Interconnection of Surface and Groundwater Systems – River Losses from Losing/Disconnected Streams

*Border Rivers Site Report*
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Cover Photograph:
From: S. Lamontagne
Description: Dumaresq River downstream from Texas, Qld
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EXECUTIVE SUMMARY

Background

This report summarises the field studies at the Dumaresq River in the Border Rivers region, one of the six field sites for the project Interconnection of Surface and Groundwater Systems – River Losses from Losing / Disconnected Streams. The objectives of the field program at the Dumaresq River were to:

- Determine at two locations downstream from Texas (Qld) whether losing-connected or losing-disconnected conditions were present;
- Instrument and monitor a piezometer transect at each location to estimate the depth to water table and evaluate the piezometric response to changes in river stage;
- Measure the hydraulic conductivity of the streambed;
- Sample on one occasion groundwater from the piezometer transects for a range of environmental tracers (stable isotopes of water, CFCs, SF6, Radon-222, major ions, noble gases) to evaluate the sources of water to the aquifer and the infiltration rates from the river; and,
- Estimate infiltration rates through the streambed.

Field and lab results

The Dumaresq River was connected at the two sites visited in October 2009, but one site was gaining (Site 1) and the other losing (Site 2) to the alluvial aquifer. The presence of terrigenic He-4 (4He\text{terr}) in surface water and alluvial groundwater indicated that the river reach received some old regional groundwater discharge. Thus, the Dumaresq River is either a gaining or a flow-through system at the regional scale at the study reach. The source of the regional groundwater is unclear at present but could include either rock aquifers abutting the alluvial aquifer or the underlying Great Artesian Basin (GAB). The gaining transect had significant bank recharge – discharge cycles during floods but the losing transect was apparently consistently losing.

Alluvial groundwater at the transects was fresh and had a large range in stable isotopes of water, with groundwater closer to the river having a distinct evaporation signal (that is, similar to river water during low flow conditions). Chlorofluorocarbons (CFCs) and sulfur hexafluoride (SF6) dating indicated that alluvial groundwater was relatively young (a few decades-old or less). However, discrepancies between CFC-12 and SF6-derived ages suggested that some CFC degradation occurs in this aquifer and that the SF6-derived ages were more reliable. The few SF6 dates available indicated that the alluvial groundwater was 15 years-old or less. Overall, the patterns in the environmental tracers indicated two recharge mechanisms for the alluvial aquifer. The presence of groundwater with a depleted isotopic signature, high SF6 concentrations and low 4He\text{terr} concentrations is consistent with recharge during floods. On the other hand, groundwater with high SF6 and 4He\text{terr} concentrations and with an evaporation signal represents river infiltration under low flow conditions.

The unusual tracer signature in near-stream groundwater highlighted that the recharge process is complex, including features of both piston flow for a single water source and
mixing between different sources of recharge water. Thus, further interpretation of environmental tracers to estimate infiltration rates from the river will require a careful consideration of the different spatial and temporal scales of groundwater – surface water interaction between the river and the alluvial aquifer.

Attempts were made at the Dumaresq River to estimate the reach-scale infiltration rates by differential gauging. The stretch of river between Texas Bridge and Site 1 was gaining but no clear trends emerged downstream from Site 1 to Cunningham Weir. However, conditions for differential gauging were not ideal because the field trip coincided with the tailing end of an irrigation release (that is, discharge was not steady at daily time scales along the study reach). Thus, the differential gauging results must be considered with some caution.

**Recommendations**

The Losing Streams project was successful in developing and applying a methodology to identify the type of connection present at specific points along losing river systems. This methodology can now be used to provide calibration points during regional-scale assessment of connectivity. The riparian transect experimental design used for the study appears suitable to estimate infiltration rates when using groundwater age-dating tools such as CFCs and especially SF$_6$. However, only a few SF$_6$ samples were obtained as a part of this study because this dating technique (including noble gas measurements) has only become recently available in Australia.

At the Dumaresq River and the other study reaches, the least successful aspect of the project has been attempts at estimating reach-scale infiltration rates by differential gauging. At present, the only reach-scale estimates of infiltration rate along losing rivers in the MDB have been obtained through the calibration of regional groundwater models. Ideally, infiltration should be measured independently in order to better constrain the groundwater models. Thus, there is a need to develop a methodology to estimate reach-scale infiltration along losing rivers in the MDB applicable under a range of flow conditions.

The recommendations arising from the site characterisation at the Dumaresq River are to:

- Use the field measurements, especially the identification of gaining and losing-connected conditions to help constrain existing groundwater models for the Dumaresq River alluvial aquifer;
- Monitor the piezometric and surface water levels for a longer period of time at the two study transects to better evaluate the near-stream hydraulic head response for different flow events (floods and irrigation releases);
- Re-assess the connectivity at the two sites following a prolonged wet period to evaluate if it changes over time;
- Determine and apply an appropriate hydrometric technique to measure infiltration at the reach-scale;
- Undertake additional alluvial groundwater dating in the riparian piezometer transects using SF$_6$ and noble gases measurements to estimate site-specific infiltration rates;
• Identify the source of regional groundwater discharge to the Dumaresq River by characterising the geochemical and environmental tracer signature of nearby rock aquifers and the underlying GAB;

• Characterise the seasonal variability in the stable isotopes of river water as this tracer could be a good marker for the source of recharge to the alluvial aquifer.
1. INTRODUCTION

To address some of the uncertainties associated with surface water – groundwater interaction in losing streams, the NSW Office of Water, National Water Commission, CSIRO Land and Water, Heritage Computing Inc., and Flinders University have collaborated on a major investigation of six rivers in New South Wales (Fig. 1). The project is titled *Interconnection of Surface and Groundwater Systems – River Losses from Losing / Disconnected Streams.*

The general aim of this project was to further advance the current understanding of groundwater – surface water interaction in Australian rivers by developing new approaches and techniques to determine the nature of the connection in losing streams and the rates of surface water leakage to groundwater. In particular, the study aimed to better understand the behaviour of losing-connected and losing-disconnected streams and what these conditions might mean for water management.

In losing-connected streams, the water table is an extension of the stream in the subsurface and slopes away from it. In losing-disconnected streams, the water table is well below the streambed and infiltration from the river occurs through an unsaturated zone. It is necessary to know what kind of connection is present in a given area to evaluate current and future exchanges between streams and aquifers. In other words, how further groundwater extraction will impact on streamflow or how environmental releases of surface water will recharge alluvial aquifers will be dependent on the type of connection present in a given area. The detailed objectives of the project were to:

- Develop new groundwater modelling techniques to study losing stream systems;
- Identify whether losing-connected or losing-disconnected conditions occur along six NSW river reaches (Fig. 1);
- Estimate the infiltration rate at selected areas along these river reaches;
- Add this information to existing models used to manage groundwater and surface water resources.

This report describes the field sampling and laboratory measurements at the Dumaresq River in the Border Rivers area (Fig. 1) and discusses their implications for the management of losing stream environments. Brownbill et al. (2011) provides a general overview of the project’s results. The development of improved conceptual representations for losing stream environments (Brunner et al. 2009a,b) and their application to regional groundwater models (Brunner et al. 2010a,b) including those specific to each study rivers (Heritage Computing 2009; 2010) are dealt with in companion publications to this report. The other site reports and an overview of the connection status at all sites are presented in Lamontagne et al. (2010; 2011a-e). The Dumaresq River was also chosen as the site for the project where groundwater dating using sulfur hexafluoride (SF₆) was tested. This was the first application of this technique in Australia. The use of He-4 to detect zones of regional groundwater discharge was also trialled at the Dumaresq site, one of the first applications of this technique in Australia.

