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Field assessment of surface water–groundwater connectivity in a semi-arid river basin (Murray–Darling, Australia)

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Abstract:

In semi-arid and arid river basins, understanding the connectivity between rivers and alluvial aquifers is one of the key challenges for the management of groundwater resources. The type of connection present (gaining, losing-connected, transitional and losing-disconnected) was assessed at 12 sites along six Murray–Darling Basin river reaches. The assessments were made by measuring the hydraulic head in the riparian zone near the rivers to evaluate if the water tables intersected the riverbeds and by measuring fluid pressure (ψ) in the riverbeds. The rationale for the latter was that ψ will always be greater than or equal to zero under connected conditions (either losing or gaining) and always lesser than or equal to zero under losing-disconnected conditions. A mixture of losing-disconnected, losing-connected and gaining conditions was found among the 12 sites. The losing-disconnected sites all had a riverbed with a lower hydraulic conductivity than the underlying aquifer, usually in the form of a silty clay or clay unit 0.5–2 m in thickness. The riparian water tables were 6 to 25 m below riverbed level at the losing-disconnected sites but never lower than 1 m below riverbed level at the losing-connected ones. The contrast in water table depth between connected and disconnected sites was attributed to the conditions at the time of the study, when a severe regional drought had generated a widespread decline in regional water tables. This decline was apparently compensated near losing-connected rivers by increased infiltration rates, while the decline could not be compensated at the losing-disconnected rivers because the infiltration rates were already maximal there. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS Murray–Darling Basin; groundwater–surface water interactions; losing streams

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INTRODUCTION

Losing streams and rivers are a common feature in semi-arid regions, especially where extensive pumping of alluvial groundwater takes place (Sophocleous *et al*., 1988; Braaten and Gates, 2003; Vázquez-Suñé *et al*., 2007). Despite recent developments, quantifying groundwater–surface water exchange in losing rivers is difficult (Sophocleous, 2002; Ruehl *et al*., 2006; Rassam *et al*., 2008; Brunner *et al*., 2009a, 2010a). Part of the difficulty with losing rivers is that different types of connection are present and influence the infiltration rate (Fox and Durnford, 2003; Fox and Gordji, 2007; Su *et al*., 2007). In losing-connected rivers, the water table in surrounding aquifers is an extension of the river in the subsurface and slopes away from it. In losing-disconnected rivers, the water table is well below the riverbed, and infiltration occurs through a vadose zone. It is necessary to know what kind of connection is present in a given area to evaluate current and future exchanges between rivers and aquifers (Brunner *et al*., 2010b; Wang *et al*., 2011). In losing-connected rivers, the infiltration rate is proportional to the head difference between the river and the aquifer. By contrast, in losing-disconnected rivers, the infiltration rate is independent of the hydraulic head difference. In addition, when the water table is close to the riverbed, a transitional stage occurs where a vadose zone exists beneath the riverbed but the infiltration rate is still related to the head difference (Fox and Gordji, 2007; Brunner *et al*., 2009a). Losing-disconnected rivers usually have a riverbed with a lower hydraulic conductivity (K) than the underlying aquifer (or 'clogging layer') (Sophocleous *et al*., 1995; Fox and Durnford, 2003; Treese *et al*., 2009; Wang *et al*., 2011; Irvine *et al*., 2012).

Most assessments of surface water–groundwater connectivity are made by comparing the position of the water table to river stage locally (Burt *et al*., 2002; Lamontagne *et al*., 2005) or by extension from regional water table maps (Ivkovic, 2009). However, these approaches will not always be successful in losing rivers because recharge mounds can occur in the vicinity of rivers (Brunner *et al*., 2009a,b) and may be difficult to represent when monitoring networks are sparse

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(Parsons *et al*., 2008). Distinguishing between losing-connected and losing-disconnected conditions will be especially difficult near the critical depth of disconnection, the riparian water table elevation at which disconnection takes place under the river (Fox and Gordji, 2007; Brunner *et al*., 2009a). In this case, connectivity must be preferably determined from measurements in the riverbed rather than approximated from the position of the water table some distance away from the river. Overall, few attempts have been made, and few methods are available to identify connectivity in the field (Brunner *et al*., 2010b).

In this study, the connectivity at 12 sites along six river reaches in the Murray–Darling Basin (MDB; southeastern Australia; Figure 1) was assessed in the field using two different methods. The river reaches were located in areas where the connectivity of the river to the aquifer was uncertain based on regional assessments (see Parsons *et al*., 2008, for example). One of the classification methods was based on the comparison of river levels and water table elevation in the riparian zone (*riparian water table* method), and the other used direct measurements of fluid pressure (ψ) in riverbeds (*riverbed fluid pressure* method). In the following, we describe the two classification methods, provide general and detailed results from some river reaches, and explore the trends in water table depth between the connected and disconnected sites. All assessments were made during an extensive regional drought (CSIRO, 2008) when regional water tables were declining across the basin.

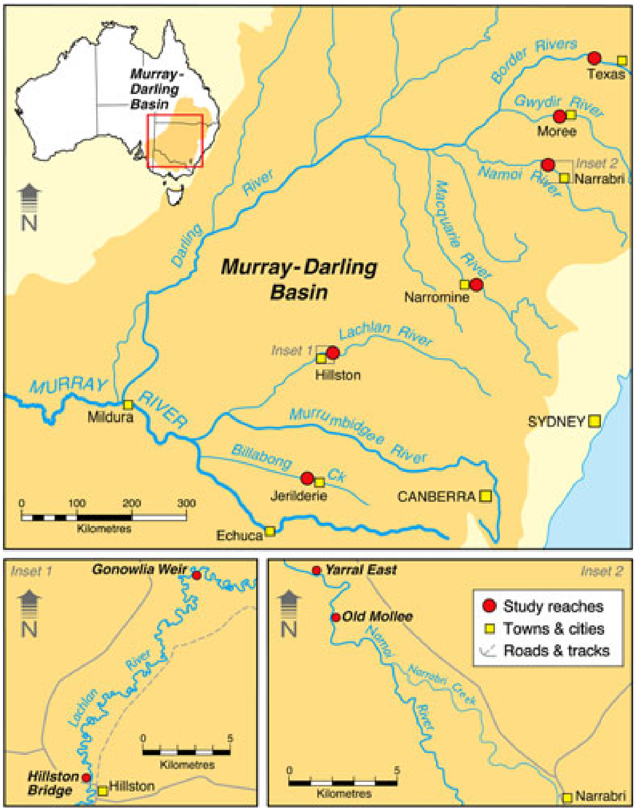

Figure 1. Location of the six study reaches and nearby towns or cities and (in inset) the detailed location of the Lachlan and Namoi rivers study reaches

METHODS

Study area

The MDB is the largest river system in Australia, with a catchment of over 1 million km^2. Climate is generally sub-tropical in the northernmost section of the Darling–Basin (with an episodic summer rainfall pattern) and semi-arid further south (with a winter rainfall pattern). Most of the runoff originates from small temperate areas in the headwaters of the catchment. Almost all rivers in the basin are regulated by reservoirs near the headwaters and are a part of an elaborate irrigation network. Groundwater accounts for about 16% of water consumption in the basin but this proportion increases during droughts (CSIRO, 2008). Most of the groundwater extraction occurs from alluvial aquifers associated with major tributaries. These aquifers have formed at the transition zone between upland regions and the flatter riverine plains and consist of a mixture of clay, silt, sand and gravel units. Groundwater use away from rivers is frequently constrained by high salinity, consistent with high evapotranspiration rates under semi-arid vegetation (Allison *et al*., 1990; Herczeg *et al*., 2001). Common irrigated crops include pastures, rice, cotton, vineyards and stone fruits.

