Investigation of groundwater-surface water interaction in the Te Arai River, Gisborne, using radon-222 and concurrent stream flow gauging

H Martindale

R van der Raaij

GNS Science Report 2018/13
April 2018

GNS SCIENCE
TE PŪ AO

DISCLAIMER

The Institute of Geological and Nuclear Sciences Limited (GNS Science) and its funders give no warranties of any kind concerning the accuracy, completeness, timeliness or fitness for purpose of the contents of this report. GNS Science accepts no responsibility for any actions taken based on, or reliance placed on the contents of this report and GNS Science and its funders exclude to the full extent permitted by law liability for any loss, damage or expense, direct or indirect, and however caused, whether through negligence or otherwise, resulting from any person's or organisation's use of, or reliance on, the contents of this report.

BIBLIOGRAPHIC REFERENCE

Martindale H, van der Raaij R. 2018. Investigation of groundwater-surface water interaction in the Te Arai River, Gisborne, using radon-222 and concurrent stream flow gauging. Lower Hutt (NZ): GNS Science. 27 p. (GNS Science report; 2018/13). doi:10.21420/G2SD24.

H. Martindale GNS Science, PO Box 30368, Lower Hut 5040
R. van der Raaij GNS Science, PO Box 30368, Lower Hut 5040

www.gns.cri.nz

ISSN 2350-3424 (Online)
ISBN 978-1-98-853072-7 (Online)
http://dx.doi.org/10.21420/G2SD24

CONTENTS

ABSTRACT .... **III**

KEYWORDS .... **III**

1.0 INTRODUCTION **1**

2.0 LITERATURE REVIEW AND NEW ZEALAND CASE STUDIES **2**

2.1 RADON – WHAT IS IT AND HOW IS IT USED FOR GW-SW INTERACTION STUDIES? 2

2.2 TECHNIQUES FOR MEASURING GW-SW INTERACTION 2

2.3 ADVANTAGES AND LIMITATIONS OF USING RADON FOR IDENTIFYING GW-SW INTERACTION 4

2.4 COMBINING RADON SURVEYS AND STREAM FLOW GAUGING TO INVESTIGATE GW-SW INTERACTION – NEW ZEALAND CASE STUDIES 4

2.4.1 Mangatainoka River 5

2.4.2 Hutt River 6

2.4.3 Waiokura Stream 7

2.4.4 Shag River 9

3.0 SAMPLING REGIME RECOMMENDATIONS **11**

4.0 STUDY SITE **12**

5.0 METHOD **13**

6.0 RESULTS **14**

6.1 GROUNDWATER 14

6.2 RIVER SURVEY 14

7.0 INTERPRETATION AND DISCUSSION **15**

7.1 GROUNDWATER CONTRIBUTION 15

7.2 RIVER SURVEY 15

8.0 CONCLUSIONS AND RECOMMENDATIONS **21**

9.0 REFERENCES **22**

FIGURES

Figure 2.1 Measured flows (red) and radon concentrations (blue) in the Mangatainoka River during low flow conditions (February - March 2015) (Martindale 2015). 5

Figure 2.2 Measured radon concentrations from the low resolution survey in the Hutt River, April 2014: Red-high, yellow-medium, green-low radon concentrations (Martindale et al. 2014). 6

Figure 2.3 Measured radon concentrations in the Waiokura Stream, 2016 (van der Raaij and Martindale 2016), where the radon concentrations are represented by the coloured circles and the asterisks denote the sites where further chemistry and isotope samples were collected. 8

Figure 2.4 Measured radon concentrations, as indicated by the coloured symbols, and flows (m^3s^{-1}) in the Shag River, 2017 (Martindale et al. 2017). 9

Figure 2.5 Range of calculated discharge rates for reach 3 and reach 5 (as designated on Figure 2.4) of the Shag River using different radon groundwater input concentrations. 10

Figure 4.1 Location of the Te Arai River, water quantity zones and GDC monitoring sites. 12

Figure 5.1 Location of the 44 surface water sampling sites and 1 groundwater sampling site, Te Arai River, Gisborne. 13
Figure 6.1 Radon concentration and flow gauging measurements along the approximately 20 km reach of the Te Arai River from samples collected during the 30, 31 January and 1 February, 2018 investigation. 14
Figure 7.1 Small seeps observed (circled) along the river bank in the Te Arai River between sites numbers 4 and 5. 16
Figure 7.2 Measured radon concentrations, in BqL^{-1}, (orange) and electrical conductivity, μScm^{-1}, (blue) in the Te Arai River as well as radon concentrations (grey) and conductivity (yellow) for two tributaries. 17
Figure 7.3 Measured radon concentrations, in BqL^{-1}, (orange) and DO, mgL^{-1}, (blue) in the Te Arai River as well as radon concentrations (silver) and DO (yellow) for two tributaries. 18
Figure 7.4 Measured radon concentrations, in BqL^{-1}, (orange) and temperature, °C, (blue) in the Te Arai River as well as radon concentrations (silver) and temperature (yellow) for two tributaries. 19

APPENDICES

APPENDIX 1: FIELD PARAMETERS AND SAMPLING RESULTS 25
APPENDIX 2: FLOW GAUGING SUMMARY 27

APPENDIX TABLES

Table A 1.1 Summary of location, field parameters, radon concentration, and radon error, for samples collected from a 20 km reach of the Te Arai River investigated in this project. 25
Table A 2.1 Summary of location and flow from the 7 flow gauging sites across a 20 km reach of the Te Arai River investigated in this project. 27

ABSTRACT

Understanding of groundwater - surface water (GW-SW) interaction processes is integral for comprehending the hydrological characteristics of a catchment. Knowledge of the relationship between surface- and ground-water is required for effective management of water resources, such as setting of minimum flow and water allocation limits.

To investigate GW-SW interaction processes, a combined approach of using radon-222 and concurrent stream flow gauging can be used. This report details a study commissioned by Gisborne District Council to assist in planning and interpreting a radon and flow gauging survey in order to investigate GW-SW interaction processes along a 20 km reach of the Te Arai River, Poverty Bay.

The study identified that groundwater discharge occurs along a significant proportion of the 20 km reach. However, in at least two locations the concurrent stream flow gauging appeared to provide contradictory results to radon. This is most likely caused by surface water abstraction for horticultural/agricultural use or parafluvial exchange.

KEYWORDS

Groundwater-surface water interaction, radon, isotope.

1.0 INTRODUCTION

Gisborne District Council (GDC) commissioned GNS Science via an Envirolink grant to assist in the planning and interpretation of a radon and flow gauging survey in order to investigate groundwater-surface water (GW-SW) interaction processes in the Te Arai River, Gisborne. Knowledge of the relationship between surface water and groundwater is required to enable water resources management, such as setting of minimum flow and water allocation limits. The primary purpose of this study was to delineate gaining and losing reaches of the Te Arai River. Improved understanding of flow interactions will input into GDC's policies and procedures on irrigation abstraction from the Te Arai River during sustained low flow periods, and inform minimum flow restrictions to protect in stream habitat.

Over the last five years, GNS Science has been developing an environmental tracer technique, using radon-222 (herein referred to as radon), to improve characterisation of GW-SW interaction. Since refining the laboratory analysis method for measuring radon at GNS Science (Martindale et al. 2014), radon and concurrent stream flow gauging methods have been increasingly used to investigate the location and fluxes of GW-SW interaction in New Zealand rivers (e.g., Martindale et al. 2014; Martindale 2015; Martindale et al. 2016; Martindale et al. 2017).

The project was undertaken in three stages, which are detailed in this report. Stage 1 included a literature review of previous studies which incorporate radon and concurrent flow gauging methods in New Zealand. This stage was developed with the aim to provide GDC with sufficient information to plan a survey of the Te Arai River. Stage 2 was the execution of the radon and concurrent gauging survey of the Te Arai River, which was undertaken by GDC and GNS Science in January and February 2018. In Stage 3, an interpretation and provision of the location and extent of groundwater (GW) discharge along the Te Arai River reach that was surveyed was carried out. This project was funded by an Envirolink Medium Advice Grant, and undertaken in 2017 – 2018. In addition to the Envirolink funding, the cost of the radon sample analysis was predominantly funded by GDC, with GNS Strategic Science Investment Fund (SSIF) also supporting some of the sample collection and analysis cost as the study contributes to technique development.

2.0 LITERATURE REVIEW AND NEW ZEALAND CASE STUDIES

2.1 RADON – WHAT IS IT AND HOW IS IT USED FOR GW-SW INTERACTION STUDIES?

Radon is a soluble, colourless, gaseous, unstable isotope with a half-life of 3.8 days (Cecil and Green 2000). Radon is generated naturally as part of the uranium decay series and is therefore present in most rocks and soils. Radon releases from the aquifer matrix into groundwater, resulting in elevated radon concentrations, but upon entering a river system the radon gas quickly degasses such that surface waters have negligible concentrations of radon (Kies et al. 2005). Surface waters that contain elevated concentrations of radon indicate locations where groundwater is discharging, or has discharged slightly upstream of the sampling site. Radon is therefore a useful tool for identifying where groundwater is being discharged into a river or stream.

Radon concentrations can vary considerably within groundwater systems, and are affected by the uranium content and radon emanation potential of the aquifer material. Generally, geological units with more uranium will result in groundwaters with higher radon concentrations. For example, groundwaters in exchange with quartzite can have radon concentrations of over 900 BqL^{-1}, whereas groundwaters in sands or ignimbrites can have radon concentrations of <3 BqL^{-1} (Cecil and Green 2000). Radon emanation potential can be described as the ease in which the radon can move from the minerals into the water. When the parent material (radium-226) decays from uranium, it emits a radon particle and an alpha particle. This release of energy can cause the radon particle to diffuse out of the rock grain if it is housed close enough to a surface of the material (Cecil and Green 2000). The radon emanation potential of most materials is very low, with a radon emanation coefficient of approximately 0.2 (Nazaroff 1992).

Radon samples can be collected and measured in a number of different ways. However, for large scale surveys in New Zealand, the most efficient method is direct-count liquid scintillation counting (Martindale 2015). This involves collecting two 20 mL grab samples, usually from a location in the middle of the river cross-section, and at the river bed interface. Samples are sent to the GNS Science Water Dating Laboratory, Wellington where they are analysed within 1 – 2 days due to the short half-life of radon. The analysis process involves mixing the water sample with an organic scintillant cocktail, then the decay of radon and its daughter products are measured using low level scintillation counters.

2.2 TECHNIQUES FOR MEASURING GW-SW INTERACTION

At both catchment and individual river reach scale, GW-SW interaction processes can be highly variable and complex. Understanding GW-SW interaction processes is important for water resources management, and there can be large uncertainties in the modelling of catchment systems if these processes are not adequately understood. There are many measurement techniques which have been developed to study how groundwaters and surface waters interact. Examples of several techniques that have been widely used in New Zealand are provided below.

