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Mapping groundwater-surface water interaction using radon-222 in gravel-bed rivers: a comparative study with differential flow gauging

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Abstract

Accurate measurements of groundwater-surface water interactions at high spatial and temporal resolution can provide information to better manage integrated groundwater and surface water resources and their dependent freshwater ecosystems. We evaluated the emerging method of radon-222 measurements and commonly-used concurrent flow gauging to measure and map groundwater-surface water interactions in two gravel-bed rivers, the Hutt and Mangatainoka rivers, located in the lower North Island of New Zealand. River surveys were conducted over a 50 km reach of the Mangatainoka River and a 16 km reach of the Hutt River, with low (500–800 m apart) and high (50 m apart) resolution radon-222 grab sample measurements and concurrent flow gauging sites. Radon-222 measurements were found to be successful for measurement and mapping of groundwater discharge patterns in the study rivers. However, in both rivers the groundwater discharge patterns identified by radon were not always matched by the concurrent flow gauging surveys, highlighting the ambiguity surrounding the use of flow gauging in isolation to measure and map groundwater-surface water interactions in gravel-bed rivers. In some reaches of both studied rivers the concurrent flow gauging suggested areas of either groundwater recharge or discharge, where the radon measurements indicated the opposite process. This suggests that underflow beneath the gravel surface and other parafluvial exchange processes in gravel-bed rivers can cause the interpretation of concurrent flow gauging or radon-222 data alone to be misleading. Flow gauging combined with radon measurements is suggested for more precise and accurate measurements of groundwater and river water interaction processes in gravel-bed rivers.

Keywords

environmental isotopes; groundwater discharge; concurrent flow gauging; gravel-bed rivers; groundwater-surface water interaction

Introduction

Understanding how surface waters and groundwaters interact is crucial for managing freshwater resources, including land use impacts on river and groundwater quality, and maintaining river and groundwater levels (Stellato *et al.*, 2013). One facet of understanding how groundwater and surface water interacts is to measure and map spatial and temporal patterns of groundwater and river flow exchanges within the river systems (Fleckenstein *et al*., 2010).

Numerous measurement techniques have been developed to study how groundwater and river flows interact (Fleckenstein *et al*., 2010). Seepage meters have been used to directly capture and measure groundwater-surface water (GW-SW) exchange (Rosenberry, 2008). However, the single-point seepage measurement can easily be distorted by currents, and only limited spatial data can be obtained. Additionally, this method cannot differentiate between hyporheic exchange and GW-SW interaction (Anibas *et al*., 2011; Kalbus *et al*., 2006; Murdoch and Kelly, 2003; Santos *et al*., 2012). A recent approach that does capture GW-SW exchange processes at a higher resolution is distributed temperature sensing (DTS). DTS captures surface water temperature data at pre-set spatial intervals along a fibre optic cable (Moridnejad, 2015). However, this method is expensive, which can limit its use in large-scale surveys, and the fibre optic cable is delicate. Furthermore, this method is only applicable where there is a significant temperature difference between groundwater and surface water, which can be strongly affected by environmental conditions such as seasonal scale temperature changes, wind and turbidity and landscape features such as shadows cast by bush (Johnson, 2003).

An emerging tool for simple measurement and mapping of GW-SW interaction is the analysis of radon-222 (Rn) in surface water. Rn is a soluble, colourless, gaseous, unstable isotope and is generated as part of the uranium decay series (Cecil and Green, 2000). Uranium is ubiquitous in almost all rocks and soils, resulting in the release of Rn from uranium-bearing minerals in groundwater (Stellato *et al*., 2013). It should be noted that uranium concentrations do vary substantially between different minerals and therefore 'high' levels of Rn in one catchment may be very different to 'high' levels in a catchment with different geology. Rn is abundant in groundwaters but has almost negligible concentrations in surface waters due to rapid Rn loss to the atmosphere through degassing and a short half-life of 3.8 days (Garcia-Vindas and Monnin, 2005; Kies *et al*., 2005). The large contrast in Rn concentrations between groundwaters and surface waters makes Rn an ideal environmental tracer to measure and map groundwater discharge into streams, rivers, and lakes (Burnett *et al.* 2001; Burnett *et al*., 2013; Burnett *et al*., 2010; Cook *et al*., 2003; Dimova, *et al*., 2013; Dulaiova *et al*., 2010; Stellato *et al*., 2013). However, for the measurement of GW-SW interactions in braided gravel-bed rivers, a common feature in temperate mountain-valley areas with young and pro-glaciated eroding mountains worldwide (e.g., in New Zealand, Canada, the Himalayas, European Alps, and Japanese Alps (Tockner *et al*., 2006)), there are very few studies using Rn. There are only a few examples of Rn studies in New Zealand that quantify the flux of surface water recharge to groundwater systems (Close, 2014; Close *et al*., 2014) and neither of these studies examined gravel-bed river systems.

