Groundwater–surface water interaction in inland New South Wales: a scoping study

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Abstract Groundwater and surface water have traditionally been managed separately in New South Wales (NSW). However, where rivers and aquifers are hydraulically connected, groundwater pumping has the potential to deplete streamflow. To highlight the major areas of connection in inland NSW, major streams were overlaid with groundwater depth data and the locations of irrigation bores. A consistent pattern was revealed related to basin geomorphology. The main areas of connection are the mid-sections of the major rivers where alluvial systems are well developed yet still narrow and constricted and groundwater depths are shallow. The mapping was validated and the processes explored by calculating water balances for a connected and disconnected reach in the Murrumbidgee River. These showed that, in highly connected reaches, river losses and/or gains are closely related to groundwater levels.

Keywords Allocation; connectivity; groundwater; interaction; New South Wales; surface water

Introduction
Allocation of water from aquifers and rivers has traditionally been managed separately in Australia, in part due to the artificial division between the disciplines of hydrology and hydrogeology. However, almost all surface water is in continuous interaction with groundwater. Rivers, wetlands, lakes and estuaries may act as recharge sources for an aquifer, or groundwater may discharge to surface water. Where the water table is close to the base of a riverbed, the two systems are said to be hydraulically connected. Here, groundwater and surface water might be considered one resource and extraction of water from one system will reduce water availability in the other.

Hydraulic connection is difficult to measure and has commonly been ignored in water allocation with the result that, in many systems, the same parcel of water has been allocated twice, once to a groundwater user and once to a surface water user. This overlap can become a serious issue where allocation is high relative to resource availability. Development of groundwater resources may result in gradual depletion of flow in the stream, reducing water availability for surface water users. In streams where flows are not regulated by an upstream structure such as a dam or a weir, stream depletion due to groundwater pumping will also have a disproportionate effect on the low flows that are crucial for maintenance of the ecological function of the stream.

This paper assesses the extent of groundwater–surface water interaction in New South Wales (NSW), Australia. It presents a broad-scale assessment of connection between major rivers and aquifers across the state, and then focuses on more detailed case studies of stream water balances in the Murrumbidgee River in an attempt to quantify the effect and explore the processes at work.

Technical background
Prior to development, groundwater systems are usually considered to be in equilibrium. While the balance between recharge and discharge varies from year to year, over long time periods recharge is equal to discharge and water levels fluctuate around a constant average. Sources of recharge may include seepage from rivers, lakes and other surface water
features and infiltration through the soil from rainfall. The aquifer may discharge to rivers, lakes and wetlands and water may be lost to evaporation or transpiration by plants.

Groundwater extraction introduces a new form of discharge and the system begins to move to a new equilibrium. A cone of depression forms around the pumping wells. As the cone expands, it meets features that act as conduits for water transfer between the aquifer and the surface, such as rivers, lakes, wetlands, springs or deep-rooted plants. The lower groundwater levels induce additional recharge and/or reduce the rate of discharge via the surface feature. The cone of depression continues to expand until reduced discharge and increased recharge balance the pumping. While ecological impacts on other surface water features like lakes or billabongs can be serious, for water allocation the main feature of concern is the river.

Increased river seepage losses or decreased baseflow gains due to groundwater level decline will occur only where the river is in hydraulic connection with the aquifer. Hydraulic connection exists where the river is in direct contact with the underlying aquifer via a zone of saturated material or where the river is separated from the aquifer by a narrow unsaturated zone, generally less than twice the stream width (Bouwer and Maddock, 1997). Where the groundwater level is much deeper than the base of the river, reductions in the water table will have little or no effect on the stream. Hydraulically connected systems can have flows going from stream to aquifer or from aquifer to stream depending on their relative hydraulic heads.Disconnected reaches, on the other hand, always lose water to seepage, with the seepage rate limited by the stream’s hydraulic head and the hydraulic conductivity of the bed sediments.

