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

Lachlan River Site Report

Lamontagne, S., Taylor, A.R., Crosbie, R.S., Cook, P.G., Kumar, P.B.

Final Revised Version 16 May 2011

Report to NSW Office of Water
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_Citation_: Lamontagne¹, S., Taylor¹, A.R., Crosbie¹, R.S., Cook¹, P.G., Kumar², P.B. 2011. Interconnection of surface and groundwater systems – River losses from losing/disconnected streams. Lachlan River site report. CSIRO: Water for a Healthy Country National Research Flagship, Adelaide. 35 pp.

¹CSIRO Land and Water, Waite Campus, PMB 2, Glen Osmond SA 5064
²NSW Office of Water, Corner Sturt and Olympic Highway, P.O. Box 10, Wagga Wagga NSW 2650

This project is a National Water Commission (NWC) initiative, funded through the Raising National Water Standards Program. Additional funding was provided by NSW Office of Water.

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From: Sebastien Lamontagne
Description: Gonowlia Weir, Lachlan River
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ACKNOWLEDGMENTS

Funding for this project is provided by a National Water Commission Grant to the New South Wales Office of Water (NoW) under the program: *Improving Knowledge and Understanding of Australia’s Water Resources. 2.2.3.1 Groundwater.* Ken Kolstad (NoW) and Towhid Islam (University of Technology Sydney) contributed to the sampling trip at the Lachlan site. Continuous monitoring for surface and groundwater levels at the sites was overseen by Nathan Payne (NoW). The Losing Streams project was coordinated by Rob Brownbill (NoW) and Mike Williams (NoW).
EXECUTIVE SUMMARY

This report summarises the field studies at the Lachlan River, 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 Lachlan River were to:

- Determine at two locations (Hillston Bridge and Gonowlia Weir, near Hillston, NSW) 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, radon-222, major ions) to evaluate the sources of water to the aquifer and the infiltration rates from the river; and,
- Develop a methodology to estimate infiltration rates through the streambed.

The two locations investigated on the Lachlan River had losing-disconnected conditions at the time of the study, with the regional water table being more than 20 m below the streambed. At Hillston Bridge, the streambed consisted of 1 – 2 m of clay over sand. Moisture and matric potential profiles collected by augering in the alluvial aquifer through the streambed confirmed that an unsaturated zone was present under the river. The hydrogeological environment was more complex at Gonowlia Weir, where the alluvial aquifer near the stream contained several sand and clay layers. In addition to the regional water table, up to two perched aquifers may have been present underneath the river. However, due to the presence of one of the perched aquifers, it was not possible to collect a profile of the alluvial aquifer below the streambed at Gonowlia to confirm that an unsaturated zone was present.

While intact cores of the streambed clays were collected at Hillston Bridge, attempts to estimate their hydraulic properties using pressure plate techniques failed. The vertical hydraulic conductivity ($K_v$) of the clays was also below the practical detection limit using field permeameters ($K_v < 2 \times 10^{-7}$ m s$^{-1}$). Preliminary estimates of infiltration rates below the streambed were attempted at Hillston Bridge using the moisture and matric potential profiles collected by augering. The infiltration rates were apparently higher in the underlying sands than through the streambed clays. This indicated that the infiltration process at Hillston Bridge is more complex than the simple vertical 1-D approach used here. In other words, higher infiltration rates probably occurred through the streambed in the vicinity of where the profiles were collected.

The pattern in environmental tracers suggested that there is some recharge of river water under low flow conditions, as demonstrated by the presence of an evaporation signal in the stable isotopes of water in shallow groundwater. All groundwater samples were fresh ($<350$ mg L$^{-1}$) which is also consistent with significant recharge from river water. CFC-11 and CFC-12 concentrations in groundwater were usually at or near detection limit, suggesting that groundwater was recharged prior to 1965. However, it is likely that CFC degradation
occurred because of the anoxic conditions in the aquifer. Thus, it is probable that recharge occurred earlier than 1965. Because of the uncertainties associated with CFC dating at the transects, infiltration rates using environmental tracers could not be estimated.

In general, there was a gradual one meter drop in the water table at both transects over the course of the monitoring period (April 2009 to March 2010). The only exceptions were the two piezometers presumably located in perched aquifers near the river at Gonowlia Weir, with the shallower one following the trends in river stage while the deeper one remained stable. Unlike at the Billabong transects, the lack of a strong instantaneous barometric response indicated that the Lachlan piezometers were all within an unconfined aquifer. Overall, the water table at the two Lachlan transects appeared to be controlled by regional processes rather than variations in river stage. However, a delayed response to significant flow events (floods and irrigation releases) may still occur at these transects but could not be evaluated here because of the short monitoring period.

**Recommendations**

The Losing Streams project developed and applied a methodology to identify whether a river is losing-connected or losing-disconnected using simple field and laboratory measurements. The project was less successful in estimating the infiltration rates from the rivers because of difficulties with the use of hydrometric techniques (like differential gauging) in this environment and the uncertainties encountered with groundwater dating with CFCs. Nevertheless, the riparian piezometer network design used was satisfactory and the application of an alternative groundwater dating technique should enable the estimation of infiltration rates in future studies. In summary, the recommendations from the Lachlan River site studies are to:

- Use the field measurements, especially the demonstration of losing-disconnected conditions, to constrain existing regional groundwater models;
- Monitor piezometric surface and surface water levels at the Lachlan transects for a longer period of time in order to capture a greater range in seasonal water level variations;
- Develop a suitable modelling tool to evaluate delayed recharge events caused by travel through the unsaturated zone in losing-disconnected streams;
- Further characterise the spatial and temporal variability in infiltration through the streambed in losing-disconnected environments, in particular investigate the possibility of infiltration “hotspots”;
- Attempt to age alluvial groundwater at the transects with an alternative technique (SF₆ dating); and,
- 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 this 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, 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.

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 stream 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 are 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;
- Directly measure 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 Lachlan River site (Fig. 1). 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).

1.1. General study design

Lachlan River and the other study reaches were each instrumented with two piezometer transects perpendicular to the river. Each transect spanned from the top of the high bank next to the river channel to 100 – 200 m further away from the river, and usually consisted of three nests of paired piezometers. 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 piezometric response to flow events (natural floods and irrigation releases).

