Using Radon-222 and concurrent flow gauging to understand groundwater and surface water interaction in the Lower Kauru River, North Otago

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ABSTRACT

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

This report details a combined approach using Radon-222 and concurrent flow gauging to investigate GW–SW interaction between the Kakanui-Kauru Alluvial Aquifer and the Kauru River, North Otago. This survey was undertaken collaboratively by the Otago Regional Council and GNS Science in March 2023 along a 5.7 km reach of the Lower Kauru River.

Results confirms that the Lower Kauru River is a losing reach, with flow decreasing by ~35% over 5.7 km from the Kauru Hill Road Bridge to the Kakanui Valley Road Bridge. Radon concentrations generally increased along the investigated Lower Kauru River reach. The presence of elevated radon (>0.5 Bq/L) in the Kauru River along a significant proportion of the surveyed reach suggests groundwater discharge from the Kakanui-Kauru Alluvial Aquifer to river flow. Groundwater discharge to the Kauru River increases downriver based on increased radon concentrations, despite the overall reduced river flow in this reach.

The hydrochemical composition of the Kakanui-Kauru Alluvial Aquifer at bore J41/0763 overlaps the composition of the Kauru River surface water measured in three locations along the investigated reach. This, in addition to increased radon concentration at bore J41/0763, suggests that the hyporheic zone (the region of sediment beneath and alongside a riverbed where shallow groundwater and surface water are mixing) plays an important role by facilitating the mixing of shallow groundwater and surface water. Overall, these results show that the surface water and groundwater are highly connected along the Lower Kauru River.

KEYWORDS

Groundwater–surface water interaction, radon-222, isotope, Kauru River, North Otago

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1.0 INTRODUCTION

The Otago Regional Council (ORC) commissioned GNS Science via an Envirolink grant to assist in the planning and interpretation of a radon and flow-gauging survey to investigate groundwater–surface water (GW–SW) interaction processes between the Kakanui-Kauru Alluvial Aquifer (KKAA) and the Kauru River, North Otago (Figure 1.1). Knowledge of the relationship between surface water and groundwater is required to improve water resource management, such as setting of minimum flows and GW–SW allocation limits. The primary purpose of this study was to delineate gaining and losing reaches of the Lower Kauru River and to better understand the role of groundwater discharge in sustaining river flow during dry periods. Improved understanding of GW–SW interactions will inform ORC's policies regulating water abstraction from the Kauru River during sustained low-flow periods (e.g. ORC 2004) and inform minimum flow restrictions to protect the habitat of the endangered Lowland longjaw galaxias (McDowall and Waters 2002).

Over the last decade, GNS Science has been developing Radon-222 (herein referred to as radon, ^{222}Rn or Rn) as an environmental tracer to improve characterisation of GW–SW interaction. The method for ^{222}Rn analysis in groundwater and surface water was developed at GNS Science by Martindale et al. (2016). As a result of this work, radon and concurrent 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. 2016, 2018), including several studies across Otago (e.g. Jackson 2018; Martindale et al. 2017; Mourot et al. 2022).

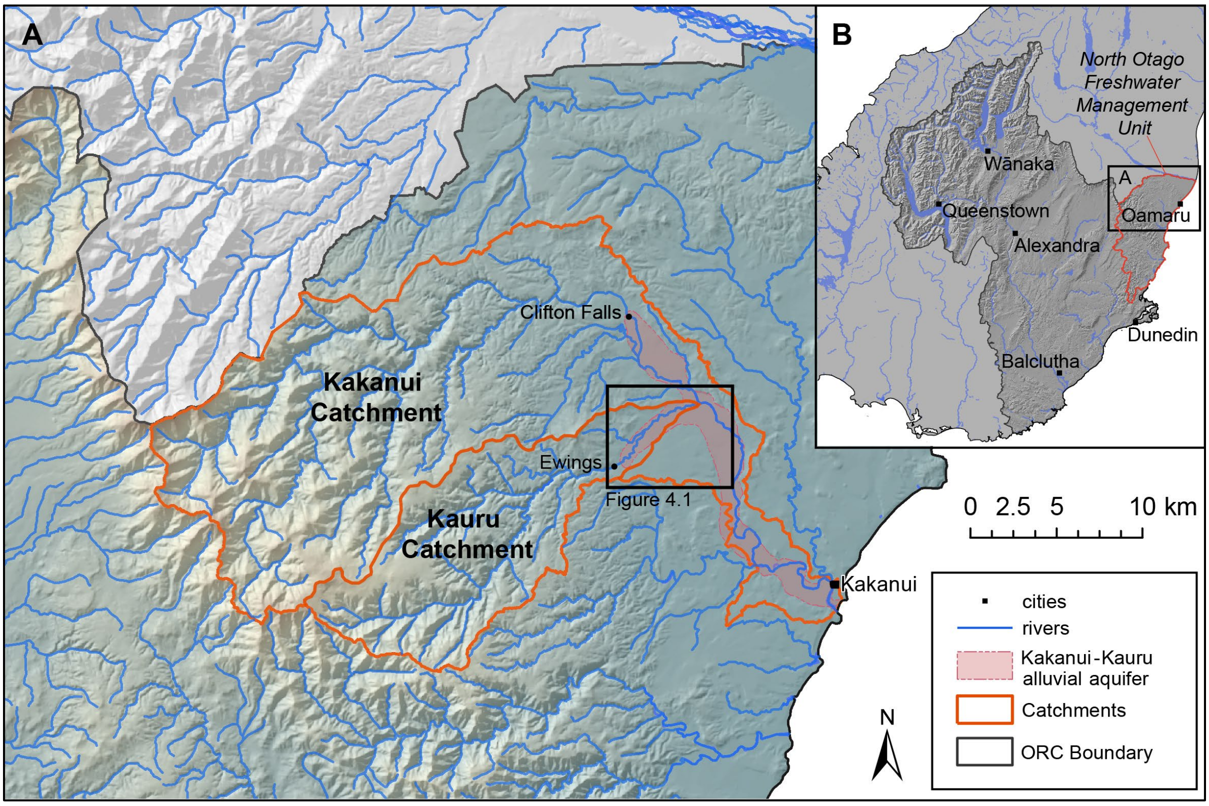

Figure 1.1 Map of the study area in North Otago, highlighting the location of the Kakanui and Kauru river catchments and of the Kakanui-Kauru Alluvial Aquifer. The locations of the Clifton Falls and Ewings monitoring stations are also noted.

This project was undertaken in two stages:

- **Stage 1** included the planning and execution of a radon sampling and concurrent gauging survey along the Kauru River, which was undertaken by ORC and GNS Science staff on 14 March 2023.
- **Stage 2** focused on the interpretation of the radon sampling results and reporting. This report was funded by a 2023 Envirolink Small Advice Grant. In addition to the Envirolink funding, the cost of the radon sample analysis was funded by GNS Science as part of the Ministry of Business, Innovation & Employment (MBIE) Endeavour programme 'Te Whakaheke o Te Wai' (TWOTW). The flow gauging measurements and hydrochemistry analyses were provided by ORC.

2.0 BACKGROUND

The study area is located in North Otago along the Lower Kauru River (Figures 1.1 and 2.1), which is part of the North Otago Freshwater Management Unit (Figure 1.1, inset). The North Otago sub-region extends from the Waitaki River in the north to the Pleasant River in the south and includes the catchments of the Shag, Waianakarua and Kakanui rivers. These and other catchments in the sub-region are naturally subject to low flows during dry periods (i.e. between November and April) due to decreased rainfall and low groundwater levels.

Figure 2.1 Photo along the Kauru River looking upstream (west), highlighting the discontinuous nature of the main channel network. Water is commonly observed seeping from beneath gravel bars (lower right in the image above). ORC staff for scale.

The Kauru River catchment is one of three main tributaries of the Kakanui River and comprises 16% of the total catchment area of the Kakanui River (Figure 1.1). The Kauru River lies between the catchment of the main branch of the Kakanui and Island Stream catchment and is bound in the south by the Kakanui Mountains. Hector's Stream is the main tributary of the Kauru River, and the catchment rises to an elevation of 1272 m southwest of Mt Dasher (see Appendix 1 for topographic map of the area).

Over the past two decades, land use in the Kakanui catchment has intensified rapidly. The Lower Kakanui River and Waiareka Creek are dominated by a mixture of beef/sheep/deer/cropping and, increasingly, dairy farming, particularly since the introduction of irrigation water into the Waiareka Creek catchment (Ozanne and Wilson 2013).

