater source i.e. run-off from rainfall.

There are a number of caveats that need to be discussed before radon-222 results from stream samples can be interpreted with confidence:

- Some rocks have high proportions of ^{238}U, for example igneous rocks such as granites, while others have much lower concentrations. Therefore it is necessary to sample groundwater directly to determine a representative radon-222 signature.
- Radon-222 decays naturally and relatively quickly (half-life, 3.82 days) as it flows down stream. It became evident during the sampling program that there were a significant number of dams located along the reaches of most streams, particularly in the upper catchment areas. Dams inhibit the natural flow of water and consequently affect the ^{222}Rn concentrations.
- Radon-222 gas dissolved in stream water is lost to the atmosphere through an equilibration process. The rate at which this process takes place depends primarily on stream turbulence, volume of discharge and stream gradient (Ellins et al., 1990).

2 SAMPLE SITES, METHODS AND ANALYSIS

Sampling occurred in two stages to coincide with winter high and summer low rainfall. The first sampling was undertaken on 9-10 September 2003. In total 34 sites were selected, and included 29 stream points (plus 1 repeat) and four Fractured Rock Aquifer wells. Table 1 lists the site numbers, site locations, and parameters measured. Photographs of each site are attached in Appendix A. Sample sites are located on Figure 1.

The second part of the program took place in the first week of March 2004 using the same sites sampled during the first stage of the investigation. However, on the second visit only five streams were observed to be flowing, and resulted in a total of only seven samples being taken. Three of the sites were located on the same stream, Willunga Creek, (see Table 1, in red).

At each site the salinity as electrical conductivity (in μS/cm @ 25^{o}C), pH and temperature (^{o}C) were recorded using a WTW® field chemistry meter (Plate 1). Stream samples for stable isotopes were collected directly or from a bucket and transferred into 25 mL glass McCartney bottles. The method for estimating flow rates varied from timing the filling of a bucket in low flow conditions to measurement of the cross-sectional of high flowing streams and the length of time for an object to move one metre downstream.

Plate 1. Stream sampling

Oxygen isotope compositions were analysed after equilibrating 1 mL of water with carbon dioxide gas at 25 ^{o}C (Socki et al., 1992). Hydrogen isotope compositions were analysed by mass spectrometry after reducing water to H_2 gas over hot uranium metal (Dighton et al., 1997).

Radon samples were collected by syringe (Plate 2) and injected into low diffusion vials containing a mineral oil scintillant (Plate 3). Sampling of the fractured rock aquifer wells occurred only after three equivalent borehole volumes of water were removed and field

Table 1. Sample site locations

Site Number	Location[1]		Parameter sampled (✓ — September 2003, ✓ — March 2004)							Local Site Description
	E	N	Salinity as EC[2]	pH[2]	Temp[2]	Flow	Stable Isotopes	Major Ions[3]	Radon	
1	289905	6105258	✓	✓	✓	✓	✓	✓	✓	Soak, Old coach Rd
2A	290263	6106577	✓	✓	✓	✓	✓	✓	✓	Cnr.Dashwood Gully Rd. and Hilly fields Rd.
2B	290274	6106582	✓	✓	✓	✓	✓	✓	✓	Cnr.Dashwood Gully Rd. and Hilly fields Rd.
3	287894	6107198	✓	✓	✓	✓	✓	✓	✓	Dashwood Gully Rd. Kuitpo Forest Entrance
4	286241	6108144	✓	✓	✓	✓	✓	✓	✓	Sand Rd. Kangarilla
5	285276	6106903	✓	✓	✓	✓	✓	✓	✓	McLaren Flat Rd.
6	286496	6105617	✓	✓	✓	✓	✓	✓	✓	Peter Creek Rd.
7	285781	6105840	✓	✓	✓	✓	✓	✓	✓	Bottom Peter Creek by disused windmill
8	284390	6103666	✓ ✓	✓ ✓	✓ ✓	✓ ✓	✓ ✓	✓	✓ ✓	McLaren Flat Rd.
9	283317	6101631	✓	✓	✓	✓	✓	✓	✓	Cnr. McLaren Flat Rd. and Elliot Rd.
10	283371	6100818	✓	✓	✓	✓	✓	✓	✓	Elliot Rd. small ford across rd.
11	282953	6100482	✓	✓	✓	✓	✓	✓	✓	Cnr. Elliot Rd. and Truscott Rd.
12	281632	6100371	✓	✓	✓	✓	✓	✓	✓	Truscott Rd. near DIP sign - small stream
13	281163	6099257	✓	✓	✓	✓	✓	✓	✓	Oakley Rd. Nth of McMurtrie Rd.
14	281230	6098730	✓	✓	✓	✓	✓	✓	✓	Pennys Hill Rd.
15	280146	6097596	✓	✓	✓	✓	✓	✓	✓	Sth end of Hunts Rd.
16	280261	6096809	✓	✓	✓	✓	✓	✓	✓	Tim Cawte's spring
17	279523	6096148	✓	✓	✓	✓	✓	✓	✓	Edwards Rd. Nth.

Site Number	Location[1]		Parameter sampled (✓ — September 2003, ✓ — March 2004)							Local Site Description
	E	N	Salinity as EC[2]	pH[2]	Temp[2]	Flow	Stable Isotopes	Major Ions[3]	Radon	
18	279398	6095986	✓	✓	✓	✓	✓	✓	✓	Edwards Rd. Sth
19	278143	6094251	✓ ✓	✓ ✓	✓ ✓	✓ ✓	✓ ✓	✓	✓ ✓	east of Willunga township
20	277893	6094140	✓ ✓	✓ ✓	✓ ✓	✓ ✓	✓ ✓	✓	✓ ✓	Wirra Crk. (Willunga)
21	278427	6093366	✓	✓	✓	✓	✓	✓	✓	Linke property
22	277416	6094531	✓ ✓	✓ ✓	✓ ✓	✓ ✓	✓ ✓	✓	✓ ✓	McLaren Vale Willunga Rd. -100m down from bridge
23	277633	6093095	✓ ✓	✓ ✓	✓ ✓	✓ ✓	✓ ✓	✓	✓ ✓	Bangor Rd.
24	276502	6092814	✓ ✓	✓ ✓	✓ ✓	✓ ✓	✓ ✓	✓	✓ ✓	Colville Rd. bridge under road
25	274746	6092545	✓	✓	✓	✓	✓	✓	✓	Almond Grove Rd.
26	274564	6091474	✓	✓	✓	✓	✓	✓	✓	Hahn Rd. by caravan
27	273577	6090234	✓	✓	✓	✓	✓	✓	✓	Ryan Rd.
28	272593	6090145	✓	✓	✓	✓	✓	✓	✓	Cnr. Culley Rd and Rogers Rd.
29	270571	6087281	✓	✓	✓	✓	✓	✓	✓	200m past Victory Hotel
30	285029	6104918	✓	✓	✓	✓	✓	✓	✓	KTP33
31	284228	6102553	✓ ✓	✓ ✓	✓ ✓			✓ ✓	✓	WLG148
32	280090	6096735	✓ ✓	✓ ✓	✓ ✓			✓ ✓	✓	WLG147
33	278354	6094358	✓ ✓	✓ ✓	✓ ✓			✓ ✓	✓ ✓	WLG146
34	278223	6093770	✓ ✓	✓ ✓	✓ ✓	✓ ✓	✓		✓	By small wooden bridge

1 Spheriod/Datum WGS84

2 Measurements taken in field

3 Not analysed

Plate 2. Radon collection

Plate 3. Radon sampling

measured parameters had stabilised. Radon concentrations were measured by liquid scintillation counting (Herczeg et al., 1994).

Three of the four wells were also sampled during the second visit and analysed for major ions (App. B for results). Well KTP033 was not sampled due to problems with the pump.

3 RESULTS

Groundwater, springs and stream flow

In September 2003 a total of 22 streams were flowing. Flow rates for September are shown on Table 2. Total flow to the plain in September was estimated to be ~250 L/s (21.6 ML/d) with approximately 40% of the flow coming out of Kangarilla Creek. During March 2004 only five of the streams were still flowing (Table 3). The total estimated flow from these streams was less than 18 L/s (1.55 ML/d), with no flow recorded in Kangarilla Creek. Given there were only two sample periods and that there was such a marked difference in flow no attempt was made to extrapolate the field data and estimate annual flow.