To get some indication of 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, $^{222}\text{Rn}$, 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 $^{222}\text{Rn}$ and 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), whereas CFCs are anthropogenic in origin and can date groundwater from ~1965 to the present (Cook and Herczeg 2000).

The vertical hydraulic conductivity of the streambed ($K_v$), the presence of an unsaturated zone below the streambed, and the infiltration rate through the streambed were evaluated in situ on one occasion at each transect. Different strategies had to be used in losing-connected and losing-disconnected environments. The type of connection present was first evaluated by collecting auger profiles in the streambed (through a casing) or along the banks. Dry holes or apparently unsaturated clay and sand profiles were used as evidence that losing-disconnected conditions were present. These field observations were later verified in the laboratory from measurements of the water content and matric potential in the profiles. In losing-connected environments, $K_v$ was estimated using falling or constant head permeameter tests (Horslev 1951). The vertical hydraulic gradient ($i$) through the streambed was estimated using drive points and oil-water manometers (Kennedy et al. 2007) so that the specific infiltration rate ($q$) could be estimated as $q = -K_v \cdot i$. Because of significant spatial variability, several measurements of $K_v$ and $i$ over the whole streambed must be made (Genereux et al. 2008).

Figure 1. Location of the Murray-Darling Basin and of the six Losing Streams project study reaches.
Measuring infiltration rates through the streambed in losing-disconnected environments is more complex because of the presence of an unsaturated zone and, as a result, has seldom been attempted. Different approaches were trialled at the Lachlan River and other losing-disconnected sites as a part of this study. At the Lachlan River, infiltration rates were estimated by inverse modelling using vertical moisture and matric potential profiles collected through the streambed. At some river reaches, reach-scale estimates of the infiltration rate were made on one or several occasions by differential gauging (summarised in Brownbill et al. 2011).

2. METHODS

2.1. Site description

The Lachlan River study reach was located upstream of Hillston, in the Lower Lachlan region (Fig. 2). This area is classified as a riverine plain environment and is a part of the Lower Lachlan Groundwater Management Unit (N12). The aquifers consist of unconsolidated alluvial sediments forming a broad alluvial fan at the point where the Lachlan River emerges into the riverine plain near Hillston (CSIRO 2008a). The unconsolidated sediments are subdivided into the shallow and heterogeneous Sheparton Formation unconfined aquifer and underlying leaky confined aquifers in the Calivil Formation and Renmark Group (CSIRO 2008a). One of the piezometer transects was located just upstream of Hillston within a weir pool (Hillston Bridge) and the other was downstream from Gonowlia Weir. Both sites were located in the area where a transition between losing-connected and disconnected conditions was expected (CSIRO 2008a; R.M. Williams, NoW, personal observation).

Figure 2. Location of the study reach and of the two piezometer transects on the Lachlan River.
2.2. Piezometer installation

Piezometer construction and installation at the two Lachlan River transects was undertaken by the NoW groundwater drilling unit (and under supervision by NoW hydrogeologists) starting in September and later completed in November 2008. The piezometer network at each site consisted of three pairs of nested piezometers, with the exception of the Gonowlia weir transect where a third piezometer was installed by the river to intercept a suspected perched aquifer. The piezometer network at the Gonowlia weir site is perpendicular to the river running in a south-easterly direction and spanning up to 200 m further away from the river on the eastern side of the river channel. At the Hillston Bridge site, the network is on the western side of the river channel running directly west of the river spanning the same distance inland.

Rotary drilling using air was employed to drill a 216 mm diameter hole until moisture was detected in the formation and the hole began to collapse, at which point drilling switched to that of rotary mud. Upon drilling completion, the piezometers were installed. They consisted of 100 mm diameter class 12 PVC in glued lengths, a 2 m length screen (slots 1 mm wide and 40 mm in length), and a 1 m sump. The annulus was backfilled with waterworn rounded gravels and sealed with bentonite. The piezometers were protected at the surface with a lockable steel casing 168 mm in diameter and 1 m in height bolted into a cement base. Additional details about the piezometer network are summarised in Appendix A.

Plate 1. Lachlan River – Hillston Bridge site (left) and sampling for environmental tracers at one of the Lachlan piezometer nests (right). See front cover for a picture of the river at Gonowlia Weir.

2.3. Piezometric surface monitoring

The NoW Hydrometric Unit undertook monitoring of surface water and groundwater levels at each transect from April 2009 to March 2010. 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.
Loggers were suspended in the piezometers by marine grade stainless steel trace wire in known lengths from a surveyed level. Every three months, the hydrometrics team took manual water level readings, retrieved the individual loggers, downloaded them, 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. A second pressure transducer is used to measure the atmospheric pressure; this pressure is then subtracted from the absolute pressure to convert the measurement to gauge pressure. The gauge pressure is equivalent to the water level in the piezometer and is called hydraulic head in this report:

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

### 2.3.1. Barometric effects

Hydraulic head in the Lachlan piezometers showed significant background noise of short-term, small-scale variations apparently associated with changes in barometric pressure. In hydraulic head time series, barometric effects can mask underlying trends by adding “noise” to the data. Rasmussen and Crawford (1997) define three types of barometric effects on hydraulic head:

- An instantaneous response for confined aquifers;
- A delayed response due to borehole storage in confined and unconfined aquifers; and,
- A delayed response in unconfined aquifers due to the passage of barometric pressure changes through the unsaturated zone.

In a confined aquifer, the instantaneous response results in the hydraulic head to fluctuate synchronously with changes in barometric pressure. This relationship will generally be seen in a time series of hydraulic head as “noise” and it will fluctuate over a range of less than 0.5 m. This is an inverse relationship where an increase in barometric pressure causes a decrease in hydraulic head. The ratio of this change is the barometric efficiency of the aquifer (Rasmussen and Crawford 1997):

\[
\alpha = -\frac{\Delta W}{\Delta B} \tag{2}
\]

where \( \alpha \) is the barometric efficiency, \( \Delta W \) is the change in hydraulic head of some unit of time and \( \Delta B \) is the change in barometric pressure over the same time interval.