The river reaches selected for the study were located (from north to south) on the Border (Dumaresq branch), Gwydir, Namoi and Macquarie rivers in the Darling sub-basin and the Lachlan River and Billabong Creek in the Murray sub-basin (Figure 1; Table I). All reaches were located along alluvial aquifers, exploited primarily for irrigation. The reaches were selected for detailed field investigation because they were located in areas where the nature of the connectivity (connected or disconnected) was unclear based on regional water table maps.

Riparian piezometer network

Each reach was 5–40 km in length and was instrumented with two riparian piezometer transects. Each transect usually consisted of three pairs of piezometer nests

Table I. Location for the 12 piezometer transects used during the study. The Billabong and Lachlan sites are in the Murray sub-basin and the others in the Darling sub-basin

River	Site	Eastings	Northings
Billabong	East	382697	6087209
Billabong	West	363738	6086463
Lachlan	Gonowlia weir	369210	6306792
Lachlan	Hillston bridge	363535	6295244
Macquarie	Woodlands	623243	6432461
Macquarie	Macs Reserve	617547	6437511
Namoi	Old Mollee	757990	6650039
Namoi	Yarral East	757048	6651966
Gwydir	Yarraman bridge	776053	6741432
Gwydir	Brageen crossing	746989	6745226
Border	Site 1	308872	6812390
Border	Site 2	304877	6819133

extending from the top of the high bank next to the river channel to 100–200 m further away from the river (Figure 2). Because of large variations in discharge during floods in MDB tributaries, it was not practical to install piezometers in the river channels. At each nest, one piezometer was usualy located 4–5 m below the water table and the second 10–15 m below the water table. In general, a combination of air and mud drilling was used but in some cases drilling had to switch to cable tool. Each piezometer consisted of a PVC pipe (51 mm diameter OD), a 2 m screen and a 1 m sump. The piezometers were protected by a lockable steel casing extending above flood level and secured on a concrete base. The annulus around the piezometers was filled with rounded gravels up to 1–3 m above the screen, sealed with bentonite, and the rest of the annulus grouted. Minor variations to this general design occurred at some of the sites. Each site also had a river level gauge. The elevation of piezometers, surface water level gauges and a cross-section of the river channels was surveyed.

Piezometers were used rather than water table wells because of the necessity to have the screens isolated from the vadose zone for other components of the study (groundwater dating using chlorofluorocarbons and sulfur hexafluoride; Cook and Herczeg, 2000). However, because the screens were not very far below the water table (<10 m), hydraulic head measurements in the shallow piezometers are unlikely to have differed greatly from the position of the free water table. For logistical reasons, it was not practicable to measure the water table on each side of the rivers. However, an effort was made to measure hydraulic gradients in the riverbed from bank to bank by piezometry during the site visits (see *Riverbed fluid pressure classification*) to evaluate the possibility of different conditions between banks (such as gaining on one side and losing on the other). While water level in piezometers and rivers was measured continuously from early 2009 to early 2010, only the manual water level measurements made at the time of the assessments of the riverbed ψ are presented here for simplicity.

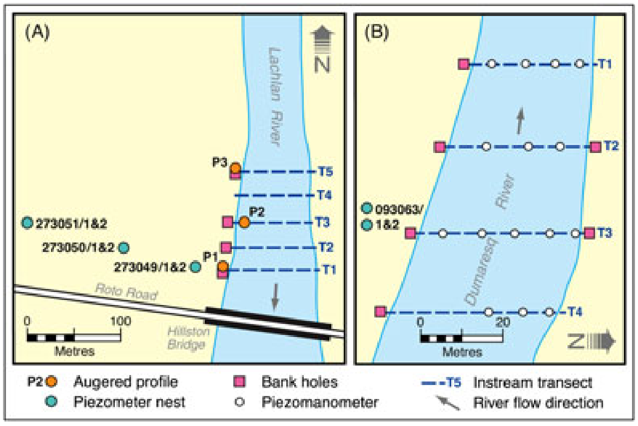

Figure 2. Experimental design for the field assessments of connectivity, with examples of the spacing of the riparian piezometer network and the measurement locations for riverbed fluid pressure assessment for (A) a losing-disconnected site (Lachlan–Hillston Bridge) and (B) a losing-connected one (Border–Site 2). AHD, Australian Height Datum (~mean sea level)

Riparian water table classification

This approach to connectivity classification requires the measurement of hydraulic head in at least one monitoring well or shallow piezometer near the river (h_x), surface water hydraulic head (h_r), the elevation of the lowest point in the riverbed (h_b) and, in some cases, to determine whether or not a clogging layer is present in the riverbed (Figure 3). The presence of a clogging layer was determined in the field by comparing riverbed to aquifer material texture and by measurements of the hydraulic conductivity of the riverbed by permeametry and other techniques (Lamontagne *et al.*, 2011a,b). When a clogging layer is present in the riverbed, h_b should be set at the base rather than the top of the clogging layer (Brunner *et al.*, 2009a). The approach assumes that the monitoring well or piezometer is in the aquifer connected to the river and sufficiently close to the river to minimise external influences other than variations in river level (such as groundwater pumping, irrigation recharge, etc).