Non-point source discharge to the streams inferred from increased stream flow rates was a common observation during the study (that is there were no obvious point source discharge points to correlate with the increased flow). Flow in both Willunga and Kangarilla creeks increased with no obvious groundwater discharge points at a number of the sample locations.

In Dashwood Gully on Kangarilla Creek, one of the effects of the steep terrain is that during winter the groundwater table rises to a level such that it intersects the ground surface. This occurs at numerous locations across the valley. Figure 8 shows hydrographs of four recently completed Fractured Rock Aquifer observation wells, KTP033, WLG146, WLG147, WLG148, see Figure 1 for location and all illustrate the seasonal change in groundwater levels. This rise in groundwater table activates a number of discrete groundwater discharge points in the form of springs and seeps, as observed along the slopes of the valley immediately above the level of the stream (Plate 4).

The other type of point source discharge was a spring associated with a small (1–2 m), decrease in the level of the stream channel bed. This resulted in what appears to be a significant increase in stream flow. These breaks in slope were usually near the boundary between the fractured rock and the sediments of the plain (Plate 5).

A good example of this type of spring was observed about 200 metres up stream of the small wooden bridge near the old courthouse east of Willunga township. It is possible that the sharp break in stream bed delineates the trace of the Willunga Fault and that the change in topography while small, is sufficient to allow the shallow water table to intercept the ground surface. There are two suggested sources for the observed flow:

- Localised flow (surface and shallow groundwater) sourced from a recharge zone immediately up (hydraulic) gradient of the lineation.
- The lineation is the fault trace and the fault is a conduit providing a preferential flowpath for deeper regional groundwater to outflow at the surface.

Generally however, it was difficult to precisely locate point source discharges (e.g. springs). The reasons varied from stream to stream but were mainly due to:

- Overgrown vegetation.
- Dams disguise or have changed the natural flow gradient in the streams.

Table 2. September 2003 - Results

Site Number	**Easting**	**Northing**	**Salinity as EC** µS/cm@25°C	**pH**	**Temp.** °C	**Flow (est.)** L/s	**Stable Isotopes** $\delta^{18}O$ (‰, VSMOW)	$\delta^{2}H$ (‰, VSMOW)	^{222}**Radon** (mBq/L)	**Groundwater % from** δ^{18}**O**	δ^{2}**H**
1	289905	6105258	215	6.57	13.3	–	-2.4	-7.8			
2A	290263	6106577	1377	7.41	12.4	7	-3.55	-15.4	**1829**		
2B	290274	6106582	1385	7.76	12.6	4	–	–	**2831**	47	46
3	287894	6107198	1016	8.16	12.9	35	-3.81	-16.6	**743**	58	53
4	286241	6108144	996	8.31	13.4	100	-4.01	-16.8	**1297**	66	54
5	285276	6106903	817	8.25	14.9	4	-3.81	-16	**628**	58	49
6	286496	6105617	843	8.00	13.8	5	-4.07	-17	**359**	69	55
7	285781	6105840	795	8.17	13.8	12	-3.92	-16.1	**308**	63	50
8	284390	6103666	1726	8.42	16.1	2	-4.52	-19.6	**25**	87	71
9	283317	6101631	583	8.00	17.6	0.5	-4.16	-18.3	**590**	73	63
10	283371	6100818	767	7.80	13.3	1	-3.57	-19.7	**14176**	48	71
11	282953	6100482	1591	8.34	15.6	7	-3.84	-18.3	**527**	59	63
12	281632	6100371	737	8.40	16.4	1	-3.64	-15.9	**1372**	51	49
13	281163	6099257	1010	8.90	16.1	4	-4.04	-16.7	**566**	68	53
14	281230	6098730	970	7.96	15.9	3	-4.34	-19.1	**2295**	80	68
15	280146	6097596	1509	8.15	14.1	5	-4.07	-21.2	**2656**	69	80
16	280261	6096809	1908	7.79	15.7	0.4	-4.65	-22.8?	**59161**	93	90
17	279523	6096148	904	8.00	13	0.4	-4.11	-20.3	**11144**	71	75

Site Number	Easting	Northing	Salinity as EC μS/cm@25^{o}C	pH	Temp. ^{o}C	Flow (est.) L/s	Stable Isotopes		^{222}Radon	Groundwater % from	
							δ^{18}O (‰, VSMOW)	δ^{2}H (‰, VSMOW)	(mBq/L)	δ^{18}O	δ^{2}H
18	279398	6095986	700	8.05	13.1	1.5	-4.2	-20.9	**5736**	74	78
19	278143	6094251	1450	8.16	15.9	5	-4.43	-21.7	**202**	84	83
20	277893	6094140	2050	8.38	16.5	10	-4.91	-22.5	**487**	104	88
21	278427	6093366	1372	8.36	15.4	1.5	-4.36	-13.8	**3072**	81	36
22	277416	6094531	1841	8.42	15.4	15	-4.53	-23	**115**	88	91
23	277633	6093095	1973	8.36	15.5	8	-4.68	-21.6?	**832**	94	
24	276502	6092814	1242	8.22	14.9	2	-3.63	-19.1	**558**	51	68
25	274746	6092545	592	7.94	13.4	2	-4.03	-18.7	**1235**	67	65
26	274564	6091474	461	7.85	14.7	3	-4.24	-17.7? 25.6?	**3039**	76	
27	273577	6090234	405	7.62	12.5	0.6	-4.17	-19.4	**6501**	73	69
28	272593	6090145	562	7.96	14.6	1.5	-4.64	-23	**752**	92	91
29	270571	6087281	713	8.65	14.3	0.8	-4.35	-22.4	**245**	80	87
30	285029	6104918	1967	7.08	15.6	–	-5.01	-26.7	**49762**		
31	284228	6102553	1764	7.03	19.6	–	-5.17	-25.4	**32189**		
32	280090	6096735	1856	6.92	19.6	–	-4.37	-23	**33586**		
33	278354	6094358	6470	6.74	19.3	–	-4.75	-22.9	**62678**		
34	278223	6093770	1987	8.45	16.4	7					

Table 3. March 2004 - Results

Site Number	**Salinity as EC** µS/cm@25°C	**pH**	**Temp.** °C	**Flow (est.)** L/s	**Stable Isotopes**		^{222}**Radon** (mBq/L)	**Groundwater % from**	
					δ^{18}O (‰, VSMOW)	δ^{2}H (‰, VSMOW)		δ^{18}**O**	δ^{2}**H**
1									
2A									
2B									
3									
4									
5									
6									
7									
8	2810	8.05	21.1	0.10	-4.03	-20.8	119	67	78
9									
10									
11									
12									
13									
14									
15									
16									
17									
18									
19	2340	8.05	22.8	1.00	-4.39	-23.3	125	82	93
20	2370	8.24	22	6.00	-4.68	-24.3	294	94	99
21									
22	2360	8.19	21.9	4.50	-4.38	-23.7	55	82	96
23	2440	8.16	23.1	0.50	-4.93	-25.3	515	104	105
24	2490	8.13	23.6	0.25	-3.00	-17.0	133	25	56
25									
26									
27									
28									
29									
30	Couldn't pump								
31	1830	7.02	21.4						
32	1735	7.27	20.9						
33	6290	6.93	21.1						
34	2310	8.3	24.3	5.00	-4.64	-25.3	40	92	105

Plate 4. Examples of seasonally activated springs.