To identify locations of groundwater discharge and recharge within riverine environments in New Zealand, concurrent river flow gauging is frequently used, with national environmental monitoring standards to guide methodology (NEMS, 2013). However, concurrent flow gauging is time consuming and captures only river flow changes between a limited number of measurement points, and does not capture processes occurring between the measurement points (Kalbus *et al*., 2006). Concurrent flow gauging also only captures flow changes above the river or stream bed surface. In braided and meandering gravel river and stream beds, occurrences of hyporheic and parafluvial flow processes in the river channel are common. Hyporheic and parafluvial flow processes pose a challenge to the accuracy and utility of concurrent flow gauging. On the other hand, little has been done to evaluate Rn measurements to measure and map GW-SW interactions in the New Zealand gravel-bed rivers.

The aim of this paper is to compare the Rn and concurrent flow gauging techniques in the New Zealand gravel-bed river environment to establish whether the information given by Rn can be combined with concurrent flow gauging to better understand GW-SW interactions. We measured Rn to map groundwater discharge locations in two gravel-bed rivers, the Hutt and Mangatainoka rivers, located in the lower North Island of New Zealand. We then compared the Rn results with concurrent flow gauging to evaluate any ambiguity surrounding the use of Rn measurements and/or flow gauging for determining patterns of GW-SW interaction in gravel-bed rivers.

Study rivers

Two gravel-bed rivers were investigated for this study: the Hutt River and the Mangatainoka River in the lower North Island of New Zealand (Fig. 1a and 1b). These rivers were chosen as they both have river beds consisting of greywacke gravels, which is representative of many New Zealand rivers. The Hutt River is located in the Hutt Valley, north east of Wellington, and flows in a south westerly direction. The Hutt River catchment covers an area of 655 km^2 (Lawrence *et al.*, 2011) and consists of two basins: the Upper Hutt and Lower Hutt basins (Fig. 1a), which are effectively divided by Taita Gorge. The geological setting of the Lower Hutt Valley is strongly influenced by the Wellington fault which has caused a half graben, a geological feature where a fault line has caused a basin shape that lies parallel to the fault line. This wedge-shaped basin is confined to the west by the Wellington fault and to the east by greywacke bedrock (Boon *et al.*, 2011; Jones and Baker, 2005). The basin has been infilled with gravels, sand and silts, deposited by the Hutt River from the Tararua Range, and marine sediments, deposited during marine transgressions and regressions resulting from Quaternary sea level changes (Boon *et al.*, 2011). The gravel deposits have led to the formation of aquifers, which are confined by the marine sediments from their seaward extent until approximately 6 km upstream from the foreshore, and are unconfined upstream for approximately 6 km until Taita Gorge (shown as gauging station on Fig. 1a). The unconfined aquifer is known as the Taita Alluvium Aquifer, which comprises 10–15 m of gravels and gravels and sands (Boon *et al.*, 2010). Water within the Taita Alluvium flows at a depth of 3–10 m with the depth of flow closely correlated with the stage of the Hutt River and the tide (Phreatos, 2003). This shallow aquifer is recharged from the overlying, directly hydraulically-connected, Hutt River (Phreatos, 2003). In the Upper Hutt basin, with greywacke bedrock material, there are two known aquifers: a shallow unconfined aquifer and a deeper aquifer confined by a dense silt layer (Jones and Baker, 2005; Phreatos, 2003). The shallow unconfined aquifer is strongly influenced by the Hutt River. The river water is thought to seep into the aquifer at the upper part of the basin. Groundwater is thought to discharge back into the river at the downstream end of the Upper Hutt basin, just upstream of Taita Gorge, due to bedrock outcrop to the surface, where a weir is located (Fig. 1a). There is a fixed flow gauging station at the Taita Gorge on the Hutt River.

The Mangatainoka River lies in the North Island to the east of the Tararua Range (Fig. 1b). The river, with a catchment of approximately 440 km^2 (Brougham, 1987; Taylor *et al.*, 2015), flows to the north east,