The first step in the classification is straightforward – when the hydraulic head in the piezometer is greater than or equal to surface water hydraulic head ($h_x \geq h_r$), the river is *gaining-connected* (Figure 4) otherwise it is *losing*. The second step is also straightforward – when the river is losing and a clogging layer is absent, the river is *losing-connected*. In the cases of losing rivers with a clogging layer, the classification becomes more complex because several outcomes are possible. When the hydraulic head in the riparian zone is between surface water hydraulic head and riverbed elevation ($h_r > h_x \geq h_b$), the river is deemed to be *losing-connected*. Otherwise, when the hydraulic head in the riparian zone is below riverbed elevation ($h_b > h_x$), the maximum elevation of the recharge mound (h_{max}) and of the top of the capillary zone (h_c) has to be estimated before classification can proceed. These can be estimated by

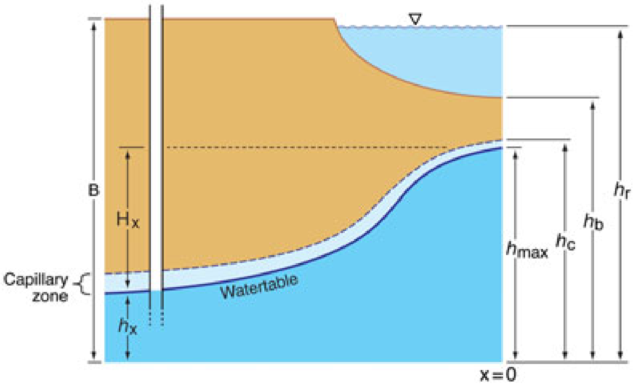

Figure 3. Conceptual diagram representing the shape of a groundwater mound and capillary zone underneath a losing-disconnected river. B, aquifer thickness; h_x, free water table elevation at distance x from the middle of the river; height from the water table to the top of the recharge mound at distance x from the middle of the river; h_{max}, maximum elevation of the recharge mound; h_c, maximum elevation of the capillary zone; h_b, riverbed elevation; h_r, river stage elevation. The capillary zone is defined as the part of the vadose zone with a volumetric water content between residual and fully saturated (Brunner *et al.*, 2009a,b). When a clogging layer is present h_b is set at the base of the clogging layer instead of at the riverbed surface

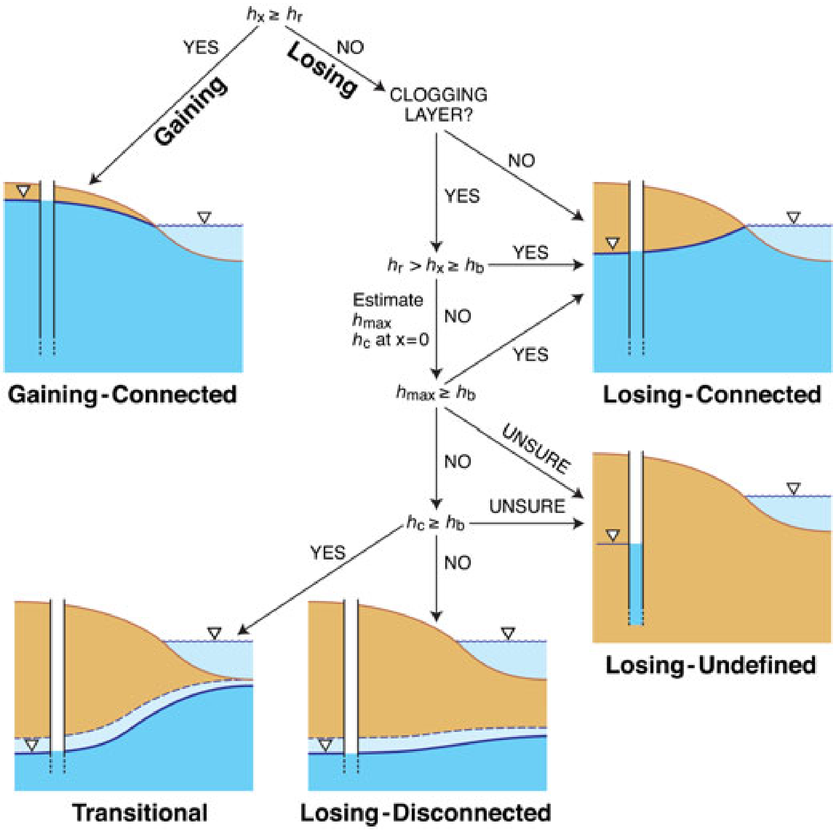

Figure 4. Flow chart for the riparian water table connectivity classification method

modelling infiltration below the riverbed when an estimate of the maximum infiltration rate (q_{max}) is available (Brunner *et al*., 2009a). If q_{max} is not known, the river can be classified as *losing-undefined* and prioritised for further investigation by using the riverbed fluid pressure method. Alternatively, if at least two head measurements are available in the riparian zone, the following procedure can be used to estimate h_{max} and h_c.

For a simplified river–aquifer system (including a clogging layer of even thickness and a no-flow boundary condition at the base of the aquifer), Brunner *et al.* (2009a) demonstrated that the shape of the recharge mound is a function of river width (w), aquifer thickness (B) and a proportionality constant $I = \frac{wq_{max}}{BK_a}$ representing the overall hydraulic gradient in the system (with K_a the aquifer hydraulic conductivity). The height to the mound at a distance x from the middle of the river (H_x; Figure 3) is equal to fI, where f is the slope of the relationship between H_x and I for different combinations of x, w and B. Nomograms relating f to x for different w and B were calculated using the fully-coupled surface-groundwater numerical model HydroGeoSphere (Therrien *et al*., 2006) following the procedure described in Brunner *et al.* (2009a) (Figure 5). When an estimate of q_{max} is available,

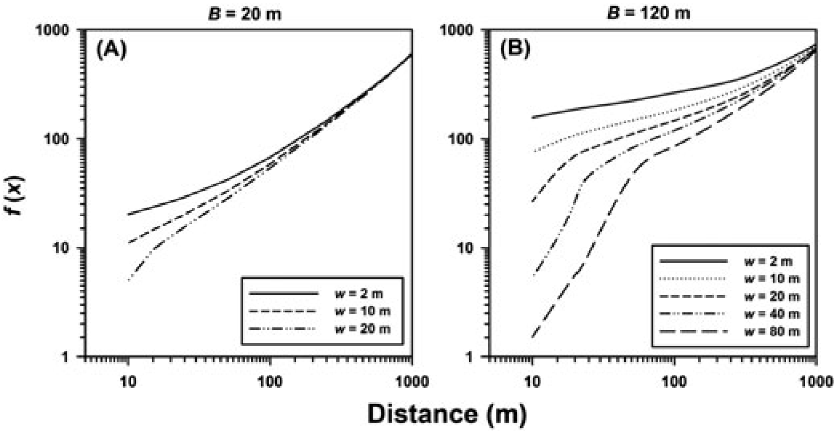

Figure 5. Nomograms relating the *f* function to distance from the middle of the river for different combination of river width (w) and aquifer thickness (B). Derived from Brunner *et al.* (2009a)

H_x can be estimated from a single observation point. When q_{max} is not known but two or more observation points are available (say, h_1 and h_2), both h_{max} and q_{max} can be estimated by setting-up a system of linear equations:

$$H_1 = f_1 I = f_1 \frac{w q_{max}}{B K_a} = h_{max} - h_1 \tag{1}$$

$$H_2 = f_2 I = f_2 \frac{w q_{max}}{B K_a} = h_{max} - h_2 \tag{2}$$

Re-arranging (1),

$$q_{max} = \frac{(h_{max} - h_1) B K_a}{f_1 w} \tag{3}$$

Substituting (2) in (3) and re-arranging,

$$h_{max} = \frac{f_2 h_1 - f_1 h_2}{f_2 - f_1} \tag{4}$$

The thickness of the capillary zone (c) will be a function of sediment texture and q_{max} and can be estimated with another set of nomograms (Figure 6). Thus, $h_c = h_{max} + c$.

