INVESTIGATING GROUNDWATER-RIVER INTERACTIONS USING ENVIRONMENTAL TRACERS

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Abstract: Groundwater and surface water are hydraulically connected in many landscapes and better understanding of their connectivity is critical for effective management of water resources. Environmental tracers are a useful preliminary tool to study the interaction between groundwater and surface water and provide independent means for corroborating or refuting information based on more traditional investigations. This paper discusses the results of using major ions, stable isotopes (deuterium and oxygen-18) and a radioactive isotope (radon-222) as environmental tracers to better understand groundwater-surface water interactions in the Border Rivers catchment, Australia.

In the upstream reaches of the catchment, shallow groundwater close to the river has similar major ion and stable isotope chemistry to that of the river water, and is different to the groundwater distant from the river. The near-stream groundwater has an enriched isotopic signature (less negative) whereas groundwater far from the river has a depleted isotopic signature. Overall, the comparison of chloride concentrations with deuterium suggests that three types of groundwater occur in the Border Rivers catchment – the near-stream groundwaters influenced by direct recharge from the river, the groundwaters marginal to the river that are more influenced by diffuse rainfall recharge, and saline groundwaters in the downstream part of the catchment which never (or rarely) receive recharge from surface water. River water samples obtained during the high flow season show very low variation in radon concentrations (ranging from 0.11 to 0.39 Bq/L). The longitudinal transect of radon concentration measurements in river water during the high flow season indicate that there is no groundwater contribution to stream flow. Radon concentrations are lower in groundwater close to the rivers and increase with distance from the river, in general coincidence with the salinity and chloride concentration. This indicates river water infiltration into nearby alluvial aquifers, rather than groundwater discharge to the river.

The results of hydrochemical and environmental isotope sampling indicate that in the upper catchment area (upstream of Keetah) the river is connected to and actively recharges the near-stream shallow alluvial aquifer. Using the environmental isotope data, we have also demonstrated that recharge of the alluvial aquifers by surface water occurrs by bank infiltration, with diffuse recharge during high rainfall events more dominant further away from the river. This information would be useful for a better understanding of the nature and extent of hydrogeological processes at the river-aquifer interface and their links with biogeochemical processes and ultimately water allocation policies.

Key Words: groundwater-river interaction, environmental tracers, major ion chemistry, stable isotopes, radon, Border Rivers, Australia.

INTRODUCTION

The Border Rivers catchment is located in southern Queensland and northern New South Wales in Australia on the western side of the Great Dividing Range, and is part of the Murray-Darling Basin (Figure 1). The two major rivers in the Border Rivers catchment, the Dumaresq River and the MacIntyre River, define the border between the two states. The catchment is facing substantial pressure for increased water resources to be made available for irrigation, especially in association with the expansion of cotton production in recent years. To cope with limited surface water supplies, particularly during drought, groundwater resources are being developed to use in conjunction with surface water. Any groundwater extraction will ultimately affect the flow in the river and consequently existing irrigation use from surface water supplies.

In the Border Rivers catchment there is a high degree of connectivity between surface water features such as streams, wetlands and drains and their underlying groundwater systems. It has been reported that the Dumaresq River and the shallow aquifers are intimately related (Williams et al. 1987; Chen 2003). The concept of conjunctive use of surface water and groundwater was introduced for the Border Rivers region in 1990. The conjunctive system enables the users of the surface water to access groundwater when the seasonal allocation from dams decreases. Groundwater- surface water interactions are also critical from a water quality perspective.

In highly saline groundwater environments (as evident in the downstream reaches of the catchment), the role of fluctuating watertables and discharge of shallow saline groundwater into rivers is central to the potential generation and export of salts. This highlights a need to better understand the spatial and temporal interactions between groundwater and surface water systems in the Border Rivers catchment.

