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Hyporheic zone exchange fluxes and residence times inferred from riverbed temperature and radon data

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SUMMARY

Vertical profiles of temperature, radon and electrical conductivity are used to characterise downwelling, neutral and upwelling hyporheic zones along a pool–riffle sequence in the Haughton River in north-eastern Australia. Water residence times and vertical fluxes are derived from temperature and radon data and then directly compared for downwelling profiles. Temperature and radon-derived fluxes in downwelling zones ranged from 0.02 to 24 m day^{-1} with a mean of 1.69 m day^{-1} while residence times across the study site ranged from tens of minutes to greater than 15 days. The radon approach has the lowest uncertainty for residence times between 0.1 and 15 days while the uncertainty of the temperature approach (using a diel river signal) is lowest for residence times that are less than a few days. For 83% of depths in downwelling profiles, radon-derived residence times were greater (some up to two orders of magnitude greater) than temperature-derived residence times. When the error bounds of the residence time estimates were accounted for, 57% of radon-derived residence times were considerably greater than temperature-derived residence times in downwelling profiles. We suggest that this disparity is due to the different influence of small scale heterogeneity on temperature and radon transport. These field based results indicate that small scale heterogeneity may play a far more important role than has been previously considered in groundwater–surface water interaction studies.

1. Introduction

Hyporheic exchange is the movement of water from a river into the underlying or adjacent sediments and then back into the river. The hyporheic zone, where this exchange occurs, is now widely recognised as a biogeochemical hotspot in river ecosystems (Boulton et al., 1998). Hyporheic zones exist across a broad range of spatial and temporal scales depending on the riverbed substrate, geomorphology and larger scale river-aquifer exchanges (e.g. Bencala, 1993; Thibodeaux and Boyle, 1987; Vaux, 1968). The biological, chemical and hydraulic characterisation and dynamics of hyporheic zones have been the focus of numerous studies since the mid-1950s (Boulton et al., 2010). However, methods for quantifying exchange fluxes and associated water residence times in the hyporheic zone across a range of spatial scales require further development.

Two environmental tracers that have been applied to quantify the exchange between rivers and the subsurface are temperature and radon (^{222}Rn). The natural temperature variation of rivers allows the water fluxes into or out of the hyporheic zone and/or groundwater system to be calculated (e.g. Conant Jr., 2004; Lautz and Fanelli, 2008; Bhaskar et al., 2012). This is done by comparing the temperature signal in the river with the temperature signal in the subsurface at one or more depths. Where downward vertical flux is large, diel temperature signals propagate rapidly into the subsurface while if fluxes are small or upwards, the diel temperature signal in the subsurface is attenuated. Radon is produced by riverbed sediments so that as river water travels into the subsurface the radon activity of that water increases with time. This allows the residence time and flux of water travelling into the subsurface to be calculated (e.g. Hoehn and von Gunten, 1989; Hoehn and Cirpka, 2006; Lamontagne and Cook, 2007). These naturally occurring tracers are often used independently to quantify groundwater–surface water exchanges but only a few examples can be found where they have been directly compared (e.g. Hoehn and Cirpka, 2006; Vogt et al., 2010). Other tracers, including electrical conductivity (EC) in some cases, can also be used to differentiate between sources of water (e.g. regional groundwater and river water) if the end members have distinct signatures (e.g. McCallum et al., 2010).

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In this study we use temperature, radon and electrical conductivity data collected in detailed vertical profiles, to describe the spatial variability of hyporheic exchange along a pool–riffle sequence (Fig. 1). Observed trends in these parameters are used to characterise the downwelling, neutral and upwelling locations along the study reach. Hyporheic exchange processes are observed on both small (tens of centimetres) and larger scales (meters to tens of meters beneath a pool–riffle sequence). For downwelling profiles, the vertical flux and residence times of water are quantified using both temperature and radon profile data. The uncertainty of these residence time values are quantified, compared and discussed along with the practical limitations of each approach. The field site selected for this study is a shallow, primarily gaining river in north-eastern Australia (Haughton River), which flows within a wide sandy alluvial channel.