Seepage meters have been widely used to directly capture and measure GW-SW exchange (Rosenberry 2008). In 2005 seepage meters were deployed in parts of Lake Taupo to locate and estimate groundwater flux (Gibbs et al. 2005). The results from individual seepage meters were extrapolated across bays within the lake as only limited spatial data can be obtained from an individual seepage meter. While useful in identifying point source locations of groundwater discharge, the groundwater inflow estimates from this study potentially have very large errors due to the assumed extrapolation. Adding to the potential error, each single point seepage measurement can easily be distorted by currents. Additionally, this method does not differentiate between hyporheic exchange and GW-SW interaction (Kalbus et al. 2006; Murdoch and Kelly, 2003).

Hyporheic exchange, for the purposes of this report, refers to the mixing of surface water with subsurface water in the stream beds and banks. This mixing occurs on a very small scale, i.e., centimetres to tens of centimetres. This subsurface water does not carry the signature of purely groundwater or purely surface water, rather, an intermediary mix. Mixing between the surface water and subsurface water which occurs on a greater scale, e.g., metre to hundreds of metres scale, is classified as parafluvial flow. This typically occurs in course-grained, unconsolidated sediments (Cartwright and Hofmann, 2016),

Hydrochemical tracers are non-conservative tracers which collect their signatures through water-rock interaction (Herczeg and Edmunds 2000), and can be used to determine groundwater and surface water interaction. Chemical parameters used in hydrochemical tracer studies often include (but are not limited to): sodium (Na), silica (SiO_2), electrical conductivity (EC), magnesium (Mg), and other trace elements (e.g., strontium (Sr)) (Kalbus et al. 2006). The hydrochemical tracer method involves comparison between the concentrations of the tracer in groundwater and surface water. Mixing models or mixing ratios are then used to calculate the percentage of groundwater inflow (Katz et al. 1997; Stellato et al. 2013). The hydrochemical tracer method is limited to settings where the tracer in the groundwater is significantly different to that of the receiving surface water. Furthermore, to refine mixing models, more than one tracer is often required. A collection of different parameters and the costs associated with their analysis can render this technique expensive (Kalbus et al. 2006).

Concurrent river flow gauging is frequently used to identify locations of groundwater discharge and recharge within riverine environments throughout New Zealand. Methodology for measurement of concurrent gaugings, including acceptable uncertainty and error, are guided by the National Environmental Monitoring Standards (LAWA 2013). A major limitation of concurrent flow gauging is that the measurement method is time consuming and only captures river flow at a point scale, allowing for changes between a limited number of measurement locations to be obtained. Therefore, information on the physical processes occurring between the measurement locations is unable to be captured (Kalbus et al. 2006). Concurrent flow gauging is also limited to measurement of flow changes that occur above the river- or stream-bed surface (e.g., hyporheic and parafluvial flow processes in the river channel are common, yet unable to be measured). These limitations pose challenges to the accuracy and utility of concurrent flow gauging when used in isolation.

Fibre optic distributed temperature sensing (FODTS) methods are used internationally (e.g., Europe and USA), and have more recently been validated in the New Zealand setting (Moridnejad 2015; Lovett et al. 2014). FODTS methods can be used to infer GW-SW interaction processes at a high spatial (e.g., 1 m) and temporal (e.g., every minute) resolution, over large distances (e.g., 100 m – 5 km). FODTS captures temperature data at a user-defined spatial interval along the length of a fibre optic cable (Moridnejad 2015). FODTS has been found to be most suitable to settings where there is a sufficient temperature difference between the discharging groundwater and the receiving surface water. In a temperate climate such as New Zealand, FODTS is generally most effective during the summer (when surface waters are comparatively warmer), or during winter (when surface waters are comparatively cooler than groundwater). Measurement of the temperature difference using FODTS can be influenced by environmental conditions, such as wind, turbidity and landscape features (e.g., shadows cast by vegetation), particularly if the river is shallow (Johnson 2003). Although FODTS is suitable for collection of high resolution data, there are several logistical considerations regarding the reach length, river morphology, and deployment methods. FODTS is generally better suited to targeted deployments of 500 m to 2,000 m, potentially identified as the result of a radon survey, rather than an initial large scale deployment to identify whether GW-SW interaction is occurring.

2.3 ADVANTAGES AND LIMITATIONS OF USING RADON FOR IDENTIFYING GW-SW INTERACTION

The short half-life of radon, its low solubility and the large difference between radon concentrations in groundwater and surface waters, provide radon many advantageous properties for GW–SW interaction investigations. For example, the naturally occurring gradient between the concentration of radon in surface water and groundwater, makes radon a more versatile tool compared to methods such as FODTS, where temperature gradients are not always present or large enough to be determined. Furthermore, radon concentration measurements are exclusive of water from rainfall and surface runoff as both of these inputs contain negligible concentrations of radon (Cook et al. 2008). In addition, the solubility of radon gas makes it an ideal tracer to measure short term temporal variations because any radon measured will not be from historical groundwater discharge as the radon will quickly de-gas when it is discharged to the surface. Thus, unlike flow gauging and other hydrochemical parameters, the exact locations or sources of the groundwater discharge can be captured using radon methods. Another advantageous attribute of radon measurement is that radon is inert, therefore it cannot be chemically or biogenically altered between its emanation and measurement.

Radon, like all tracers for measuring GW-SW interaction, has several limitations. Rainfall or increased river or stream flow can swamp the radon signature in surface water. Therefore, radon sampling is recommended to be undertaken when the river or stream is under low-flow conditions, and during a period without rainfall. It can also be difficult to distinguish whether small increases in radon concentrations are caused by low-volume groundwater seepage, or from parafluvial flow (Cartwright and Hofmann 2016, Martindale et al. 2016; Martindale et al. 2017). Furthermore, radon measurements alone can only show relative, qualitative changes in concentration. Quantifying discharge rates using radon in isolation is not possible, and requires additional information on the river conditions and applying this to a ‘box model’ approach. Another consideration is that radon concentrations are also a function of the geology from which they were produced, as described in section 2.1. Therefore, if there are geological changes within the survey area, the groundwater concentration of radon can differ considerably.

2.4 COMBINING RADON SURVEYS AND STREAM FLOW GAUGING TO INVESTIGATE GW-SW INTERACTION – NEW ZEALAND CASE STUDIES

Combining data from large scale radon surveys with a small number of stream flow gauging measurements can provide high resolution spatial knowledge of groundwater discharge locations. Flow gauging measurements provide quantitative values to give the radon measurements context, and have been shown to enable quantification of groundwater discharging into rivers using measured radon data (Cartwright and Hofman 2016; Martindale et al. 2017). Since 2014, several combined radon and flow gauging surveys have been undertaken in New Zealand to obtain detailed information and quantify groundwater discharge into rivers. While this combined technique has been applied for decades internationally

(Hammond et al. 1977; Cook et al. 2003; Cartwright and Hofmann 2016), this methodology has only recently been applied in New Zealand. Four New Zealand case studies where combined radon and flow gauging methods have been used simultaneously are described below.

2.4.1 Mangatainoka River

A radon and flow gauging survey was undertaken in the Mangatainoka River during February and March 2015 for Horizons Regional Council (HRC). Prior to the study, very little was known about the hydrological processes in the catchment and river system (Rawlinson and Begg 2014). HRC studies had determined that nutrients, in particular soluble inorganic nitrogen, were entering the river system, predominantly through GW discharge as opposed to point source inputs (McArthur and Clark 2007). With the Mangatainoka River quality in decline, substantially reduced fish stock over the past 20 years and increasing cyanobacteria growth, the radon survey was conducted to determine where the excess nutrient loads were entering the river from the GW system.

A combined radon and flow gauging survey was carried out along an approximately 70 km reach (45 Euclidean km) of the Mangatainoka River, over two days. Radon samples were collected at 500 m – 800 m intervals, and 20 flow measurements were recorded (Figure 2.1). Groundwater samples were collected from two adjacent wells, and were also measured for radon to identify the baseline groundwater concentration.

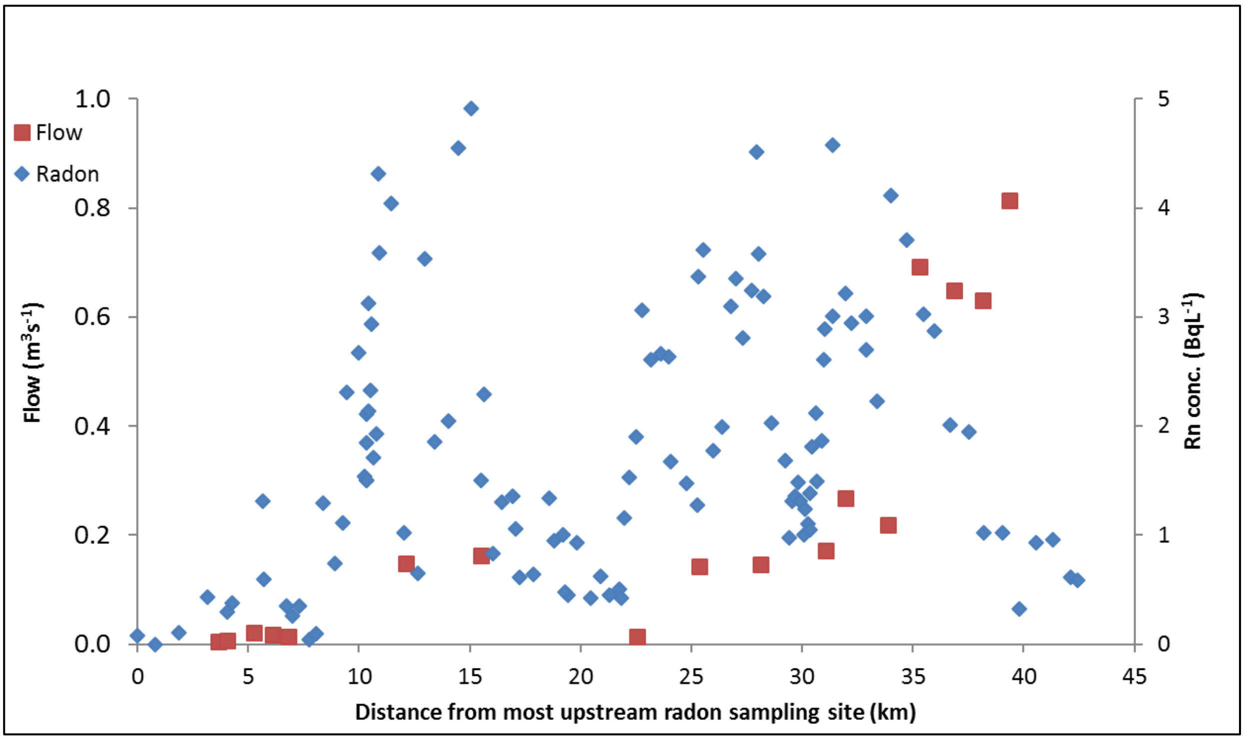

Figure 2.1 Measured flows (red) and radon concentrations (blue) in the Mangatainoka River during low flow conditions (February - March 2015) (Martindale 2015).

