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

Gwydir River Site Report
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A Report for the NSW Office of Water
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Cover Photograph:
From: Sebastien Lamontagne
Description: Gwydir River near Yarraman Bridge
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EXECUTIVE SUMMARY

Background

This report summarises the field studies at the Gwydir 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 Gwydir River were to:

- Determine at two locations (Yarraman Bridge and Brageen Crossing, near Moree 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,
- Estimate infiltration rates through the streambed.

Field and lab results

At the time of the site visit (7 – 11 December 2009), the Gwydir River at Yarraman Bridge and Brageen Crossing was losing-disconnected. Both sites had a clogging layer (a clay unit 0.5 m or more in thickness) in the streambed and relatively deep water tables in the riparian zone (6 and 12 m below the streambed at Yarraman Bridge and Brageen Crossing, respectively). Streambed profiles at Yarraman Bridge also confirmed the presence of a vadose zone below the streambed. However, the clogging layer was below a thin gravel unit at Yarraman Bridge (0.3 to 1 m in thickness) and the river was also losing-connected with respect to the gravel unit.

Hydraulic heads in the piezometer network and in surface water showed limited variations over time during the monitoring period (March 2009 to March 2010). However, the river remained losing at all times and one deep piezometer apparently located in a confined aquifer showed evidence of pumping-induced drawdowns.

Groundwater at the two transects was fresh and appeared to originate mainly from flood recharge. There was little evidence for recharge under low flow conditions. However, it was not possible to confirm the mechanism for recharge or evaluate the recharge rates because of the uncertainties in groundwater dating with CFCs in the aquifer. Because of the very low flow conditions, it was not possible during the site visit to estimate infiltration along the river by differential gauging.

Recommendations

The Losing Streams project developed and successfully 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 infiltration rates from the rivers in the field 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 design of the riparian piezometer network 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 Gwydir River site studies are to:

- Use the field measurements, especially the identification of losing-disconnection, to help constrain existing groundwater models for the Gwydir River;

- Monitor the piezometric and surface water levels for a longer period of time at the two transects to better evaluate the near-stream hydraulic head response for losing-disconnected rivers;

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

- Determine and apply an appropriate hydrometric technique to measure infiltration rates at the reach scale in the Gwydir River and identify potential “hotspots” for recharge;

- Attempt to date the alluvial groundwater in the riparian piezometer transects with an alternative technique (SF\(_6\) dating);

- Characterise the seasonal variability in the stable isotopes of water of river water as this tracer could be a good marker for the source of the 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 understand 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 occurs through an unsaturated (or vadose) 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 Gwydir River (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 result. 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 design for the Losing Streams field studies

1.1.1. Piezometer transects

The Gwydir River and the other study reaches were each instrumented with two piezometer transects perpendicular to the river. Each transect usually consisted of three nests of paired piezometers extending from 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, 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 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).

1.1.2. 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

![Figure 1. Location of the Murray-Darling Basin and of the six study reaches for the Losing Streams project.](image)
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).

![Figure 2. Experimental design used 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).](image)

1.1.3. 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 be 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 Gwydir region is in northeastern NSW and represents 2% of the total area of the Murray-Darling Basin. CSIRO (2007) presented an overview of the hydrology of the catchment and Barrett (2009) described the hydrogeology of the Lower Gwydir region. The dominant land use is dryland pasture and irrigated cotton. The Rasmar-listed Gwydir Wetlands on the floodplain of the lower Gwydir is one of key environmental assets in the Murray-Darling Basin. Mean annual rainfall is 644 mm and is generally higher in the summer months. From a hydrogeological perspective, the Gwydir region is divided into two broad areas – the hilly highland country to the east and the broad alluvial plain to the west. The primary groundwater resource in the region is in the alluvial aquifer associated with the main rivers and channels of the western floodplain. In general, the alluvial aquifer consists of sequences of clay, sand and gravel units and can be divided in the shallower Narrabri Formation (10 – 30 m depth) and the deeper confined or semi-confined Gunnedah Formation (35 – 80 m depth). The region is also underlain by sandstones, shales and mudstones from the Great Artesian Basin.

