A2E Piako Waihou Catchment Group

Review of existing hydrology and water quality data and information

Report 1630-01 R1

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Lincoln Agritech Ltd

May 2024

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ACTION	NAME	SIGNED	DATE
Approved By	Simon Pollock Group Manager Environmental Research		**14 May 2024**
BD Manager	Nevan Ofsoski Key Account Manager		**10 May 2024**

EXECUTIVE SUMMARY

Background

- The data and information on hydrology, water quality, and land-to-water contaminant transfers in the catchments of the Piako and Waihou rivers compiled in this report largely originated from Waikato Regional Council (WRC) databases and reports published by WRC. Supplementary information was sourced from Lincoln Agritech, particularly its MBIE-funded Critical Pathways research programme (2018-2023).
- The combined catchment area of both rivers accounts approximately for 14% of the Waikato Region and is characterised by intensive agricultural land use (nearly 70%). Average annual rainfall (900-1100mm) is lower than in many other parts of the region, and a significant decline has been observed between 1961 and 2020. This restricts the availability of water that can be allocated for irrigation or other uses.
- When aiming to understand land-to-water contaminant transfers responsible for the concentrations measured in waterways, it has proven useful to systematically consider three fundamental questions. Firstly, what are the relevant pathways? Secondly, how long does it take? Thirdly, what happens during transfer?

Pathways

- Results from a modelling study suggest that deep groundwater discharge is responsible for more than half of the flow in the fairly steady Waihou River, but contributes only between 11 and 21% of the flow in the flashier Piako, Waitoa, and Ohinemuri rivers.
- This distinction between the rivers is also evident in the mean transit time (or 'mean age') of stream water derived from tritium-sampling. Mean ages at mean flow were three to seven years at the five Piako, Waitoa, and Ohinemuri sampling sites, but 20 and 14 years at the two Waihou River sites.
- Both, the higher deep groundwater contributions, and the higher mean ages of the Waihou River water reflect the substantial storage capacity of the highly porous volcanic aquifers on the Mamaku Plateau in the headwater area of the Waihou River.

River water quality state and trends

- Since 1993/94, WRC has carried out monthly grab sampling at six sites in the Piako River catchment and 11 sites in the Waihou River catchment, analysing a range of physico-chemical water quality parameters. Bottom lines of the now deferred National Policy Statement for Freshwater Management (NPS-FM, 2020) would most frequently have been failed for microbial contamination (E. coli) and sediment, while ammonia and nitrate nitrogen predominantly would have fallen into the A and B bands.
- 30-year trends (1991-2020) showed 44 important improvements and 24 important deteriorations. Many improvements occurred in the Piako River catchment and the north-eastern part of the Waihou River catchment (Ohinemuri, Waitekauri, Hikutaia). Deteriorations in turbidity, visual clarity, and nitrogen concentrations were observed in the upper Waihou River catchment. More widespread deteriorations were recorded for Enterococci (apart from north-eastern part of the Waihou River catchment).
- Unfortunately, 10-year trends (2011-2020) were less positive, with 21 important improvements by far outweighed by 50 important deteriorations. Many important deteriorations concerned nitrogen concentrations in the Waihou River catchment and microbial contamination almost everywhere apart from the north-eastern part of the Waihou River catchment. The latter area also featured several important improvements in turbidity/visual clarity. Other important improvements were recorded for phosphorus concentrations at several Piako River catchment sites.

- These contrasting trend results for the two periods considered in parts reflect changes in the management of point-source discharges. Visual inspection of time series (1993-2023) highlighted that exceptionally high concentrations of some parameters (e.g. ammonia nitrogen, total and dissolved reactive phosphorus) were concentrated in early phases of the monitoring period (1990s, early 2000s). In some instances, clear step changes are evident in the data, presumably reflecting stricter resource consent conditions for wastewater treatment plants and industries (dairy factories, meat works).
- Analysis of concentration-discharge relationships (CDRs) for six sites where concurrent flow and chemistry data was available demonstrated that contaminant concentrations typically increase with increasing flow. However, the steepness of the increase varies between the contaminants and between the rivers, and is further affected by point-source discharges.

Nitrogen and phosphorus loads into the Firth of Thames

- The need to consider concentrations and flows concurrently can be illustrated by the estimated nitrogen and phosphorus loads being discharged into the Firth of Thames. Due to its higher concentrations, the Piako River contributes only 17% of the flow, but 38% of the nitrogen load and 36% of the phosphorus load. In contrast, the lower concentration Waihou River accounts for 73% of the flow, but only 60% and 61% of the nitrogen and phosphorus loads, respectively.
- Nitrogen loads from Hauraki rivers into the Firth of Thames were estimated to originate to 6% from point sources, 21% from background, and 73% from agricultural land use. In contrast, point sources were estimated to account for 23% of the phosphorus load, background 37%, and agricultural land use 40%.

Integrative ecosystem health assessments

- While water quality has traditionally been assessed considering a range of physico-chemical parameters, integrative measures of ecosystem health have become more popular in recent years. Unfortunately, macroinvertebrate indices (MCIs) have only been determined for six Piakp River catchment sites and seven Waihou River catchment sites, with little overlap with the sites sampled for physico-chemical parameters. Accordingly, it is difficult to interpret the complex patterns of state and trends reported for these sites. With the recent development of a taxon-independent community index for eDNA-based ecological health assessment, eDNA analysis may allow in the future for a truly integrative assessment.

Implications for way ahead

- Concerning priority areas for protective or remedial actions, decision-makers should take into account that headwaters play a role that is much greater than their fraction of the catchment area. This is due to the combination of typically high rainfall and low current land use intensity.
- Nitrogen, phosphorus, E. coli, and sediment, all pose significant water quality challenges in parts of the Piako and Waihou river catchments. As near-surface pathways (surface runoff, interflow, artificial drainage) play a major role in transferring all of them from land to water, any measure to reduce or intercept near-surface flows will have multiple benefits ('transfer control'). However, such measures get easily overwhelmed during high-flow events, particularly during winter when the entire catchment is near saturation. This limitation highlights the great importance of 'source control', which anyway is crucial for nitrogen (as a high fraction of it travels on the shallow groundwater pathway that cannot be effectively intercepted by transfer control measures).

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1. INTRODUCTION

1.1 Project

This Access to Experts (A2E) project is being carried out on request by the Piako Waihou Catchment Group, a community-based organisation aiming to achieve 'A thriving community for a sustainable future'. This goal aligns well with the vision expressed in the Waihou Piako Zone Plan 'Well managed catchments that enhance economic and environmental sustainability, recognise community and cultural aspirations, while mitigating natural risks', (WRC, 2018).

The area of interest encompasses the topographical catchment area of the Piako and Waihou Rivers, the two major rivers flowing in a largely northerly direction through the Hauraki sub-region and discharging into the Firth of Thames (Fig. 1). Accordingly, both the ecosystem health of the streams and rivers within the Hauraki sub-region, and the flow-on effects on the Firth of Thames and the wider Hauraki Gulf need to be considered ('*ki uta, ki tai*').

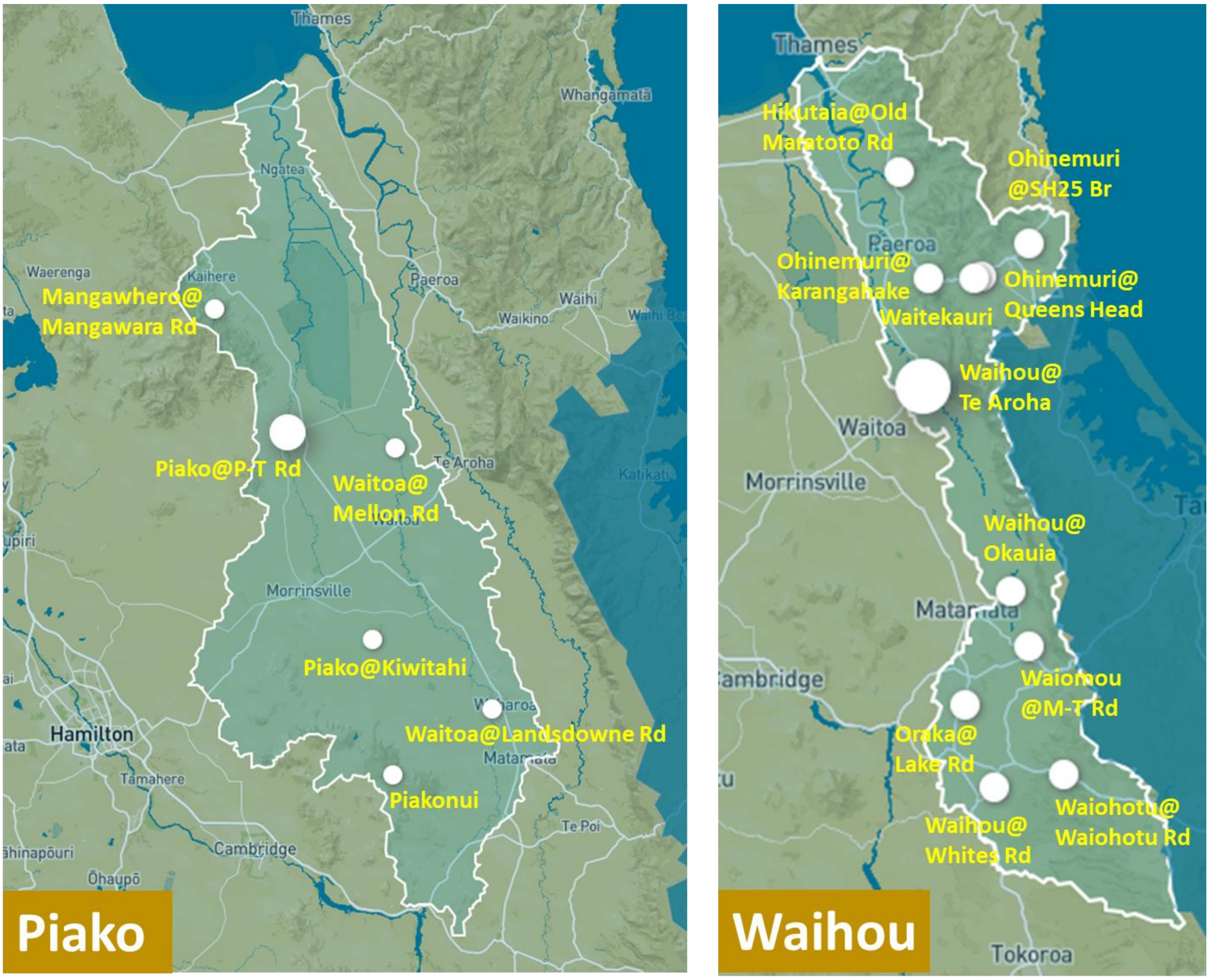

Figure 1: Piako River (left) and Waihou River catchments (right), containing 17 monitoring sites operated by Waikato Regional Council (WRC); maps copied from https://www.lawa.org.nz.

Until recently, all regional councils were obliged to incorporate the National Policy Statement for Freshwater Management (NPS-FM, 2020) into regional plans by December 2024. However, the new government has pushed back this deadline by three years and has also signalled further freshwater policy changes. Accordingly, there is currently uncertainty about the way ahead with regional freshwater policy. Nevertheless, it should be noted that exceedances of suggested national bottom lines were observed for several sites within the Hauraki sub-region, particularly for suspended fine sediment, dissolved reactive phosphorus, and E. coli (WRC, 2022c).

Incidentally, excessive sediment, nutrient, and microbial pathogen loads are considered main causes of degraded marine habitats in estuaries, harbours and the Inner Hauraki Gulf (Seachange, 2017). Additionally to immense ecological, social, and cultural values, the Hauraki Gulf is also of substantial economic value to the country. NZIER (2023) estimated the ecosystem services associated with the Hauraki Gulf to amount to $5.14 billion per year.

The overall A2E project comprises an initial review of existing hydrological and water quality data and other relevant information (i.e. this report), a workshop with catchment group trustees to discuss key concepts and findings (held on 02/05/2024), and a subsequent presentation at a public event organised by the catchment group (now deferred to spring 2024).

By compiling data and information from multiple sources, and presenting them graphically in maps and charts, this report also aims to facilitate the information of, and interaction with, the wider catchment community and help them prioritise remedial measures to tackle existing water quality challenges.

1.2 Catchment

The catchment area of the Piako (1,480 km^2) and Waihou Rivers (1,980 km^2) equates to approx. 14% of the Waikato Region and is predominantly characterised by intensive agricultural land use (nearly 70%), particularly dairy farming. Some cropping/horticultural land use is concentrated around Matamata. Indigenous forest is very rare in the Piako River catchment (Maungakawa, Te Tapui, Te Miro) and somewhat more common in the Waihou catchment (Coromandel and Kaimai Ranges, Mamaku Plateau), with exotic forest additionally covering some Waihou River headwater areas (Mamaku Plateau). The Kopuatai and Torehape peat domes are the only significant remnants of natural vegetation in the northern part of the plains.

Poorly or very poorly drained Gley and Organic soils occur widespread on the low-lying northern plains, where comprehensive drainage and flood protection schemes have been put in place since the early 1900s to enable agricultural land use and protect settlements. The currently operating scheme consists of 177 km of stopbanks, 75 floodgates and 20 pump stations (WRC, 2017). In contrast, well drained Allophanic and Brown soils with good soil physical conditions are most common south of a line connecting Morrinsville and Manawaru.

The Hauraki plains are characterised by below-average rainfall in the Waikato Region (together with the Hamilton and Reporoa basins). Long-term annual averages are mainly in the 900 – 1100 mm range (WRC, 2022b). Moreover, a significant decline in average annual rainfall has been observed between 1961 and 2020.

The Piako River arises a few kilometres south-east of Morrinsville, at the confluence of the Piakoiti and Piakonui Streams. The Waitakaruru and Topehaehae Streams are the other two major headwater streams feeding into the Piako River near Morrinsville. The Waitoa River, arising near Piarere, is a major tributary of the Piako River. It enters just west of the Kopuatai peat dome, approximately 40 km south of the Piako River mouth. In contrast to these streams arising in lowland areas, the Waihou River receives a high fraction of its flow from upland headwater areas further south on the Mamaku Plateau. The Ohinemuri River, its major tributary, arises in the north-east near Waihi and joins the Waihou River near Paeroa (Fig. 1).

Typically starting in 1993 or 1994, Waikato Regional Council (WRC) has operated 17 long-term stream monitoring sites in the area that are sampled monthly for a range of mainly physico-chemical parameters (see Section 2.2.1). Six of them are located in the Piako River catchment in the west, 11 in the Waihou River catchment in the east .

Due to tidal influences, river discharges into the Firth of Thames are difficult to quantify. However, the most downriver measurements available suggest that the Waihou River (51.1 $m^3 s^{-1}$) discharges on average approximately four times the flow of the Piako River (11.9 $m^3 s^{-1}$; WRC, 2022a). The foreshore of the Firth of Thames is a RAMSAR wetland of international significance and the Firth itself is considered one of the most important coastal stretches in Aotearoa New Zealand, with 74 flora and fauna species recorded (WRC, 2017).

1.3 Fundamental concepts on land-to-water contaminant transfers

Before delving into existing monitoring results, it seems warranted to reiterate the three fundamental questions that need to be addressed when aiming to understand land-to-water contaminant transfers that are responsible for the concentrations measured in streams and rivers (Fig. 2).

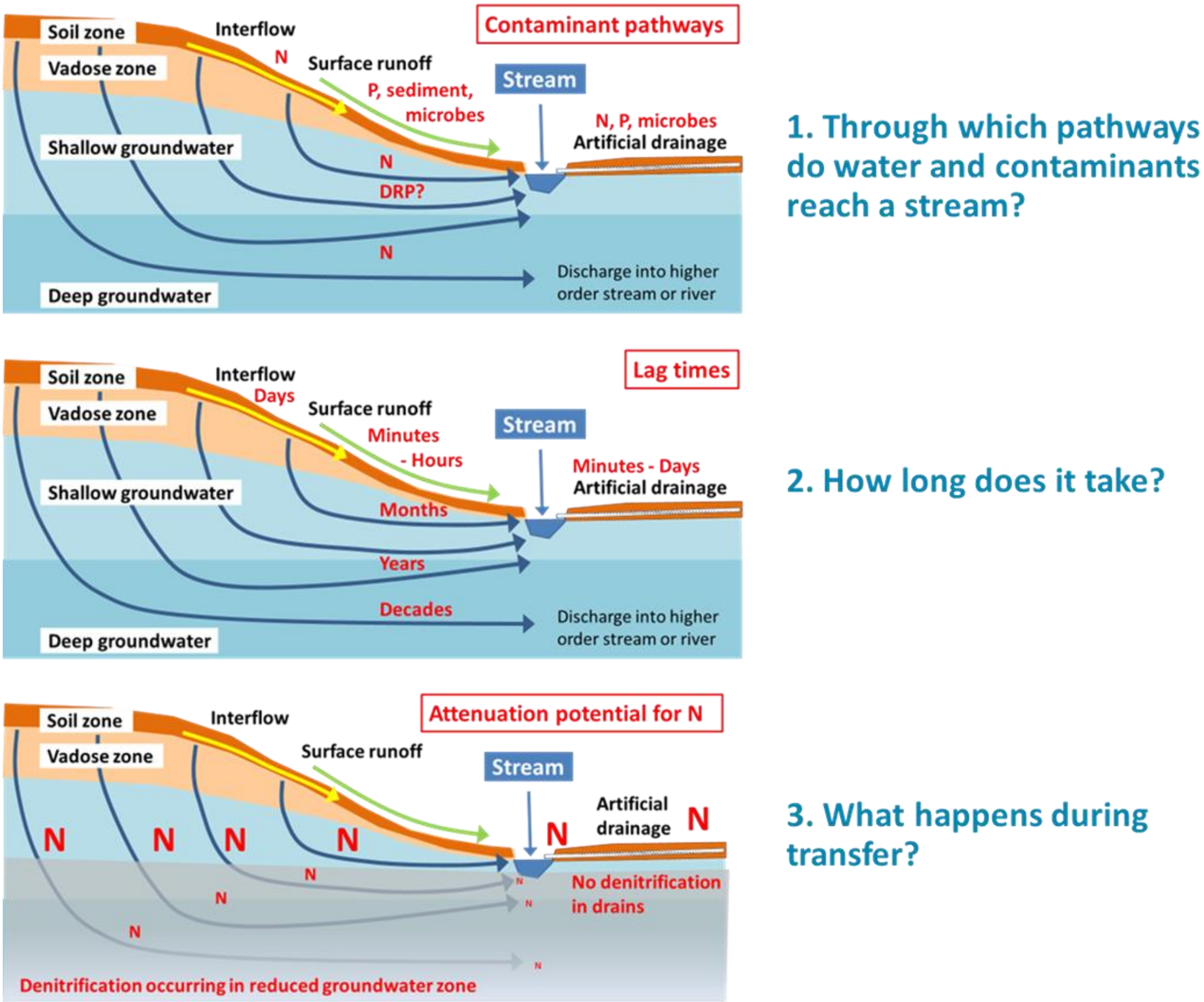

Figure 2: Schematics on three fundamental questions concerning land-to-water contaminant transfers.

Water, and contaminants transported by it, can reach a stream via a range of pathways (Fig. 2). Surface runoff (also called overland flow), interflow (lateral flow within the soil zone), and artificial drainage (surface drains or subsurface pipes) can often be pragmatically lumped together as near-surface pathways (NS). Transfers on NS pathways have in common that they typically occur episodically, are very fast, and very localised.

Shallow groundwater (SGW) contributions to streamflow typically show a strong seasonality; they are driven by seasonal climatic patterns and occur locally. In contrast, deep groundwater (DGW) sustains stream flow all year long; it responds slowly and tends to be regional.

It is also important to recognise that phosphorus, sediment, and microbes are predominantly transferred on near-surface pathways, while the groundwater pathway is usually the most important one for nitrogen (Fig. 2, top).

Contaminant transfers on near-surface pathways occur very quickly, typically within a few days after a rainfall event. The shallow groundwater pathway may take from a couple of months to possibly 2 or 3 years, while the deep groundwater pathway can take from a few years to several decades. This means that NS and SGW can be grouped together as 'young water' with a quality reflecting recent land use intensity, while DGW is 'old water' of a quality reflecting historical land use intensity. It is important to acknowledge that the age range of 'young water' is very narrow compared to that of 'old water' (Fig. 2, middle).

Finally, it's important to recognise that not all contaminants leached from the root zone ('source load') necessarily arrive at a stream ('delivered load'), e.g. there can be substantial attenuation occurring during transfer. Microbial denitrification tends to be the key nitrogen attenuation process in catchments underlain by oxygen-depleted, reduced groundwater zones (Fig. 2, bottom).

2. EXISTING DATA AND INFORMATION

This section comprises hydrological and water quality information from a range of sources, mainly from the WRC database and published WRC reports, but also from a couple of research providers (e.g. Manaaki Whenua Landcare Research, Lincoln Agritech). While the focus is on physico-chemical monitoring data related to overall water quality, for which long time series exist, more recently introduced integrative measures (e.g. eDNA analysis) are also noted.

