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Characterisation of hyporheic exchange in a losing stream using radon-222

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SUMMARY

Hyporheic and parafluvial flows between streams and the underlying streambed, or adjacent alluvium, are important drivers of biogeochemical cycling in streams. Here we present a new method for characterising this exchange in a losing stream based on longitudinal stream radon activities. A mass balance approach is used to constrain the radon influx into the stream and estimate exchange parameters: flux, residence time and exchange zone thickness. A net radon flux into the stream of 5.4×10^4 Bq m^{-1} d^{-1} is required to balance radon losses to groundwater recharge, gas transfer and radioactive decay. Given the radon production rate of the sediments (1.3 ± 0.7 Bq L^{-1} d^{-1}), the minimum volume of alluvium flushed by either hyporheic or parafluvial exchange is 168 m^3 per m length of stream. Based on the stream width, depth of alluvial sediments and porosity, this implies that the exchange zone extends beneath the stream and an additional 11 m either side. The results of this new method are compared to two existing methods; streambed radon disequilibrium and transient storage modelling of breakthrough curves of an injected tracer. The stream radon mass balance provides a relatively simple means of estimating hyporheic (and parafluvial) exchange over tens to hundreds of kilometres of stream. Concurrent application of the stream radon method, transient storage modelling of injected tracer breakthrough curves and hydraulic methods is recommended to capture the full spectrum of hyporheic exchange in losing streams.

1. Introduction

Hyporheic exchange exerts an important influence on nutrient distribution, productivity and contaminant transport in streams (Bencala, 1984; Boulton et al., 2010; Findlay, 1995; Jones and Mulholland, 2000). While definitions of hyporheic exchange vary, the term generally refers to the cycling of water between a stream and the groundwater below and adjacent to it, creating an exchange zone with chemical properties that are different to both the stream and the aquifer. This cycling occurs at a range of scales and can be related to stream bed-forms, turbulent eddies, gravel bars and meanders (Boano et al., 2011; Cardenas et al., 2004; O'Connor and Harvey, 2008; Stonedahl et al., 2010).

A common technique for estimating hyporheic exchange is to inject a tracer into the stream and use a transient storage model to interpret the tracer breakthrough curves measured downstream (Bencala and Walters, 1983; Harvey and Wagner, 2000). Transient storage models were originally developed to represent exchange between the stream and one storage zone (e.g.), but have since been extended to represent exchange between the stream and multiple storage zones, (e.g. Choi et al. (2000)). The time scale of tracer injection and measurement is usually on the order of hours with breakthrough curves measured at locations within one kilometre of the injection point. The sensitivity of the method is limited to flow paths on smaller spatial and temporal scales than the injection experiment. As a result, this scale of tracer injection usually captures fluxes with residence times of hours or less and spatial scales of hundreds of metres or less (Harvey et al., 1996). Although they remain widely used, recent studies have highlighted the non-uniqueness of transient storage model parameters (Kelleher et al., 2013), and the need for concurrent application of multiple methods, rather than a reliance on transient storage modelling alone (Ward et al., 2013).

Radon-222 (hereafter referred to as radon) is a radiogenic noble gas with a half-life of 3.8 days that is produced by most sediment through the decay of uranium series isotopes (Cecil and Green,

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2000). Radon activity in surface water is low as radon is readily lost to the atmosphere through gas transfer. Water that enters the subsurface increases in radon activity over a period of around 20 days until equilibrium between radon production and decay is reached. In losing streams, radon activity in groundwater has previously been used to infer rates of infiltration (Bertin and Bourg, 1994; Hoehn and Von Gunten, 1989). Disequilibrium of radon activities within the streambed has been used to infer residence times in the hyporheic zone (Lamontagne and Cook, 2007). Streambed radon activities are relatively easy to measure but interpretation of streambed radon profiles requires an estimate of the radon production rate of the sediments, which can be highly variable in heterogeneous alluvial sediments (Cecil and Green, 2000). Also, calculation of hyporheic fluxes from streambed radon activities requires an independent estimate of groundwater recharge or discharge.

In gaining stream systems, groundwater inflow rates and hyporheic exchange have been estimated based on stream radon activities using a 1D mass balance model (Cook et al., 2003, 2006). One of the major difficulties with this approach is separating the radon contribution through hyporheic exchange from the radon contribution of groundwater discharge.

In a losing stream where there is no groundwater discharge, the only influx of radon is through hyporheic exchange. As water enters the sub-surface hyporheic zone, the radon activity will increase with increasing hyporheic residence time. This radon is then introduced into the stream upon re-emergence of water from the hyporheic zone. The radon activity in the stream is therefore determined by the balance of losses to groundwater recharge, radioactive decay and gas transfer with the atmosphere, and additions through hyporheic exchange. If these loss terms are known, longitudinal stream radon activities in a losing stream can be used to estimate hyporheic exchange parameters (hyporheic zone depth, flux and residence time). In this paper we apply this new method for characterising hyporheic exchange parameters based on longitudinal stream radon activities in a losing stream. We then compare the results to estimates from two existing methods with differing scales of sensitivity: streambed radon disequilibrium and transient storage modelling of tracer breakthrough curves.