Results of the investigation highlighted the limitations of using flow gauging data alone to assess river gains and losses (Martindale et al. 2016). Flow gauging showed only the net gain or loss between gauging sites and did not capture any GW-SW interactions that occurred between the two gauging sites. The radon data enabled a much more detailed understanding of the groundwater to surface water exchange processes occurring within the Mangatainoka River to be captured in comparison to the flow gauging data alone. In addition, higher resolution flow gauging may further reduce the differences observed in discharge patterns between the two techniques. However, radon sampling was much quicker to achieve at a higher spatial resolution than flow gauging. Furthermore, underflow beneath the gravels and other parafluvial exchange processes have been identified as likely occurring in the Mangatainoka River, and can give ambiguous flow gauging results (Martindale et al. 2016).

2.4.2 Hutt River

The Hutt River, northeast of Wellington, was investigated using radon and flow gauging over the summers of 2014 and 2015, under low flow conditions of approximately 4 $m^3 s^{-1}$. Two initial low resolution radon surveys were undertaken that informed a follow-on high resolution survey.

The low resolution surveys were undertaken in April 2014 and January 2015. Two surveys were conducted to confirm whether the groundwater discharge patterns remained the same between low flow periods. For the low resolution surveys, samples were collected every 500 – 800 m, along a 16 km reach of the Hutt River. Kayaks were used to allow a team of two people to cover the 16 km sampling reach in one day. Greater Wellington Regional Council run permanent gauging stations were initially used to measure flow. In addition, nine groundwater samples were collected from the Hutt River catchment as part of the radon analysis in this study.

Once the low-resolution sampling had been used to identify reaches of the Hutt River where groundwater was being discharged (Figure 2.2), higher resolution radon sampling was undertaken in January 2015 at a resolution of 50 m between samples. In addition, flow gauging measurements were undertaken to investigate the areas of discharge in more detail. Radon profiles across the river width were also taken at three different locations where it was understood that groundwater was being discharged. At the cross-sections, radon samples were taken at approximately 2 m intervals. High resolution sampling was also undertaken below a weir, at which point the bedrock geology of the river dictates that a negligible amount of groundwater could be recharged or discharged. This river morphology allowed for the rate of radon degassing from the surface water to be calculated. Knowledge of the degassing rate allows for more certainty in the interpretation between two adjacent radon sites i.e., it identifies whether the radon measured in a downstream sampling point is actually from groundwater discharge or whether it is residual radon from the adjacent upstream sampling point.

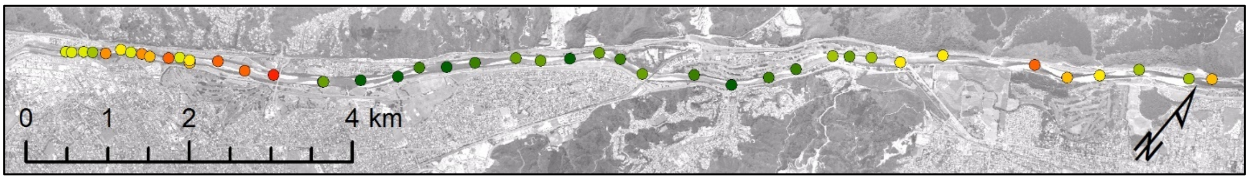

Figure 2.2 Measured radon concentrations from the low resolution survey in the Hutt River, April 2014: Red-high, yellow-medium, green-low radon concentrations (Martindale et al. 2014).

The river cross-section sampling showed that in the Hutt River, groundwater is being discharged predominantly from the true left river bank. This is likely a function of local geology, as the gravels found on the true left abruptly end on the right side of the river where bedrock has been uplifted along the fault line (Boon et al. 2011; Martindale 2015).

High resolution radon sampling and flow gauging along the Hutt River identified that in most instances where high radon concentrations were observed, the gauged discharge increased. However, there were a few instances where discharge decreased where there were increases in radon concentrations. The disparity between results was predominantly observed near meanders, and was interpreted to be due to the effects of parafluvial flow (e.g., water flowing beneath the surface of the exposed part of the gravel river bed meander) (Martindale et al. 2016). Measured degassing rates downstream of the weir support this hypothesis, but no further validation has been undertaken to date.

Overall, the Hutt River case study demonstrated that radon measurements were useful in helping to assess GW-SW interactions at a much more detailed scale than using flow gauging method independently. The radon survey provided a complementary, cost-effective tool to combine with flow gauging to get a more comprehensive picture of the GW-SW interaction processes in the Hutt River.

2.4.3 Waiokura Stream

In 2016 a collaborative project between GNS Science and Taranaki Regional Council combined a survey of radon and hydrochemical tracers. The aim of the study was to increase the understanding of nutrient loads from groundwater reaching the spring-fed Waiokura Stream (van der Raaij and Martindale 2016). The project aimed to help resolve the differing flow paths and origin of water and contaminants by sampling, analysis, and interpretation of a targeted suite of hydrochemical and isotopic tracers.

In the first phase of this project, 29 radon samples were collected over an approximate 18 km reach of the Waiokura Stream (Figure 2.3). A single flow measurement was taken in the reach surveyed. Eight sites (denoted with an asterisks on Figure 2.3), which had previously indicated higher radon concentrations and therefore suggested groundwater discharge was occurring, were sampled for stable isotopes (e.g., $\delta^{18}O$ and $\delta^{2}H$ of H_2O, $\delta^{15}N$ and $\delta^{18}O$ of NO_3-N), hydrochemistry (Cl, Br, Na, Ca, Mg, K, alkalinity, DOC, SO_4, N, P, and SiO_2), and age tracers (tritium, CFCs, and SF_6). Seven groundwater wells within the catchment were also sampled for these tracers for comparison (van der Raaij and Martindale 2016).

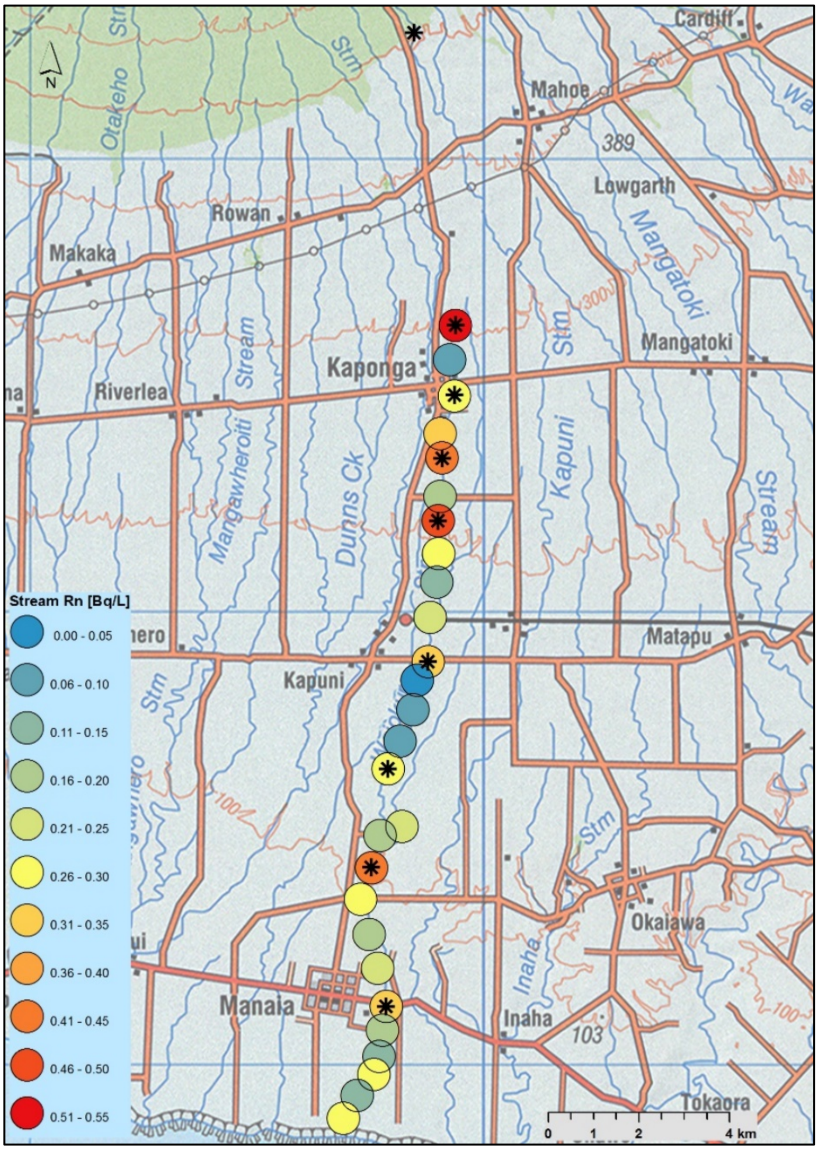

Figure 2.3 Measured radon concentrations in the Waiokura Stream, 2016 (van der Raaij and Martindale 2016), where the radon concentrations are represented by the coloured circles and the asterisks denote the sites where further chemistry and isotope samples were collected.

The Waiokura Stream study results identified clear differences between the surface water and the eight sites in the stream where radon identified groundwater discharge to be occurring. The mean age of the water being discharged into the stream ranged from 6 to 14 years. The nitrate isotope testing identified different sources of nitrate discharging into the stream within the measured stream profile (van der Raaij and Martindale 2016).

Chemistry data for the Waiokura Stream and nearby groundwater system indicated the influence of groundwater evolution and water-rock interaction, as well as an influence from land-surface inputs (van der Raaij and Martindale 2016). Application of hierarchical cluster analysis (HCA) identified that relationships were present between the upper reach stream water and groundwater, and the lower reach stream water and groundwater.

This multifaceted study provided a good indication of where groundwater was entering the Waiokura Stream, the composition of the groundwater entering the stream, and the likely source of that groundwater. However, only one gauging measurement was taken during the study. In future studies, additional flow gauging measurements are required to allow for estimates of the proportion of the different sources of groundwater being discharged.

2.4.4 Shag River

An investigation of the GW-SW water dynamics in the Shag River, North Otago, was completed by GNS Science in collaboration with Otago Regional Council (ORC) in 2017 (Martindale et al. 2017).

The field site was a 16 km reach of the Shag River where GW-SW interaction was understood to be occurring. Fieldwork was undertaken in February 2017, under low flow conditions of approximately 0.3 $m^3 s^{-1}$. A total of 27 radon samples were collected at a resolution of 400 – 600 m, and stream flow was measured at 7 concurrent sites. The radon sampling was carried out on foot, by walking through the river, as large parts of the river were too shallow for kayaks or boats to be used. Two groundwater samples were collected from shallow bores to measure the radon concentration. In March 2017, higher resolution radon sampling, at a spatial interval of 200 m, was undertaken in three 1.5 – 2.0 km reaches of the Shag River previously sampled in February. One additional radon sample was collected from a piezometer penetrating shallow groundwater in March 2017.