1.1. General design for the Losing Streams field studies

1.1.1. Piezometer transects

The Dumaresq River and the other study reaches were each instrumented with two piezometer transects perpendicular to the rivers. Each transect usually consisted of three nests of paired piezometers extending from the top of the high bank next to the river channel to 100 – 200 m further away from the river. At each nest, one piezometer was usually
located 4 – 5 m and the second 10 – 15 m below the water table. The design of the piezometer transects was a compromise to achieve several goals, including to:

- Map in 2-D the piezometric surface in the vicinity of the river, in particular to evaluate the likelihood that the river is connected or disconnected;
- Follow the response of the piezometric surface to changes in stream stage over time, such as bank recharge – discharge cycles during floods; and,
- Be at the right spatial scale to enable the estimation of infiltration rates using groundwater-dating environmental tracers such as CFCs or Rn-222.

At each transect, the piezometers and a nearby surface water station were monitored for changes in water level to evaluate the hydraulic head response to flow events (natural floods and irrigation releases). To get some indication on the source and magnitude of recharge, the piezometer network was sampled on one occasion during the study for water quality (pH, dissolved oxygen, electrical conductivity and major ions) and environmental tracers (stable isotopes of water, $^{222}$Rn, CFC-11 and CFC-12). The stable isotopes of water can be used to help identify the source of the water in an aquifer, while $^{222}$Rn and chlorofluorocarbons (CFCs) can be used to determine groundwater “age” (that is, when water was recharged to the aquifer; Cook and Herczeg 2000). Rn-222 and CFCs were selected because they can “age” groundwater within the time–scales expected for recharge processes in near-stream environments. Radon-222 is a short-lived naturally-occurring radioactive gas with a short half-life ($t_{1/2} = 3.82$ days). CFCs are anthropogenic in origin and can date groundwater from ~1965 to the present (Cook and Herczeg 2000). SF$_6$ and He-4 dating were also trialled at the Dumaresq River and the theory for the use of these techniques is provided below.

![Figure 1. Location of the Murray-Darling Basin and of the six study reaches for the Losing Streams project.](image-url)
1.1.2. Theory for $\text{SF}_6$ dating, He-4 dating and excess air measurements using noble gases

$\text{SF}_6$

$\text{SF}_6$ is an anthropogenic gas which has been monotonously increasing in the earth's atmosphere for the past 50 years or so. The concentration of $\text{SF}_6$ measured in groundwater can be used to estimate when it was recharged. However, for accurate $\text{SF}_6$ dating the physical conditions at recharge – temperature, pressure, salinity and amount of excess air – must be known. The addition of excess air is extremely important in the case of $\text{SF}_6$ due to its low solubility. Noble gases concentrations in groundwater were measured to estimate excess air entrapment at recharge.

Noble gas-derived excess air

With the exception of helium, noble gas concentrations are set at recharge and are a function of the physical conditions at recharge. Thus, measured noble gas concentrations can be used to infer recharge temperature, salinity, pressure and amount of excess air. We use excess air calculated from noble gas compositions to correct $\text{SF}_6$ ages for excess $\text{SF}_6$ added by forced solution. The concentration of noble gases at recharge was modelled using the unfractionated excess air model (Porcelli et al. 2002) to solve for the amount of excess air which provided the best match to observed noble gas concentrations.

$^4\text{He}$

Uranium and thorium are present in all crustal materials. $^4\text{He}$ is produced throughout the U and Th decay chains and slowly builds up in groundwater along flow paths. The build-up occurs at geological time scales ($10^3$ – $10^8$ years) in most settings and $^4\text{He}$ concentrations above atmospheric background are only found in old groundwaters. Production rates of $^4\text{He}$ can vary spatially and temporally, with measured rates up to 100 times theoretical production (Solomon et al. 1996). Quantitative dating is only possible in areas where the production rate has been accurately quantified. While quantitative dating of groundwater using $^4\text{He}$ is difficult, it can be used semi-quantitatively as a tracer of old, regional groundwater, given the long times needed to build high concentrations.

1.1.3. Evaluation of the type of connection

A two-step approach was used to determine what kind of connection was present at each piezometer transect at the time of sampling. The first step was the bank test. At or near the piezometer transects, a 100-m section of the river was chosen and stations were staked at 20-m intervals along the banks. At each station (and on both sides of the river when possible), a pit or hole 1-2 m from the river’s edge was dug or augered to well below river level. When the pits or holes filled (became wet), the river was preliminary classified as being connected. When the holes or pits remained dry, the river was preliminary classified as being losing-disconnected.

The second step to confirm the type of connection was to measure the fluid pressure ($\psi$) in the streambed. The rationale for this approach is that $\psi$ will always be greater than or equal to 0 (positive) under connected conditions (either losing or gaining) and always lesser than or equal to 0 (negative) under losing-disconnected conditions (Lamontagne et al. 2010). In other words, a vadose zone is present when $\psi < 0$. Following wet bank tests, piezomanometry was used to confirm positive fluid pressures in the streambed. Following dry bank tests, vertical sediment profiles of the streambed (usually 2-4 m long) were
collected and fluid pressure in sediment samples measured in the laboratory using different techniques. Different techniques had to be used to determine positive or negative fluid pressures because piezomanometry cannot measure negative fluid pressures (Freeze and Cherry 1979). The detailed methodology for the piezomanometry is described in the Macquarie River report (Lamontagne et al. 2011c). More details about the determination of fluid pressures in sediment profiles are provided in the Billabong Creek and Lachlan reports (Lamontagne et al. 2011a,b).

![Diagram](image)

**Figure 2.** Experimental design to evaluate the type of connection at each piezometer transect. The piezometers were used to evaluate if the river was gaining or losing and, when losing, to evaluate how deep below river level was the water table in the riparian zone. Along a 100-m section of the river near the piezometers, six stations (flags) were set 20 m apart at the edge of the river. Bank tests were made at the stations (on both sides of the river when possible). Based on the results of the bank tests, fluid pressure in the streambed under the river was measured either by piezomanometry (along transects from bank to bank, see orange lines), or by collecting sediment profiles in the streambed (usually one profile from every other station).

### 1.1.4. Estimation of streambed hydraulic conductivity and infiltration rates

The vertical hydraulic conductivity of the streambed ($K_v$) and the infiltration rate through the streambed were evaluated *in situ* on one occasion at each transect. Because different techniques must be used to measure positive or negative fluid pressures (see section above), different strategies had to be used in losing-connected and losing-disconnected environments. In connected environments, $K_v$ was estimated using falling or constant head permeameter tests (Horslev 1951) and vertical hydraulic gradients ($i$) using piezomanometers (Kennedy et al. 2007). The infiltration rate (as the specific discharge; $q$) was then estimated using Darcy’s Law ($q = -K_v i$). The detailed procedure is described in the Macquarie River report (Lamontagne et al. 2011c).
In losing-disconnected environments, estimating the infiltration rate is more complex because $K_v$ will vary as a function of the sediment water content. Preliminary methodologies to measure the infiltration rate in losing-disconnected environments based on streambed $\psi$ profiles are presented in the Billabong Creek and Lachlan River reports (Lamontagne et al. 2011a,b).
2. METHODS

2.1. Site description

The Border Rivers region, the northernmost site for the study, covers approximately 4% of the Murray-Darling Basin. The selected study reach was on the Dumaresq River downstream from Texas, Qld (Fig. 3). The Dumaresq River joins MacIntyre Brook downstream from the study reach to become the MacIntyre River. CSIRO (2007) recently reviewed the hydrology and hydrogeology of the region. The region has a subtropical climate (wet summers) with an average annual rainfall of 641 mm. The study reach is located in the slopes region of the catchment, characterised by undulating country with numerous permanent or semi-permanent billabongs. The main land use is broadacre livestock grazing and the main irrigated crops are lucerne and cotton.