Regional monitoring bores show evidence of recharge from flooding events within the Narrabri Formation, but the longer-term groundwater level trend has been consistently downward. The study area is located within the Lower Gwydir management unit (N03) downstream from Moree (Fig. 3).

![Figure 3](image-url) **Figure 3.** Location of the Gwydir study reach and of the two riparian piezometer transects.
2.2. Piezometer installation

The installation of the piezometer network was undertaken in January 2009 by Mannion Drilling under the supervision of NoW hydrogeologists. Three piezometer nests were installed at Brageen Crossing; one at the high bank and the others 75 m and 130 further away in the floodplain. However, only four piezometers were installed at Yarraman Bridge. A piezometer nest was installed at the high bank but only the shallow piezometers at the other distances because of the absence of significant water-bearing features at depth (i.e., mostly clay).

With one exception, the piezometers were installed using the rotary mud technique (Appendix A). One piezometer (GW093056/1) was installed by cable tool with drill and drive casing. All piezometers were made of Class 12 PVC (100 mm dia.OD) with a 2 m machine slotted screen (1 mm x 40 mm) and a 1 m sump. The gravel pack consisted of waterworn rounded gravels and the annulus above it was sealed with bentonite. The piezometers were protected at the surface with a lockable steel casing 169 mm dia. extending 2 m above the surface and bolted into a cement base (Plate A).

Plate A. Piezometer nest at Brageen Crossing. Photograph: S. Lamontagne.
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:

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

2.4. Water quality and environmental tracers

2.4.1. Field measurements

Groundwater samples were collected from all piezometers at the Gwydir River. Piezometers were purged for three bore volumes, with care taken that water level in the piezometers never dropped to 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 H\textsubscript{2}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 \( \mu \text{m} \) 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 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.

As no surface water sample could be collected at Brageen Crossing, two surface water samples were collected at Yarraman Bridge instead (one before and the other during an irrigation release).

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 chromatography (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. Bank tests, hydraulic conductivity and streambed \( \psi \) measurements

Due to the complex streambed environment, a combination of bank tests, piezomanometry and streambed vertical profiles were used to determine the type of connection at the Gwydir sites. The detailed procedure for the collection of streambed vertical profiles are presented in the Billabong Creek and Lachlan River reports (Lamontagne et al. 2011a,b) and the ones for the piezomanometry in the Macquarie River report (Lamontagne et al. 2011c). The hydraulic conductivity \( (K_{FH}) \) of the bank along a gravel bar at Yarraman Bridge was obtained from falling head permeameter tests using PVC pipes (Lamontagne et al. 2011a). At one location along the gravel bar, the hydraulic conductivity and groundwater velocity were measured using point dilution tests in small test wells (Lamontagne et al. 2002).

3. RESULTS

3.1. Geological cross-sections

The shallow alluvial aquifer at the two transects consisted of a mixture of clay, silt, sand and cobble units (Figs. 4 and 5). At Yarraman Bridge, the uppermost unit was clay underlain by a significant (10 – 15 m) gravel unit (Fig. 4). However, underneath the gravel unit was mostly clay again. All shallow piezometers were located in the shallow gravel unit and the sole deep piezometer was located in another small gravel unit approximately ~38 m below the surface and separated from the uppermost one by 10 m of silt and clay. At Brageen Crossing, a similar pattern in sediment texture was observed. There was an uppermost clay unit and two underlying gravel units separated by silt and clay (Fig. 5). At each piezometer nest, the shallow screen was in the uppermost gravel unit and the deeper screen in the deep gravel unit.

At the time of the site visit (7 – 11 December 2009), the water table in the riparian zone at Yarraman Bridge was approximately 6 m below the level of the streambed (Fig. 4). There was a small horizontal gradient away from the river in the shallow piezometers and a strong downward vertical gradient in the piezometer nest. At Brageen Crossing, the water table in the riparian zone was ~12 m below the streambed (Fig. 5), with no distinct horizontal or vertical hydraulic gradients. While pools were present at Yarraman Bridge, the riverbed was nearly completely dry at the time of the site visit at Brageen Crossing.
Figure 4. Geological cross-section of the Yarraman Bridge transect, showing the surface and groundwater levels during 7 – 11 December 2009. The water levels on the right are for the shallow piezometers and the one on the left for the deeper one.