Plate 5. **Example of spring flow from sharp break in ground surface**

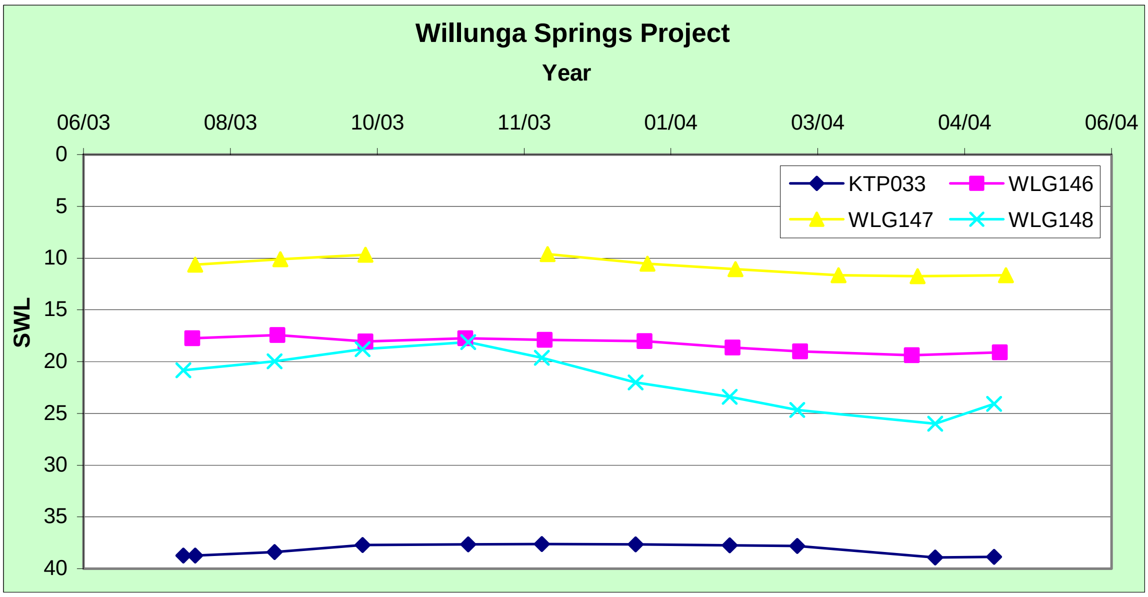


Figure 8. **Hydrographs for KTP033, WLG146, WLG147 and WLG148**

- Tributaries to the main stream channel not investigated (no access) are important sources to surface flow.
- Non-point source discharge.

Salinity, pH and temperature

Salinity as specific electrical conductivity (EC), pH and temperature readings taken during the September and March sampling are shown on Tables 2 and 3 respectively.

SEPTEMBER SAMPLING

The electrical conductivity of surface water taken in September from the outflow of a dam at the top of Dashwood Gully was 215 μS/cm (Site 1).

The salinity of the water sampled from the streams during the September ranged from ~400 to 2050 μS/cm. Groundwater samples were also taken from four recently established observation wells in the Fractured Rock Aquifer located on the eastern side of the fault (Fig. 1). Three of the sampled wells had an EC that plotted in a small range from 1764 to 1967 μS/cm. One well, WLG146, located on Taylors Hill Road just north of Willunga township, had an EC of 6740 μS/cm, which is much higher when compared with regional data and is possibly related to the local geology. Ignoring the anomalous salinity value results in an average salinity of the groundwater in the Fractured Rock Aquifer of ~1860 μS/cm.

Generally (except for two samples), the salinity of the streams was lower than the average groundwater salinity. The lower EC in the streams suggests that they are also recharged from a source other than groundwater (i.e. run-off from rainfall).

Neither pH nor temperature displayed any significant spatial or temporal relationships except for a down stream increasing pH trend in both Kangarilla and Peters creeks. No such trend was identified in Willunga Creek.

MARCH SAMPLING

The average groundwater salinity during the March sampling was 1780 μS/cm (disregarding WLG146). The salinity of the five streams that were still flowing in March 2004 ranged from 2340 to 2810 μS/cm and was therefore higher than that of the average groundwater. The data is however skewed towards the area east of Willunga township and may reflect higher groundwater salinity in this area.

COMPARISON OF SEPTEMBER AND MARCH DATA

Salinity of the groundwater sampled from each of the wells in September 2003 showed little change when resampled in March 2004. A comparison of streamflow salinity however shows significantly higher concentrations during the March sampling (Tables 2 and 3).

This higher salinity in March reflects the higher proportion of groundwater in the stream flow. It is also possible that highly evaporated and therefore saline dam water may also be contributing to the higher salinity.

Stable Isotopes

The stable isotopic compositions of both $\delta^{18}O$ and $\delta^{2}H$ (Tables 2 and 3) plot as linear trends on Figure 9 for the two sampling periods (blue diamonds – September, brown dots – March).

Groundwater $\delta^{18}O$ and $\delta^{2}H$ compositions (same diagram, yellow triangles from September sampling) are relatively isotopically lighter to the samples taken from the streams. The annual mean (amount-weighted) isotopic rainfall composition (pink square) for Adelaide is also plotted and falls within this grouping. There are a number of observations that can be inferred from this information:

- The closeness in isotopic composition between groundwater and that of the mean annual isotopic rainfall composition suggests that groundwater recharge occurs only when rainfall is equal or less than the mean isotopic rainfall composition. Rainfall that is isotopically lighter than the average mean weighted isotopic rainfall is associated with above average winter rainfall.
- The closeness in isotopic composition between groundwater and rainfall meant that they could not be used directly to determine relative stream flow compositions.
- However, three days prior to the September sampling, significant rainfall (~10 mm) occurred (BOM website, 2004). Most of the dams were therefore full with recent rainfall via surface run-off, particularly the large dams located at the headwaters of most of the streams. Surface waters contained in large open water bodies such as dams are commonly enriched in ^{2}H and ^{18}O through evaporation. The most enriched stable isotope composition was taken at Site 1, the non-groundwater sample taken from a dam outflow at the top of Dashwood Gully.

The linear trend of the plotted data for both September and March in terms of stream flow composition can be interpreted in two ways:

- Each stream sample is a mixture of groundwater and evaporated dam water (which is considered to be a proxy for rainfall sourced from surface run-off). The observed linear trend observed for both the September and March sampling represent mixing between two end members; groundwater and surface water.
- Alternatively, it could equally be argued that the isotopic trend represents simple evaporation of groundwater. However, if this interpretation was correct then all the samples would have a similar salinity as groundwater, and they do not.

The slope of the September isotopic data is ~5.6. Experiments undertaken by Allison, (1982) show that trends with a slope of more than five are ultimately derived from evaporated open water bodies. Sampling from Kangarilla and Willunga creeks show a clear trend of relatively isotopically enriched water at the top of the catchment becoming isotopically lighter as the water flows along the stream, inferred to represent an increase

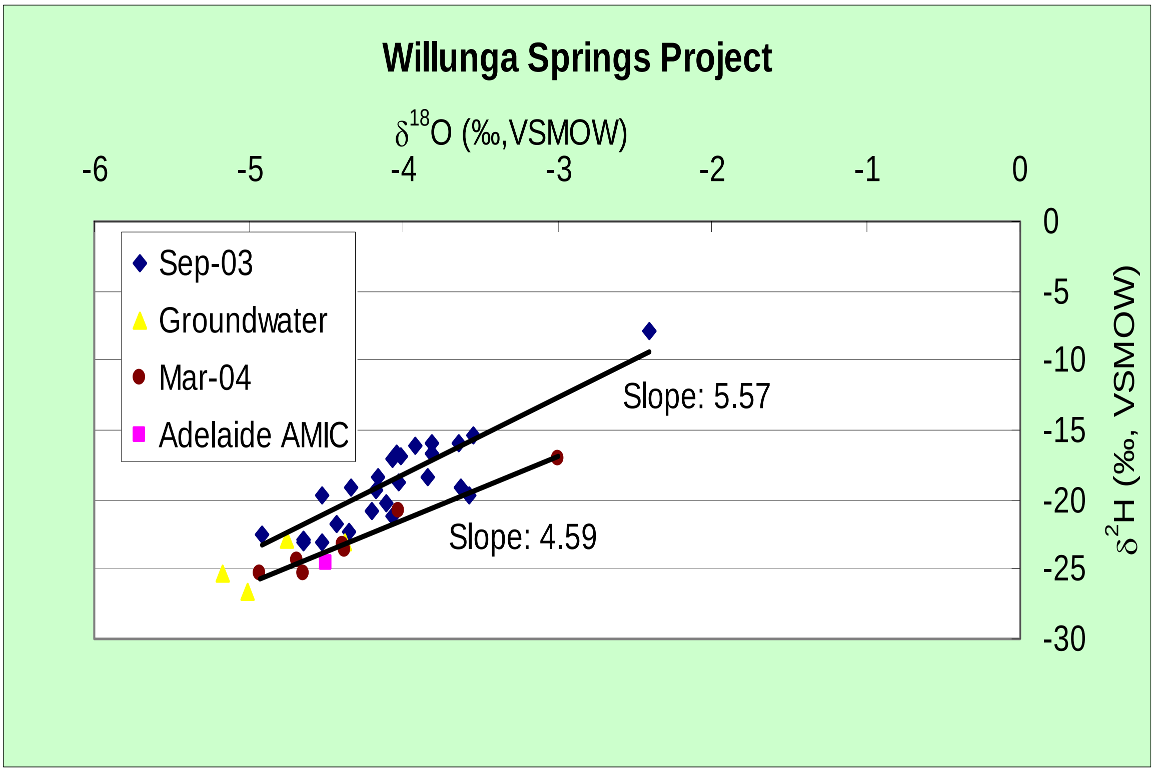


Figure 9. Plot of September and March d18O against d2H

in groundwater contribution. Both observations, in addition to the salinity data, support the hypothesis that there are two sources for the stream water and that the first interpretation of the trend is most likely at least for the September data.