The catchment includes a number of hydrogeological systems, including various types of rock aquifers in the upland areas, alluvial aquifers in the valleys, and also intake beds for the Great Artesian Basin (CSIRO 2007). An area of dryland salinity occurs downstream from the study reach (Yelarbon salinity scald) and is thought to be derived from upwelling of GAB water through the Peel Fault (Knight et al. 1989). The alluvial aquifers are the main groundwater resource for the region. They usually consist of sand, gravel and clay sediments in units of varying thicknesses. Locally, the alluvial aquifers are classified as being “shallow” (when less than 30 m deep) or “deep” (when deeper than 30 m). The major source of recharge to the alluvial aquifers is thought to be infiltration from the river. In general, groundwater levels have been declining since the 1990s and significant cones of depression in the water table are found in the vicinity of major irrigation areas (CSIRO 2007). The Dumaresq River has a mixture of gaining and losing sections along its length (CSIRO 2007).

![Figure 3](image-url). Location of the study reach and of the two piezometer transects (Site 1 and Site 2) on the Dumaresq River.
2.2. Piezometer installation

The piezometer network was installed in March and April 2009 under supervision by a NoW hydrogeologist (M. O’Rourke). Due to the extreme heterogeneity of alluvial aquifer material encountered (from silty clay to cobbles), a number of drilling techniques had to be used. In general, a combination air and mud drilling was used but in some cases drilling had to switch to cable tool. The design of the piezometers was similar to the ones used at the other Losing Streams sites. Each piezometer consisted of a PVC pipe (51 mm dia. OD), a 2-m screen (slits), and a 1-m sump. The piezometers were protected by a lockable steel casing extending several meters below ground level and secured by a concrete base. Above ground, the steel casing was 2-m in length and consisted of two 1-m sections bolted together. The annulus around the piezometer was filled with rounded gravels up to 1-3 m above the screen, sealed with bentonite, and the rest of the annulus grouted. Three nested piezometers were installed at Site 2. However, at Site 1, the alluvial aquifer consisted only of low permeability features at depth (i.e., >10 m from the water table) and as a result three shallow and only one deep piezometer were installed at that transect. Site 1 also had an existing bore (GW040365/1) with a similar screen depth as the shallow ones installed for the project. Further details about the piezometer transects are provided in Appendix A.

2.3. Piezometric surface monitoring

The NoW Hydrometric Unit undertook monitoring of surface water and groundwater levels at each transect from March 2009 to March 2010. At each site, the river level and the water level in each piezometer were monitored using unvented pressure transducers (Mini-Diver; Schlumberger Water Services). The loggers recorded water levels at 15 min intervals with an accuracy of ±0.5 cm. A barometric pressure logger with the same technical specifications was also placed in one of the piezometers at each site.

Each logger was suspended in the piezometers by marine grade stainless steel trace wire in known lengths from a surveyed level. Every three months, the NoW Hydrometric Unit took manual water level readings, retrieved the individual loggers, downloaded the recorded data and ensured the loggers were operating correctly. Manual readings of the groundwater levels were also undertaken by CSIRO during their one-off field sampling campaign at which time each piezometer was purged and sampled for water quality and a suite of environmental tracers.

The water levels as measured by the pressure transducers are absolute pressures. This means that the pressure transducers are sealed and so are measuring the weight of water and the atmosphere above them. The barometric loggers at each transect were used to measure the atmospheric pressure and to convert absolute pressure into gauge pressure (or hydraulic head) following:

\[
\text{Hydraulic head (h) = Absolute Pressure – Barometric Pressure} \tag{1}
\]

2.3.1. Water quality and environmental tracers

Groundwater samples were collected from all piezometers, with the exception of piezometer GW093061/2 which tended to dewater to below the top of the screen. In addition, at each transect two groundwater samples were collected ~1 m below the streambed with a drive point (hereafter referred to as the “porewater” samples). Piezometers were purged for three bore volumes, with care taken that water level in the piezometers never dropped below the
top of the well screen. Field EC, field pH and temperature were measured under gently flowing conditions in a collection vessel. The probes were calibrated daily with standard solutions. The presence of H₂S (rotten egg odour) was noted when detected during sampling. Dissolved oxygen concentration was measured using a Winkler titration. Porewater samples were collected using the drive point component of a piezomanometer (Lamontagne et al. 2011c).

2.3.2. Collection of samples for laboratory measurements

All groundwater and surface water samples were 0.45 μm filtered in a field laboratory. For the stable isotopes of water, a subsample was then stored in a gas-tight collection vessel. For major cations, a 50 mL subsample was acidified (to pH<2) and stored in a well-rinsed 125-mL PET bottles. For major anions, total alkalinity, lab EC and lab pH, another sample was stored in a similar manner but without acidification. A field blank for major cations and anions was also prepared by processing a distilled water sample in the same way as the field samples. All samples were stored at 4°C until shipping for analysis at the CSIRO Analytical Chemistry Laboratory (Waite Campus, Adelaide).

Groundwater samples were also collected for radon-222 and CFCs. Briefly, radon-222 samples were collected in a 1.25 L PET bottle by inserting the end of the pump tube into the bottom of the bottle and allowing several volumes of overflow to minimise contact with the atmosphere. The bottles were then tightly capped and the time and date of collection recorded. Radon-222 samples were later extracted in mineral oil following Leaney and Herzeg (2006) and shipped within two days to the CSIRO Environmental Isotope Laboratory (EIL; Waite Campus, Adelaide) for counting. CFC samples were also collected with minimal exposure to the atmosphere following the standard protocol of the EIL. Briefly, this involved placing triplicate glass bottles at the bottom of a larger stainless steel container. Groundwater was then pumped through a nylon tube the end of which was placed at the bottom of one of the glass jars. Care was taken to place the pump above the well screen and to pump at a gentle flow rate to avoid dewatering the piezometer and exposing samples to the atmosphere. The jar and the larger container were then filled to overflow. Once filled and well flushed, the glass jars were sealed with a metal screwcap while still underwater. The jars were stored at room temperature until shipped to the EIL.

He-4, SF₆ and noble gases were sampled from all piezometers and from surface water at the two transects (but not from porewater). SF₆ was sampled in a similar manner to Rn-222 except that samples were collected and stored in 2 L amber glass bottles. For noble gases and He-4, equilibrium head space samples were collected using passive diffusion samplers (Gardner and Solomon 2009). Diffusion samplers were allowed to equilibrate with sample water (i.e., immersed in the piezometers or in the river) for 24 hours, retrieved, and clamped vacuum tight. Many SF₆ samples were lost during transit but three intact samples were measured.

2.3.3. Analytical methods

Laboratory EC (Meterlab CDM230) and pH (Orion 960) were measured with calibrated probes in a constant temperature room. Total alkalinity was measured by titration to a pH 4.5 end-point. Major cations were measured by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES; Spectro ARCOS) and anions by ion chromatrography (Dionex ICS – 2500). Total Dissolved Solids (TDS) was estimated from the sum of all major cations and anions in a sample.
Radon activities were measured in the laboratory by liquid scintillation on a LKB Wallac Quantulus counter using the pulse shape analysis program to discriminate alpha and beta decay (Herczeg et al. 1994). CFC-11 and CFC-12 concentrations were measured by first stripping the CFC gas from the water sample under a stream of ultra-high purity nitrogen gas. The CFC/nitrogen mixture was then passed through a gas chromatograph where the CFC-11 and CFC-12 peaks were identified and measured separately. The analytical set-up used at CSIRO is similar to the one described in Busenberg and Plummer (1992). The procedure used to convert CFC concentrations to apparent groundwater age is described in Plummer and Busenberg (2000). The isotope ratios in water were measured by isotope ratio mass-spectrometry (Europa Geo 20-20) using the WES technique or the uranium reduction method. The latter technique was used when the presence of H$_2$S in the samples was suspected to interfere with the measurement of deuterium using the WES technique. The isotopic ratios were expressed in parts per thousands (‰) relative to Vienna Standard Mean Ocean Water (VSMOW) using the delta ($\delta$) notation. For deuterium:

$$\delta^2H = \left[ \frac{R_{\text{sample}}}{R_{\text{std}}} - 1 \right] \times 1000$$

where $R_{\text{sample}}$ and $R_{\text{std}}$ are the $^2H$/H ratios in the sample and the standard, respectively.