Surface water and groundwater interactions can be determined using a variety of methods, which describe the type of linkage, and its importance, in either a qualitative or quantitative manner. Environmental tracers are a useful preliminary tool to study the interaction between groundwater and surface water and provide independent means for corroborating or refuting information based on more traditional investigations. Use of stable isotopes of water, such as deuterium (δD) and oxygen-18 (δ^{18}O), as natural tracers to study the interaction between groundwater and surface water has been a useful tool in many studies (McCarthy *et al*. 1992; Ojiambo *et al*. 2001; Herczeg *et al*. 2001). It has also been shown that radon (^{222}Rn) can be used to identify the locations and amounts of groundwater entering streams (eg. Ellins *et al*. 1990; Cook *et al*. 2003). In this study we have used major ions, δD, δ^{18}O and ^{222}Rn as environmental tracers to investigate the stream-aquifer connectivity in the Border Rivers catchment.

Study area description

The Border Rivers catchment ranges from the rugged mountains of the Great Dividing Range in the east to a broad, flat alluvial plain in the west (Figure 2). The topography is largely determined by the geology of the region. The prevailing climate is dry winters with sporadic and unreliable rainfall and warm to hot summers with moderate to heavy rainfall. Annual median rainfall decreases from the east (>800 mm) to the west (500 mm) in the study area. The annual evaporation potential (as determined by pan evaporation) exceeds annual precipitation. Agriculture is the dominant activity in the region. Along the Dumaresq River, lucerne and other fodder crops are irrigated by groundwater whereas cotton is the main irrigated crop along the MacIntyre River. Surface water is the main source for the predominately flood irrigation of cotton.

Figure 1. Location of the Border Rivers Catchment study area

Alluvial sediments of Quaternary and Tertiary age fill the base of the valley. Alluvial sediments of the Dumaresq and MacIntyre River system can be subdivided into two geomorphological regions (upstream of Keetah and downstream of Keetah). Upstream of Keetah, the alluvial deposits are confined to a narrow valley, but west of the Dumaresq/MacIntyre confluence the deposits become more extensive, characteristic of an alluvial plain (Figure 2). The main aquifers in the alluvial sediments are referred to as Unit A, B and C, based on age, rock type and morphology. Most water bores occur in the area upstream of Keetah, and many of these bores are located near or close to the Dumaresq River.

METHOD

Groundwater and river water sampling and analysis

Groundwater and river water samples were collected during November-December 2004, coinciding with the main irrigation season (Baskaran *et al*. 2005). With connectivity being the focus, water samples were taken from the Dumaresq River and MacIntyre River and from bores adjacent to the rivers (Figure 2). A subset of existing cross-section State monitoring bores were selected and sampled using a 50 mm Grundfos electric submersible pump with a teflon sampling line. At least three casing volumes of groundwater were removed from each bore prior to sampling. Surface water samples were collected from the Dumaresq River and MacIntyre River at a depth of about 25 cm. Samples collected were analysed for a range of physicochemical parameters (pH, electrical conductivity (EC), dissolved oxygen (DO), redox and temperature) under field conditions. The field water quality parameters were monitored until the values stabilised. After filtration (0.45 μm), samples were processed in the field and stored under recommended conditions until analysis for major ions, deuterium (δD) and oxygen-18 ($\delta^{18}O$). The stable isotopes of water (deuterium and oxygen-18) as well as Radon (^{222}Rn) were analysed by the CSIRO Land and Water Laboratory, Adelaide. This laboratory determined δ^2H and $\delta^{18}O$ using an Europa Scientific Geo 20-20 isotope mass spectrometer and routine analytical procedures (Dighton *et al*., 1997; Socki *et al*., 1992). Sampling and analysis for radon (^{222}Rn) followed established methodologies (Herczeg *et al*. 1994).

Standard Quality assurance/quality control (QA/QC) procedures (duplicates, blanks and spikes) were followed in the field. Data audit and verification were performed using quality procedures, including matching results with sample description sheets and manual checking for outliers. All results less than the limit of detection were halved prior to calculation of medians and also graphed for the purposes of presentation.

