Groundwater lag times in the water discharges from the Whanganui, Rangitikei and Manawatu catchments

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ABSTRACT

Tritium dating of water at 29 river and stream sampling sites in the Horizons Region was undertaken during base flow conditions. The sites were located in the Whanganui, Rangitikei and Manawatu river catchments. To obtain information about the origin of the stream and river water and potential impacts by evaporation, the stable isotopes of the water molecule ^{2}H and ^{18}O were also measured.

The tritium dating results show that the mean residence times (MRT) of the water in the rivers and streams range from 0 to 11 years. Tritium ages show consistent patterns, with MRT of 6 – 7 years in the Whanganui River, 3 – 3.5 years in the Rangitikei River; and in the Manawatu catchment 9 – 11 years in the large discharges from the Tertiary sediments east of the Ruahine and Tararua ranges, 2.5 – 4.5 years in the discharges from the Tertiary sediments west of the Ruahine Range, and very young water with MRT of 0 – 2 years in the discharges from the eastern Ruahine and Tararua Ranges. The MRTs give insight into the lag times between rainfall infiltrating to groundwater and the arrival of the groundwater, and therefore nutrients associated with different land use, at the river. This lag time needs to be considered in models for prediction of land use changes on river water quality over time.

In addition to this first survey of groundwater lag time in Horizons' rivers, we recommend to analyse more samples collected at the 2013 low-flow condition to obtain the lag-time distribution through the whole region, covering all geologic formations, and to identify areas and rates of groundwater discharge into the rivers, with relevant groundwater capture zones.

KEYWORDS

Tritium dating, water lag time, catchments, stable isotopes, groundwater, surface water, land use impact

1.0 INTRODUCTION

The impact of both historic and existing land use is widely known to affect water quality throughout Horizons' Region where contaminants are readily transported via groundwater from land to lakes, rivers and streams (Horizons, 2013). This is particularly true for nitrate, arising from land use activities, which can leach out of the root zone of crops into the deeper part of the unsaturated zone and ultimately contaminate underlying groundwater resources. Known degradation of river water quality, coupled with increasing pressure from changing land use across the Region, have prompted investigations by Horizons Regional Council to better understand impacts of land use on river water quality (Roygard *et al*., 2012 and Clark and Roygard, 2013).

Developing an understanding of the transport mechanisms of contaminants such as nitrate is fundamental to understanding and effectively managing land use activities that adversely impact our surface water systems. Nitrate travels with the groundwater, and then discharges into surface water causing eutrophication of surface water bodies. To understand the source, fate, and future nitrogen loads to ground and surface water bodies, detailed knowledge of groundwater flow dynamics is essential (Morgenstern *et al.,* 2010).

In large groundwater systems, significant lag times can occur between land use intensification and the arrival of nutrients in surface water bodies. Understanding this lag time is essential to the effective management of land use activities, particularly in areas where nutrient enrichment is occurring or has the potential to occur with future development.

This project aims to determine the age of the water at various river and stream sampling sites across the Region at base flow conditions. Groundwater is feeding the rivers and streams, and the age of the water in the rivers and streams indicates how long it takes for the water, and contaminants from landuse activities, to pass through the groundwater system and eventually discharge into the surface water bodies (lag time). Tritium is used for dating the river and stream water.

With the lag time between land use change and impact on surface water quality, this study provides crucial information to inform the effectiveness of Horizon's Regional Policy and Plan ("One Plan"), particularly with regard to nutrient management, and how improvements to the Region's water quality can best be achieved. A number of areas of the Region have been delineated as "Target Water Management Sub-Zones" for nutrient management, whereby intensive farming practices will be specifically controlled under Regional Plan Rule 13.1. Nitrogen leaching limits set out in the One Plan for these target areas will ensure that discharges of nutrients to land (and subsequently water) are reduced or minimised over a twenty year period (Horizons, 2013). Establishing the lag time (via age dating) between land and surface water bodies helps to establish the effectiveness and inform the management of these rules by enabling Horizons' to determine the time between initial changes in nutrient management being made on land, and the resulting improvements in water quality of the Region's rivers, lakes, streams and aquifers.

2.0 METHODS

The tritium method was used to date the water in the streams and rivers [Morgenstern *et al.,* 2010]. Tritium is produced naturally in the atmosphere by interaction of cosmic rays with atmospheric particles and subsequently incorporated into meteoric water. Once the rain water infiltrates into the ground and is separated from the atmosphere, the tritium concentration in the water starts to decrease due to radioactive tritium decay. With its half-life of 12.32 years, tritium dating can cover the age range 1 – 150 years.

Tritium dating utilises convolution of the known tritium input via the rain into the groundwater, with a suitable system response function, and matching to the tritium concentration measured in the groundwater. Tritium in rain has been measured at various monitoring stations throughout New Zealand, mainly in Kaitoke Regional Park 40 km north of Wellington, in monthly rain samples since 1960. The Kaitoke tritium input can be scaled to other regions in New Zealand and is about 2 TR around the Horizons region. The Exponential Piston flow Model system response function was used for age interpretation, with 70% exponential flow volume within the total flow volume (Morgenstern *et al.,* 2010).

To obtain information about the origin of the stream and river water and potential impacts by evaporation, the stable isotopes of the water molecule ^{2}H and ^{18}O were also measured.

3.0 SETTING

3.1 GEOLOGY AND HYDROGEOLOGY OF THE WHANGANUI, RANGITIKEI AND MANAWATU CATCHMENTS

The area consists mainly of Tertiary and Quaternary marine sediments bisected by a central backbone of Triassic to early Cretaceous greywacke rocks which form the axial ranges (Figure 1; Begg and Johnston, 2000 and references therein). East of the ranges, a foreland fold and thrust belt lies above the Hikurangi subduction zone. Cretaceous to Neogene sediments form most of the eastern foreland area, which is cut by many NE-SW striking faults, responsible for forming localised basins and depocentres throughout the Neogene. West of the ranges, marine Neogene rocks of the Whanganui Basin were deposited in relative tectonic quiescence. Volcanic rocks (lavas and volcanic sediments) of the Taupo Volcanic Zone predominate in the north. Quaternary marine terraces are extensive in the west and Quaternary alluvium has been deposited adjacent to rivers throughout the entire area.

East of the axial ranges, most major drainages are aligned NE-SW with the tectonic grain of the landscape until they cut gorges through uplifted blocks. West of the ranges most rivers drain SW, across the tilted Neogene marine strata.

In general, younger clastic sediments, including sand and gravel, will have the highest permeability. However, in many places these young permeable rocks will be thin (e.g., alluvial gravels may be up to a few metres thick). Tertiary sandstone and limestone will have moderate to high permeability, whereas finer grained or poorly sorted sediments such as silt, clay and mud will have lower permeability. Lithified or indurated rocks may have high or low permeability, depending on jointing and fracture density; more joints will allow more connected pore space.

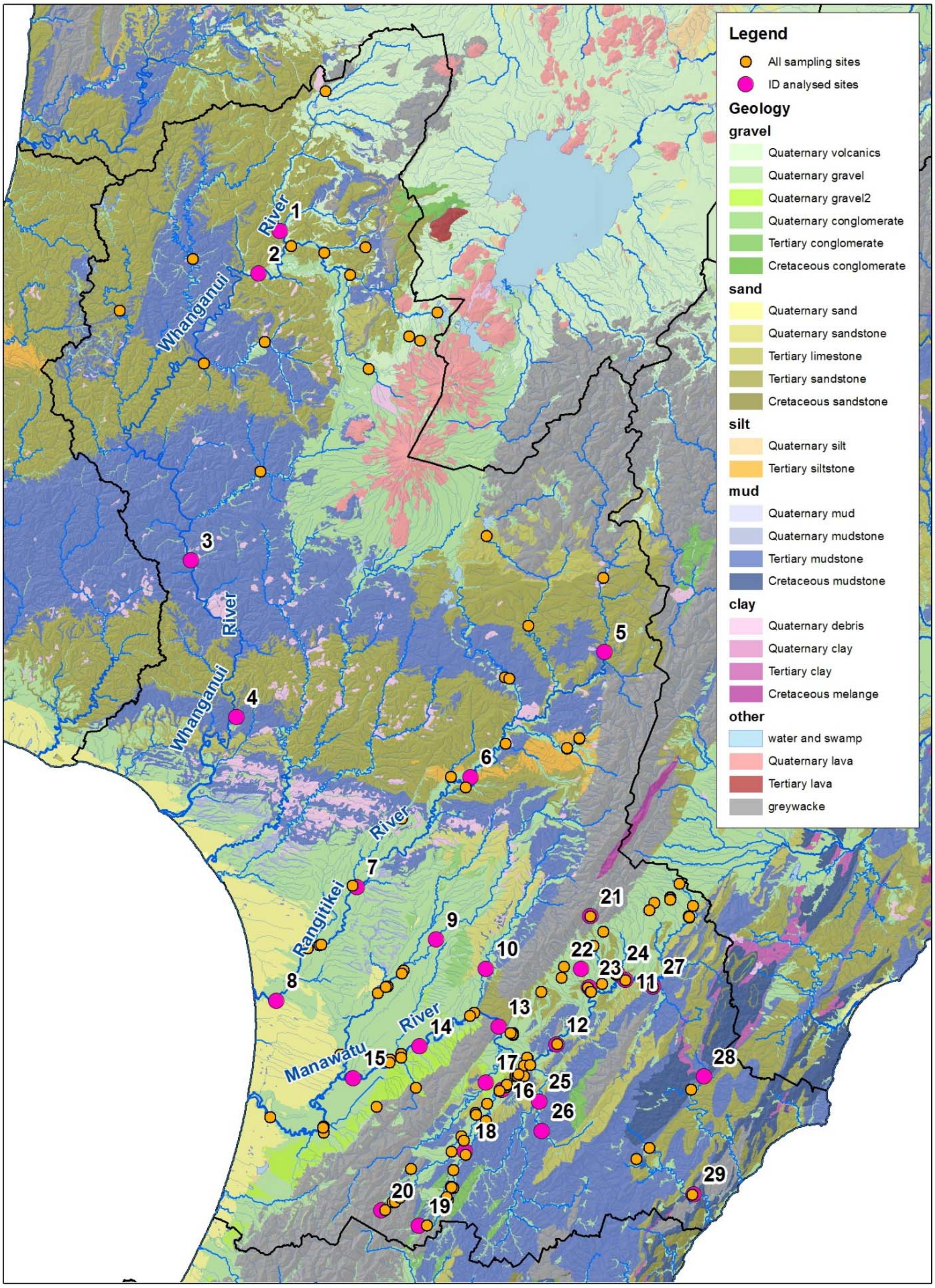

Figure 1 Map of surface geology and sampling locations for the Horizons region. Label numbers refer to ID in Table 1. Red symbols are sites with age data. Yellow symbols are additional sites that were sampled at low flow conditions.

Catchments with the impermeable basement rock near the surface or covered with only a thin layer of high-permeability gravels are expected to have very little water retention time and low mean residence time of the main water discharges from the catchment. Tertiary sandstone and limestone sediments with moderate to high permeability may let a significant fraction of the rain infiltrate into the geologic formation, and discharge the water after years or decades of travel time through the formation. These catchment dynamics are still very poorly understood internationally. Therefore the age tracer tritium was measured in rivers and streams of the Horizons region to shed light into the residence times of the water in the various geologic formations.

3.2 SAMPLING SITES AND FLOW CONDITIONS

Samples from 161 sites were collected by Horizons Regional Council during low base flow conditions in March 2013, of which, 29 samples were selected for initial tritium analysis and subsequent age interpretation. These 29 sites include four sites along the Whanganui River, four sites along the Rangitikei River, twenty sites in the Manawatu catchment, and one site near the East Coast. Sampling locations for the sites, with age interpretation results, are shown by red symbols in Figure 1, and the additional site locations where samples are available are shown with yellow small symbols. Appendix 1 shows the available river flow data in relation to the sampling date (represented by red circles), demonstrating that all samples were collected at low base flow conditions when surface water samples are less likely to be affected by rainfall runoff, and instead present a representative picture of aquifer conditions. Appendix 2 shows photos of the sampling sites that have age data. Site names, coordinates, and sampling dates of the sites with age data are listed in Table 1.