In hydraulically connected systems, the time lag between the start of groundwater pumping and depletion of water from the stream is crucial for management decisions. Initially, all groundwater pumped will come from a decrease in aquifer storage. As the cone of depression expands toward the river, the proportion of groundwater derived from streamflow will gradually increase until it is maximised, with an associated drop in the proportion sourced from storage to zero. Then, as long as groundwater pumping continues, stream depletion will remain constant. Several methods exist for quantifying this response function in an idealised aquifer (e.g. Balleau, 1988; US Army Corps of Engineers, 1999). These methods show response to be a function of aquifer diffusivity, a measure of the rate at which a change in head is propagated through the aquifer, and the square of the distance between the river and the pumping bore.

Also crucial for management is the proportion of groundwater extraction that will eventually be derived from induced stream losses. This proportion depends on the presence of discharge sinks or recharge sources other than the river, and the proximity of pumping bores to hydraulically connected river reaches and these other sources and sinks. Alternative discharge sinks could include surface depressions, springs, billabongs, playa lakes, wetlands, deep-rooted vegetation, and the ocean. Alternative recharge sources, like lakes or ponds, are less common. However, in certain situations, rainfall recharge can be increased by groundwater pumping. This effect can occur where groundwater storage regularly fills up such that potential recharge is lost to runoff or evaporation. When groundwater levels are lowered, this additional potential recharge may be realised.

Research from the United States often assumes that 100% of groundwater pumping is derived from stream depletion (Balleau, 1988; Sophocleous, 2001; Winter et al., 1998). However, in Australia, arid conditions and deep layers of weathered subsurface material can cause deep groundwater levels and long stretches of hydraulically disconnected river reaches. In these areas, particularly where groundwater extraction occurs distant to the stream, it is likely that a large proportion of the water pumped will be sourced from features other than the river and the impact on streamflow will be substantially lower than 100% of groundwater extraction (SKM, 2001).
Methods

Statewide mapping

A broad-scale assessment of groundwater–surface interaction water was undertaken for the major inland valleys of New South Wales, where the majority of the state’s water extraction occurs. These valleys lie in the Murray-Darling Basin, which drains to the sea through the Murray River at Adelaide. For the purposes of this assessment, it was assumed that connectivity is high and response times short where hydraulic connection is present and groundwater extraction occurs near the river.

Hydraulic connection was established by overlaying groundwater depths with the locations of major rivers. Several digital groundwater maps were used, covering different parts of the state at scales ranging from 1:250,000 to 1:1,000,000 (Evans, 1988; Evans et al., 1994; NLWRA, 2001). All monitoring bores in the Department of Land and Water Conservation database within 1 km of major rivers were also used. In systems with multiple aquifers, water levels in the shallowest aquifer were used. Hydraulic connection was assumed to be present where river reaches overlay groundwater levels less than 10 m from the surface. The 10 m figure is an estimate of the difference in elevation between the floodplain, where groundwater levels are measured, and the base of the riverbed. It was established by comparing gauging station cross-sections with a digital elevation model (AUSLIG, 2001). The map of hydraulic connection was adjusted in areas with sparse information or other influences such as geological controls based on geological mapping and knowledge of structure, groundwater levels and landform.

The locations of all irrigation bores were plotted on the map of hydraulic connection to provide a general idea of the distance between groundwater extraction and major connected reaches. While further analysis could have been done to quantify the actual rates of groundwater extraction at various distances to connected river reaches, the visual display of irrigation bores alone was enough to reveal a consistent geomorphological pattern of groundwater–surface water interaction. It also provided sufficient information for a first-cut prioritisation of connected river-aquifer systems for further research and policy development.

Reach water balances

Two reaches in the Murrumbidgee River were selected for more detailed water balance analysis, one mapped as highly connected and one not connected (Figure 4). The purpose of the analysis was to quantify the river aquifer flux, validate the broad-scale mapping and provide insight into the processes. The Murrumbidgee River was selected because it provides a good representation of the patterns observed in the statewide mapping, its aquifers are well understood (Lawson and Webb, 1998; Webb, 2000), and good quality groundwater level and river extraction data are available.

Groundwater-stream fluxes are difficult to measure directly and must be estimated from the “unaccounted difference” after all other fluxes of a river reach water balance have been quantified. Separating the groundwater component from the unaccounted difference is notoriously difficult because the groundwater flux is often of the same order as the error bounds of the other fluxes. Nonetheless it was thought that the unaccounted difference might at least be able to set bounds on the groundwater flux and provide some insight into its direction. It was also speculated that if a relationship could be found over time between bore water levels and river losses, this would be good evidence of hydraulic connection between the river and aquifer.