Previous work by Ozanne and Wilson (2013) identified that groundwater recharge into the KKAA (Figure 1.1) is largely controlled by surface-water flows. This close connection between the shallow KKAA and surface water results in relatively high nitrate levels in the groundwater due to agricultural activities (Ozanne and Wilson 2013). Groundwater recharge occurs in the alluvial gravels in the Kauru River and the main stem of the Kakanui River. The Kakanui-Kauru alluvium has been a recognised riverine ribbon aquifer since the Otago Catchment Board investigation of the North Otago groundwater resource in the 1980s. The alluvial sands and sandy gravels making up the floodplains of the Kakanui and Kauru rivers are thin and within less permeable sedimentary, volcanic and metamorphic rocks, such as the North Otago tuffs, sandstone/siltstone, quartzose conglomerate and pelitic schist (Forsyth 2001; Rekker et al. 2008).

It has been well documented (e.g. ORC 1993) that the lower reach of the Kauru River ceases to flow in dry weather, as the alluvium drains river flow and conducts it underground through the KKAA and into the Kakanui River. Groundwater levels in the shallow alluvial aquifer change seasonally and correlate with high-flow events. The volume of water replenished during a high-flow event, and then drained during flow recession, can represent a high proportion of groundwater storage. At the end of each summer, most of the available dynamic groundwater storage has been drained into the Kakanui River as base flow (Ozanne and Wilson 2013). Water extraction from the shallow KKAA is currently used for irrigation, human consumption, stock drinking-water supply and farm dairy water (ORC 2004).

The Otago Water Plan (ORC 2004) designates the KKAA as a shallow aquifer that is closely associated with the Kakanui and Kauru river hydrology. Accordingly, the aquifer is managed as if it was a surface water body. Specifically, the alluvium and any bores drawing on it are subject to the minimum flow restrictions of the Kakanui River (ORC 2004).

The Kauru River is a habitat for the endangered Lowland longjaw galaxias. This fish has been identified primarily in high-elevation tributaries in Canterbury and North Otago. The Kauru River is the only low-elevation site where populations of the fish have been identified, which are described as a distinct species (*Galaxias cobitinis*). It has been proposed that the longjaw galaxias rely on the discharge of relatively cool groundwater into the Kauru River for survival during the summer (McDowall and Waters 2002).

3.0 METHODS

3.1 Radon-222 Measurements

^{222}Rn is a soluble gas and a short-lived (half-life ~3.8 days) intermediate daughter in the decay of uranium-238 to lead-206, which occurs at very low levels in most rocks and soils. Groundwaters, in a closed system and in contact with these rocks, can accumulate ^{222}Rn released from the U-enriched minerals, resulting in elevated ^{222}Rn concentrations in the groundwater. These concentrations are a result of equilibrium between ^{222}Rn delivery and radioactive decay (half-life 3.8 days) and can vary considerably depending on the uranium content and ^{222}Rn emanation potential of the aquifer material. ^{222}Rn concentrations in surface water are typically negligible due to rapid degassing to the atmosphere. Identification of elevated ^{222}Rn concentrations in rivers therefore indicates active groundwater discharge to the river. However, groundwater fluxes based on ^{222}Rn concentrations alone can yield over-estimated flux rates due to the additional ^{222}Rn source contribution from parafluvial and hyporheic flow[1] (Cartwright and Hofmann 2016). Simplified estimations of the hyporheic zone area, and thus the ^{222}Rn contribution from hyporheic flow, can be made (Cartwright and Hofmann 2016; Tonina and Buffington 2011) but are beyond the scope of this investigation.

Samples were collected along a 5.7 km reach of the Kauru River, where GW–SW interaction was inferred. Fieldwork was undertaken on 14 March 2023 under relatively low-flow conditions, ranging from 0.30 to 0.47 m^3/s along the study area. The timing of this study occurred following the end of the driest period of the summer (January to February), with two relatively large rain events occurring in the weeks prior to sampling (Figure 3.1). Because surface water is known to infiltrate rapidly into the shallow KKAA and flow towards the Kakanui River, the Kauru River was near base-flow conditions at the time of sampling.

Two groundwater samples were also collected from shallow bores:

- J41/0763 is a 10.1-m-deep bore screened from 5.5 to 8.4 m and located ~200 m southeast of the Kauru River near the middle of the profile.
- CC18/0108 is a 6.0-m-deep bore screened from 2.8 to 5.8 m and located ~500 m southeast of the Kauru River (see Appendix 2 for bore logs).

^{222}Rn samples from groundwater and river water were collected in 20 mL glass vials with metal-lined lids. Surface-water samples were collected from 26 sites along the Kauru River at an average interval of 230 m from the main river trace, whereas minor flows in small ribbons or braids were avoided. The exception to this is site KE22, which is discussed below. Each sample was collected from near the centre of the river in 30–40 cm water depth; areas with stagnant water were avoided to minimise degassing loss of radon. Rapidly flowing rough water where air bubbles could be entrained were also avoided. Due to the short half-life of ^{222}Rn, the samples were measured within a few days after sampling. ^{222}Rn was measured by liquid scintillation spectroscopy. 10 mL of sample water was transferred into counting vials and mixed with a mineral-oil-based scintillant and ^{222}Rn absorber, followed by decay counting in a Quantulus™. Detection limits were typically <0.1 Bq/L. The ^{222}Rn analytical technique was validated by an inter-laboratory comparison organised by Flinders University, Adelaide, in 2018.

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[1] The parafluvial zone is located in the area that floods during high flows and dries during low flows. The hyporheic zone is the region of sediment beneath and alongside a riverbed, where shallow groundwater and surface water are mixing.

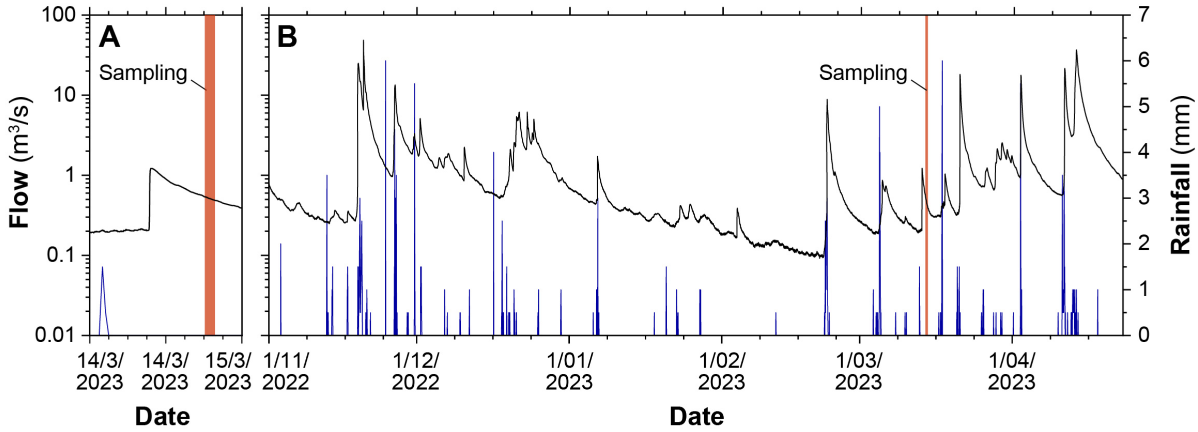

Figure 3.1 Rainfall data (blue) and river flow data (black) for the Kauru River shown for (A) a 48-hour period at the time of sampling (red vertical area) and for (B) a period over 5.7 months to provide more context. Rainfall data is measured hourly at the Clifton Falls Bridge monitoring station near the Kakanui River, and the Kauru River flow is measured every five minutes at Ewings monitoring station (see Figure 1.1).

3.2 Flow-Gauging Measurements

Flow-gauging measurements were undertaken by ORC at three concurrent sites located at the beginning, middle and end of the ^{222}Rn sampling transect (K1, K2 and K3, respectively). Kauru River flow was measured by ORC staff using a FlowTracker2 at the same time as the ^{222}Rn sampling (14 March 2023). The reported uncertainty is the interpolated variance estimator (IVE). For reference, Kauru River flow rates are continuously monitored at the Ewings monitoring station (see Figure 1.1).

3.3 Hydrochemistry Measurements

At the two bores (J41/0763, CC18/0108) and flow-gauging measurement locations (K1, K2 and K3), water samples were collected for chemical analysis. The hydrochemical composition of groundwater and surface water was measured at Hill Laboratories (Hamilton, New Zealand) following standard protocol for State of the Environment (SOE) groundwater sampling (see Appendix 3 for measurement details and detection limits).

4.0 RESULTS

4.1 Radon-222 Concentrations in the Kauru River

The ^{222}Rn concentration in the Kauru River ranges from 0.18 ± 0.05 to 1.74 ± 0.17 Bq/L and generally increases downriver over the 5.7 km reach of the Kauru River, starting at the Kauru River Hill Road Bridge (Figure 4.1).