4.0 RESULTS AND DISCUSSION

Analytical results for ^{18}O, ^{2}H, and tritium are listed in Table 1.

Table 1 Sample names, coordinates, date of sampling, $^{18}O/^{2}H$/tritium results, and mean residence time. ‰- notation according to Stewart and Morgenstern [2001], TR = Tritium Ratio according to Morgenstern *et al.,* [2010], with one TR corresponding to an atomic ratio of tritium/total hydrogen of 10^{-18}, and a tritium concentration of 0.11919 Bq/kg. Sig = one sigma error, and MRT = mean residence time in years.

ID	Site Name	E	N	Date	$\delta^{18}O$ [‰]	$\delta^{18}O$ [‰]	T code	TR	sig	MRT [y]
1	Ongarue @ Taringamotu	2704300	6257800	13/03/2013	-6.02	-33.8	TPN108	1.316	0.032	**7**
2	Whanganui @ Te Maire	2699800	6249000	13/03/2013	-6.80	-39.3	TPN109	1.363	0.034	**6**
3	Whanganui River @ Pipiriki	2685900	6189700	14/03/2013	-6.44	-37.0	TPN105	1.372	0.035	**6**
4	Whanganui River @ Te Rewa	2695200	6157300	14/03/2013	-6.29	-36.9	TPN106	1.379	0.036	**6**
5	Rangitikei @ Pukeokahu	2771329	6170723	6/03/2013	-7.86	-49.9	TPN92	1.661	0.039	**3.5**
6	Rangitkei @ Otara	2743600	6144900	6/03/2013	-7.66	-48.1	TPN93	1.704	0.04	**3**
7	Rangitikei @ Onepuhi	2720100	6122200	7/03/2013	-7.41	-47.3	TPN94	1.62	0.039	**3.5**
8	Rangitkei @ McKelvies	2703430	6098660	7/03/2013	-7.19	-45.7	TPN95	1.655	0.04	**3**
9	Oroua @ Almadale Slackline	2736539	6111346	14/03/2013	-6.87	-42.0	TPN115	1.65	0.039	**2.5**
10	Pohangina @ Mais Reach	2746800	6105300	13/03/2013	-6.52	-39.7	TPN111	1.465	0.033	**4.5**
11	Manawatu @ Weber Road	2775551	6102930	15/03/2013	-6.16	-37.8	TPN116	1.112	0.03	**11**
12	Manawatu @ Hopelands Res.	2761325	6089635	11/03/2013	-5.98	-36.5	TPN96	1.469	0.036	**4.5**
13	Manawatu @ upper Gorge	2749400	6093300	13/03/2013	-5.68	-33.9	TPN112	1.441	0.034	**5**
14	Manawatu @ Teachers College	2733100	6089200	13/03/2013	-5.80	-35.2	TPN113	1.335	0.032	**6**
15	Manawatu @ Opiki Bridge	2719352	6082711	14/03/2013	-5.80	-35.1	TPN114	1.3	0.036	**7**
16	Mangatainoka @ Pahiatua Town bridge	2750100	6080200	12/03/2013	-5.27	-30.7	TPN102	1.807	0.043	**0-1**
17	Mangahao @ Ballance	2746800	6081827	12/03/2013	-4.74	-26.0	TPN99	1.695	0.04	**0-1.5**
18	Makakahi @ Hamua	2742400	6067600	12/03/2013	-4.13	-26.2	TPN101	1.828	0.043	**0**
19	Makakahi @ end Kaiparoro Rd.	2732873	6052127	12/03/2013	-6.03	-33.4	TPN107	1.919	0.039	**0**
20	Mangatainoka @ Tararua Park (Putara)	2725236	6055317	12/03/2013	-5.77	-32.5	TPN100	1.684	0.04	**0-2.5**
21	Tamaki @ Tamaki Res.	2768395	6116140	11/03/2013	-7.04	-40.1	TPN97	2.104	0.046	**0**
22	Kumeti @ Te Rehunga	2766407	6105229	11/03/2013	-6.69	-37.4	TPN98	2.11	0.047	**0**
23	Oruakeretaki @ SH2	2768080	6101400	15/03/2013	-5.18	-31.2	TPN118	1.944	0.044	**0**
24	Raparapawai @ Jackson Road	2773900	6104400	15/03/2013	-6.32	-37.5	TPN117	1.892	0.04	**0**
25	Tiraumea @ Ngaturi	2757751	6077877	12/03/2013	-6.37	-36.6	TPN103	1.099	0.032	**11**
26	Makuri @ Tuscan Hills	2758334	6071775	12/03/2013	-6.48	-36.9	TPN104	1.117	0.032	**10.5**
27	Mangatoro @ Mangahei Road	2781312	6101603	15/03/2013	-6.40	-37.0	TPN110	1.184	0.031	**9.5**
28	Akitio @ Weber Road	2791796	6083028	1/03/2013	-2.37	-19.7	TPN90	1.558	0.037	**4**
29	Owahanga @ Branscombe Bridge	2789657	6058717	1/03/2013	-0.84	-10.1	TPN91	1.928	0.043	**0**

4.1 STABLE ISOTOPES

Most of the stable isotope data (Figure 2) plot along the local meteoric water (LMW) line D=8x^{18}O+13 (Stewart and Morgenstern, 2001), indicating these data are not significantly impacted by evaporation despite very dry conditions at the time of sampling. However, the data from 3 sites (site IDs 18, 28, 29) divert from the MLW, with a slope of 5, indicating impact by evaporation. These are sites with extremely low flow at the time of sampling. The sites with the lowest flows (sites 28 and 29 with flows of 7 L/s and 1 L/s respectively) show the greatest deviation from the LMW. Such low water flows in large stream beds are likely to be impacted by evaporation under dry conditions.

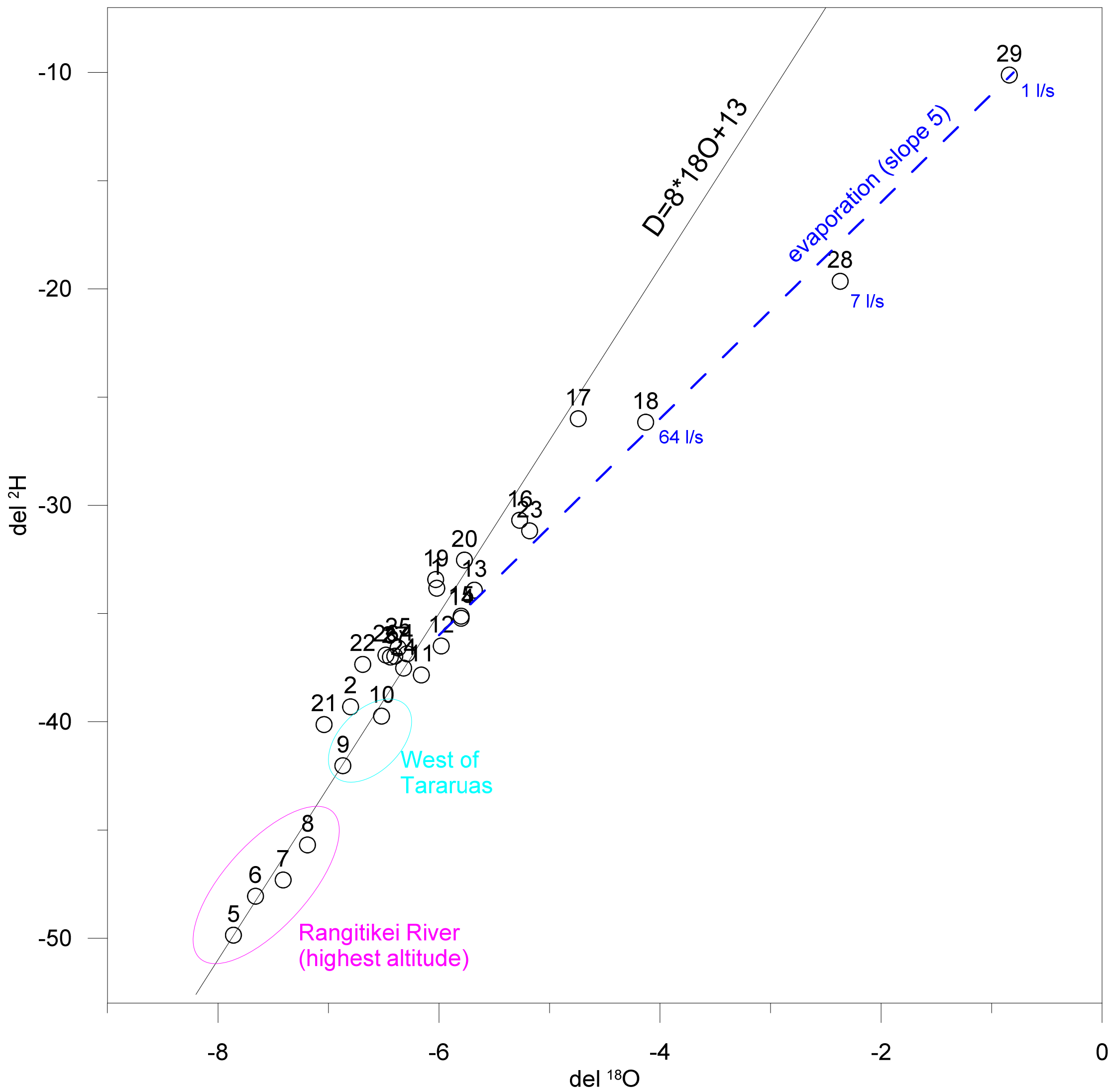

Figure 2 Stable isotope results. Labels refer to ID in Table 1.

Tritium in rain near the coast can potentially be diluted by direct input of low-tritium oceanic moisture. On the other hand, high-altitude rain, also characterised by a more negative stable isotope composition, is less diluted by direct input of low-tritium oceanic moisture. The samples from the Rangitikei River (site IDs 5 – 8) show the most negative stable isotope concentrations, consistent with the fact that the Rangitikei River originates from the highest altitude with the most negative stable isotope composition in the North Island (Stewart and Morgenstern, 2001). This hydrologic system is expected to have the least dilution by low-tritium oceanic moisture. The stable isotope composition of the four Rangitikei River sites (in order of lowest to highest altitude, IDs 8, 7, 6 and 5) become increasingly negative with an increase in altitude. The samples with rain origin in the west of the Tararuas (site IDs 9 and 10) also show more than average negative stable isotope composition.

4.2 MEAN RESIDENCE TIME OF THE WATER

For age interpretation, an exponential piston flow model was used with 70% exponential flow volume within the total flow volume (Maloszewski and Zuber, 1982; Morgenstern *et al.,* 2010). The tritium input function from Kaitoke was scaled with factor 0.93 – 1.00 to adjust for local tritium deposition patterns. Calculated mean residence times (MRT) in years are listed in the last column of Table 1 and are shown in Figure 3.