If the goal of the water level monitoring is to calculate hydraulic gradients, then the hydraulic head measurements are used directly. If the goal of the measurements is to investigate hydraulic head changes due to some other process (recharge from rainfall, infiltration from a river, etc) then the barometric signal should be removed to create a time series of corrected hydraulic head:

\[
W_c(t) = W(t) - \alpha[B(t) - \overline{B}] \tag{3}
\]
where $W_c(t)$ is the corrected hydraulic head at time $t$ and $\overline{p}$ is the mean barometric pressure of the time series.

This approach will only remove the noise due to the instantaneous barometric effect in confined aquifers. The barometric efficiency was calculated for all Lachlan piezometers. The rationale for the approach was that, in Lower Murray floodplains, semi-confined conditions are common even in the uppermost aquifer.

Additional corrections for delayed barometric effects were not attempted for the Lachlan time series. In the hydrogeological context of the Lachlan transects, the most likely delayed barometric effect would be due to the passage of barometric pressure changes through the unsaturated zone. These barometric effects can occur in unconfined and semi-confined aquifers with a deep unsaturated zone of fine textured material.

In summary, the procedure used to estimate corrected hydraulic head will remove most of the barometric signal. However, a residual barometric signal could still occur in the corrected hydraulic heads, especially in piezometers located in unconfined or semi-confined aquifers.

2.4. Water quality and environmental tracers

2.4.1. Field measurements

Groundwater samples were collected from all piezometers at the two transects, with the exception of GW273046/2 because it was nearly dry (see Section 3.1 and Appendix A for piezometer location details). The piezometers were purged for three bore volumes, with care taken to ensure that water level in the piezometers did not drop 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 $\text{H}_2\text{S}$ (rotten egg odour) was noted when detected during sampling. Dissolved oxygen concentration was measured using a Winkler titration.

2.4.2. 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 chlorofluorocarbons (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 top of 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 until
overflowing. 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.

2.4.3. 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 H₂S 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 (δ) 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 \(^2\text{H}/\text{H} \) ratios in the sample and the standard, respectively.

2.5. Streambed hydraulic conductivity

At Hillston Bridge, measurements of the hydraulic conductivity of the streambed were made using falling head permeameter tests (Horslev 1951) using the steel permeameter design. The detailed methodology for the use of the steel permeameter test is presented in the Billabong Site report (Lamontagne et al. 2011a).

2.6. Unsaturated zone profiles

2.6.1. Augered profiles

At Hillston Bridge, three profiles of the streambed and shallow alluvial aquifer were taken to identify if losing-disconnected conditions were present (Fig. 3). The profiles were taken 20 m from one another either on the bank at the edge of the river (Profiles 1 and 3) or directly through the streambed (Profile 2) in ~30 cm of water. For profile 2, an outer casing (9 cm dia. PVC pipes) was first inserted to ~50 cm depth into the streambed. The inside of the casing was then dewatered using a small bilge pump. Once dewatered, the casing remained dry throughout the subsequent collection period. Augering in the streambed through a casing was also attempted near the location of profiles 1 and 3 but was not successful, usually because the holes tended to collapse during augering. Sediment profiles were augered by 20 cm increments using sand or clay augers with extensions. Sediment samples were
bagged and labelled for transport to the laboratory for the measurement of water content, texture and matric potential. It was not possible to collect profiles at Gonowlia Weir because the nature of the streambed (silty sand instead of clay) did not allow for the formation of a watertight seal around the casing. However, the short profiles collected indicated that the streambed was saturated to at least one meter depth.

The texture of sediments was assessed by the behaviour of a small handful of field moist sample pressed out between the thumb and forefinger, and classified by the proportion of gravel, coarse sand, fine sand, silt and clay in the soil. The gravimetric water content of each sample was determined in the laboratory using an analytical balance and an oven. Each sample was weighed to determine its field moist weight ($M_w$) and then placed in an oven at $105^\circ\text{C}$ for 24 hours to dry, and then re-weighed to determine its oven dry weight ($M_d$). The gravimetric water content was then determined as:

$$\theta_g = (M_w - M_d)/M_d$$  \hspace{1cm} (5)

and expressed in g g$^{-1}$.

Three complementary techniques (the filter paper method, chilled-mirror psychrometry and mini pressure transducer tensiometers) were used to measure negative fluid pressures ($\psi$; or matric potential) in augered samples. The filter paper method involves the equilibration of air-dry analytical filter paper with the matric potential of a soil or sediment sample in the laboratory. The technique requires very limited equipment, has a vast measurement range (–100,000 to –1 kPa; Fawcett and Collis-George 1967) and can be used on either intact or disturbed samples. Details of the method can be found in Greacen et al. (1989).

Chilled-mirror psychrometry (WP4 Dewpoint PotentiMeter, Decagon Devices Inc.) estimates the matric potential using the dew point under isothermal conditions in a sealed chamber (Bulut and Leong 2008). It measures water potential from –300 to –0 MPa with an accuracy of ±0.1 MPa from –10 to 0 MPa and ±1% from –300 to –10 MPa. More information can be
T5x Pressure Transducer Tensiometers (UMS) were used to estimate the matric potential by tensiometry. A pair of tensiometers was inserted horizontally into sediment samples and left to equilibrate, usually for several hours. During the equilibration period, the samples were kept sealed in zip lock bags to avoid drying. More information about how the instruments are operated can be found in the user manual at www.mea.com.au/files/User%20Manuals/T5_Manual_revised.pdf.

**2.6.2. Intact cores**

In addition to the three augered sediment profiles, three intact sediment cores were also collected at Hillston Bridge. The cores were taken by pounding 5 cm dia. PVC pipes into the streambed as far as practical (usually ~1 m). Cores were cut into 6 cm increments in the field using a hand saw and sawing guide, wrapped tightly in cling wrap and sealed in plastic zip-lock bags to be transported to the laboratory. While shorter than the augered profiles, the PVC cores enabled the measurement of matric potential and other hydraulic properties on relatively undisturbed profiles. Photographs of the coring procedure with augers and PVC cores can be found in the Billabong Creek site report (Lamontagne et al. 2011a).