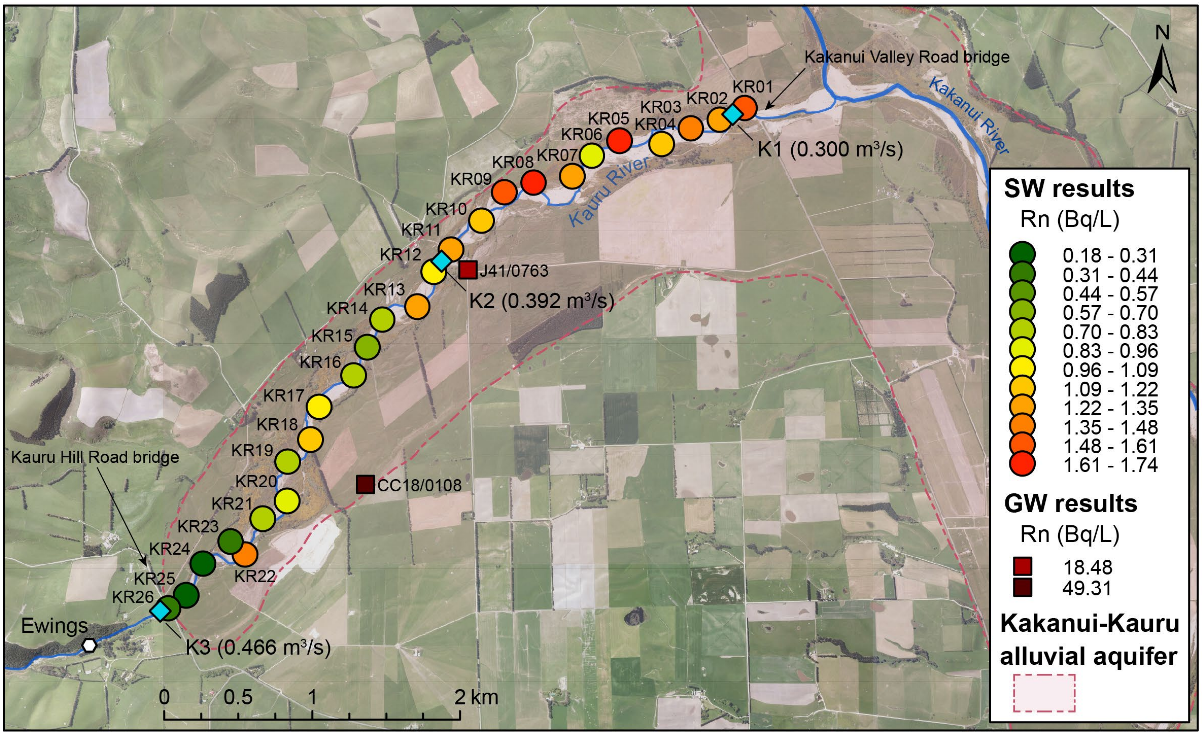

Figure 4.1 Map of ^{222}Rn (Rn) concentrations for surface water (SW) samples collected along the Lower Kauru River. Blue diamonds are the locations of river flow gauging measured concurrently along the profile and flow rates. Squares are the locations of groundwater (GW) sites, and the white hexagon is a continuous flow recording station at Ewings. The boundary of the Kakanui-Kauru Alluvial Aquifer is outlined in red.

Although scattered, a liner trend through the data (Figure 4.2A) suggests that Rn increases approximately 0.2 Bq/L/km downriver. The notable outlier to this trend is site KR22, which yielded a relatively high value of 1.45 ± 0.15 Bq/L compared to sample KR23, which was collected 131 m away and yielded 0.35 ± 0.07 Bq/L. Sample KR23 was located along the main river access, whereas KR22 was collected from a smaller disconnected channel that, upon further inspection, was fed largely by groundwater discharging from beneath a gravel bar (similar to Figure 2.1).

The relative scatter in the downriver ^{222}Rn profile (Figure 4.2A) is likely the result of areas with high groundwater flux (i.e. high ^{222}Rn) at spatial scales smaller than the 230 m sample spacing.

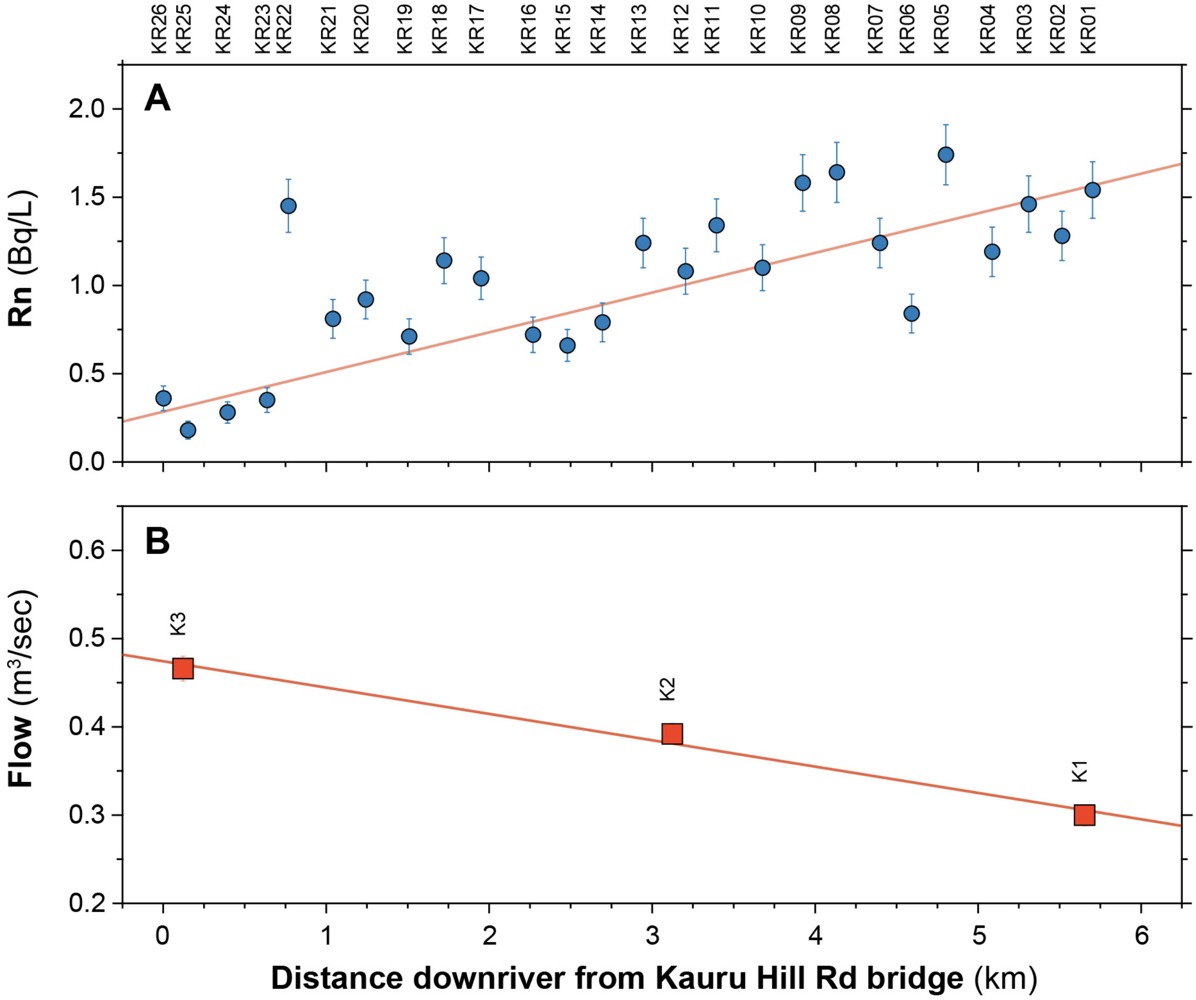

Figure 4.2 (A) Radon-222 (Rn) concentrations and (B) flow-gauging results plotted relative to distance down the Kauru River. The red line is the linear fit through both datasets (excluding site KR22; see text). Data are available in Tables 4.1 and 4.2.

Table 4.1 Radon-222 (Rn) concentration, 1σ error and sampling locations for surface water (SW) and groundwater sites. All samples collected on 14 March 2023.