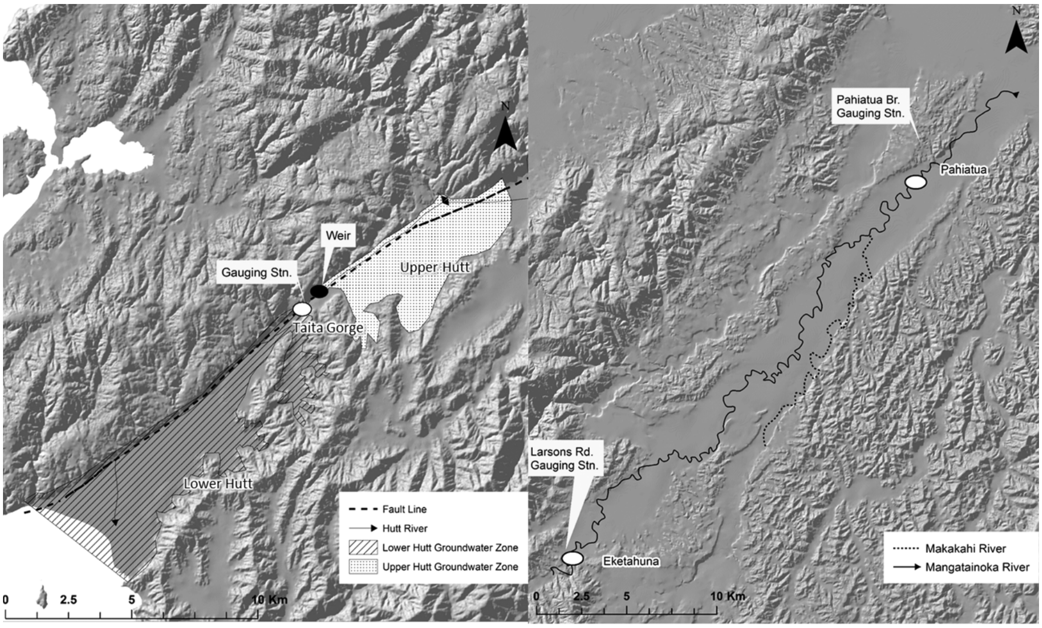

Figure 1 – Geographical settings of the (a) Hutt and (b) Mangatainoka rivers

through the township of Pahiatua before joining the Tiraumea River and ultimately flowing into the Manawatu River. The geology surrounding the Mangatainoka River comprises highly-faulted greywacke basement of the Tararua Formation (Rawlinson and Begg, 2014). Tertiary Miocene and Pliocene rock deposits are also found, trending younger in age in a westerly direction (Brougham, 1987). In the Mangatainoka River there are major flow losses occurring in the upper reaches with further significant flow losses in part of the upper middle reach, with the river flow loss transferring to the neighbouring Makakahi River (Brougham, 1987). Groundwater discharge into the Mangatainoka River occurs in the lower middle reaches (Brougham, 1987). There are two fixed gauging stations in the Mangatainoka River: one located in the upper reaches at the Larsons Road Bridge and the other located in the lower reaches at the Pahiatua Township Bridge (Fig. 1b).

Methods

Under low flow conditions, twelve Rn surveys were undertaken during April and August 2014 and January and February 2015. Tables 1 and 2 summarise the Rn survey dates, the river flow as measured at the regional council permanent gauging stations, whether the Rn samples were collected at a low (500–800 m) resolution or high (50–100 m) resolution and survey distances for the Hutt (Table 1) and Mangatainoka (Table 2) rivers. The surveys covered the entire, approximate 50 km, of the Mangatainoka River and a 16 km reach of the Hutt River. Initially, Rn surveys were carried out at low resolution along the entire river section, collecting Rn grab water samples at a distance of ~500 to 800 m between each sampling point. These were followed by higher resolution Rn surveys, where grab samples were collected ~50 m apart, to investigate smaller sections of the river at a more detailed scale. Rn samples were usually collected in the middle of the river width, at the bottom of the river bed. Rn profiles across the river width were also taken at three different locations within each study river, with samples taken at approximately 2 m intervals across the river. In addition, nine groundwater wells in the Lower Hutt basin and two groundwater wells in the Mangatainoka River catchment (near the middle and lower reaches, respectively) were sampled for Rn analysis. This was so that the Rn concentrations measured in the rivers could be compared to the Rn concentrations measured in the study catchments' groundwater.

Water samples were collected for Rn measurement in 20 mL glass vials with foil-lined caps. The samples were transported to the GNS Science Water Dating Laboratory on the same day as collection and analysed using the liquid scintillation counting measurement method (Hahn and Pia, 1991), where 10 mL of sample water is combined with 10 mL of Opti-Fluor organic compound, shaken, and then measured for 100 minutes in a low level scintillation counter. The detection limit of this measurement method is 0.1 Bq L^{-1}.