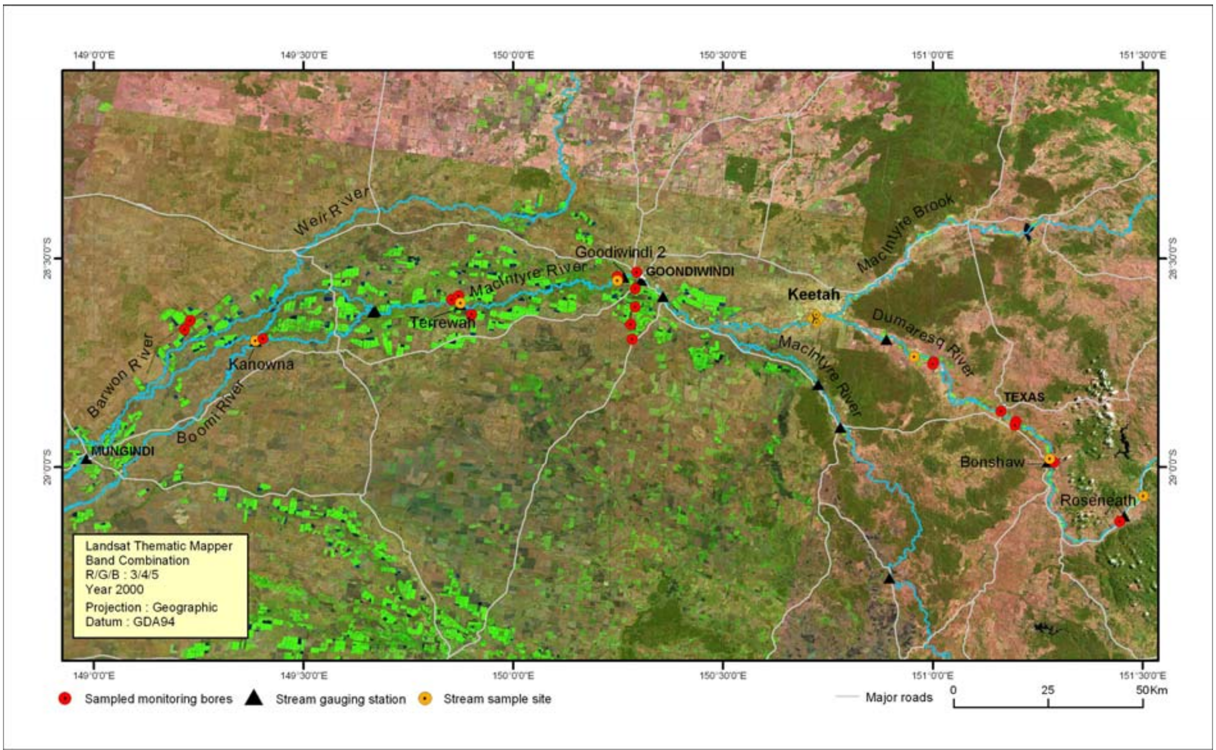

Figure 2. Border Rivers study area showing groundwater and surface water sample sites.

RESULTS AND DISCUSSION

Major ion chemistry

The results of chemical analyses of groundwater and surface water samples are shown in the Piper diagram (Figure 3). The major ion chemistry results show that sodium and magnesium are the dominant cations and bicarbonate the dominant anion in the river water samples. Sodium is the dominant cation with lower proportions of magnesium and calcium, with bicarbonate and chloride the dominant anions in the majority of the groundwaters upstream of Keetah. The groundwaters from the area between Keetah and Goondiwindi are sodium and bicarbonate dominant and are characterised as a Na-HCO_3-Cl water type, whereas groundwaters further downstream of Goondiwindi are sodium and chloride dominant and are characterised as a Na-Cl water type. The shallow groundwater has a stronger Na and Cl (and to a lesser extent HCO_3) component, but less Mg (than surface water), which is probably the result of evaporation near the ground surface and return flow. The deep groundwater has a stronger Na - HCO_3 component. Some deep groundwater samples show higher Cl (than surface water), but overall there is a similarity with the shallow groundwater composition.

In general, some shallow groundwaters close to the Dumaresq River in the area upstream of Keetah have similar chemistry to that of the river water. This indicates that the surface water and this near-stream groundwater are hydrochemically similar and related, and probably have the same origin. A similar observation was also made in an earlier investigation (Please *et al*., 2000). However, the hydrochemistry results presented in this paper are from a single (high flow) sampling run, and additional sampling during the low flow season is needed to better understand the dynamics of groundwater-surface water interaction. For example, changes in chemical compositions of river water and groundwater have been observed between high flow and base flow seasons in the lower Suwannee River basin, Florida, USA. This has been inferred as evidence for mixing of river water and groundwater (Crandall *et al*. 1999).