Once h_{max} and h_c have been estimated, the classification proceeds as follows – if $h_{max} \geq h_b$, the river is *losing-connected*. Otherwise, if $h_{max} < h_b$ and $h_c \geq h_b$, the river is *transitional*. Finally, when $h_c < h_b$, the river is *losing-disconnected* (Figure 4).

Riverbed fluid pressure classification

Each site was visited on one occasion in 2009 to assess connectivity using the riverbed fluid pressure method. This classification procedure was a two-step process (Figure 7). First, *bank tests* were performed for an initial classification of the riverbeds as connected or disconnected. Bank tests simply involved augering holes or digging pits on the banks as close to the rivers as practical. Generally, pits or holes were dug at 20 m intervals along a 100 m section of both riverbanks in front of the piezometer network (Figure 2). If the pits or holes filled with water (became *wet*) ψ at the base of the pits had to be >0 and the riverbeds were preliminary classified as being connected. If the pits or holes remained free of water (were *dry*) after a certain length of time (~1 h), the beds were preliminary classified as being transitional or disconnected. The main purpose of the bank tests was to select the appropriate method to measure fluid pressure in the riverbeds. Following wet bank tests, piezometry was used to confirm positive fluid bed pressures (that is, *connected* conditions). Following dry bank tests, riverbed sediment profiles were collected and ψ measured in the laboratory to confirm negative fluid pressure (that is, *transitional or losing-disconnected* conditions). This switch in methodology was required because negative fluid pressures cannot be measured by piezometry (Freeze and Cherry, 1979).

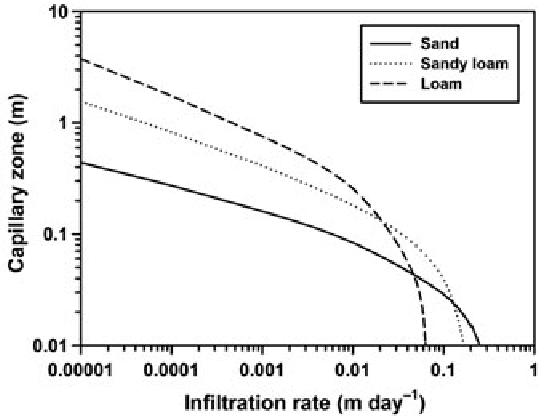

Figure 6. Nomograms estimating capillary zone thickness as a function of specific infiltration for different aquifer material textures. Derived from Brunner *et al.* (2009a)

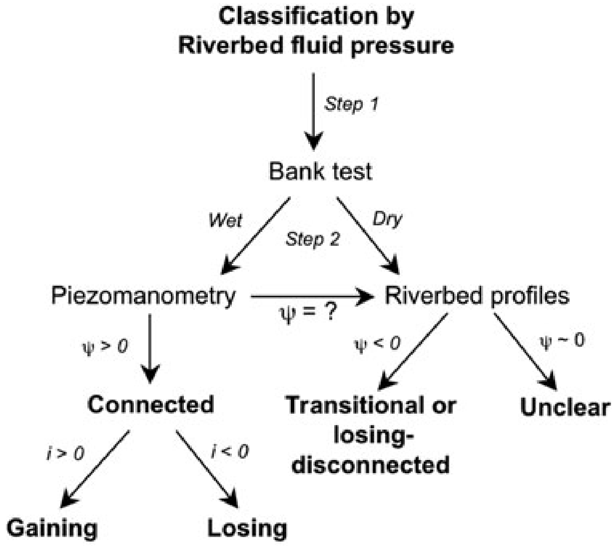

Figure 7. Flow chart demonstrating the steps and summarising the possible connectivity scenarios using the riverbed fluid pressure classification method. The vertical hydraulic gradient (i) is measured using river stage as the reference elevation. 'Riverbed profiles' is the collection of sediment cores by augering followed by measurement of ψ in the laboratory on preserved samples

Following *wet* bank tests, a drive point and manometer system similar to the piezomanometer of Kennedy *et al.* (2007) was used for the riverbed piezometry measurements. Both air–water and oil–water manometers were used, the advantage of the oil–water manometer being that hydraulic head differences are magnified 8 to 10-fold relative to an air–water manometer (Kennedy *et al.*, 2007). Drive points were deployed along transects crossing the riverbeds where the bank tests were made (Figure 2(B)). At each transect, three to six drive point deployments were made, with an aim to have measurements along both banks and the middle of the river. The drive points were inserted at a depth of 0.75–1 m in the riverbed. Two to six riverbed transects were surveyed in this fashion at each site where piezometry was used. The piezometry provided two pieces of information. Firstly, whenever water entered a drive point (that is, whenever a manometer reading could be made) ψ had to be positive by definition (Freeze and Cherry, 1979). In addition, the direction of the hydraulic gradient confirmed whether the riverbed was gaining or losing. Estimates of the infiltration rate through the riverbeds were also made using the hydraulic gradients but will not be discussed here.

Following dry bank tests or failure to deploy drive points (that is, when no groundwater could be drawn from them), vertical profiles of riverbed sediments were collected by augering. This approach was selected over alternative ones (such as the installation of tensiometers in the riverbed) because the remoteness of the site only allowed for one site visit to establish connectivity. Generally, three profiles were collected per site, usually 20–40 m from one another along one of the banks (Figure 2(A)). To collect each profile, a PVC casing was inserted ~50 cm into the riverbed at 30–50 cm water depth and dewatered using a bilge pump. The casing was then observed for several minutes to confirm that it was watertight. When watertight seals could not be obtained, the auger profiles were collected on a bank as close to the river as practical instead (usually within 1 m). Riverbed sediments were sampled in 20 cm increments and double-bagged in zip-lock bags. Profiles were collected up to 4 m depth or as far as practical. In general, the presence of saturated or unsaturated conditions in the sediment profiles could be readily ascertained based on field observations (dry holes, changes in clay texture, etc). However, laboratory measurements were used to back-up the field observations, especially for the clay-rich profiles.