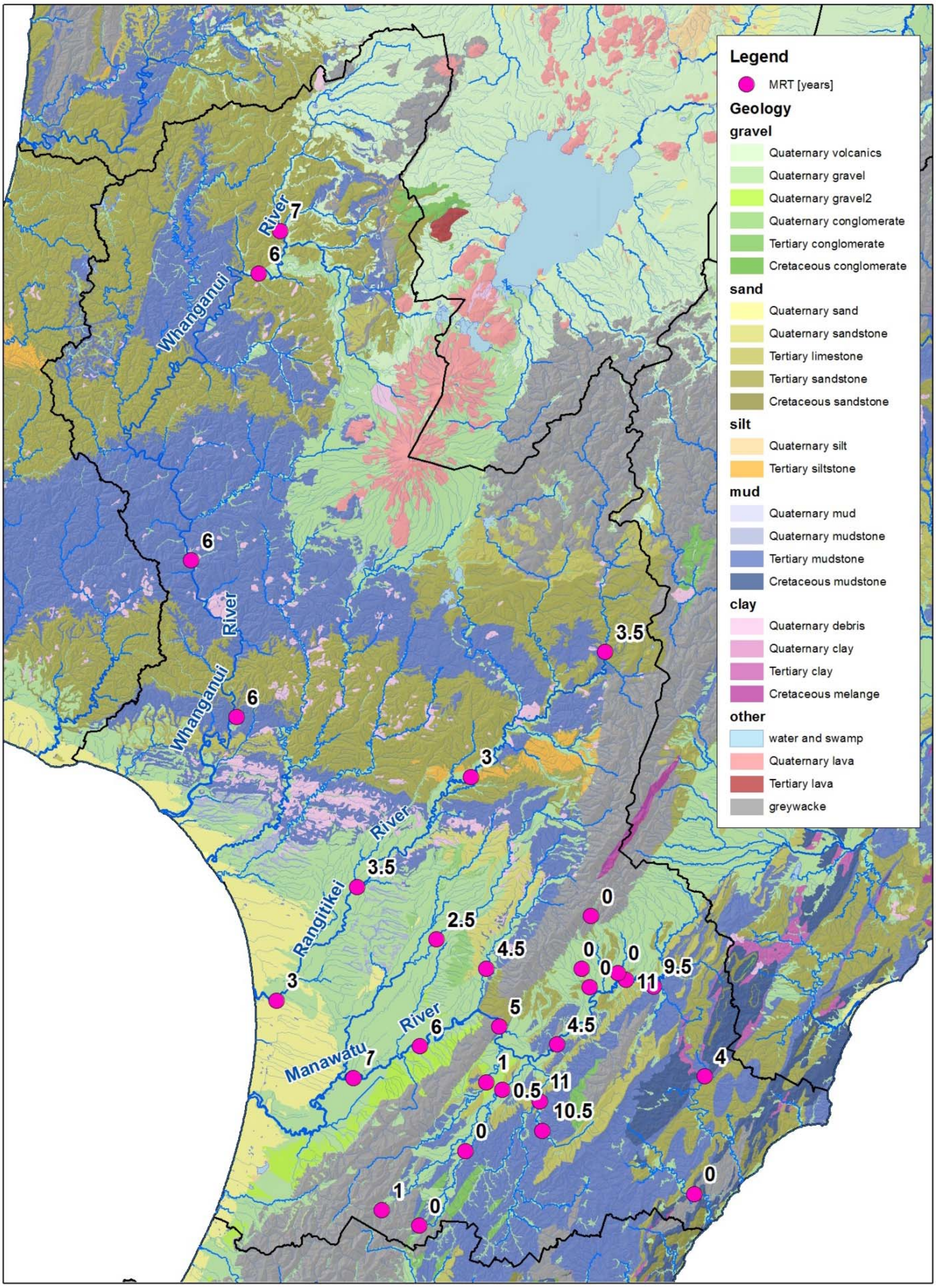

Figure 3 Mean residence time (labels, in years) for sampling sites of rivers and streams.

In general, the MRT as derive from tritium show consistent patterns, with MRT of 6 – 7 years in the Whanganui River, 3 – 3.5 years in the Rangitikei River, and in the Manawatu catchment 9 – 11 years in the large discharges from the Tertiary sediments east of the Ruahines and Tararuas, 2.5 – 4.5 years in the discharges from the Tertiary sediments west of the Ruahines, and very young water with MRT of 0 – 2 years in the discharges from the Eastern Ruahines and Tararuas.

The streams east of the Ruahines (site IDs 21 – 24) discharge very young water of 0 years. The discharges directly in the headwaters from the greywacke basement rock formation are expected to be very young. Further downstream after the streams have passed through the Quaternary sediment formations, the water in the streams is still very young despite that these sediments have the highest permeability. Such short residence in these water discharges indicates that the main water flow is very shallow or via the surface stream. The streams in the east of the Tararuas (site IDs 16 – 20) also discharge very young water but slightly older with MRT 0 – 1 years.

The upper Manawatu River and tributaries from the sand- and mudstone formation (site IDs 11 and 25 – 27) contain older water of MRT 10 – 11 years. This indicates that this geologic unit allows easier infiltration of rain water into a large storage capacity groundwater system.

Towards the gorge (site IDs 12 and 13), the water in the Manawatu River becomes younger, with MRT of 4 – 5 years due to input of the very young water via tributaries from the eastern Tararua and Ruahine ranges (see above).

Downstream of the gorge (site IDs 14 and 15), the Manawatu river water is slightly older again with MRT of 6 – 7 years. This older water in the river may be caused by (1) contribution of old water to the river via the Tokomaru sand aquifer, and/or (2) para-fluvial flow through enhanced river-groundwater interaction in the gravel outcrop area between the gorge and the Teachers college. Enhanced river-groundwater interaction with part of the river water flowing through the shallow gravels has potential to add a mean residence time of 1 – 2 years to that of the river water. This hypothesis of para-fluvial flow may be confirmed via radon measurements along the whole Manawatu River. Radon accumulates in subsurface water, leading to elevated radon concentrations in groundwater compared to those of surface water. Therefore, elevated radon in the river would indicate areas of enhanced river-groundwater interaction in the gravel outcrop areas.

The most eastern water samples are rather young. However, with only two samples in this area of complex geology it is difficult to obtain general patterns. The sample at site 29, with MRT of 0 y, indicates straight drainage of the water from a catchment of little water storage capacity, probably due to the greywacke basement formation being close to the surface. The sample at site 28, with MRT of 4 y, indicates discharge from a catchment with higher water storage capacity, and that the Cretaceous mudstone “basement” rocks have a larger water storage capacity than the greywacke. However, the water is significantly younger compared to the discharges further west from the same formation.

In summary, at low baseflow conditions, there is a considerable lag time of 6 – 11 years of water discharges, and therefore nitrate discharges, from land to the Manawatu and Whanganui rivers. This lag time needs to be considered in models for prediction of land use changes on river water quality. These low-flow conditions, with high lag time, may not contribute a large fraction of the total discharge. However, riverine health in summer, when the rivers are most used for recreation, is controlled by lagged response to land use changes.

4.3 AGE DISTRIBUTION

Riverwater comprises a mixture of water of different ages due to mixing of water from different length underground flow paths. Therefore, the groundwater doesn't have a discrete age but has an age distribution or spectrum, with one parameter the mean residence time, and a second parameter that describes the mixing for different hydrogeological situations (Maloszewski and Zuber, 1982).

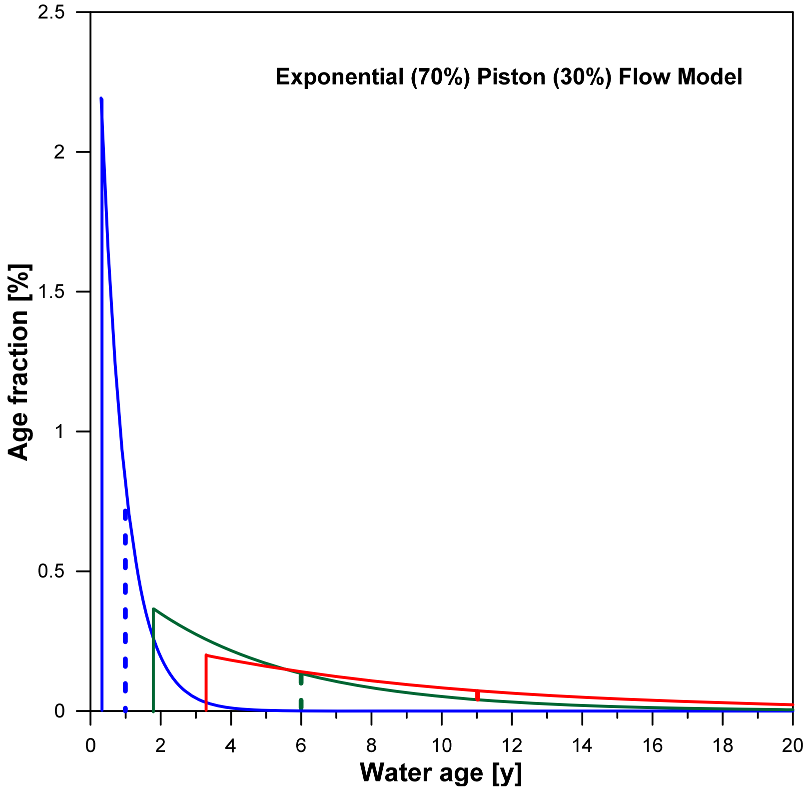

Figure 4 Age distribution for the exponential piston flow model with 70% exponential flow within the total flow volume. Blue curve MRT = 1y, green curve MRT = 6 years, and red curve MRT = 11 years.

Figure 4 shows three examples of age distributions found in the rivers in the Horizons region. The blue curve represents the age distribution for the water discharges with very young water of MRT = 1 year, the green curve for water discharges of MRT = 6 years, and the red curve for water discharges of MRT = 11 years. The mean residence time is indicated for each age distribution curve by the broken line (same colour). Note that for example for the age distribution with MRT = 11 years (red curve), there is water present in this discharge with ages significantly younger than 11 years, and there is also a tail of old water. No water in this discharge is younger than 3.3 years, the piston flow component which for this model is 0.3 * MRT. 3.3 years after an event, contaminants will start breaking through into this water discharge (at baseflow). Contaminant concentrations in the water discharge will build up slowly over time, due to the presence old pristine groundwater which will dilute the contaminated water for some time. On the other hand, once the pristine groundwater is completely displaced by contaminated water, the same time scales are required to flush out the contaminated groundwater. For the water discharge with MRT 1 year (blue curve), 90% of the event water is flushed through the groundwater system after 2 years, for MRT 6 years (green curve) it takes 12 years, and for MRT 11 years (red curve) it takes 21 years. These lag times between changes in nutrient application on land, and the resulting improvements in water quality of the Region's rivers, lakes, streams and aquifers have to be included in land management models.

5.0 RECOMMENDATIONS

In addition to this first survey of groundwater lag time in Horizons' rivers, we recommend to analyse more samples collected at the 2013 low-flow condition to obtain the lag-time distribution through the whole region, covering all geologic formations, and to identify areas and rates of groundwater discharge into the rivers, with relevant groundwater capture zones.

5.1 LAG TIME IN RELATION TO GEOLOGY

For improved land and water management establish the lag time of the water discharge for the various geologic formations. A unique set of river and stream water samples collected during low baseflow in March 2013 is available (Figure 5, age results together with additional sampling sites), and the following additional tritium samples are recommended for analysis - from North to South:

1) At least one sample from the volcanics NW of Lake Taupo. No sample is yet available from the ignimbrite. These water discharges are expected to be very old, in the order of decades;
2) Several samples from the mudstone formation in the Whanganui catchment. Do the discharges from the mudstone formation show similar lag times compared to sandstone? The so far analysed samples from the Whanganui River show consistent pattern but are more representative of sandstone;
3) A few samples from the NW flanks of Tongariro. No data are yet available from the lava formation;
4) A few samples from tributaries of the Rangitikei River. Is the lag time for the various geologic formations in the Rangitikei catchment uniform, and the younger age by factor two compared to the Whanganui River potentially caused by shallower depth to the greywacke basement?
5) A few samples to extend the data to the Northern end West of the Ruahines;
6) A few additional samples west of the Tararuas to understand why the water discharges West of the Tararuas are slightly older compared to West of the Ruahines;
7) A few samples from the two branches of the Mangatainoke catchment for comparison because one is more influenced by greywacke basement, the other by gravel and mudstone;
8) A few samples from near the East Coast. This is an area of complex geology and the only available date is significantly younger than the discharges further west from the same formation.

5.2 POTENTIAL FOR DENITRIFICATION

Evaluate the potential for anaerobic denitrification in the groundwater systems, including the consideration that anoxic groundwater systems often contain significantly older water compared to overlaying oxic layers, indicating that nitrate-rich water may not flow efficiently through these anoxic zones and therefore denitrification may be insignificant.