2.1 Catchment hydrology

2.1.1 River flows

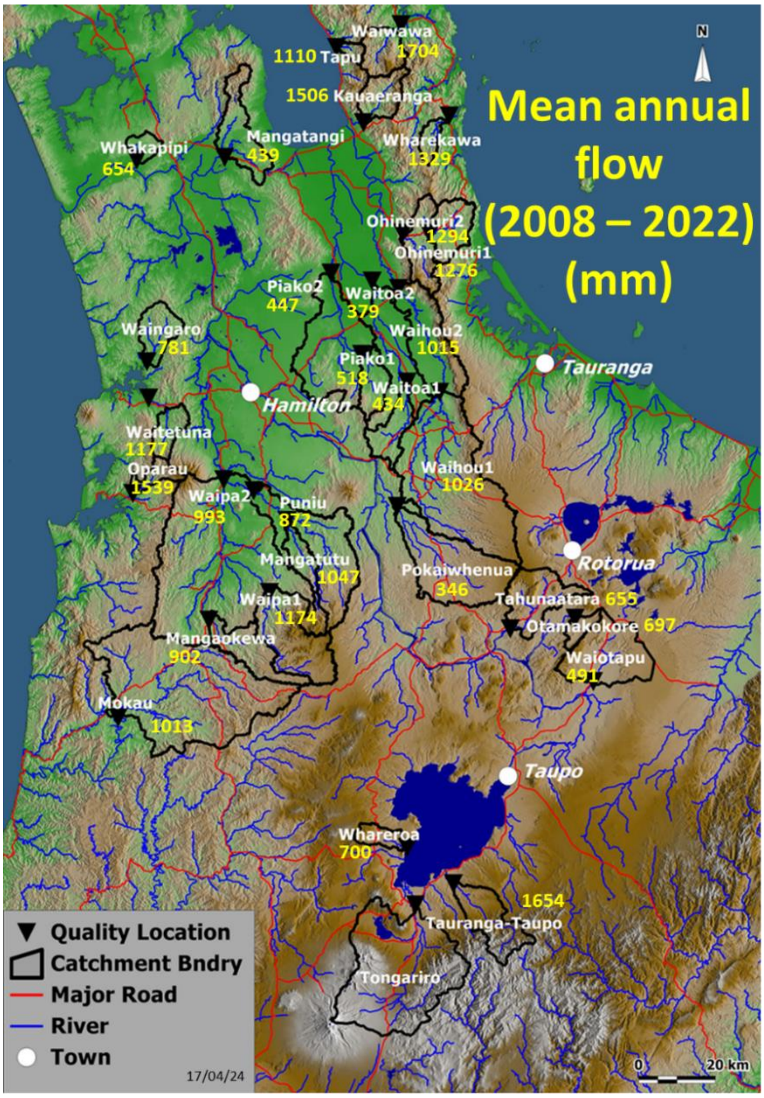

Figure 3: Mean annual flow (2008 – 2022) for selected monitoring sites across the Waikato region (Lincoln Agritech).

To put the flow recorded in Hauraki rivers into perspective, Fig. 3 shows the mean annual flow for a 15-year period (2008 – 2022) for a selection of monitoring sites across the Waikato region. To facilitate comparison with rainfall data that catchment communities are typically familiar with, the flows are expressed in mm, which equals litres of water per square metre of catchment area (1 mm = 1 L m^{-2}).

A very clear distinction is evident between the Piako and the Waihou rivers (including their tributaries). While relatively low flows were calculated for the Piako and Waitoa sites (379 – 518 mm), the Waihou River (1026 and 1015 mm) and particularly the Ohinemuri River sites (1276 and 1294 mm) featured substantially higher flows.

This pattern largely reflects the spatial distribution of rainfall and potential evapotranspiration. In contrast to the Piako and Waitoa rivers, which arise in the lowland area characterised by relatively low rainfall and high evapotranspiration, the Waihou River receives a substantial portion of its flow from its relatively wet and cool headwater area on the Mamaku Plateau. The high flow of the Ohinemuri river reflects its location at the southern end of the high-rainfall Coromandel Ranges.

Two aspects need to be separated when considering what these differences in water flows might mean for freshwater pollution. As water is the key transport medium for contaminants from land to waterways, higher water flows typically result in greater contaminant transfers (expressed as loads, e.g. kg ha^{-1} nitrogen loss). However, higher flows can also result in a dilution effect on contaminant concentrations (e.g. mg L^{-1} nitrogen measured in a river). This is important, as environmental legislation usually refers to concentrations (e.g. NPS-FM), but loads can be more critical for some receiving environments (particularly lakes, estuaries, coastal zones). The implication for the Hauraki rivers is that the Piako River will discharge relatively low loads into the Firth of Thames despite relatively high concentrations, while the opposite applies to the Waihou River.

2.1.2 Climate change impacts on river flows

Analysing trends in hydrology and water resources, WRC scientists found that from 1961 to 2020, there has been an overall declining trend in annual rainfall across the Waikato region, with each decade generally drier than the preceding one. Concurrently, potential evapotranspiration (PET) was found to have increased. The change in rainfall excess (defined as Annual Rain – Annual PET) was most pronounced in the Lower Waikato, Hauraki and Coromandel sub-regions; e.g. dropping by 84% for Hauraki between 1972 and 2020 (WRC, 2022c).

The combination of decreased rainfall and increased evapotranspiration, together with increased water usage (for irrigation, municipalities, and industries) resulted in reduced mean river flows at many sites. In 2020, the region recorded its lowest regional rainfall and lowest mean river flows (WRC, 2022c).

As there is less water flowing in the streams during summer, there is also less flow available over this period that can be allocated for irrigation or other uses. The majority of continuously monitored flow sites showed a declining trend in annual low flow since the 1990s, with some sites displaying a 50% reduction in summer flow over that 30-year period (WRC, 2022c). A few examples from the Hauraki sub-region are shown in Fig. 4.

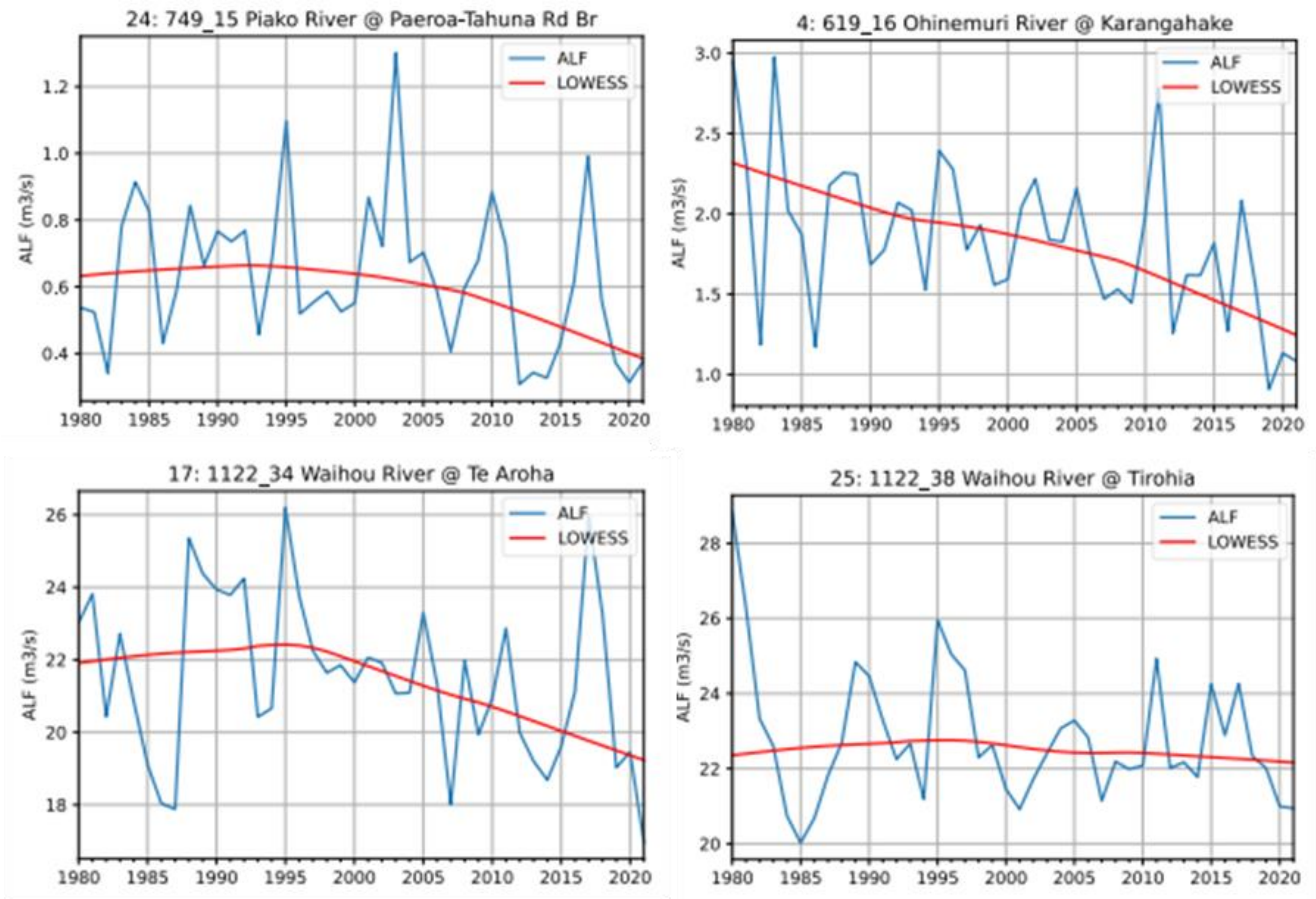

Figure 4: History of Annual Low Flow 1980-2020 for selected monitoring sites in the Hauraki sub-region (reorganised from WRC, 2022c).

2.1.3 Mean ages of river water

The mean transit time (MTT), or simplified the 'mean age', of water sampled at a monitoring site varies over time, as the relative contributions by different pathways through the catchment vary with streamflow (see Section 2.1.4). This also means that a river water sample never has one unique age, but always consists of a mixture of components with different ages. As it is difficult to visualise and discuss the variation of age distributions in space and time, the MTT is typically used to provide an impression of age differences between sites. All MTTs reported here were calculated by GNS Science by applying an Exponential-Piston flow Model (EPM) to the tritium concentration measured in the water samples and long-term input functions for atmospheric tritium (Lincoln Agritech, 2024).

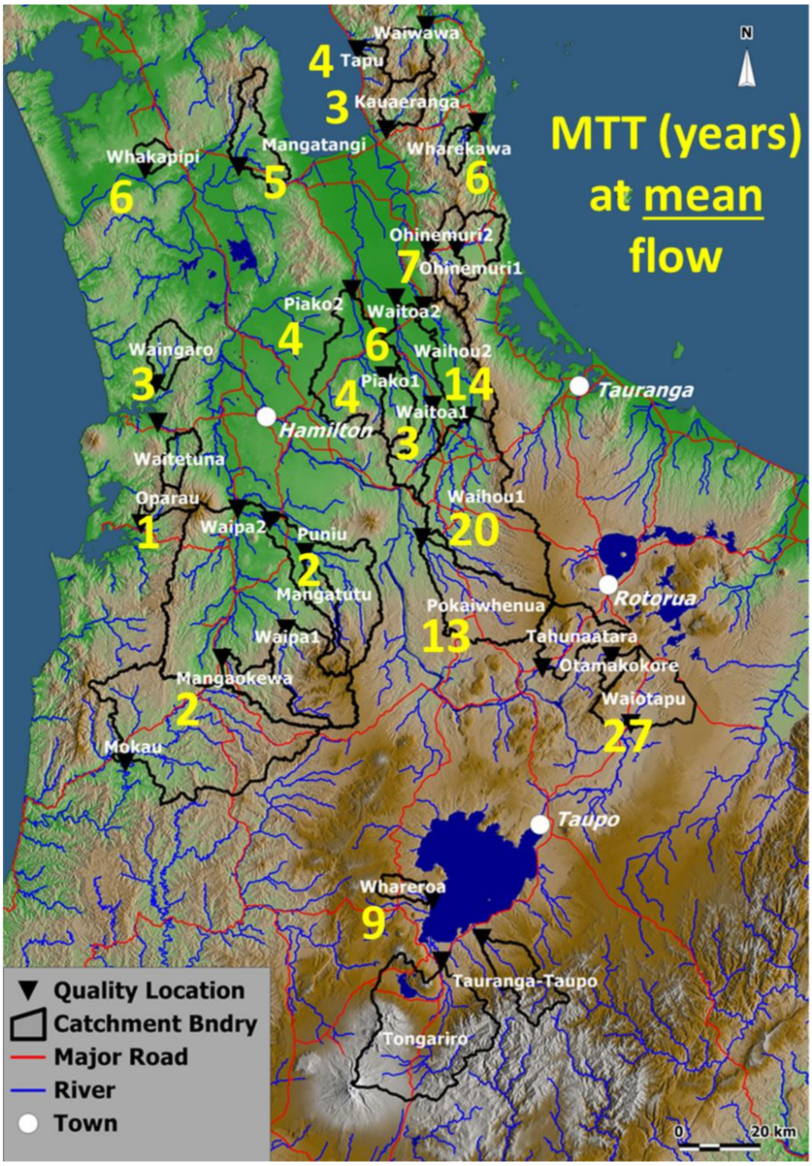

Figure 5: MTTs (years) at mean flow estimated for 19 catchments across the Waikato region (from Lincoln Agritech, 2024).

The continuous variation of MTT with streamflow was first described based on data from Toenepi Stream in the upper Piako River catchment (Morgenstern et al., 2010). Lincoln Agritech and WRC have collaborated in recent years to investigate MTTs across the flow range for 19 additional sites across the Waikato Region (Lincoln Agritech, 2024).

MTTs at mean flow were below five years in 10 catchments, between five and 10 years in five more, and between 13.5 and 27.4 years in the remaining four catchments (Fig. 5).

In Hauraki, mean flow MTTs were below seven years for all five Piako, Waitoa, and Ohinemuri monitoring sites. However, substantially higher MTTs of 20 and 14 years were determined for the two Waihou sites. These sites resembled the Pokaiwhenua and Waiotapu sites on the Central Plateau (13 and 27 years, respectively).

This similarity is due to the fact that a substantial fraction of the Waihou River water originates from recharge in its Mamaku Plateau headwaters area. Like in other Central Plateau catchments, substantial groundwater storage exists in the young and highly porous volcanic deposits of this area, resulting in elevated MTTs of the river water.

The estimated variation of MTTs with streamflow is illustrated in Fig. 6. Cumulative flow percentiles are used on the x-axis to enable comparison of rivers with vastly differing flows. The lowest observed flow at each river plots near zero, while 100 marks the highest observed flow.

MTTs estimated for the lowest observed flows ranged from 6.5 to 97 years, with MTTs ≥ 21 years estimated for 10 monitoring sites, including six Hauraki sites (Piako1+2, Waitoa1+2, Waihou1+2). These relatively high MTTs indicate that a deeper and older groundwater reservoir sustains the flow in these catchments under prolonged dry conditions.

However, MTTs drop down steeply with increasing streamflow in the Piako and Waitoa rivers, resulting in MTTs at mean flow of ≤ 7 years as described in the previous section. Reflecting the larger underlying groundwater reservoirs, MTTs decrease more slowly in the Waihou River, particularly at the upper monitoring site (Waihou1, at Okauia). The lower MTTs and the slightly faster decrease with increasing flow at Waihou2 (at Te Aroha) reflects that younger water enters the stream between these two monitoring sites, either via small local streams or diffuse groundwater discharge.

In contrast, very little MTT variation was observed at the seventh Hauraki site, Ohinemuri2 (at Karangahape). This site closely resembled the other Coromandel catchments (Tapu, Kauaeranga, Wharekawa) and Mangatangi, Oparau, Waingaro, Mangaokewa, and Whareroa. The low and stable MTTs suggest that old groundwater contributes little to flow in these nine streams, and even the deeper part of the groundwater system that is connected to these streams is relatively young (< 15 years; in line with the high rainfall in many of these catchments).

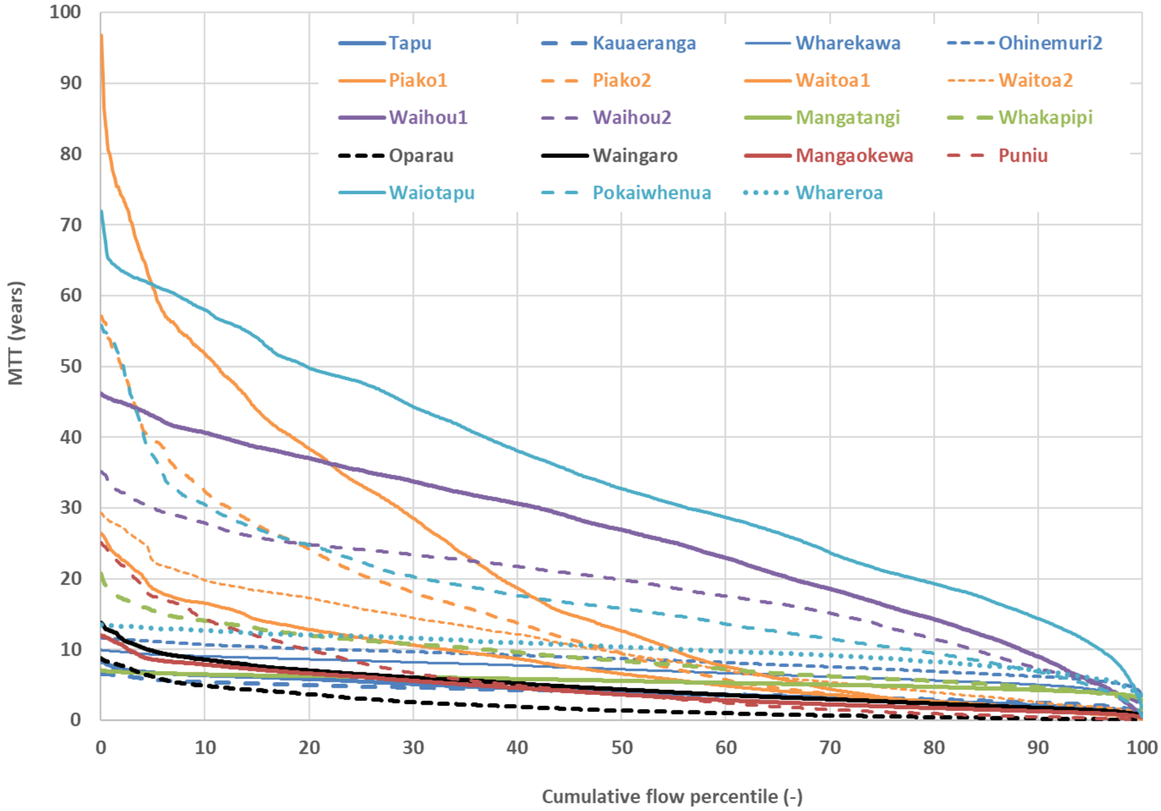

Figure 6: Estimated MTT variation with flow (from Lincoln Agritech, 2024).

These MTT estimates suggest that hydrologic lag times are small in the Piako, Waitoa, and Ohinemuri River catchments, but markedly higher in the Waihou River catchment. This means that land management or land use changes will be detectable much later in the water quality of the Waihou River compared to the other Hauraki rivers.

2.1.4 Critical water flow and contaminant transfer pathways from land to water

Using a modelling technique called Bayesian chemistry-assisted hydrograph separation (BACH; Woodward and Stenger, 2018), we estimated the flow contributions made by near-surface (NS), shallow groundwater (SGW), and deep groundwater (DGW) pathways to the flow and Total Nitrogen concentration dynamics recorded at 29 Waikato Regional Council monitoring sites (Stenger et al., 2024; Lincoln Agritech, 2024). In the following section, we present 15-year average results (2008 – 2022) for eight Hauraki monitoring sites, and two Coromandel sites for comparison purposes (Figs. 7 and 8).

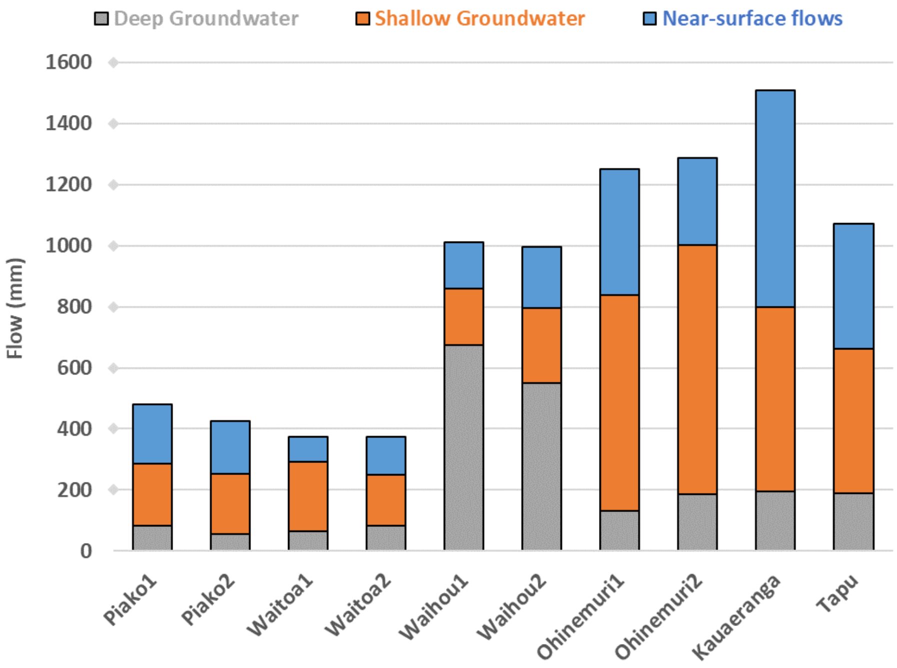

Figure 7: Long-term average flow contributions (in mm) estimated for deep groundwater (DGW), shallow groundwater (SGW), and near-surface (NS) flows in Hauraki and Coromandel catchments (2008 – 2022).

