Dynamics of stream and groundwater exchange using environmental tracers

submitted by
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\( C^0 \)  \( ^{222}\text{Rn} \) activity upstream (Bq L\(^{-1}\))

\( C_{\text{max}}^0 \) Maximum predicted upstream \( ^{222}\text{Rn} \) activity (Bq L\(^{-1}\))

\( C_{\text{ss}} \) Steady state \( ^{222}\text{Rn} \) activity of groundwater (Bq L\(^{-1}\))

\( C_{\text{ss}}^{AGW} \) Steady state \( ^{222}\text{Rn} \) emanation from alluvial aquifer sands (Bq L\(^{-1}\))

\( C^B \) Background \( ^{222}\text{Rn} \) activity in stream water (Bq L\(^{-1}\))

\( C_{\text{max}}^{RGW} \) Maximum \( ^{222}\text{Rn} \) activity measured in regional groundwater (Bq L\(^{-1}\))

\( C_{\text{min}}^{RGW} \) Minimum \( ^{222}\text{Rn} \) activity measured in regional groundwater (Bq L\(^{-1}\))

\( C_{\text{GW}}^{RGW} \) \( ^{222}\text{Rn} \) activity of groundwater (Bq L\(^{-1}\))

\( C_{i-1}^{\text{int}} \) \( ^{222}\text{Rn} \) activity upstream of a distance interval, \( i \) (Bq L\(^{-1}\))

\( C_{i}^{\text{int}} \) \( ^{222}\text{Rn} \) activity downstream of a distance interval, \( i \), due to radioactive decay losses (Bq L\(^{-1}\))

\( C_{\text{TR}}^{\text{int}} \) \( ^{222}\text{Rn} \) activity downstream of a distance interval, \( i \), due to turbulent losses (Bq L\(^{-1}\))

\( C_{\text{min}}^{\text{int}} \) Minimum \( ^{222}\text{Rn} \) activity of groundwater input to streamflow (Bq L\(^{-1}\))

\( C^{\text{int}} \) \( ^{222}\text{Rn} \) activity of stream water lost to the adjacent aquifer (Bq L\(^{-1}\))

\( c_n^{\text{int}} \) \( ^{222}\text{Rn} \) activity within aquifer matrix (Bq L\(^{-1}\))

\( C_{\text{m}} \) Cl\(^-\) concentration of mixed pore water and deionised water (mg L\(^{-1}\))

\( C_{\text{pw}} \) Cl\(^-\) concentration of pore water (mg L\(^{-1}\))

\( C^n \) \( ^{222}\text{Rn} \) activity downstream (Bq L\(^{-1}\))

\( C^n_R \) \( ^{222}\text{Rn} \) activity downstream due to radioactive decay (Bq L\(^{-1}\))

\( C^n_T \) \( ^{222}\text{Rn} \) activity downstream (Bq L\(^{-1}\))

\( C^n_{\text{TR}} \) Predicted \( ^{222}\text{Rn} \) activity downstream after turbulent and radioactive losses (Bq L\(^{-1}\))

\( C^{222} \) The \( ^{222}\text{Rn} \) concentration in a closed system (Bq L\(^{-1}\))

\( C^{226} \) \( ^{222}\text{Rn} \) concentration produced by the radioactive decay of \( ^{226}\text{Ra} \) (Bq L\(^{-1}\))

\( D \) Molecular diffusivity of \( ^{222}\text{Rn} \) (at 23°C 1.2 × 10\(^{-9}\) m\(^2\) s\(^{-1}\))
\( E \)  
\( ^{222}\text{Rn} \) emanation rate  
\( \text{Bq kg}^{-1} \)

\( \varepsilon \)  
Porosity  
\( \text{cm}^3 \text{ cm}^{-3} \)

\( f \)  
Fraction of surface water lost to the adjacent aquifer

\( f_{aq} \)  
Porosity of aquifer material (expressed as a fraction)

\( f^0 \)  
Fraction of surface water lost to the adjacent aquifer that originates from \( Q^0 \)