Results from the initial radon and flow gauging survey allowed identification of reaches where groundwater was being discharged in the Shag River (Figure 2.4). Radon data provided much more detailed information about the groundwater discharge patterns than flow gauging alone. For example, along reach 3 (1.8 km, Figure 2.4) a substantial increase in flow was measured. However, radon concentrations indicated that groundwater discharge was only occurring over a 500 m section of the 1.8 km reach.

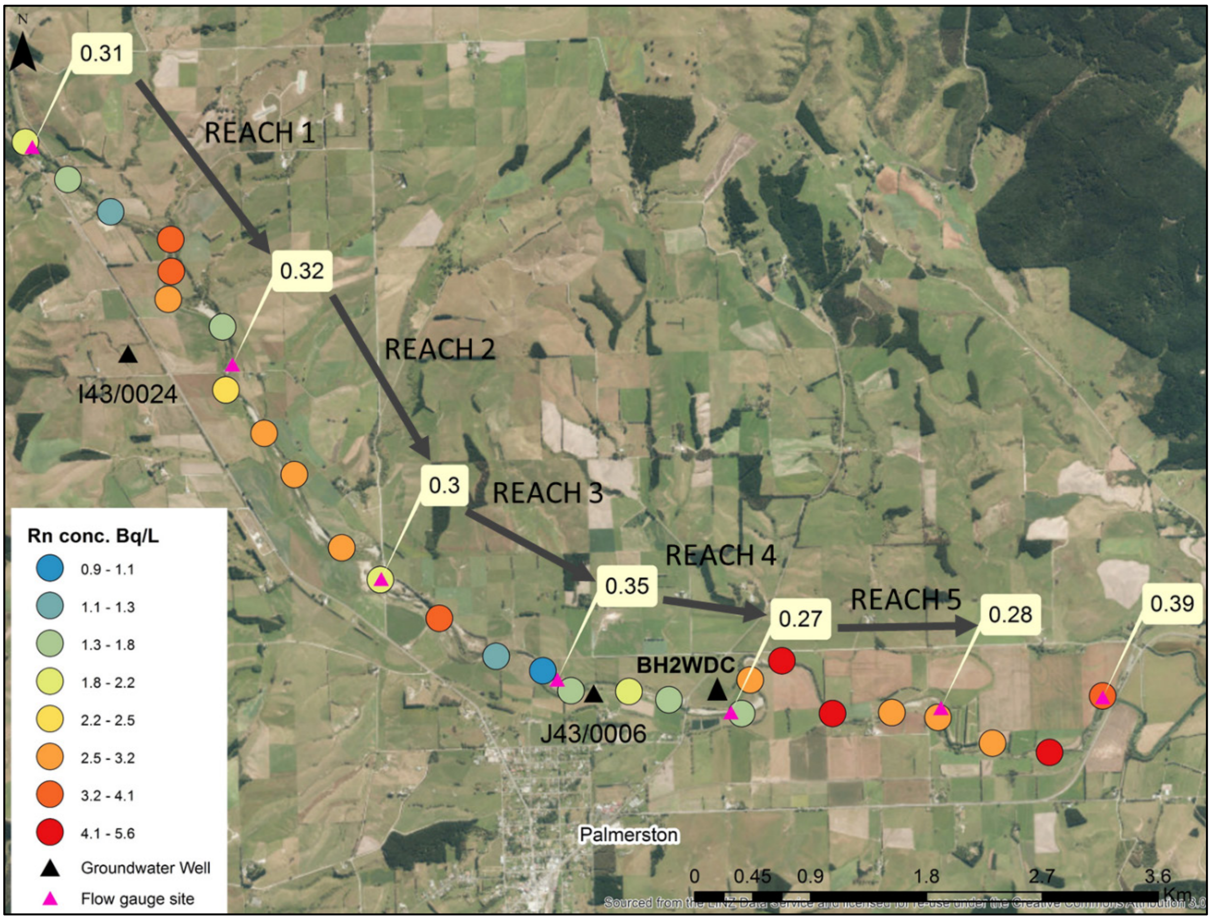

Figure 2.4 Measured radon concentrations, as indicated by the coloured symbols, and flows (m^3s^{-1}) in the Shag River, 2017 (Martindale et al. 2017).

Analogous to the Hutt and Mangatainoka River case studies, river reaches in the Shag River where the radon concentration and flow gauging data provided contradictory results in the groundwater discharge patterns, were observed (i.e., reach 2, Figure 2.4). In this instance, the discrepancy between methods was either due to parafluvial flow, low-discharge groundwater seepage, or a combination of the two processes.

Groundwater radon concentrations were variable along the Shag River reach, and ranged between 14 BqL^{-1}, 16 BqL^{-1} and 179 BqL^{-1}. This large difference in concentration was not observed in the previous studies in the Mangatainako River, Hutt River, and Waiokura Stream, as described previously in this report. A further observation, not seen in the previous studies, was that the reach with the highest measured radon concentrations only had a small increase in measured flow. To better understand these observations, a secondary, (experimental) study was undertaken. In addition to further high-resolution radon sampling, the radon data was applied to a mass-balance approach for quantifying groundwater flux to the gaining reaches, and to one reach where the radon and flow gauging results were inconsistent with one another. To express the uncertainty associated with the input variables in the mass balance model, a Monte-Carlo statistical sampling approach was applied.

The results of the Monte-Carlo statistical analysis, as well as additional sampling, identified two different groundwater systems with different radon signatures that were likely discharging into the river (Figure 2.5).

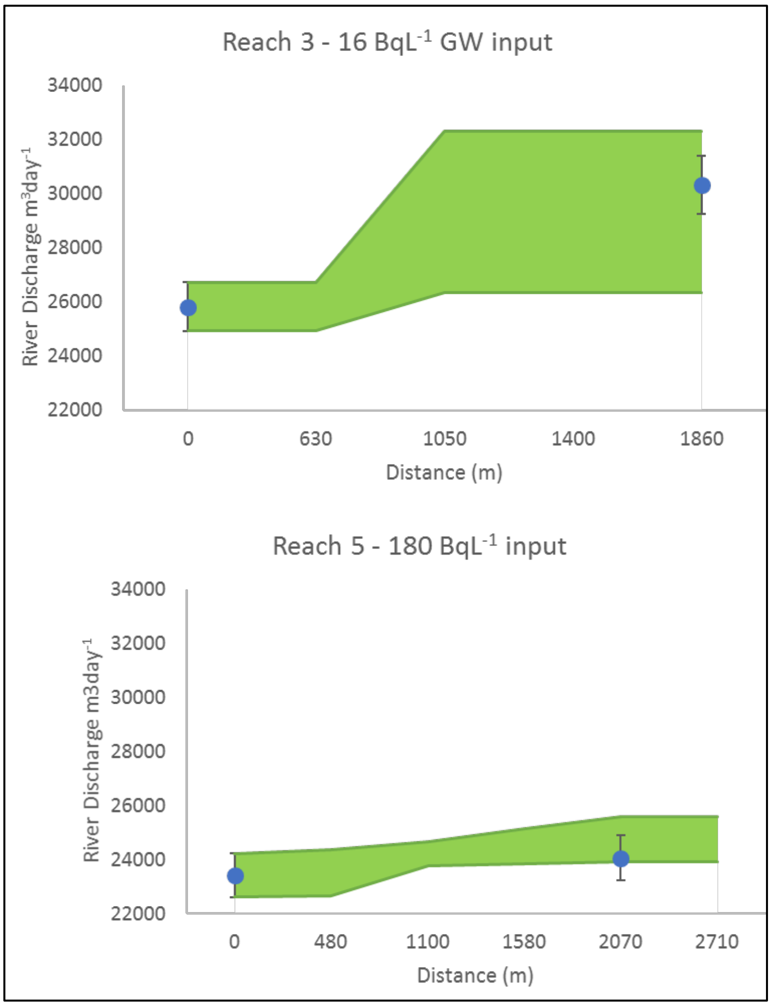

Figure 2.5 Range of calculated discharge rates for reach 3 and reach 5 (as designated on Figure 2.4) of the Shag River using different radon groundwater input concentrations. The measured gauged flows are also graphed (blue symbols) (Martindale et al. 2017).

3.0 SAMPLING REGIME RECOMMENDATIONS

The initial sampling recommendations for the Te Arai River sampling survey are outlined below. These recommendations are based on information of the Te Arai River provided by GDC and the previous studies outlined in this section of the report:

- Radon sampling must be carried out under low-flow conditions. Sampling under higher flow conditions or during a rainfall event will significantly reduce the quality and usefulness of the survey results.
- Radon sampling resolution should be carried out a minimum of approximately 500 m intervals. Exact distances between sampling points will vary depending on the nature of the river morphology. There is a relationship between radon degassing rates, river water depth and river velocity. High rates of degassing are expected in the Te Arai River where the river depth is shallow. Where the river depth is deep, the flow is very slow and de-gassing rates are likely to be much lower. Due to these flow characteristics a high sampling resolution, similar to that of the Shag River, is required.
- Concurrent stream flow gauging provides quantifiable values for radon interpretation. Preferably, stream gauging would be carried out at a minimum of 7 – 8 sites along the Te Arai River reach (not including gauging of contributing tributaries).
- There should be a minimum of five stream gauging sites between Pykes Weir and Whakatere Road, as well as gauging of the contribution from the Waimata Stream at the confluence, unless this runs dry in summer, as this reach seems to be the main focus of the study.
- The radon and flow gauging survey should be carried out on the same day(s) to ensure the flow conditions are the same for both measurements.

4.0 STUDY SITE

The Te Arai River is located in the Poverty Bay Region, to the southwest of Gisborne (Figure 4.1). The river lies within predominantly mudstone and sandstones from the Tolaga Group formation. Within the Lower Water Quantity Zone (LWQZ) of the Te Arai River there are Holocene, gravel, river deposits, which overlay the mudstone (Mazengarb and Speden, 2000). The Te Arai River flows north from its headwaters in native forest hill country, the Upper Water Quantity Zone (UWQZ) and then to a north easterly direction through neighbouring agricultural and horticultural land use in the LWQZ to the confluence with the Waipaoa River. The Gisborne municipal water supply is collected from the Te Arai River in the UWQZ. Downstream in the LWQZ there are 7 consented water takes which are subject to low flow restrictions. The area of focus for this study is in the LWQZ.