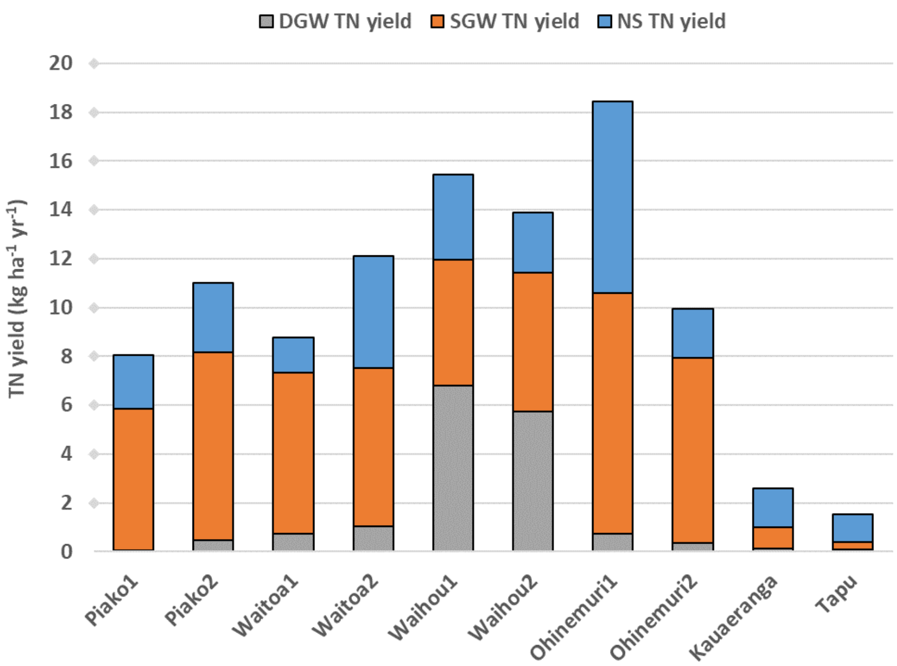

Figure 8: Long-term average Total Nitrogen (TN) yields (in kg ha^{-1} yr^{-1}) estimated for deep groundwater (DGW), shallow groundwater (SGW), and near-surface (NS) flows in Hauraki and Coromandel catchments (2008 – 2022).

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As already described in Section 2.1.1, annual flows in the Waitoa and Piako rivers were substantially lower than in the Waihou and Ohinemuri rivers; the latter resembling other Coromandel rivers (Tapu, Kauaeranga; Fig. 7). Despite their differences in water flows, the Waitoa, Piako and the Coromandel catchments had relatively similar relative flow contributions by 'old' water (DGW: 11 – 21%) and 'young' water (NS+SGW: 78 – 87%). In contrast, young water accounted for only 33 and 45% at the two Waihou sites vs. 67 and 55% old water. This high DGW contribution to the Waihou River flow corroborates the age-interpretations presented in Section 2.1.3.

TN yields (Fig. 8) showed a very different spatial pattern than water yields (Fig. 7), reflecting the big differences in land use intensity between these catchments. In particularly, the Waitoa and Piako catchments stand out for relatively high TN yields despite their low water yields, while Tapu and Kauaeranga feature the by far lowest TN yields despite their high water yields. Absolute TN yields ranged from only approx. 2 – 3 kg ha^{-1} yr^{-1} for Tapu and Kauaeranga via approx. 8 – 12 kg ha^{-1} yr^{-1} for the Waitoa, Piako and Ohinemuri2 catchments, to approx. 14 – 18 kg ha^{-1} yr^{-1} for the Waihou and Ohinemuri1 catchments. Critically, DGW contributed less than 1 kg ha^{-1} yr^{-1} (or less than 10% of the TN yield) in all catchments but Waihou (where it contributes approx. 6 kg ha^{-1} yr^{-1}, equating to just over 40%).

While long-term averages are best suited to recognise differences between catchments, it is crucial to also be cognisant of the temporal variation of pathway contributions within a year and between years in response to varying weather patterns. Figs. 9 and 10 illustrate this temporal variation for two Hauraki sites that represent catchments with substantial DGW flow contribution (Waihou1) and catchments with a predominance of shallower pathways (Waitoa2). Time series are presented for two years (2016 top, 2022 bottom) to illustrate differences between years.

Of all 29 Waikato monitoring sites studied by Lincoln Agritech (2024), Waihou1 (i.e. Waihou River at Okauia), had the steadiest flow, as expressed by its very low flashiness index of only 0.09. While the monitoring site is located in the Hauraki sub-region, the very low flashiness index reflects its similarity in flow dynamics with Upper Waikato and Lake Taupo sub-region sites, which is due to the fact that the Waihou River receives a very high fraction of its flow from groundwater recharge on the northern slopes of the Central Plateau (e.g. 'Blue Springs').

BACH modelling suggested that very steady DGW discharge of approximately 18 m^3 s^{-1} (grey time series in Fig. 9) results in a long-term average DGW contribution of 68% of the total streamflow. Substantial contributions by the SGW system (orange colour in Fig. 9) are largely restricted to winter and spring, but subject to preceding periods of excess rain, there can also be noteworthy SGW discharge in other periods (e.g. summer/autumn 2016). The long-term average SGW contribution has been estimated at 18%. Near-surface (NS) flows account for the remaining 15% of total streamflow, occurring episodically in response to excess rainfall, particularly in winter after the catchment has wetted up (blue colour in Fig. 9).

The BACH modelling concept (Woodward and Stenger, 2018; Stenger et al., 2024) involves the fitting of concentration time series for two tracers; Total Nitrogen (TN) and Electrical Conductivity (EC) proved the most suitable tracer combination in the study by Lincoln Agritech (2024). The reasonably good agreement between measured (symbols) and modelled (coloured dotted lines) tracer concentrations provide confidence in the pathway estimates. Given the high flow contributions by DGW, TN and EC concentrations were only modestly affected by streamflow changes, as also evident in their relatively weak positive (TN) or negative (EC) concentration-discharge relationships.

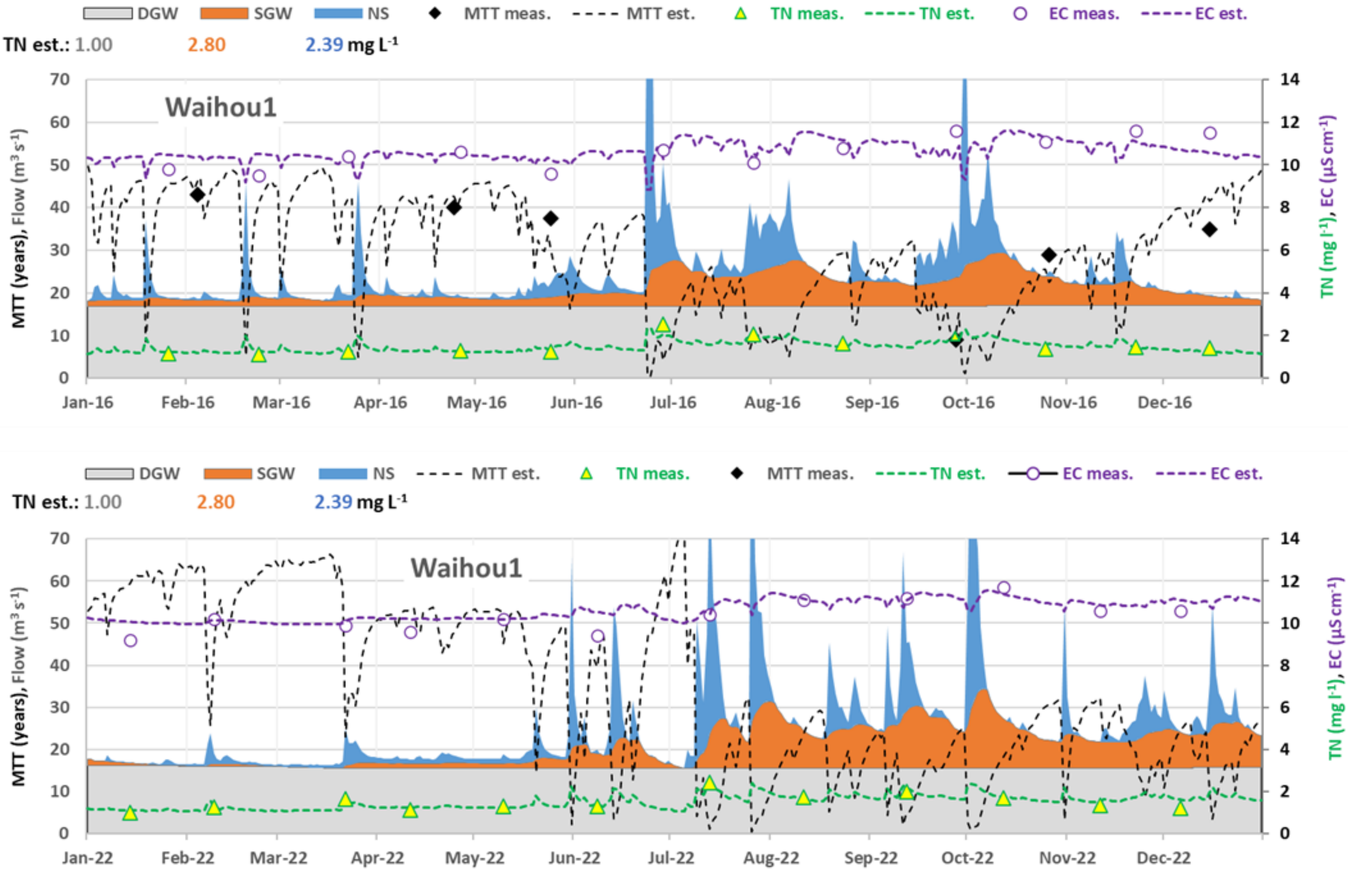

Figure 9: Pathway contributions, tracer concentrations, and MTTs for Waihou1, Waihou River at Okauia, Hauraki (2016 top, 2022 bottom).

The modelled MTT time series (black dotted line) derived from the tritium concentrations determined at five dates in 2016 (black diamonds) suggests that MTTs in summer/autumn 2016 were largely in the 40-50 years range, unless episodic heavy rain resulted in short-lived substantially lower MTTs. MTTs below 20 years became more common from June onwards, concurrent with increasing flow contributions by NS and SGW pathways under the wet winter conditions. When NS flows became less frequent in spring and the SGW store was gradually depleted, estimated MTTs rose again from less than 10 years in late September and early October to nearly 50 years in late December 2016.

While the overall pattern was similar in 2022, different weather conditions between (and preceding) these two years are clearly reflected in the estimates. In contrast to 2016, there was hardly any SGW discharge modelled for the first half of 2022, presumably reflecting that this store had already been depleted by that time. Accordingly, estimated MTTs for this period were higher than in 2016, reaching up to approximately 65 years. However, estimated MTTs oscillated between 30 and less than 10 years from early July till December, as prolonged rainfall excess resulted in substantial NS and SGW flow contributions.

Despite the estimated MTT at mean flow being the second-highest of all catchments (20.2 years), the temporal variation of MTTs was also one of the highest. This means that the available tritium and modelling results strongly indicate that substantial volumes of young water are discharged from the catchment (NS+SGW = 32%), even in this very strongly groundwater-dominated catchment. Consequently, the nitrogen ‘load to come’ is in all likelihood smaller than what one would expect not taking these fast transfers into account.

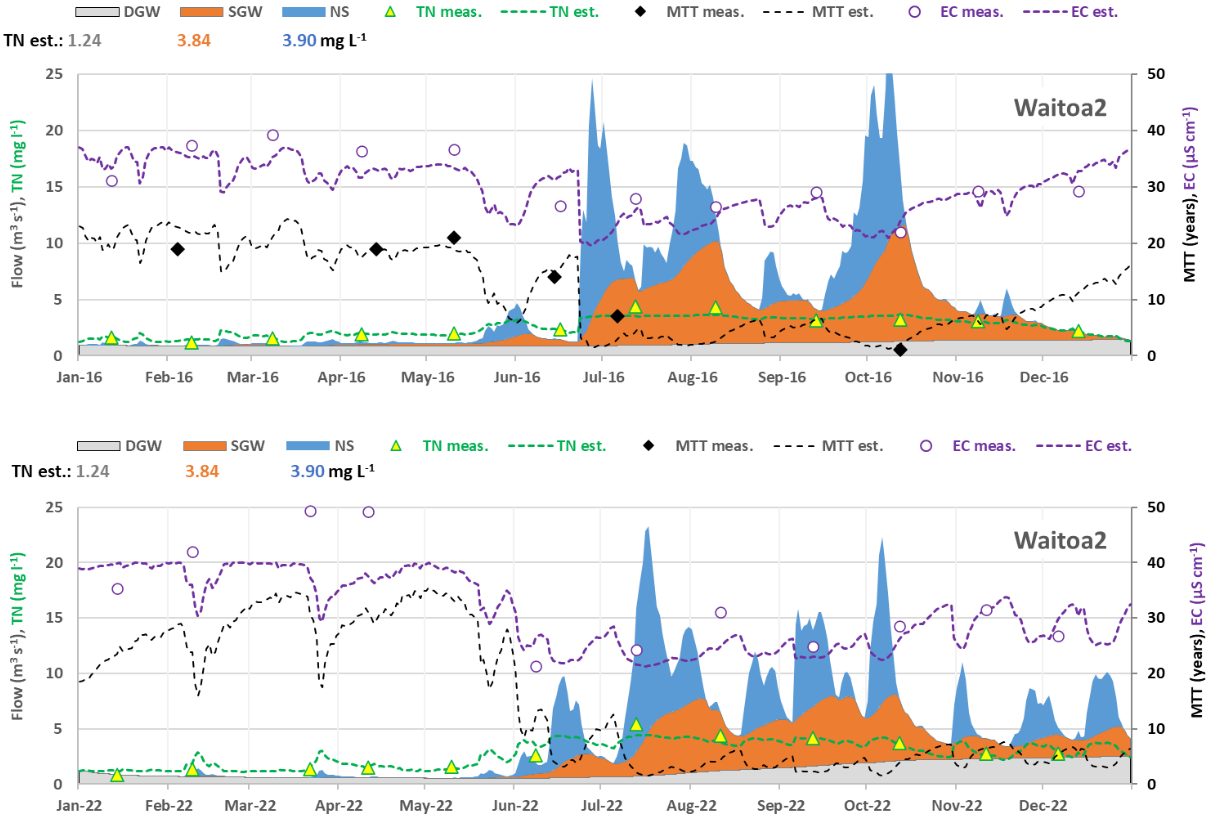

Figure 10: Pathway contributions, tracer concentrations, and MTTs for Waitoa2, Waitoa River at Mellon Rd, Hauraki (2016 top, 2022 bottom).

Compared to the Waihou River, flow in the Waitoa River (and most other Hauraki rivers) is substantially more dynamic (Fig. 10). Very little flow, sustained by DGW, is typically observed during summer and autumn. This older water (MTT mainly 20 – 35 years) has relatively low TN and high EC concentrations. Flow increases steeply once the catchment has wetted up in late autumn or early winter and NS and SGW become the dominant flow contributors. This transition to younger water (MTTs largely < 10 years) is also reflected in increasing TN and decreasing EC concentrations in the river. Note that long-term average TN concentrations in DGW have been estimated as 1.2 mg L^{-1}, while corresponding values were 3.8 – 3.9 mg L^{-1} for the two shallower pathways (SGW, NS).

Sporadic high-frequency monitoring with optical nitrate sensors suggests that these strong concentration dynamics are in flashy streams poorly reflected by routine monitoring programmes (monthly grab samples). The first high-flow events in late autumn/winter, which are often not captured by the monthly sampling schedule, can be responsible for very high nitrate exports, particularly in years with dry autumn conditions.

Differences between individual years are also very evident in Fig. 10. While flows greater than 5 m^3 s^{-1} were largely restricted to late June to mid-October in 2016, they occurred from mid-June till the end of the year in 2022.

2.2 Catchment water quality

2.2.1 Summary statistics for water quality at WRC monitoring sites

For the last 30 years, Waikato Regional Council has been monitoring a range of water quality parameters at 17 sites in the Piako and Waihou catchments on fixed monthly intervals (see Fig. 1). Some information on these sites, as provided on the LAWA website (https://www.lawa.org.nz/), is given in the Appendix I and a comprehensive summary statistics table for the last 10 years (2014 – 2023) is presented in Appendix II.

In this section, we present maps for selected parameters to illustrate the spatial variation of results, followed by consideration of variation over time in Section 2.2.2.

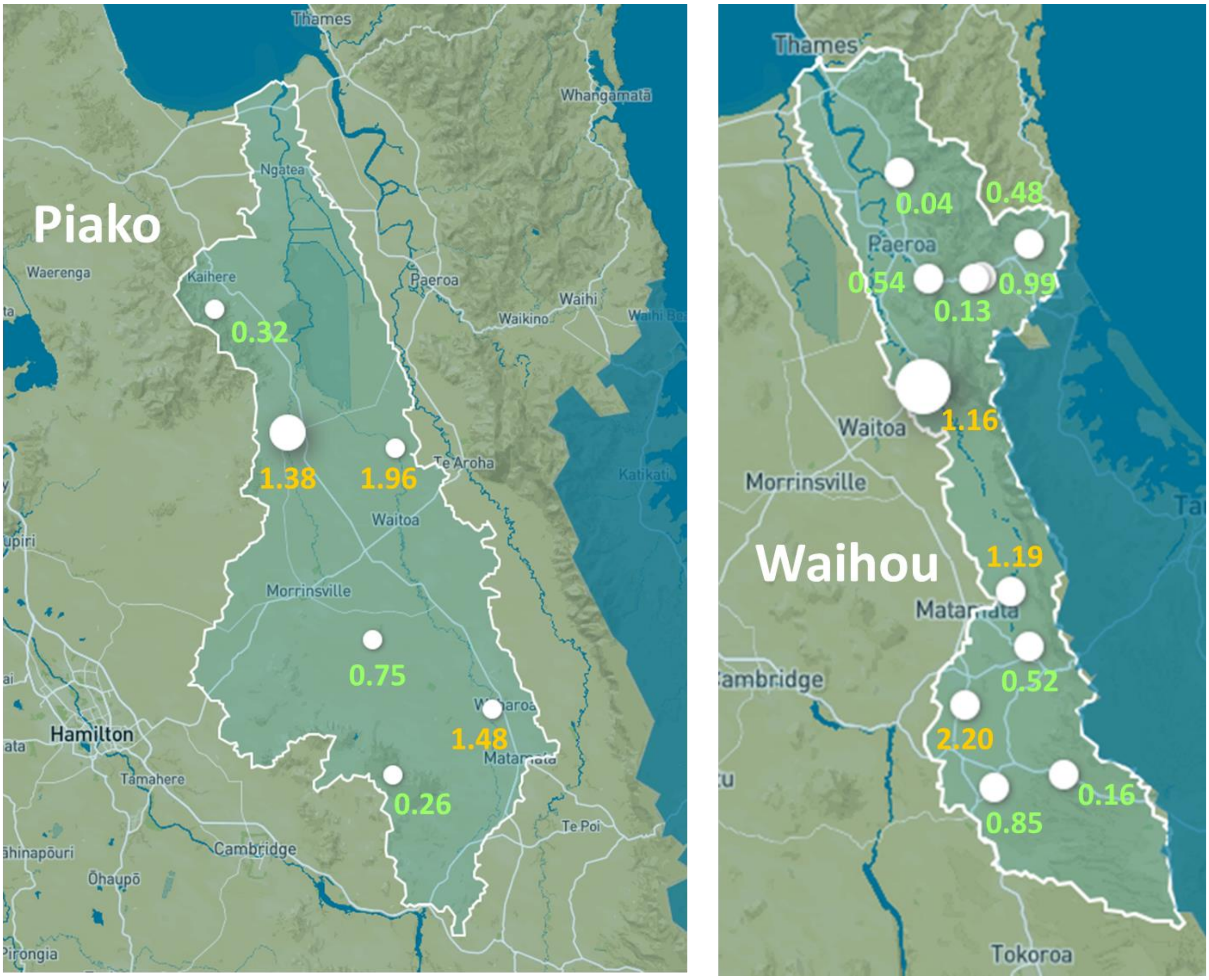

Figure 11: Median Nitrate-Nitrogen (NO_3-N, in mg l^{-1}) concentration at Piako and Waihou monitoring sites (2014 - 2023).

The 10-year median Nitrate-Nitrite-Nitrogen (NNN) concentrations shown in Fig. 11 would at eleven of the 17 sites have resulted in assigning the highest NOF Band (A), unlikely to experience any toxicity effects (green colour in Fig. 11). Some growth effects on up to 5% of species might occur at the remaining six sites in Band B (orange colour in Fig. 11). These sites comprise the Piako River site at the Paeroa-Tahuna Road, both Waitoa River sites, Oraka Stream at Lake Road, and both Waihou River sites. The lowest NNN concentrations were found at headwater streams with high percentages of native bush or plantation forestry (Piakonui, Mangawhero, Hikutaia, Waitekauri, and Waiohotu Streams). It should be noted that the NOF only considers nitrate toxicity and that accounting for the effect of nitrate on the trophic state of a waterbody might require more stringent criteria.

Median ammonia-nitrogen concentrations were very low throughout the sub-region, with all but three sites falling into the A band (≤ 0.03 mg L^{-1}). Only Piako at Paeroa-Tahuna Road, Waitoa at Mellon Road, and Ohinemuri at Queen's Head having somewhat higher concentrations (B Band).