Figure 5. Geological cross-section of the Brageen Crossing transect, showing the surface and groundwater levels during 7 – 11 December 2009.
3.2. Bank tests and piezomanometry

At Yarraman Bridge, the river channel consisted of clay banks with a silty sand and gravel bottom upstream of the piezometer and a gravel bar downstream (Fig. 6). River level was low (but increased later during the week following an irrigation release). Most bank tests were “wet” but a few “dry” ones were also found. Repeated attempts to measure \( \psi \) in the streambed by piezomanometry failed (no water entered the drive points). However, the piezomanometry suggested that a clay layer occurred below the gravel in the streambed.

At Brageen Crossing, the riverbed was nearly completely dry and bank tests or piezomanometry could not be performed.

![Figure 6](image.png)

**Figure 6.** Planar view of the streambed transects at Yarraman Bridge showing the location of bank pits and auger profiles. The transects upstream of the bridge were inundated on December 8 and had to be abandoned. The remaining measurements were made on a downstream gravel bar between T1 and T4. Most bank pits were “wet” (including T1 – T4) but the locations where auger profiles were collected had more clay and remained dry during sampling (i.e., equivalent to “dry” bank tests). A falling head test was made near each bank pit for T1 – T4 (not shown) and at additional locations along the gravel bar (not shown). The horizontal hydraulic gradient between river and pits was measured at T1 – T4. Several piezomanometer deployments were made in the streambed at T2 and T3 but failed.

3.3. Streambed \( \psi \) profiles at Yarraman Bridge

The combination of some “dry” bank tests and the failure to measure positive \( \psi \) by piezomanometry suggested that a vadose zone occurred not far below the streambed. Using some of the “dry” bank pits, three streambed profiles were collected by augering to verify the presence of a vadose zone (Fig. 6). All streambed profiles had an uppermost silty
gravel or gravelly clay layer overlying a clay unit. The profiles demonstrated that a vadose zone occurred below the river under a thin (∼ 50 cm) saturated layer (Figs. 7 – 9). Negative \( \psi \) tended to peek at 1 – 3 m below the stream and became less negative at depth. However, relative to the other losing-disconnected sites for the project, relatively low \( \psi \) (i.e., relatively high soil tensions) were measured (−1200 to −1000 kPa; see Lamontagne et al. 2011a,b).

Thus, the Yarraman Bridge site was losing-disconnected at the time of sampling. However, the river was perched and a small amount of water may have been lost laterally through the gravel bank as a losing-connected system (see hydraulic gradients in Section 3.6).

While several attempts were made, it was not possible to collect streambed profiles at Brageen Crossing because of the presence of cobbles in the streambed, which prevented augering. The river was also nearly completely dry at the time of sampling. However, the combination of a clogging layer in the streambed (clay and cobbly clay) and a relatively deep water table at that site (12 m below the streambed) suggests that the river was also losing-disconnected at that transect.

![Figure 7](image.png)

**Figure 7.** Gravimetric water content and \( \psi \) in auger profile P1 at Yarraman Bridge. \( \psi \) was measured with three different complementary techniques (Taylor et al. 2010). Note that the constant values measured at depth by tensiometry represent the maximum tension that can be measured with this instrument. The most accurate record is the one obtained by the filter paper technique (see Taylor et al. 2010 for details). All techniques showed that \( \psi < 0 \) deeper in the profile. Location of water table approximate.
Figure 8. Gravimetric water content and $\psi$ in auger profile P2 at Yarraman Bridge.

Figure 9. Gravimetric water content and $\psi$ in auger profile P3 at Yarraman Bridge. Location of water table approximate.
3.4. Temporal variations in hydraulic head

There were only relatively small variations in surface water level during the monitoring period at both transects (Figs. 10 and 11). At Yarraman Bridge, the river was losing at all times and there was a gradual declining trend in hydraulic head in all shallow piezometers (Fig. 10). However, hydraulic heads varied by up to 6 m in the deep piezometer, with a pronounced declining trend between June and December 2009 (Fig. 10). This suggests that the deeper piezometer is in a confined aquifer and may have been responding to groundwater pumping deeper in the alluvium.