The slope of the March data is 4.6. This lies in the range of 2.4 to 4.7 suggesting the water originally evaporated within a soil profile (Allison, 1982). Salinity data showed the stream samples were of a higher salinity than that of groundwater. This implies an alternative source of higher salinity water, however three of the seven samples were taken from the one stream (Willunga Creek) and therefore the data is skewed towards it. The assumption that the local groundwater salinity near Willunga Creek is equal to the average salinity may be incorrect. A possible explanation for this observation is that during winter the stream is predominantly recharged by local low salinity groundwater and in the summer by deeper more saline regional groundwater.

The proportion of groundwater and surface water represented in a sample can be estimated using a mass balance approach if it is assumed that the most extreme $\delta^{18}O$ and $\delta^{2}H$ compositions represent end members. The groundwater end member was assumed to be the average $\delta^{18}O$ and $\delta^{2}H$ composition of the well samples and the surface water end member of the dam sample from Site 1.

From the September $\delta^{18}O$ data flow at the base of the range at Kangarilla Creek was estimated to be 65% groundwater ($\delta^{2}H$ data suggests 55%). At the bottom of the Willunga Creek, estimated contribution of groundwater to total stream flow was calculated to be ~90% for both $\delta^{18}O$ data $\delta^{2}H$ data.

The difference in the relative contribution of groundwater and surface water to Kangarilla and Willunga creeks is consistent with the large dams situated at the headwaters coupled with the high number of dams (open water bodies) located on Kangarilla Creek compared to Willunga Creek.

A plot of the percentage estimated groundwater contribution to stream flow using $\delta^{2}H$ data at each sample point (or farthest downstream point for both Kangarilla and Willunga creeks) against the average dam size area for each stream is shown on Figure 10. Whilst illustrating considerable scatter, the plot shows a reasonable trend of decreasing groundwater fraction with increasing dam area.

Groundwater contributions calculated from the $\delta^{2}H$ isotope using the mass balance approach for the March sampling ranged from ~95 to 105% except for Site 8 (78%) and Site 24 (56%). The high percentage values (within error limits) indicate all the stream flow is sourced only from groundwater. The reasons for the results for Sites 8 and 24 are not clear.

Radon-222

The radon concentrations for the September and March sampling program are tabled in Tables 2 and 3. In total, 34 radon samples were taken during September with concentrations ranging from 25 to 62 678 mBq/l. Radon concentrations in the four groundwater samples ranged from ~32 200 to ~62 700 mBq/l during the September 2003 sampling.

Only seven radon stream flow samples were taken during March. The March data, with the exception of Site 8, showed slightly lower radon concentrations compared to September and may reflect lower flow rates coupled with higher levels of evaporation.

A cumulative plot of all the radon concentrations for September against distance travelled along the flow path of each stream is shown on Figure 11. The plot shows a reasonable correlation between distance travelled and decrease in radon concentration. The data is distorted however by the high number of radon samples with low concentrations at relatively short travel distances at one end of the plot and the one high value at the other.

The high number of radon samples with less than 600 mBq/l can be attributed to the following:

- The proliferation of dams on the majority of watercourses has seriously impacted on the natural flow, and therefore the natural decay cycle in the streams.
- There is generally no one point source discharge point for groundwater to the streams. The point the radon enters the stream can therefore be subjective.
- Turbulence has resulted in the loss of dissolved radon to the atmosphere.

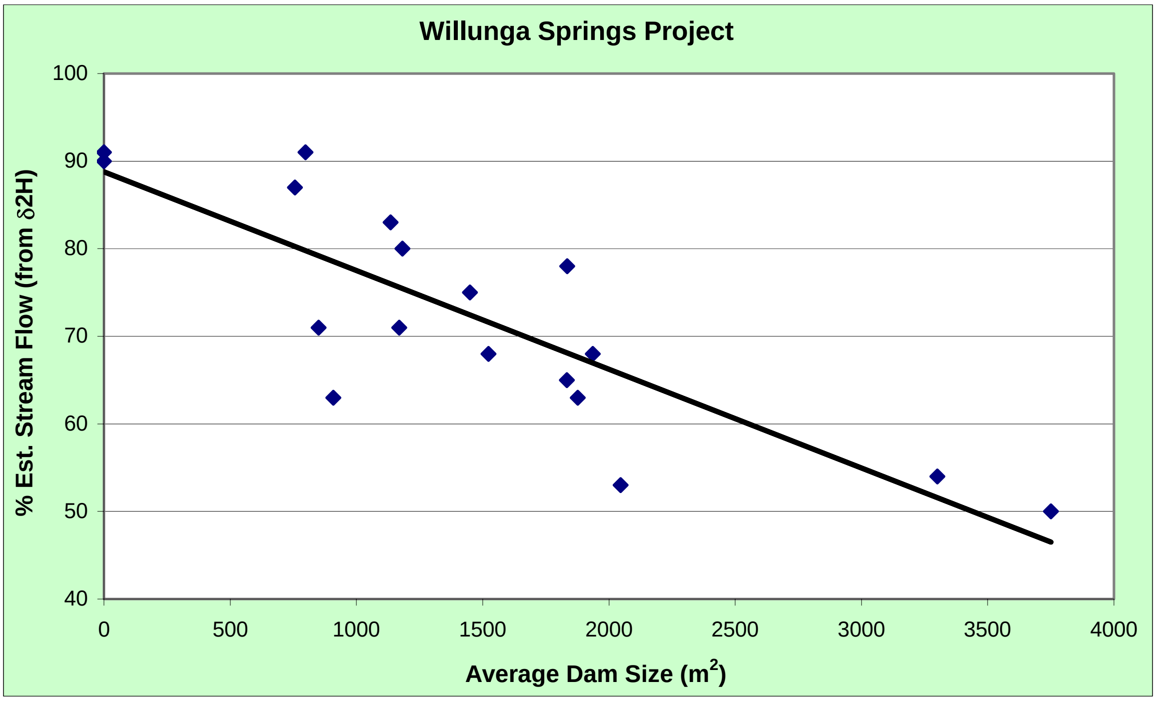


Figure 10. Plot of percentage estimated stream flow (from d2H) against average dam size