Three concurrent flow gauging surveys were undertaken, one on each study

Table 1 – Summary of Hutt River radon surveys

Survey date	River flow at Taita Gorge ($m^3 s^{-1}$)	Survey resolution/type	No. Rn samples collected	Survey site (Lower/Upper Hutt basin)	Survey distance (m)
04/04/2014	4.0	Low and high	45	Lower & Upper	14000
04/04/2014	4.0	River width profiles	10	Lower	n/a
10/08/2014	8.2	River width profiles	8	Lower	n/a
10/01/2015	5.7	Low	28	Lower & Upper	16000
11/01/2015	5.7	High	18	Lower	400
18/02/2015	3.2	River width profiles	5	Lower	n/a

Table 2 – Summary of Mangatainoka River radon surveys

Survey date	River flow at Larsons Road ($m^3 s^{-1}$)	River flow at Pahiatua Town Bridge ($m^3 s^{-1}$)	Survey resolution/type	No. Rn samples collected	Survey site (upper/middle/lower reaches)	Survey distance (m)
02/02/2015	1.2	1.1	Low	67	Upper[1], lower & part of middle	7000
07/02/2015		1.8	High & river width profiles	16	Middle	2200
08/02/2015	0.6		High	11	Upper	1200
15/02/2015	0.4		Low	22	Upper	12000
20/02/2015		0.9	Low	12	Middle	6000

[1] 8 radon results from the headwaters were discarded due to suspected dilution from rainfall.

river section (Upper Hutt River, Lower Hutt River and Mangatainoka River), in January to March 2015 during low flow conditions. Flow gauging was conducted using a Son Tek M9 River Surveyor, where 6 to 10 transects were measured at each site to calculate average river flow, or by the velocity-area method using a Son Tek FLOWTRACKER® HANDHELD-ADV® or a Pygmy Universal Current Meter Model OSS-PC1. All flow measurements were carried out in accordance with the National Environmental Monitoring Standards for open flow channel measurements in New Zealand (NEMS, 2013). In the Hutt River, only flows measured by the same method were compared. This was not the case for the Mangatainoka River, and unfortunately no comparison between the measurement methods was undertaken.

Results and discussion

Mapping groundwater-surface water interactions using Rn

The international literature infers that Rn concentrations in groundwater typically range from 10–70 $Bq\,L^{-1}$ in gravel aquifers (Cecil and Green, 2000). The Rn concentrations measured in groundwater samples from both study catchments fell within this range, varying between 27 $Bq\,L^{-1}$ and 37 $Bq\,L^{-1}$. In both study rivers the Rn concentrations measured in the river water samples ranged from below the detection limit to approximately 5.0 $Bq\,L^{-1}$; the higher the measured Rn concentration, the higher the proportion of groundwater contribution to the measured sample. The measured Rn concentrations were used to identify and map groundwater discharge patterns in the study rivers. A relative increase in Rn concentration from the previously measured upstream site was interpreted as an indication of groundwater discharge (gain) to the river. A relative decrease in Rn concentrations does not necessarily indicate a reach of no groundwater discharge. Consideration of the Rn degassing rate is needed to interpret decreases in Rn concentrations, large or small. The rate at which radon degasses is dependent on river depth, river velocity, turbulence and temperature (Genereux and Hemon, 1992). Rn will degas faster from a shallow, turbulent reach of river than from a deep, slow flowing reach.

Figure 2 shows Rn results for the two full river, low resolution (~500–800 m apart) surveys undertaken in the Hutt River nine months apart. Interestingly, both surveys showed the same groundwater discharge patterns in the Hutt River (Fig. 2), with relatively high Rn concentrations (indicating

Table 3 – Flow gauging survey summary

Survey Date	Measurement methods	River	Location	No. of gauging sites
13/01/2015	Son Tek M9 River Surveyor	Hutt	Lower Hutt	6
18/02/2015	Son Tek FLOWTRACKER® HANDHELD-ADV®	Hutt	Upper Hutt	16
05/03/2015	Son Tek M9 River Surveyor Pygmy Universal Current Meter Model OSS-PC1	Mangatainoka	Full River	19

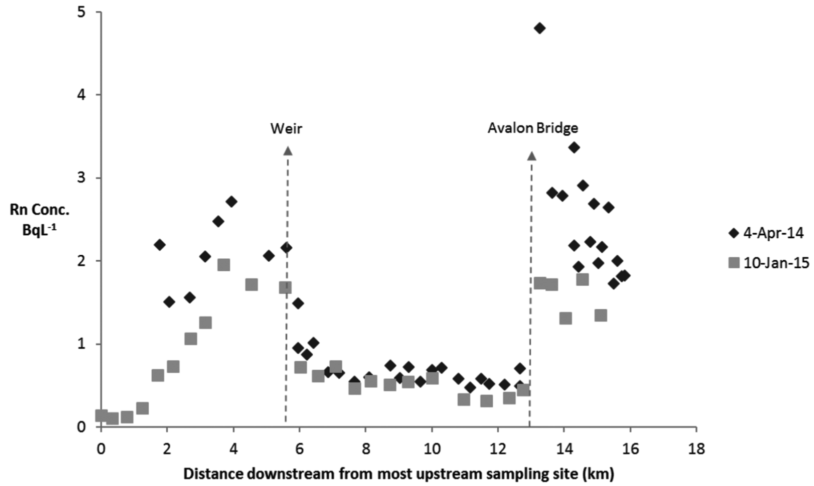

Figure 2 – Measured Rn concentrations in the Hutt River on 4 April 2014 and 10 January 2015. Flow measured at the Hutt River at Taita Gorge monitoring station was 4.0 $m^3 s^{-1}$ and 5.7 $m^3 s^{-1}$ for the 2014 and 2015 surveys, respectively.