The river (when not dry) was also always losing at Braggen Crossing. Hydraulic heads in piezometers showed little variability over time and there was no difference between shallow and deep piezometers. This suggests that the shallow and deep piezometers are part of the same aquifer.

Overall, there was no obvious response in hydraulic head to changes in river stage, unlike what was observed at the losing-connected sites for the project (Macquarie, Namoi and Border rivers; Lamontagne et al. 2011c,d,e). On the other hand, it is difficult to evaluate the hydraulic head response to changes in river stage at the Gwydir transects because of the short monitoring period, the lack of significant floods in the Gwydir during this period, and the possibility that the water table response will be delayed and more gradual under losing-disconnected conditions. A delayed response is expected under losing-disconnected conditions because flood pulses must travel through the vadose zone before reaching the water table.
Figure 10. Temporal variations in river stage and in hydraulic head in piezometers at Yarraman Bridge. Symbols represent manual water level measurements.
Figure 11. Temporal variations in river stage and in hydraulic head response at Brageen Crossing. Symbols represent manual water level measurements.
3.5. Environmental tracers

Groundwater was fresh in all samples, with salinities less than 300 mg L\(^{-1}\). There was a distinct pattern in salinity and deuterium content between the shallow and deep piezometer samples at Yarraman Bridge and Brageen Crossing (Fig. 12). The shallower piezometer tended to have slightly more saline and isotopically enriched samples. On the other hand, the samples from Brageen Crossing tended to have a slightly higher TDS relative to their counterparts from Yarraman Bridge. There was a weak tendency for more isotopically-enriched samples when closer to the river (Fig. 12). All groundwater samples fell close to the Murray Basin Local Meteoric Water Line (Fig. 13), with little evidence of evaporative enrichment. The two surface water samples from Yarraman Bridge had a strong evaporation signal (i.e., fell to the right of the local meteoric water line).

![Figure 12. Deuterium concentrations at the Gwydir transects as a function of (A) salinity (as TDS) and (B) distance from the river.](image-url)
There was a significant contrast in CFC-11 and CFC-12 concentrations between the Yarraman Bridge and Brageen Crossing samples. At Yarraman Bridge CFC concentrations were relatively elevated and highest in the shallower piezometers (Fig. 13 and Appendix C). In contrast, CFC concentrations were all at the detection limit at Brageen Crossing. At Yarraman Bridge, the CFC-11 and CFC-12 ages did not agree, indicating that some CFC degradation probably occurred in the aquifer (Happell et al. 2003). Using the more conservative CFC-12, the apparent age of recharge at Yarraman Bridge would be mid-1980s in the shallow piezometers and early 1970s in the deep one. At Brageen Crossing, the lack of CFC suggests that groundwater was recharged prior to the mid-1960s. There was no significant difference in CFC-inferred groundwater age with distance from the river at Yarraman Bridge. This could represent one large recharge event covering this whole section of the aquifer rather than gradual infiltration from the river. However, because of the potential for CFC-12 degradation in the aquifer, the possibility remains that groundwater ages are overestimated at both transects. This will need to be confirmed by comparison with alternative dating techniques.

**Figure 13.** Relationship between $\delta^2$H and $\delta^{18}$O at the Gwydir River transects. The opened symbols are for Yarraman Bridge and the closed ones for Brageen Crossing. Murray Basin Meteoric water line: $y = 7.6x + 8$ (Simpson and Herczeg 1991a). Brisbane Meteoric Water Line: $y = 7.7x + 12.6$. 