2. Theory

Definitions of hyporheic exchange are many and varied (Gooseff, 2010). Hydrochemically, the hyporheic zone can be considered as a zone where the interstitial water composition is a mixture of stream water and groundwater (Boulton et al., 2010; Hoehn and Cirpka, 2006; Triska et al., 1993). Hydrologists often define the hyporheic zone based on the extent of flow paths which originate from and return to the stream (O'Connor and Harvey, 2008; Stonedahl et al., 2010; Storey et al., 2003; Worman et al., 2002). In this context, hyporheic exchange can be considered to include a spectrum of flow paths ranging from shallow exchange between the stream and streambed on the scale of centimetres to longer return flows across stream meanders on the scale of tens to hundreds of metres (Stonedahl et al., 2010), without a clear boundary between these.

In this paper we find it useful to partition the total spectrum of hyporheic exchange into two components. We restrict our use of the term hyporheic exchange to refer to the relatively short flowpaths between the stream and streambed, characterised by residence times less than a day and spatial scales of tens of metres or less. This is the scale of hyporheic exchange that is most commonly to be captured by injected tracer experiments and streambed radon profiles. Exchange fluxes with longer residence times of days to weeks and spatial scales of tens to hundreds of metres are not commonly captured by injected tracer experiments, and are not well resolved by radon profiles beneath the streambed. These longer flow paths are often within the alluvium adjacent to the stream, and so we use the term parafluvial to refer to this exchange. Of course, these longer flow paths may also occur beneath the stream, flowing through the sub-surface approximately parallel to the direction of streamflow.

2.1. Stream radon activity

In a losing stream, the change in streamflow with distance is a function of groundwater recharge and evaporation, and is given by:

$$\frac{\partial Q}{\partial x} = -q_{gw} - Ew \tag{1}$$

where Q is the streamflow ($\mathrm{m^3\,d^{-1}}$), q_{gw} is the groundwater recharge flux per metre length of stream ($\mathrm{m^2\,d^{-1}}$), E is the evapotranspiration rate ($\mathrm{m\,d^{-1}}$) and w is stream width (m). This groundwater recharge flux is related to the infiltration rate, I, of Cook et al. (2006) through the stream width: $q_{gw} = Iw$.

For dissolved gases like radon, gas transfer has a much greater than evaporation and therefore, the evaporation term can be neglected in the tracer mass balance. Cook et al. (2006) expressed the mass balance of radon in a losing stream as:

$$\frac{\partial Qc}{\partial x} = q_h(c_h - c) - q_{gw}c - kwc - \lambda dwc \tag{2}$$

where c is the radon activity within the stream, c_h is the radon activity within the hyporheic zone, q_h is the hyporheic exchange flux ($\mathrm{m^2\,d^{-1}}$), k is the gas transfer velocity across the water surface ($\mathrm{m\,d^{-1}}$), λ is the radioactive decay constant of radon ($0.181\ \mathrm{d^{-1}}$), and d is the stream depth (m). Although this model does not explicitly include diffusion of radon from streambed sediments into the stream, this will be much smaller than the advective flux of radon associated with hyporheic exchange, and can be neglected.

Following Cook et al. (2006) and Lamontagne and Cook (2007), we model the hyporheic zone as a one-layer, uniform, well-mixed hyporheic zone. The steady state solute mass balance can be written:

$$q_h c - q_h c_h + q_{gw} c - q_{gw} c_h - \lambda wh\theta c_h + \gamma wh\theta = 0 \tag{3}$$

where h is the hyporheic zone depth (m), γ is the radon production rate of the sediments ($\mathrm{Bq\,L^{-1}\,d^{-1}}$) and θ is porosity (Lamontagne and Cook, 2007). This conceptual model implies an exponential distribution of hyporheic residence times with a mean residence time, t_h (d) given by:

$$t_h = \frac{wh\theta}{(q_h + q_{gw})} \tag{4}$$

The concentration of radon within the hyporheic zone (c_h) will increase as the hyporheic zone residence time (t_h) increases, and hence the sensitivity of stream radon concentrations (c) to the hyporheic exchange flux (q_h) increases as the residence time (t_h) increases. Therefore, when the hyporheic exchange flow field includes both very short (fast) and very long (slow) flowpaths, it may be useful to explicitly differentiate between them. The mass balance of radon in the stream therefore becomes:

$$\frac{\partial Qc}{\partial x} = q_h(c_h - c) + q_p(c_p - c) - q_{gw}c - kwc - \lambda dwc \tag{5}$$

where q_p is the fluid flux in or out of the parafluvial zone ($\mathrm{m^2\,d^{-1}}$), and c_p is the concentration of water discharging from the parafluvial zone into the stream.

The exponential distribution of travel times implied by Eq. (3) has been widely implemented in transient storage models (Bencala and Walters, 1983; Harvey et al., 1996; Runkel, 1998). Fig. 1 compares the effect of residence time distribution on the