groundwater discharge) between 2 km and 4 km downstream of the most upstream sampling point and below the Avalon Bridge in the Lower Hutt, approximately 13 km downstream of the most upstream sampling point (Fig. 2). While both surveys were undertaken during low flow conditions, the survey carried out during 2014 was during lower flows. Thus, as expected, the measured Rn concentrations during the 2014 survey were relatively higher than in the 2015 survey.

The most upstream sampling point in January 2015 was selected due to this reach lying in a section of greywacke bedrock. It is unlikely that groundwater is discharged through the bedrock due to the low permeability of greywacke, therefore Rn concentrations through this reach are negligible. Thus any increases in Rn concentrations are easily observed further downstream as the river bed material changes.

Elevated Rn concentrations were measured approximately 2–4 km downstream from the first sampling point (Fig. 2), and are interpreted to indicate groundwater seepage into the river at the end of the Upper Hutt groundwater system where the river channel is lined with greywacke bedrock. At this location there is a weir, identified on Figures 1 and 2. Directly downstream from the weir, Rn concentrations rapidly decreased. The initial rapid decrease is likely due to high turbulence as the river water flows over the weir and through a narrow, fast flowing reach which extends for approximately 100 m downstream of the weir. The greywacke bedrock reach extends for another approximately 1500 m, during which a more gradual decrease in Rn concentrations was observed, likely due to a slower degassing rate of Rn as the river flow becomes less turbulent. In the bedrock outcrop area through Taita Gorge, significant groundwater influx to the river is impeded, confirmed by low Rn concentrations throughout the gorge.

Approximately 1500 m downstream of the weir, the river bed material changes to gravels as it enters the Lower Hutt groundwater zone. The slight decrease in Rn concentrations observed through this reach indicates no groundwater inflow and is consistent with the losing reach of the unconfined Taita Alluvium Aquifer modelled by Gyopari (2014). Slight fluctuations in Rn concentrations of, or less than, approximately 0.5 Bq L^{-1} observed in this reach could be due to exchange in the hyporheic zone. However, the Rn contribution from the hyporheic zone was not examined extensively in this study.

Approximately 200 m downstream of the Avalon Bridge a sharp increase in Rn concentrations was observed, indicating groundwater influx to the river (Fig. 2). This is likely due to the start of confining layers in the aquifer forcing the groundwater back to the surface water.

To investigate whether the fault line, running along the north western side of the river bank (Fig. 1a), had any impact on the distribution of groundwater discharge in the Lower Hutt groundwater zone, river-width Rn profiles were taken. The profiles were taken along straight, non-turbulent reaches of the river to avoid the influence of mixing or eddies on the Rn results. The river-width Rn profiles showed that groundwater discharge occurs on the south eastern side and to a lesser extent on the north western side of the river bank. This indicates a strong geological influence from the fault line on groundwater discharge (Fig. 3), where the aquifer extends to the south eastern side of the river bank, but the groundwater discharge ends on the north western side where the fault and bedrock are present (Fig. 1) (Boon *et al.*, 2011; Jones and Baker, 2005).