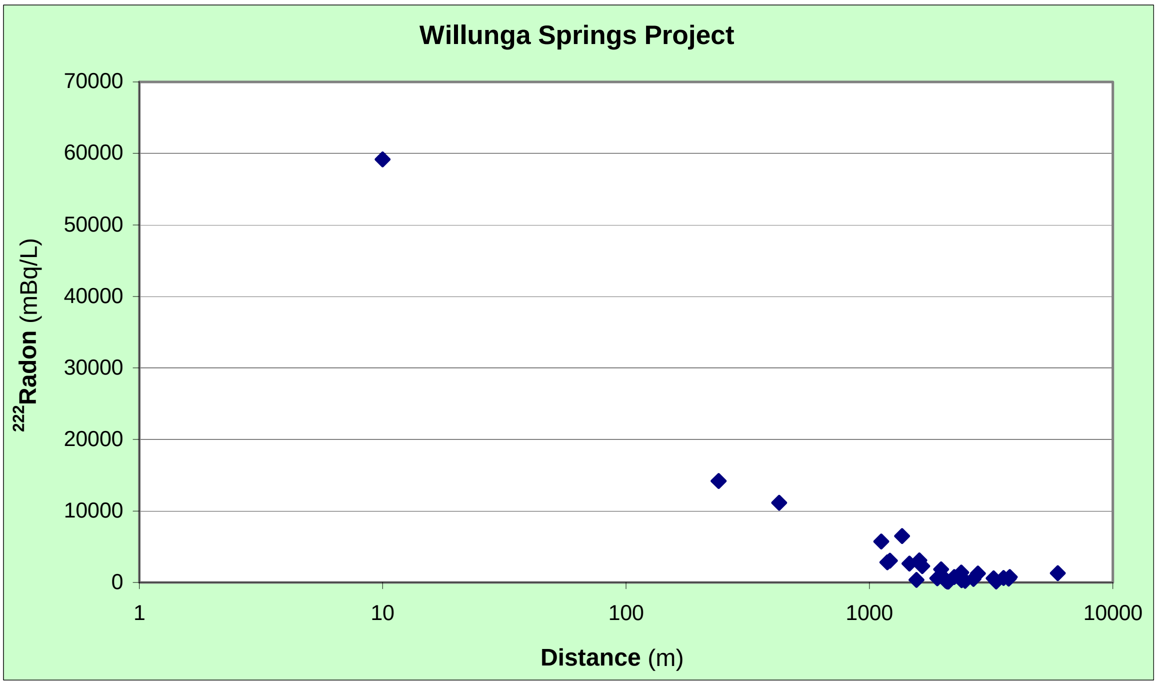


Figure 11. Cumulative plot of radon concentration against distance along stream path

Flow in Willunga Creek

Results from sampling along the reach of the Willunga Creek in September 2003 are shown graphically on Figure 12.

Flow increases from about 1.5 L/s at the uppermost sample site, Site 21, to 15 L/s at Site 22 located on the Plain. Salinity generally increases down stream while stable isotopes become more depleted.

The influence of an additional flow of 5L/s originating from Wirra Creek (Site 19) is evident in the salinity and stable isotope data at Site 22, the outflow of Willunga Creek onto the plain.

Flow in Kangarilla Creek

Figure 13 is a graphical representation of stream flow sampling along the Kangarilla Creek. Flow increases from negligible at the uppermost dam to more than 100 L/s where the creek flows out on to the plain. Salinity increases sharply from the dam site to Site 2A/2B and then decreases slightly down flow gradient. The stable isotopes become more depleted along the length of the stream.