5.3 GROUNDWATER INFLUX HOT SPOTS

Perform radon survey along the main rivers to identify areas of groundwater influx. Radon-222, a decay product of uranium which is part of the minerals in the earth’s crust, occurs in high concentration in groundwater due to release of radon from the uranium bearing minerals. Radon is a gas, and after groundwater discharges into the surface water, the radon is lost to the atmosphere through degassing, resulting in low concentrations of radon in surface water. This contrast of high radon concentration in groundwater and low concentration in river, stream, and lake water enables identification of groundwater discharges to surface water and recharge of surface water to groundwater.

Undertake fibre optic distributed temperature sensing (FODTS) in stream reaches where radon screening indicates groundwater inflow occurs. FODTS utilises the temperature contrast between surface- and ground-water to identify locations of groundwater discharge to the stream. The rate of discharge at each location can then be easily and accurately calculated using a mass energy balance approach. The technique quickly detects very small changes in temperature (~0.03 ^{o}C) over large distances (up to 5 km), which makes it ideal for detailed characterisation of groundwater discharge into streams, which would be impractical by traditional methods such as concurrent gauging.

5.4 Radon And Noble Gases For Detailed Groundwater Influx/Loss

In areas where rivers potentially lose water or have preferential influx or loss from/to one bank, perform radon survey with higher analytical sensitivity. This should enable us to distinguish between losing and neutral stretches of the river, and to identify from/to which side of the river the groundwater influx/loss occurs. Test applicability of other gases (Ar, N_2, Ne) for identification of groundwater discharge to rivers (MSc Heather Martindale).

5.5 Surface Water-Groundwater Interaction Identification Via HCA

Compile existing and new hydrochemistry data in the region including surface and groundwater for a comprehensive hydrochemistry cluster analysis (HCA) in order to determine the aquifer that supplies the inflowing groundwater, and/or estimate the land area that contributes the recharge that passes through the aquifer and ultimately discharges into the river at the points that the samples were collected. If at the time of 2013 low-flow tritium sampling also standard hydrochemistry samples had been collected, then HCA should be conducted, with comparison to previous HCA on groundwater in the region (Daughney *at al.,* 2009).

5.6 Hydrochemistry Age Proxy

Check for any significant relationships between concentrations of major cations/anions/silica and water age. This is to build a regression that might be used to estimate the water age even if age tracer concentrations haven't been measured.

5.7 Temporal Variations To Enable Calibration Of Transient Coupled Gw-Sw Models

Collect samples for radon, tritium and hydrochemistry bimonthly over one year at baseflow, from ca. 5 – 10 locations with enhanced inflow of old groundwater. Groundwater age is not constant: it changes depending on flow [Morgenstern *et al.,* 2010]. All the samples should be collected under baseflow conditions but at different rates of flow to establish relationships between water age, hydrochemistry and flow rate at selected locations in the region.

5.8 Capture Zones

Evaluate the capture zones/areas for the GW that is infiltrating into the rivers. This would involve modelling using Horizons GW models. The objective is to map the area in which land use activities could affect the quality of GW that is flowing into the rivers at each location. The hydrochemistry would assist with this, but only the modelling would provide maps of the capture zones.

5.9 SOCIOECONOMIC BENEFITS

All of the above information should be wrapped up into a socioeconomic assessment derived from current land and water management strategies to enable optimising policy options in terms of socioeconomic benefits, e.g., improved water quality, for the region or sub-regions.

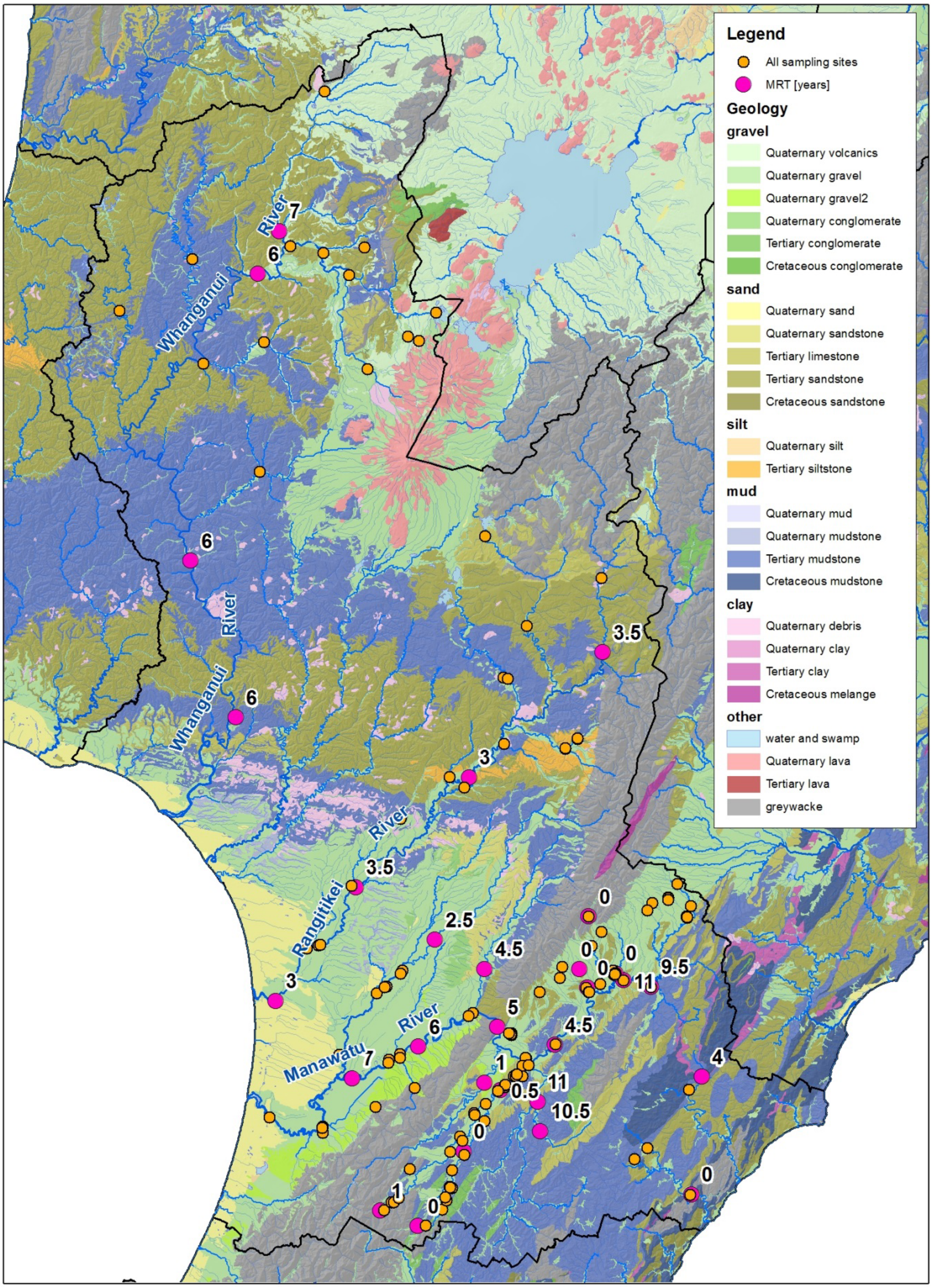

Figure 5 Water age results (red circles, labels are MRT in years) together with additional available samples (yellow circles).

6.0 ACKNOWLEDGEMENTS

We would like to thank the Horizon catchment data team for carrying out the sampling campaign at the right time of low-flow condition in the rivers, and Troy Baisden and Mike Stewart (GNS Science) for useful suggestions.

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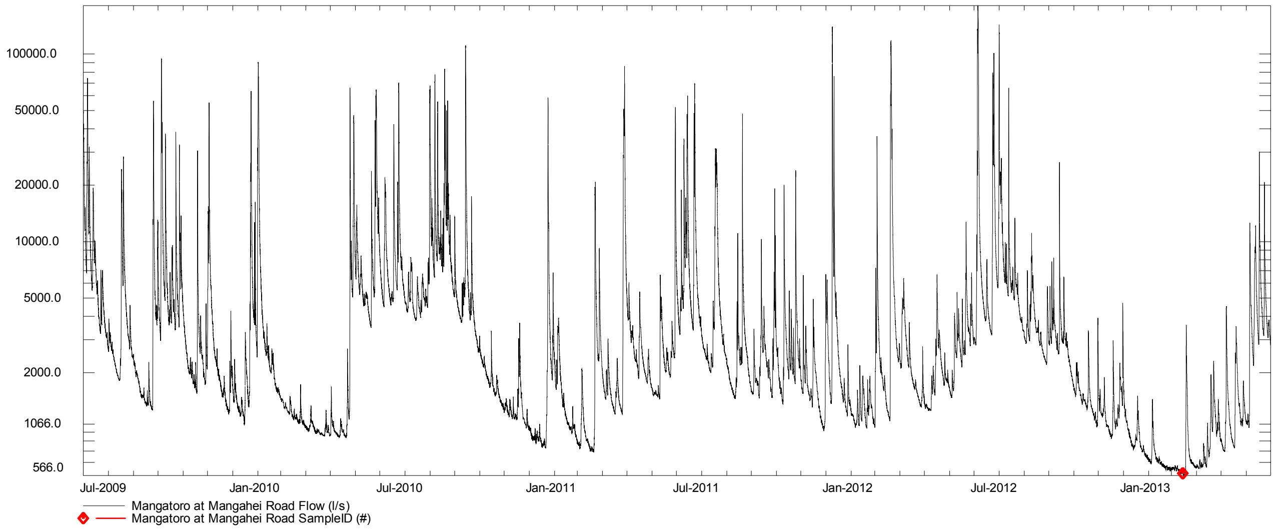
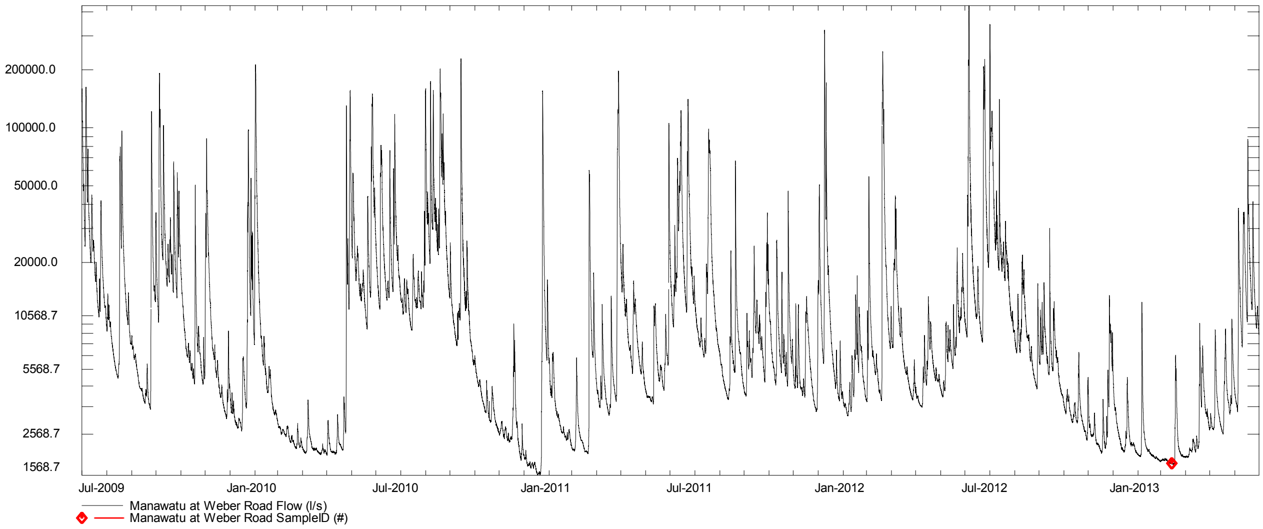
APPENDICES

APPENDIX 1: RIVER FLOWS AT VARIOUS GAUGING SITES, WITH RED CIRCLE SHOWING DATE OF SAMPLING. ALL SAMPLES WERE COLLECTED AT LOW-BASEFLOW CONDITION.