**2.6.3. Pressure plate analysis – Intact cores**

Characteristic curves that relate soil water content to pressure in soil or sediments are used to model unsaturated zone processes (Freeze and Cherry 1979). The standard approach to derive the characteristic curves is the pressure plate technique, where soil samples are put under different suctions and the water content estimated after equilibrium has been reached. The characteristic curves for pressure versus water content were estimated for the streambed clay samples at Hillston Bridge using pressure plates. The intact core sections were sent to Soil Water Solutions (Adelaide) for analysis.

**2.6.4. Estimation of infiltration rate using the WAVES model**

At the Billabong site, the estimation of infiltration rate through the unsaturated zone was made using the characteristic curves for the streambed clays (Lamontagne et al. 2011a). However, the properties for the streambed clays could not be measured at the Lachlan site (see Section 3.6.2). Thus, an alternative technique was trialled where the measured moisture and matric potential profiles collected by augering were used to estimate the hydraulic properties of the streambed clay and sand by inverse modelling. For simplicity, only the profile collected directly through the streambed was used (Profile 2).

The 1-D numerical model WAVES (Zhang and Dawes 1998) was used to simulate the water leaking from the river to the groundwater. WAVES solves Richard’s Equation numerically with a specified head as the upper and lower boundary conditions. WAVES uses the Broadbridge-White soil moisture and hydraulic conductivity functions (Broadbridge and White 1998) and these require five parameters for each soil layer: saturated hydraulic conductivity ($K_s$, m s$^{-1}$), saturated moisture content ($\theta_s$, cm$^3$ cm$^{-3}$), residual moisture content ($\theta_r$, cm$^3$ cm$^{-3}$), inverse capillary length scale ($\lambda$, m) and an empirical constant based on soil properties ($C$, unitless).

Because of the large number of parameters required to be fitted, PEST (Doherty et al. 2000) was used for the inverse modelling. PEST estimates the parameters needed by WAVES by adjusting them until the objective function is minimised. The objective function is the sum of squared residuals between the observed and predicted moisture content and matric potentials.
The boundary conditions used in the model were idealised from field observations. The water level in the river was 0.5 m above the top of the soil column and the water table was at a depth of 8 m below the bed of the river. The actual depth to water table was >20 m, but this will not impact on the modelled infiltration estimates because a depth of 8 m was sufficient to ensure that the modelled water table capillary zone did not extend to the maximum depth at which measurements were made. Three soil layers were used in the modelling based upon observations: a clay layer to a depth of 1.6 m, a sandy-clay layer below the clay to a depth of 2.8 m, and a sand layer below the sandy-clay to the water table.

3. RESULTS

3.1. Geological cross-sections

Consistent with an alluvial environment, the geological cross-sections at both sites were a mixture of sand, sandy clay and clay horizons of varying thicknesses. At Hillston Bridge, a relatively thick (tens of meters) sand lens was found below the surface clay layer covering the floodplain and streambed (Fig. 4). The horizontal hydraulic gradient was away from the river and the vertical one downward at the time of sampling (11 – 22 May 2009). The water table was approximately 21 m below the streambed.

A more complex hydrogeological environment was found at Gonowlia Bridge, with the presence of two perched aquifers in the piezometer nest closest to the river (Fig. 5). In both cases, the perched aquifers were sand or silty sand above a significant clay unit. The water level in the shallowest perched aquifer was ~116.8 m AHD and the one in the deeper perched aquifer was ~108 m AHD. By contrast, stream water level was ~120.1 m AHD and the regional water table was ~93.8 m AHD. In the piezometers located in the regional aquifer, a downward vertical hydraulic gradient and a horizontal hydraulic gradient away from the river were present.
Figure 4. Geological cross-section of the Hillston Bridge transect, showing the surface and groundwater levels during 11 – 22 May 2009. Water levels on the right are for shallow screens and the ones on the left are for the deeper screens.

Figure 5. Geological cross-section at the Gonowlia Weir transect, showing surface and groundwater levels on 11–22 May 2009.
3.2. Piezometric surface responses

3.2.1. Barometric efficiency

Unlike at the Billabong transects, with a few exceptions (see Fig. 6) there was generally a poor relationship between $\Delta W$ and $\Delta B$ in the Lachlan piezometer time series. In addition, unlike at Billabong, corrected hydraulic heads did not have less noise than the uncorrected ones (Fig. 7). This indicates that the Lachlan piezometers are located in an unconfined aquifer environment and do not require a correction for *instantaneous* barometric effects, as these only apply for confined aquifers. Some of the noise in the hydraulic head time series could be associated with a *delayed* barometric response in an unconfined aquifer. However, this effect is more difficult to correct for (Rasmussen and Crawford 1997) and probably not essential here because the noise was small relative to the main trends in the data. Thus, only the hydraulic head data (as defined by Eq. 1) is further discussed in the rest of this report.

![Figure 6. Barometric efficiency as calculated at GW273050 – 1 for a 12 hour time period.](image)

![Figure 7. The hydraulic head (blue), barometric pressure (red) and corrected hydraulic head (green) at GW273050 – 1. Unlike at the Billabong transects, correction for instantaneous barometric effects did not remove the noise in the time series.](image)
3.2.2. Temporal response

At Hillston Bridge, hydraulic heads gradually declined by about 1 m between April 2009 and March 2010 in all piezometers (Fig. 8). There was no evidence of a response to the floods that occurred in February and March 2010. However, as these events occurred near the end of the monitoring period, a delayed response could still have occurred.

At Gonowlia Weir, variations in hydraulic head in the shallowest perched aquifer (GW273046-1) followed the variations in river stage (Fig. 9), while hydraulic heads remained fairly constant in the deeper perched layer (GW273046-2). However, the hydraulic head in the deeper piezometers all declined by about a meter during the monitoring period.