Site ID	Sample Type	Sample Time (14/03/2023)	Rn (Bq/L)	Easting	Northing
KR01	Kauru River SW	12:49	1.54 ± 0.16	1426335	5005880
KR02	Kauru River SW	12:57	1.28 ± 0.14	1426166	5005799
KR03	Kauru River SW	13:04	1.46 ± 0.16	1425970	5005741
KR04	Kauru River SW	13:10	1.19 ± 0.14	1425772	5005636
KR05	Kauru River SW	13:18	1.74 ± 0.17	1425489	5005659
KR06	Kauru River SW	13:27	0.84 ± 0.11	1425304	5005558
KR07	Kauru River SW	13:33	1.24 ± 0.14	1425169	5005419
KR08	Kauru River SW	13:40	1.64 ± 0.17	1424908	5005373
KR09	Kauru River SW	13:49	1.58 ± 0.16	1424709	5005308
KR10	Kauru River SW	13:56	1.10 ± 0.13	1424555	5005116
KR11	Kauru River SW	14:03	1.34 ± 0.15	1424350	5004922
KR12	Kauru River SW	14:09	1.08 ± 0.13	1424232	5004774
KR13	Kauru River SW	14:16	1.24 ± 0.14	1424121	5004538
KR14	Kauru River SW	14:23	0.79 ± 0.11	1423887	5004450
KR15	Kauru River SW	14:31	0.66 ± 0.09	1423782	5004262
KR16	Kauru River SW	14:39	0.72 ± 0.10	1423692	5004071
KR17	Kauru River SW	14:46	1.04 ± 0.12	1423457	5003857
KR18	Kauru River SW	14:55	1.14 ± 0.13	1423398	5003638
KR19	Kauru River SW	15:00	0.71 ± 0.10	1423243	5003489
KR20	Kauru River SW	15:09	0.92 ± 0.11	1423241	5003223
KR21	Kauru River SW	15:15	0.81 ± 0.11	1423078	5003105
KR22	Kauru River SW	15:23	1.45 ± 0.15	1422956	5002860
KR23	Kauru River SW	15:29	0.35 ± 0.07	1422862	5002951
KR24	Kauru River SW	15:37	0.28 ± 0.06	1422673	5002799
KR25	Kauru River SW	15:44	0.18 ± 0.05	1422559	5002585
KR26	Kauru River SW	15:51	0.36 ± 0.07	1422438	5002495
J41/0763	KKAA Groundwater	17:02	18.5 ± 1.1	1424463	5004787
CC18/0108	KKAA Groundwater	17:23	50.8 ± 2.8	1423769	5003337
CC18/0108	KKAA Groundwater	17:34	47.8 ± 2.7	1423769	5003337
CC18/0108	KKAA Groundwater	17:44	49.3 ± 2.8	1423769	5003337

4.2 Radon-222 Concentrations in the Kakanui-Kauru Alluvial Aquifer

^{222}Rn concentration was measured at two bores located within KKAA: J41/0763 and CC18/0108, located ~200 m southeast and ~500 m southeast of the Kauru River, respectively (Figure 4.1; Table 4.1). ^{222}Rn concentrations increase with distance away from the Kauru River (Table 4.1). At site J41/0763, the ^{222}Rn concentration was 18.5 ± 1.1 Bq/L, and, at CC18/0108, the concentration was 49.3 ± 1.5 Bq/L.

Three aliquots (representative sub-samples) of groundwater were collected and measured from site CC18/0108, which yielded results that were reproducible within the 1σ analytical precision of the measurement technique (Table 4.1). The reported value of 49.3 ± 1.5 Bq/L for CC18/0108 is the mean and 1σ standard deviation of the three measurements.

4.3 Kauru River Flow Gauging

Kauru River flow gauging was performed at three sites (Table 4.2). Measured flow rates decrease linearly from 0.466 m^3/s measured at the Kauru Hill Road Bridge to 0.300 m^3/s measured at the end of the profile near the Kakanui Valley Road Bridge (Figures 4.1 and 4.2B). The FlowTracker2 gauging data at site K3 (Figure 4.1) is ~15% lower than the continuous flow recorder data located ~500 m upstream at Ewings (Figure 3.1). This variance is likely due to differences in calibration of the two instruments. See Appendix 4 for full measurement.

Table 4.2 Kauru River flow-gauging results measured at the same time as radon sampling. Flow was calculated using FlowTracker2, and reported uncertainty is the interpolated variance estimator. SW = surface water.

Site ID	Sample Type	Flow (m^3/s)	Temperature (°C)	Easting	Northing
K1	Kauru River SW	0.300 ± 0.012	17.9	1426290	5005898
K2	Kauru River SW	0.392 ± 0.012	17.5	1424262	5004850
K3	Kauru River SW	0.466 ± 0.014	15.1	1422529	5002579

4.4 Hydrochemistry

The hydrochemical composition of groundwater and connected surface waters reflects the recharge conditions and evolutionary flow pathways. Various land-use activities and dissolution of geological formations can result in specific water-chemistry signatures that can be traced back to the source. Increasing ion concentrations of the water due to water-rock interaction with the aquifer material can indicate flow pathways and groundwater processes.

Results highlight that the shallow groundwater at bore J41/0763, located ~200 m southeast of the main Kauru River and within KKAA, is a magnesium bicarbonate type (Figure 4.1) and has Ca, Mg, K, Na and Cl concentrations that overlap the range of compositions measured from the Kauru River water samples (K1, K2 and K3; Table 4.3). Bore CC18/0108, which is located ~500 m southeast of the main river and near the edge of the alluvium aquifer (Figure 4.1), is a sodium chloride type with notably different chemistry compared to bore J41/0763 and the Kauru River water samples, including elevated cations (Ca, Na, Cl) and nitrate concentrations (nitrate reported as nitrate-nitrogen or NO_3-N). See Appendix 3 for full measurement results and detection limits.

Table 4.3 Selected hydrochemistry results for groundwater (Kakanui-Kauru Alluvium Aquifer) and surface water (Kauru River) samples.

Site ID	pH	Ca (g/m^3)	Mg (g/m^3)	K (g/m^3)	Na (g/m^3)	Cl (g/m^3)	NO_3-N (g/m^3)	P (Total) (g/m^3)	SO_4 (g/m^3)	*E. coli* (MPN/100 ml)
J41/0763	7.0	5.7	1.65	0.82	6.4	4.7	0.178	0.007	2.0	< 1
CC18/0108	6.6	14	5.8	5.6	29	29	6.00	0.153	11.5	< 1
K1	7.5	5.8	1.86	0.90	6.5	5.5	0.058	0.004	2.8	70
K2	7.6	5.4	1.59	0.81	5.5	4.0	0.041	0.005	1.8	192
K3	7.7	5.3	1.40	0.63	4.7	2.9	0.011	0.004	1.4	179

5.0 DISCUSSION AND CONCLUSION

The lower reach of the Kauru River has been interpreted as a losing reach (ORC 1993), as river flow will often cease in some parts during prolonged dry weather and it has been assumed that surface water infiltrates into the KKAA and ultimately discharges into the Kakanui River (Figure 4.1). During the sampling campaign on 14 March 2023, there was continuous flow through the entire lower reach of the Kauru River. Gauging results from three locations along the Lower Kauru River show flow decreases by ~35% over 5.7 km from the Kauru Hill Road Bridge to the Kakanui Valley Road Bridge (Figures 4.1 and 4.2; Table 4.3), supporting the hypothesis that this section of the Kauru River is a losing reach.

^{222}Rn concentrations generally increase along this 5.7 km section of the Lower Kauru River. Downriver from the Kauru Hill Road Bridge, the first ~0.75 km of the Kauru River has ^{222}Rn concentrations that are low and relatively constant, ranging from 0.18 to 0.36 Bq/L (sites KR26, KR25, KR24 and KR23). These low ^{222}Rn concentrations (<0.5 Bq/L) suggest negligible contribution from groundwater, which is consistent with other New Zealand studies of radon in degassed surface waters (e.g. Daughney et al. 2015; Lovett et al. 2015). Downriver from site KR21, ^{222}Rn concentrations generally increase from 0.8 to 1.7 Bq/L (Figure 4.1). This rise in ^{222}Rn concentration indicates increased groundwater discharge downriver.

^{222}Rn from bores J41/0763 and CC18/0108 yielded ^{222}Rn concentrations of 18.5 ± 1.1 and 49.3 ± 1.5 Bq/L, respectively, which are consistent with typical groundwater values of 10–70 Bq/L from gravels (Cecil and Green 2000; Martindale et al. 2017; Mourot et al. 2022). Bore CC18/0108 is located in the parafluvial zone, relatively far away from the Kauru River such that it was not influenced by hyporheic flow (the movement of water between a river or stream and the adjacent sediments; Boano et al. 2014) at the time of sampling (near baseflow conditions). This is supported by the hydrochemistry results, which show that the groundwater at CC18/0108 has elevated Ca, Na, Cl and NO_3-N concentrations that are distinctly different than the composition of the Kauru River surface water and KKAA at bore J41/0763 (Table 4.3). Based on these observations, the relatively high ^{222}Rn concentration 49.3 ± 1.5 Bq/L at bore CC18/0108 likely represents the local groundwater steady-state ^{222}Rn concentration in the Lower Kauru River area. This is similar to what was observed in the Shag River ^{222}Rn study (Mourot et al. 2022), where the paleo-river channel was more connected to the main river than distal parts of the Shag Alluvial Aquifer.

The fact that the composition of groundwater at J41/0763 is the same as the Kauru River surface water (Table 4.3) suggests that the hyporheic zone plays an important role in mixing shallow groundwater and surface water. Assuming steady-state flow of both groundwater discharge and surface-water recharge into KKAA, the ^{222}Rn concentration of 18.5 Bq/L at J41/0763 represents 37.5% contribution of high ^{222}Rn (~49.3 Bq/L) groundwater and 62.5% surface water that has been completely degassed (~0 Bq/L). These results further strengthen the observations that the surface water and groundwater are highly connected in the Lower Kauru River and KKAA.