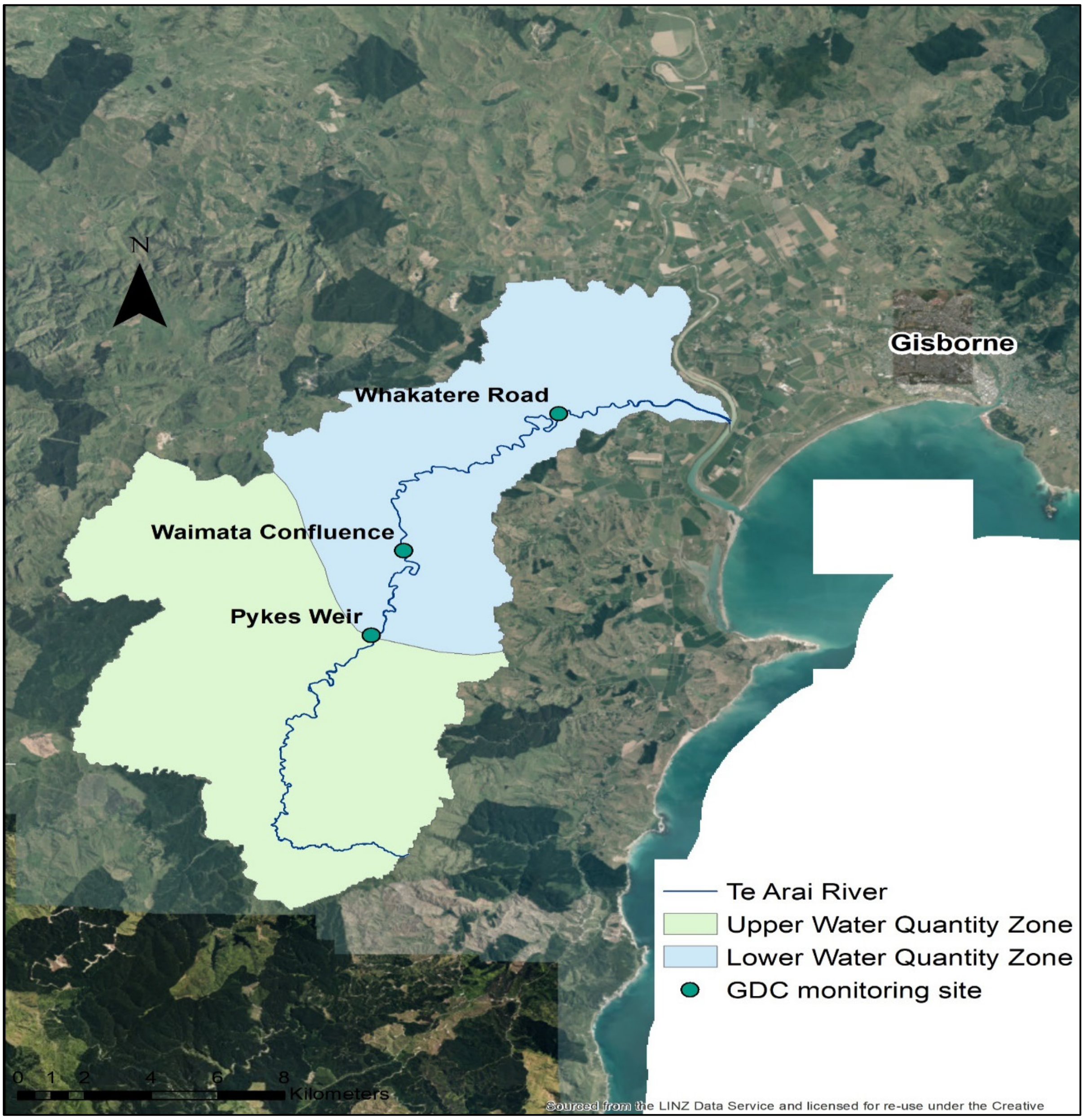

Figure 4.1 Location of the Te Arai River, water quantity zones and GDC monitoring sites.

5.0 METHOD

During the investigation, water samples and field variables were collected from a total of 44 surface water sites, on January 30, 31 and February 1, and one groundwater site, on January 16, along the 20 km reach of the Te Arai River (Figure 5.1). Samples were collected at suitable locations (e.g., accessible, upstream of riffles) at approximately 500 m intervals along the river. In addition, field parameters including conductivity, temperature, and dissolved oxygen (DO) were collected at each sampling site (Appendix 1). Seven concurrent stream flow measurements were carried out by GDC staff along the surveyed reach of river, while the radon samples were being collected (Appendix 2).

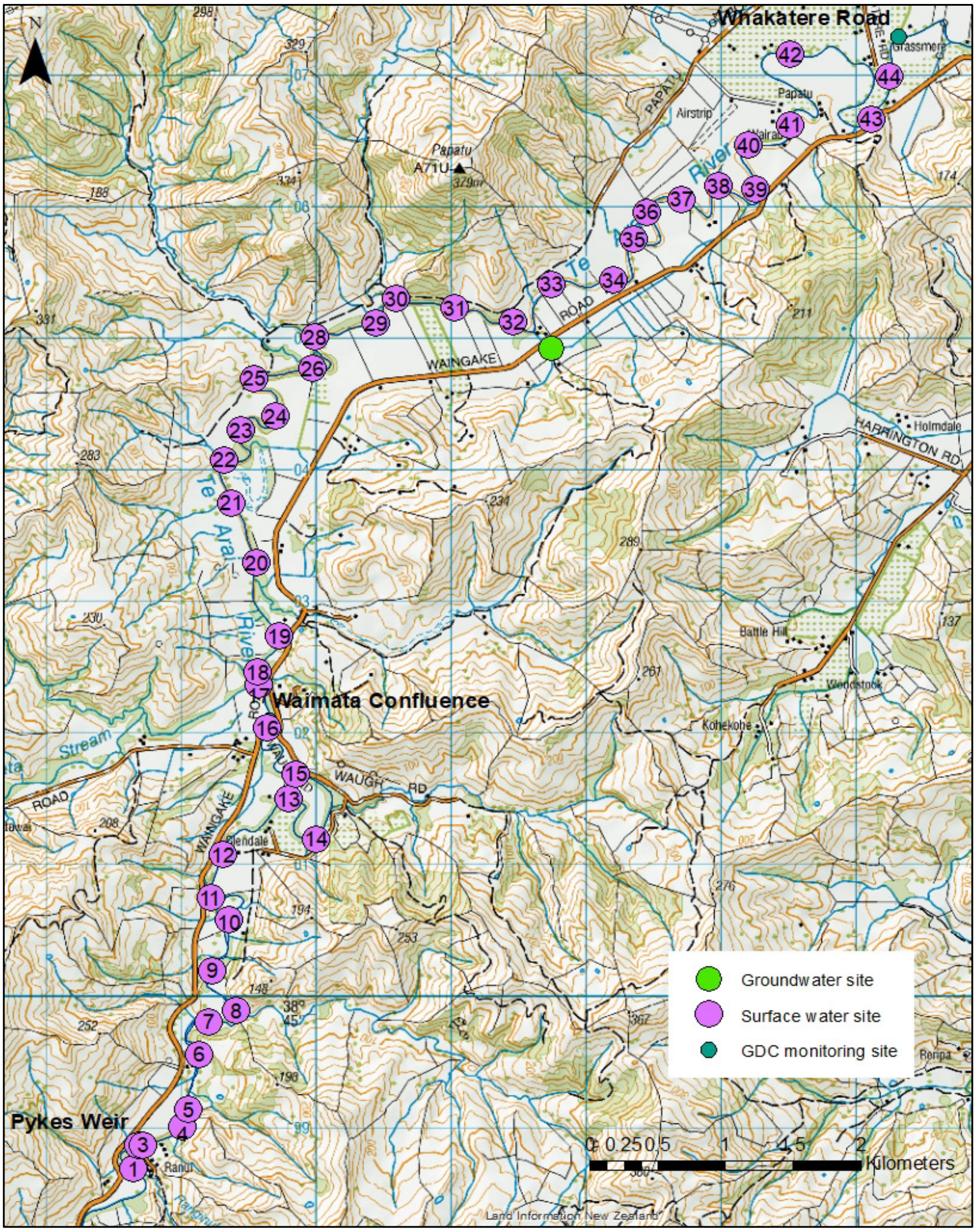

Figure 5.1 Location of the 44 surface water sampling sites and 1 groundwater sampling site, Te Arai River, Gisborne. The numbers refer to the surface water sampling site ID.

6.0 RESULTS

6.1 GROUNDWATER

Only one groundwater radon sample from a nearby shallow well (5 m deep) was taken, due to low groundwater levels at the time. The radon concentration of 17.9 BqL^{-1} is within the expected range of mudstone, sandstone and gravels (Cecil and Green, 2000).

6.2 RIVER SURVEY

Radon concentrations along the investigated Te Arai River ranged from below the detection limit (0.1 BqL^{-1}) to a maximum of 0.9 BqL^{-1} (Figure 6.1; Appendix 1). Overall, electrical conductivity (EC) increased gradually, from 425 μScm^{-1}, as the river flowed downstream, to 588 μScm-1 at the end of the sampled reach. Larger step wise increases of EC were observed between sample sites 14 and 15 (with an increase of 18 μScm^{-1}) and after the Waimata confluence (with an increase of 32 μScm^{-1}). An EC of 746 μScm^{-1} was observed in a small tributary at site 28. DO was variable along the reach and ranged from a minimum of 4.5 mgL^{-1} to a maximum of 10.1 mgL^{-1} (Appendix 1). Water temperatures of between 22.9 – 27.8°C were recorded and one tributary had an observed temperature of 19.9°C.

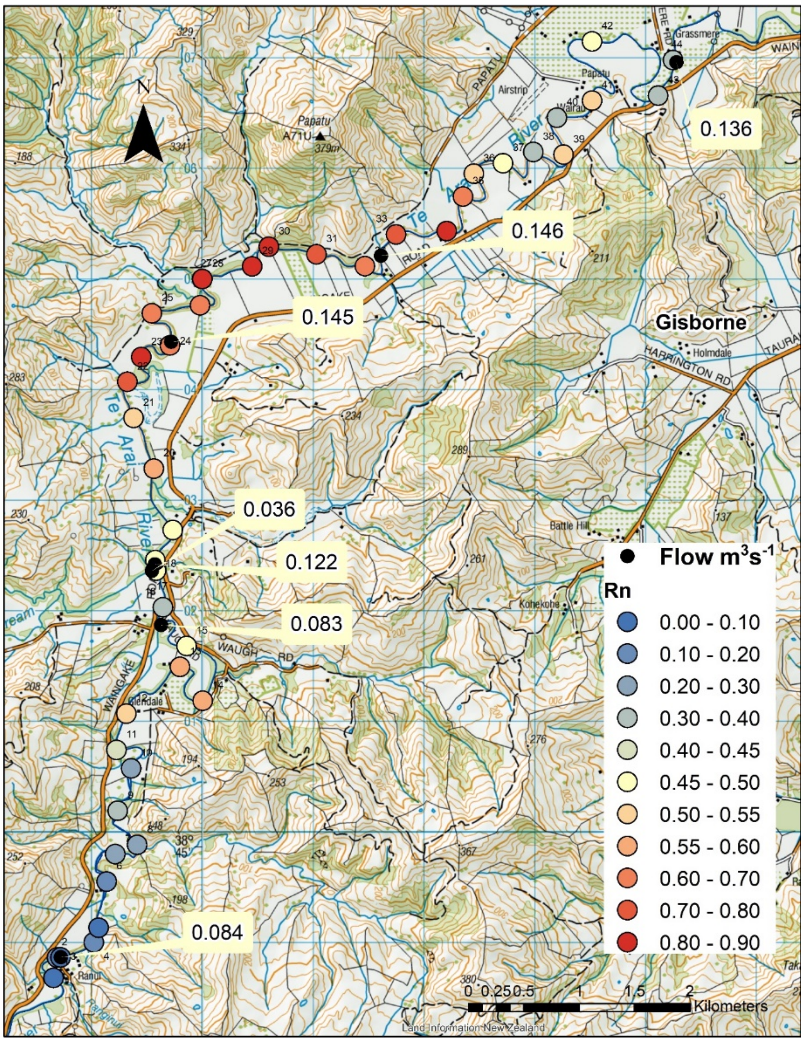

Figure 6.1 Radon concentration and flow gauging measurements along the approximately 20 km reach of the Te Arai River from samples collected during the 30, 31 January and 1 February, 2018 investigation. The radon concentrations are represented by the coloured circles and the flows are written on the figure in m^3s^{-1}.