$^{20}$Ne, $^{40}$He, N$_2$, and $^4$He concentrations were measured using a quadrupole mass spectrometer with cryogenic separation (Poole et al. 1997). SF$_6$ was analysed using purge and trap and electron capture gas chromatography.

### 2.4. Bank tests, streambed hydraulic conductivity and piezomanometry

At the Dumaresq River, a 100 m section of the streambed was staked more or less in the alignment of the piezometers at both transects. Bank tests were made on both sides of the river at most streambed transects. At each transect, $K_v$ and $i$ were then measured at several points in the streambed from bank to bank whenever possible. Measurements of the hydraulic conductivity of the streambed were made using both a falling head permeameter test and a constant head test. However, due to the presence of large gravels and cobbles, only constant head tests were possible at many measurement points. For the falling head test, a steel-base permeameter was used and is described in the Billabong Creek site report (Lamontagne et al. 2011a). Briefly, the permeameters were first inserted to a known depth in the streambed, a head of water (30 – 40 cm) was added using river water, and the rate of fall of this head was recorded. $K_v$ was estimated following Horslev (1951) and Genereux et al. (2008). The constant head tests were performed using the drive point component of the piezomanometer (see below) following Lamontagne et al. (2011c) and Cardenas and Zlotnik (2003).

A piezomanometer similar in design to Kennedy et al. (2007) was used to measure vertical hydraulic gradients in the streambed. The system was described in detail in the Macquarie River site report (Lamontagne et al. 2011c). Briefly, the piezomanometer consisted of a steel drive point with a 5 cm screen connected to an oil-water (or occasionally an air-water) manometer. The drive points were usually inserted 75 – 100 cm in the streambed. From two to four measurements of the hydraulic gradient were made at each streambed transect. The manometers were also used to measure the horizontal hydraulic gradient between the river and some of the bank pits. All hydraulic gradient measurements were made relative to
stream hydraulic head. Thus, negative gradients indicate losing conditions and positive gradients represent gaining conditions. The location of all permeameter and piezomanometer measurement points was measured relative to the true left bank using a measuring tape.

There were usually distinct patterns in hydraulic gradient from bank to bank along the streambed transects at most connected Losing Streams sites (for example, one side of the river was gaining and the other losing). For this reason, transects rather than individual sampling points on transects were used as the experimental units. The infiltration rate was estimated as the average specific infiltration rate per transect \((q, \text{ m day}^{-1})\) and also as the infiltration per unit stream length per unit time \((Q_L = \text{m}^3 \text{m}^{-1} \text{day}^{-1} \text{or ML km}^{-1} \text{day}^{-1})\). These were estimated as:

\[
Q_L = -\sum_{x=1}^{n} K_x i_x w_x
\]

and,

\[
q = \frac{Q_L}{w},
\]

where \(K_x\) and \(i_x\) are, respectively, the hydraulic conductivity and the hydraulic gradient at measuring point \(x\) on the transect, \(w_x\) the distance represented by the half-way mark from the preceding to the subsequent measuring point, and \(w\) the stream width. For sampling points nearest to the banks, \(w_x\) was the distance from the bank to the half-way mark to the next measurement point.

### 2.5. Differential gauging

Two sets of differential flow gauging were made during the site visit to estimate the reach-scale infiltration rates. On October 20, river discharge was measured upstream and downstream from Site 1 and, on October 22, at Texas Bridge (upstream of Site 1), Site 1, Site 2 and Cunningham Weir (downstream from Site 2). Casual observations indicated that tributaries inflows and surface water abstractions were minimal along the reach during the measurement period. At each location, a measuring tape was laid across the stream. Stream velocity was measured at 0.2 and 0.8 maximum depth at 10 – 12 equidistant point across the stream using an electromagnetic flow meter. At most locations, the whole procedure was repeated in order to derive the error on the discharge measurements.

### 3. RESULTS

#### 3.1. Geological cross-sections

The key feature of the geological cross-sections at both transects was that they contained significant gravel units at about the same depth as the streambed (Figs. 4 and 5). However, the alluvial aquifer also included sand, silt and clay layers of varying thicknesses. At Site 1, the alluvial aquifer was thin (<10 m) and in contact with weathered bedrock (Texas Beds). The alluvial plain at the transects was 5 – 10 m below the high bank and included extensive sand and gravel banks with a meandering or braided channel (see picture on cover).

At the time of the site visit (19 – 23 October 2009), low flow conditions were present and most of the stream was less than 1 m deep. At Site 1, the horizontal hydraulic gradient in the riparian zone was towards the river (i.e., gaining). However, there was a large downward
vertical hydraulic gradient in the only piezometer nest at that transect (Fig. 4). At Site 2, the horizontal hydraulic gradient was away from the river (losing) and there was a distinct downward hydraulic gradient in only one piezometer nest (Fig. 5).

**Figure 4.** Cross-sectional profiles at the Site 1 transect, showing the hydraulic head in piezometers and the surface water elevation in the river at the time of the site visit (19 – 23 October 2009). The geological logs were taken during drilling and the surface topography and alluvial plain profiles measured by surveying. The bottom-most sandy clay unit corresponds to weathered bedrock. For the piezometer nest, the left water level is for the deep and the right one for the shallow piezometer.

**Figure 5.** Cross-sectional profiles at the Site 2 transect, showing the hydraulic head in piezometers and the surface water elevation in the river at the time of the site visit (19 – 23 October 2009).
3.2. Temporal variations in hydraulic head

The monitoring period (April 2009 to April 2010) had two significant floods (May–June 2009 and December 2009–January 2010) and one prolonged flow recession period punctuated by smaller flow events (primarily irrigation or environmental releases from Glenlyon Dam). At Site 1, there were flow reversal events associated with the floods and irrigation releases (Fig. 6). The river was gaining under low flow conditions but losing for about a week during floods. The flood hydrographs had sharp peaks 4 – 5 m higher than low flow levels. These corresponded to an increase in hydraulic head of 2 – 3 m for the piezometer closest to the river and an increase of 1 m or less for the others. There was only a weak response to flow events in the single “deep” piezometer at Site 1. Smaller gradient reversals were also observed during some of the dam releases.

Losing conditions prevailed at Site 2 during the whole monitoring period (Fig. 7). Hydraulic heads responded to the flood pulses, more or less rising and falling in synchrony with river stage. The hydraulic head response was greater in those piezometers closest to the river than at a distance. At the high bank piezometer nest, a downward hydraulic gradient also remained present throughout the monitoring period.
Figure 6. Temporal variations in hydraulic head and in stream stage during the monitoring period at Site 1. Symbols represent manual water level measurements.
Figure 7. Temporal variations in hydraulic head and in stream stage during the monitoring period at Site 2. Symbols represent manual water level measurements.
3.3. Water quality and environmental tracers

3.3.1. Salinity and stable isotopes of water

Surface and groundwater was fresh at both transects, with salinities ranging from 60 to 100 mg L$^{-1}$ as Total Dissolved Solids (Fig. 8 and Appendix B). The two samples with the highest TDS were from shallow groundwater at Site 1 (i.e., the gaining reach). As for most of the other Losing Streams sites, there was a greater variation in isotopic composition than in salinity (Fig. 8). In general, deuterium values were more elevated in the river and values in groundwater declined with distance from the river. At a given distance from the river, values in groundwater were generally more elevated at Site 1 than at Site 2. The higher isotopic values in the river and in groundwater close to the river were due to evaporative enrichment (Fig. 9). This suggests that some recharge occurs at both transects under low flow conditions, when surface water will tend to have an evaporation signal.