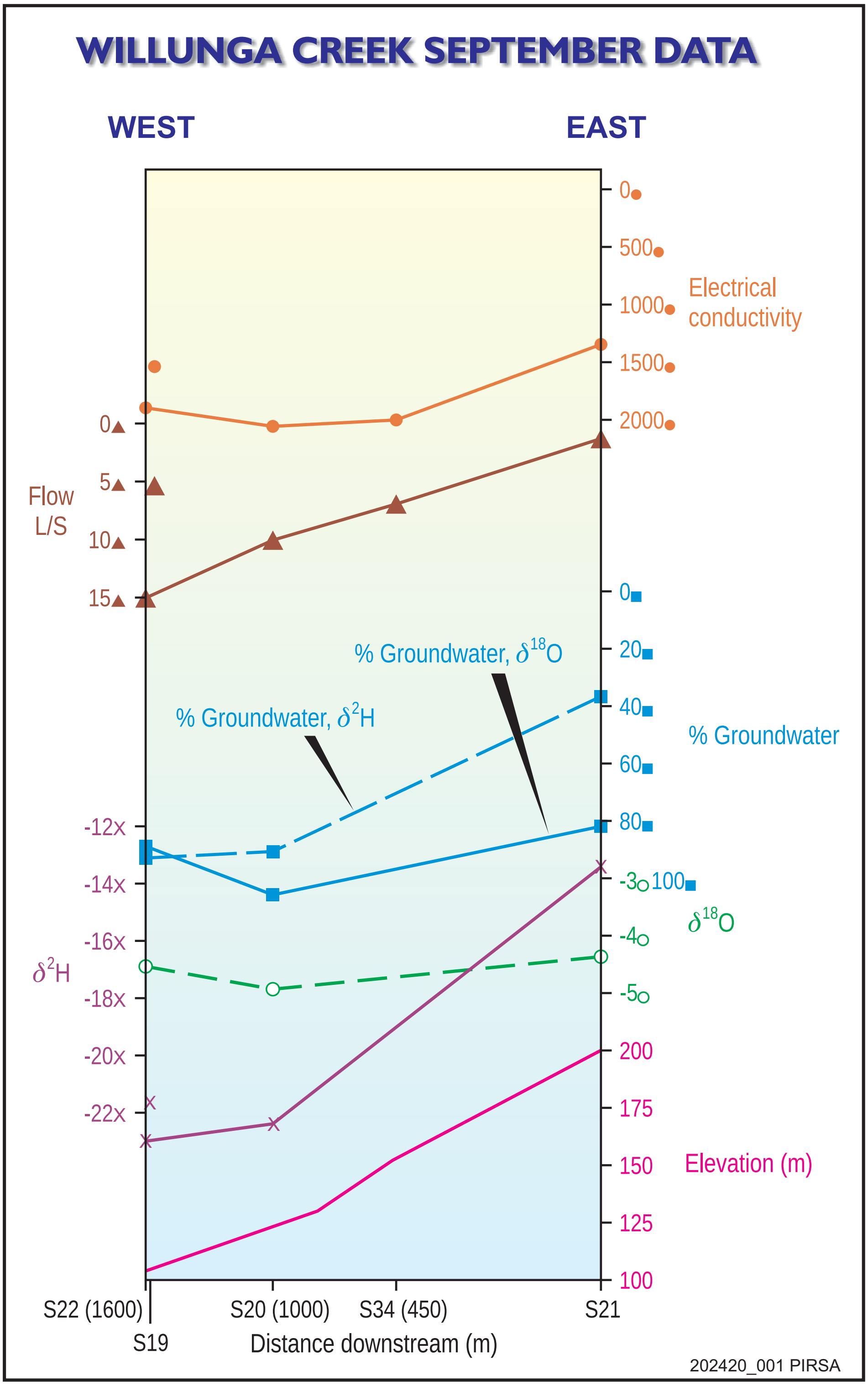


Figure 12. Graph of Willunga Creek stream flow results

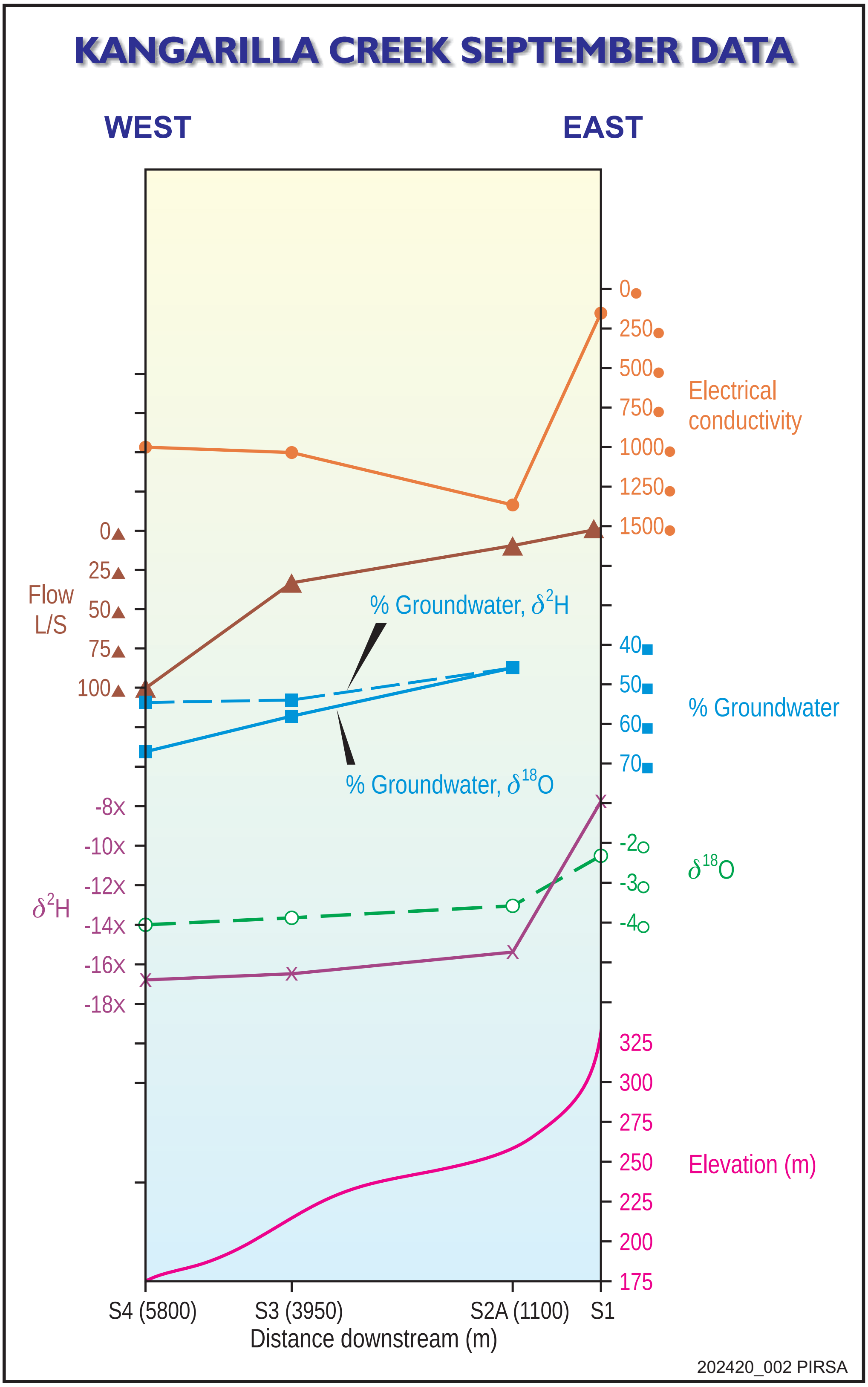


Figure 13. Graph of Kangarilla Creek stream flow results

4 DISCUSSION

A comparison of stream flows from Kangarilla Creek and Willunga Creek

From this study, flow from Kangarilla Creek can be characterised as ephemeral and in September 2003 was in excess of 100 L/s. In March 2004 the stream was not flowing. In contrast, Willunga Creek was still flowing, with an estimated flow in September of 10 L/s and 6 L/s in March.

The question is then, why does Kangarilla Creek flow at a high rate in September but not in March, while flow in Willunga Creek was considerably less than that of Kangarilla Creek in September but was maintained through to March?

It is inferred from the salinity and stable isotope data that flow in Kangarilla Creek during winter comes from two main sources; groundwater supplied by springs that are activated due to the seasonal rise in the groundwater table and dam water derived from rainfall via surface run-off. Lower rainfall in summer however, has two negative effects on stream flow, the dams empty and therefore cease to contribute to flow and the groundwater table falls resulting in a cessation of spring flows.

The catchments that contain Willunga and Kangarilla creeks are similar in that the groundwater table changes seasonally. This is reflected by the difference in September and March flow rates in Willunga Creek. However, the flow in Willunga Creek remains permanent because the groundwater level stays above the level of the ground surface. If the groundwater level were to decline below ground then flow would cease as has been observed in other spring-fed streams in the area.

Historical stream flow data (Fig. 6) from a gauging station located on one of the tributaries to Kangarilla Creek showed very little flow occurred outside of the winter period. It is possible therefore that the high winter/zero summer flows in Kangarilla Creek are a normal event. The gauging station was installed after the establishment of a *pinus radiata* forest located further up the catchment therefore it was not possible to assess the impact of the plantation on stream flow.

Conceptual Models

Water samples taken from groundwater wells and stream flows were measured for salinity, stable isotopes ($^{18}O/^{16}O$ and $^{2}H/^{1}H$) and radon. The analytical results were used in conjunction with hydrological data (groundwater and surface flows) to construct conceptual models that explain the mechanisms that control spring flow in the valleys and that describe the hydrochemical and hydrological processes that ultimately result in the chemical make-up of a stream water sample.

TYPES OF SPRINGS

Two conceptual models for spring flow are presented (Fig. 14):

- The first type are seasonally activated springs, most common in the Dashwood Gully area where the water table rises during winter and intersects the ground surface in the steep valleys. These can be either point source or non-point source zones of recharge to the streams.
- The second type of spring is related to sharp linear changes in stream bed topography, possibly a fault line, for example Willunga Stream. The change in ground elevation, while small, is enough for the groundwater table to intersect with the ground surface.

GROUNDWATER AND SURFACE WATER CONTRIBUTIONS TO STREAM FLOW

The composition of the stream water is assumed to be a mixture of mainly groundwater and dam water. Dam water consists mainly of surface run-off derived from rainfall that has undergone evaporation. Having determined the isotopic signatures of the main components a mass balance method was used to calculate the relative composition of each stream water sample.

Potential Impacts on Spring Flow

Results from this study combined with rainfall, historic stream flow and irrigation patterns have highlighted a number of issues related to the potential impacts climate, land use change and irrigation activity can have on springs and therefore stream flow. In particular, the information gained from this investigation may explain why a number of springs, based on anecdotal evidence, have ceased to flow over the last five years.

Below is a discussion of the three main processes that have been identified as potentially impacting on spring flows.

CLIMATE CHANGE

Figure 3 shows the cumulative deviation from mean rainfall for Willunga, McLaren Vale and Mount Bold. With the exception of Mount Bold, all show a decline in mean annual rainfall since the end of 1994. Unfortunately there is only limited long-term groundwater level data available in the area, so it is not possible to determine any correlation between rainfall and recharge to the aquifer, nor is there any substantive evidence to show any long term decline in groundwater levels in the Fractured Rock Aquifer in this area.

LAND USE CHANGE

The most notable land use change has been the introduction of farm dams in to the Mount Lofty Ranges over the last ten years. These dams are generally located on natural surface water drainage channels, intercepting rainfall run-off that would normally flow into the streams. The impact these dams have on aquifer recharge is a matter of debate. From