Although the lower reach of the Kauru River is losing surface water at a rate of 0.03 m^3/L/km based on gauging results, the ^{222}Rn results suggest that the Lower Kauru River is also gaining flow by increased groundwater discharge. The presence of radon in the river water is evidence that groundwater is likely contributing to river flow and that the groundwater contribution increases downriver.

These results further strengthen the observations that the Lower Kauru River is highly connected to the KKAA. It should be noted that the interpretations in this report are based on a limited number of groundwater sites. A more comprehensive sampling campaign is needed to develop a mass balance model to estimate the rates of groundwater discharge into the Kauru River. This could include measuring radon from water within riverbed gravels to better understand hyporheic flow through the KKAA (e.g. Martindale et al. 2017; Mourot et al. 2022).

6.0 ACKNOWLEDGMENTS

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APPENDICES

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APPENDIX 1 REGIONAL TOPOGRAPHIC MAP

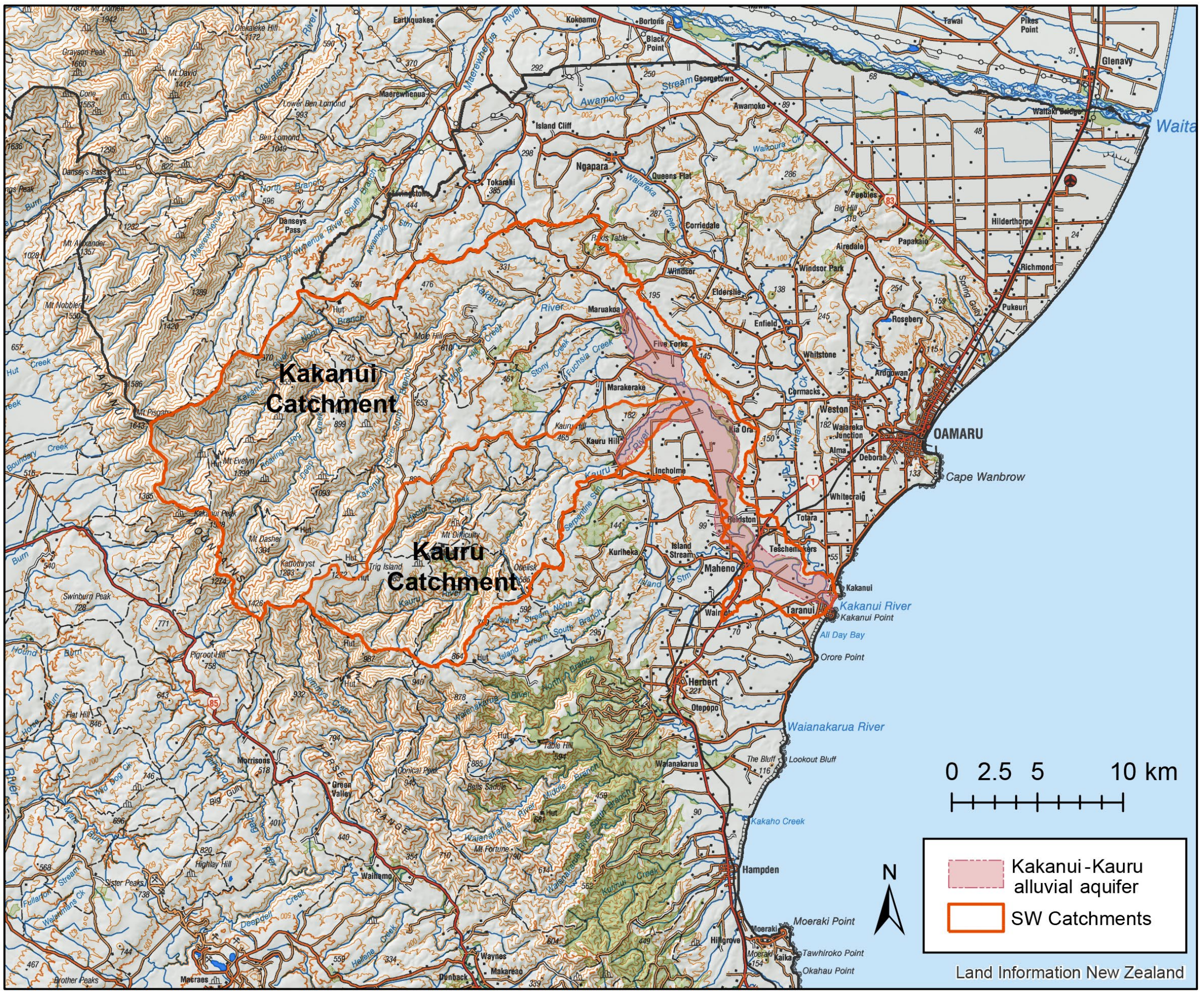
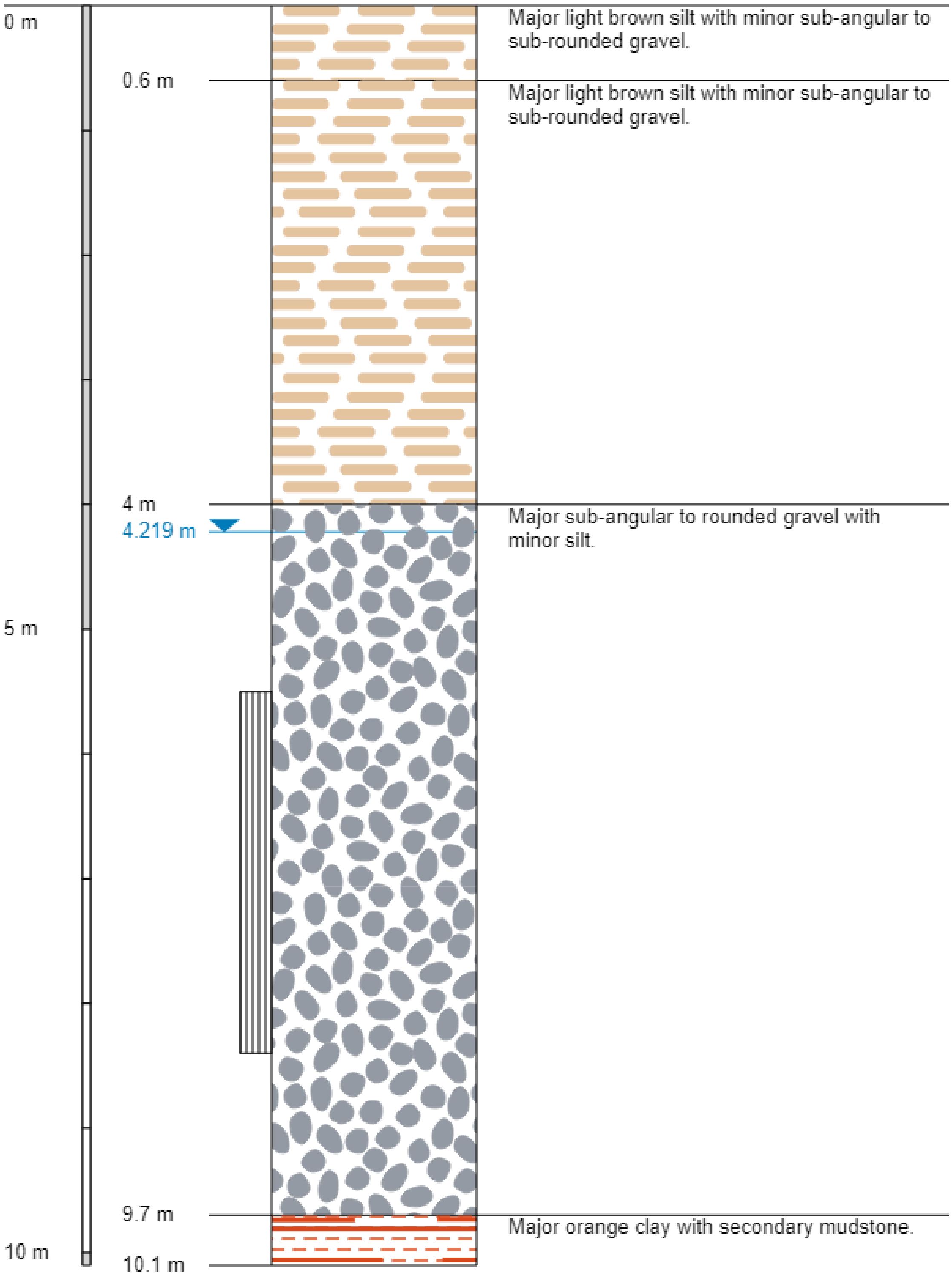