Figure 8. Deuterium values at the Dumaresq River transects as a function of (A) salinity (as TDS) and (B) distance from the river.

Figure 9. Deuterium – $^{18}$O plot for the Dumaresq River transects, showing the Murray Basin Meteoric Water Line ($\delta^2$H = 7.6 $\delta^{18}$O + 8; Simpson and Herczeg 1991a), the Brisbane Meteoric Water Line ($\delta^2$H = 7.7 $\delta^{18}$O + 12.6) and the evaporation line ($\delta^2$H = 5.2 $\delta^{18}$O – 6.8) for the Dumaresq samples.
3.3.2. SF₆ and CFCs

The three SF₆ samples contained modern amounts of SF₆ and indicated very young groundwater ages using the piston flow model (Table 1). SF₆ concentrations are highly sensitive to forced solution of excess air and noble gas concentrations were used to estimate excess air addition. Noble gas derived excess air (Aₑ) amount in cubic centimetres of air at standard temperature and pressure per gram of water (ccSTP g⁻¹), percent neon enrichment over atmospheric equilibrium (ΔNe), and total dissolved gas pressure (TDG) are given in Table 2 and were used to correct the total SF₆ concentrations measurements.

The SF₆ recharge ages corrected for excess air did not correspond well to the CFC-12 recharge ages using either a piston flow or a mixing model (Fig. 10). In all cases, the CFC-12 ages appeared older than the ones obtained with SF₆. One possibility is that some SF₆ contamination occurred, yielding SF₆ ages younger than expected. However, as for all the other Losing Streams sites, the lack of agreement between CFC-11 and CFC-12 derived ages in many samples suggested that the discrepancies between SF₆ and CFC-12 ages was due to CFC-12 degradation in the aquifer (Appendix C). This was especially apparent in the porewater samples, which are unlikely to be more than a few years old but in many instances only had trace concentrations of CFCs. CFC degradation can occur under anoxic or suboxic conditions, which were common in groundwater at both piezometer transects (Appendix B).

Table 1. Total SF₆ concentrations, excess air, calculated atmospheric concentrations and piston flow recharge year and age.

<table>
<thead>
<tr>
<th>Well</th>
<th>Total SF₆ at STP fmol kg⁻¹</th>
<th>Excess air cc kg⁻¹</th>
<th>Calculated SF₆ partial pressure pptv</th>
<th>Piston flow model recharge year</th>
<th>Piston flow model SF₆ recharge age</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW093060/1</td>
<td>1.74</td>
<td>3.7</td>
<td>4.10</td>
<td>1999</td>
<td>10.88</td>
</tr>
<tr>
<td>GW093065/1</td>
<td>1.70</td>
<td>7.4</td>
<td>3.21</td>
<td>1995.5</td>
<td>14.38</td>
</tr>
<tr>
<td>GW093062/1</td>
<td>1.90</td>
<td>6.4</td>
<td>3.87</td>
<td>1998</td>
<td>11.88</td>
</tr>
</tbody>
</table>

Table 2. Excess air (Aₑ), Neon enrichment, and total dissolved gas pressure (TDG).

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Ae (ccSTP g⁻¹)</th>
<th>Δ Ne (%)</th>
<th>TDG (atm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>0.0037</td>
<td>31.55</td>
<td>0.92</td>
</tr>
<tr>
<td>D3</td>
<td>0.0074</td>
<td>71.22</td>
<td>1.07</td>
</tr>
<tr>
<td>D12</td>
<td>0.0064</td>
<td>57.53</td>
<td>1.24</td>
</tr>
</tbody>
</table>
3.3.3. Terrigenic $^4\text{He}$

Helium-4 concentration in groundwater is the sum of atmospherically derived helium ($^4\text{He}_{\text{atm}}$), helium from excess air ($^4\text{He}_{\text{Ae}}$) and terrigenic helium ($^4\text{He}_{\text{terr}}$) produced from radioactive decay within the aquifer and (in some cases) transport from deeper in the mantle’s crust. Thus, the mass-balance for total $^4\text{He}$ concentration in groundwater ($^4\text{He}_i$) is:

$$^4\text{He}_i = ^4\text{He}_{\text{atm}} + ^4\text{He}_{\text{Ae}} + ^4\text{He}_{\text{terr}}$$  \hspace{1cm} (5)

Dissolved concentrations of $^{20}\text{Ne}$, $^{40}\text{Ar}$, and $\text{N}_2$ were fitted with the closed equilibrium model to calculate the total amount of helium from atmospheric equilibrium and excess air (Aeschbach-Hertig et al. 2000). Excess helium above that from atmospheric sources is due to terrigenic $^4\text{He}$. Noble gas concentrations, best fit model parameters, and derived terrigenic helium are given in Appendix D.

There was considerable $^4\text{He}_{\text{terr}}$ in all samples at Site 2 but only in surface water and in the piezometer closest to the river at Site 1. Comparisons between $^4\text{He}_{\text{terr}}$, CFC-12 and SF$_6$ show a complex mixture of tracers at both transects. These will be reviewed in more detail in the Discussion.
3.4. Bank tests and Darcy flux measurements

3.4.1. Bank tests

From four to six bank tests were performed at both Site 1 and Site 2 and they were all “wet”. Some of the hydraulic gradients between bank pits and the river are presented in Section 3.4.3.

3.4.2. Hydraulic conductivity

With the exception of a sand bar at Site 2, it was difficult to insert the permeameter for the falling head test in the Dumaresq streambed because of the presence of gravels and cobbles. Despite fewer deployments, a wider range in $K$ was measured with the falling than the constant head test (Fig. 11). In particular, the highest $K$ values were measured with the falling head test. As discussed in other site reports, the constant head test may have an upper detection limit of $\sim 10^{-3.5}$ m s$^{-1}$ with the instrumentation used. The log-averaged streambed hydraulic conductivity was 5E-5 and 9E-5 m s$^{-1}$ using the constant and falling head tests, respectively, equivalent to a silty sand or sand porous medium. This is consistent with the texture of the streambed, which consisted of gravels and cobbles imbedded in a silt and sand matrix.

Figure 11. Hydraulic conductivity measurements for the streambed of the Dumaresq River using (A) Falling head tests and (B) Constant head tests.
3.4.3. Hydraulic gradients

A mixture of gaining and losing conditions were found in the streambed at Site 1 and Site 2. At Site 1 (Fig. 12), there was a tendency for gaining conditions along the banks and losing conditions in the middle of the stream channel. At Site 2 (Fig. 13), the true right bank (i.e., right bank when facing downstream) was gaining and the left one losing. Both sites had well-developed sand and gravel bars in the alluvial plain. Drainage from sand and gravel bars as the river stage was slowly receding may have contributed to the positive vertical hydraulic gradients along the edges of the river.
Figure 12. Hydraulic conductivity derived from constant head tests ($K_{CH}$) and hydraulic gradients along the streambed transects at Site 1. River stage was low and receding at the time of sampling. Additional details in Appendix E.

Figure 13. Hydraulic conductivity from constant head tests ($K_{CH}$) and hydraulic gradients along the streambed transects at Site 2. River stage was low and receding at the time of sampling. Additional details in Appendix F.
3.4.4. Darcy flux

As described in the Namoi and Macquarie reports, because of the tendency for systematic variations in hydraulic gradients along streambed transects, whole transects rather than individual measurement points were used as the experimental units. As a result, only transects with hydraulic head measurement points from bank to bank were used to avoid introducing a bias. There were gaining and losing streambed transects at both Site 1 and Site 2 (Appendices E and F). On average, the specific infiltration rate was –0.44 and –0.03 m day\(^{-1}\) at sites 1 and 2, respectively (that is, they were net gaining). However, the error on these infiltration rates was large at both sites (Appendices E and F) and both could have been either gaining or losing. Receding flow conditions at the time of sampling (Figs. 6 and 7) are likely to have introduced more gaining conditions at the scale of the alluvial plain through the drainage of sand and gravel bars along the river.