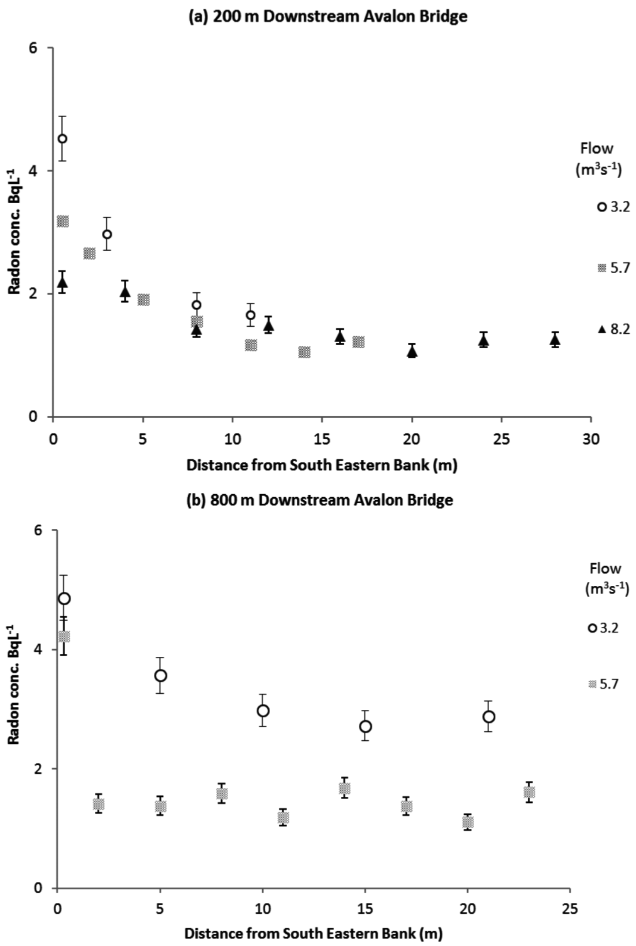

Figure 3 – Rn river-width profiles of the lower Hutt River at two locations under low flow conditions

Rn surveys were also carried out in the Mangatainoka River to assess whether the method could successfully show patterns of GW-SW interaction in another gravel-bed river. The Mangatainoka River Rn surveys indicated large reaches of both groundwater discharge and possible recharge, as shown in Figure 4, where 0 m indicates where the river leaves the mountain range and sampling began. Heading downstream from the most upstream sampling site, low Rn concentrations were measured over an approximate 5 km reach. This reach of the river lies at the beginning of infilled valley deposits. Thus, the low Rn concentrations are consistent with insignificant groundwater discharge, as expected with the

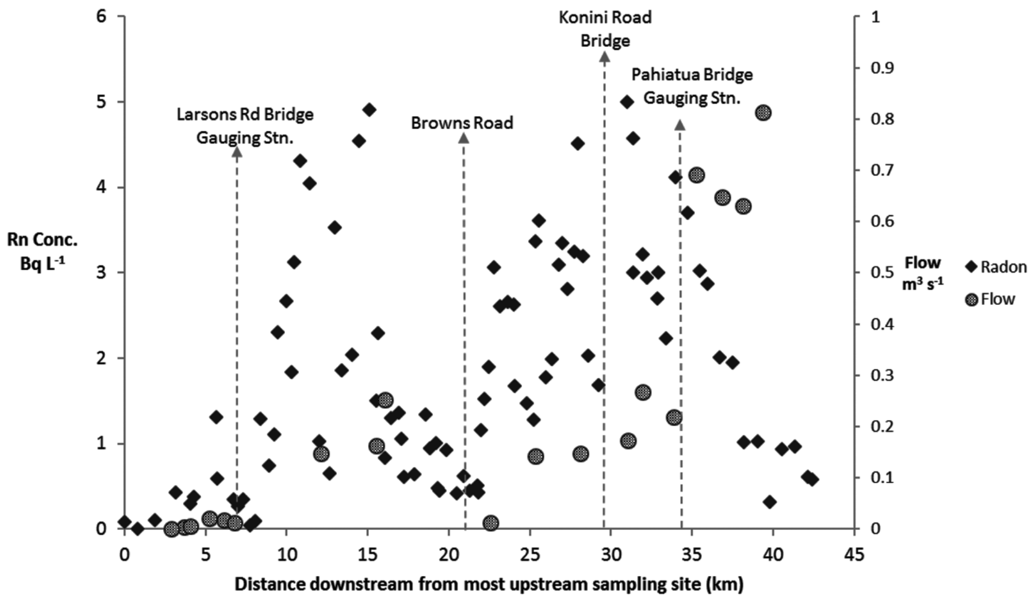

Figure 4 – Rn concentrations in the Mangatainoka River at low flow (between 0.4 $m^3 s^{-1}$ and 1.2 $m^3 s^{-1}$ at the Larsons Road Bridge gauging station, and between 0.9 $m^3 s^{-1}$ and 1.8 $m^3 s^{-1}$ at the Pahiatua Bridge gauging station) measured during low resolution surveys in February 2015 and measured flows ($m^3 s^{-1}$) on 5 March 2015.

geology of the area. Approximately 1 km downstream of the Larsons Road gauging station (Fig. 4) elevated radon concentrations were measured, indicating significant groundwater discharge. Sustained high Rn concentrations suggest that this discharge continues for about 7 km. Downstream of here, Rn concentrations were observed to decline, matched by a decrease in measured flow, indicating recharge to the groundwater system. An increase in Rn concentrations 23 km to 35 km downstream from the initial sampling point, in the lower middle reaches of the Mangatainoka River, indicate groundwater discharge; this may be due to the ending of an unconfined aquifer or confining layers forcing the water back to the surface. These results align somewhat with the groundwater discharge patterns identified by Brougham (1987), who suspected that there were major streamflow losses in the upper parts of the Mangatainoka River around the Larsons Road Bridge (Fig. 4) with further significant stream flow losses at the reach near Browns Road (Brougham, 1987) (Fig. 4). Furthermore, he found significant groundwater discharge to occur around the Konini Road Bridge (Fig. 4).