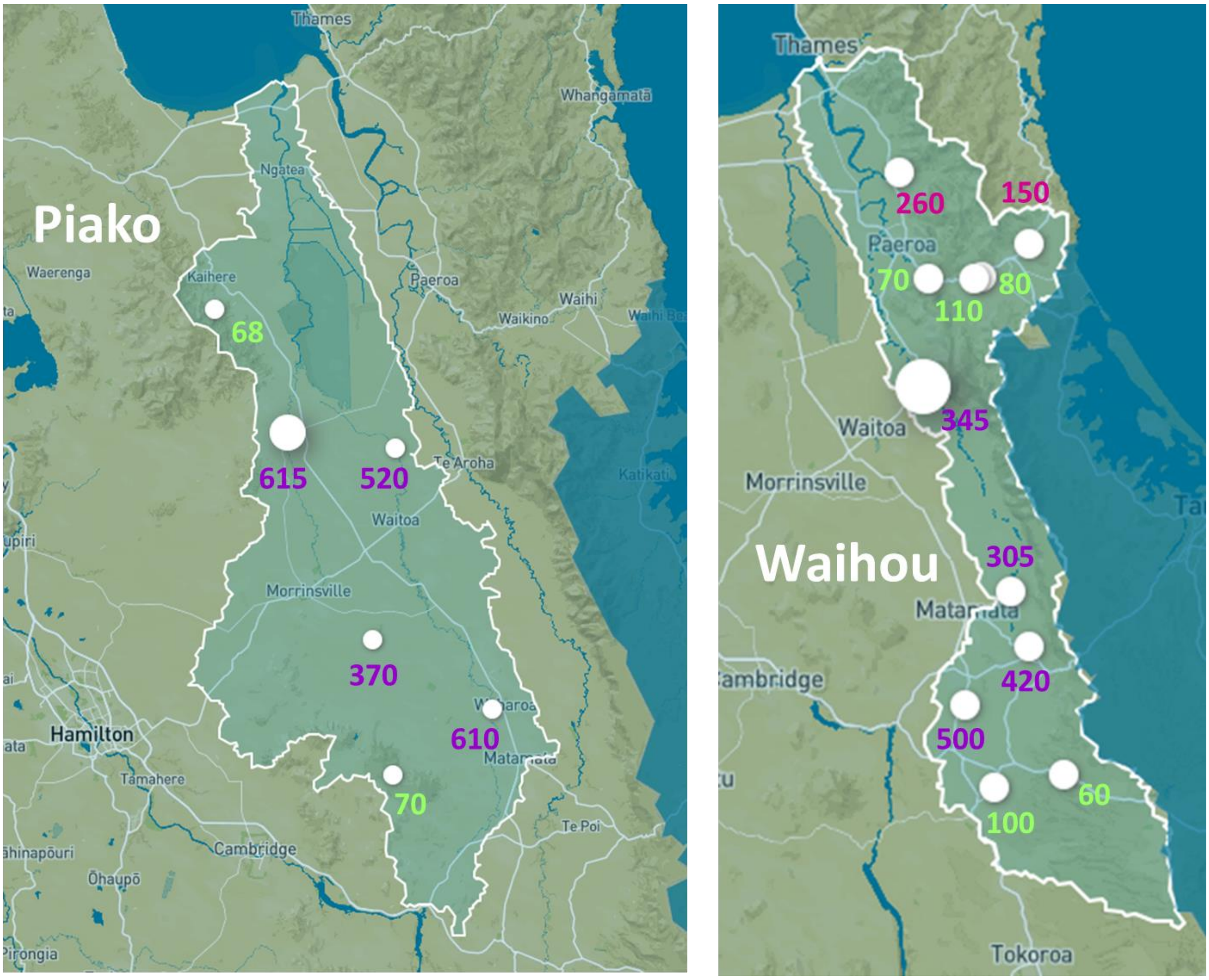

Figure 12: Median E. coli concentration (cfu 100 ml^{-1}) at Piako and Waihou monitoring sites (2014 - 2023).

In contrast to nitrate and ammonia, Escherichia coli (E. coli) data indicate widespread exceedance of acceptable levels. Only using the median concentrations (and neglecting additional criteria on the frequency distributions) suggests that several sites would fall into Bands D and E, i.e. the two lowest categories (Fig. 12). The lowest E. coli concentrations were observed at five headwater sites (Piakonui, Mangawhero, Waitekauri, Waiohotu, Waihou at Whites Road), and the two Ohinemuri River sites at Queen's Head and Karangahape.

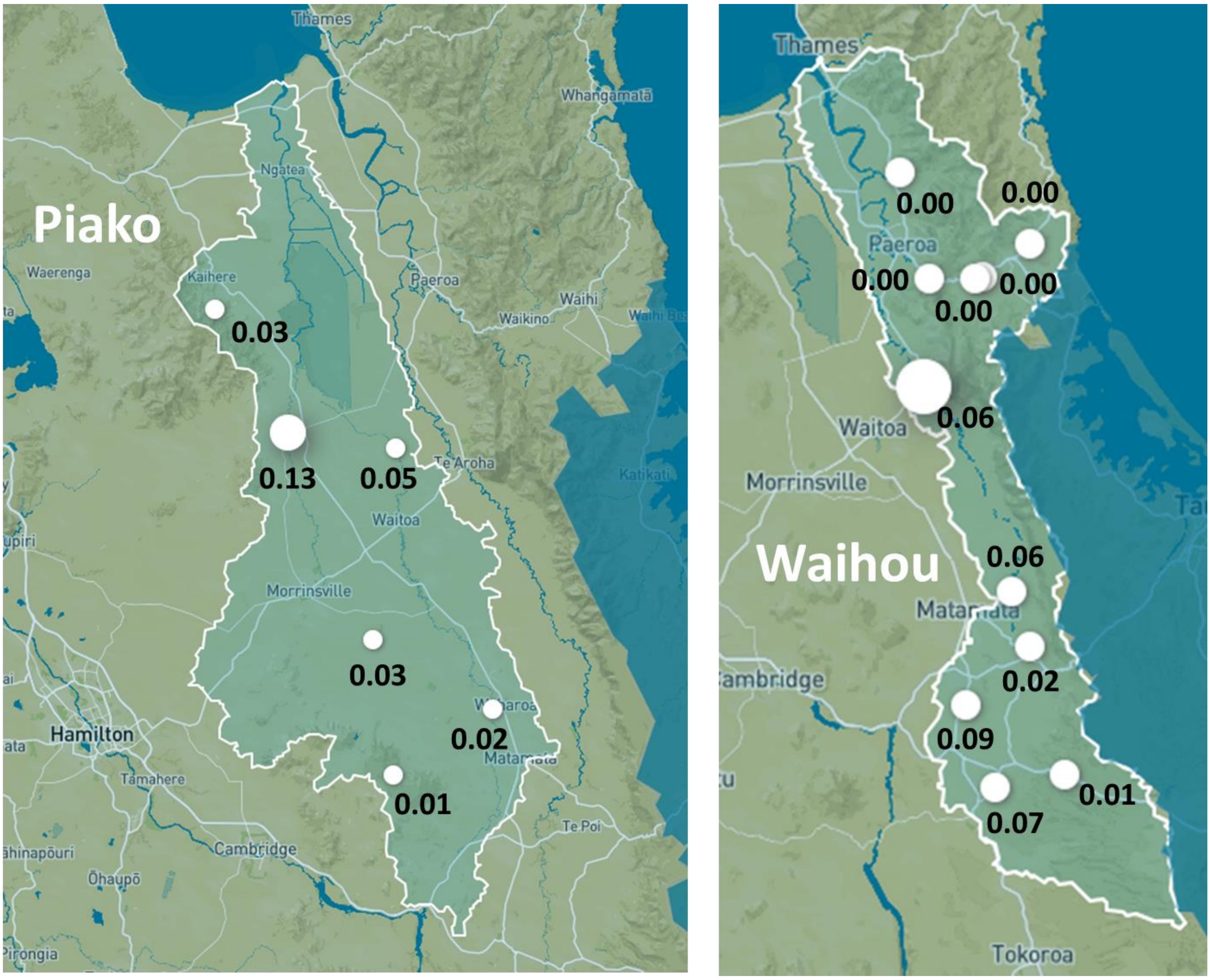

Figure 13: Median Dissolved Reactive Phosphorus (DRP) concentration (mg l^{-1}) at Piako and Waihou monitoring sites (2014 - 2023).

Dissolved Reactive Phosphorus (DRP) constitutes the most easily plant-available fraction of Total Phosphorus (TP). DRP concentrations (Fig. 13) were lowest at the north-eastern monitoring sites (Hikutaia, Waitekauri and Ohinemuri) and headwater sites elsewhere (Piakonui, Waiohotu). Elevated concentrations at downriver sites are not exclusively due to agricultural land use, but also affected by industrial (dairy factories, meat works) and municipal discharges (wastewater treatment plants). See Sections 2.1.6 and 2.2.5 for detail.

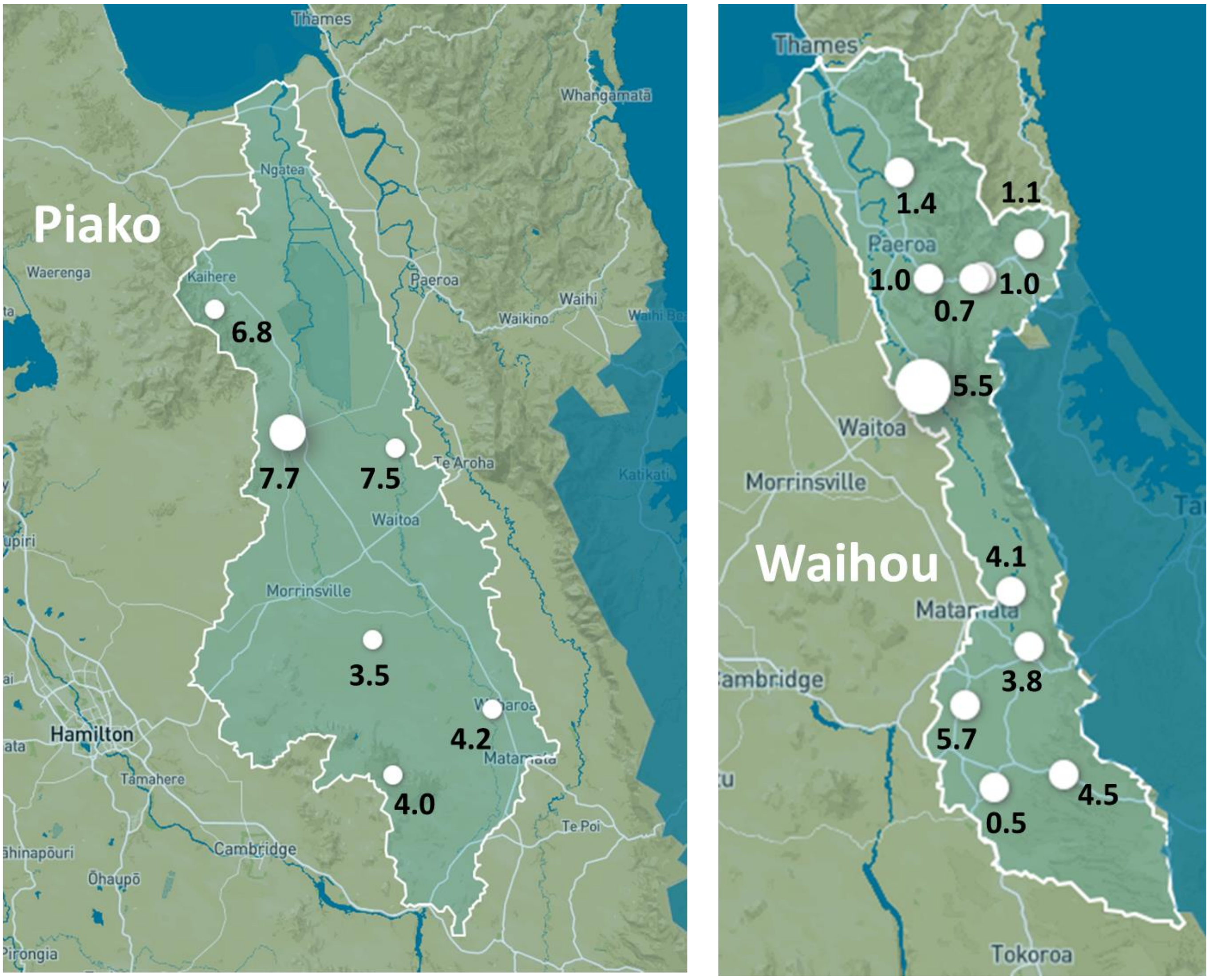

Figure 14: Median turbidity (in NTU) at Piako and Waihou monitoring sites (2014 - 2023).

The Waihou River monitoring site at Whites Road (near the well-known 'Blue Springs') had the lowest turbidity of all sites, followed by the north-eastern monitoring sites (Hikutaia, Waitekauri and Ohinemuri). In contrast, most lowland sites were rather turbid and deteriorating in a downriver direction (Fig. 14).

The median Dissolved Oxygen (DO) saturation tends to be lower in the Piako River catchment than in the Waihou River catchment, with highest percentages observed in Ohinemuri and Waitekauri rivers, and lowest in Piako and Waitoa Rivers (Fig. 15). A saturation level of no less than 80% is often used as a broad-brush guideline to protect aquatic life. However, it should be noted that medians of monthly measurements taken during daylight hours are not truly reflecting conditions experienced by stream biota, as substantial diurnal variation (with overnight minima) is a major factor concerning ecosystem health. See Section 2.1.6 for selected time series data.

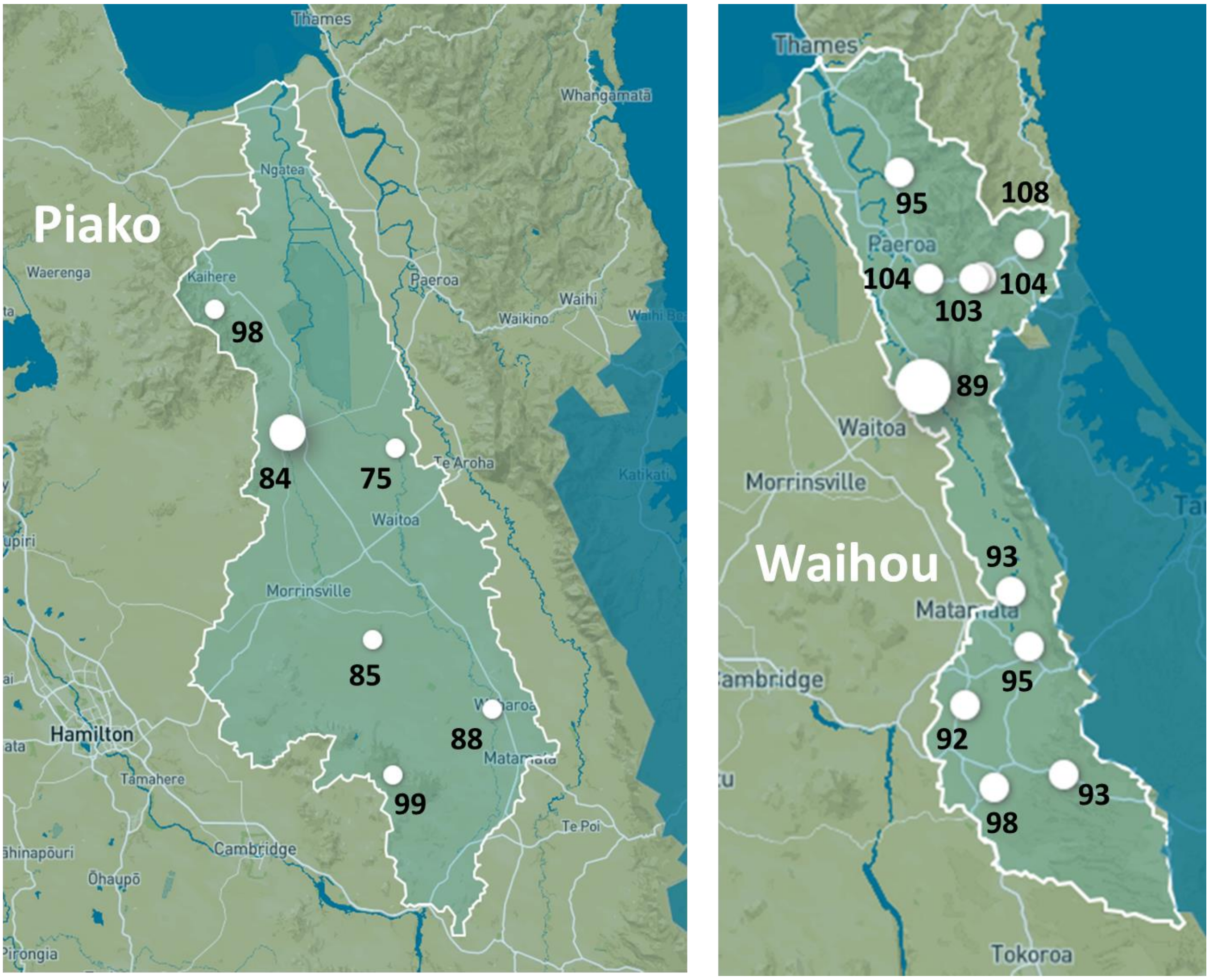

Figure 15: Median Dissolved Oxygen (DO) saturation (in %) at Piako and Waihou monitoring sites (2014 - 2023).

While change in government policy means that the National Objectives Framework (NOF) of the NPS-FM is at least deferred, if not obsolete, references to NOF bands and national bottom lines were included above to provide a scale for the evaluation of measured concentrations. Note that a more comprehensive assessment for a 5-year period ending September 2017 was provided by WRC (2022c). This analysis incorporated a range of additional attributes (e.g. dissolved inorganic nitrogen, DIN) that were discussed at that time but ultimately not included in the 2020 version of the NPS-FM. Some key results of WRC's analysis are reproduced in Table 1.

It should be noted that Ammonia and Nitrate Nitrogen would predominantly have fallen into the NOF bands A and B, i.e. above the national bottom line. Suspended fine sediment (Visual Clarity) would more often have rated worse, C at a few Piako catchment sites, and D at a few upper Waihou catchment sites. Dissolved Reactive Phosphorus (DRP) was one of the attributes requiring an action plan, rather than default limits. WRC's analysis highlighted widespread exceedances apart from the Ohinemuri, Waitekauri, and Hikutaia catchment areas in the north-east. The highest percentage of exceedances, and typically the worst rating in individual catchments, applied to E. coli. Eleven out of 17 sites were rated as 'E', the worst band.

Table 1: Attribute states and NOF bands for a range of water quality parameters (2012-2017), (from WRC, 2022c).

	Ammonia max	Ammonia median	Nitrate 95th percentile	Nitrate median	Susp. fine sed. median	DRP 95th percent.	DRP median	E. coli overall
Piakonui	0.03 A	0.002 A	0.67 A	0.205 A	1.51 C	0.02 a	0.011 c	B
Piako at Kiwitahi	0.268 B	0.003 A	3.35 B	0.815 A	1.5 C	0.067 d	0.042 d	E
Piako, P-T Rd	0.058 B	0.016 A	4 C	1.37 B	0.96 A	0.57 d	0.2 d	E
Mangawhero	0.007 A	0.003 A	0.495 A	0.315 A	0.93 A	0.048 c	0.036 d	A
Waitoa at Landsdowne	0.034 A	0.005 A	2.75 B	1.5 B	1.46 C	0.044 c	0.022 d	E
Waitoa at Mellon Rd	0.161 B	0.018 A	3.5 B	1.98 B	1.23 A	0.111 d	0.058 d	E
Waiohotu at Waiohotu Rd	0.003 A	0.002 A	0.235 A	0.145 A	--	0.02 a	0.013 c	A
Waiomu,M-T Rd	0.051 B	0.004 A	1.045 A	0.51 A	1.28 D	0.026 b	0.018 c	E
Oraka	0.32 B	0.015 A	2.75 B	2.1 B	1 D	0.172 d	0.079 d	E
Waihou at Whites Rd	0.011 A	0.002 A	0.865 A	0.76 A	5.2 A	0.08 d	0.074 d	A
Waihou at Okauia	0.081 B	0.005 A	1.645 B	1.145 B	1.09 D	0.078 d	0.06 d	E
Waihou at Te Aroha	0.116 B	0.01 A	1.621 B	1.094 B	0.9 B	0.084 d	0.05 d	E
Ohinemuri at SH25	0.019 A	0.002 A	0.915 A	0.455 A	3.01 A	0.013 a	0.004 a	B
Ohinemuri at Queens Head	0.139 B	0.021 A	1.29 A	0.94 A	3.09 A	0.01 a	0.002 a	E
Ohinemuri at Karangahake	0.056 B	0.01 A	0.898 A	0.384 A	2.96 A	0.005 a	0.002 a	E
Waitekauri	0.022 A	0.002 A	0.361 A	0.108 A	3.5 A	0.008 a	0.002 a	E
Hikutaia	0.037 A	0.002 A	0.255 A	0.02 A	3.18 A	0.006 a	0.002 a	D

2.2.2 Trends in water quality

Trends in river water quality at 114 sites in the Waikato region were analysed by WRC staff for the 30-year 1991-2020 period using non-parametric statistical methods (seasonal Kendall slope estimator and slope direction probability; WRC, 2021). The values reported in Table 2 are slopes (in % per year) of very likely trends (i.e. with slope direction probability >95%) in flow-adjusted water quality data. A trend was considered 'important; if the absolute value of the slope exceeded 1% per year.

Table 2: Compilation of water quality trend analysis results for 1991-2020 (from WRC, 2021). The values are slopes (in % per year) of very likely trends (i.e. with slope direction probability >95%) in flow-adjusted water quality data. Important improvements are shown in bold blue type; important deteriorations are bold red and underlined; 'nvl' stands for 'not very likely, i.e. trend slope probability <95%.