3.5. Differential gauging

There were significant variations in river discharge along the river reach during the site visit. On October 20, the average discharge was 37.38 and 33.52 ML day\(^{-1}\) two km upstream and downstream from Site 1 but the difference was not statistically different (Table 3). Discharge was 50% lower on October 22 at Site 1 relative to two days before (Table 3), consistent with the field trip coinciding with the recession of an irrigation pulse (Fig. 6). On October 22, there was a significant increase in discharge between Texas Bridge and Site 1 but no statistically significant change in discharge from Site 1 onward. Thus, the river section between Texas Bridge and Site 1 appeared to be gaining. On the other hand, the result could have been biased by the non-steady flow conditions. In particular, the section of the river between Texas Bridge and Site 1 is connected to a number of oxbows. These would tend to empty back into the river during river recession and sustain the discharge relative to upstream areas. In other words, the irrigation pulse may have passed Texas Bridge but not Site 1 by October 22.
Table 3. River discharge measurements on the Dumaresq River on 20 and 22 October 2009. The average discharge between upstream and the next downstream location were compared with $t$ tests. On October 22, only one measurement was made at Texas Bridge and Site 2 and the average variance to mean ratio from Site 1 and Cunningham Weir (2.2%) was used as an estimate of the measurement error. The resulting statistical tests in this case had two degrees of freedom instead of three (* indicates a statistical difference at $P = 0.05$ or less relative to the preceding discharge measurement). Confidence intervals on the infiltration rates estimated following Zar (1999). Negative infiltration indicates groundwater discharge.

<table>
<thead>
<tr>
<th>Location</th>
<th>Measurement #1 (ML day$^{-1}$)</th>
<th>Measurement #2 (ML day$^{-1}$)</th>
<th>Average ± SD (ML day$^{-1}$)</th>
<th>River km from first location</th>
<th>Infiltration rate (ML km$^{-1}$ day$^{-1}$) (mean ± 95% C.I.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 October 2009</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upstream Site 1</td>
<td>36.40</td>
<td>38.36</td>
<td>37.38 ± 1.39</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>Downstream Site 1</td>
<td>36.64</td>
<td>30.40</td>
<td>33.52 ± 4.41$^{n.s.}$</td>
<td>3.96</td>
<td>$-0.97 ± 1.9$</td>
</tr>
<tr>
<td>22 October 2009</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Texas Bridge</td>
<td>7.72</td>
<td>–</td>
<td>7.72</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>Site 1</td>
<td>20.06</td>
<td>19.44</td>
<td>19.75 ± 0.438*</td>
<td>18.5</td>
<td>0.65 ± 0.081</td>
</tr>
<tr>
<td>Site 2</td>
<td>19.18</td>
<td>–</td>
<td>19.18$^{n.s.}$</td>
<td>29.6</td>
<td>$-0.05 ± 0.21$</td>
</tr>
<tr>
<td>Cunningham Weir</td>
<td>21.23</td>
<td>22.45</td>
<td>21.84 ± 0.86$^{n.s.}$</td>
<td>34.2</td>
<td>0.58 ± 0.58</td>
</tr>
</tbody>
</table>
4. DISCUSSION

4.1. Connection status

The Dumaresq River transects were connected, but one transect was gaining and the other losing. This was not unexpected because alternating losing and gaining sections are common along this river (CSIRO 2007) and locally losing conditions can be induced by drawdown cones (CSIRO 2007). Another feature of the Dumaresq transects relative to the other Losing Streams site was the presence of extensive sand and gravel bars and banks in the alluvial plain. Some of the gravel bars were extensive, ranging in size from up to hundreds of meters in length and several meters in thickness (S. Lamontagne, personal observations). These alluvial plain deposits also appear to readily exchange water with the river, as shown by the patterns in hydraulic head gradient in the streambed. During low flow periods, irrigation releases probably continuously mix surface and alluvial groundwater by generating bank recharge-discharge cycles with alluvial plain deposits.

Because of the presence of a permeable streambed, the two Dumaresq River transects are not likely to become losing-disconnected with further pumping from the alluvial aquifer. To generate disconnected conditions, a clogging layer with a lower hydraulic conductivity than the alluvial aquifer must be present in the streambed (Brunner et al. 2009a). When there is no clogging layer, further alluvial groundwater pumping lowers the water table, increases the hydraulic gradient, and increases the infiltration rate from the river. Thus, rather than disconnecting, the river eventually dries out.

4.2. Environmental tracers

The Dumaresq transects demonstrated the usefulness of several new tracer techniques to study groundwater – surface water interaction and infiltration rates in losing streams. The information provided by environmental tracers, in particular their ability to “age” groundwater, must be interpreted in the context of what possible recharge and mixing processes occur in the aquifer. In other words, the “age” provided is often an “apparent” age and is context-specific. The simplest case for the interpretation of tracers is the “piston flow” scenario, where a parcel of water moves along a flow path without mixing with surrounding groundwater. In this case, groundwater will get progressively older along the flow path. The piston flow scenario is probably too simplistic in near-stream environments, where groundwater can be from a mixture of different sources. For example, an alluvial aquifer can be infrequently but evenly recharged during a large flood, yielding a constant age throughout the system. However, subsequent bank recharge - discharge cycles (from irrigation releases, etc) could mix old and young groundwater together, especially near the river. In this case, groundwater would have an even age at a distance from the river but progressively younger ages closer. The interpretation of the Dumaresq SF$_6$, CFC-12 and He-4 data illustrates how age-dating with environmental tracers is context-dependent and is reviewed in some detail in the following.

4.2.1. SF$_6$ and CFCs

All three SF$_6$ samples contain some excess air (Table 1), showing that the alluvial aquifer recharge mechanism(s) tended to dissolve more gases in groundwater than what would be expected from equilibrium with the atmosphere alone. On average, excess air correction resulted in lower SF$_6$ apparent ages by about 10 years. However, even with excess air correction, all three samples showed a significant discrepancy between SF$_6$ and CFC-12 concentrations. This can be the result of either CFC-12 degradation or SF$_6$ contamination.
Due to the presence of anoxic conditions in the aquifer and the mismatch between the CFC-11 and CFC-12 ages, CFC degradation is the most likely scenario. Nevertheless, CFC-12 (the less degradable of the two) can still be used in a qualitative sense. If some CFC-12 is found, the groundwater was recharged after 1960. If no CFC-12 is found, groundwater could be older or younger than 1960. Using this approach, both Site 1 and Site 2 had some groundwater recharged after 1960 (Appendix C). However, the few groundwater ages available using SF6 suggest that groundwater was recharged more recently at both transects. Using the piston flow model, the SF6-derived recharge dates range between 1995.5 and 1999. Again, these are “apparent” recharge ages and may represent the “average” date of recharge from a mixture of groundwater sources. If mixing also occurred, the groundwater could be younger (see below).

4.2.2. Terrigenic He-4

The presence of elevated 4He in river water at the Dumaresq transects is interesting. The only way to have elevated 4He in surface water is via discharge of regional groundwater within about 5 km upstream of the sampling point because 4He will degas to the atmosphere once in surface water. On the other hand, in the Dumaresq 4He may be more conservative (i.e., could be transported over greater distances) because of transport within and exchange with the parafluvial groundwater pool. The parafluvial groundwater pool could be enriched in CFC, SF6 and 4He due to the continuous mixing with the river provided by bank recharge-discharge cycles and hyporheic exchange. Hyporheic exchange (the exchange of water promoted by flow over uneven streambeds; Jones and Mulholland 2000) is probably more significant at the Dumaresq relative to the other Losing Streams river reaches because of the combination of permeable sediments and a number of runs and riffles (see picture on cover). Overall, mixing processes during low flow conditions will result in the water infiltrating in the alluvial aquifer having a mixed signature of “old” (He-4) and “young” water (SF6 and CFCs) along the Dumaresq study reach.