Comparison of concurrent flow gauging and Rn measurements

Figure 5 compares the high resolution Rn survey results and a concurrent flow gauging survey undertaken in the lower Hutt River in January 2015. At the most upstream flow gauging point the measured Rn concentrations were relatively low, 0.32 Bq L^{-1} to 0.45 Bq L^{-1}. At the next downstream flow gauging point, which is downstream of the Avalon Bridge, the flow increased by approximately 25% from 3.9 $m^3 s^{-1}$ to 5.1 $m^3 s^{-1}$ and, consistently, the Rn concentration increased from 0.3 Bq L^{-1} to 1.9 Bq L^{-1} between these two flow gauging sites. Between 260 m and 650 m downstream of the Avalon Bridge there is a meander over which the river flow becomes very shallow and turbulent. Downstream of the meander the flow decreased from 5.1 $m^3 s^{-1}$ to 3.9 $m^3 s^{-1}$, indicating a loss of river water to the groundwater system. A final flow measurement of 4.3 $m^3 s^{-1}$ was taken approximately 200 m downstream from this site after a second meander, indicating groundwater discharge. The Rn concentration measured downstream of the first meander was 0.2 Bq L^{-1} lower than the upstream measurement site, at 1.7 Bq L^{-1}. Ordinarily, a small decrease in Rn concentration would indicate Rn loss through degassing and no additional groundwater inflow. However, given the shallow and turbulent nature of flow at this location, it is unlikely that only 0.2 Bq L^{-1} of Rn would be lost through degassing between the two measurement sites and some groundwater inflow is assumed, based on Rn loss through degassing of 1.0 Bq L^{-1} over 500 m at the turbulent reach of the river below the weir. Again, downstream of the second meander the Rn concentrations remained consistently high, which was not expected due to the flow over a second, shallow and turbulent meander. This is likely indicating more groundwater inflow. The discrepancies between the groundwater discharge patterns indicated by Rn and flow gauging suggest there are more complex processes, such as parafluvial flow, occurring at the meanders. However, further investigation into degassing rates is necessary to confirm this hypothesis.

A comparison between flow gauging and Rn concentration surveys was also undertaken in the upper Hutt River. The comparison showed inconsistencies in the discharge patterns deduced by the measured Rn concentrations and concurrent flow gauging. Groundwater discharge is shown to occur further downstream of site 1, by the measured relative increase in Rn concentrations, than was indicated by the concurrent flow gauging data (Table 4). However, downstream of this discrepancy, at site 5, the concurrent flow gauging and Rn measurements were found to be in agreement on the groundwater discharge or recharge patterns up to the Ferguson Drive Bridge. Between sites 6 and 7, the increase in flow is attributed to the tributaries entering the river and the Rn decrease is likely caused by degassing. Between sites 7 and 8 the measured flow decreased, yet the Rn concentration remained constant. It is unlikely that over the 1 km between the sites no Rn degassing would occur. Therefore, it is assumed that the Rn indicates some groundwater discharge but further investigation of the Rn degassing rates is needed to confirm this. Again, there was a discrepancy between concurrent flow gauging and Rn measurements from site 8 to site 10. Between these two sites, the concurrent flow

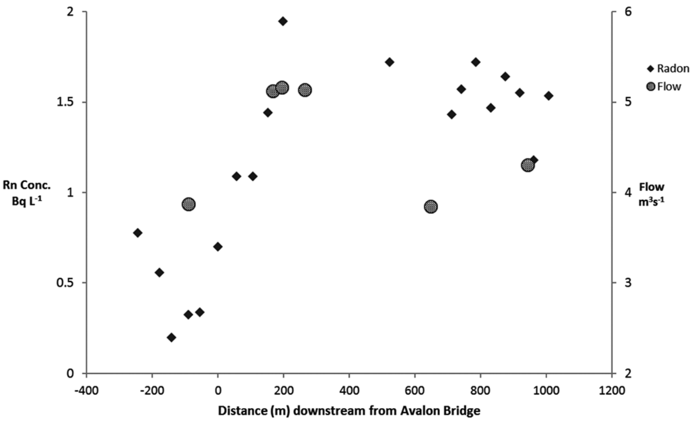

Figure 5 – Measured river flows (on 13 January 2015) and Rn concentrations (on 11 January 2015) in the lower Hutt River. The Avalon Bridge is located at distance 0 m

gauging measured a groundwater discharge, while the Rn measured no groundwater discharge. As with the river reach surveyed in the lower Hutt River, the disparity in results between the flow gauging and the measured radon concentrations is likely due to the effects of parafluvial flow beneath the surface of the gravel bed river. However, as previously mentioned, further investigation into the degassing rates of Rn from the river are needed to confirm this.