Table 1 shows the main fluxes and the methods by which they were quantified. Water balances were computed on a monthly basis from mid-1980s onward. These were the finest level of resolution and longest time period for which extraction data were available. It was
not possible to accurately quantify flooding losses and return flows. Instead, months in which flooding was thought to have occurred were removed from the analysis. Daily flow thresholds for flooding were identified through inspection of gauging station cross-sections and rating tables. Ungauged tributary input was also difficult to estimate accurately so reaches were selected to avoid areas with significant ungauged inflow.

Upper and lower bounds were set on the groundwater flux by accumulating the error bounds for the water balance terms through the unaccounted difference calculation. The main error term was uncertainty associated with river flow measurements, specifically error introduced in converting measured water levels to discharge with a rating table. Rating table error was calculated as the 95% confidence interval for each rating table based on every flow gauging completed during the table’s period of applicability. Rating table errors were generally about 5–10% of flow. Canal diversion error bounds were assumed to be 10%, the upper end of the gauging error. River pumping error bounds were also assumed to be 10%, the figure normally associated with metering error. All other fluxes in the water balance were so low that error was considered to be negligible.

**Results and discussion**

**Statewide assessment**

The results of the statewide assessment of river–aquifer connection are mapped in Figure 1. This map shows a consistent spatial pattern of river–aquifer connection in the Murray-Darling Basin, moving from the Dividing Range down to the confluence with the Darling, Barwon or Murray rivers. This pattern, illustrated in Figure 2, reflects basin geomorphology.

Small streams draining high relief upland areas are generally mapped as hydraulically connected. These streams have high gradients and small or absent alluvial systems. They derive a significant proportion of their flow from discharge from fractured rock aquifers. Because of the lack of alluvial sediments, aquifer transmissivity is low. As a result, bore yields are low and lag times between groundwater pumping and stream depletion are long. These systems are not high priorities for development of groundwater–surface water interaction policy.

Moving from the hills into the mid-sections of the larger Murray-Darling Basin rivers, the alluvial systems are more developed but still narrow and constricted by bedrock. The narrow floodplain and still relatively high rainfall produce shallow alluvial water tables and strong hydraulic connection between river and aquifer. The direction of the river–aquifer flux can vary over time. For example, after major recharge events like floods,
the aquifer may drain back to the river for several years, followed by a period of the river recharging the aquifer. Changes in flux direction may also be seasonal with the river recharging the aquifer during the irrigation season when the river stage is high and the reverse during the off-season when the river hydraulic head is low.

Large-scale irrigation bore development is common across the floodplains, in part because of the ease with which groundwater pumpers can access river water through their bores (Kalf and Woolley, 1977). About one-third of the total groundwater extraction in New South Wales occurs in these areas, most of it within a few hundred metres of the river. Because of the proximity of groundwater extraction to the river and the high degree of

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**Figure 1** Hydraulic connection of major inland rivers and aquifers and locations of irrigation bores

**Figure 2** Schematic geomorphological transect showing river–aquifer connection (arrows show flux direction)
hydraulic connection, groundwater pumping is expected to impact streamflow to a large degree within a relatively short time frame. Such systems include the upper Murray, Billabong Creek, mid-Murrumbidgee, portions of the upper Lachlan, upper Namoi and Peel, and several tributaries of the Macquarie.

As the constricted mid-sections of the rivers spill out onto the wider semi-arid plains of the lower valleys, water levels fall and the hydraulic connection is broken. Extensive alluvium has provided the opportunity for widespread development of bores, the majority of which are many kilometres from the nearest connected river reach. This difference in bore distribution is illustrated for the mid and lower Murrumbidgee in Figure 3. In the mid-Murrumbidgee, most bores are clustered within 5 km of the river. In the lower Murrumbidgee, bores are widely distributed with an average distance of around 50 km from the nearest hydraulically connected reach.