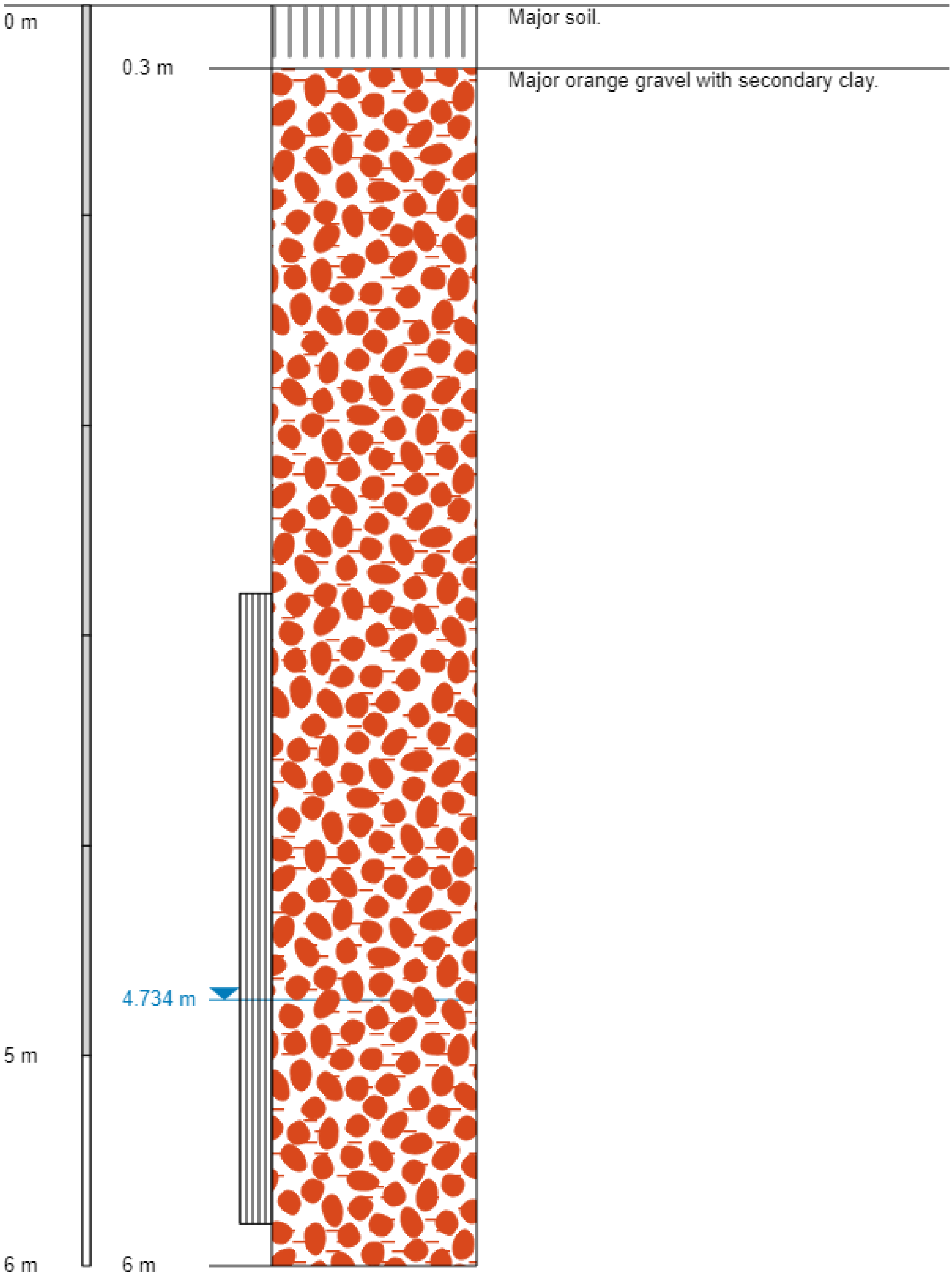
Figure A1.1 Topographic map of the study area in North Otago, highlighting the location of the Kakanui and Kauru river catchments and of the Kakanui-Kauru Alluvial Aquifer.

APPENDIX 2 BORE LOGS FOR J41/0763 AND CC18/0108

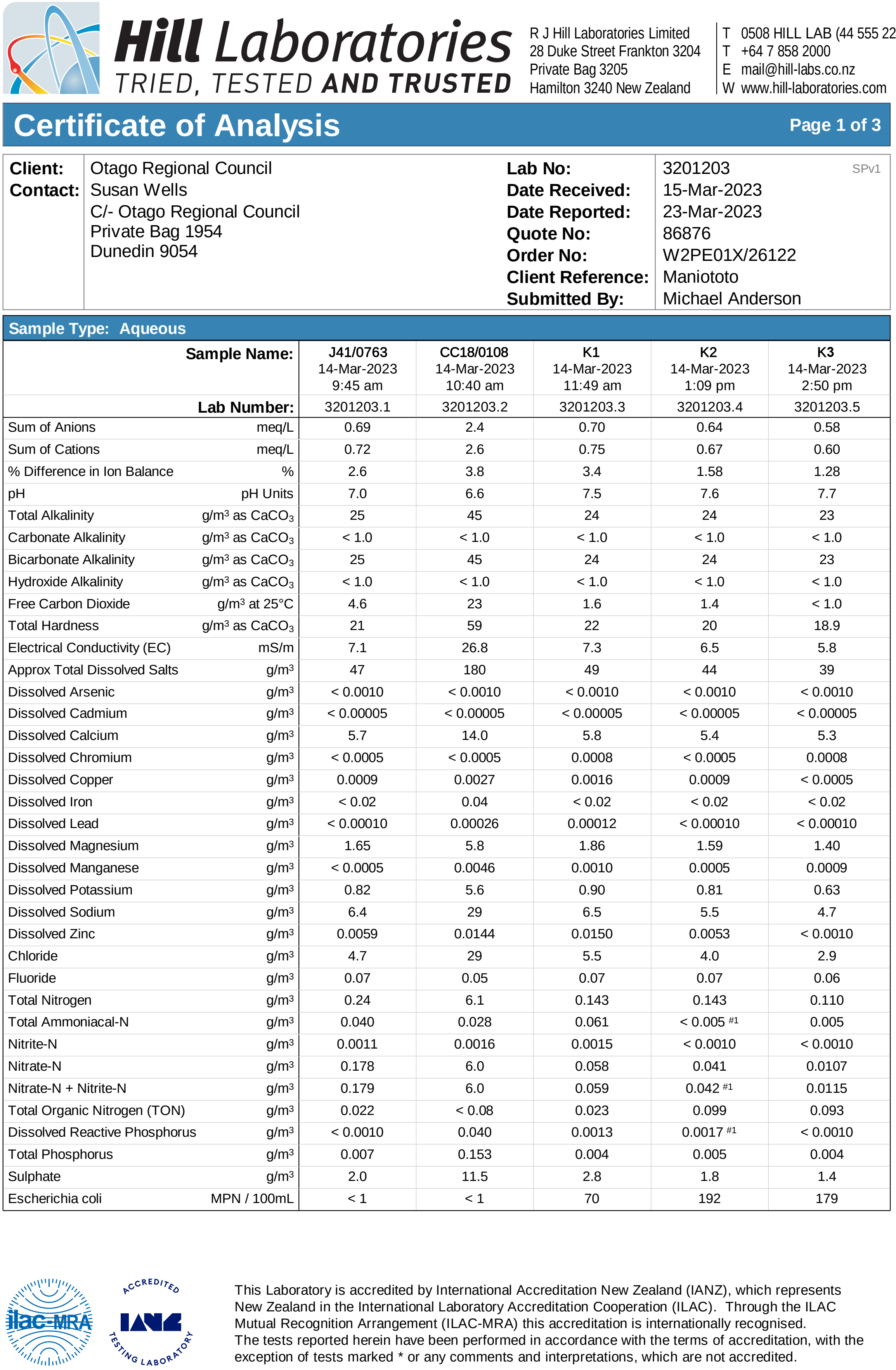
Council well number : J41/0763
Well name : Kakanui at Bore 4 Kininmont Road
Drilling company : McNeill Drilling
Drilling date : 24/01/2014
Drilling method : Tubex
Locality : -
Total depth drilled : 10.1m
NZTM : 1424467 : 5004780



Council well number : CC18/0108
Well name : Kakanui River Piezo BH1
Drilling company : Speight Drilling
Drilling date : 23/03/2022
Drilling method : Sonic
Locality : -
Total depth drilled : 6m
NZTM : 1424278 : 5004988