\( 1 - f^0 \)  
Fraction of surface water lost to the adjacent aquifer that originates from \( Q^{gw} \)

\( h \)  
Average depth of stream  
\( \text{m} \)

\( h_{eq} \)  
Equivalent freshwater head  
\( \text{m} \)

\( h_m \)  
Measured head  
\( \text{m} \)

\( i \)  
Interval number, integer fraction of \( n \)

\( L_n^0 \)  
\( ^{222}\text{Rn} \) loss from stream water between consecutive surface water sampling stations (i.e. between \( 0 \) and \( n \))  
\( \text{Bq L}^{-1} \)

\( L_{nw}^g \)  
\( ^{222}\text{Rn} \) loss from groundwater that contributes to stream flow between consecutive surface water sampling stations (i.e. between \( 0 \) and \( n \))  
\( \text{Bq L}^{-1} \)

\( L_j^0 \)  
\( ^{222}\text{Rn} \) loss from stream water before it discharges to the adjacent aquifer  
\( \text{Bq L}^{-1} \)

\( L_{ij}^g \)  
\( ^{222}\text{Rn} \) loss from groundwater that contributes to stream flow and later recharges the adjacent aquifer  
\( \text{Bq L}^{-1} \)

\( \lambda \)  
\( ^{222}\text{Rn} \) decay constant  
\( 2.098 \times 10^{-5} \text{ s}^{-1} \)

\( M_{cw} \)  
Mass of wet soil and chipette  
\( \text{g} \)

\( M_{cd} \)  
Mass of dry soil and chipette  
\( \text{g} \)

\( M_c \)  
Mass of chipette  
\( \text{g} \)

\( M_d \)  
Mass of oven-dried soil  
\( \text{g} \)

\( M_{dw} \)  
Mass of deionised water  
\( \text{g} \)

\( M_{pw} \)  
Mass of pore water (\( M_{pw} = \theta_g \times M_w \))  
\( \text{g} \)

\( M_w \)  
Mass of wet soil  
\( \text{g} \)

\( n \)  
Number of equal sections over a constant distance, \( x \)

\( Q^0 \)  
Stream discharge at upstream sampling station  
\( \text{m}^3 \text{ s}^{-1} \)
\( Q' \) Stream water discharged (lost) to the adjacent aquifer \( (m^3 \text{ s}^{-1}) \)

\( Q'' \) Stream discharge at downstream sampling station \( (m^3 \text{ s}^{-1}) \)

\( Q_{gw} \) Groundwater discharged to stream flow \( (m^3 \text{ s}^{-1}) \)

\( Q'\text{w} \) Stream discharge \( (m^3 \text{ s}^{-1}) \)

\( Q_{gw}/Q'\text{w} \) Fraction of groundwater in stream water at downstream sampling station

\( ^{222}\text{Rn}_{\text{meas}} \) \(^{222}\text{Rn} \) activity measured in groundwater \( (\text{Bq L}^{-1}) \)

\( \rho_b \) Bulk density \( (\text{g cm}^{-3}) \)

\( \rho_{fw} \) Density of freshwater \( (1 \text{ kg m}^{-3}) \)

\( \rho_m \) Density of measured groundwater \( (\text{kg m}^{-3}) \)

\( \rho_p \) Particle density \( (\text{g cm}^{-3}) \)

\( \theta_g \) Gravimetric water content of soils \( (\text{g}^{-1} \text{ g}^{-1}) \)

\( t \) Travel time between consecutive sampling stations \( (\text{s}) \)

\( T \) Time of \(^{222}\text{Rn} \) ingrowth \( (\text{s}) \)

\( \text{TDS} \) Total dissolved solids \( (\text{mg L}^{-1}) \)

\( \text{TDS}_{\text{m}} \) Total dissolved solids measured in groundwater \( (\text{kg m}^{-3}) \)

\( v \) Velocity of stream water \( (\text{m s}^{-1}) \)

\( V \) Volume of soil core \( (\text{cm}^{3}) \)

\( V_{gw} \) Volume of groundwater discharged to the stream channel \( (\text{L}) \)

\( x \) Distance between sampling stations \( (\text{m}) \)