The lower reaches also contain many other potential sources of water that could respond to falling water tables, including discharge sinks such as playa lakes and wetlands, and recharge sources such as irrigation areas. The low hydraulic connectivity, high distance between bores and connected reaches of the river and alternative sources of recharge/discharge suggest that the proportion of groundwater pumping derived from reduced streamflow will be low and response times long. Systems with these characteristics include the lower Murray, lower Murrumbidgee, lower Lachlan, lower Namoi and lower Gwydir.

Near the confluence of the major inland rivers with the Darling, Barwon and Murray Rivers, factors such as basement highs and reduced aquifer transmissivity caused by progressive fining of material force groundwater levels near the surface re-establishing hydraulic connection to the river. In these reaches, flow direction is again variable, but in the long-term tends to be toward the river. Groundwater is generally of high salinity and groundwater discharge is known to degrade river water quality. Because of the high salinity, there are few irrigation bores and little groundwater extraction. The floodplain remains relatively wide and, were bores to be developed, response times would be long. However, even if groundwater pumping were to reduce discharge to the stream, it would likely have the beneficial effect of improving stream water quality.

Some exceptions to the general basin-scale pattern occur in third-order catchments with well-developed alluvial systems. In these streams, such as Mooki River in the Namoi Valley and Bland Creek in the Lachlan Valley, the basin-wide pattern can be repeated at a smaller scale. The lower Bogan River in the Macquarie Valley in central NSW is also anomalous in that its lower reaches have been mapped as hydraulically connected. While the main areas of deep older alluvium in the Macquarie Valley lie under the path of the Macquarie River, the Bogan runs through shallow, more recent alluvium which causes elevated water tables.

Reach water balances
Two Murrumbidgee reaches were selected for detailed water balances, one in the mid-
section of the river where the alluvium is narrow and hydraulic connection high, and one in the dry and wide lower valley where connection is low (Figure 4). Both reaches are about 100 km in length. Monthly unaccounted difference and error bounds are shown in Figure 5. A negative unaccounted difference implies a river loss. Also shown are groundwater levels for selected monitoring bores with long time series within 3 km of the reaches. To highlight longer-term trends in groundwater levels and their relationship to stream losses, groundwater levels were standardised and averaged for each reach. A 12-month moving average was then applied to the standardised average water levels and the unaccounted difference, and both were plotted in Figure 6.

The first reach lies between Wagga Wagga and Narrandera in the narrow, hydraulically connected mid-section of the Murrumbidgee River. Monthly unaccounted difference ranges from large losses greater than 100 GL to large gains greater than 100 GL (Figure 5). Over the entire period of analysis, the net flux is a smaller loss averaging 22 GL/year. Although error bars are large due to the high flow and canal diversions in the reach, there is a clear relationship between unaccounted difference and groundwater levels indicating that the two systems are in hydraulic connection.

Two time scales of correspondence are apparent. At the seasonal time scale, groundwater levels are lowest at the beginning of the water year and rise over the season in response...
to higher river levels before dropping off again at the end of the water year. The unaccounted difference follows this trend with lower losses or bigger gains during the irrigation season tapering off as bore levels fall in the off-season. A general pattern is also apparent at the inter-annual scale (Figure 6). Large recharge events such as the flooding that occurred in 1989, apparent from the rise in the water table in that year, lead to elevated water tables, causing groundwater to drain back into the river over a period of several years. Eventually the aquifer becomes depleted and the flow direction reverses with the river recharging the aquifer over another several year period until the next major recharge event. On an annual basis, there is a highly significant correlation between the unaccounted difference and average groundwater levels, with a correlation coefficient of 0.78 \((p = 3 \times 10^{-7})\).

While this interannual pattern appears to be largely driven by climatic variability, the clear correspondence between groundwater levels and river gains/losses in this reach suggests that any water pumped from the aquifer must deplete the river. As the floodplain is only 5–10 km wide in the mid-Murrumbidgee, most irrigation bores are in close proximity to the river and time lags between groundwater pumping and river depletion will be short. This finding is supported by Kalf and Woolley (1977) who advised in the construction of the Gumly Gumly bore scheme near this reach, supplying town water to Wagga Wagga and other towns in the area. They estimated that within 4.5 years 88% of the water pumped from the Gumly bores would directly deplete the river. The estimated maximum annual groundwater extraction from the mid-Murrumbidgee alluvium in this reach and the reach above it between Gundagai and Wagga Wagga is 31 GL (Lawson and Webb, 1998). This is in the same order as the average river losses of about 22 GL, suggesting that additional river losses could be supplying much of the pumped groundwater.