In the laboratory, gravimetric water content variations in the profiles were measured on individual sub-samples by weighing sediments before and after oven-drying at 105 °C for 24 h. Because of the range encountered, two techniques were used to measure variations in ψ in the profiles. The filter paper technique (Greacen *et al.*, 1989) was applicable over a wide range (from $-100\,000$ to -1 kPa; ± 5–10% error) whereas mini-tensiometers (T5X Pressure transducer tensiometer; UMS) provided more precise ψ at the higher range (from -150 to -1 kPa; ± 1 kPa). All laboratory ψ measurements were made in a constant temperature room at CSIRO Waite Campus, Adelaide. Within their respective measurement ranges, the two methods usually provided similar ψ measurements in clays but not always in coarse sands. Because of the greater surface area covered by the measurement, it was felt that the filter paper technique was more accurate in coarse sands.

RESULTS

In general, all alluvial aquifers studied consisted of a mixture of sediment units of varying textures, including clays, silts, sands and gravels (Figure 8). With one exception (see next section), the hydraulic head in riparian piezometers was always less than river stage, showing that the rivers were losing. Within piezometer nests, the hydraulic gradients were usually downward, especially for the nests closest to the rivers, also consistent with losing environments. At the Lachlan–Gonowlia Weir site, two perched aquifers were identified during drilling and each instrumented with a piezometer (Figure 8(B)). The uppermost confining unit was 3–5 m below the riverbed at Gonowlia Weir. However, the assessment at this site was only made relative to the deeper regional water table.

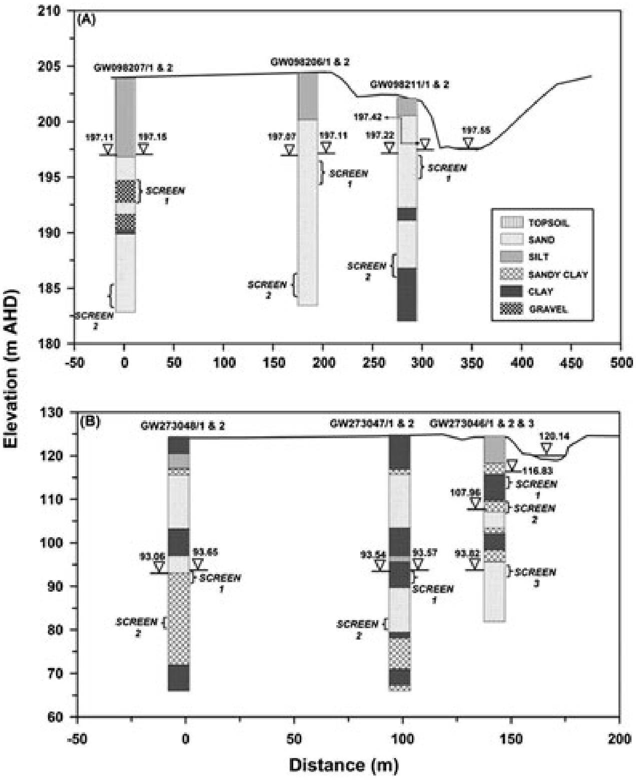

Figure 8. Alluvial aquifer cross-sectional profile and location of piezometer nests at (A) Namoi River–Old Mollee; (B) Lachlan River–Gonowlia Weir. For a given piezometer nest, the water level on the right is for the shallow screen and the one on the left is for the deeper screen at the time of the field assessment of connectivity. Note the presence of two perched aquifers at the Gonowlia Weir site associated with distinct clay units near the river

Connectivity classification by the riparian water table

On the basis of the riparian water table elevations, a mixture of gaining, losing-connected and losing-disconnected conditions were found among sites (Table II; Figure 9). Border–Site 1 was the only gaining site, with the riparian water table above river stage (Figure 9(F)). The Macquarie–Macs Reserve and Border–Site 2 sites had a riparian water table elevation below river stage but above riverbed elevation (at least for the piezometers closest from the rivers; Figure 9(D,F)), indicating that they were losing-connected. The two Namoi sites (Figure 9(E)) had a riparian water table slightly below riverbed elevation but, on the basis of field permeameter measurements, had no apparent clogging layer. Thus, they were both classified as losing-connected. The Macquarie–Woodlands site (Figure 9D) had a riparian water table elevation slightly below riverbed level, and the riverbed apparently had a clogging layer (that is, the riverbanks near the piezometers were clay-lined). However, the estimated $h_{\max}$ was greater than h_r at Macquarie–Woodlands so the site was classified as losing-connected. The Billabong, Lachlan and Gwydir sites (Figures 9(A–C)) all had a riparian water table 6.6–25 m below riverbed elevation as well as a well-defined clogging layer in the riverbed (usually a 0.5–2 m

Table II. Summary of the connectivity classification using the riparian water table method

River/Site	h_r (m)	h_b (m)	h_1 (m)	h_2 (m)	Clog	f_1	f_2	q_{max} (m day^{-1})	h_{max} (m)	h_c (m)	B (m)	w (m)	Connectivity
Billabong–East	104.57	102.04	90.39	90.48	Yes	—	—	—	~90.48[a]	~90.52[b]	20	20	LD
Billabong–West	99.47	98.30	89.91	88.31	Yes	25	55	0.05	91.23	91.27	20	20	LD
Lachlan–Hillston	115.89	113.11	91.39	91.37	Yes	90	125	3E–3	91.46	91.56	120	25	LD
Lachlan–Gonowlia	120.14	118.93	93.82	93.57	Yes	70	100	0.06	94.40	94.44	120	15	LD
Macquarie–Macs	222.85	221.40	222.42	222.35	No	—	—	—	—	—	20	35	LC
Macquarie–Woodlands	227.14	225.59	225.52	225.06	Yes	200	450	0.2[c]	225.89	225.90	20	15	LC
Namoi–Yarral	195.29	195.22	195.19	195.12	No	—	—	—	—	—	20	10	LC
Namoi–Old Mollee	197.55	197.45	197.42	197.11	No	—	—	—	—	—	20	20	LC
Gwydir–Brageen	~180.67	180.67	169.70	168.81	Yes	30	60	0.3[c]	168.73	~168.73	20	2	LD
Gwydir–Yarraman	202.51	201.89	195.24	195.08	Yes	25	70	0.3[c]	195.33	~195.33	20	20	LD
Border–Site 1	258.31	258.15	258.48	258.57	No	—	—	—	—	—	20	20	G
Border–Site 2	252.62	251.69	252.31	251.91	No	—	—	—	—	—	20	25	LC

Assumes $K_a = 10^{-5}$ m s^{-1} unless otherwise shown. All elevations in metre, Australian Height Datum. In a piezometer pair, h_1 is the one closest to the river. h_b not adjusted to clogging layer thickness. LD, losing-disconnected; LC, losing-connected; G, Gaining.

[a] Hydraulic gradient towards river (Figure 9(A)). Mound is probably very small ($h_{max} \sim h_1$).

[b] Assuming $q_{max} = 0.05$ m day^{-1}.

[c] $K_a = 10^{-3}$ m s^{-1}.