The variations in CFC-12, SF6 and 4He_{terr} concentrations in alluvial groundwater were complex and had features consistent at times with recharge by piston flow or by mixing between different water sources (Figs. 14 and 15). In general, the main difference between alluvial groundwater samples was the presence or absence of 4He_{terr}, suggesting that there is a recharge process bringing low 4He_{terr} to the aquifer. The pattern was different between Site 1 and Site 2. At Site 1, 4He_{terr} was only found in surface water and in the piezometer closest to the river, while at Site 2 4He_{terr} was present in all groundwater samples.
Figure 14. Comparison of CFC-12 and $^{4}\text{He}_{\text{terr}}$ concentrations at (A) Site 1 and (B) Site 2. Also illustrated are the expected concentrations assuming either mixing between an old and a young groundwater source or a piston flow model for a single water source. The groundwater ages inferred from $^{4}\text{He}_{\text{terr}}$ dating (in red) are indicative only. However, groundwater must be at least thousands of years old to contain $^{4}\text{He}_{\text{terr}}$ above background.

Figure 15. Comparison of $^{4}\text{He}_{\text{terr}}$ and SF$_6$ concentrations (corrected for excess air) from three groundwater samples at the Dumaresq piezometer transects.
4.2.3. Salinity and stable isotopes

Salinity and stable isotopes of water appear useful indicators of the origin of groundwater for the Dumaresq alluvial aquifer and the other sites investigated in the Losing Streams project. In a regional survey of Border Rivers alluvial groundwater and surface water, Baskaran et al. (2009) also found distinct groundwater types based on salinity and stable isotopes. They hypothesised that saline groundwater only occurred where the aquifer was infrequently or never recharged from the river. For the fresher groundwaters (less than 1000 mg L$^{-1}$), they also found a wide range in isotopic signatures (–39 to –12‰ for deuterium) and this was hypothesised to represent different modes of recharge from the river. Stable isotopes could be good markers to distinguish recharge during floods as opposed to during low flow conditions because floods will tend to have depleted isotopic signatures and the low flow waters an enriched one that includes an evaporation signal (Lamontagne et al. 2005; Cartwright et al. 2010). Long water residence times in reservoirs and in rivers will foster evaporative enrichment in most Murray-Darling Basin tributaries, yielding higher isotopic signatures under low flow conditions (Simpson and Herczeg 1991a,b). Subsequent groundwater transpiration by phreatophytes could increase salinity but will not change the isotopic signature of groundwater. The isotopic signature of diffuse rainfall recharge should closely approximate winter rainfall in the Murray-Darling Basin (Allison et al. 1985; Herczeg et al. 2001). If the end-member signature of different floods and subsequent low flow events was known more precisely, it would be possible to estimate the proportion of different sources of water at a particular point in the alluvial aquifer. This could be achieved by including sampling for stable isotopes of water in routine surface water quality monitoring programs for the major MDB tributaries.

4.3. Recharge processes at the Dumaresq

Based on the environmental tracer data, alluvial groundwater recharge at the Dumaresq appears to have different spatial and temporal scales. Significant recharge to the alluvial aquifer probably occurs during overbank flood events. This is consistent with the presence of low salinity water with a depleted isotopic signature and no evaporation signal in the piezometers furthest from the river. It can also be hypothesised that during floods the proportion of deep regional groundwater in the river would be low and that surface water would have atmospheric He-4 concentrations (that is, no $^{4}\text{He}_{\text{terr}}$). At the gaining site (Fig. 16), the combination of high SF$_6$ concentrations and low $^{4}\text{He}_{\text{terr}}$ in alluvial groundwater is consistent with recent flood recharge as the source of water. During low flow periods, this groundwater flows back towards the river. However, this is not strictly a piston flow process because groundwater closest to the river also included some “low flow” water (as shown by high SF$_6$, $^{4}\text{He}_{\text{terr}}$, and the evaporation signal in the stable isotopes of water). Under low flow conditions, some mixing of river and alluvial groundwater probably occurs near the river because of bank recharge-discharge cycles induced by irrigation releases and hyporheic exchange. At the losing site (Fig. 16), the presence of $^{4}\text{He}_{\text{terr}}$ in all piezometers indicates either that flood recharge has not occurred recently or that this source of water has been flushed out by the infiltrating “low flow” river water since the last flood recharge event. In the latter case, groundwater with high SF$_6$ and low $^{4}\text{He}_{\text{terr}}$ may be found at a further distance from the infiltration front (that is, there may be flood recharge water further away into the floodplain).

The overall pattern at the Dumaresq transects is for a complex recharge environment with some features from both piston flow and mixing processes. Thus, the interpretation of tracer-derived ages and the inferences of infiltration rates must be done with care. To estimate the infiltration rate using environmental tracers at the Dumaresq transects requires further SF$_6$ dating due to the uncertainties associated with CFC dating in this alluvial aquifer. In addition
the tracer data will need to be interpreted using a groundwater flow model that takes into account mixing and transport processes.

Figure 16. Conceptual diagrams representing the different sources of groundwater at the Dumaresq transects (with their expected $^{4}\text{He}_{\text{tert}}$ and SF$_6$ concentrations) and different potential recharge and mixing processes (A) Gaining conditions; (B) Losing conditions.
4.4. Conclusions and recommendations

The Dumaresq River was connected at the two sites visited in October 2009, but one site was gaining and the other losing to the alluvial aquifer. The presence of $^{3}$He$_{aerr}$ in surface and alluvial groundwater also indicates that the river reach is a regional groundwater discharge area. Thus, the Dumaresq River is either a gaining or a flow-through system at the regional scale. The source of the regional groundwater is unclear at present. The northern side of the alluvial aquifer abuts rock aquifers and the area downstream from the study reach is thought to receive discharge from the Great Artesian Basin through a fault line. The origin of the regional groundwater could be determined in future studies by comparing the geochemistry and environmental tracer signature of alluvial aquifers, rock aquifers and the GAB in the area.

Sampling at the Dumaresq River highlighted the usefulness of SF$_{6}$ and noble gas measurements as dating tools for alluvial groundwater near rivers in the Murray-Darling Basin. SF$_{6}$ can date groundwater over the same age-range as CFCs but appears less susceptible to degradation in anoxic streambed or aquifers (Plummer and Busenberg 2000; Happel et al. 2003). Noble gas measurements are required to estimate excess air in groundwater in order to age it more accurately with SF$_{6}$. One of the noble gases, He-4, can be used to identify the presence of very old groundwater in rivers or alluvial aquifers. Unfortunately, too few SF$_{6}$ measurements were obtained as a part of this study to estimate infiltration rates at the transects. The interpretation of the tracer data will also require a careful consideration of the different spatial and temporal scales of groundwater – surface water interaction between the river and the alluvial aquifer.

As was also seen at other Losing Streams study reaches, the steady flow conditions needed to estimate infiltration rates by differential gauging appear to rarely occur under low flow conditions at the Dumaresq River. This is attributed in part to the “working” nature of the river, where irrigation releases regularly send flow pulses through the river system. Alternative hydrometric techniques to estimate infiltration rates from rivers are briefly discussed in the Namoi report (Lamontagne et al. 2011d)

Recommendations

The Losing Streams project was successful in developing and applying a methodology to identify the type of connection present at specific points along losing river systems. This methodology can now be used to provide calibration points during regional-scale assessment of connectivity. The riparian transect experimental design used for the study appears suitable to estimate infiltration rates when using groundwater age-dating tools such as CFCs and especially SF$_{6}$. However, only a few SF$_{6}$ samples were obtained as a part of this study because this dating technique (including noble gas measurements) has only become recently available in Australia. Post-bomb tritium (Morgenstern et al. 2010) could also be trialled as a groundwater dating technique using this piezometer transect design.