APPENDIX 3 HYDROCHEMISTRY RESULTS FROM HILL LABORATORIES



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Certificate of Analysis

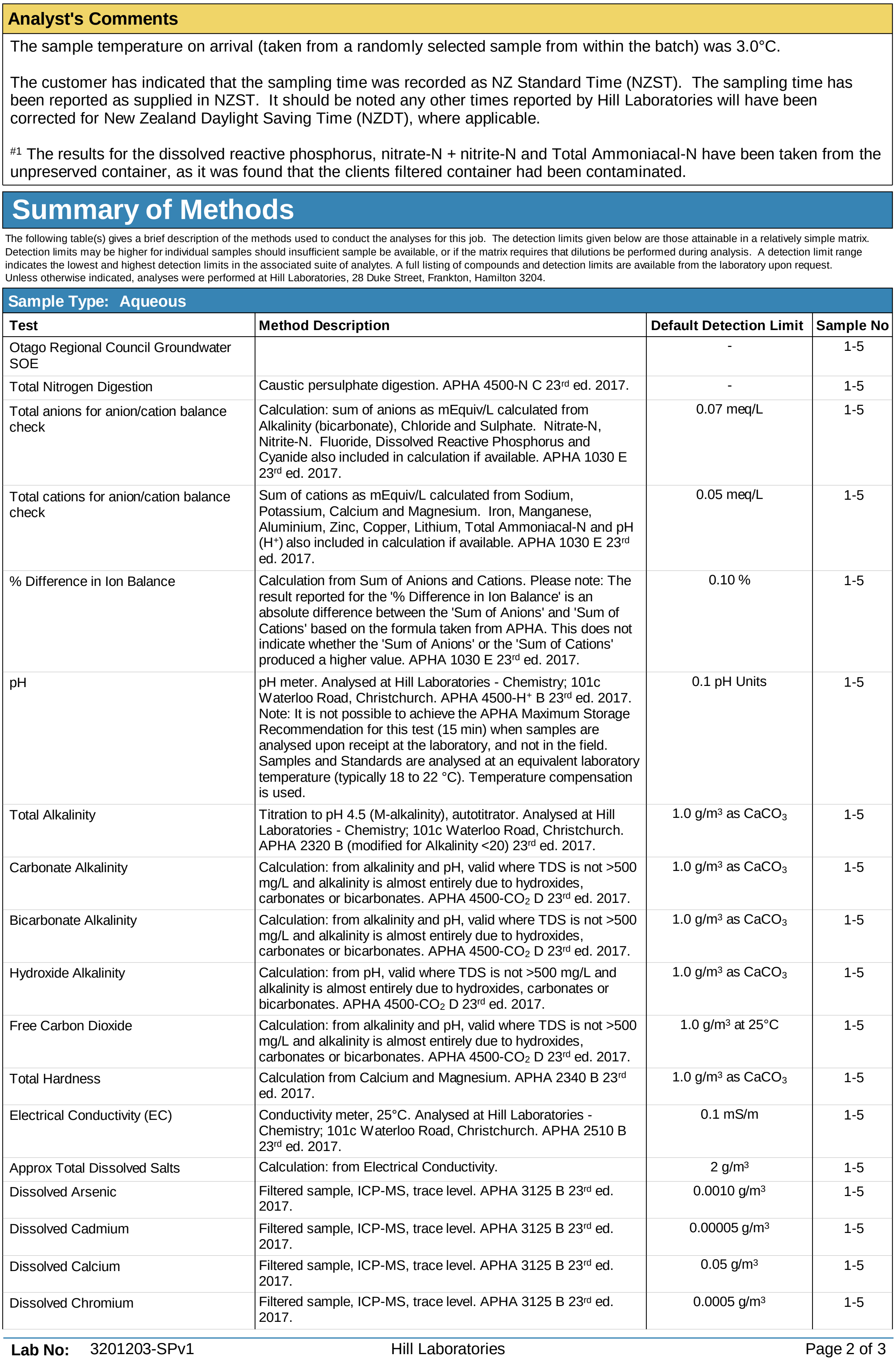
Page 1 of 3

Client:	Otago Regional Council	**Lab No:**	3201203 SPv1
Contact:	Susan Wells	**Date Received:**	15-Mar-2023
	C/- Otago Regional Council	**Date Reported:**	23-Mar-2023
	Private Bag 1954	**Quote No:**	86876
	Dunedin 9054	**Order No:**	W2PE01X/26122
		Client Reference:	Maniototo
		Submitted By:	Michael Anderson

Sample Type: Aqueous

Sample Name:		**J41/0763** 14-Mar-2023 9:45 am	**CC18/0108** 14-Mar-2023 10:40 am	**K1** 14-Mar-2023 11:49 am	**K2** 14-Mar-2023 1:09 pm	**K3** 14-Mar-2023 2:50 pm
Lab Number:		3201203.1	3201203.2	3201203.3	3201203.4	3201203.5
Sum of Anions	meq/L	0.69	2.4	0.70	0.64	0.58
Sum of Cations	meq/L	0.72	2.6	0.75	0.67	0.60
% Difference in Ion Balance	%	2.6	3.8	3.4	1.58	1.28
pH	pH Units	7.0	6.6	7.5	7.6	7.7
Total Alkalinity	g/m^3 as CaCO$_3$	25	45	24	24	23
Carbonate Alkalinity	g/m^3 as CaCO$_3$	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0
Bicarbonate Alkalinity	g/m^3 as CaCO$_3$	25	45	24	24	23
Hydroxide Alkalinity	g/m^3 as CaCO$_3$	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0
Free Carbon Dioxide	g/m^3 at 25°C	4.6	23	1.6	1.4	< 1.0
Total Hardness	g/m^3 as CaCO$_3$	21	59	22	20	18.9
Electrical Conductivity (EC)	mS/m	7.1	26.8	7.3	6.5	5.8
Approx Total Dissolved Salts	g/m^3	47	180	49	44	39
Dissolved Arsenic	g/m^3	< 0.0010	< 0.0010	< 0.0010	< 0.0010	< 0.0010
Dissolved Cadmium	g/m^3	< 0.00005	< 0.00005	< 0.00005	< 0.00005	< 0.00005
Dissolved Calcium	g/m^3	5.7	14.0	5.8	5.4	5.3
Dissolved Chromium	g/m^3	< 0.0005	< 0.0005	0.0008	< 0.0005	0.0008
Dissolved Copper	g/m^3	0.0009	0.0027	0.0016	0.0009	< 0.0005
Dissolved Iron	g/m^3	< 0.02	0.04	< 0.02	< 0.02	< 0.02
Dissolved Lead	g/m^3	< 0.00010	0.00026	0.00012	< 0.00010	< 0.00010
Dissolved Magnesium	g/m^3	1.65	5.8	1.86	1.59	1.40
Dissolved Manganese	g/m^3	< 0.0005	0.0046	0.0010	0.0005	0.0009
Dissolved Potassium	g/m^3	0.82	5.6	0.90	0.81	0.63
Dissolved Sodium	g/m^3	6.4	29	6.5	5.5	4.7
Dissolved Zinc	g/m^3	0.0059	0.0144	0.0150	0.0053	< 0.0010
Chloride	g/m^3	4.7	29	5.5	4.0	2.9
Fluoride	g/m^3	0.07	0.05	0.07	0.07	0.06
Total Nitrogen	g/m^3	0.24	6.1	0.143	0.143	0.110
Total Ammoniacal-N	g/m^3	0.040	0.028	0.061	< 0.005 $^{\#1}$	0.005
Nitrite-N	g/m^3	0.0011	0.0016	0.0015	< 0.0010	< 0.0010
Nitrate-N	g/m^3	0.178	6.0	0.058	0.041	0.0107
Nitrate-N + Nitrite-N	g/m^3	0.179	6.0	0.059	0.042 $^{\#1}$	0.0115
Total Organic Nitrogen (TON)	g/m^3	0.022	< 0.08	0.023	0.099	0.093
Dissolved Reactive Phosphorus	g/m^3	< 0.0010	0.040	0.0013	0.0017 $^{\#1}$	< 0.0010
Total Phosphorus	g/m^3	0.007	0.153	0.004	0.005	0.004
Sulphate	g/m^3	2.0	11.5	2.8	1.8	1.4
Escherichia coli	MPN / 100mL	< 1	< 1	70	192	179

This Laboratory is accredited by International Accreditation New Zealand (IANZ), which represents New Zealand in the International Laboratory Accreditation Cooperation (ILAC). Through the ILAC Mutual Recognition Arrangement (ILAC-MRA) this accreditation is internationally recognised.
The tests reported herein have been performed in accordance with the terms of accreditation, with the exception of tests marked * or any comments and interpretations, which are not accredited.



Analyst's Comments

The sample temperature on arrival (taken from a randomly selected sample from within the batch) was 3.0°C.

The customer has indicated that the sampling time was recorded as NZ Standard Time (NZST). The sampling time has been reported as supplied in NZST. It should be noted any other times reported by Hill Laboratories will have been corrected for New Zealand Daylight Saving Time (NZDT), where applicable.

[#1] The results for the dissolved reactive phosphorus, nitrate-N + nitrite-N and Total Ammoniacal-N have been taken from the unpreserved container, as it was found that the clients filtered container had been contaminated.