With the exception of the perched aquifers near the river, the water table at the Lachlan transects appeared to be controlled by regional processes rather than by changes in stream stage.
**Figure. 8.** Surface and groundwater level variations at Hillston Bridge during the monitoring period, the star represents a period where the surface water level fell below the sensor, triangle and circles depict manual water level measurements.
Figure 9. Surface and groundwater level variations at Gonowlia Weir during the monitoring period, the star represents a period were the surface water level fell below the sensor, triangles and circles depict manual water level measurements.
3.3. Water quality and environmental tracers

The environmental tracers suggest that there was some infiltration of surface water at both transects under low flow conditions (Fig. 10). Groundwater was fresh, with salinities (as TDS) ranging from 150 to 350 mg L\(^{-1}\), with the exception of the deeper piezometers at Hillston Bridge where salinity was \(\sim 50\) mg L\(^{-1}\) (Appendix B). The deuterium signature in the surface water samples was relatively enriched (–4 to 0‰) when compared to groundwater from the deeper piezometer samples (–38 to –29‰; Appendix C). However, groundwater from the shallower piezometers at Hillston Bridge and from the piezometer nest closest to the river at Gonowlia Weir had an isotopic signature similar to surface water.

The water samples were roughly divided into three groups along the \(\delta^2 H – \delta^{18} O\) evaporation line. One group (surface water, Hillston shallow piezometers, and the Gonowlia nest closer to the river) was isotopically enriched with a distinct evaporation signal, another (the remaining Gonowlia Weir samples) had some evaporation signal and the third (Hillston deep piezometers) had little or no isotopic enrichment signal (Fig. 11). Overall, there is a clear indication that some infiltration occurs during low flow periods near the river. The isotopically-depleted signature away from the river could represent recharge during floods or by winter rainfall. However, the low salinity across the aquifer is more consistent with rapid recharge, like floods, rather than slower processes like diffuse rainfall recharge. In the latter, plant transpiration would tend to increase salinity but would not impact on the isotopic signature.

Figures 10. Deuterium values at the Lachlan transects relative to (A) TDS and (B) Distance from the river. No sample was collected from GW273046 – 2 at Gonowlia Weir (deeper perched aquifer).
3.4. CFC and $^{222}$Rn

CFC concentrations were generally low in all groundwater samples at the Lachlan transects (Fig. 12 and Appendix C). However, there was a tendency for slightly more elevated CFC concentrations in shallower groundwater and (at Gonowlia) when closer to the river. However, the presence of anoxic conditions in the aquifer (Appendix B) and the lack of agreement between apparent CFC-11 and CFC-12 ages (Appendix C) indicate that partial CFC degradation may have occurred. Shallow groundwater was recharged sometime after 1965 because at least trace CFC concentrations were measured. However, complementary information is required before the CFC-inferred ages can be used to estimate infiltration rates at these transects. The presence of evaporated water in groundwater (see section above) suggests recent (months or years) recharge from the river, but this would need to be confirmed by accurate groundwater dating.

There were no obvious trends in groundwater $^{222}$Rn activity, with most values ranging between 5 and 10 Bq L$^{-1}$ (Appendix C). In contrast, $^{222}$Rn activities in the river were 0.06 – 0.08 Bq L$^{-1}$. The $^{222}$Rn activities indicate that groundwater age is >1 month old (that is, beyond the range for $^{222}$Rn dating).

Figure 11. Relationship between $\delta^{2}$H and $\delta^{18}$O at the Lachlan River transects. The meteoric water line (solid) represents the range in isotopic signature in rainfall expected for the region. The evaporation line (dashed) shows the change in isotopic signature due to partial evaporation. The overall pattern here is that all groundwater samples had the same origin, similar in signature to the Hillston – Deep groundwater (i.e., where the two lines intersect). This depleted signature is consistent with winter rainfall in the Murray-Darling Basin. The isotopic enrichment in most groundwater samples is consistent with some infiltration from upstream reservoir releases, which would tend be isotopically enriched relative to winter rainfall.
3.5. Permeameter tests

Several attempts were made to measure streambed hydraulic conductivity at the Hillston Bridge site using the steel permeameter. These were largely unsuccessful because it was too difficult to insert the instruments through the clays present. Limited measurements indicated that the vertical hydraulic conductivity was most likely below the detection limit for the instrument ($K_v < 2 \cdot 10^{-7} \text{ m s}^{-1}$), consistent with a clay environment.

3.6. Lachlan unsaturated zone profiles

3.6.1. Augered profiles.

The streambed at the Lachlan – Hillston Bridge site was characterised by a clay layer 1 – 2 m thick overlying sandy clay and/or coarse sand (Figs. 13 and 14). The in situ (field moist) water contents in the profiles tended to decrease with depth. However, the patterns in matric potential were more complex. In general, the matric potential was ~0 kPa (saturated) near the surface of the streambed but decreased to ~50 to ~30 kPa near the bottom of the clay, showing that an unsaturated zone was present. However, in some profiles tension was lost at the clay/sandy clay interface (that is, $\psi$ went back to ~10 to 0 kPa) and increased slightly again at depth. This loss of tension indicates that water movement is not strictly vertical once in the sandy clay (i.e., a lateral influx of water must have occurred in the sand for tension to have been lost). Nevertheless, the key finding is that an unsaturated zone was present in the streambed and that it began in the clays within a few decimeters from the surface.

There was good agreement between the matric potential measurements made using minitensiometers and the filter paper technique in the clays (Figs. 13 and 14). The minitensiometer values were usually lower than the filter paper values in the sands. However, the overall pattern in matric potential across the profiles was the same with both techniques.

Figure 12. CFC-12 concentrations at the Lachlan River transects.
Figure 13. Gravimetric water content ($\theta_g$) and matric potential ($\psi$) profiles from a bank (Profile 1, top) or the streambed (Profile 2, bottom) of the Lachlan River, Hillston Bridge.
3.6.2. Pressure Plate Analysis - Intact cores.

Intact cores were placed in a constant temperature room and saturated in a water bath for three to four weeks. Samples were then placed on pressure plates within an initial pressure of 0.5 kPa applied and left to equilibrate for several days, when they were removed and weighed to obtain volumetric water content. Samples were then re-established on the plates and subjected to incremental pressure increases of 10 kPa for a week, 35 kPa for 2 weeks and 200 kPa for four weeks. After the stated equilibration time periods, each sample was removed and weighed to obtain volumetric water content at the known applied pressures.