	T	DO	EC	Turb.	VC	TN	NO3-N	NH4-N	TP	DRP	E. coli	Ent.
Piakonui	0.1	-0.1	0	-0.8	**1.6**	-0.2	0.0	0.0	**-2.0**	**-1.6**	**-2.2**	-0.5
Piako at Kiwitahi	0.1	-0.2	0.3	**-1.3**	0.7	-0.7	-0.5	**-5.0**	**-2.2**	**-2.0**	-0.4	**2.5**
Piako, P-T Rd	0.0	0.1	0.6	-0.6	0.3	**-1.0**	**-1.0**	**-3.3**	-0.9	-0.7	-0.4	**3.7**
Mangawhero	0.0	-0.1	0.3	0.6	-0.6	0.1	0.3	0.0	-0.5	-0.2	-1.8	-1.4
Waitoa at Landsdowne	0.1	0.1	0.5	-0.5	-0.2	0.0	0.1	**-3.3**	**-1.9**	**-2.0**	1.3	1.3
Waitoa at Mellon Rd	-0.2	0.3	0.1	**1.2**	**-1.1**	-0.5	-0.3	**-2.5**	**-10.9**	**-16.8**	0.3	**1.4**
Waiohotu at Waiohotu Rd	0.4	-0.1	-0.1	0.7	n.a.	0.7	0.1	0.0	-0.5	**-2.4**	**-4.3**	**3.1**
Waiomu, M-T Rd	-0.1	0.0	0.3	**1.6**	-0.7	**1.2**	**1.2**	-0.1	-0.7	**-2.0**	**1.9**	**2.0**
Oraka	0.0	-0.1	**1.0**	**1.8**	-0.8	0.8	0.8	0.6	-0.6	-0.8	**-3.1**	1.1
Waihou at Whites Rd	0.0	-0.2	0.4	0.9	-0.4	**1.8**	**1.9**	0.0	-0.5	-0.6	**3.6**	**2.8**
Waihou at Okauia	-0.1	0.0	0.6	**1.2**	-0.7	**1.0**	**1.0**	-0.1	-0.5	-0.7	**2.1**	**2.3**
Waihou at Te Aroha	-0.2	-0.2	0.5	0.4	0.9	0.6	0.6	0.0	-0.1	-0.3	1.4	n.a.
Ohinemuri at SH25	0.1	0.0	0.0	0.0	-0.8	0.1	0.0	-0.9	**-1.9**	**-3.0**	**-4.4**	-0.6
Ohinemuri at Queens Head	-0.1	-0.2	1.9	**-1.5**	0.7	0.7	0.8	**1.3**	**-6.8**	**-11.6**	**-9.7**	-0.7
Ohinemuri at Karangahake	0.3	-0.1	**1.1**	0.0	**1.2**	-0.1	-0.2	**-1.2**	**-3.1**	**-5.1**	0.0	n.a.
Waitekauri	0.2	0.0	**-1.4**	-0.7	-0.2	**-2.6**	**-3.1**	**-2.7**	**-1.3**	0.0	**-5.2**	-0.4
Hikutaia	-0.1	0.0	0.0	**-1.1**	0.5	**-1.0**	**-1.6**	**-6.1**	**-2.1**	**-2.6**	-0.4	2.0

Of the 12 parameters analysed for trends, Temperature and Dissolved oxygen were the only two that did not show a single important trend, and important Conductivity trends were only found at four sites (three deteriorations at Oraka, Ohinemuri at Queens Head and at Karangakake; one improvement at Waitekauri). Turbidity deteriorated at Oraka, Waihou at Okauia, Waiomu, and Waitoa at Mellon Rd (n=4), but showed important improvements at Piako at Kiwitahi, Hikutaia, and Ohinemuri at Queens Head (n=3). Visual clarity improved markedly at Piakonui and Ohinemuri at Karangahake (n=2), but deteriorated at Waitoa at Mellon Rd (n=1). Total Nitrogen and Nitrate Nitrogen improved at Piako at Paeroa-Tahuna Rd and at Waitekauri (n=2), but deteriorated at Waiomu, Waihou at Whites Rd and Waihou at Okauia (n=3). Ammoniacal nitrogen (NH4-N), Total Phosphorus (TP), and Dissolved Reactive Phosphorus (DRP) were at most sites stable (n=7-8) or improving (n=6-9), with no significant deterioration detected. E. coli trends were quite mixed, with important improvements at Oraka, Piakonui, Waitekauri, Waiohotu, and two Ohinemuri River sites (n=6), but important deteriorations at Waiomu and two Waihou River sites (n=3). In contrast, all important Enterococci trends were deteriorations (n=7). In total, 44 important improvements were observed and 24 important deteriorations.

With regard to the spatial variation of these trends (Fig. 16), it is noteworthy that stable or improving values were predominant at most Piako River catchment sites. Deteriorating trends were only recorded for Waitoa at Mellon Rd (turbidity, visual clarity, and Enterococci) and both Piako River sites for Enterococci. The north-eastern monitoring sites within the Waihou River catchment (Ohinemuri, Waitekauri, and Hikutaia) also showed largely stable or improving trends. The only exceptions were conductivity at Karangahake and ammonical nitrogen at Queens Head. In contrast, only four improving trends were detected at the remaining six sites of the Waihou catchment, DRP and

E. coli at Waiohotu, DRP at Waiomu, and E. coli at Oraka. Important deteriorations concerned turbidity, TN and Nitrate-N, E. coli (all n=3), and Enterococci (n=4).

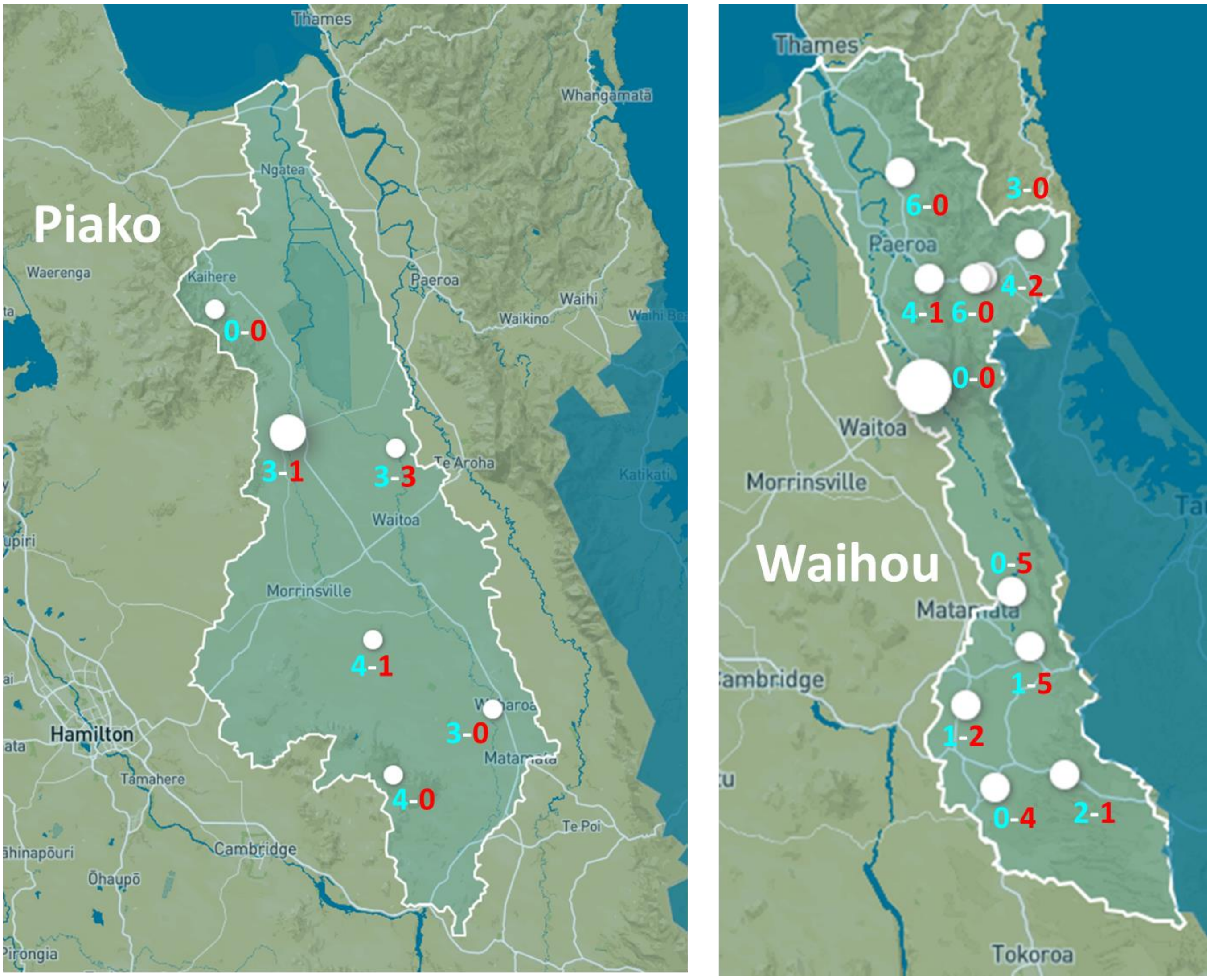

Figure 16: Number of observed important improvements vs important deteriorations in measured water quality parameters (1991-2020). Data from WRC, 2021.

Trends were also calculated for the 10-year period from 2011-2020 (WRC, 2021). Unfortunately, this analysis of more recent conditions yielded less encouraging results (Table 3). In contrast to the 30-year period, important deteriorations by far outweighed important improvements (50 vs 21). Important improvements were recorded for TP and DRP at several Piako catchment sites and Visual Clarity of the Ohinemuri River and neighbouring streams. However, TN and NO_3-N worsened at most Waihou catchment sites and microbial contamination deteriorated at many sites apart from the wider Ohinemuri River area (Fig. 17).

Table 3: **Compilation of water quality trend analysis results for 2011-2020 (from WRC, 2021). The values are slopes (in % per year) of very likely trends (i.e. with slope direction probability >95%) in flow-adjusted water quality data. Important improvements are shown in bold blue type; important deteriorations are bold red and underlined; 'nvl' stands for 'not very likely, i.e. trend slope probability <95%.**

	T	DO	EC	Turb.	VC	TN	NO3-N	NH4-N	TP	DRP	E. coli	Ent.
Piakonui	-0.6	0.2	0	-1	1.4	0.7	**2.2**	0.0	0.0	**-2.1**	2.3	1.7
Piako at Kiwitahi	-1.0	0.4	0.2	-1.1	**4.0**	-0.4	-0.3	0.0	**-3.2**	**-7.2**	**10.0**	**9.2**
Piako, P-T Rd	-0.6	-0.2	0.3	**2.9**	-1.8	0.5	0.8	**3.8**	**-3.2**	**-6.7**	**14.2**	**14.0**
Mangawhero	0.8	0.2	0.5	-1.0	**-2.3**	-0.6	-1.1	0.0	**1.1**	**-1.5**	0.3	2.0
Waitoa at Landsdowne	-0.7	0.4	0.6	0.1	**3.2**	0.5	1.0	0.7	-1.0	**-4.2**	**11.2**	**7.2**
Waitoa at Mellon Rd	-0.3	-0.2	**1.2**	**3.6**	-1.9	0.7	0.9	2.4	2.1	-1.8	**15.3**	**7.6**
Waiohotu at Waiohotu Rd	0.4	0.2	-0.2	-1.8	n.a.	**2.1**	**2.2**	0.0	0.5	**-2.0**	-0.5	**8.3**
Waiomu, M-T Rd	-0.9	0.4	0.2	1.5	0.3	**1.3**	**2.4**	0.8	-0.1	**-3.1**	**5.0**	**2.9**
Oraka	0.4	0.2	**1.1**	1.6	0.6	0.9	0.6	3.2	**5.5**	**4.4**	**10.0**	**10.7**
Waihou at Whites Rd	-0.3	-0.4	0.6	0.8	0.6	**2.2**	**2.2**	0.0	0.0	-0.9	**14.0**	**10.3**
Waihou at Okauia	-0.9	0.2	0.6	-0.2	-0.2	**1.0**	**1.4**	**4.7**	**2.6**	1.1	**6.5**	**5.1**
Waihou at Te Aroha	**-1.2**	-0.7	0.4	-1.3	**3.4**	**1.9**	**1.2**	**7.6**	**1.4**	**4.1**	2.7	n.a.
Ohinemuri at SH25	0.1	0.4	-0.1	-0.2	**4.5**	**1.2**	**2.2**	0.0	0.2	1.1	-0.5	2.0
Ohinemuri at Queens Head	-0.1	-0.1	-0.7	-2.2	**5.5**	-0.3	0.6	0.1	-0.1	0.0	3.1	1.8
Ohinemuri at Karangahake	0.0	0.1	-0.8	**-3.2**	**2.5**	**2.0**	**1.9**	-1.5	**-2.9**	-0.2	-3.0	n.a.
Waitekauri	0.1	0.0	0.0	**-1.5**	**4.8**	0.3	**1.8**	0.0	1.0	0.0	**7.2**	0.5
Hikutaia	-0.6	-0.4	0.2	1.3	**3.8**	**2.7**	2.0	0.0	1.9	0.0	**6.3**	4.9

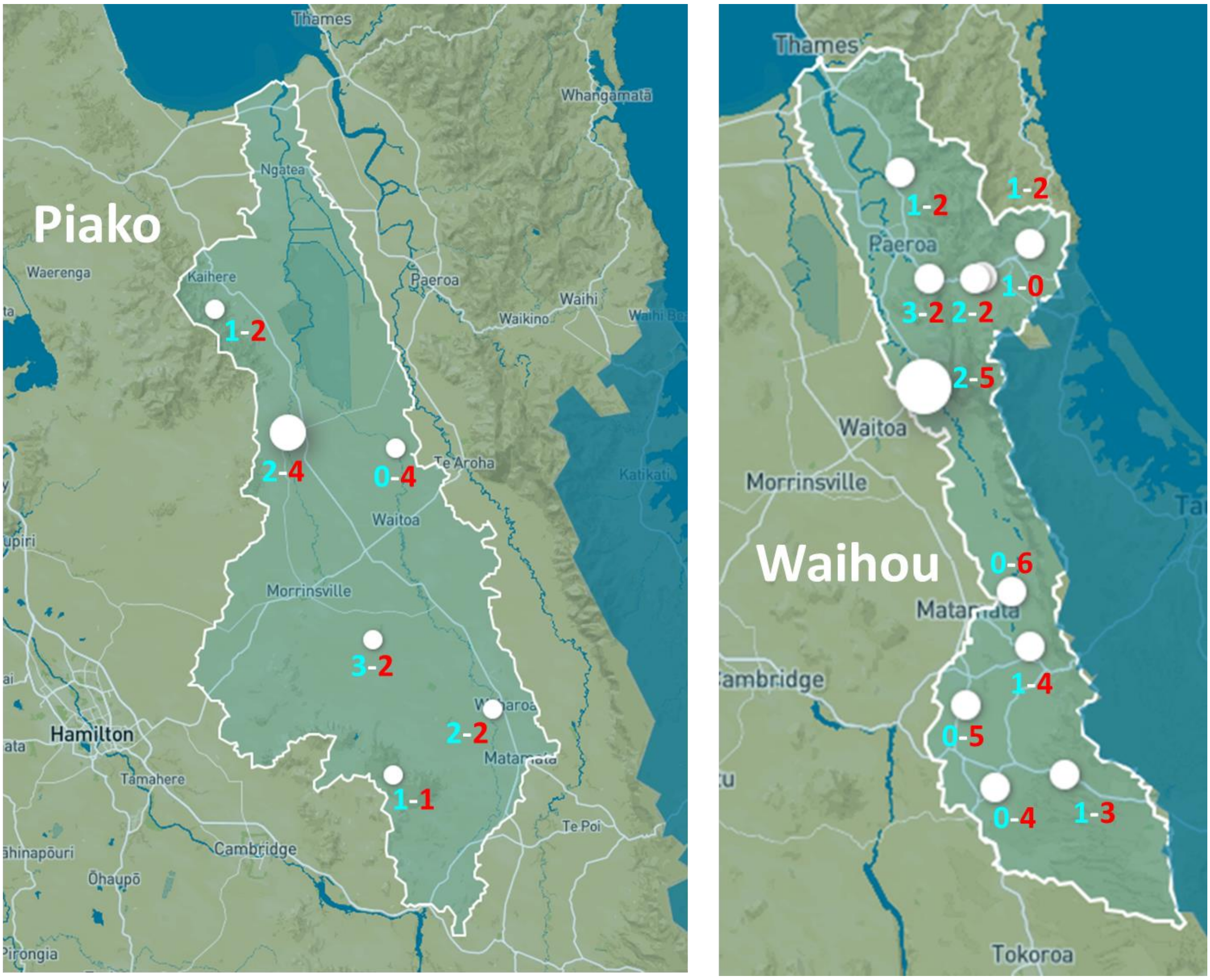

Figure 17: Number of observed important improvements vs important deteriorations in measured water quality parameters (2011-2020). Data from WRC, 2021.

2.2.3 Water quality time series at WRC monitoring sites

The 30-year NNN concentration time series for three sites each along the Piako and Waihou rivers (Fig. 17) offer themselves for the discussion of a few topics of interest. A noteworthy caveat is that analytical methods have changed over time, which may have affected some of the existing time series. This possibility was considered insignificant for the current analysis, although WRC considers the phosphorus results 'preliminary' (WRC, 2021).

The strong concentration increases between the Piakonui monitoring site high up in the Piako headwater area (mainly bush) and the Piako at Kiwitahi site less than 20 km downriver demonstrates that agricultural land use quickly results in substantially elevated NNN concentrations. In contrast, only modest further concentration increases have been recorded between Kiwitahi and the Paeroa - Tahuna Rd site (Fig. 17, top). Secondly, concentration trends are very difficult to detect visually, especially in flashy streams with positive concentration-discharge relationships (see Section 2.2.4). Accordingly, WRC staff applied non-parametric statistical methods to determine trends (as reported in Section 2.2.2). In contrast, clearly increasing NNN concentrations since the early 2000s are evident in the substantially less dynamic time series from the uppermost Waihou River site at Whites Road (Fig. 17, bottom; note the different scale on the y-axis). However, the substantial flow contribution by groundwater recharged on the Mamaku Plateau means that downriver concentrations at Okauia and at Te Aroha are still substantially lower than in Piako River, despite rising headwater concentrations.

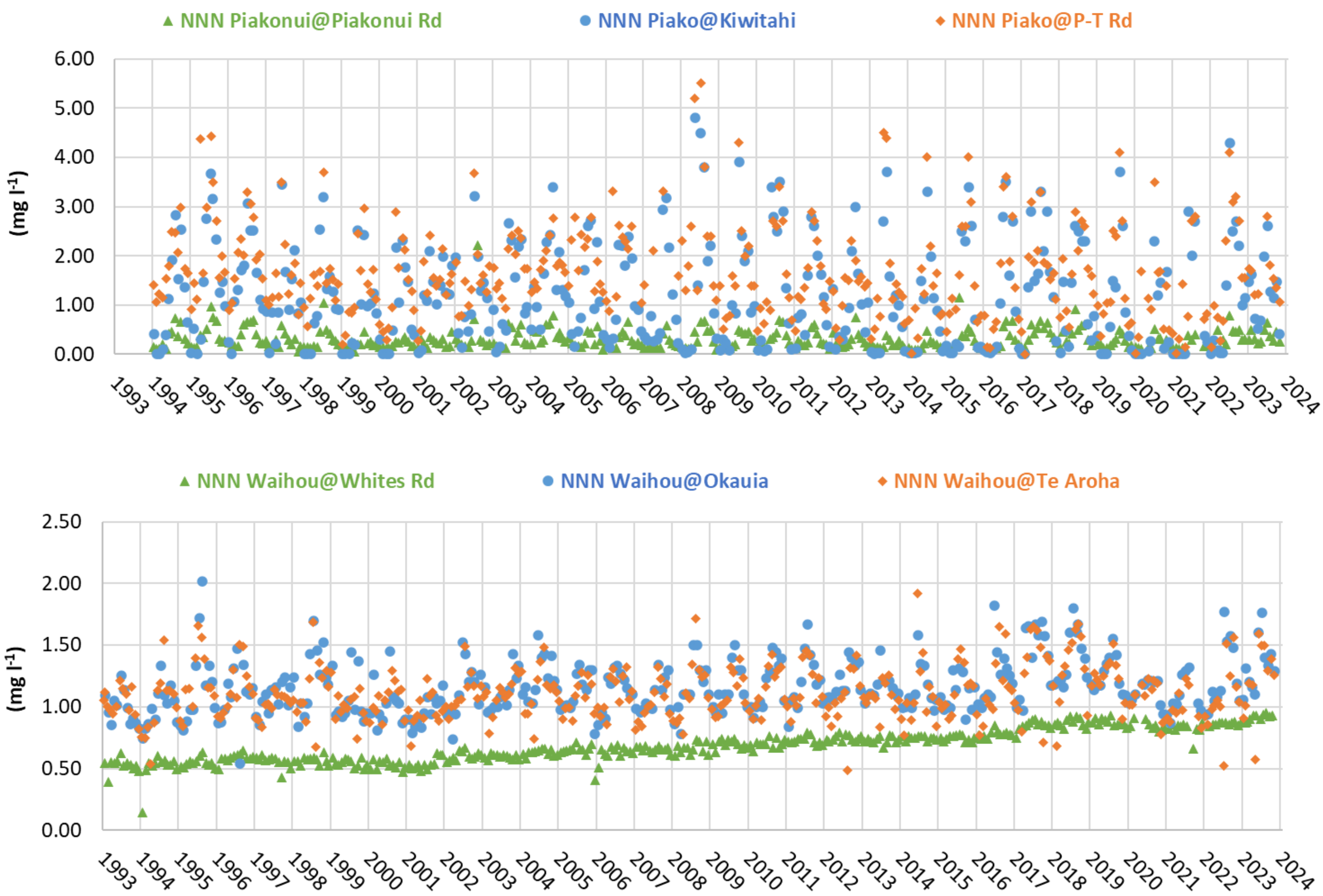

Figure 18: Nitrate-Nitrite-Nitrogen (NNN) concentrations (in mg l^{-1}) for Piako River sites (top) and Waihou River sites (bottom); 1993 - 2023.