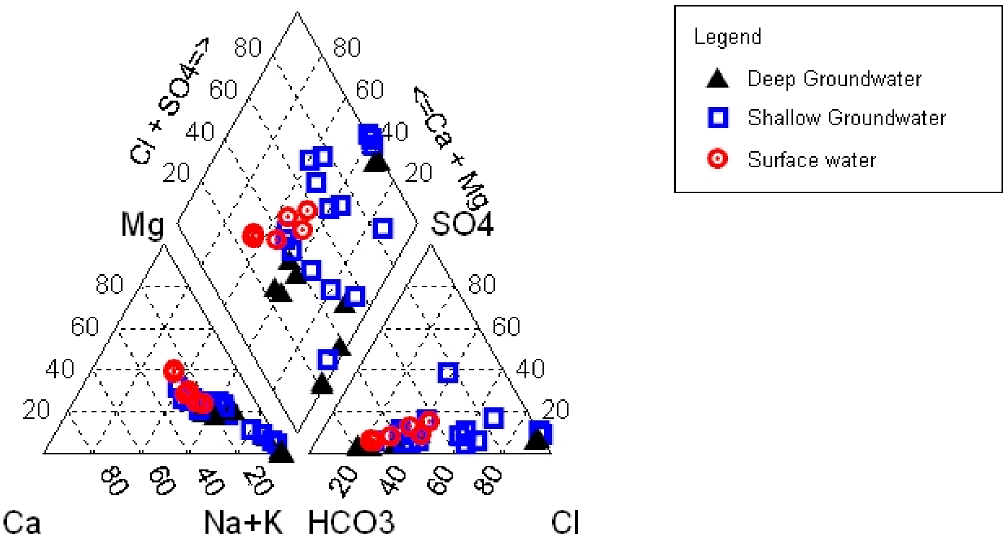

Figure 3. Piper diagram for water samples in the Border Rivers catchment

Stable isotope composition of groundwater and river water

Figure 4 shows the δD and $\delta^{18}O$ compositions of groundwater and river water collected during high flow conditions (November-March). The local meteoric water line for Barakula (a town near the Border Rivers catchment), obtained from samples collected during the period 1998 – 2000, was selected for comparative purposes because of it’s proximity. The δD and $\delta^{18}O$ data fall into distinct groups, providing information on the secondary processes acting on the water as it travels from precipitation to groundwater. The river water samples plot to the right of the local meteoric water line (LWML) along a shallow-sloping trend, suggesting a typical evaporation pattern. The majority of groundwaters in the area upstream of Keetah fall within a cluster either close to or to the right of the local meteoric water line, indicating that these samples have undergone some evaporation prior to infiltration. The majority of highly saline groundwaters in the area downstream of Keetah also plot along a shallow-sloping trend to the right of the LMWL, indicating that evaporative concentration is a significant process for these samples.

The stable isotope data plotted in Figure 4 provides some interesting insights. The δD and $\delta^{18}O$ compositions for the groundwater that are close to the river are different from the isotopic composition of the groundwater that is farthest from the river. For example, the near-stream groundwaters upstream of Keetah have a relatively enriched isotopic signature (less negative) that is similar to that of the river water. This indicates that infiltrating river water is the main source for the groundwater that is close to the river. Under low or average flow conditions, river water tends to be isotopically enriched relative to rainfall because of surface water evaporation (Simpson and Herczeg, 1991). The more depleted signature for groundwater that is further from the river suggests that this water may not originate from infiltrating river water. However, recharge following large flood events could have such a depleted isotopic signature because heavy rain tends to have a relatively negative isotopic composition and there is relatively less evaporation. This is supported by the fact that many of the groundwaters distant from the river upstream of Keetah cluster about the average (more depleted) signature for rainfall from large events, exceeding 200mm/month (Figure 4).