The Darlington Point to Hay reach is in the lower Murrumbidgee, in the wide semi-arid plains with deep groundwater levels disconnected from the stream. The unaccounted difference is less variable than the previous reach (Figure 5). Most months show a loss, with the loss averaging 8 GL/month or 101 GL/year. The relatively constant and high loss would be expected where the river is not hydraulically connected to the aquifer. Although the monthly data show little relationship between bore levels and stream losses, on an annual basis (Figure 6), a weak relationship is apparent in the reverse direction to the Wagga to Narrandera reach, with higher river losses associated with shallower groundwater levels. This relationship reflects the contribution of river losses to aquifer recharge. The correlation between annual unaccounted difference and groundwater depth is significant but weak \((r = 0.35; p = 0.005)\), suggesting that other recharge mechanisms are also important.

The difference between the two reaches and their interaction with groundwater is further illustrated in Figure 7 showing bore water levels compared to Murrumbidgee river stage at Wagga Wagga and Darlington Point. At Wagga Wagga, the water table fluctuations are very closely related to the river stage and groundwater levels are within a few metres of the river level. The bore GW030455 is about 5 km downstream of Wagga Wagga and

![Figure 6](https://iwaponline.com/wst/article-pdf/48/7/215/423623/215.pdf)
GW030020 about 2 km upstream. The true groundwater level at Wagga Wagga would be
between the two, probably slightly below the river level producing the net flux from river to
aquifer observed in Figures 5–6. The bores at Darlington Point are located only a few hun-
dred metres from the stream gauge. Here the water table is more than 10 m below the river
stage and shows little fluctuation related to the river stage. The flux direction should there-
fore be from river to aquifer and river losses should be relatively constant.

Overall, the reach water balances confirm the statewide mapping. They also indicate
that analysis of the unaccounted difference in river reaches can lend insight into groundwa-
ter–river interaction. While it is difficult to put an actual number on the river–aquifer flux,
the pattern of unaccounted difference can be illuminating when compared to bore levels.
Where rises in groundwater levels are associated with a change in flux toward the river
(greater gains or lower losses) and groundwater level declines with flux away from the river
(greater losses or lower gains), this is good evidence that the river is hydraulically connect-
eted to the underlying aquifer. Where shallower groundwater levels are associated with
greater losses from a river, the stream is likely disconnected.

Conclusions
There is a consistent pattern of groundwater–surface water interaction in the Murray-
Darling Basin related to basin geomorphology. The major areas of concern with respect to
water allocation are the mid-sections of the major rivers, with well-developed yet still nar-
row and constricted alluvial systems and shallow groundwater levels. In these areas, such
as in the Murrumbidgee River between Wagga Wagga and Narrandra, stream losses are
strongly related to groundwater levels and there is a high likelihood of stream depletion due
to groundwater pumping within a relatively short time frame. One-third of total groundwa-
ter extraction in NSW occurs in these areas.

In the lower valleys of the major Murray-Darling Basin rivers, where the majority of
groundwater extraction occurs, river–aquifer systems are generally not hydraulically con-
nected and groundwater pumping is more distant from the river. In these areas, groundwa-
ter extraction is likely to have much less significant impacts on streamflow and time lags
between groundwater pumping and impacts on the stream will be much longer. Stream
losses in these reaches are more constant and higher stream losses may be associated with
shallower water tables reflecting the significance of the river as a groundwater recharge
source.
While surface water use has been capped in the Murray-Darling Basin valleys under an inter-governmental agreement, groundwater use in some of the highly connected river–aquifer systems has the potential to grow into the aquifer’s sustainable yield. This potential growth may impact on the reliability of supply to river users and, in unregulated rivers, on ecologically critical low flows. Managing the potential impact of groundwater extraction on river flows will require extensive community consultation and development of state policy.

References