7.0 INTERPRETATION AND DISCUSSION

7.1 GROUNDWATER CONTRIBUTION

Only one groundwater radon sample was taken. Similar concentrations of radon in groundwater have been measured on the boundary of Holocene gravels and Tolaga Group mudstone in the Gisborne District in 2017 (van der Raaij, 2018). However, it cannot be said with any certainty that this one measured sample is representative of the concentration of radon entering the Te Arai River from the groundwater system across the entire surveyed area.

7.2 RIVER SURVEY

The 44 radon samples taken from the Te Arai River ranged in concentration from 0.1 BqL^{-1} to 0.9 BqL^{-1}. In comparison to other studies conducted in New Zealand, the higher concentrations of radon observed in the Te Arai River are relatively low. These comparatively low concentrations are likely due to: increased degassing due to a large amount of debris (willows etc) creating additional riffles in the river system; the radon concentration of the groundwater actually entering the river is lower than that measured from the one groundwater sample; the presence of many deep, almost stagnant pools resulting in the radon either being strongly diluted or decayed before the next sampling site; and/or a poor connection of the river system with the parafluvial/hyporheic zone due to the low permeability of the sand/mudstone in the river. The hyporheic zone is generally defined as flow that occurs on the scale of centimetres to tens of centimetres in the stream bed and banks, whereas parafluvial flow refers to flow that occurs on the metre to hundreds of metres scale, typically in course-grained, unconsolidated sediments (Cartwright and Hofmann, 2016), whereas the Te Arai river bed predominantly consisted of finer grained gravels and mudstones. In this report radon concentrations are interpreted quantitatively, taking into account the groundwater concentrations, observed river conditions, dissolved oxygen, and river temperature. A quantitative assessment, using a mass balance approach, will be supplied to GDC in a separate report as part of an independent GNS Science funded study to which GDC have contributed their Te Arai River results.

Radon sampling began approximately 350 m upstream of Pykes Weir (Figure 4.1), where the most upstream concurrent stream flow gauging was taken. Very low to negligible concentrations of radon were observed in the grab sample measurement between this initial sampling site and approximately 3500 km downstream, indicating no groundwater discharge to the river through this reach. Small, shallow, seeps through the river banks were observed while sampling (Figure 7.1). However, their contribution to radon concentrations measured in the river were negligible.

Figure 7.1 Small seeps observed (circled) along the river bank in the Te Arai River between sites numbers 4 and 5.

Between sites 11 and 15 radon concentrations increased to 0.6 BqL^{-1}, which strongly indicated groundwater discharge. Downstream of site 15 the measured flow remained at 0.083 m^3s^{-1}, which was the observed flow at Pykes Weir. While sampling, a water take from the Te Arai River was observed between sites 12 and 13 (likely to be the LeaderBrands consented mobile take). This further supports the radon findings that groundwater discharge is occurring between sites 11 and 15, as opposed to other flow processes such as parafluvial flow. Otherwise, a loss in flow, due to the abstraction from the river, would have been observed downstream of site 15.

Between sites 16 and 18 there is a significant increase in conductivity of 32 μScm^{-1} (Figure 7.2). This is likely caused by the contribution from the Waimate Stream (site 17). Radon concentrations are relatively constant from site 16 through to site 21 and likely indicating the occurrence of groundwater discharge along this reach.

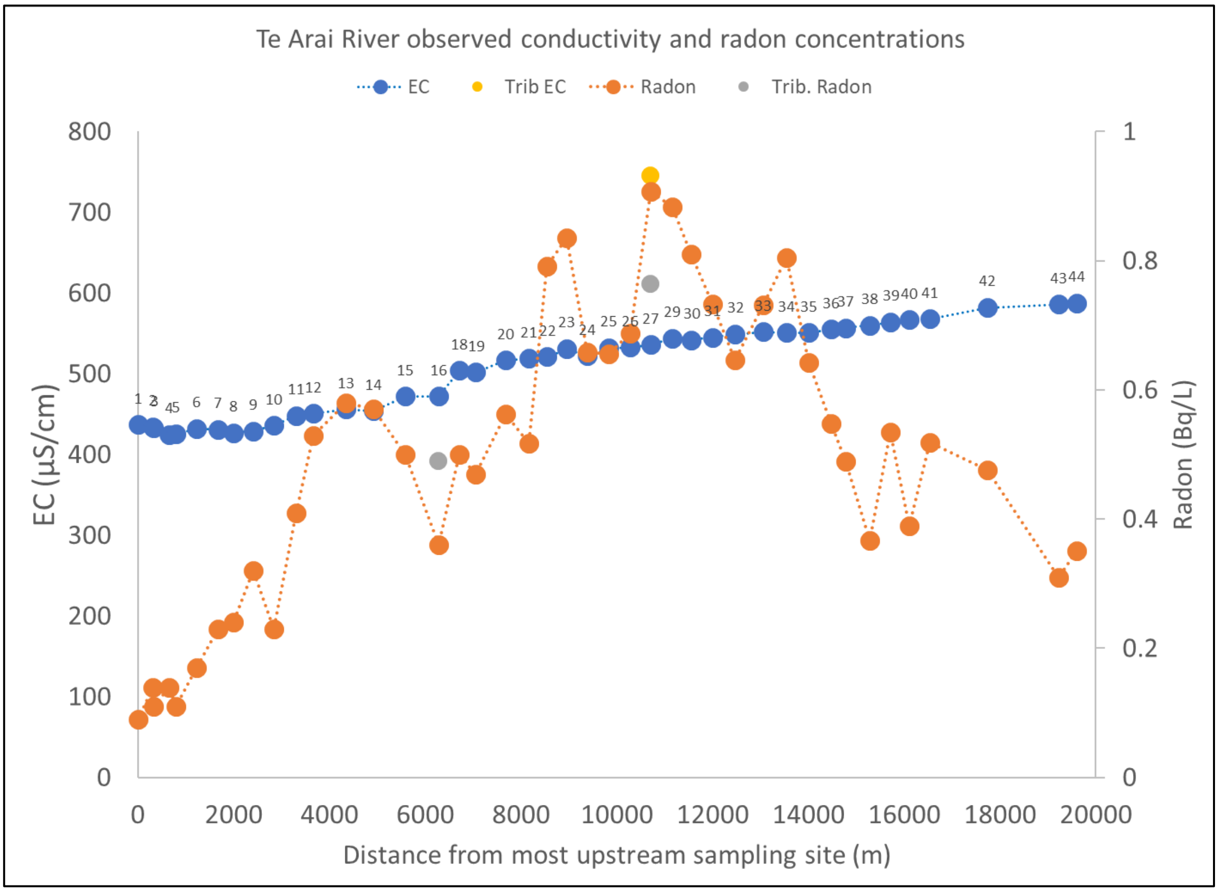

Figure 7.2 Measured radon concentrations, in BqL^{-1}, (orange) and electrical conductivity, µScm^{-1}, (blue) in the Te Arai River as well as radon concentrations (grey) and conductivity (yellow) for two tributaries. The site numbers are labelled above each electrical conductivity measurement.

Radon concentrations significantly increase between sites 21 and 23, strongly indicating a reach of groundwater discharge. Flow gauging provides further evidence of groundwater discharge through this reach; at site 24 a concurrent stream flow measurement was taken and showed that the river flow had increased by approximately 20% from the upstream measurement near site 18. The radon measured at site 24 itself however, is likely an artefact of groundwater discharge occurring upstream at site 23, rather than a continuation of the gaining reach. DO also decreases between sites 22 and 24 from 5.31 mgL^{-1} to 4.62 mgL^{-1} (Figure 7.3). While this may support the radon and concurrent stream gauging findings that groundwater is being discharged, conclusions drawn from in field DO and temperature measurements must be analysed with some degree of scepticism. DO and temperature observations can be greatly influenced by in-stream features such as vegetation cover, riffles and the ambient air temperature.