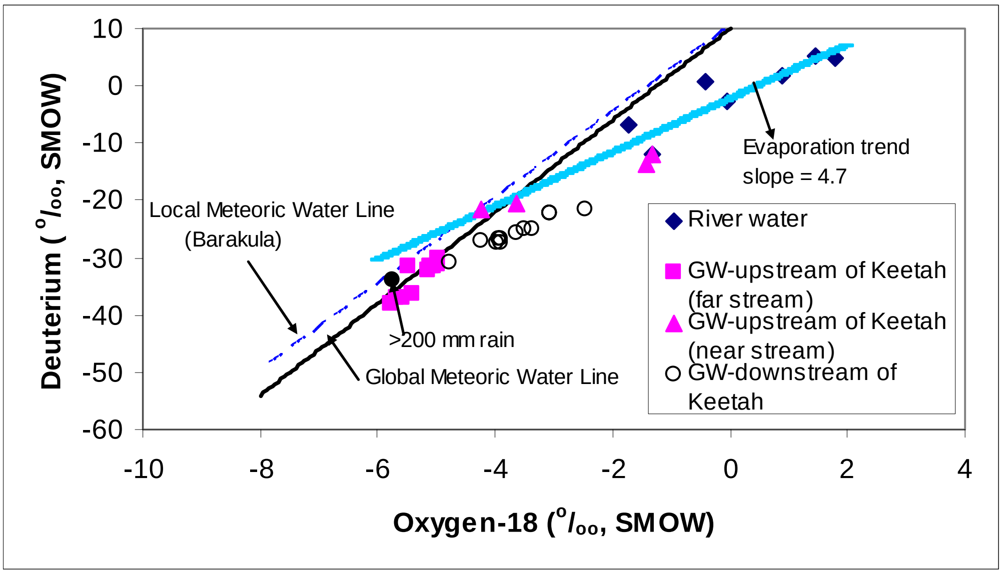

Figure 4. Deuterium versus oxygen-18 concentrations for river water and groundwater in the Border Rivers Catchment

Regional distribution of environmental tracers

A comparison of the deuterium and chloride data provides greater understanding of the scale of groundwater-surface water interaction processes in the Border Rivers catchment. The chloride-deuterium plot (Figure 5) suggests that three types of groundwater occur in the study area namely: (i) some groundwater from upstream of Keetah, characterised by low chloride and relatively enriched δD, that is most frequently recharged by river water (ii) some groundwater upstream of Keetah and a few groundwaters that are close to the MacIntyre River reach near Goondiwindi Weir, with low chloride and depleted δD, representing areas that are recharged less frequently by the river and more frequently by high rainfall and (iii) highly saline groundwaters further downstream of Goondiwindi, with very high chloride and lower δD, that never or rarely receive recharge from surface water. It has been reported that recharge by surface water via bank infiltration would be characterised by low chloride and relatively enriched δD signatures whereas diffuse recharge would tend to be enriched in chloride and depleted in δD (Lamontagne *et al*. 2002).

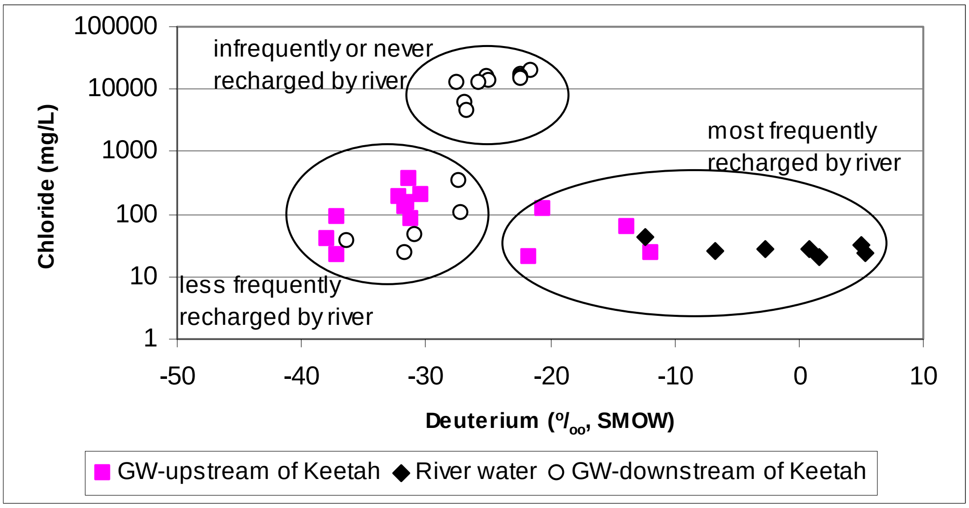

Figure 5. Chloride versus deuterium concentrations for river water and groundwater in the Border Rivers Catchment