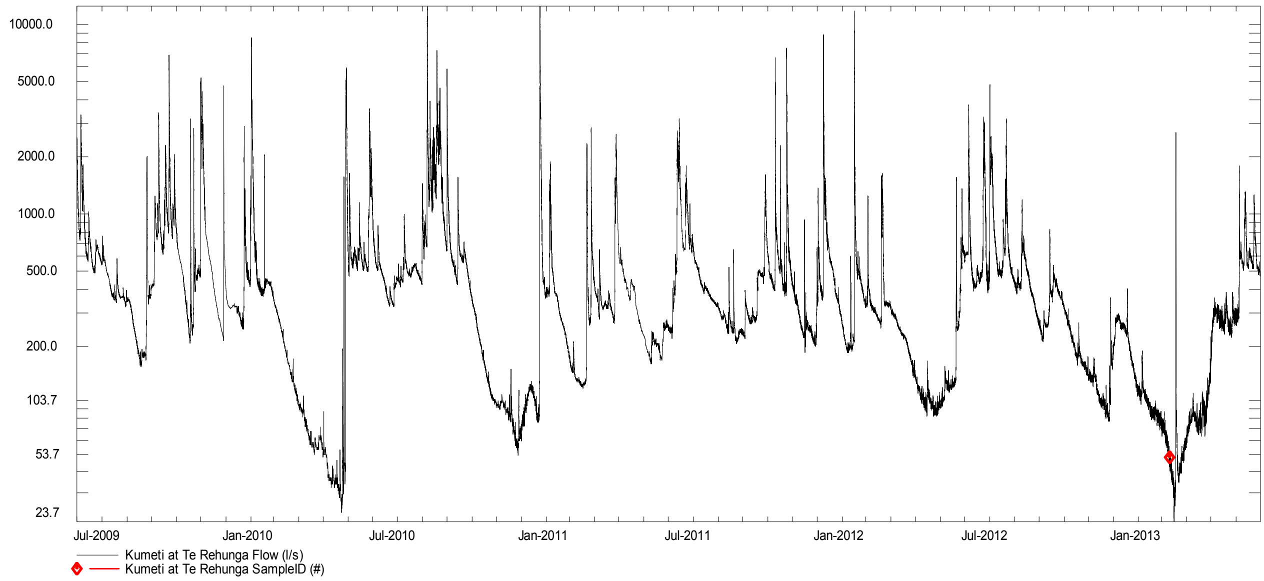
Mangatoro at Mangahei Road



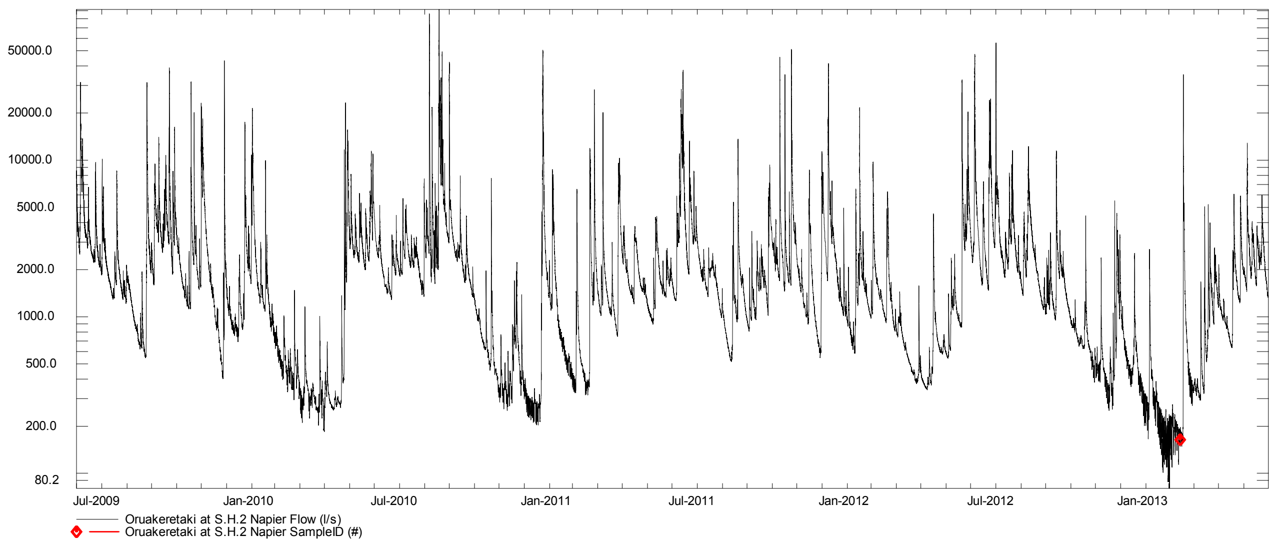
Manawatu at Weber Road



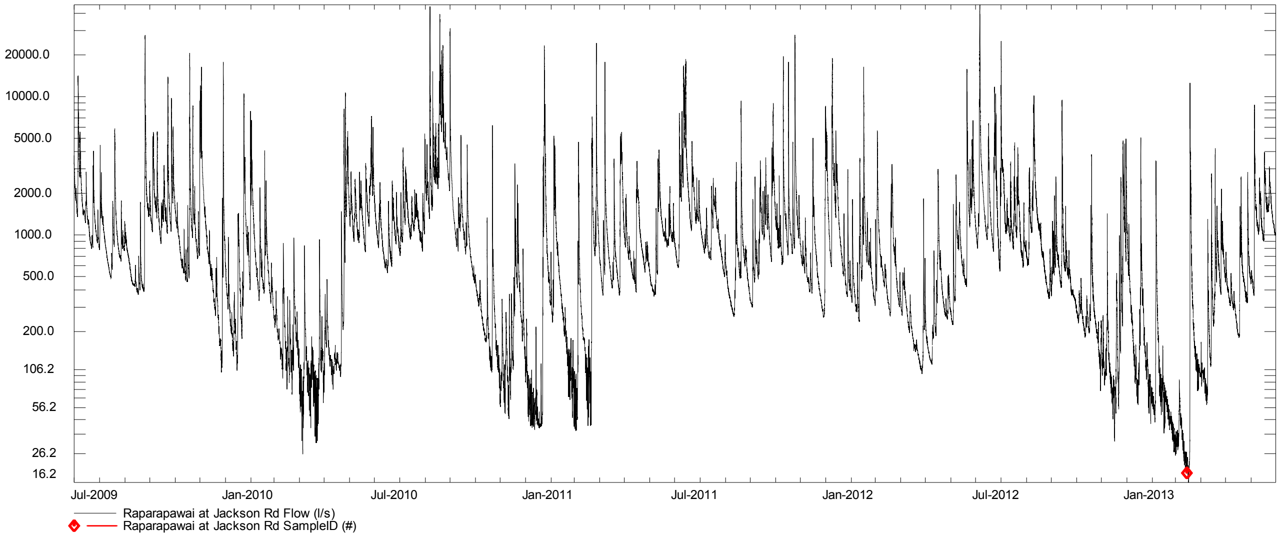
Kumeti at Te Rehunga



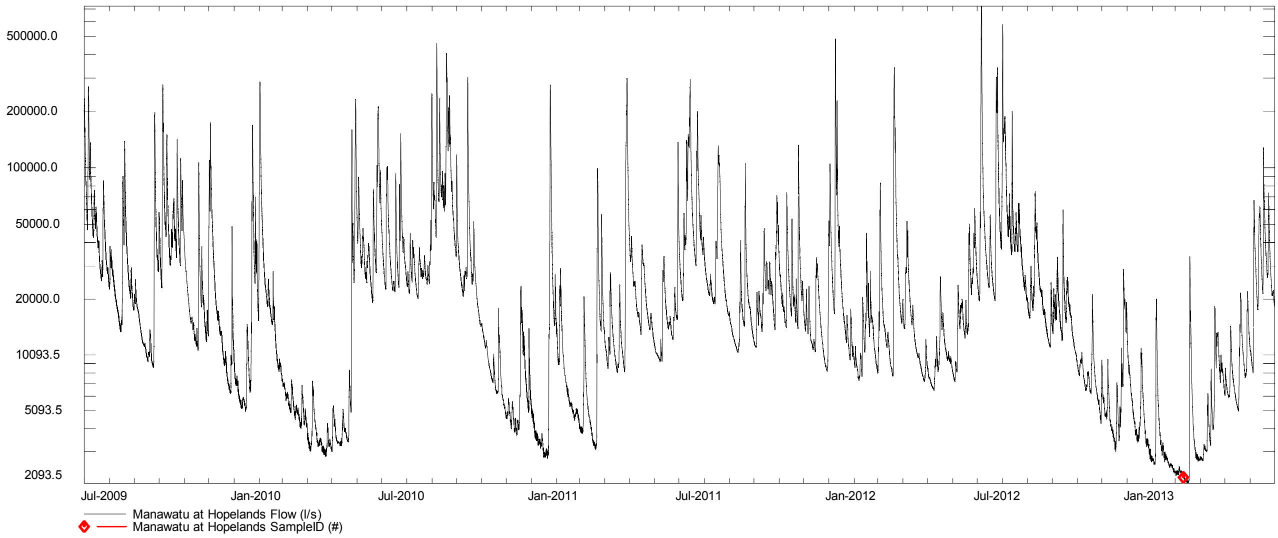
Oruakeretaki at S.H.2 Napier



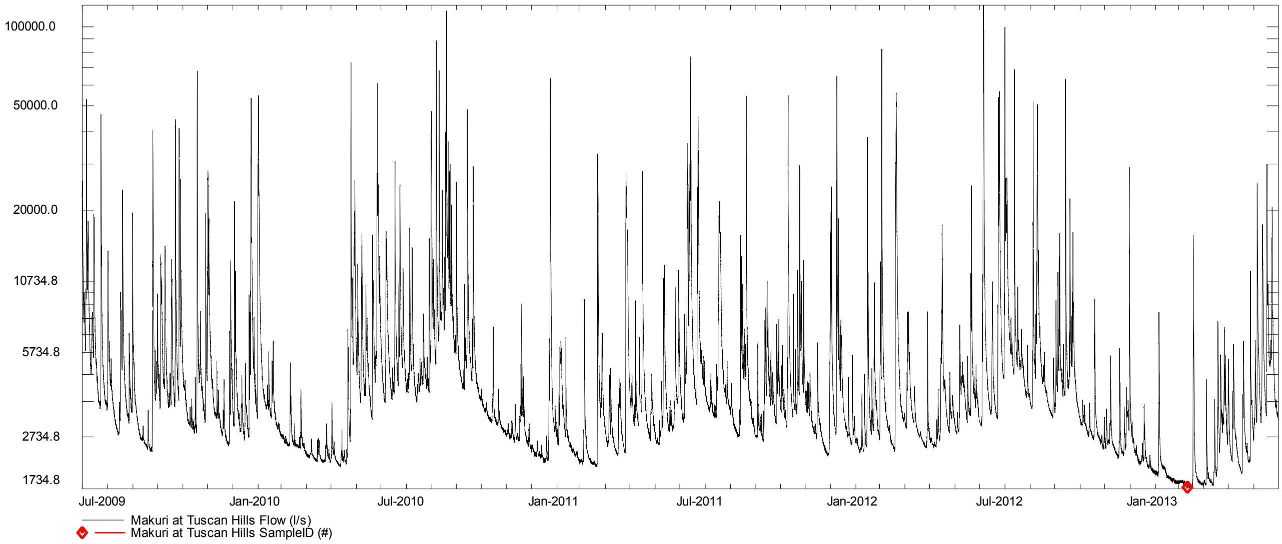
Raparapawai at Jackson Rd



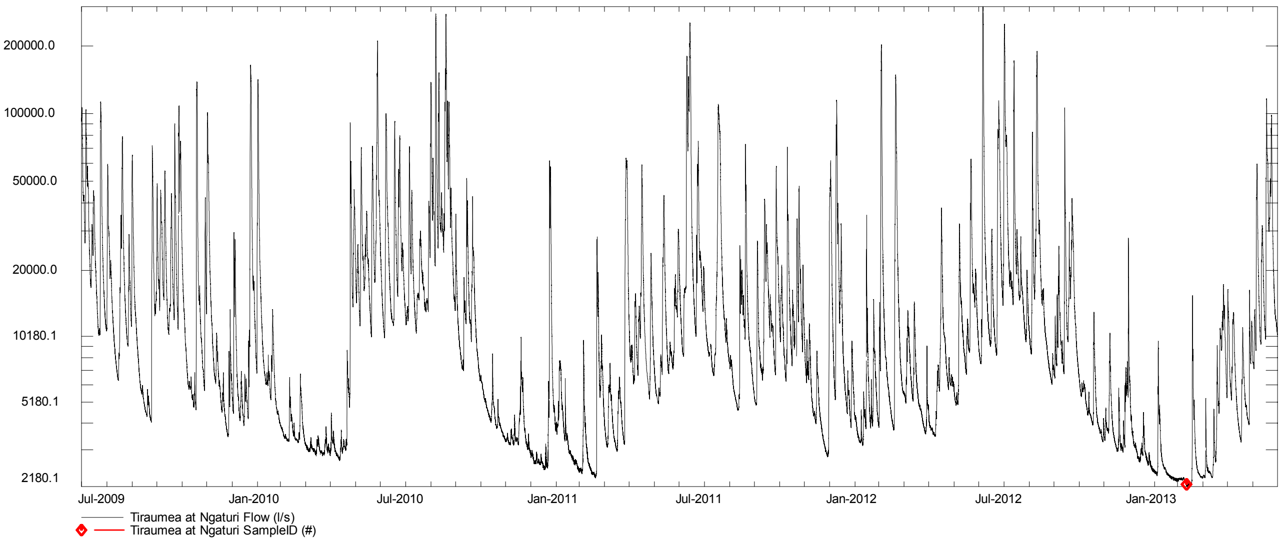
Manawatu at Hopelands



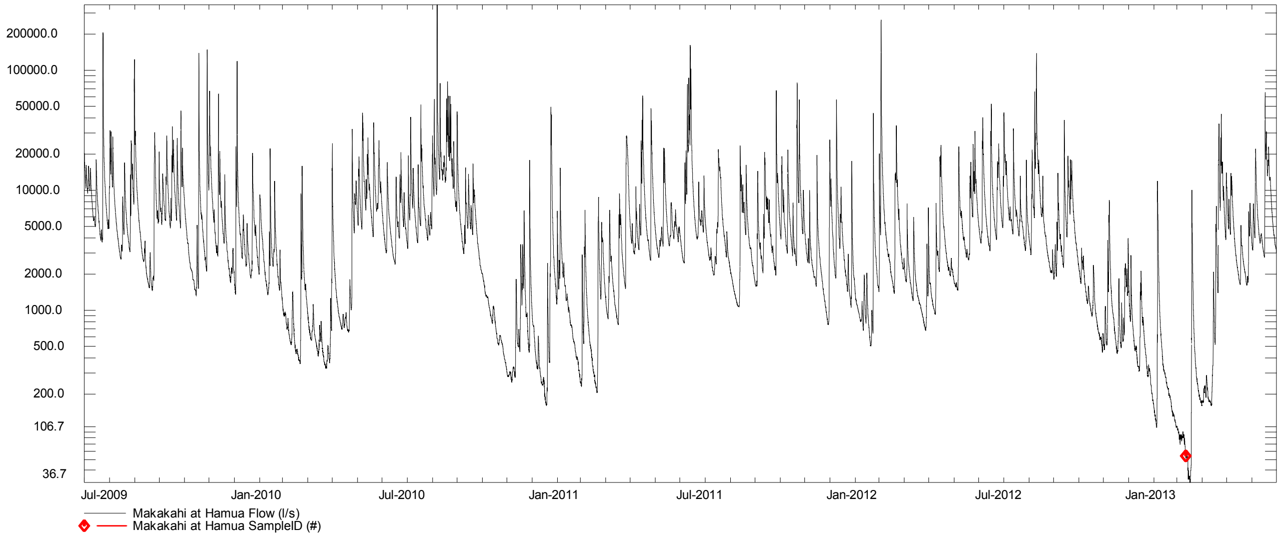
Makuri at Tuscan Hills



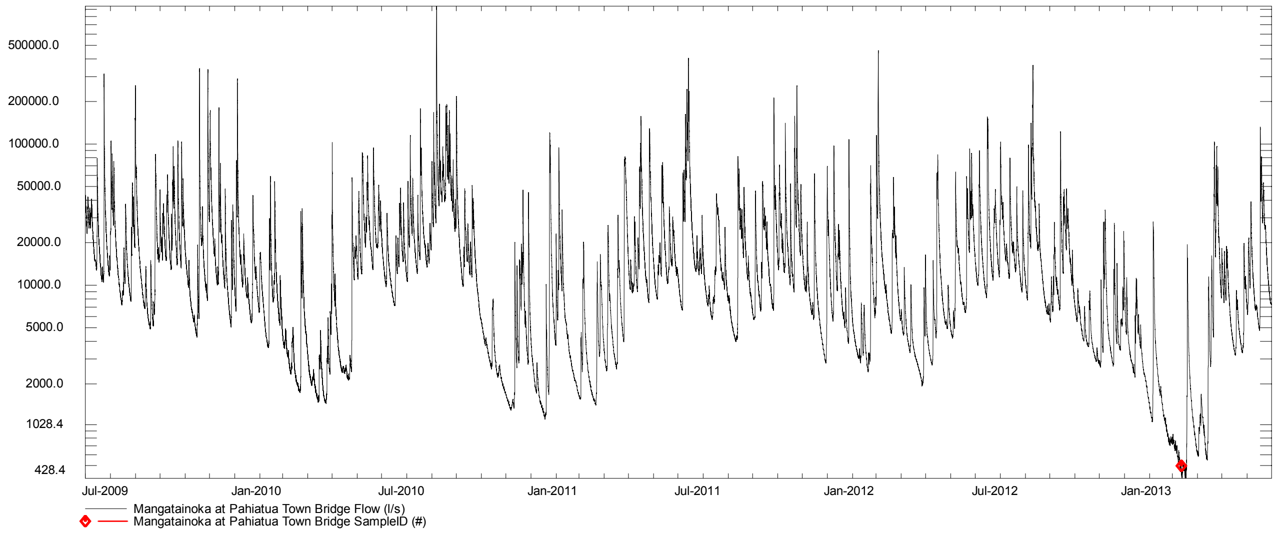
Tiraumea at Ngaturi



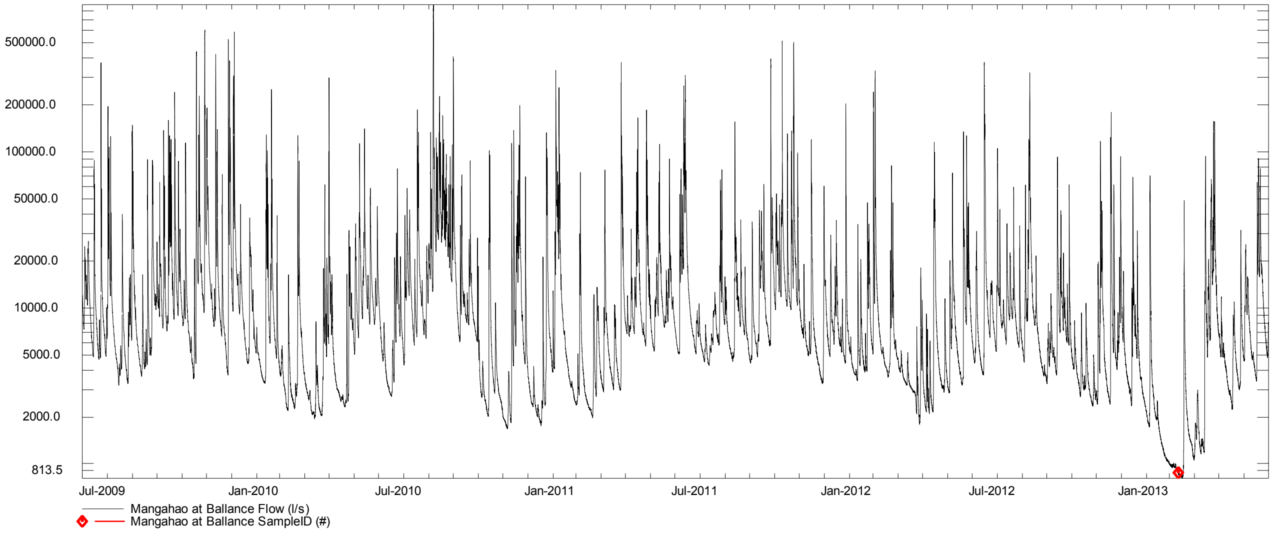
Makakahi at Hamua



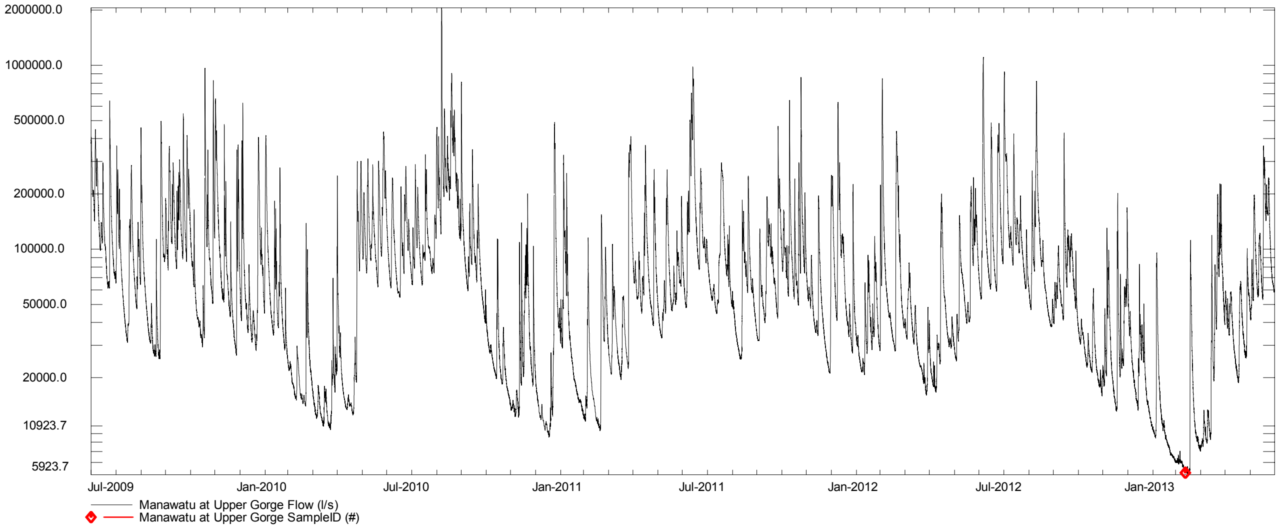
Mangatainoka at Pahiatua Town Bridge



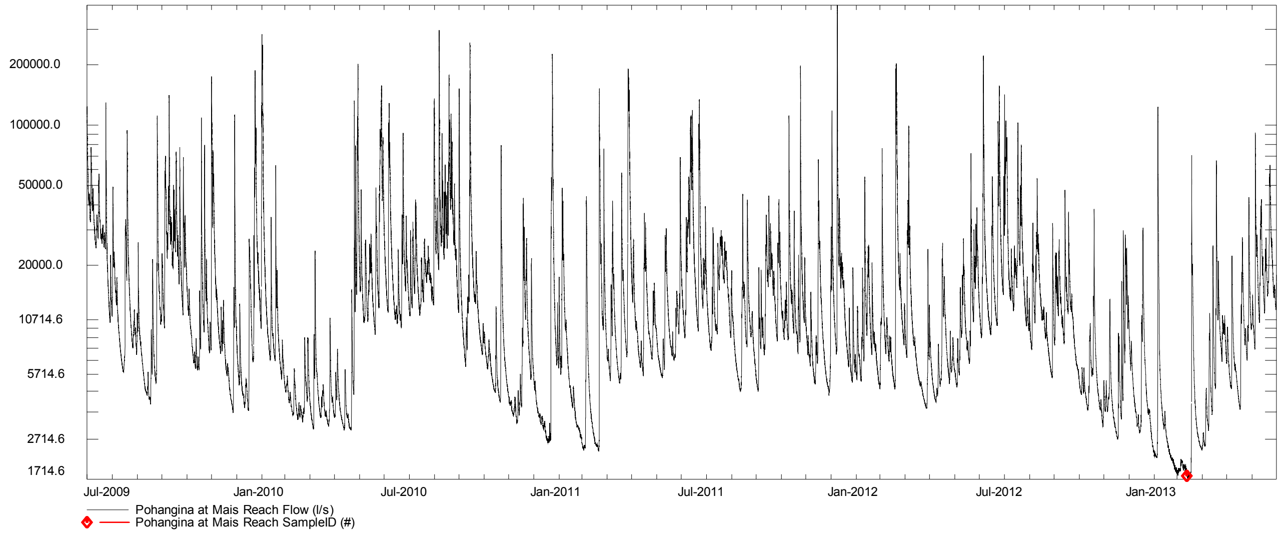
Mangahao at Ballance