There was a significant contrast in CFC-11 and CFC-12 concentrations between the Yarraman Bridge and Brageen Crossing samples. At Yarraman Bridge CFC concentrations were relatively elevated and highest in the shallower piezometers (Fig. 13 and Appendix C). In contrast, CFC concentrations were all at the detection limit at Brageen Crossing. At Yarraman Bridge, the CFC-11 and CFC-12 ages did not agree, indicating that some CFC degradation probably occurred in the aquifer (Happell et al. 2003). Using the more conservative CFC-12, the apparent age of recharge at Yarraman Bridge would be mid-1980s in the shallow piezometers and early 1970s in the deep one. At Brageen Crossing, the lack of CFC suggests that groundwater was recharged prior to the mid-1960s. There was no significant difference in CFC-inferred groundwater age with distance from the river at Yarraman Bridge. This could represent one large recharge event covering this whole section of the aquifer rather than gradual infiltration from the river. However, because of the potential for CFC-12 degradation in the aquifer, the possibility remains that groundwater ages are overestimated at both transects. This will need to be confirmed by comparison with alternative dating techniques.
Figure 13. CFC-12 concentrations at Yarraman Bridge (opened symbols) and Brageen Crossing (closed symbols) relative to distance from the river.
3.6. Hydraulic conductivity of the Yarraman gravel bar

Using the falling head test, a large range in hydraulic conductivity ($K_{FH}$) was found along the Yarraman Bridge gravel bar (Fig. 14). The average log $K_{FH}$ was $\sim 1E-5$ m s$^{-1}$, but individual values ranged from $1E-6$ m s$^{-1}$ (the lower detection limit for the instrument) to $5E-4$ m s$^{-1}$. The $K_{FH}$ values appeared to be determined, in part, by whether or not permeameters were partially inserted into the underlying clay layer. To get an estimate of the lateral infiltration rate into the gravel banks, $K_{FH}$ values were matched with the horizontal hydraulic gradients measured between the river and bank pits (Fig. 6). The specific horizontal infiltration rate ($q_h$) and the longitudinal infiltration rate ($Q_L$) were defined as:

$$q_h = -K_{FH}i_h$$

(3)

and,

$$Q_L = -K_{FH}i_hz$$

(4)

where $z$ is the thickness of the gravel bank over the clay (assumed to be $\sim 0.5$ m on average). Note that $K_{FH}$ is used as a proxy for the horizontal hydraulic conductivity ($K_h$) and probably underestimates $K_h$. The infiltration into the gravel bank ranged from $-0.036$ (i.e., stream gaining) to $+0.29$ m day$^{-1}$ (Table 1). While a net infiltration into the gravel bank was measured, the error on the estimate was also quite large (Table 1). Assuming similar conditions on the other bank, these infiltration estimates must be multiplied by two to account for losses along both sides of the river. These infiltration estimates also do not account for the vertical infiltration through the streambed clays. While not attempted here, Lamontagne et al. (2011a,b) demonstrated how the streambed $\psi$ profiles can be used to estimate the vertical infiltration rate under losing-disconnected streams. In summary, lateral exchange with sand and gravel banks appears a significant component of the water balance for the Gwydir under low flow conditions.
Table 1. Estimation of the specific lateral infiltration rate \( (q_h) \) and longitudinal infiltration rate \( (Q_L) \) along the Yarraman Bridge gravel bar.

<table>
<thead>
<tr>
<th>Transect</th>
<th>( K_v ) ( (m \ s^{-1}) )</th>
<th>( i_h ) ( (m \ m^{-1}) )</th>
<th>( z ) ( (m) )</th>
<th>( q_h ) ( (m \ day^{-1}) )</th>
<th>( Q_L ) ( (ML \ km^{-1} \ day^{-1}) )</th>
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</thead>
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<tr>
<td>T1</td>
<td>1.2E–4</td>
<td>0.003</td>
<td>0.5</td>
<td>–0.031</td>
<td>–0.016</td>
</tr>
<tr>
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<td>0.28</td>
<td>0.14</td>
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<tr>
<td>T3</td>
<td>2.0E–5</td>
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<td>0.5</td>
<td>0.007</td>
<td>0.0035</td>
</tr>
<tr>
<td>T4</td>
<td>1.9E–5</td>
<td>–0.002</td>
<td>0.5</td>
<td>0.003</td>
<td>0.0016</td>
</tr>
<tr>
<td></td>
<td>( \text{Average} \pm \text{SD} )</td>
<td>0.065 ± 0.14</td>
<td>0.032 ± 0.072</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 14. Histogram of gravel bank \( K_{FH} \) at the Yarraman Bridge site. All tests made at the edge of the bank or in small pits within one meter from the river’s edge.
3.7. Point dilution test