\( z \) Thickness of stagnant film \( (\text{m}) \)

\( \%AGW_{\text{min}} \) Minimum percentage of stream water sourced from alluvial groundwater

\( \%RGW_{\text{min}} \) Minimum percentage of stream water sourced from regional groundwater

\( \%AGW_{\text{max}} \) Maximum fraction of stream water sourced from alluvial groundwater

\( \%RGW_{\text{max}} \) Maximum fraction of stream water sourced from regional groundwater
ABSTRACT

Regions of surface water and groundwater exchange are major sites for the transfer and transformation of solutes and nutrients between stream and subsurface environments. Conventional stream and groundwater exchange investigations are limited by methodologies that require intensive field investigations and/or the set-up of expensive infrastructure. These difficulties are exacerbated where hydraulic gradients are very low and stream discharge highly variable. This thesis uses a suite of environmental tracers (Cl, $^{222}$Rn, $\delta^2$H & $\delta^{18}$O, $^{87}$Sr/$^{86}$Sr) to characterise the extent of stream and groundwater exchange between a sand bed stream and adjacent alluvial aquifer in a subtropical catchment (the Wollombi Brook) of eastern Australia. The aims were to identify sources and relative contributions of different sources of groundwater to stream discharge and specifically to improve the methodology of using $^{222}$Rn to obtain quantitative estimate of groundwater fluxes.

The sensitivity of the $^{222}$Rn technique for identifying groundwater discharge based on the $^{222}$Rn concentration in stream water was improved via an iterative numerical approach to account for $^{222}$Rn loss from stream water via turbulent gas exchange and radioactive decay. Optimal distances between stream sampling points for defining the magnitude of groundwater discharge to stream flow based on $^{222}$Rn concentrations in stream water is a function of average stream velocity and water depth. The maximum allowable distance between sampling points for determining the magnitude of groundwater discharge to the Wollombi Brook was 2 km. This work showed that groundwater discharged to all reaches of the Wollombi Brook during baseflow and flood recession conditions. Alluvial groundwater contributed $<30\%$ of water to stream flow in the mid Wollombi Brook catchment.
Dilution of steady-state $^{222}\text{Rn}$ concentrations measured in transects from the stream to the alluvial sediments showed that significant surface water and groundwater exchange occurs even when gradients between surface water and groundwater are low. Lateral stream water influx to the adjacent alluvial aquifer was more extensive in the lowland areas of the Wollombi Catchment during low flow than flood recession conditions. Extensive stream water influx to the adjacent alluvial aquifer occurs contrary to the net direction of surface water and groundwater flux (as indicated by hydraulic gradients toward the stream channel). The rate of stream and groundwater exchange within the adjacent alluvial aquifer appears to be greatest during baseflow conditions. Fresh alluvial groundwater appeared to provide a buffer against higher salinity regional groundwater discharge to the alluvial aquifer in some reaches of the Wollombi Brook catchment. Pumping of the alluvial aquifer and diversions of surface water may jeopardise the water quality and volume of the alluvial aquifer and induce water flow from the regional aquifer toward the stream, potentially salinising the fresh alluvial aquifer and subsequently the stream.

The change in the Cl$^{-}$ concentration and the variation in slope of the $\delta^2$H-$\delta^{18}$O line between consecutive stream sampling points could be used to differentiate between regional and alluvial groundwater discharge to stream flow. Incorporating this information with three-component end-member mixing using $[\text{Sr}^{2+}]$ and $^{87}\text{Sr}^{86}\text{Sr}$ showed that stream and alluvial groundwater exchange within the stream channel was highest in the lowland floodplains during low flow conditions. The least stream and alluvial groundwater exchange occurred in the low streambed gradient mid reaches of the Wollombi Brook regardless of stream stage. The greatest difference in the degree of stream and alluvial groundwater exchange between high and low stream stages occurred in the lowland floodplains of the Wollombi Brook.
DECLARATION OF ORIGINALITY

I certify that this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by any other person except where due reference is made in the text.

Jodie Lee Pritchard
August 2005
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