Results shown in Appendix D indicate that often there was very little change in water content even at applied pressures of 35 kPa (3.5 m water equivalent) and 200 kPa (20 m water equivalent). During the 35 kPa equilibrium period, small tensiometers were installed in three samples to see if the water in the sample was responding to the water tension applied to the plate. Results were mixed. In the surface samples T5-C5-0-10 and T5-C6-0-10, the soil water at the top of the core responded in a few days. In T3-C4-0-10, there was little response to any applied pressure (Appendix D). This indicates that hydraulic conductivity is very low and coincides with very high soil density (and low porosity) in some samples, but this was not the case in all samples.

To attempt to improve drainage at higher pressures, a small subsample was taken from alternate cores and placed in a pressure plate at 200 kPa. These smaller samples (~5mm
might be expected to reach equilibrium faster than the original full sized cores. The samples were left on the plate for 10 days. Several of these samples produced a volumetric water content at 200 kpa which was greater than the volumetric water content of the parent sample at 35 kPa, which is not possible. The cause could be (a) that the samples were not left long enough to equilibrate or that (b) some of the clays were highly expansive and may have lost intimate contact with the plate. In summary, it was not possible to estimate the characteristic curves for the streambed clays at the Lachlan site using pressure plates, but the clays appeared to have a low hydraulic conductivity.

3.7. Estimation of infiltration rate using WAVES

The observed profiles of moisture content and matric potential for Profile 2 taken from the Hillston Bridge site did not appear to meet the assumptions of 1-D flow that is required by the modelling (see section 2.6.4). It appears that there is lateral flow within the sandy-clay layer. For this reason the profile was treated as two sections. One section included the top 7 observations made in the clay layer, where flow was most likely to be vertical only, and the other consisted of the bottom 7 observations in the sand.

The results of the inverse modelling are displayed in Figure 15 for the top 7 observations and in Figure 16 for the bottom 7 observations. The optimised parameters are displayed in Table 1. The infiltration rate estimated by WAVES was 0.3 mm d$^{-1}$ when fitted to the top of the soil profile and 8.7 mm d$^{-1}$ when fitted to the bottom of the soil profile. The infiltration rate estimate from the clay is probably more reliable than the one from the sand because the clay part of the profile is most likely to meet a key assumption of the model (1-D vertical flow only). However, if correct, the higher infiltration rate estimated from the sand demonstrates the infiltration rate through the streambed across the area is larger than what suggested by the clay layer in Profile 2. In other words, higher infiltration rates occur nearby in areas where the streambed clay layer is thinner or absent.
Figure 15. Calibration of model to top 7 observations of moisture content and matric potential in Profile 2.
Figure 16. Calibration of model to bottom 7 observations of moisture content and matric potential in Profile 2.

Table 1. Broadbridge-White parameters used by WAVES for the top part of the soil profile and the bottom part of the profile.

<table>
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<th>Parameter</th>
<th>Unit</th>
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<th>Bottom</th>
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<td>1.01</td>
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</table>
4. DISCUSSION

4.1. Connection status

The Lachlan – Hillston Bridge and Lachlan – Gonowlia transects were both losing-disconnected during the study period. This was inferred from the presence of an unsaturated zone at Lachlan – Hillston Bridge and, at both transects, a very deep regional water table (>20 m below the streambed surface). While not a fool-proof diagnostic (Brunner et al. 2009a), when the water table is >10 m below the streambed surface in riparian piezometers, streams are probably disconnected in the context of Murray-Darling Basin tributaries (Lamontagne et al. 2010). The depth to the water table at the Lachlan transects was the deepest for all of the Losing Streams project sites (Lamontagne et al. 2010).

The occurrence of losing-disconnected conditions at the Lachlan transects is consistent with the criterion developed by Brunner et al. (2009a) to indicate where disconnection is possible. For disconnection to occur, a clogging layer must be present in the streambed and

\[
\frac{K_c}{K_a} \leq \frac{h_c}{d + h_c}
\]

where \(K_c\) and \(K_a\) is the hydraulic conductivity of the clogging layer and alluvial aquifer, respectively, \(h_c\) the thickness of the clogging layer, and \(d\) the stream depth. At Lachlan – Hillston Bridge, the hydraulic conductivity of the streambed clay and underlying sand aquifer are not known. However, they should be similar to values estimated at the Billabong transects (\(K_c \sim 10^{-9} \text{ m s}^{-1}, K_a \sim 10^{-5} \text{ m s}^{-1}\)). These values are also similar to the ones used for the unsaturated zone modelling (Table 1). With \(h_c \sim 2 \text{ m}, d \sim 1 \text{ m}, K_c/K_a \sim 0.0001\) and \(h_c/(h_c+d) \sim 0.67\), which easily satisfies the criterion set by Eq. 5.

Assessing the Brunner et al. (2009a) criterion at Lachlan – Gonowlia is more complex because the river is set in a perched aquifer (discussed in more detail below). As a first approximation, the same \(K_c\) and \(K_a\) values can be used. However, estimating \(h_c\) and \(d\) is more difficult. As a first approximation, \(d\) will be set as the distance between the stream surface and the top of the clay layer apparently generating the perched conditions (~4 m; see GW273046 geological profile; Fig. 4) and \(h_c\) as the thickness of this clay layer (~6 m). Under these conditions, \(K_c/K_a \sim 0.0001\) and \(h_c/(h_c+d) \sim 0.6\), which again easily satisfies the criterion.

In summary, the large contrast in hydraulic conductivity between clays and sands at the Lachlan transects made these sites susceptible to the establishment of losing-disconnection.

4.2. Variability in the extent and distribution of clogging layers

The two Lachlan transects had a more complex losing-disconnected environment than the one often idealised for this type of connection. For example, Brunner et al. (2009a) portray the clogging layer as having constant thickness from one side of the stream to the other and to be at the top of the streambed. At Lachlan – Hillston Bridge, we suspect that the thickness of the clogging layer varies significantly across the streambed. It was not possible to characterise streambed clay \(K\) and thickness across the river at this site because it was located in a relatively deep weir pool. However, the patterns in matric potential in the unsaturated zone profiles suggest a more complex infiltration environment. In particular, the estimated infiltration rate in the underlying sand aquifer appeared higher than in the clay layer, which does not conform well with a simple vertical infiltration process. Such differences in infiltration rates could arise if zones of point recharge occur in the streambed in...
areas where the clogging layer is thinner or absent. Point recharge appears common in other clay-lined environments elsewhere in the Murray-Darling Basin (Jolly et al. 1994; Lamontagne et al. 2005; Holland et al. 2009).