An alternative approach to estimate infiltration from rivers is through the use of point dilution tests. A technique to perform this test in the parafluvial zone is described in Lamontagne et al. (2002). Briefly, a small well made of a length of PVC pipe with a 1-m screen was inserted along the banks with the top of the screen just below the water table. Some saline water was then added to the well and the change in EC over time measured. Two deployments were made near Transect T1 (and the test repeated for the first deployment). The rate of change in EC in the well is a function of the apparent groundwater velocity within the well ($v^*$; Freeze and Cherry 1979), which can be estimated using characteristic curves (Lamontagne et al. 2002).

The specific infiltration ($q$) can be estimated from $v^*$ using:

$$q = \frac{v^*}{\alpha}$$  \hspace{1cm} (5)

where $\alpha$ is the well focussing or well-shape factor (Freeze and Cherry 1979). For the well design used, $\alpha$ is ~2 (Lamontagne et al. 2002). Because the horizontal hydraulic gradient ($i_h$) in the vicinity of the wells was known, the point dilution test can also be used to estimate $K_h$ by re-arranging the Darcy Equation ($q = -K_i i_h$). The tests were performed on 11 December 2009.

The apparent velocities were ~54 and ~1 cm h$^{-1}$ for Test #1 and #2, respectively (Fig. 15). Following the convention for the definition of the hydraulic gradient and changing the units, these corresponded to $q = -6.5$ and $-0.12$ m day$^{-1}$ for Test #1 and #2, respectively (note that the river was gaining at that transect). This represented a larger discharge to the river than the $q$ estimated using the permeameter and manometer measurements at T1 (Table 1). The discrepancy may have been caused by the use of $K_{FH}$ as an estimate of $K_h$ for the gravel bar. Using the $i_h$ from the nearby pit on that day (0.003), $K_i$ would be $\sim$2.5E–2 and $\sim$4.6E–4 m s$^{-1}$ for Test #1 and #2, respectively. This suggests that $K_i > K_v$ along the gravel bar.
Figure 15. Results of point dilution tests along the gravel bar at Yarraman Bridge Transect T1 (A) Test #1; (B) Test #2.
4. DISCUSSION

4.1. Connection status

Due to the heterogeneity of the aquifer material in the vicinity of the streambed, it is suspected that the connectivity of the alluvial aquifer with the lower Gwydir River will tend to vary significantly at the stream-reach scale. At Yarraman Bridge the river was losing-disconnected. However, the river was also possibly losing-connected to the riparian zone through shallow permeable features like gravel bars located above the streambed clogging layer. A definitive assessment of the connection status could not be made at Brageen Crossing because – with the exception of a few small pools – the river was dry. However, the presence of a clay-lined streambed and a deep water table in the riparian zone (12 m below the streambed) suggest that the river was probably losing-disconnected at this transect as well.

It was noted that significant shallow gravel and cobble units occur in the alluvial aquifer near the river. This suggests that when these features outcrop to the river bed, the nature of the connection could change. The presence of a clogging layer in the streambed is a necessary condition to establish losing-disconnection when the water table drops below the river (Brunner et al. 2009a). If the clogging layer is absent, the river will remain losing-connected when the regional water table drops. In other words, the infiltration rate will increase in proportion to the drop in the water table and the river will dry-out rather than become losing-disconnected (Brunner et al. 2009a). It is possible to have alternating river sections with losing-connected and -disconnected conditions. Because of the lower water tables fostered by neighbouring losing-disconnected sections, the infiltration rates at losing-connected sections would tend to be high and the recharge mounds would have very steep slopes. Losing-connected sections within losing-disconnected river reaches may be difficult to detect using only the water table depth in the riparian zone.