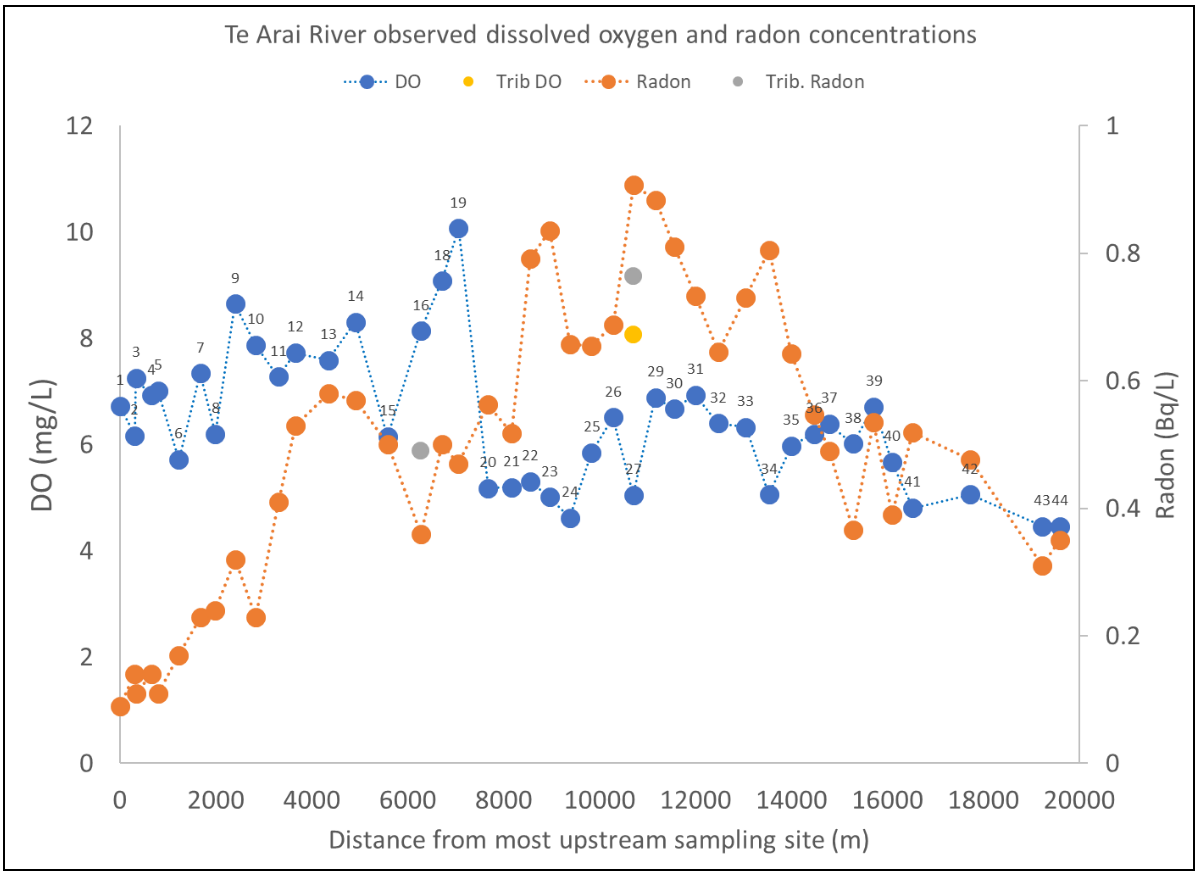

Figure 7.3 Measured radon concentrations, in BqL^{-1}, (orange) and DO, mgL^{-1}, (blue) in the Te Arai River as well as radon concentrations (silver) and DO (yellow) for two tributaries. The site numbers are labelled above each DO measurement.

Radon concentrations remain relatively high from site 26 through to site 29, ranging from 0.6 BqL^{-1} to 0.9 BqL^{-1}, indicating that between these sites there is an approximately 1 km reach where groundwater discharge is occurring. The highest radon measurement of the survey (0.9 BqL^{-1}) occurred at sites 28 (a tributary) and 29. The tributary was 4.7 °C, colder than the Te Arai River (Figure 7.4), and had much higher conductivity of 746 μScm^{-1}. The visibly higher flow of the tributary and lower depth, resulting in higher radon degassing rates relative to the Te Arai River, coupled with the high radon measurement observed, strongly indicates that this tributary is groundwater fed. Groundwater discharge appears to continue through to site 29, after which radon concentrations decline because of degassing.

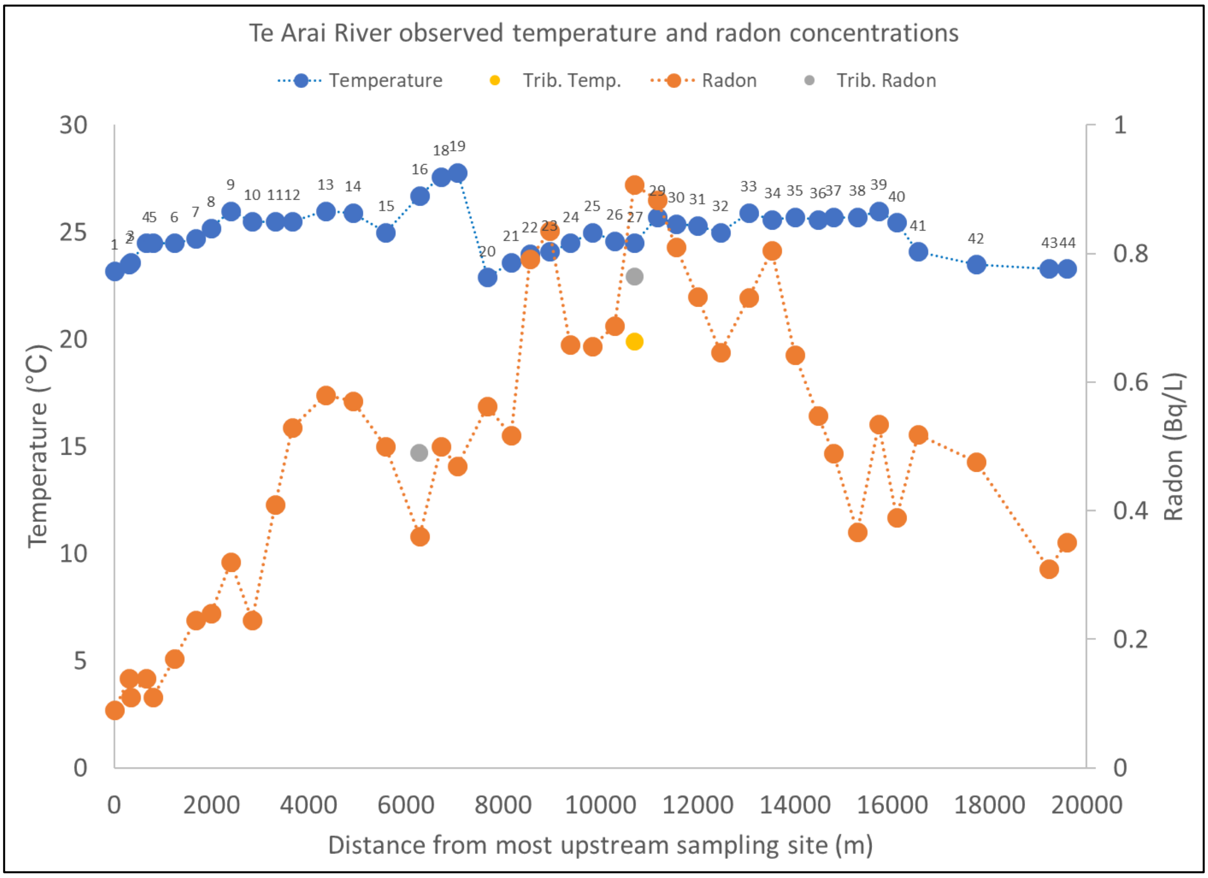

Figure 7.4 Measured radon concentrations, in BqL^{-1}, (orange) and temperature, °C, (blue) in the Te Arai River as well as radon concentrations (silver) and temperature (yellow) for two tributaries. The site numbers are labelled above each temperature measurement.

Downstream of site 29 through to site 32 radon concentrations decrease from 0.9 BqL^{-1} to 0.6 BqL^{-1}. The radon concentrations observed at sites 30 – 32 are likely to be residual radon carried through from the upstream area, rather than continued groundwater discharge. However, degassing rates of radon need to be investigated in more detail to confirm this.

Downstream of site 32 another concurrent stream flow measurement was taken. The flow measurement here was 0.146 m^{3}s^{-1}, the same as measured upstream at site 18. This flow measurement is contradictory to the groundwater discharge patterns observed by the measured radon concentrations. There are several possible reasons why these two methods for investigating groundwater-surface water interaction do not correlate. The most likely reason is that abstraction from the river through the consented LeaderBrands or DeCosta Enterprises Mobile takes is occurring between the concurrent stream gaugings. Unfortunately, daily records of actual takes were not available for the sampling period.

Another possible reason for the discrepancy between the radon and measured flow data could be due to streamflow loss to the groundwater system or parafluvial flow, i.e., under flow beneath the river bed/gravels. The majority of the reach between sites 22 – 36 consisted of large, deep, slow flowing pools, with soft mud/clay river bed lithology. However, between sites 30 – 32 the river bed was often overlaid with gravels and had shallower, fast(er) flowing riffles, which provides favourable conditions for parafluvial exchange to occur. Furthermore, this flow measurement was taken approximately 100 m downstream of a meander. Meanders are also a strong driver of parafluvial exchange. Another factor to consider for the discrepancy between the radon and flow measurement results is the uncertainty associated with the flow measurements. Due to the extent of the reach in which radon indicates groundwater discharge, it is highly unlikely that this is the sole cause for the discrepancy. However, it should be acknowledged as a possible contributing factor.

Observed radon concentrations between sites 33 and 35 indicate that groundwater discharge is occurring along this reach. Radon concentrations then reduce between sites 36 to 38 indicating a reach of no discharge. The observed radon concentrations ranged between 0.4 to 0.5 BqL^{-1} between sites 39 and 42. This may be due to a number of scenarios: 1) that some groundwater discharge is occurring but not to the same extent as in the reach between sites 26 – 29; 2) that the groundwater discharge is the same or greater than at sites 26 – 29 due to groundwater with a lower radon concentration being inputted into the river, and/or 3), that the groundwater signal is diluted due to discharge of the groundwater into deeper pools resulting in greater dilution of the radon.

The radon concentration for the last two measured sites, 43 and 44, indicate a reach of no groundwater discharge. The measured flow at site 44 is lower, at 0.136 m^3s^{-1}, but within the range of uncertainty in comparison to the flow measured at site 32. There is potential, as described previously, that these reaches of no groundwater discharge could be losing reaches. However, these cannot be identified using radon measurements

8.0 CONCLUSIONS AND RECOMMENDATIONS

The radon survey of the Te Arai River has identified that groundwater discharge is occurring along a significant proportion of the 20 km reach surveyed. In particular, the reaches between sites 11 to 15, sites 21 – 23 and sites 26 – 29 are identified as gaining reaches. At least two of the concurrent stream flow gaugings appeared to provide contradictory observations to the GW-SW interaction patterns observed by the radon. This is most likely caused by surface water abstraction for horticultural/agricultural use or parafluvial exchange.

To provide further insight into the volumes of groundwater being discharged into the Te Arai River, the data from this report will be used in a mass balance model to estimate groundwater discharge. This will be provided to GDC in a separate report. In addition, to investigate the GW-SW interaction dynamics in greater detail and to assess robust minimum flow restrictions the following is recommended:

- Further high resolution radon sampling should be carried out at sites 15 – 16 and sites 35 – 37 (where there was apparent loss or no gain in river discharge) to further refine the rate at which the radon degasses from the river water. This will better explain if the radon measurements indicate groundwater discharge or that they are an artefact from radon discharged further upstream. However, it is acknowledged that river access for sampling at this higher resolution is very difficult.
- Development of an integrated numerical groundwater and surface water model, that specifically simulates the interaction between groundwater and surface water, to explore how different minimum flow settings will impact the flow of the Te Arai River and groundwater system. This will this provide quantitative values and their uncertainties for analysis for minimum flow settings.
- In future radon and flow gauging surveys carried out in the GDC region, it is highly recommended that abstraction volumes and rates are recorded during the survey to assess the extent to which the measured flow rates in the river are influenced by anthropological activity.

9.0 REFERENCES

Boon D, Perrin ND, Dellow GD, Van Dissen RJ, Lukovic B. 2011. NZS1170.5:2004 site subsoil classification of Lower Hutt. In: *Ninth Pacific Conference on Earthquake Engineering: Building an earthquake resilient society*; 2011 Apr 14-16; Auckland, NZ. Auckland (NZ): 9PCEE. Paper 013.