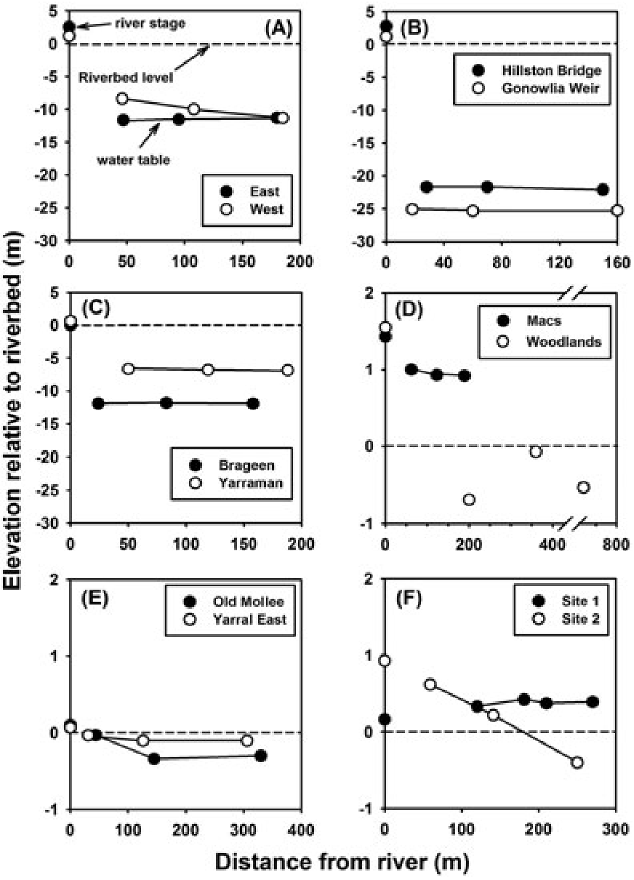

Figure 9. Position of the water table relative to the lowest point in the riverbed at the study sites at the time of the field assessments (based on the shallowest piezometer from each nest). The values at 0 m on the x-axis represent river stage at the time of the riverbed fluid pressure measurements

clay to silty clay unit) relative to the underlying aquifer material (sand to silty sand). The estimated h_{max} and h_c at Billabong, Lachlan and Gwydir were well below riverbed elevation, and the sites were classified as losing-disconnected (Table II), even when h_b was adjusted to the base of the clogging layer.

Connectivity assessment by riverbed fluid pressure

All bank tests results were dry at the Billabong and the Lachlan–Hillston Bridge sites and wet at the Lachlan–Gonowlia Weir, Macquarie, Namoi and Border sites (Table III). At the Gwydir River, the Yarraman Bridge site had a mixture of dry and wet bank test results, and Brageen Crossing had dry results only. However, the river was also nearly completely dry at the latter site at the time of sampling. In general, the sites with dry bank test results had silty clay or clay-lined riverbeds, whereas the ones with wet results had a mixture of poorly sorted silty sand, gravel or cobble riverbeds. One exception was the Macquarie River sites which consisted of alternating sections of clay-lined channels and silty sand and gravel bars. At the Macquarie sites, bank tests were made along both the clay-lined sections as well as along the sand and gravel bars. While in all cases the Macquarie bank holes partially filled with water, the ones along clay-lined banks had a significantly lower water level (10 to 50 cm over a lateral distance of 1 m) relative to river level. This may have either represented a very steep water table in clay banks or the presence of a small vadose zone at the edge of the river (i.e. transitional conditions; Brunner *et al.*, 2009a).

On the basis of the bank tests, piezometry surveys were undertaken at the Macquarie, Namoi, Gwydir–Yarraman Bridge and Border sites to measure riverbed fluid pressure (Table III). However, no successful drive point deployment could be made at the Gwydir–Yarraman Bridge site, and the assessment of riverbed ψ switched to the collection of sediment profiles by augering along the banks. Drive points were successfully deployed at the other sites where this technique was used (see Namoi example in Figure 10),

Table III. Summary of the connectivity assessments at the 12 sites using both the riparian water table and riverbed fluid pressure methods

River and transect	Riparian piezometers	Riverbed fluid pressure Bank tests	ψ	Classification	Riverbed texture	Overall assessment
Billabong–East	LD	Dry	<0[a]	TD	Clay	LD
Billabong–West	LD	Dry	<0[a]	TD	Clay	LD
Lachlan–Hillston	LD	Dry	<0	TD	Clay	LD
Lachlan–Gonowlia	LD	Wet	No data	—	Silty sand	LD[b]
Macquarie–Macs	LC	Wet	>0	C	Clay/silty sand	LC
Macquarie–Woodlands	LC	Wet	>0	C	Clay/sand/cobbles	LC
Namoi–Yarral East	LC	Wet	>0	C	Silty sand	LC
Namoi–Old Mollee	LC	Wet	>0	C	Silty sand	LC
Gwydir–Brageen	LD	Dry	No data	—	Gravelly clay	LD[c]
Gwydir–Yarraman	LD	Dry/wet	<0	TD	Silty sand/clay	LD[b]
Border–Site 1	G	Wet	>0	C	Silty sand/cobbles	G
Border–Site 2	LC	Wet	>0	C	Silty sand	LC

The last column represents the best estimate of the connectivity based on both classification systems and other field observations. Connection status: G, Gaining; LC, losing-connected; LD, losing-disconnected; TD, transitional or losing-disconnected; C, Connected.

[a] Inferred from moisture profiles and field observations (dry augered holes in riverbed).

[b] The riverbed is in a perched aquifer.

[c] River dry at the time of sampling.

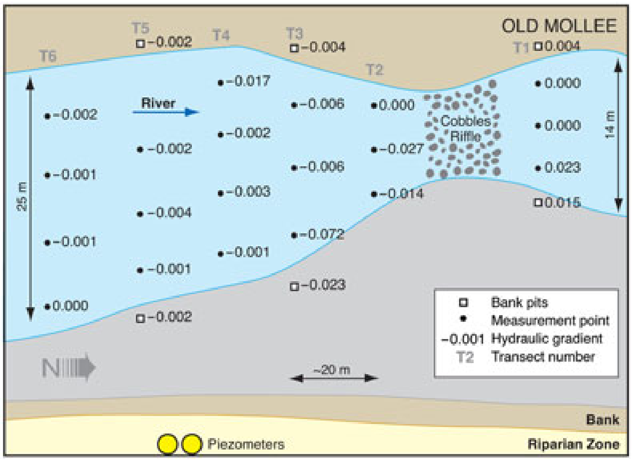

Figure 10. Vertical hydraulic gradients in the riverbed measured by piezometry at Namoi River–Old Mollee. Negative gradients indicate a losing riverbed section. The values next to bank pits represent horizontal hydraulic gradients measured by manometry relative to river stage (with negative values also indicating losing river conditions). Note that whenever a hydraulic gradient can be measured by piezometry (negative or positive), $\psi > 0$ and the riverbed is connected

showing that the riverbeds were connected. However, a mixture of gaining and losing conditions at the scale of the riverbeds were encountered at many sites. These were attributed in part to hyporheic exchange between riffle–pool sequences and drainage from sand and gravel bars because of slowly receding river stages at the time of the surveys. Thus, no attempt was made to classify connected sites as gaining or losing on the basis of the riverbed vertical hydraulic gradients.