Summary of Methods

The following table(s) gives a brief description of the methods used to conduct the analyses for this job. The detection limits given below are those attainable in a relatively simple matrix. Detection limits may be higher for individual samples should insufficient sample be available, or if the matrix requires that dilutions be performed during analysis. A detection limit range indicates the lowest and highest detection limits in the associated suite of analytes. A full listing of compounds and detection limits are available from the laboratory upon request.
Unless otherwise indicated, analyses were performed at Hill Laboratories, 28 Duke Street, Frankton, Hamilton 3204.

Sample Type: Aqueous

Test	Method Description	Default Detection Limit	Sample No
Otago Regional Council Groundwater SOE		-	1-5
Total Nitrogen Digestion	Caustic persulphate digestion. APHA 4500-N C 23rd ed. 2017.	-	1-5
Total anions for anion/cation balance check	Calculation: sum of anions as mEquiv/L calculated from Alkalinity (bicarbonate), Chloride and Sulphate. Nitrate-N, Nitrite-N. Fluoride, Dissolved Reactive Phosphorus and Cyanide also included in calculation if available. APHA 1030 E 23rd ed. 2017.	0.07 meq/L	1-5
Total cations for anion/cation balance check	Sum of cations as mEquiv/L calculated from Sodium, Potassium, Calcium and Magnesium. Iron, Manganese, Aluminium, Zinc, Copper, Lithium, Total Ammoniacal-N and pH (H^+) also included in calculation if available. APHA 1030 E 23rd ed. 2017.	0.05 meq/L	1-5
% Difference in Ion Balance	Calculation from Sum of Anions and Cations. Please note: The result reported for the '% Difference in Ion Balance' is an absolute difference between the 'Sum of Anions' and 'Sum of Cations' based on the formula taken from APHA. This does not indicate whether the 'Sum of Anions' or the 'Sum of Cations' produced a higher value. APHA 1030 E 23rd ed. 2017.	0.10 %	1-5
pH	pH meter. Analysed at Hill Laboratories - Chemistry; 101c Waterloo Road, Christchurch. APHA 4500-H^+ B 23rd ed. 2017. Note: It is not possible to achieve the APHA Maximum Storage Recommendation for this test (15 min) when samples are analysed upon receipt at the laboratory, and not in the field. Samples and Standards are analysed at an equivalent laboratory temperature (typically 18 to 22 °C). Temperature compensation is used.	0.1 pH Units	1-5
Total Alkalinity	Titration to pH 4.5 (M-alkalinity), autotitrator. Analysed at Hill Laboratories - Chemistry; 101c Waterloo Road, Christchurch. APHA 2320 B (modified for Alkalinity <20) 23rd ed. 2017.	1.0 g/m^3 as $CaCO_3$	1-5
Carbonate Alkalinity	Calculation: from alkalinity and pH, valid where TDS is not >500 mg/L and alkalinity is almost entirely due to hydroxides, carbonates or bicarbonates. APHA 4500-CO_2 D 23rd ed. 2017.	1.0 g/m^3 as $CaCO_3$	1-5
Bicarbonate Alkalinity	Calculation: from alkalinity and pH, valid where TDS is not >500 mg/L and alkalinity is almost entirely due to hydroxides, carbonates or bicarbonates. APHA 4500-CO_2 D 23rd ed. 2017.	1.0 g/m^3 as $CaCO_3$	1-5
Hydroxide Alkalinity	Calculation: from pH, valid where TDS is not >500 mg/L and alkalinity is almost entirely due to hydroxides, carbonates or bicarbonates. APHA 4500-CO_2 D 23rd ed. 2017.	1.0 g/m^3 as $CaCO_3$	1-5
Free Carbon Dioxide	Calculation: from alkalinity and pH, valid where TDS is not >500 mg/L and alkalinity is almost entirely due to hydroxides, carbonates or bicarbonates. APHA 4500-CO_2 D 23rd ed. 2017.	1.0 g/m^3 at 25°C	1-5
Total Hardness	Calculation from Calcium and Magnesium. APHA 2340 B 23rd ed. 2017.	1.0 g/m^3 as $CaCO_3$	1-5
Electrical Conductivity (EC)	Conductivity meter, 25°C. Analysed at Hill Laboratories - Chemistry; 101c Waterloo Road, Christchurch. APHA 2510 B 23rd ed. 2017.	0.1 mS/m	1-5
Approx Total Dissolved Salts	Calculation: from Electrical Conductivity.	2 g/m^3	1-5
Dissolved Arsenic	Filtered sample, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.0010 g/m^3	1-5
Dissolved Cadmium	Filtered sample, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.00005 g/m^3	1-5
Dissolved Calcium	Filtered sample, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.05 g/m^3	1-5
Dissolved Chromium	Filtered sample, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.0005 g/m^3	1-5

Sample Type: Aqueous

Test	Method Description	Default Detection Limit	Sample No
Dissolved Copper	Filtered sample, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.0005 g/m^3	1-5
Dissolved Iron	Filtered sample, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.02 g/m^3	1-5
Dissolved Lead	Filtered sample, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.00010 g/m^3	1-5
Dissolved Magnesium	Filtered sample, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.02 g/m^3	1-5
Dissolved Manganese	Filtered sample, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.0005 g/m^3	1-5
Dissolved Potassium	Filtered sample, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.05 g/m^3	1-5
Dissolved Sodium	Filtered sample, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.02 g/m^3	1-5
Dissolved Zinc	Filtered sample, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.0010 g/m^3	1-5
Chloride	Filtered sample. Ion Chromatography. APHA 4110 B (modified) 23rd ed. 2017.	0.5 g/m^3	1-5
Fluoride	Direct measurement, ion selective electrode. APHA 4500-F$^-$ C 23rd ed. 2017.	0.05 g/m^3	1-5
Total Nitrogen	Alkaline persulphate digestion, automated Cd reduction/sulphanilamide colorimetry. APHA 4500-N C & 4500-NO3$^-$ I (modified) 23rd ed. 2017.	0.010 g/m^3	1-5
Total Ammoniacal-N Trace	Phenol/hypochlorite colorimetry. Flow injection analyser. (NH4-N = NH4+-N + NH3-N). APHA 4500-NH$_3$ H 23rd ed. 2017.	0.005 g/m^3	1-5
Nitrite-N Trace	Automated Azo dye colorimetry, Flow injection analyser. APHA 4500-NO$_3^-$ I (modified) 23rd ed. 2017.	0.0010 g/m^3	1-5
Nitrate-N	Calculation: (Nitrate-N + Nitrite-N) - NO2N. In-House.	0.0010 g/m^3	1-5
Nitrate-N + Nitrite-N Trace	Total oxidised nitrogen. Automated cadmium reduction, flow injection analyser. APHA 4500-NO$_3^-$ I (modified) 23rd ed. 2017.	0.0010 g/m^3	1-5
Total Organic Nitrogen (TON), trace level	Calculation: TN - (NH$_4$-N + NO$_3$-N + NO$_2$-N). In-house calculation.	0.012 g/m^3	1-5
Dissolved Reactive Phosphorus (trace)	Filtered sample. Molybdenum blue colorimetry. Flow injection analyser. APHA 4500-P G 23rd ed. 2017.	0.0010 g/m^3	1-5
Total Phosphorus	Total phosphorus digestion, automated ascorbic acid colorimetry. Flow Injection Analyser. APHA 4500-P H (modified) 23rd ed. 2017.	0.002 g/m^3	1-5
Sulphate	Filtered sample. Ion Chromatography. APHA 4110 B (modified) 23rd ed. 2017.	0.5 g/m^3	1-5
Escherichia coli	MPN count using Colilert 18 (Incubated at 35°C for 18 hours) and 97 wells. Analysed at Hill Laboratories - Microbiology; 101c Waterloo Road, Hornby, Christchurch. APHA 9223 B 23rd ed. 2017.	1 MPN / 100mL	2-5
Escherichia coli	MPN count using Colilert (Incubated at 35°C for 24 hours) and 97 wells. Analysed at Hill Laboratories - Microbiology; 101c Waterloo Road, Hornby, Christchurch. APHA 9223 B 23rd ed. 2017.	1 MPN / 100mL	1

These samples were collected by yourselves (or your agent) and analysed as received at the laboratory.

Testing was completed between 16-Mar-2023 and 23-Mar-2023. For completion dates of individual analyses please contact the laboratory.

Samples are held at the laboratory after reporting for a length of time based on the stability of the samples and analytes being tested (considering any preservation used), and the storage space available. Once the storage period is completed, the samples are discarded unless otherwise agreed with the customer. Extended storage times may incur additional charges.

This certificate of analysis must not be reproduced, except in full, without the written consent of the signatory.

Ara Heron BSc (Tech)
Client Services Manager - Environmental

APPENDIX 4 FLOWTRACKER2 FLOW MEASUREMENTS

Appendix 4 is provided as an attachment in the report PDF.

www.gns.cri.nz

Principal Location

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Other Locations

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Dunedin 9054
New Zealand
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F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
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Taupo 3352
New Zealand
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F +64-4-570 4657