It was not possible to evaluate the changes in infiltration rate along the Gwydir study reach because conditions were not suitable for differential gauging during the site visit. However, this should be attempted in the future to detect potential infiltration “hotspots” along the reach (and the lower Gwydir River in general). Mapping areas with exposed gravels and cobbles may also provide some clues for where preferential infiltration sites may be. However, this will not be fool-proof because – as demonstrated at Yarraman Bridge – the clogging layer can be at depth in the streambed. Some additional hydrometric approaches to estimate the infiltration rate along a stream reach are discussed in the Namoi report (Lamontagne et al. 2011d).

4.2. Environmental tracers

Unlike the nearby Namoi River study reach, there was little evidence of alluvial aquifer recharge under low flow conditions in the Gwydir one. However, groundwater was fresh and its salinity and isotopic composition were consistent with flood recharge. Other sources of recharge (diffuse rainfall recharge, irrigation return, etc) would tend to have higher salinities (Lamontagne et al. 2005; Herczeg et al. 2001; Simpson and Herczeg 2001b). The CFC-inferred groundwater ages suggested an even age distribution at the scale of the riparian piezometer transects. This would also be consistent with the bulk of recharge occurring during flood events. This hypothesis could be verified by re-sampling groundwater at the transects with different dating methods (such as SF6) to confirm the trends observed with CFCs. Likewise, continuous measurements of the isotopic signature of river water over time
would enable to know the range in signature encountered over time, including the ones associated with occasional larger floods.

## 4.3. Conclusion and recommendations

While both sites appeared losing-disconnected, it is suspected that the type of connection could vary significantly in space or in time in the Gwydir River. The assessment of losing-disconnection at Yarraman Bridge and Brageen Crossing are also only valid for the sampling period (December 2009). In particular, Yarraman Bridge had the shallowest water table for all the losing-disconnected sites identified in the Losing Streams project and could become losing-connected following significant periods with increased river flows. This could be evaluated by re-assessing the nature of the connection at the two transects over time, especially after a prolonged wet period.

In common with the other losing-disconnected sites covered by the project, there was no apparent response in hydraulic head to stage variations in the river. However, there were also few or no significant flow events during the monitoring period, and the monitoring period may also have been too short in the context of losing-disconnected environments. Because flood pulses must first travel through an unsaturated zone, it is anticipated that the hydraulic head response will be delayed and subdued at losing-disconnected sites. While the hydraulic head response to flood pulse events has been studies in some detail in losing-connected environments (Pinder et al. 1969; Jolly et al. 1994; Boutt 2010), it is still unclear how losing-disconnected sites respond to floods.

Due to the uncertainties associated with CFC-dating at the Gwydir and the other study reaches, it is recommended that the riparian groundwater be dated with alternative techniques, such as SF6 (Plummer and Busenberg 2000). Better known groundwater ages along the two riparian transects would enable to estimate the infiltration rate to the aquifer, as well as the likely mechanisms of groundwater recharge.

The successful use of point dilution tests along the river bank at Yarraman Bridge highlighted that this technique could also be used more widely to estimate infiltration from rivers to alluvial aquifers. The approach could also be used in the riparian zone using the piezometer transects. The advantage of using the riparian piezometers would be that tests could still be performed during bankfull and (moderate) overbank floods. Thus, infiltration rates could be measured under a greater range in flow conditions than when using the test at the bank-scale alone.

The use of hydrometric techniques to measure reach-scale infiltration rates, possibly in combination with large-scale environmental tracer releases, was discussed in the Namoi report (Lamontagne et al. 2011d). As the lower Gwydir River is known to be a strongly losing environment (CSIRO 2007), it would be desirable to know if losses occur gradually along the river or are associated with infiltration hotspots where permeable sediments outcrop in the river valley. In addition to differential flow gauging, other techniques could also be used to estimate changes in infiltration rate along river reaches. One drawback of differential flow gauging is that it requires steady flow conditions over the whole measurement period. Due to the “working” nature of the lower Gwydir River, this may be difficult to achieve because of frequent flow variations induced by irrigation and environmental releases. One alternative would be to coordinate with management agencies significant periods (probably weeks) with constant flow releases from the main upstream reservoir (Copeton Dam). Irrigation and natural flood pulses have also been used elsewhere to estimate infiltration along ephemeral rivers (Vázquez-Suñé et al. 2007; Niswonger et al. 2008). What approach, or combination of
approaches, would be best suited to measure infiltration at the reach-scale (tens of kilometres) under a range of flow conditions in MDB tributaries is still unclear.