Riverbed sediment profiles were collected at the Billabong (for moisture content only), Lachlan–Hillston Bridge and Gwydir–Yarraman Bridge sites. Attempts were made to collect sediment profiles at Lachlan–Gonowlia Weir and Gwydir–Brageen Crossing but were not successful because of the presence of cobbles (Brageen Crossing) or poorly consolidated sediments (Gonowlia Weir). Otherwise, all augered holes remained dry during profile collection, consistent with the presence of a vadose zone below the rivers (that is, transitional or disconnected conditions). The gravimetric moisture content tended to decline, and ψ became more negative at depth in all augered profiles (see Lachlan examples in Figure 11), also consistent with a present of a vadose zone below the river at these sites. However, while negative ψ were found, the trends across the profiles were often complex. Notably, ψ became less negative at the interface between the riverbed clays and the underlying sands (Figure 11). Within the sands, ψ tended to become more negative, again deeper in the profiles. Thus, while the profiles showed that a vadose zone was present below the rivers, infiltration was clearly more complex than a simple one-dimensional process. In other words, less negative fluid pressures in the sand suggest that the clay layer is thinner or absent elsewhere in the riverbed.

Summary of connection status

Gathering all lines of evidence, the connection status of the 12 sites can be made with some confidence (Table III). A mixture of losing-disconnected, losing-connected and gaining conditions was found among the 12 sites. The sites on the Namoi and Macquarie rivers were losing-connected, and the ones on the Lachlan River, Gwydir River and Billabong Creek were losing-disconnected. The Border River sites were connected, but one site was gaining whereas the other was losing. The lack of surface water at Gwydir–Brageen Crossing during the site visit makes the assessment at this site less reliable. On the other hand, a clay-lined riverbed combined with a deep riparian water table (~12 m below riverbed elevation) is more consistent

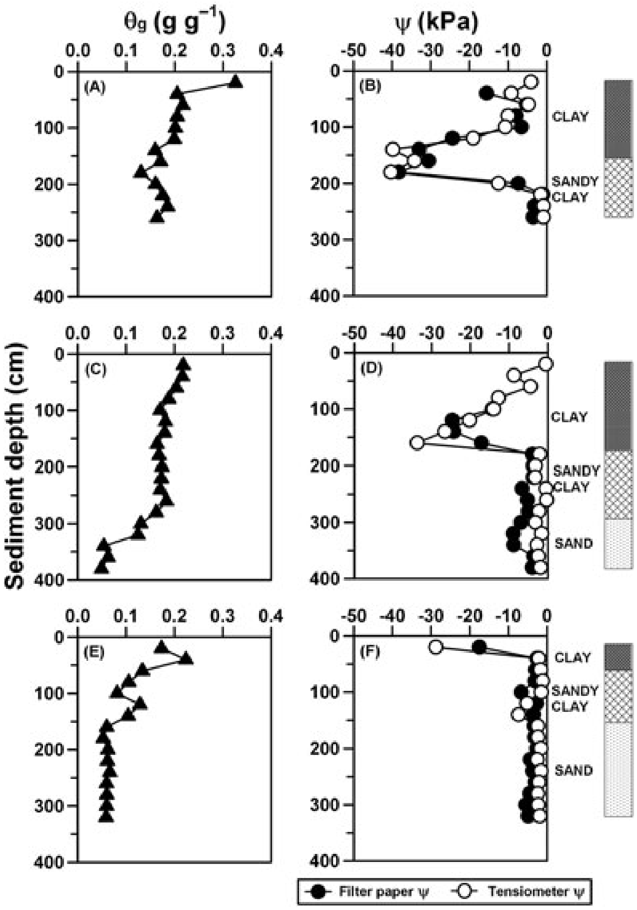

Figure 11. Variations in gravimetric water content (A, C and E) and in fluid pressure head (B, D and F) in augered riverbed profiles at the Lachlan–Hillston Bridge site for Profile 1 (A, B), Profile 2 (C, D) and Profile 3 (E, F). Profile location is shown in Figure 2(A)

with a disconnected than a connected or transitional environment at Gwydir–Brageen Crossing.

DISCUSSION

Comparison of the riparian water table and riverbed fluid pressure classifications

The connectivity assessments based on riparian water table depth were consistent with the ones obtained from the riverbed fluid pressure measurements. It was anticipated that the riverbed fluid pressure method would be needed in cases where the riparian water table method provided ambiguous results. However, this was generally not the case because the losing-disconnected sites had relatively deep water tables (>6 m below riverbed elevation) relative to the estimated size of their recharge mounds (usually <1.5 m). However, having both measurement methods was useful when the riparian water table was only slightly below riverbed elevation, such as at the Namoi and the Macquarie–Woodland sites. Whether the connected sites were gaining or losing was often difficult to establish with the riverbed fluid pressure method because of heterogeneity in the direction of hydraulic gradients at the scale of the riverbed due to hyporheic exchange (Jones and Mulholland, 2000; Woessner, 2000) and other processes (small daily variations in river stage from irrigation releases, etc). Riverbed fluid pressure may also not always be indicative of connectivity at the regional scale when a clogging layer is at depth in the aquifer (such as at the Lachlan–Gonowlia Weir site).

Contrast in water table depth between connected and disconnected sites

The large difference in riparian water table position observed between connected and disconnected rivers was probably a result of the conditions particular to the time of the study. The riparian water table at the losing-disconnected sites was 6–25 m below riverbed elevation, whereas it was never deeper than 1 m below the riverbed at the losing-connected sites. The field assessments were made near the end of an extensive drought in southeastern Australia, when regional water tables were declining across the MDB (CSIRO, 2008). In losing-connected rivers, a regional decline in the water table can be compensated near rivers by increased infiltration rates because of larger hydraulic gradients (Osman and Bruen, 2002). However, infiltration rates are already maximal under losing-disconnected rivers (Brunner *et al.*, 2009a) and a similar compensating effect cannot occur when the regional water table falls (Moore and Jenkins, 1966). In addition, the presence of a low K clogging layer in losing-disconnected riverbeds should yield relatively low infiltration rates (even if maximal) compared with most losing-connected rivers with a moderate hydraulic gradient. Thus, during the recent drought in the MDB, higher infiltration rates along losing-connected river reaches appeared to have moderated the regional water table decline, at least near the rivers, but this process apparently could not occur along losing-disconnected reaches because infiltration was already maximal there (Treese *et al.*, 2009).