The time series compiled in Fig. 19 show that two tributaries of the Waihou River in its upper reach feature lower NNN concentrations than the mainstem Waihou River at Whites Road, while a third one has substantially elevated concentrations. Consistently the lowest concentrations (median 0.16 mg l^{-1}) have been recorded for Waiohotu Stream originating under bush cover on the Mamaku Plateau. Somewhat higher concentrations (median 0.52 mg l^{-1}) with more pronounced seasonal dynamics were found at Waiomou Stream at the base of the Kaimai Ranges along the Matamata – Tauranga Road. In stark contrast, median NNN concentrations of 2.20 mg l^{-1}, never dropping below 1.2 mg l^{-1}, were recorded at Oraka Stream. This stream also originates in the Kaimai-Mamaku Forest, but gets polluted by discharges from the Putaruru and Tirau wastewater treatment plants and the Tirau dairy factory.

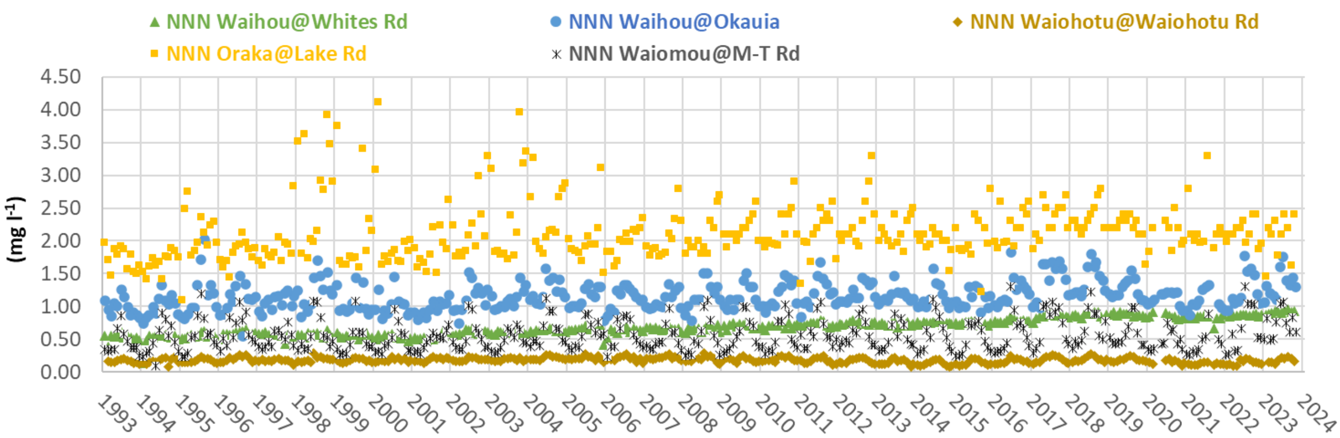

Figure 19: Nitrate-Nitrite-Nitrogen (NNN) concentrations (in mg l^{-1}) for two upper Waihou River sites and three tributaries; 1993 - 2023.

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As mentioned in the previous section, apart from the three exceptions shown in Fig. 19, median ammonia-nitrogen concentrations were generally low during the last 10 years. The long-term time series show however that higher concentrations were common at several sites earlier on during the monitoring period. While some improvements may have resulted from better effluent management on farms (e.g. Piako at Kiwitahi in Fig. 20), the biggest improvements have been recorded for sites impacted by point-source discharges (e.g. Waitoa at Mellon Rd in Fig. 19 or Waitekauri in Fig. 20).

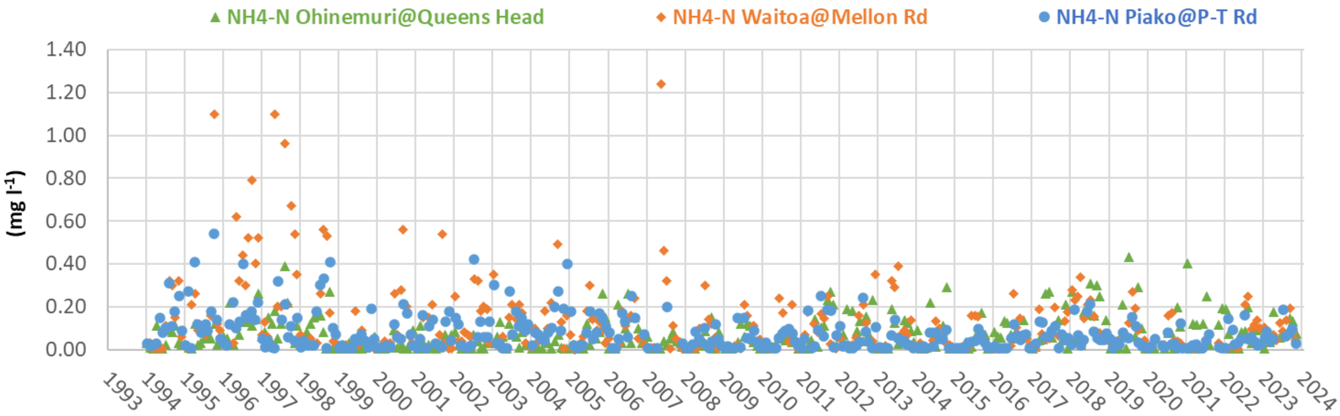

Figure 20: Ammonia-Nitrogen (NH_4-N) time series for three sites with still elevated concentrations (in mg l^{-1}); 1993 - 2023.

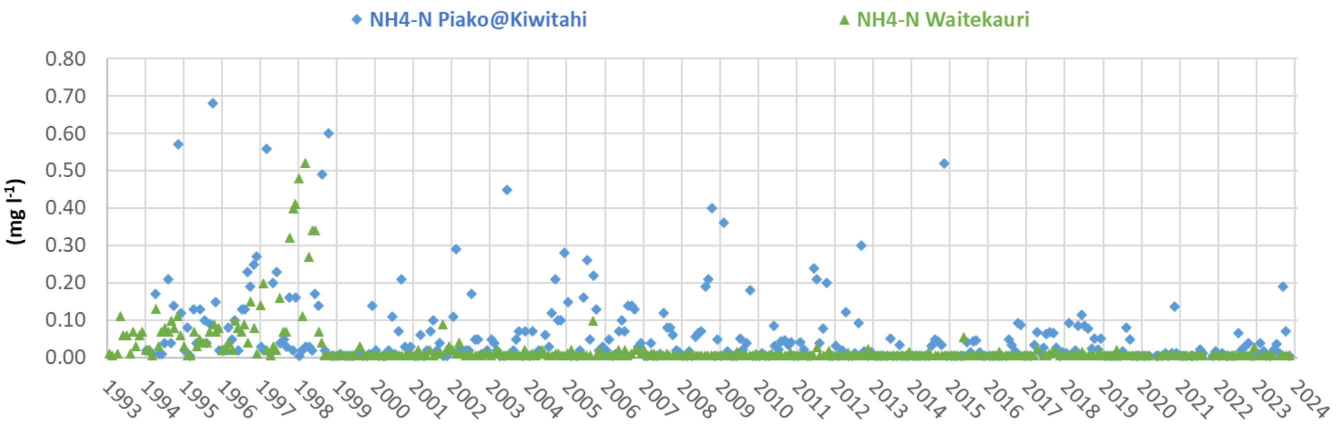

Figure 21: Ammonia-Nitrogen (NH_4-N) time series for two sites decreasing concentrations (in mg l^{-1}); 1993 - 2023.

As for ammonia-nitrogen, the highest observed Dissolved Reactive Phosphorus (DRP) concentrations also often relate to point-source discharges. This is illustrated in Fig. 22 on the example of the two monitoring sites along the Waitoa River. While the concentrations recorded at the Landsdowne Rd site largely reflect the agricultural land use in its catchment area, the Mellon Road site used to be heavily affected by industrial discharges (e.g. Waharoa and Waitoa dairy factories, meatworks, poultry processor). Stricter resource consent conditions resulted in substantial concentration decreases between the start of the monitoring period and approximately 2006.

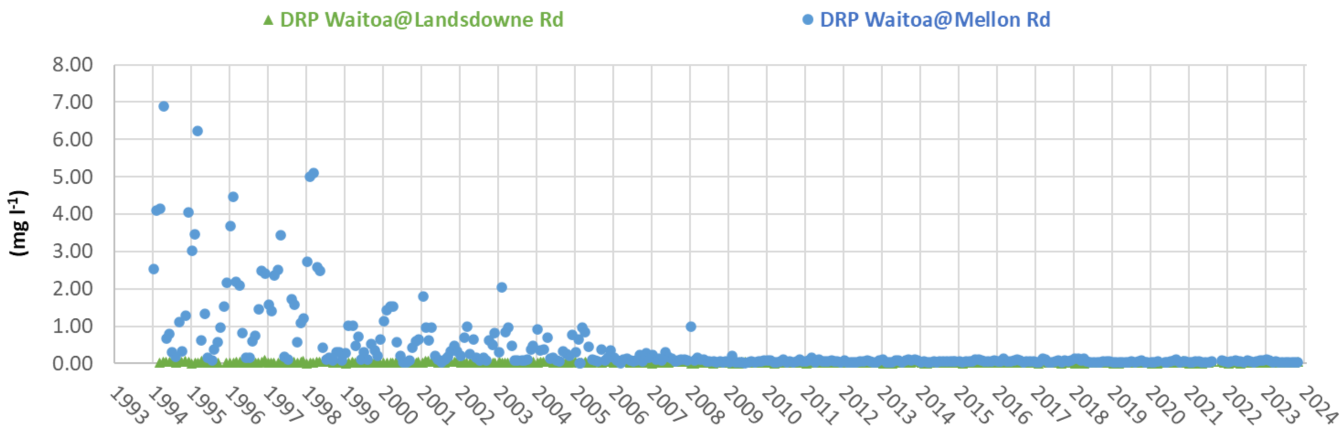

Figure 22: Dissolved Reactive Phosphorus (DRP) time series for two Waitoa River monitoring sites (in mg l^{-1}); 1993 - 2023.

Independent of extreme DRP concentrations caused by point-source discharges (Fig. 22), DRP concentrations can also serve as sensitive indicator of diffuse agricultural land use effects. This is illustrated in Fig. 23 on the example of DRP time series from the upper Waihou River catchment. While DRP concentrations at the two monitoring sites with predominant natural vegetation in their catchment area rarely exceed 0.05 mg l^{-1}, even the uppermost Waihou River site (at Whites Road) features concentrations at least four times higher.

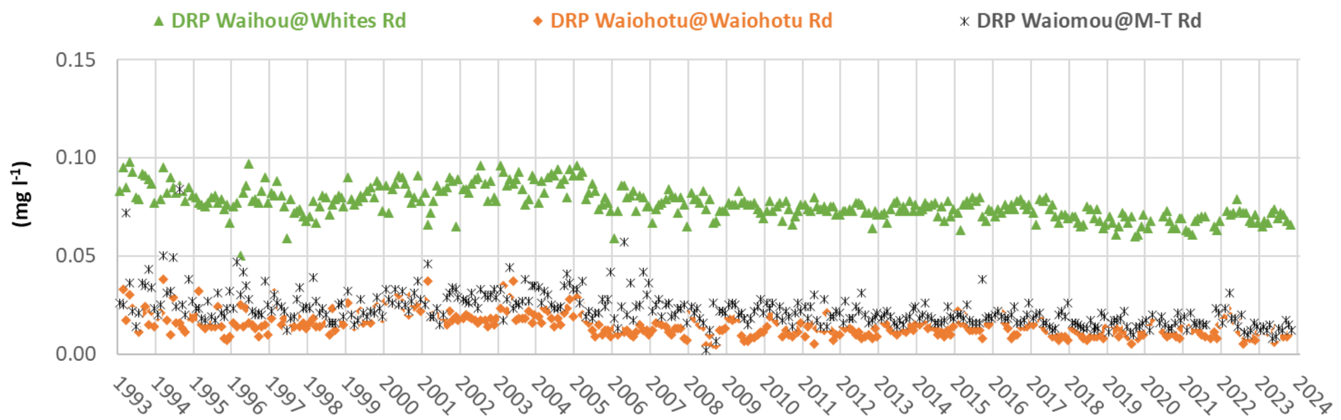

Figure 23: Dissolved Reactive Phosphorus (DRP) time series for three upper Waihou River catchment sites (in mg l^{-1}); 1993 - 2023.

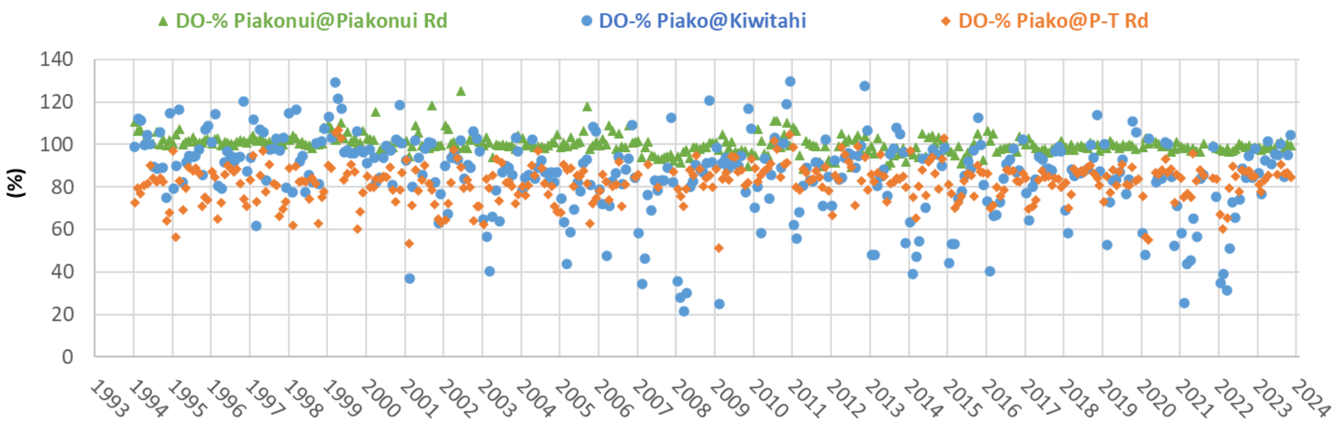

Figure 24: Dissolved Oxygen (DO) saturation time series for three Piako River catchment sites (in %); 1993 - 2023.

Further to the median Dissolved Oxygen saturation results shown in Fig. 15, Fig. 24 illustrates the frequent occurrence of concerning levels (< 80%) during summer periods along the Piako River, particularly at the Kiwitahi monitoring site. While stable and consistently high saturation levels were recorded at the Piakonui site in the headwater area on the slope of Maungakawa, substantially more variable and overall lower levels were observed at Kiwitahi. While the medians were nearly identical for the Kiwitahi and Paeroa–Tahuna Road sites (around 85%), the latter shows markedly less temporal variation and saturation levels rarely drop below 60%, while values as low as 20% have been recorded at Kiwitahi. It should be noted that these DO records are biased towards higher levels as sampling only takes place during daylight hours, while DO minima occur at night (diurnal cycle of DO concentrations).

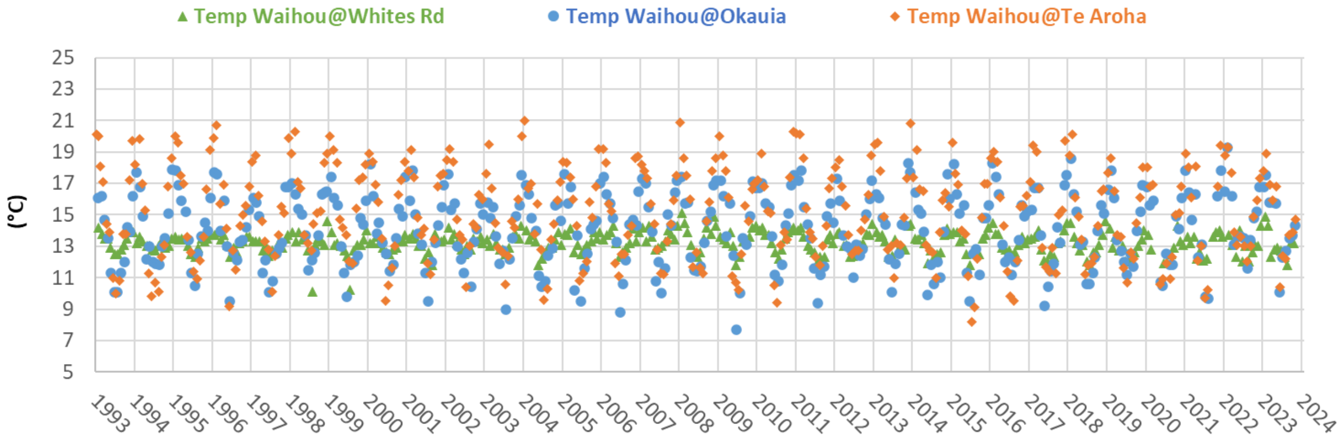

Figure 25: Water temperature time series (in °C) for three Waihou River sites; 1993 - 2023.

Typical patterns of water temperature differences are presented in Fig. 25 using the three Waihou River sites as example. Median temperatures (2014-2023) increased from the most upriver site (13.1°C at Whites Rd) via 14.1°C at Okauia, to 15.0°C at Te Aroha. Moreover, very little variation in water temperatures was observed at Whites Road, while temperature amplitudes increased substantially downriver. The overall range of recorded temperatures was only 3.1°C at Whites Rd, but 10.1°C at Okauia, and 11.9°C at Te Aroha.

The low and stable temperatures measured at Whites Road reflect that the majority of this water is groundwater discharge from the 'Blue Springs' a few kilometres upstream and the stream reach being entrenched between hills and shaded by riparian vegetation. Opening of the landscape to undulating to flat country, decreasing elevation, and lacking shading combine to cause increasing median temperatures and greater fluctuations.

2.2.4 Effect of flow on water quality parameters

How the concentration of a contaminant changes in a river with streamflow can be illustrated by creating concentration-discharge-relationship (CDR) charts, like the following ones for NNN (Fig. 26), TP (Fig. 27), and Turbidity (Fig. 28). CDRs are presented for the eight monitoring sites, for which water quality and concurrent flow data were available (two sites each along Piako, Waitoa, Ohinemuri, and Waihou rivers). CDRs are commonly plotted in log-log axes as flow data and concentration data tend to spread across a few orders of magnitude. To enable an unbiased visual comparison across rivers, we fixed the x-axis range to three orders of magnitude, and the y-axis range to four orders of magnitude (but note that the absolute values differ for the large Waihou River).

The Piako and Waitoa sites featured the widest flow range, spanning three orders of magnitude. Ohinemuri River had comparable maximum flows, but greater low-flows than Piako and Waitoa, resulting in somewhat smaller flow variation (≈ two orders of magnitude). In contrast, Waihou flows varied at both sites only by approx. one order of magnitude. Positive CDRs, with NNN concentrations increasing with increasing flow, were most evident at the Piako and Waitoa sites. The exceptionally low NNN concentrations at Piako at Kiwitahi under low-flow conditions could be due to three processes, or a combination thereof. Firstly, microbial denitrification occurring on the deep groundwater (DGW) pathway may have converted nitrate into gaseous forms of nitrogen (predominantly environmentally benign dinitrogen gas, N_2). Secondly, the DGW sustaining flow under such conditions may already have had very low initial NNN concentrations, as it was recharged decades ago under much less intensive land use. Finally, the abundant growth of macrophytes in the stream may have depleted the stream water NNN concentration when these extremely low flows occurred in dry summers. At the Ohinemuri River sites, the shape occupied by data resembles a triangle, with a very wide range of concentrations observed at low flows and maxima at low and high flows being comparable. This could point to point-source discharges increasing NNN concentrations at low flows (particularly noticeable at the Queens Head site).