Another interesting feature of the Lachlan transects was the presence of perched aquifers. At Lachlan – Gonowlia, two perched aquifers were present and associated with significant clay layers at depth. One of the perched layers also included the stream itself, but the deeper one was a small aquifer above the regional one. It is unclear how the presence of perched aquifers influences the infiltration process. In the idealised conceptual model for a losing-disconnected river (Brunner et al. 2009a), river losses only occur vertically through the streambed. However, in the case of a discontinuous perched aquifer, infiltration may also occur laterally through a saturated zone and then vertically at the ends of the perching layer. The overall picture would be one where vertical recharge occurs as a “cascading” process from one perched aquifer to another.

4.3. Piezometric surface responses

The apparent lack of temporal response in water level in the Lachlan piezometers relative to stream stage does not necessarily imply that no variation in infiltration rate with changes in stream stage occurred. Following from Brunner et al. (2009a) and Cook et al. (2010), the infiltration below a losing-disconnected stream will increase with increased stream stage for two reasons. First, at any given point in the stream, the infiltration rate will increase with increased stream stage because of the higher hydraulic head above the clogging layer. Secondly, at higher stream stages, the width of the stream will increase, resulting in a greater area through which infiltration can occur. Thus, higher infiltration rates at a given point and a larger area of infiltration will result in higher infiltration fluxes from losing-disconnected rivers during floods.

The monitoring period at Lachlan was probably too short and did not capture enough flow events (floods and irrigation releases) to evaluate changes in infiltration rate at this river reach. Water table responses will be delayed at losing disconnected sites because the infiltration pulse following a flow event will need to travel first through the unsaturated zone. At Lachlan River, the unsaturated zone is relatively deep and the travel time would probably be longer relative to the other losing-disconnected sites investigated during the study (i.e., Billabong Creek and Gwydir River; Lamontagne et al. 2011a,d). In addition, the presence of perched layers may further delay the transmission of flood pulses through the unsaturated zone by increasing the travel path of water from the stream to the regional water table.

As a component of the Losing Streams project, McCallum et al. (unpublished) attempted to develop a theoretical water table response model to floods in losing-disconnected rivers using the fully-coupled surface-groundwater model Hydrogeosphere (Therrien et al. 2006). This initial attempt was not successful because of the complexity of the process in the unsaturated zone under non steady-state conditions (J. McCallum, Flinders University, personal communication).

4.4. Environmental tracers

At the time of the study, much of the Murray-Darling Basin was in a regional drought (CSIRO 2008b). Low flow conditions were maintained in the Lachlan River by continuous or punctual releases of water from upstream reservoirs, such as Wyangala Dam. Because of extensive evaporation during storage in reservoirs and slow transit through the river, Lachlan River water had a strong evaporation signal. This enabled us to qualitatively assess the origin of water in the piezometer transects because alternative sources of recharge (diffuse rainfall and flood recharge) would not have an evaporation signal (Simpson and Herczeg 1991a,b).

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The patterns in the stable isotopes of water clearly indicate that a large proportion of the shallow groundwater near the river was infiltrated under “low flow” conditions. It is not possible to quantify this proportion further because the end-member signatures are not known. In other words, while river water probably had an evaporated signal for much of 2009, the strength of this signal probably varied significantly over time. Salinity (as TDS) was relatively low in all groundwater samples, which is consistent with river recharge as the main source. In semi-arid climates, diffuse rainfall recharge would tend to have more elevated salinity because of plant transpiration during the recharge process.

As for all the other Losing Stream project sites, groundwater dating with CFCs is not recommended at the Lachlan transects. Dissolved oxygen concentrations in groundwater were often low, potentially leading to conditions where CFC degradation can take place. As demonstrated in the Border Rivers site report (Lamontagne et al. 2011e), SF$_6$ could be an alternative tool for alluvial groundwater dating. This technique was not available at the time the Lachlan samples were collected. Because of the uncertainties associated with CFC dating at the Lachlan River transects, it was not possible to estimate infiltration rates from the river using environmental tracers. This could be attempted in the future by re-sampling the piezometer network for SF$_6$ dating.

4.5. Characteristic curves

The inability to determine characteristic curves using pressure plates was an unexpected outcome of the Lachlan field work. The reasons for the failure of the pressure plate technique are not clear at present and this approach may not be suitable to determine characteristic curves for in-stream clay-rich Murray-Darling Basin sediments.

The failure to use pressure plates led to the trial of an alternative technique to estimate characteristic curves at Billabong Creek (evaporation experiments; Schindler and Müller 2006). Characteristic curves consistent with a clay-rich environment were successfully measured at Billabong Creek with this alternative technique (Lamontagne et al. 2011a). However, most of the intact core material from the Lachlan River was used for the pressure plate measurements. Therefore, it was not possible to carry evaporation experiments for the Lachlan sediments.

4.6. Conclusion and Recommendations

The Lachlan River was losing-disconnected at the two transects investigated. It is important to identify when a stream becomes losing-disconnected because the infiltration rate from the river to the aquifer at a given river stage becomes independent of the depth to the water table. However, it was not possible to estimate the infiltration rate from the river at the transects. A methodology was trialled at Lachlan – Hillston Bridge to estimate the infiltration rate through the unsaturated zone below the stream. The approach appeared successful but these infiltration rate estimates are preliminary and cannot be used to estimate recharge to the aquifer at the transect because:

- The spatial and temporal variability in the infiltration rate through the unsaturated zone was not quantified; and,
- The estimated infiltration rates assumed that steady-state conditions were present at the time of sampling.

In addition, a part of the infiltrated river water could also be transpired by riparian vegetation, which would tend to decrease the net recharge rate to the aquifer. Nevertheless, very few direct measurements of infiltration have been made in losing-disconnected rivers and the work done at the Billabong and Lachlan sites could be the first attempts to do so in Australia.
It was also not possible to estimate the recharge rate by comparing groundwater ages along the piezometer transects due to the uncertainties associated with CFC dating in alluvial environments. However, the presence of evaporated water in shallow groundwater near the river (>100 m) indicates that some recharge occurs even during low flow period. More information about recharge processes and rates could be gained by:

- Characterising the variability in stable isotopes in surface water and groundwater over time; and
- Using an alternative method to CFCs to date alluvial groundwater.