2. Theory

2.1. Temperature

Heat has been used as an environmental tracer for investigating groundwater–surface water interaction for over 50 years and by numerous researchers (see reviews by Anderson, 2005; Constantz, 2008; Rau et al., 2014). This is possible because of diel temperature variations in surface water bodies and the damped or constant temperature signals in the hyporheic zone and shallow groundwater. These temperature differences can be used to estimate the vertical water flux between surface and subsurface water bodies. One dimensional (1D) heat transport in a homogenous porous media (i.e. with constant heat parameters) can be described by the conduction–advection equation:

$$\frac{\partial T}{\partial t} = k_e \frac{\partial^2 T}{\partial z^2} - \frac{q_H}{\gamma}\frac{\partial T}{\partial z} \quad (1)$$

where T is temperature (°C), k_e is the effective thermal diffusivity of the saturated sediments ($\mathrm{m}^2\ \mathrm{day}^{-1}$), γ is the ratio of the volumetric heat capacity of the saturated sediments to the volumetric heat capacity of water, q_H is the water flux ($\mathrm{m\ day}^{-1}$), t is time (days) and z is depth (m). Although they share the same units, the q_H term is a flux and should not be confused with the pore water velocity or thermal front velocity used in some heat tracer studies (Gordon et al., 2012). The positive direction for z and q_H is downward into the subsurface. Eq. (1) assumes that heat is transported through a representative volume where thermal equilibrium exists instantaneously between the fluid and solid phases and that θ, k_e and γ are constant both spatially and temporally. The heat parameter terms (k_e and γ are commonly estimated from the literature (e.g. Carslaw and Jaeger, 1959 or Lunardini, 1981) but can also be measured in sediment samples. In this study we have approximated k_e and γ using experimentally derived relationships for coarse grained sediments developed by Lunardini (1981) as presented in Fig. 2 of Lapham (1987).

It is common to approximate the diel temperature variation of the river with a sinusoidal function and hence solve Eq. (1) analytically to calculate the vertical water flux (e.g. Suzuki, 1960; Stallman, 1965). In this paper, we have used a 1D numerical solution to avoid making this assumption and instead use raw temperature data collected from the river and subsurface (see Section 3.3 and Cranswick et al., 2014).

The residence time of water in the hyporheic zone can be derived from temperature data if there is a downward flux. In this study temperature-derived residence time is calculated using:

$$t_r = \frac{z\theta}{q_H} \quad (2)$$

where t_r is residence time (days) and other variables are as defined previously.

2.2. Radon

Radon (^{222}Rn) is a noble gas with a half-life of 3.82 days. It is produced by the decay of radium (^{226}Ra) (part of the uranium (^{238}U) decay series) that is found both in the aquifer material itself and as dissolved radium adsorbed onto sediment surfaces in low salinity environments (Cecil and Green, 2000). There have been many studies that have used measurements of radon to calculate river infiltration rates into alluvial aquifers (e.g. Bertin and Bourg, 1994; Hoehn and von Gunten, 1989; Snow and Spalding, 1997). These studies assume that infiltrating water starts with a known radon activity, which increases with time due to production in the aquifer until secular equilibrium is reached. The equilibrium activity is dependent on the production rate of the aquifer material and can also be measured from sediment samples. It takes approximately 30 days for full secular equilibrium to be reached and the time since water entered the aquifer can theoretically be calculated within this range. While the absolute error is small at very early times, the relative error can be large due to the uncertainty of the infiltrating water radon activity. Conversely, the absolute error can be large for late times due to the uncertainty of the production rate in sediments. The radon activity at a particular time can be calculated using (after Cecil and Green, 2000):

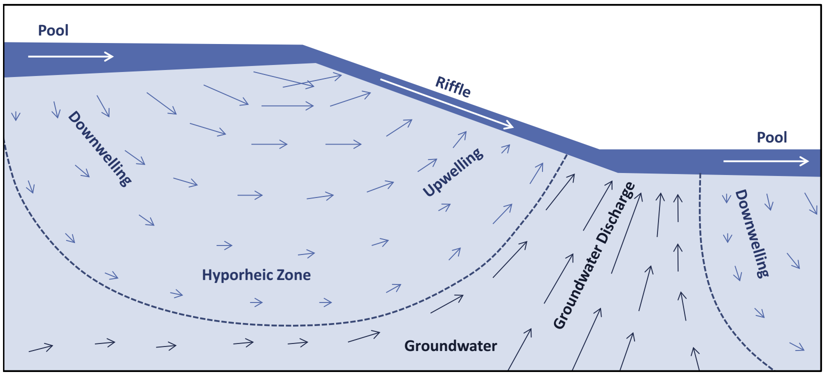

Fig. 1. A conceptual model of the exchange processes occurring over a pool–riffle sequence longitudinal cross section for a gaining river, including the partitioning between the hyporheic zone and groundwater system. Zones of downwelling in the pool sections and zones of upwelling in the lower portion of the riffle section can be seen. Additionally, groundwater discharge may occur concurrently with upwelling hyporheic exchange. Note that this figure does not display the current driven hyporheic exchange that may also occur (Thibodeaux and Boyle, 1987).