Cartwright I, Hofmann H. 2016. Using radon to understand parafluvial flows and the changing locations of groundwater inflows in the Avon River, southeast Australia. *Hydrology and Earth System Sciences.* 20(9):3581-3600.

Cecil D, Green J. 2000. Radon-222. In Cook PG, Herczeg AL, editors. *Environmental tracers in subsurface hydrology.* Norwell (MA): Kluwer Academic Publishers. p. 175-194.

Cook P, Favreau G, Dighton J, Tickell S. 2003. Determining natural groundwater influx to a tropical river using radon, chlorofluorocarbons and ionic environmental tracers. *Journal of Hydrology.* 277(1):74-88.

Cook P, Wood C, White T, Simmons, C, Fass T, Brunner P. 2008. Groundwater inflow to a shallow, poorly-mixed wetland estimated from a mass balance of radon. *Journal of Hydrology.* 354(1-4):213-226. doi:10.1016/j.hydrol.2008.03.016.

Gibbs M, Clayton J, Wells R. 2005. Further investigation of direct groundwater seepage to Lake Taupo. Hamilton (NZ): Environment Waikato. 33 p. Technical Report No.: 2005/34.

Hammond DE, Simpson HJ, Mathieu G. 1977. Radon 222 distribution and transport across the sediment-water interface in the Hudson River estuary. *Journal of Geophysical Research.* 82(27):3913-3920. doi:10.1029/JC082i027p03913.

Herczeg AL, Edmunds M. 2000. Inorganic ions as tracers. In Cook PG, Herczeg AL, editors. *Environmental tracers in subsurface hydrology.* Horwell (MA): Kluwer Academic Publishers. p. 31-78.

Johnson SL. 2003. Stream temperature: scaling of observations and issues for modelling. *Hydrological Processes.* 17(2):497-499.

Kalbus E, Reinstorf F, Schirmer, M. 2006. Measuring methods for groundwater-surface water interactions: a review. *Hydrology and Earth System Sciences*, 10(6):873-887.

Katz BG, Coplen TB, Bullen TD, Davis JH. 1997. Use of chemical and isotopic tracers to characterize the interactions between ground water and surface water in mantled karst. *Ground Water.* 35(6):1014-1028. doi:10.1111/j.1745-6584.1997.tb00174.x.

Kies A, Hofmann H, Tosheva Z, Hoffmann L, Pfister L. 2005. Using 222 Rn for hydrograph separation in a micro basin (Luxembourg). *Annals of Geophysics.* 48(1):101-107.

LAWA. 2013. National Environmental Monitoring Standards open channel flow measurement. (NZ): Land Air Water Aotearoa.

Lovett AP, Cameron SG, Reeves RR, Meijer E, Verhagen F, van der Raaij RW, Westerhoff R, Moridnejad M, Morgenstern U. 2014. Characterisation of groundwater - surface water interaction at three case study sites within the Upper Waikato River Catchment, using temperature sensing and hydrochemistry techniques. Lower Hutt (NZ): GNS Science. 74 p. (GNS Science report; 2014/64).

Martindale H. 2015. The use of radon and complementary hydrochemistry tracers for the identification of groundwater - surface water interaction in New Zealand. [MSc (Master of Environmental Management) thesis]. Palmerston North (NZ): Massey University.

Martindale H, Knowling MJ, van der Raaij RW, Lovett AP, Morgenstern U. Mourot F. 2017. A hypothesis-testing approach to quantifying groundwater discharge using radon-222 in the Shag/Waihemo River. In: *New Zealand Hydrological Society Conference*; 2017 Nov 28-Dec 1; Napier, New Zealand. Wellington (NZ): New Zealand Hydrological Society. p. 131-132.

Martindale H, Morgenstern U, Singh R, Stewart B. 2016. Mapping groundwater-surface water interaction using radon-222 in gravel-bed rivers: a comparative study with differential flow gauging. *Journal of Hydrology*. 55(2):121.

Martindale H, Morgenstern U, Toews MW, Singh R, Stewart B. 2014. Mapping groundwater-surface water interaction using radon in the Hutt River. In: *2014 Water Symposium: Integration, the final frontier*; 2014 Nov 24-28; Blenheim, New Zealand. Nelson (NZ): Water Symposium 2014. p. 323.

Mazengarb C, Speden IG. 2000. Geology of the Raukumara area. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 1 map + 60 p., scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 6).

McArthur K, Clark M. 2007. Nitrogen and phosphorus loads to rivers in the Manawatu-Wanganui Region: an analysis of low flow state. (NZ): Horizons Regional Council.

Moridnejad M. 2015. Fibre optic distributed temperature sensing (FODTS) to characterize groundwater/stream interaction in New Zealand hydrological settings. Auckland (NZ): The University of Auckland.

Murdoch LC, Kelly SE. 2003. Factors affecting the performance of conventional seepage meters. *Water Resources Research.* 39(6):1163. doi:10.1029/2002wr001347

Nazaroff WW. 1992. Radon transport from soil to air. *Reviews of Geophysics.* 30(2):137-160.

Rawlinson ZJ, Begg JG. 2014. Hydrogeology of the Upper Manawatu and Mangatainoka catchments, Tararua. Lower Hutt (NZ): GNS Science. 48 p. (GNS Science consultancy report; 2014/127).

Rosenberry DO. 2008. A seepage meter designed for use in flowing water. *Journal of Hydrology*. 359(1-2):118-130. doi:10.1016/j.hydrol.2008.06.029.

Stellato L, Terrasi F, Marzaioli F, Belli M, Sansone U, Celico F. 2013. Is ^{222}Rn a suitable tracer of stream–groundwater interactions? A case study in central Italy. *Applied Geochemistry.* 32:108-117. doi:10.1016/j.apgeochem.2012.08.022.

van der Raaij RW, Martindale H. Forthcoming 2018. Application of hydrochemical and isotopic methods to assess water source and contaminant pathways in the Waiokura Catchment, Taranaki, New Zealand. Lower Hutt (NZ): GNS Science. (GNS Science report; 2016/65).

van der Raaij RW. 2018. Results of groundwater age-tracer analyses and interpretation of groundwater age for Gisborne District Council monitoring wells. Lower Hutt (NZ): GNS Science. 8 p. (GNS Science consultancy report; 2017/230LR).

APPENDICES

APPENDIX 1: FIELD PARAMETERS AND SAMPLING RESULTS

Table A 1.1 Summary of location, field parameters, radon concentration, and radon error, for samples collected from a 20 km reach of the Te Arai River investigated in this project.

Site #	Easting (NZTM)	Northing (NZTM)	DO (mgL^{-1})	EC (μScm^{-1})	Temp. (°C)	Radon (BqL^{-1})	± 1 σ Radon (BqL^{-1})
1	2018652	5698684	6.73	437	23.2	0.1	0.0
2	2018683	5698867	6.17	434	23.5	0.1	0.0
3	2018716	5698869	7.25	433	23.6	0.1	0.0
4	2019015	5699004	6.93	425	24.5	0.1	0.0
5	2019058	5699136	7.02	426	24.5	0.1	0.0
6	2019131	5699554	5.72	432	24.5	0.2	0.0
7	2019209	5699802	7.34	431	24.7	0.2	0.1
8	2019408	5699887	6.2	427	25.2	0.2	0.1
9	2019232	5700194	8.65	429	26	0.3	0.1
10	2019352	5700578	7.88	436	25.5	0.2	0.1
11	2019221	5700745	7.28	448	25.5	0.4	0.1
12	2019310	5701073	7.73	451	25.5	0.5	0.1
13	2019794	5701496	7.59	456	26	0.6	0.1
14	2019998	5701190	8.31	454	25.9	0.6	0.1
15	2019853	5701685	6.15	472	25	0.5	0.1
16	2019640	5702034	8.14	472	26.7	0.4	0.1
17 (trib.)	2019578	5702367	n/a	n/a	n/a	0.5	0.1
18	2019571	5702461	9.08	504	27.6	0.5	0.1
19	2019728	5702734	10.07	502	27.8	0.5	0.1
20	2019557	5703289	5.18	517	22.9	0.6	0.1
21	2019374	5703747	5.2	519	23.6	0.5	0.1
22	2019319	5704074	5.31	521	24	0.8	0.1
23	2019444	5704297	5.01	531	24.1	0.8	0.1
24	2019703	5704403	4.62	522	24.5	0.7	0.1
25	2019540	5704693	5.85	532	25	0.7	0.1
26	2019975	5704766	6.51	533	24.6	0.7	0.1
27	2019993	5705004	5.05	536	24.5	0.9	0.1
28 (trib.)	2019995	5705004	8.08	746	19.9	0.8	0.1
29	2020445	5705118	6.89	544	25.7	0.9	0.1
30	2020596	5705296	6.67	542	25.4	0.8	0.1
31	2021026	5705227	6.94	545	25.3	0.7	0.1
32	2021463	5705119	6.4	549	25	0.6	0.1
33	2021745	5705407	6.33	552	25.9	0.7	0.1
34	2022201	5705438	5.06	551	25.6	0.8	0.1
35	2022348	5705749	5.98	551	25.7	0.6	0.1

Site #	Easting (NZTM)	Northing (NZTM)	DO (mgL^{-1})	EC (μScm^{-1})	Temp. (°C)	Radon (BqL^{-1})	± 1 σ Radon (BqL^{-1})
36	2022446	5705957	6.2	555	25.6	0.5	0.1
37	2022710	5706051	6.39	557	25.7	0.5	0.1
38	2022983	5706153	6.02	560	25.7	0.4	0.1
39	2023256	5706128	6.71	564	26	0.5	0.1
40	2023197	5706463	5.68	567	25.45	0.4	0.1
41	2023513	5706617	4.81	568	24.1	0.5	0.1
42	2023513	5707153	5.06	582	23.5	0.5	0.1
43	2024110	5706662	4.46	586	23.3	0.3	0.1
44	2024245	5706984	4.46	588	23.3	0.4	0.1
GW	2021743	5704916	n/a	n/a	n/a	17.9	1.0

APPENDIX 2: FLOW GAUGING SUMMARY

Table A 2.1 Summary of location and flow from the 7 flow gauging sites across a 20 km reach of the Te Arai River investigated in this project.

Site ID Reference	GDC Site reference	Easting (NZTM)	Northing (NZTM)	Flow (m^3s^{-1})
3	Pykes Weir	2018718	5698871	0.084
downstream of 15	Ray's Creek	2019623	5701875	0.083
17	Confluence	2019539	5702365	0.036
18	Site 61	2019566	5702424	0.122
24	Leaderbrand	2019713	5704436	0.145
32	638 Waingake	2021609	5705214	0.146
44	304 Waingake	2024275	5706963	0.136

GNS SCIENCE
TE PŪ AO

www.gns.cri.nz

Principal Location

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657