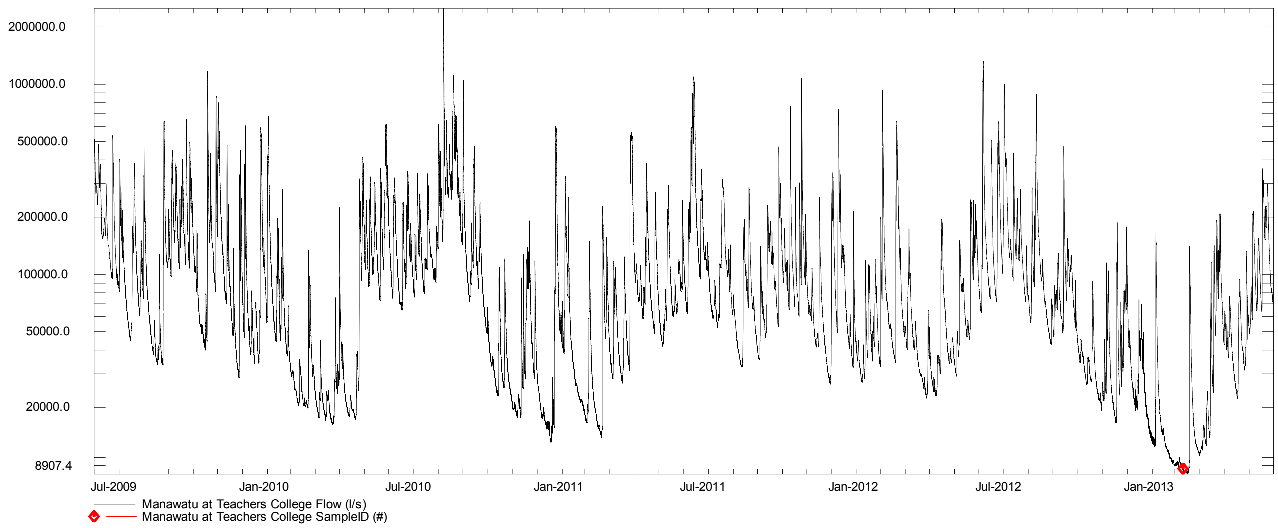
Manawatu at Upper Gorge



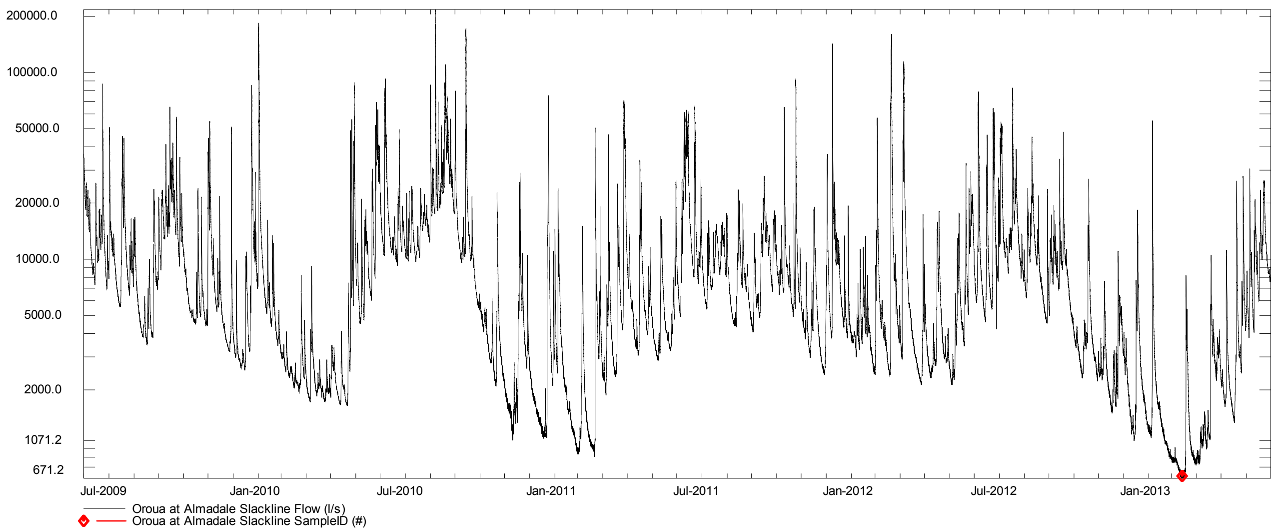
Pohangina at Mais Reach



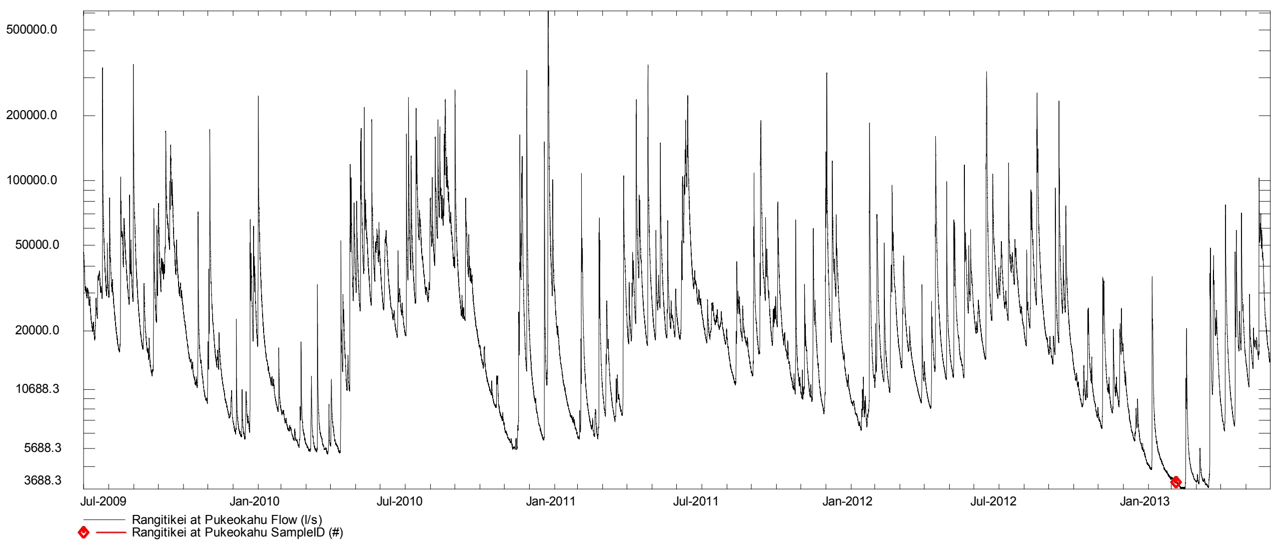
Manawatu at Teachers College



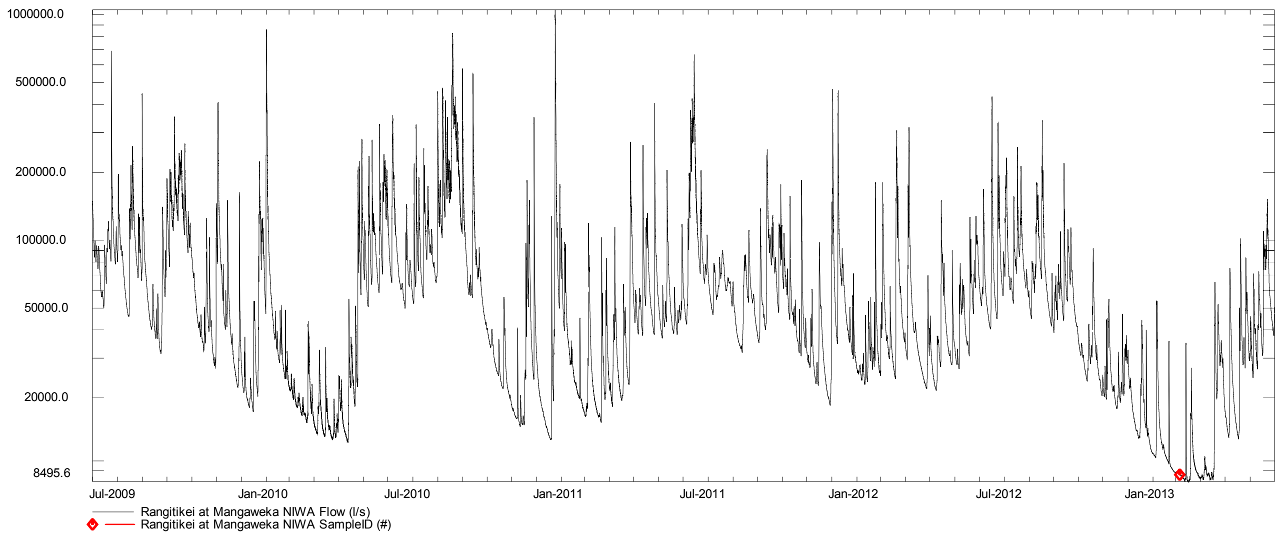
Oroua at Almadale Slackline



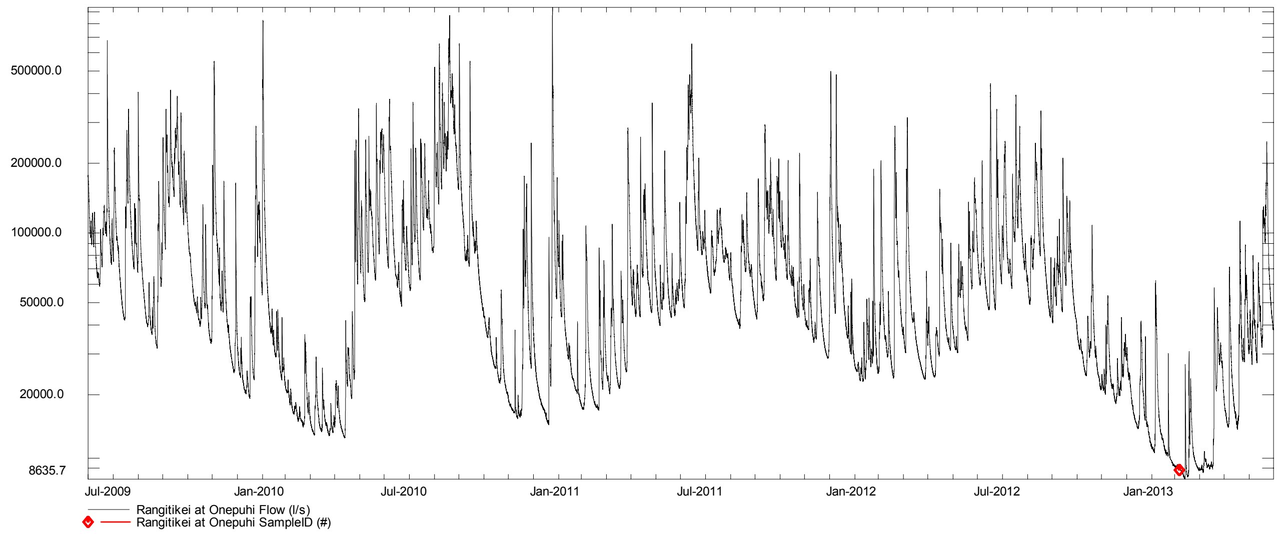
Rangitikei at Pukeokahu



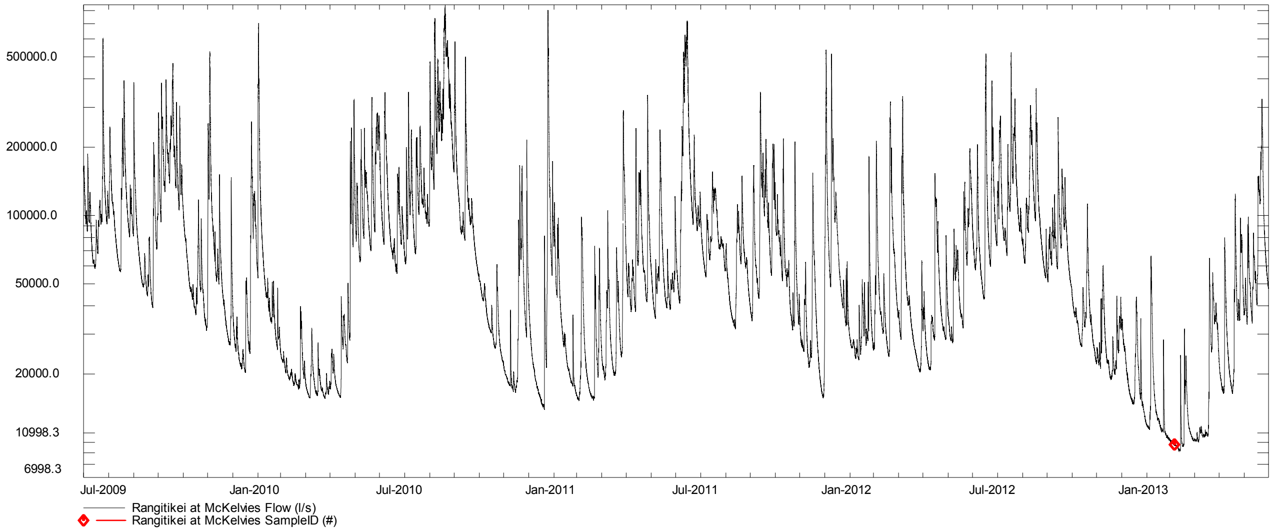
Rangitikei at Mangaweka



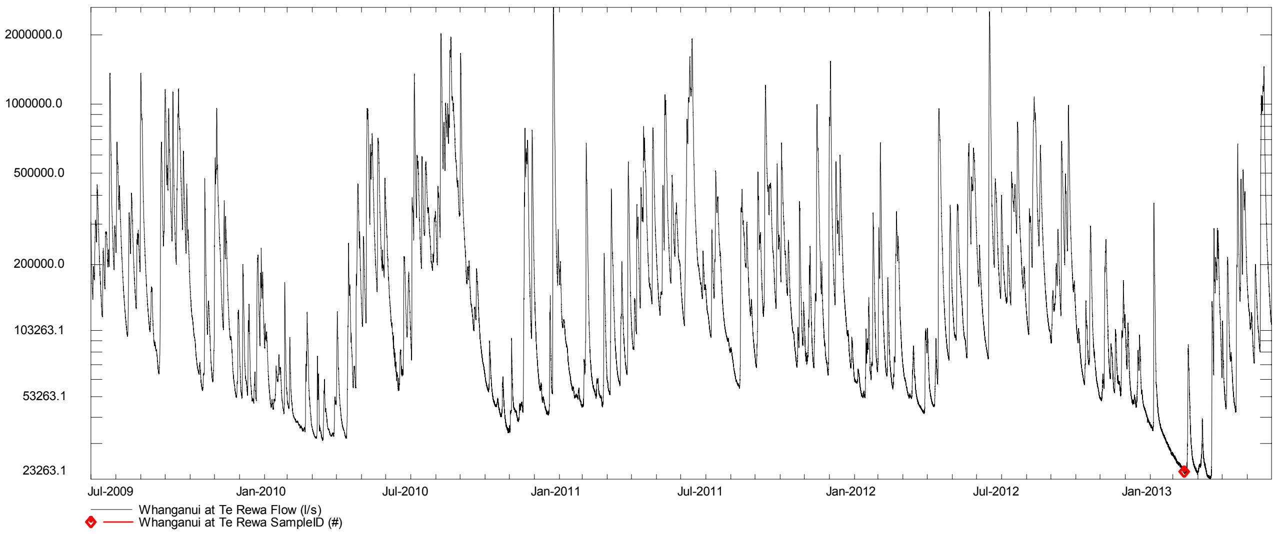
Rangitikei at Onepuhi



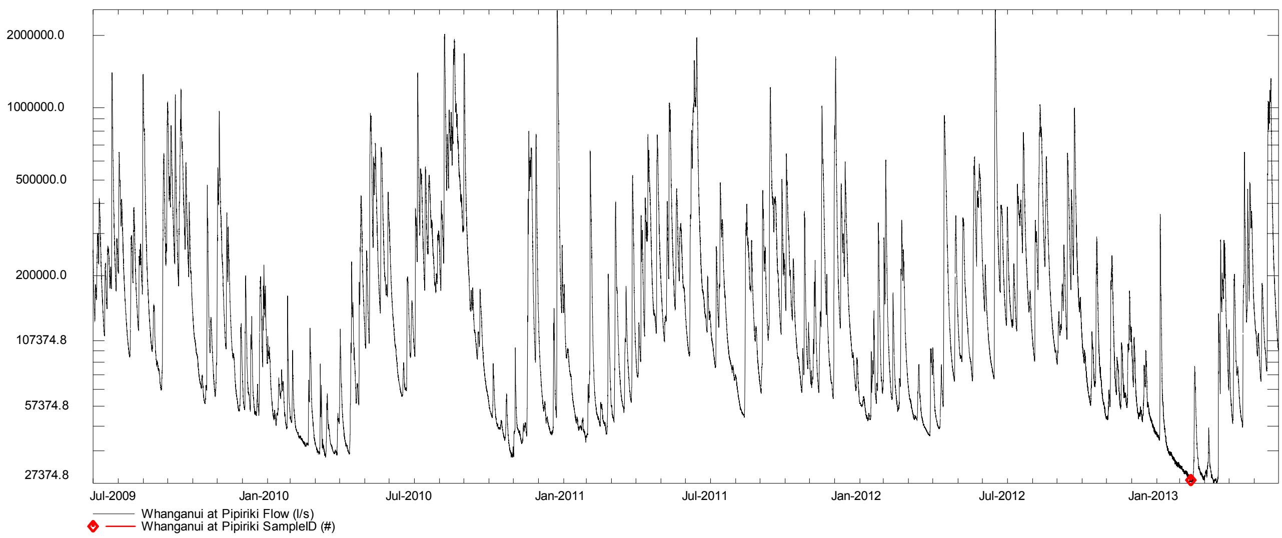
Rangitikei at McKelvies



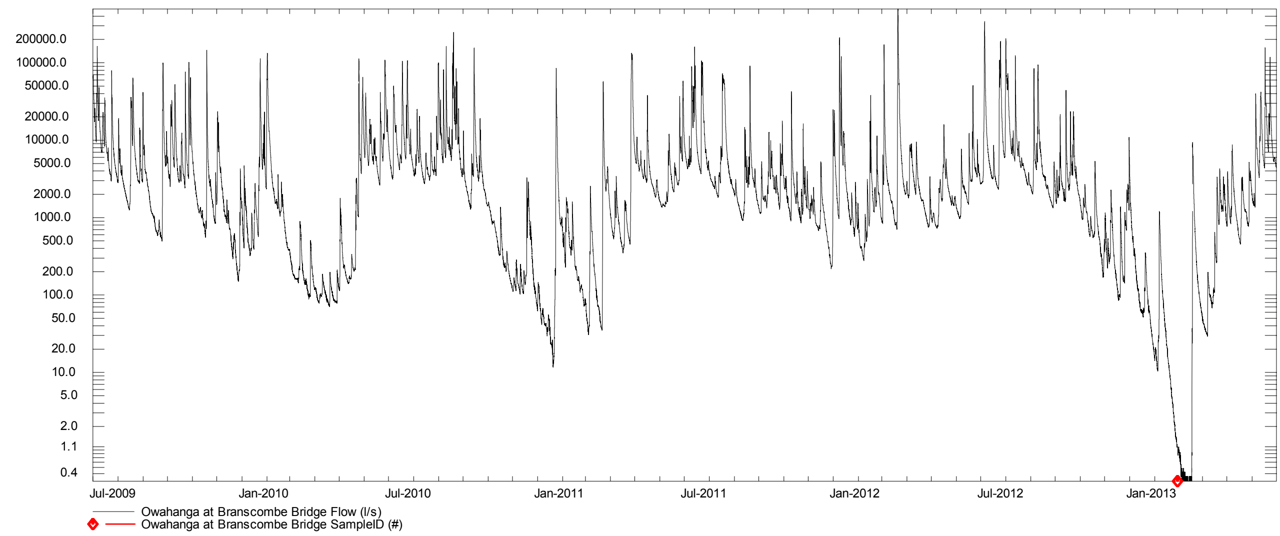
Whanganui at Te Rewa



Whanganui at Pipiriki



Owahanga at Branscombe Bridge



APPENDIX 2: PHOTOS OF SAMPLING SITES (AT TIME OF SAMPLING FOR AGE TRACERS, OR ARCHIVE).