Spring model 1 — Summer

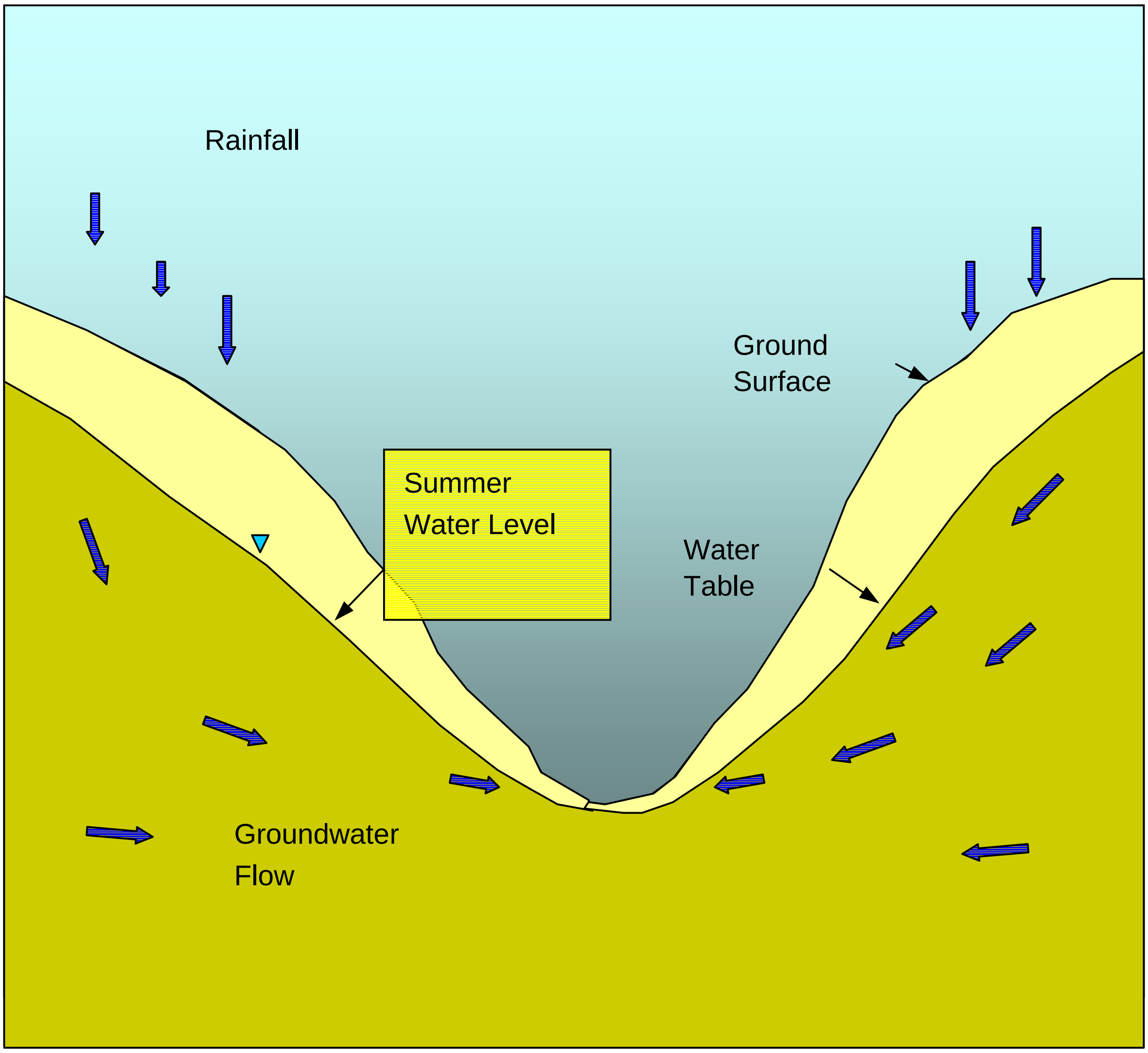


Figure 14. Conceptual model of groundwater activated springs

Spring model 1 — Winter

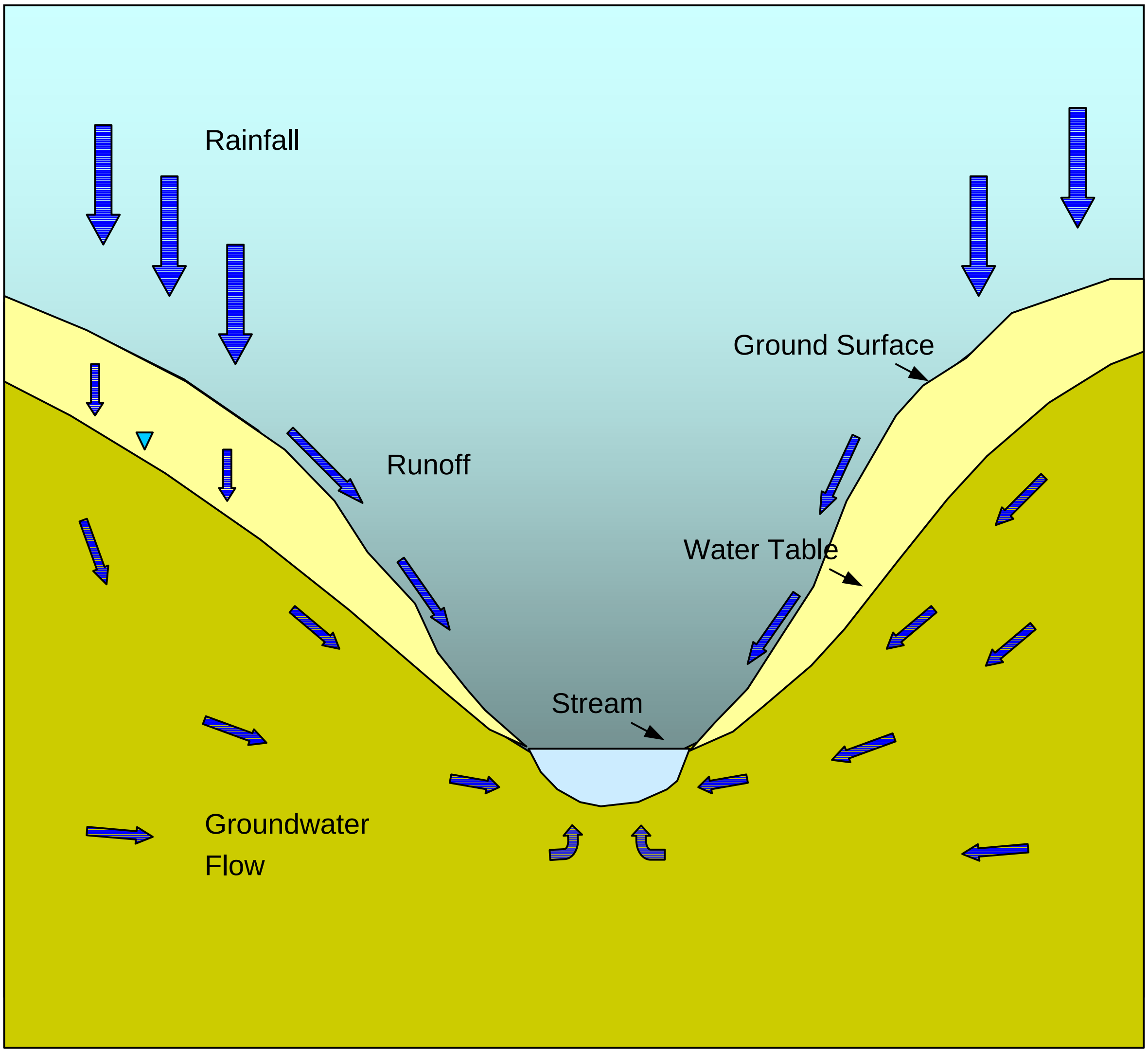


Figure 14. Conceptual model of groundwater activated springs continued

Spring model 2

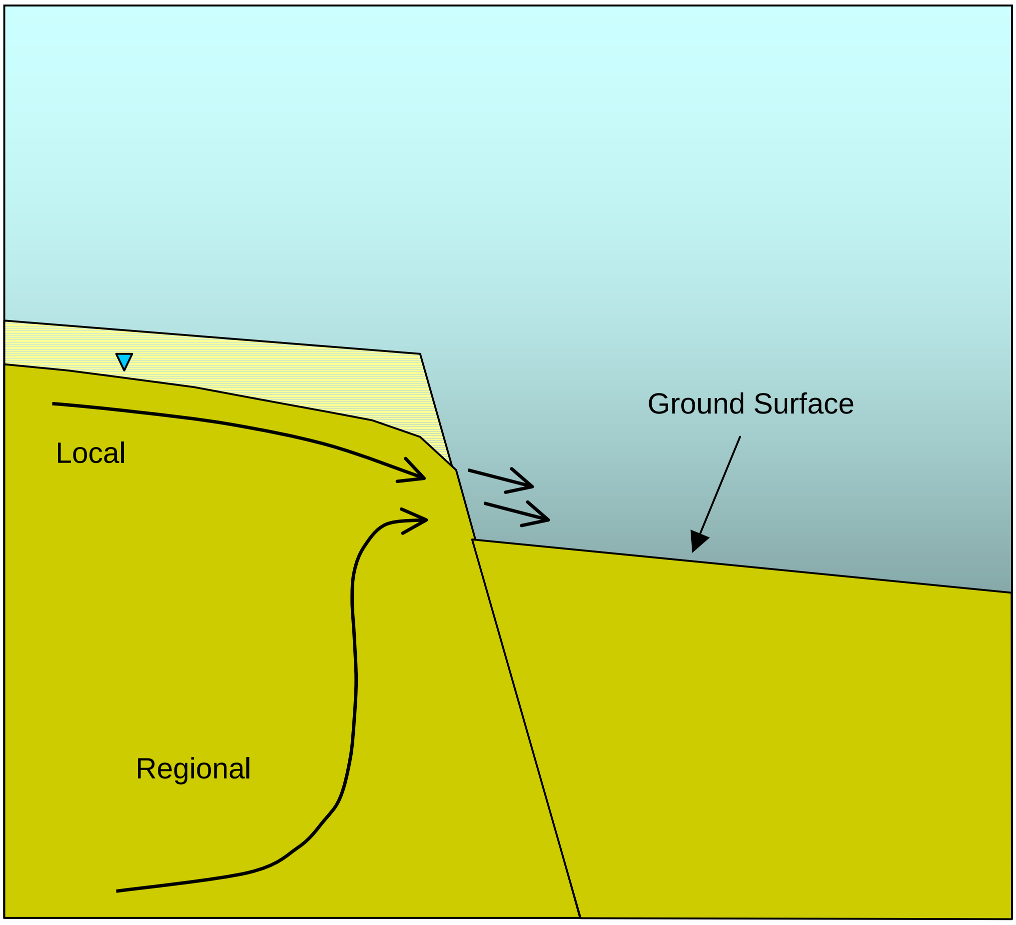


Figure 14. Conceptual model of groundwater activated springs continued

one point of view it could be argued that the dam will increase recharge locally via downward leakage through the base of the dam. The second argument is that the dams intercept flow that would otherwise partly recharge the sedimentary aquifers beneath the plain. It is possible that up to 45% of stream flow is derived from dam water. This study does not attempt to quantify how much potential flow is retained by the dams.