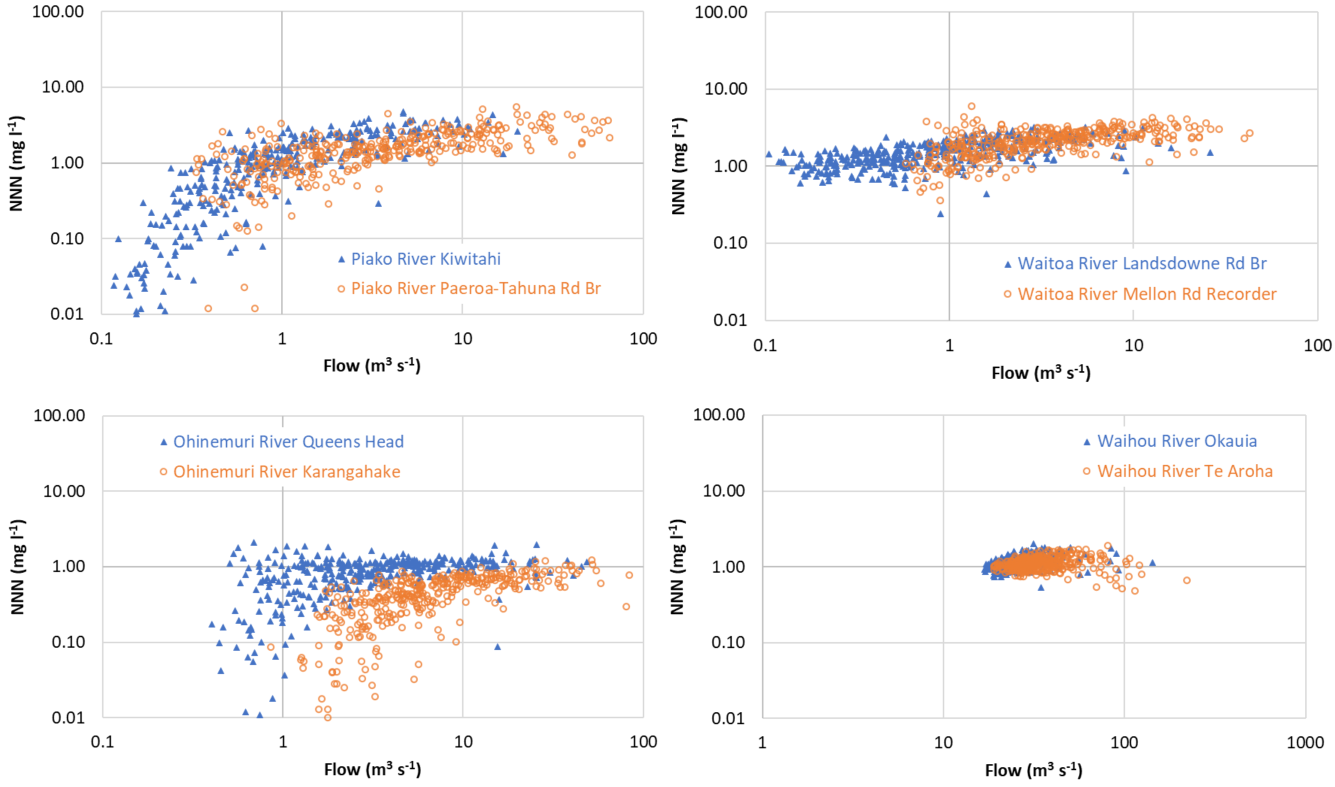

Figure 26: Nitrate-Nitrite-Nitrogen (NNN) concentration-discharge relationships for two sites each along the Piako, Waitoa, Ohinemuri, and Waihou Rivers (1993-2023).

The CDRs for Total Phosphorus show a few similarities with the NNN CDRs (esp. for Waitoa at Landsdowne Rd and both Waihou sites), but also a number of differences (Fig. 27). Most noteworthy is the strong effect point-source TP discharges exert at the Waitoa at Mellon Rd site and to a lesser degree at the Piako site at Paeroa-Tahuna Rd. At

Mellon Road, highest TP concentrations occurred at the lowest flow, as the industrial and municipal discharges then get the least diluted. As outlined in Section 2.2.3, such striking point-source effects are largely a problem of the past.

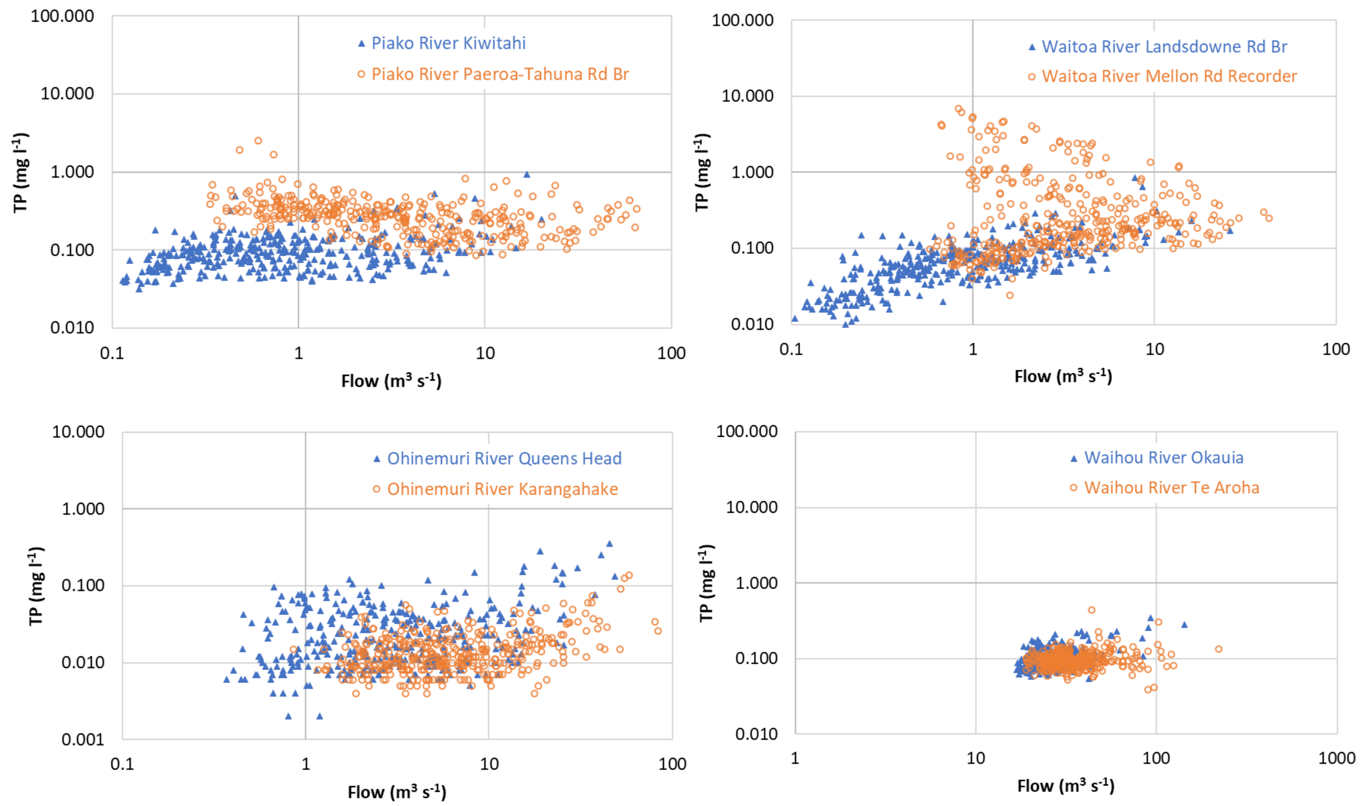

Figure 27: Total Phosphorus (TP) concentration-discharge relationships for two sites each along the Piako, Waitoa, Ohinemuri, and Waihou Rivers (1993-2023).

While NNN and TP CDRs differed markedly between the sites, turbidity CDRs showed a more homogeneous pattern (Fig. 28). Positive CDRS were observed at all eight sites, with the Ohinemuri River showing the flattest increase in turbidity with flow, while the Waihou River featured the steepest increase.

According to a SedNetNZ modelling study, the Piako and Waihou catchments stand out for particularly high stream bank erosion (LCR, 2017). The strongly increasing turbidity in the Waihou River with increasing flow might reflect this. Sediment yields for the combined Piako and Waihou catchments were estimated as 46.9 t km^{-2} yr^{-1} caused by net bank erosion, 35.3 t km^{-2} yr^{-1} from surficial erosion, 34.7 t km^{-2} yr^{-1} from landslides, and 11.5 t km^{-2} yr^{-1} from gully erosion (Fig. 29).

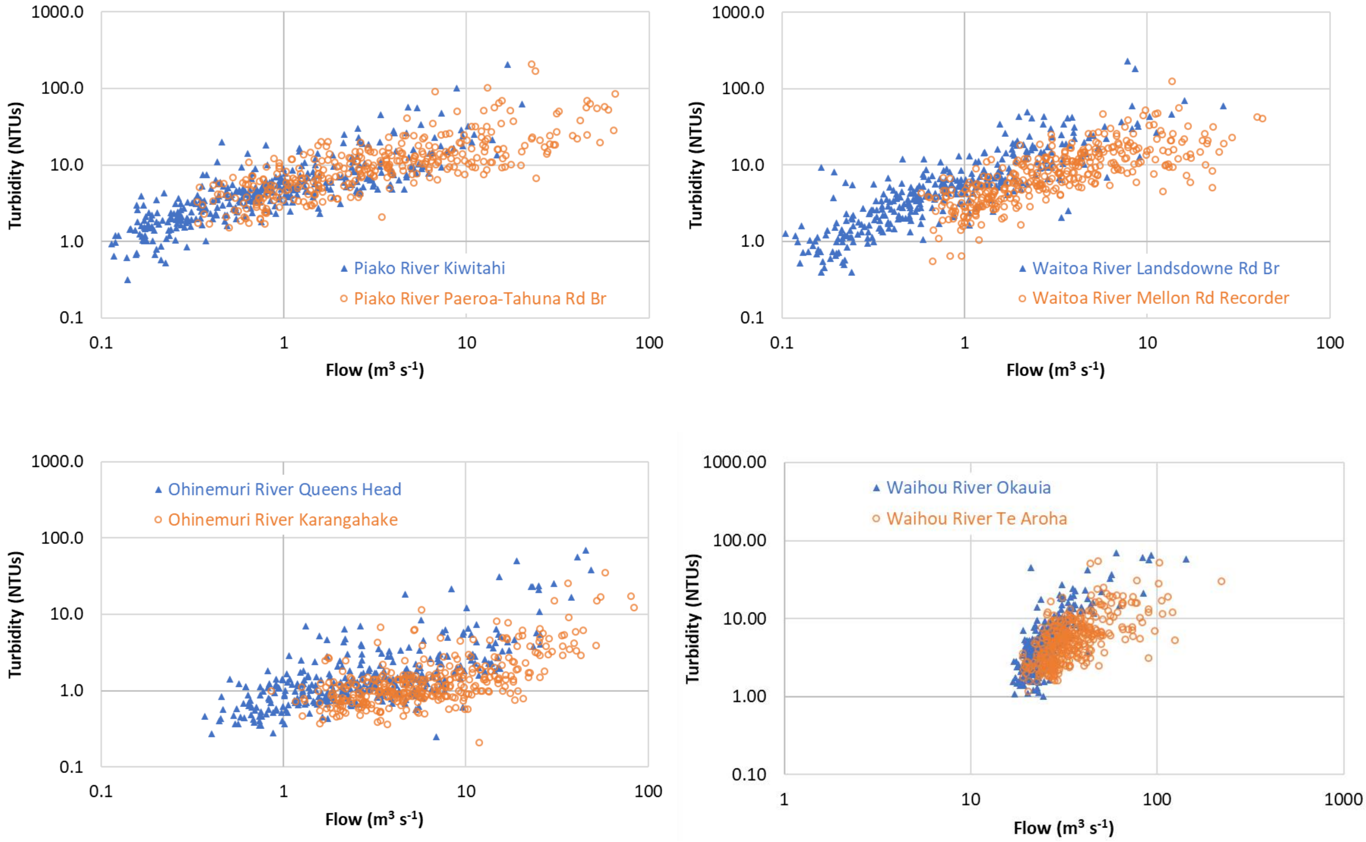

Figure 28: Turbidity concentration-discharge relationships for two sites each along the Piako, Waitoa, Ohinemuri, and Waihou Rivers (1993-2023).

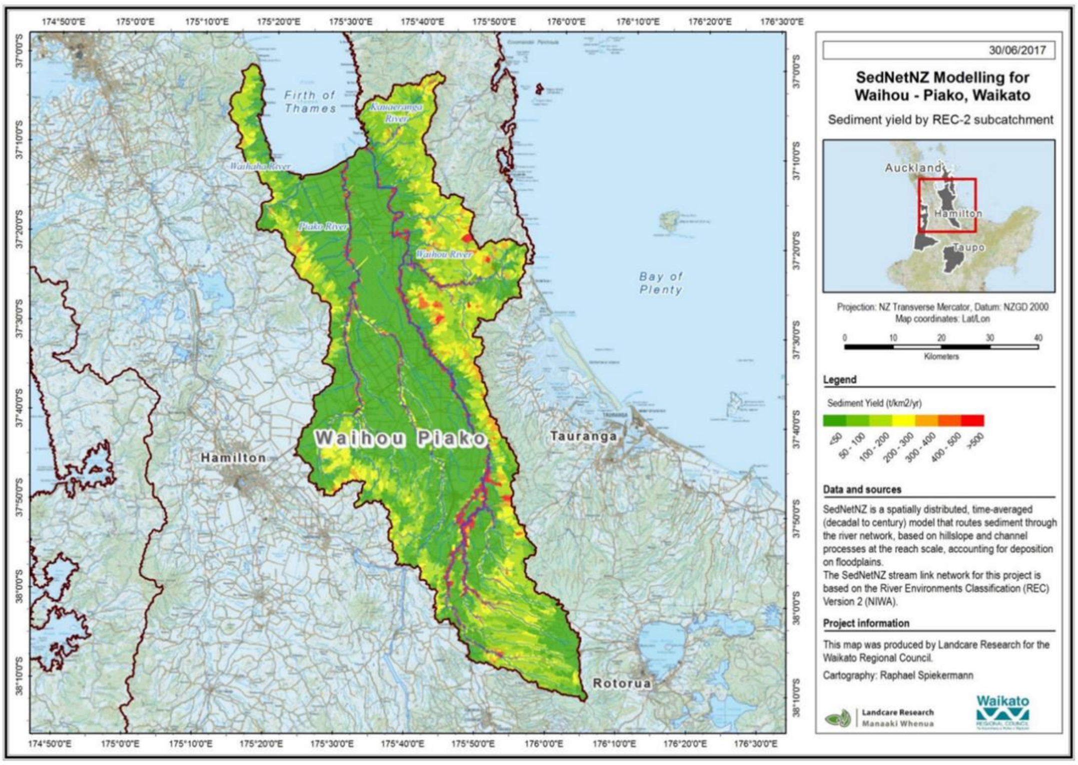

Figure 29: Sediment sources and loads (from LCR, 2017).

2.2.5 Loads of nitrogen and phosphorus discharged into the Firth of Thames

The previous sections largely focused on contaminant concentrations (e.g. expressed in units of mg l^{-1}), as concentrations typically form the basis of river water quality assessment schemes (e.g. the NOF tables of the NPS-FM). However, loads (e.g. expressed in units of t yr^{-1}) are more relevant for some environments, e.g. lakes or coastal water with restricted exchange (e.g. Firth of Thames).

This section summarises key findings of a study carried out by WRC staff to quantify nitrogen and phosphorus discharges by four rivers into the Firth of Thames for the 2011-20 period (WRC, 2022a). Additionally to the bigger Piako and Waihou Rivers, it also incorporates the smaller Waitakaruru River in the north-west and the Kauaeranga River in the north-east. It is important to recognise that tidal effects make it impossible to quantify water and contaminant discharges at or near the river mouths of the Piako and Waihou rivers. Accordingly, the most downriver WRC monitoring sites are located at least 40 km or more south of the Firth of Thames (see Fig. 1). Consequently, any increases in water flow and contaminant loading occurring in the northern plains are not included in the following calculations and the presented values should therefore be considered minima.

Piako River discharges are estimated by adding those of the Piako at Paeroa-Tahuna Rd and those at Waitoa at Mellon Rd. The combined Waihou River discharge is estimated as the sum of Waihou at Te Aroha plus Ohinemuri at Karangahake plus Hikutaia. Using this procedure, WRC estimated that the four rivers together discharged on average 69.7 m^{3} s^{-1} into the Firth (2011-20), Waitakaruru accounting for 0.9 m^{3} s^{-1} or 1%, Piako for 11.9 m^{3} s^{-1} or 17%, Waihou for 51.1 m^{3} s^{-1} or 73%, and Kauaeranga for 5.9 m^{3} s^{-1} or 8%.

Table 4: Average flows and loads of N and P in four Hauraki river systems, 2011-20 (from WRC, 2022a).

	Kauaeranga		Piako		Waihou		Waitakaruru		All four rivers	
Area (km^{2})$^{\#}$	120		948		1466		50			
Nitrogen (t yr^{-1})										
Overall	**55**		**1418**		**2222**		**32**		**3726**	
Point sources	0	0%	65	5%	149	7%	<1	1%	214	**6%**
Background	36*	66%	284	20%	440	20%	15*	47%	775	**21%**
Land use	19*	34%	1069	75%	1633	73%	17*	53%	2737	**73%**
Phosphorus (t yr^{-1})										
Overall	**3**		**74**		**127**		**3**		**207**	
Point sources	0	0%	17	23%	31	24%	<1	2%	48	**23%**
Background	≥3*	>90%	28	38%	44	35%	2*	53%	78	**37%**
Land use	<1*	<10%	29	39%	53	41%	1*	44%	82	**40%**

# Piako = Piako at Paeroa-Tahuna Rd (539 km^{2}) plus Waitoa at Mellon Rd (409 km^{2});
Waihou = Waihou at Te Aroha (1107 km^{2}) plus Ohinemuri at Karangahakw (286 km^{2}) plus Hikutaia at Maratoto (73 km^{2})
* Values imprecise, being dependent on the assumed nutrient yields for undeveloped land

Overall nitrogen and phosphorus loads originate from diffuse sources (background, land use) and point sources (industry, municipal wastewater treatment plants). The loads that would have been carried by the rivers prior to agricultural development of their catchments were labelled background loads and estimated as 3 kg ha^{-1} yr^{-1} of nitrogen and 0.3 kg ha^{-1} yr^{-1} of phosphorus. WRC estimated N and P discharges from 14 wastewater treatment plants and 10 industrial sites. The quantitatively most important wastewater discharges included those from Morrinsville, Thames, Paeroa, Waihi, Matamata, Te Aroha, and Putaruru. Significant industrial discharges were Waihi gold mine, Waitoa and Tirau dairy factories, and the Te Aroha and Waitoa meat works.

The nitrogen loads of the four rivers were estimated to amount to 3726 t yr^{-1}; 1% each from Waitakaruru and Kauaeranga Rivers, 38% from Piako River, and 60% from Waihou River (Table 4). Point-sources were estimated to be responsible for 6% of the nitrogen load, background discharges for 21%, and land use for 73%.

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The contributions by the four rivers to the overall phosphorus load of 207 t yr^{-1} were very similar to the nitrogen load contributions; 1% each from Waitakaruru and Kauaeranga Rivers, 36% from Piako River, and 61% from Waihou River. However, the origin of the P loads differed. Point sources accounted for a substantially higher percentage of the total P load, namely 23%; background discharges contributed 37%, and land use 40%.

WRC noted that compared to the previous decade (2000-09), the 2011-20 nitrogen load was about 10% higher, while the phosphorus load was about 27% lower.

2.2.6 Integrative measurements: MCIs and eDNA

The Quantitative Macroinvertebrate Index (QMCI) is an integrative measure that was included in the NPS-FM (2020). Fig. 30 shows state and trend results for the small number of sites (six in the Piako River catchment, and seven in the Waihou River catchment) for which this measure is available. Worsening trends prevail in Piako, while improving trends are more common in Waihou. Unfortunately, there is only a poor spatial overlap with the monitoring sites sampled monthly by WRC for water chemistry (cf. Fig. 1). Accordingly, it is not feasible to ascertain if QMCI trends relate to trends in physico-chemical water quality parameters.

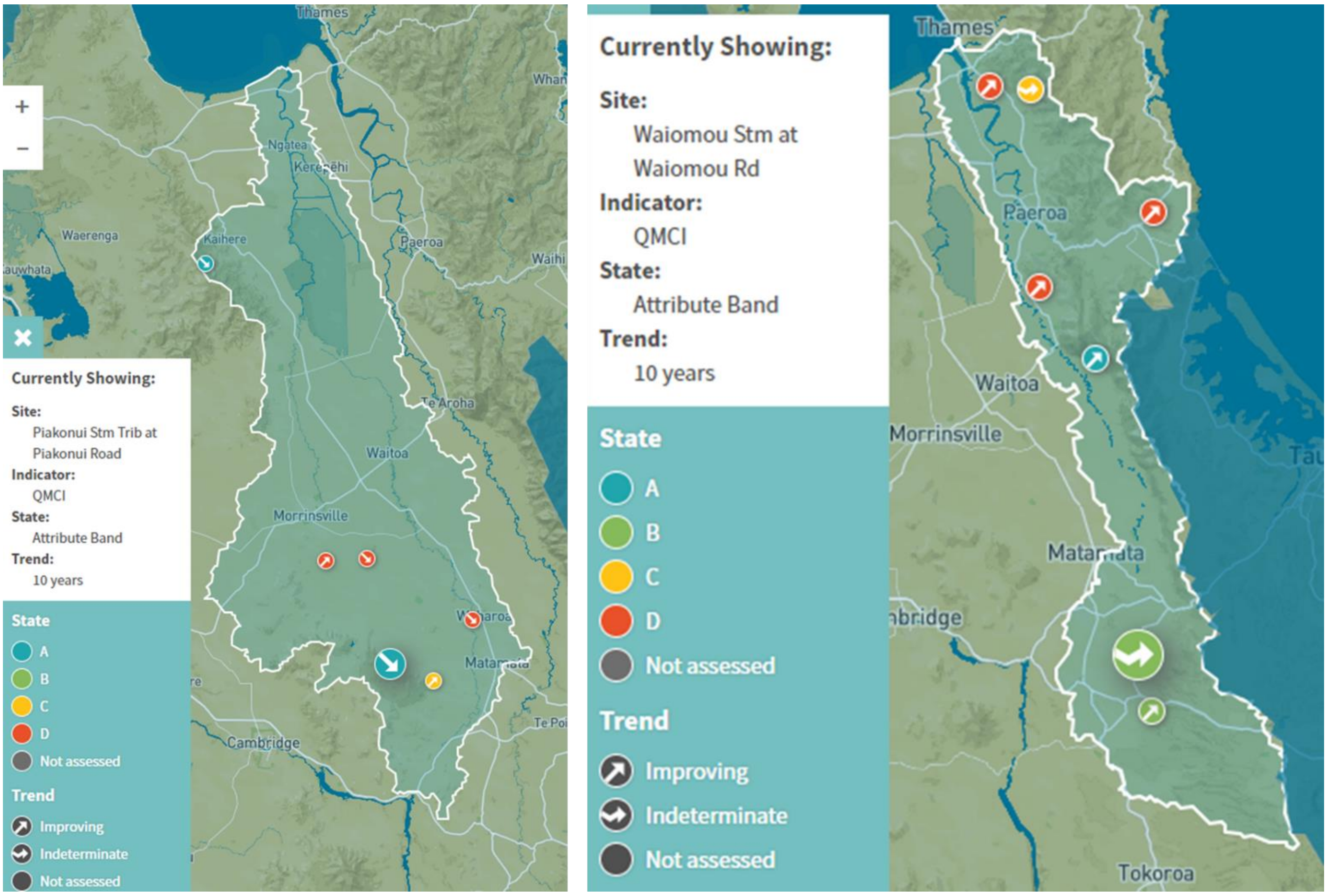

Figure 30: Quantitative Macroinvertebrate Index (QMCI) trends (from www.lawa.org.nz).