In the Mangatainoka River, the Rn measurement and flow gauging surveys also gave results that correlated in some reaches and conflicted in other reaches, in terms of indicative groundwater discharge patterns. In the upper to middle reaches of the Mangatainoka River, 12 km to 15.5 km downstream of the most upstream sampling point, the flow increase was small and within the uncertainty of the flow gauging technique (Figure 4). In contrast, the Rn measurements showed significant groundwater discharge in the same reach. In the lower middle reaches, between 16 km and 22.5 km downstream from the most upstream sampling point, Rn and flow measurements gave consistent results: the flow decreased by 95% and the measured Rn concentrations also decreased (to 0.5 Bq L^{-1}). However, the flow gauging and Rn measurements again indicated conflicting groundwater discharge patterns between approximately 3 km and 5 km downstream of the Konini Road Bridge; the Rn concentrations were relatively high (1.8–4.5 Bq L^{-1}), indicating groundwater

Table 4 – Upper Hutt River flow gauging results for the main river and inflowing tributaries (indicated with *) on 18 February 2015, and Rn measurements taken in the main river on 10 January 2015. Sites are listed in order from upstream to downstream.

Site Name	Flow ($m^3 s^{-1}$)	Estimated flow change ($m^3 s^{-1}$)	Rn conc. (Bq L^{-1})	± Rn 1σ (Bq L^{-1})	Rn indicated gain/ no gain
1	2.756		0.2	0.1	
Trib. a*	0.009*			0.1	
2	2.431	- 0.334 ± 0.052	0.6	0.1	gain
3	2.431	0.000 ± 0.048	0.7	0.1	gain
4	2.061	- 0.370 ± 0.045	1.1	0.1	gain
5	2.524	0.463 ± 0.046	1.3	0.1	gain
6	2.600	0.760 ± 0.051	2.0	0.2	gain
Trib. b*	0.002*				
Trib. c*	0.006*				
Trib. d*	0.016*				
Trib. e*	0.075*				
7	2.796	0.097 ± 0.054	1.7	0.2	no gain
8 (Ferguson Drive Bridge)	2.596	- 0.203 ± 0.054	1.7	0.2	gain
9	0.016*				
10	2.763	0.151 ± 0.054	0.7	0.1	no gain
Trib. f*	0.016*				

discharge, yet the measured flow did not change significantly. As with the Hutt River, the higher than expected Rn concentrations are thought to arise from parafluvial flow. Parafluvial flow over long reaches (100s to 1000s of metres) can contribute to significantly increased radon concentrations, as demonstrated by the findings of Cartwright and Hofmann (2015).

Conclusions

Hydrologists and water managers require accurate measurements of GW-SW interactions to gain insight and a sound understanding of coupled groundwater and surface water resources and their dependent freshwater ecosystems. Current methods and techniques to measure and map GW-SW interactions are either expensive or limited in their ability to provide information at high spatial and temporal resolution. This study has shown that Rn can be used to map groundwater discharge patterns in New Zealand gravel-bed rivers. A significant difference (i.e., 5 to 6 times) in Rn concentrations measured in the river water and groundwater enabled application of Rn measurements to measure and map GW-SW interactions in two gravel-bed rivers, the Hutt and Mangatainoka Rivers, located in the lower North Island, New Zealand. Concurrent river flow gauging has been used frequently to measure and map groundwater recharge from and discharge into gravel-bed rivers in New Zealand. However, when the groundwater discharge patterns measured by Rn measurements were compared to the concurrent flow gauging measurements the two techniques did not always correlate with each other. A major consideration into why this occurred is that the degassing rates of radon were not defined in this study. Further investigation into the rate of Rn degassing from the rivers could help to confirm whether the inconsistencies between the two methods are due to Rn degassing rates or, consistent with international studies, due to significant underflow that may be occurring in the studied gravel-bed rivers that was not captured by the flow gauging. This suggests that an assessment and mapping of GW-SW interactions in gravel-bed river environments could be somewhat misleading, if based on the concurrent flow gauging only. This study demonstrates that Rn measurements are useful in assessing GW-SW interactions at a much more detailed scale, and provide a complementary, cost-effective tool to combine with flow gauging to form a more conclusive picture of the groundwater and river water interaction processes in gravel-bed rivers.

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