**Recommendations**

The project developed and successfully applied a methodology to identify whether a river is losing-connected or losing-disconnected using simple field and laboratory measurements. However, it was less successful in estimating infiltration rates from the rivers in the field because of difficulties with the use of hydrometric techniques (like differential flow gauging) in this environment and the uncertainties encountered with groundwater dating with CFCs. Nevertheless, the design of the riparian piezometer network 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 Gwydir River site studies are to:

- Use the field measurements, especially the identification of losing-disconnection, to help constrain existing groundwater models for the Gwydir River;
- 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 losing-disconnected rivers;
- Re-assess the connectivity at the two sites following a prolonged wet period to evaluate if it could change over time;
- Determine and apply an appropriate hydrometric technique to measure infiltration rates at the reach scale in the Gwydir and identify potential “hotspots” for recharge;
- Attempt to date the alluvial groundwater in the riparian piezometer transects with an alternative technique (SF$_6$ dating);
- Characterise the seasonal variability in the stable isotopes of water 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 Gwydir transects.

<table>
<thead>
<tr>
<th>Site</th>
<th>Piezometer No.</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Ground Level Elevation (m AHD)</th>
<th>Screen Interval (m AHD)</th>
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<td>Yarraman Bridge</td>
<td>GW093056/1</td>
<td>29.426129</td>
<td>149.845363</td>
<td>208.52</td>
<td>192.02 – 190.02</td>
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<td>GW093056/2</td>
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<th>Latitude</th>
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<td>Yarraman Bridge</td>
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<td>29.4261</td>
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<table>
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### Appendix B. Surface and groundwater quality at the Gwydir transect on 7 – 11 December 2009.

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<tr>
<th>Sample</th>
<th>Lab pH</th>
<th>Field pH</th>
<th>Lab E.C. dS m$^{-1}$</th>
<th>Field E.C. dS m$^{-1}$</th>
<th>Temp. $^\circ$C</th>
<th>Winkler mg L$^{-1}$</th>
<th>Alkalinity meq L$^{-1}$</th>
<th>Cl mg L$^{-1}$</th>
<th>SO$_4$ mg L$^{-1}$</th>
<th>Ca mg L$^{-1}$</th>
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<td>54.6</td>
<td>29.6</td>
<td>23.2</td>
<td>0.87</td>
<td>12</td>
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</table>
### Appendix C. Summary of the environmental tracer data collected at the Gwydir transects on 7 – 11 December 2009.

<table>
<thead>
<tr>
<th>Sample</th>
<th>CFC-11 (pg/L)</th>
<th>CFC-12 (pg/L)</th>
<th>Apparent Age</th>
<th>δ(^{18})O (‰ VSMOW)</th>
<th>δD (‰ VSMOW)</th>
<th>(^{222})Rn (Bq L(^{-1}))</th>
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<tbody>
<tr>
<td>GW093056/1</td>
<td>146</td>
<td>119</td>
<td>1973, 1981</td>
<td>3.89</td>
<td>23.9</td>
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<td>GW093056/2</td>
<td>49</td>
<td>45</td>
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<td>34.5</td>
<td>-</td>
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<td>174</td>
<td>142</td>
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<td>191</td>
<td>152</td>
<td>1976, 1986</td>
<td>3.97</td>
<td>24.6</td>
<td>24.06</td>
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<td>184</td>
<td>1979, 2002</td>
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<td>7.7</td>
<td>0.05</td>
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<td>--</td>
<td>--</td>
<td>1.17</td>
<td>--</td>
<td>0.06</td>
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<td>GW093053/1</td>
<td>26</td>
<td>27</td>
<td>&lt;1965, 1966</td>
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<td>24.3</td>
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<td>&lt;1965, &lt;1965</td>
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