Figure A2.1 Ongarue at Taringamutu (Archive).

Figure A2.2 Whanganui at Te Maire (Archive).

Figure A2.3 Whanganui River at Pipiriki (Archive).

Figure A2.4 Whanganui River at Te Rewa (Archive).

Figure A2.5 Rangitikei at Pukeokahu (Archive).

Figure A2.6 Rangitikei at Otara (Low-flow).

Figure A2.7 Rangitikei at Onepuhi (Archive).

Figure A2.8 Rangitikei at McKelvies (Archive).

Figure A2.9 Oroua at Almadale Slackline (Archive).

Figure A2.10 Pohangina at Mais Reach (Low-flow).

Figure A2.11 Manawatu at Weber Road (Low-flow).

Figure A2.12 Manawatu at Hopelands Reserve (Archive).

Figure A2.13 Manawatu at Upper Gorge (Archive).

Figure A2.14 Manawatu at Teachers College (Archive).

Figure A2.15 Manawatu at Opiki Bridge (Archive).

Figure A2.16 Mangatainoka River at Pahiatua Town Bridge (Low-flow).

Figure A2.17 Mangahao at Balance (Archive).

Figure A2.18 Makakahi at Hamua (Low-flow).

Figure A2.19 Makakahi DS Intake at Kaiparoro Road (Low-flow).

Figure A2.20 Mangatainoka at Tararua Park – Putara (Low-flow).

Figure A2.21 Tamaki at Tamaki Res (Archive).

Figure A2.22 Kumeti at Te Rehunga (Archive).

Figure A2.23 Oruakeretaki at SH2 (Archive).

Figure A2.24 Raparapawai at Jackson Road (Archive).

Figure A2.25 Tiraumea at Ngaturi (Archive).

Figure A2.26 Makuri at Tuscan Hills (Archive).

Figure A2.27 Mangatoro at Mangahei Road (Low-flow).

Figure A2.28 Akitio – No Photo.

Figure A2.29 Owahango at Branscombe Bridge (Archive).

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