The connectivity at the sites could change following a wetter period. However, a change in connectivity (to gaining conditions) appears most likely at the losing-connected sites because of shallower water tables and a greater infiltration potential through the riverbeds during floods. The water table at the losing-disconnected sites were appreciably lower and would require a longer-term increase in infiltration rate to switch towards losing-connected conditions. This appears unlikely on the short term (years) because of ongoing high extraction rates from these aquifers (CSIRO, 2008). Thus, the connectivity over time is likely to be more variable at the connected than disconnected sites.

Clogging layers

All sites that were found to be disconnected appeared to have a well-developed clogging layer. In general, the clogging layers consisted of a 0.5–2 m clay or silty clay unit overlying a silty sand. However, in two instances (Lachlan–Gonowlia Weir and Gwydir–Yarraman Bridge), the clogging layer was deeper in the riverbed and generated a local losing-connected aquifer above, and a regional losing-disconnected aquifer below the clogging layer. The presence of riverbeds with a low hydraulic conductivity at the time of the study is consistent with the high inorganic turbidity and phytoplankton concentrations of Murray and Darling waters (Oliver, 1990; Schalchli, 1992) and the tendency for riverbeds to clog between floods (Battin and Sengschmitt, 1999; Treese *et al*., 2009).

Brunner *et al*. (2009a) developed a criterion to evaluate which river reaches can become disconnected:

$$\frac{K_c}{K_a} \leq \frac{h_{cl}}{d + h_{cl}} \tag{5}$$

where K_c is the hydraulic conductivity of the clogging layer, K_a the hydraulic conductivity of the alluvial aquifer, h_{cl} the thickness of the clogging layer and *d* stream depth. Those sites that were identified as losing-disconnected easily met the Brunner *et al*. (2009a) criterion. For example, at the Billabong sites $K_c \sim 10^{-9}\,\mathrm{m\,s^{-1}}$, $K_a \sim 10^{-5}\,\mathrm{m\,s^{-1}}$, $h_{cl} \sim 1$ m and $d \sim 1$ m (Lamontagne *et al*., 2011a), yielding $K_c/K_a \sim 0.0001$ and $h_{cl}/(h_{cl} + d) \sim 0.5$, that easily satisfies the criterion. This suggests that the Brunner *et al*. (2009a) criterion can be used to evaluate the potential for disconnection in MDB Rivers.

Comparison with other assessment methods for connectivity

The most common method to evaluate connectivity at the regional scale is to assume that rivers become disconnected once the regional water table drops below a certain level (usually representing an approximation of riverbed level). Recent regional-scale connectivity assessments in the MDB used a criterion of a water table depth at least 10 m below the land surface within 1 km for rivers to be classified as losing-disconnected (Braaten and Gates, 2003; Ivkovic, 2009). The riverbeds at our sites were generally 4–5 m and occasionally up to 10 m below the riparian zone elevation (see examples in Figure 8). At the study sites, the Braaten and Gates (2003) and Ivkovic (2009) criterion would correspond to riparian water tables ~0 to 6 m below the riverbeds. Thus, considering that recharge mounds below the losing-disconnected rivers were probably small (<1.5 m), the Braaten and Gates (2003) and Ivkovic (2009) criterion would tend to overestimate sites classified as losing-connected. In other words, losing-disconnection may be more prevalent in the MDB than what has been previously assessed using regional water table maps.

Alternative methods to establish disconnection include the installation of piezometers directly in riverbeds (Moore and Jenkins, 1966), with the provision that screens must be located below the clogging layer. Connectivity can also be inferred from changes in river discharge under different groundwater pumping regimes (Rahn, 1968; Braaten and Gates, 2003). However, this analysis is difficult if the infiltration rate is small or if there is a significant time-lag before changes in pumping rates impact on river flows.

Potential improvements to the experimental design

The combination of the riparian water table and riverbed fluid pressure classification techniques offered some degree of redundancy and certainty to evaluate river connectivity at the sites. However, there are shortcomings and potential improvements to the methodologies used in this study. Firstly, the clogging layers were not always at the riverbed surface and could be undetected by bank tests and piezometry when deeper than 1 m below the riverbed surface. On the other hand, significant shallow clay layers can be detected by careful geological logging during installation of the riparian piezometers or by using downhole geophysical techniques afterwards. Secondly, piezometry may give false connected results in cases where a vadose zone can develop at depth in the absence of a clogging layer (Wang *et al*., 2011). However, this was unlikely to have occurred at the losing-connected sites in this study because the riparian water tables were always less than 1 m below the riverbeds, which is probably not sufficient to generate an inverted water table (Wang *et al*., 2011). This shortcoming of the original design can also be addressed by collecting more detailed vertical ψ profiles by piezometry between the riverbed surface and the depth where the water table occurs in the riparian zone.

The proposed classification methods are likely to underestimate the occurrence of transitional conditions. For example, sites with $h_r > h_x \geq h_b$ are deemed losing-connected under the riparian water table classification. This assumes that, in this case, the recharge mounds start at the edges of the rivers. However, in cases where the water table gradient is nearly flat from the riparian zone all the way to the riverbed, a small vadose zone would be present at the edges of the rivers (Brunner *et al*., 2009b). Demonstrating transitional conditions in the field may be difficult. The extent of the capillary zone could be mapped by measuring the variations in both ψ and in volumetric water content across the riverbed. This would require *in situ* measurements or the collection of intact sediment cores (note that only the gravimetric water content could be measured on the augered sediment cores collected for this study). Transitional conditions may not be very common in the field but, on the basis of relatively deep water levels in some bankside pits, may have been present at the Macquarie sites in this study.

CONCLUSIONS

Many regional groundwater models used to manage alluvial aquifers do not adequately represent the changes in surface water–groundwater interaction in the vicinity of losing rivers, in particular when losing-disconnection occurs (Fox and Gordji, 2007; Brunner *et al*., 2010a). This is of concern when infiltration from rivers is an important component of either the aquifer or river water balance, or when accurate predictions of water table depth near rivers are required to protect phreatophytes and other groundwater-dependent ecosystems (Baird *et al*., 2005;

Jolly *et al.*, 2008). However, there are few practical methods to evaluate connectivity in the field (Brunner *et al.*, 2010a). The classification methods used in this study were relatively simple and should be flexible enough to enable the assessment of connectivity under a range of conditions. The methods have a range of applications, including to: (i) provide information to guide the choice of groundwater model for a given aquifer (Brunner *et al.*, 2010b; Rassam, 2011); (ii) provide calibration points in space and time for regional assessments of connectivity; and (iii) confirm the connection status in areas where rivers alternate from connected to disconnected over short distances because of pumping or other factors. Further improvements to the methods would seek to better differentiate between transitional and losing-disconnected conditions without requiring extensive additional measurements.

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