Small plantations of pine and blue gum have been established in a number of the valleys over the last 15-20 years. There are several ways this can negatively impact on groundwater recharge:

- Trees intercept the natural run-off of rainfall, preventing it from entering a stream.
- Tree roots can tap directly into an aquifer.
- Rain water that infiltrates into the unsaturated zone is transpired by the plant through the leaves via the root zone.
- Branches and leaves intercept rainfall that is evaporated directly.

IRRIGATION ACTIVITY

Water for irrigation sourced from the Fractured Rock Aquifer is relatively small compared to the volume that is extracted from beneath the Plain.

Fractured rock aquifers generally have much lower storage coefficients than sedimentary aquifers. For example, a porous (sedimentary) media aquifer may typically have a specific yield (storage value) of ~0.1, that means that approximately 10% of the aquifer is water, and the other 90% is rock. Therefore, in every 1 km^3 of aquifer there is approximately 100 ML of water. Determining storage coefficients in a fractured rock aquifer is difficult because it is a dual porosity system, but if for example the specific yield of an aquifer was 0.001 then 1 km^3 would contain only 1 ML (1000 KL) of water. Therefore any extraction, even if it were small could potentially have a significant impact on groundwater levels in the aquifer. While beyond the scope of this study the Willunga Fault may also be influencing groundwater movement in this area.

5 CONCLUSIONS

Summary of results

The Department of Water, Land and Biodiversity Conservation, funded by the Onkaparinga Catchment Water Management Board, undertook a program to ascertain the number of streams that flowed from the ranges onto the coastal plain in the McLaren Vale PWA. As part of the study flow volumes were also estimated. The following is a summary of results:

- A field survey undertaken in September 2003 recorded 22 flowing streams with an estimated total flow of ~250 L/s (21.6 ML/d). Approximately 40% of the total flow came from Kangarilla Creek. A second survey undertaken in March 2004 found only five streams flowing, total flow was estimated to be less than 18 L/s (1.55 ML/d). Kangarilla Creek was not flowing during this period.
- No estimate of total annual flow was made because the difference in flow between the two data sets was large and any extrapolation of the data would therefore have been erroneous.
- Conceptual models were developed to better understand spring flows and to quantify relative groundwater/surfacewater contributions to the streams.
- It was concluded that winter flows from streams ranged from 50 to 90% groundwater, while in summer flows are almost entirely sourced from groundwater.
- During the September sampling, outflow from Kangarilla Creek was about 60% groundwater and 40% evaporated dam water derived from rainfall. The high proportion of non-groundwater in the creek flow during September can be attributed to dams capturing run-off from a ~10 mm rainfall event that occurred approximately three days prior to sampling.
- Flows from Willunga Creek are almost entirely sourced from groundwater all year round.
- The causes for the recent cessation of spring flows in the area immediately north-east of Willunga township are not conclusive. While related to a decline in groundwater levels over the past ten years, there is insufficient groundwater level data and the reason for this decline needs further investigation.

Further work

Recommendations for further work are:

- Determine and quantify non-point source recharge areas within the stream channels.
- Further sampling of dams and groundwater wells to determine a more statistically reliable stable isotope signature.
- Radiocarbon dating of the groundwater outflow from Willunga Springs.
- An investigation into the affect climate, land use change and irrigation activity is having on groundwater levels and groundwater fed springs.
- An investigation that quantifies groundwater movement through the Willunga Fault.

6 ACKNOWLEDGMENTS

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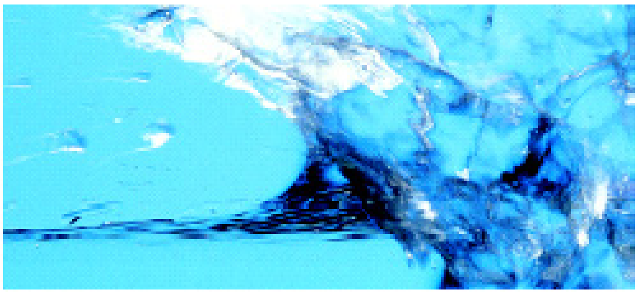
8 APPENDIX A



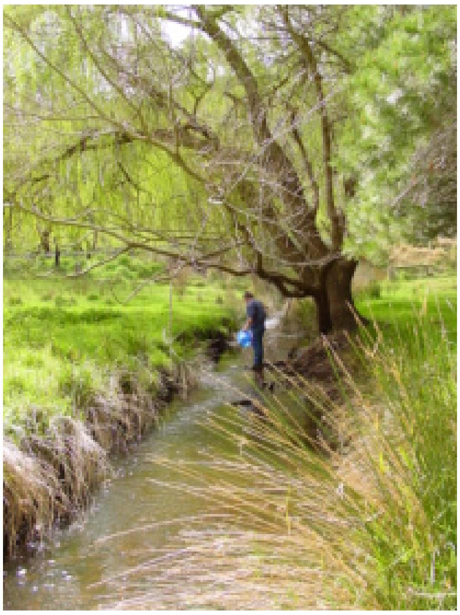
PHOTOGRAPHS

Site 1

Site 2A

Site 2B

Site 3



Site 4

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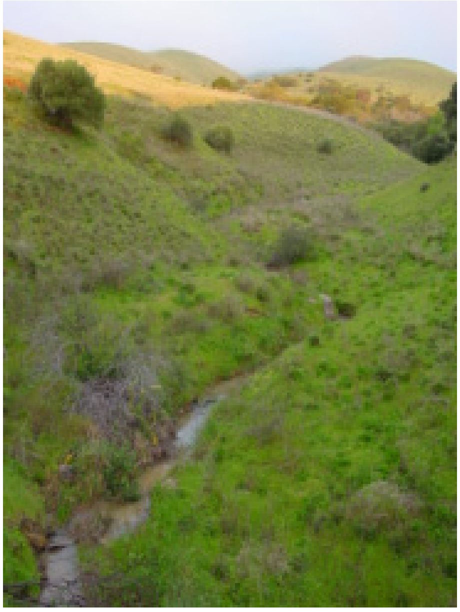
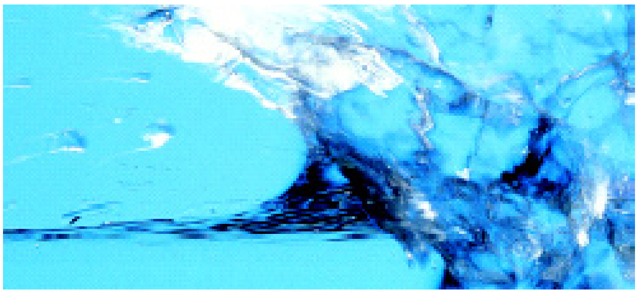


Site 34

9 APPENDIX B



Observation Well	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	Cl^{-}	[1]SO_4^{2-}	SiO_2	F^{-}	NO_3^{-}
	Mg/L									
WLG146	377	294	504	11.8	458	1920	147	16	0.74	2.3
WLG147	76	63	202	5.5	397	371	54.5	19	1.2	4.7
WLG148	104	107	137	9.3	516	316	78.6	23	1.2	7.8

[1] Total inorganic sulphur as sulphate