Radon

River water samples obtained during the high flow season, show very low variation in radon concentrations. (ranging from 0.11 to 0.39 Bq/L; Figure 6). Radon concentrations in the Dumaresq River were higher than those measured in the MacIntyre River. Radon has been used in many earlier studies to identify the locations and amounts of groundwater entering streams (eg. Ellins *et al*. 1990; Cook *et al*. 2003). It has been also shown that radon can be used to identify infiltration of river water into alluvial aquifers (Bourg and Bertin 1994). The longitudinal transect of radon concentration measurements in river water (Figure 6) indicate that there is no groundwater contribution to stream flow. This is indicated by the smooth trend in radon concentrations and the absence of any spikes of elevated radon concentration. Studies have shown that spikes of elevated radon concentrations in the streams are an indication of groundwater contribution to stream flow (Cook *et al*. 2003). In general the radon concentrations in the river (0.11-0.39 Bq/L) are much lower than those measured in the groundwater (6.9-61.2 Bq/L;), this is to be expected due to loss of radon during stream flow. Radon-222 is derived from decay of ^{238}U bearing minerals within an aquifer and is directly injected into the groundwater. High ^{222}Rn activities in groundwater are often associated with rock types such as granites or high grade metamorphic rocks and basaltic rocks with relative high abundance of minerals (apatite, zircon and allanite). Radon concentrations are lower in groundwater close to the Dumaresq/MacIntyre River and increase with distance from the river, in general coincidence with the salinity and chloride concentration. This indicates river water infiltration into nearby alluvial aquifers, rather than groundwater discharge to the river.

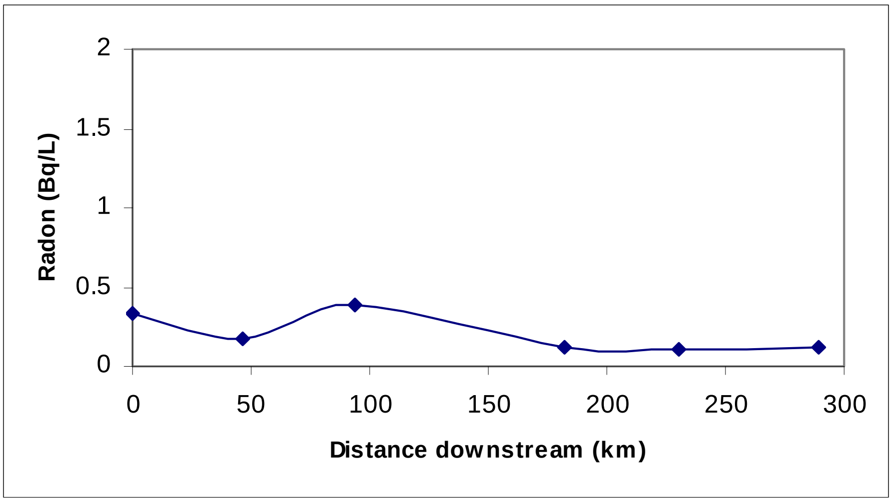

Figure 6. Radon concentrations for river waters in the Border Rivers Catchment

CONCLUSIONS

The results of hydrochemical and environmental isotope sampling from the Border Rivers catchment, Australia indicate that the river and the shallow alluvial aquifers close to the river in the area upstream of Keetah have a close hydraulic relationship. In this upper catchment area, the streams are dominantly losing and recharge the shallow aquifers. Using the environmental isotope data, we have also demonstrated that recharge of the alluvial aquifers by surface water occurs by bank infiltration as well as diffuse recharge during high rainfall events. Although hydrochemical and environmental isotope data provide an indication of a linkage between shallow groundwater and the river, more time series data (e.g. sampled during baseflow seasons) is needed to define seasonal changes to connectivity. This information would be useful for a better understanding of the hydrogeological processes at the river aquifer interface and their links with biogeochemical processes and ultimately water allocation policies.

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