There are few environmental tracers available to date groundwater in the age-range expected for near-stream alluvial groundwater under losing conditions (i.e., months to decades old). The best alternative at present would be sulfur hexafluoride (SF₆), which can date groundwater over a similar age-range as CFCs (Plummer and Busenberg 2000) but appears less susceptible to degradation. SF₆ has only recently become available as a dating tool in Australia and requires ancillary measurements. However, preliminary testing at another of the project’s sites (Border Rivers) indicated that it could be a suitable alternative to CFCs in alluvial environments typical of the Murray-Darling Basin.

**Recommendations**

The Losing Streams project developed and applied a methodology to identify whether a river is losing-connected or losing-disconnected using simple field and laboratory measurements. The project was less successful in estimating the infiltration rates from the rivers because of difficulties with the use of hydrometric techniques (like differential gauging) in this environment and the uncertainties encountered with groundwater dating with CFCs. Nevertheless, the riparian piezometer network design used was satisfactory and the application of an alternative groundwater dating technique should enable the estimation of infiltration rates in future studies. In summary, the recommendations from the Lachlan River site studies are to:

- Use the field measurements, especially the demonstration of losing-disconnected conditions, to constrain existing regional groundwater models;
- Monitor piezometric surface and surface water levels at the Lachlan transects for a longer period of time in order to capture a greater range in seasonal water level variations;
- Develop a suitable modelling tool to evaluate delayed recharge events caused by travel through the unsaturated zone in losing-disconnected streams;
- Further characterise the spatial and temporal variability in infiltration through the streambed in losing-disconnected environments, in particular investigate the possibility of infiltration “hotspots”;
- Attempt to age alluvial groundwater at the transects with an alternative technique (SF₆ dating); and,
- Characterise the seasonal variability in the stable isotopes of Lachlan River water as this tracer could be a good marker for the source of recharge to this alluvial aquifer.
REFERENCES


APPENDICES

Appendix A. Piezometer location, elevation and screen interval at the Lachlan transects.

<table>
<thead>
<tr>
<th>Transect</th>
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<th>Latitude</th>
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<th>Screen Interval (m AHD)</th>
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<td>GW273046/1</td>
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<td>75.20 – 73.20</td>
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<td>145.52994</td>
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<th>Stream Gauge</th>
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<th>Zero Gauge (m AHD)</th>
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<td>145.53133</td>
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<td>75.26 – 73.26</td>
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<th>Stream Gauge</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Zero Gauge (m AHD)</th>
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## Appendix B. Surface and groundwater quality at the Lachlan transects on 11 – 22 May 2009.

<table>
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<th>Sample</th>
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<th>Field E.C. (dS m⁻¹)</th>
<th>Temp. (°C)</th>
<th>O₂ (Winkler) mg L⁻¹</th>
<th>Carbonate Alkalinity meq L⁻¹</th>
<th>Cl mg L⁻¹</th>
<th>SO₄ mg L⁻¹</th>
<th>Ca mg L⁻¹</th>
<th>K mg L⁻¹</th>
<th>Mg mg L⁻¹</th>
<th>Na mg L⁻¹</th>
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<td>0.228</td>
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<td>1.3</td>
<td>22.2</td>
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### Appendix C: Summary of the environmental tracer data collected at the Lachlan transects.

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<tr>
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<th>CFC-11 (pg L⁻¹)</th>
<th>CFC-12 (pg L⁻¹)</th>
<th>CFC-11 (years)</th>
<th>CFC-12 (years)</th>
<th>δ¹⁸O (% VSMOW)</th>
<th>δD (% VSMOW)</th>
<th>²²²Rn (pg L⁻¹)</th>
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<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
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<td>1973</td>
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<td>1967</td>
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<td>-28.7</td>
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| **Hillston Bridge – River** |                 |                 |                |                |                |              |                |
| GW 273049/1     | 49.0            | 55.5            | 1965           | 1970           | -0.37          | -10.8        | 7.08           |
| GW 273049/2     | <25             | <20             | <1965          | <1965          | -5.29          | -36.8        | 5.01           |
| GW 273050/1     | 27.5            | 26.5            | <1965          | 1965           | -2.84          | -22.1        | 4.17           |
| GW 273050/2     | <25             | <20             | <1965          | <1965          | -5.23          | -35.9        | 5.28           |
| GW 273051/1     | <25             | 56.5            | <1965          | 1971           | -0.04          | -7.9         | 10.48          |
| GW 273051/2     | <25             | <20             | <1965          | <1965          | -6             | -37.8        | 4.97           |
## Appendix D. Summary of the pressure plate analysis on streambed sediments at the Lachlan site.

<table>
<thead>
<tr>
<th>Transect No.</th>
<th>Core No.</th>
<th>Streambed sediment depth (cm)</th>
<th>Replicate</th>
<th>Bulk density (g cm(^{-3}))</th>
<th>Porosity</th>
<th>Field moist (\theta_v) (cm(^3) cm(^{-3}))</th>
<th>(\theta_v) (cm(^3) cm(^{-3}))</th>
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<tbody>
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<td>C1</td>
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<td>A</td>
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<td>0.44 0.45 0.43</td>
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<td>A</td>
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<td>0.52</td>
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<td>B</td>
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<td>0.46</td>
<td>0.53</td>
<td>0.50 0.48 0.46</td>
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<td>0.43 0.43 0.43</td>
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<td>0.57</td>
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Appendix D (cont.). Summary of the pressure plate analysis on streambed sediments at the Lachlan site.

<table>
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<th>Transect No.</th>
<th>Core No.</th>
<th>Streambed sediment depth (cm)</th>
<th>Replicate</th>
<th>Bulk density (g cm(^{-3}))</th>
<th>Porosity</th>
<th>Field moist (\theta_v) (cm(^3) cm(^{-3}))</th>
<th>(\theta_v) (cm(^3) cm(^{-3}))</th>
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<td>Porosity</td>
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