The least successful aspect of the project has been the estimation of reach-scale infiltration rates by differential gauging. At present, the only reach-scale estimates of infiltration rate along losing rivers in the MDB have been obtained through the calibration of regional groundwater models. Ideally, infiltration should be measured independently in order to better constrain the groundwater models. Thus, there is a need to develop a methodology to estimate reach-scale infiltration along losing rivers in the Murray-Darling Basin applicable under a range of flow conditions.
The recommendations arising from the site characterisation at the Dumaresq River are to:

- Use the field measurements, especially the identification of gaining and losing-connected conditions to help constrain existing regional groundwater models for the Dumaresq River alluvial aquifer;

- Monitor the piezometric and surface water levels for a longer period of time at the two study transects to better evaluate the near-stream hydraulic head response for different flow events;

- Re-assess the connectivity at the two sites following a prolonged wet period to evaluate if it can change over time;

- Determine and apply an appropriate hydrometric technique to measure infiltration rate at the reach-scale in the Dumaresq River;

- Undertake additional alluvial groundwater dating in the riparian piezometer transects using SF₆ and noble gases measurements to estimate site-specific infiltration rates;

- Identify the source of regional groundwater discharge to the Dumaresq River by characterising the geochemical and environmental tracer signature of nearby rock aquifers and the underlying GAB aquifers;

- Characterise the seasonal variability in the stable isotopes of river water as this tracer could be a good marker for the source of the recharge to the alluvial aquifer.
REFERENCES


APPENDICES

Appendix A. Summary of the location and construction details for the piezometers and stream gauges at the Dumaresq River transects.

<table>
<thead>
<tr>
<th>Site</th>
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<td>151.0023</td>
<td>251.894</td>
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Appendix B. Surface and groundwater quality at the Dumaresq River transects on 19 – 23 October 2009.

| Sample Name                  | Lab pH | E.C. dS m\(^{-1}\) | Field E.C. dS m\(^{-1}\) | Temp. \((^\circ\text{C})\) | \(\text{O}_{2}\) mg L\(^{-1}\) (Winkler) | Alkalinity meq L\(^{-1}\) | Cl mg L\(^{-1}\) | SO\(_4\) mg L\(^{-1}\) | Ca mg L\(^{-1}\) | K mg L\(^{-1}\) | Mg mg L\(^{-1}\) | Na mg L\(^{-1}\) |
|------------------------------|--------|--------------------|---------------------------|-----------------------------|--------------------------------|------------------------|-------------|----------------|-----------------|----------------|----------------|----------------|---------|
| Dumaresq Site 1 - River      | 7.8    | 0.238              | 0.251                     | 17.8                        | 8.0                           | 1.0                    | 23.0        | 14             | 11              | 3.1            | 6.2            | 20.4           |         |
| Dumaresq Site 1 - streambed porewater 1 | 7.6    | 0.249              | –                         | –                           | –                             | 1.3                    | 27.0        | 0.45           | 11              | 2.5            | 6.6            | 23.9           |         |
| Dumaresq Site 1 - streambed porewater 2 | 8.2    | 0.275              | –                         | –                           | –                             | 1.7                    | 21.0        | 0.44           | 10              | 1.8            | 6.3            | 34.1           |         |
| GW093060/1                   | 8.0    | 0.223              | 0.255                     | 18.9                        | 1.0                           | 1.1                    | 25.0        | 2.0            | 8.6             | 1.6            | 4.2            | 23.3           |         |
| GW093061/1                   | 7.3    | 0.234              | 0.250                     | 18.5                        | 2.0                           | 1.0                    | 28.0        | 7.5            | 11              | 2.2            | 6.0            | 18             |         |
| GW093061/2                   |        |                    | –                         | –                           | –                             | –                      | –           | –              | –               | –              | –              | –              |         |
| GW040365                     | 7.4    | 0.213              | 0.257                     | 18.9                        | 0.60                          | 1.0                    | 24.0        | 2.2            | 9.3             | 1.7            | 4.9            | 20             |         |
| GW093062/1                   | 8.2    | 0.230              | 0.252                     | 18.9                        | 2.0                           | 1.2                    | 21.0        | 5.4            | 8.9             | 1.9            | 4.2            | 25.4           |         |
| Dumaresq Site 2 - River      | 7.9    | 0.246              | –                         | –                           | 8.0                           | 1.1                    | 24.0        | 14             | 11              | 3.1            | 6.3            | 21.1           |         |
| Dumaresq Site 2 - streambed porewater 1 | 7.4    | 0.207              | –                         | –                           | 0.90                          | 1.2                    | 32.0        | 1.9            | 11              | 3.8            | 5.2            | 20.9           |         |
| Dumaresq Site 2 - streambed porewater 2 | 7.4    | 0.254              | –                         | –                           | –                             | 1.2                    | 32.0        | 1.9            | 11              | 3.8            | 5.2            | 20.9           |         |
| GW093063/1                   | 7.0    | 0.233              | 0.252                     | 18.7                        | 2.0                           | 1.3                    | 23.0        | 2.0            | 9.1             | 1.2            | 4.9            | 24.1           |         |
| GW093063/2                   | 7.5    | 0.251              | 0.278                     | 18.0                        | 2.0                           | 1.7                    | 16          | 0.50           | 7.9             | 2.2            | 5.2            | 30.9           |         |
| GW093064/1                   | 7.1    | 0.263              | 0.288                     | 21.1                        | 3.0                           | 0.95                   | 34.0        | 14             | 9.1             | 1.2            | 5.8            | 27.2           |         |
| GW093064/2                   | 7.2    | 0.303              | 0.337                     | 18.5                        | 0.20                          | 2.0                    | 21.0        | 0.093          | 12              | 2.6            | 7.3            | 33.4           |         |
| GW093065/1                   | 7.2    | 0.303              | 0.384                     | 18.0                        | 0.20                          | 1.2                    | 46.0        | 1.3            | 11              | 1.9            | 5.6            | 33.7           |         |
| GW093065/2                   | 7.3    | 0.303              | 0.332                     | 18.0                        | –                             | 2.1                    | 19          | 0.68           | 14              | 2.2            | 5.5            | 35.7           |         |

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<th>CFC11 (years)</th>
<th>CFC12 (years)</th>
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Appendix D. Noble gas concentrations, closed equilibrium model parameters and terrigenic helium.

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<th>Bore</th>
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<th>Ne-20</th>
<th>N₂</th>
<th>Ar-40</th>
<th>Rech. Temp (°C)</th>
<th>Ae</th>
<th>Delta Ne</th>
<th>TDG Pres</th>
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Appendix E. Summary of the streambed infiltration rate measurements at Site 1.

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<th>$i$ (m m$^{-1}$)</th>
<th>$w$ (m)</th>
<th>$Q_L$ (m$^3$ m$^{-1}$ s$^{-1}$)</th>
<th>$Q_L$ (ML km$^{-1}$ day$^{-1}$)</th>
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**Mean**       **-0.280**       **-0.443**
**St. Dev.**   0.498          0.669
**St. Error**  0.288          0.386
**95% C.I.**   ±1.24          ±1.66
### Appendix F: Summary of the streambed infiltration rate measurements at Site 2.

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<th>(i) (m m(^{-1}))</th>
<th>(w) (m)</th>
<th>(Q_L) (m(^3) m(^{-1}) s(^{-1}))</th>
<th>(Q_L) (ML km(^{-1}) day(^{-1}))</th>
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Mean: \(-0.102\), \(-0.029\)

St. Dev.: 0.577, 0.479

St. Error: 0.333, 0.277

95% C.I.: \(\pm 1.43\), \(\pm 1.19\)