Environmental DNA has recently been promoted as a much broader integrative measure of ecosystem health. A substantial number of samples has been analysed since 2020 and many of the results are publicly available (https://www.wilderlab.co.nz/explore). It is widely recognised that eDNA sampling campaigns are an excellent opportunity to encourage active participation by catchment residents in citizen science projects and general community activities. Finding two threatened species (long fin eel, short jaw kokopu) present in eDNA samples taken from the adjacent Piakoiti and Piakonui streams in 2021 (Fig. 31) excited members of the Two Loops Catchment Group and strengthened their resolve to work collaboratively on ecosystem health improvements.

While the results of a single sample should not be over-interpreted, there are efforts under way to optimise sampling schemes and the interpretation of results. A taxon-independent community index for eDNA-based ecological health assessment has been published earlier this year (Wilkinson et al., 2024).

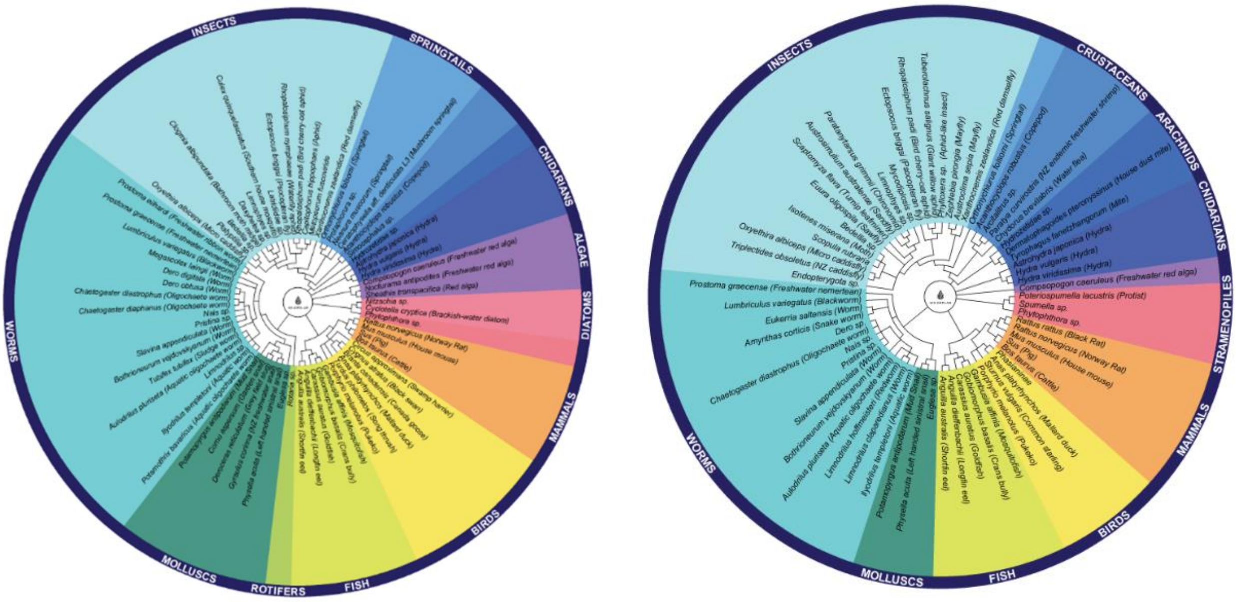

Figure 31: Wheel of life for Piakoiti and Piakonui streams eDNA samples from 2021 (from www.wilderlab.co.nz/explore).

3. IMPLICATIONS FOR MITIGATION MEASURES

The following considerations may be useful ahead of the upcoming workshop to develop feasible mitigation measures that the catchment group and wider farming community may decide to implement in the future:

Catchment context: From the mountains to the sea (ki uta ki tai)
Headwater catchments play a very important role when trying to manage contaminant transfers in catchments and discharges into estuaries and the coastal environment. Higher rainfall at higher elevations and resulting disproportional contributions to streamflow are an important reason for this. Combined with the typically low land use intensity in most headwater areas (native bush, plantation forestry), this means that headwater areas provide a substantial flow of high-quality water to the generally more intensively used lowland parts of river catchments. Accordingly, any land use intensification at higher elevation should be avoided, as it would have a disproportional negative effect on water quality that would be very difficult to mitigate with measures introduced elsewhere in the catchment.

Contaminants, their critical pathways, and control options
The existing data demonstrate that nitrogen, phosphorus, E. coli, and sediment, all pose significant water quality challenges in parts of the Piako and Waihou river catchments. Given that near-surface pathways (surface runoff, interflow, artificial drainage) play a major role in transferring all of them from land to water, any measure to reduce or intercept near-surface flows will have multiple benefits. Such 'transfer control' measures (Fig. 28) will often focus on farm tracks, culverts, and riparian management. Unfortunately, near-surface transfers are particularly prevalent during high-flow events (mainly during winter), when the entire catchment is near saturation and introduced mitigation measures may not be able to substantially reduce contaminant transfers. This limitation highlights the great importance of additional 'source control', which anyway is crucial for nitrogen (as a high fraction of it travels on the shallow groundwater pathway that cannot be effectively intercepted by transfer control measures). Accordingly, measures to reduce the load of contaminants that potentially can get lost from the production system are often most effective in reducing loads ending up in the streams. Impact control measures, like shading of streams by riparian plantings, will not reduce the delivered contaminant loads, but may help to minimise the harm they cause to the stream ecosystem (and could be an added benefit of transfer control measures).

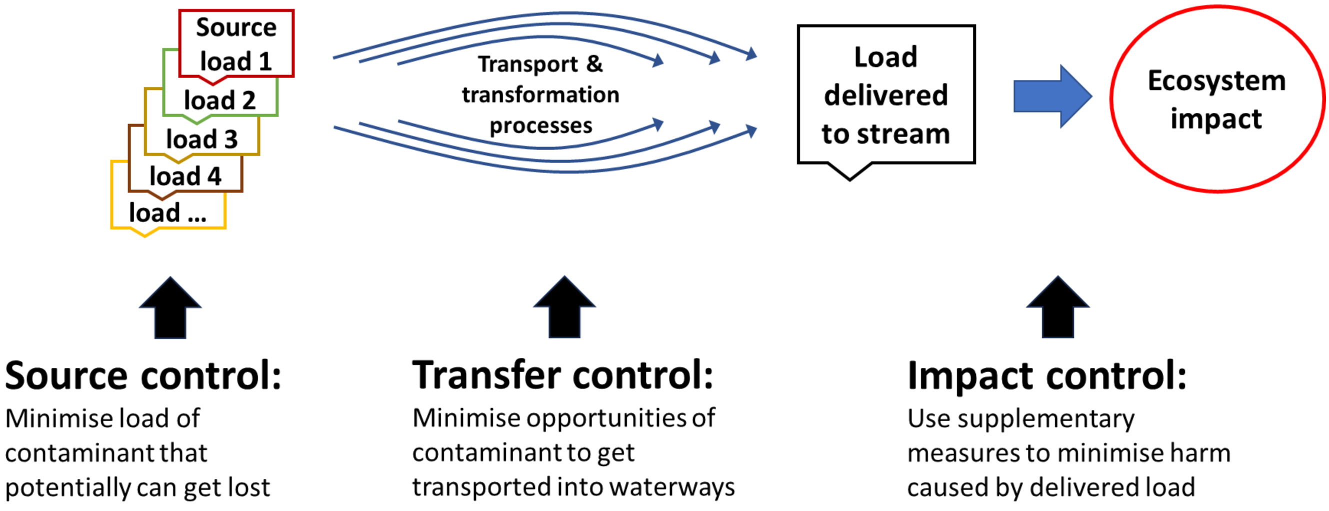

Figure 32: Schematic illustrating control options potentially available to reduce ecosystem impacts of water contaminants.

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5. APPENDICES

APPENDIX I: WRC WATER QUALITY MONITORING SITES

Description of WRC water quality monitoring sites in the Hauraki sub-region, as provided on https://www.lawa.org.nz/:

Waiohotu Stm at Waiohotu Rd (Off SH5)
The water quality site located on the Waiohotu Stream is accessed via State Highway 5 and Waiohotu Road. The sampling site is located under a small road culvert. The Waiohotu Stream is sourced from a spring in the Mamaku Forest and has a bedrock, boulder, rock and cobble substrate with exceptional water clarity. The catchment is very steep sided making access difficult in some parts. The riparian vegetation is exclusively dense native forest throughout the upper reaches of the stream before it thins out slightly as the elevation decreases and it enters a small reservoir.

Waiomou Stm at Matamata-Tauranga Rd
The water quality site located on the Waiomou Stream is accessed via Tauranga Road. The sampling locality is under the Tauranga road bridge on the downstream side. The substrate is a mixture of hard and soft-bottomed sections with fine gravel and sediment dominant. The riparian vegetation is predominantly exotic with species such as willows and poplars common and is mostly fenced. The land use is almost exclusively agricultural farming.

Oraka Stm at Lake Rd
The water quality site located on the Oraka Stream is accessed via State Highway 27 and Lake Road. The sampling point is a short distance downstream of the Lake Road bridge and is accessed via a small walking track. The stream is spring-fed and the headwaters are located in the high elevation Kaimai-Mamaku Forest before descending through farm land and passing through the townships of Putaruru and Tirau before entering the Waihou River east of the township Matamata.

Waihou River at Whites Rd
This water quality site located on the upper reaches of the Waihou River can be accesed via Whites Road a short distance east of the township of Putaruru. Water samples are collected a short distance upstream of the Whites Road bridge. The upper reaches of the Waihou River are significantly cleaner and clearer than the lower reaches and has more of a hard-bottomed gravel and cobble substrate. The riparian vegetation is relatively sparse and is dominated by exotic vegetation such as willows but does have some sections of native vegetation which is mostly fenced. Agricultural farming is the predominant landuse throughout the length and breadth of the Waihou River which is one of the Waikato regions largest river systems. The upper reaches of the river has high recreational values and has a healthy Brown and Rainbow trout population popular with anglers.

Waihou River at Okauia
This water quality and flow site located on the Waihou River can be accessed via Okauia Springs Road a short distance east of the township of Matamata. The Waihou River is a lowland system and the water clarity at this site is generally quite poor due to significant nutrient enrichment and erosion in some parts. The riparian margins are predominantly fenced and consists of exotic vegetation such as willows, poplars and bamboo with some native vegetation such as flax interspersed with the exotics. This section of the river has a substrate that is a mixture of gravel, sand and silt and is approximately 15 - 20 metres wide. The predominant landuse is agricultural farming throughout the entire length and breadth of one of the Waikato regions largest river systems.

Waihou River at Te Aroha
This site was monitored by NIWA up to 2016, and is one of the original National River Water Quality Network (NRWQN) sites dating back to 1989. The site is now monitored by Waikato Regional Council with data starting in January 2015. This sampling site is located at the boat ramp off Lawrence Avenue in Te Aroha. The catchment use is predominantly dairying; in recent years the river banks have been cleared of trees and fenced to keep stock out of the waterways.

Ohinemuri River at SH25 Br
The water quality site on the Ohinemuri River is one of two water quality sites on this river and is located under the SH25 Bridge. The site is north east of Waihi. The substrate at this site consists of gravel, sand and cobbles. The banks are fenced and lined with walnut trees. The catchment is largely farmland with most mining activity downstream of this point. The Ohinemuri river has a popular trout fishery and numerous walking tracks lining the river which are very popular with tourists.

Ohinemuri River at Queens Head
The water quality and flow recorder site is located on the Ohinemuri River is accessed via Queens Head. The substrate at this site consists of cobbles and boulders. The riparian cover is limited to grass on the true left whilst there are some native trees on the true right bank. This site is downstream of the township of Waihi, mines and the towns wastewater treatment plant. The catchment is largely dominated by agricultural farm land.

Ohinemuri River at Karangahake
This site has been monitored by NIWA up to July 2021, and is one of the original National River Water Quality Network (NRWQN) sites dating back to 1989. The site is now monitored by Waikato Regional Council with data starting in July 2017.

Waitekauri River at U/S Ohinemuri Confluence
The substrate at this site is cobbly and the river is lined with native scrub and introduced trees such as willows, poplars and pines. The tributaries of the river generally start in native forest then flow through largely agricultural catchments. The main stem of the river is sourced near the Golden cross mine before flowing through exotic forestry and farmland before joining the Ohinemuri River just downstream of this sampling point.

Hikutaia River at Old Maratoto Rd
The catchment source is in the Kaimai ranges and flows into the Waihou River further downstream. The site is open with some poplar and willows lining the bank. There is considerable bank erosion in the vicinity of the sampling site. The site is situated 20m downstream of a small tributary in pasture land.

Piakonui Stm at Piakonui Rd
The water quality site on the Piakonui Stream is accessed via Piakonui Road. This site has cold, generally clear water with a cobble/boulder stream bed lined with native scrub, barberry, blackberry and pasture grasses. The headwaters are in the native forest dominated Te Tapui Reserve which covers approximately half the catchment upstream of the monitoring site with the other half being agricultural, mainly stock finishing. From here the stream flows toward Morrinsville and across the pasture dominated Hauraki Plains to Ngatea before entering the Firth of Thames.

Piako River at Kiwitahi
There is water quality, flow and ecological information collected at this site on the Piako River situated at Kiwitahi. This site is open with a 1 metre wide fenced buffer either side of the stream and no riparian plantings to speak of. The site is often choked with macrophytes (aquatic plants) especially over summer before winter floods remove some growth from the soft, silty riverbed. The majority of the catchment (84%) upstream from this point is pasture land with the majority being dairying with a small amount used for stock finishing. In the headwaters there is native forest which makes up 14% of the catchment landuse above this site. From here the stream flows toward Morrinsville and across the pasture dominated Hauraki Plains and the Kopuatai Peat Dome to Ngatea before entering the Firth Of Thames.

Piako River at Paeroa-Tahuna Rd Br
There is a water quality and flow recording site located on the Piako River accessed via the Paeroa-Tahuna Road Bridge. The substrate at this site consists of sand and silt with macrophyte beds prevalent, especially over the summer months. The river is fenced and the riparian zone consists of grasses, exotic weeds and shrubs with native Totara trees lining the banks in places. The catchment is dominated by pastoral land utilised for dairying and stock finishing. This site is downstream of Morrinsville and the towns wastewater discharge to the river and a number of dairy company discharges also. The river flows out past Ngatea to the Firth of Thames.

Mangawhero Stm (Kaihere) at Mangawara Rd
The water quality site located on the Mangawhero Stm (Kaihere) is accessed via Mangawara Road. The substrate consists of cobbles and gravel at this site. The riparian zone is dominated by Manuka scrub with plantation forest cover further upstream. Downstream of the site the stream flows through foothills before entering the Hauraki plains where the river becomes a channelised canal before flowing into the Piako River at the Northern end of the Kopuatai peat dome via a floodgate near Patetonga, and then out past Ngatea and out to the Firth of Thames.

Waitoa River at Landsdowne Rd Br
Waitoa River water quality and ecology site at Landsdowne Road Bridge. There is also a flow recorder site just 600m downstream of this site. The substrate consists of sand and one side of this narrow incised river is fenced off at this location with oak, poplar and willows present along the banks. The catchment is dominated by pasture, the majority of which is used for dairy farming. About 1km downstream from this site a dairy factory discharges treated waste to the river. The Waitoa River then flows into the Piako River on the Western edge of the Kopuatai Peat Dome before flowing out past Ngatea to the Firth of Thames.

Waitoa River at Mellon Rd Recorder

Waitoa River water quality and flow site at Mellon Road Recorder. The water sample is collected just downstream of the bridge at the flow recorder site. The substrate consists of sand and silt and there are macrophytes present in this reach. The river is lined with sparsely spaced birch, willows, totara and pines with rank grass undergrowth. The landuse in the catchment upstream of this point is dominated by dairying, with some stock finishing further upstream in the foothills. The Waitoa River then flows into the Piako River on the Western edge of the Kopuatai Peat Dome before flowing out past Ngatea to the Firth of Thames.

APPENDIX II: SUMMARY STATISTICS FOR WATER QUALITY PARAMETERS (2014 – 2023)

Site_Station				NNN	NH4-N	TP	DRP	DO-%	EC	pH	Turbidity	Bdisk	WT	E. coli
1122_18	Waihou River	Okauia	Mean	1.23	0.02	0.10	0.07	93	106	7.3	6.3	1.1	14.1	1384
			Median	1.19	0.01	0.08	0.06	93	106	7.3	4.1	1.0	14.1	305
			stdev	0.23	0.03	0.04	0.02	3	8	0.2	7.2	0.4	2.4	6037
			CV	18	136	37	30	3	7	3	115	42	17	436
			Min	0.87	0.00	0.05	0.03	80	83	6.7	1.0	0.2	9.2	26
			Max	1.82	0.21	0.35	0.14	101	124	7.7	65.0	2.1	19.3	57000
			Range	0.95	0.21	0.30	0.11	21	41	1.0	64.0	1.9	10.1	56974
			n	116	116	116	116	115	116	116	116	111	116	116
				NNN	NH4-N	TP	DRP	DO-%	EC	pH	Turbidity	Bdisk	WT	E. coli
1122_34	Waihou River	Te Aroha	Mean	1.16	0.03	0.09	0.06	88	113	7.3	6.7	1.1	14.8	1012
			Median	1.16	0.02	0.09	0.06	89	114	7.3	5.5	0.9	15.0	345
			stdev	0.26	0.02	0.02	0.02	5	11	0.2	6.1	0.6	2.9	1954
			CV	23	77	24	34	5	10	3	90	53	20	193
			Min	0.52	0.01	0.04	0.02	58	75	6.7	1.2	0.2	8.2	72
			Max	1.92	0.14	0.19	0.10	99	141	7.7	55.0	3.0	20.1	14000
			Range	1.40	0.14	0.15	0.08	42	66	1.0	53.8	2.8	11.9	13928
			n	116	116	116	116	113	116	116	116	104	116	104
				NNN	NH4-N	TP	DRP	DO-%	EC	pH	Turbidity	Bdisk	WT	E. coli
1122_41	Waihou River	Whites Rd	Mean	0.83	0.01	0.10	0.07	98	84	7.0	4.0	4.7	13.1	1408
			Median	0.85	0.01	0.08	0.07	98	84	7.0	0.5	5.0	13.1	100
			stdev	0.06	0.02	0.21	0.01	4	3	0.2	34.7	1.3	0.7	13156
			CV	8	299	211	15	4	3	2	864	27	6	934
			Min	0.66	0.01	0.07	0.06	92	69	6.5	0.1	0.0	11.8	4
			Max	0.95	0.25	2.30	0.17	110	93	7.4	370.0	6.8	14.9	140000
			Range	0.29	0.25	2.23	0.11	19	24	0.9	370.0	6.8	3.1	139996
			n	113	113	113	113	113	113	113	113	113	113	113
				NNN	NH4-N	TP	DRP	DO-%	EC	pH	Turbidity	Bdisk	WT	E. coli
1173_2	Waiohotu Stm	Waiohotu Rd (Off SH5)	Mean	0.16	0.01	0.03	0.01	93	53	7.2	5.6		11.5	153
			Median	0.16	0.01	0.03	0.01	93	54	7.2	4.5		11.6	60
			stdev	0.04	0.00	0.02	0.00	4	5	0.2	5.2		2.7	292
			CV	27	44	54	31	4	9	3	93		24	191
			Min	0.08	0.01	0.02	0.01	72	31	6.4	1.5	0.0	5.5	1
			Max	0.27	0.02	0.13	0.02	103	60	7.5	41.0	0.0	17.2	2000
			Range	0.19	0.02	0.12	0.02	31	29	1.1	39.5	0.0	11.7	1999
			n	113	113	113	113	113	113	113	113	0	113	113
				NNN	NH4-N	TP	DRP	DO-%	EC	pH	Turbidity	Bdisk	WT	E. coli
1174_4	Waiomou Stm	Matamata-Tauranga Rd	Mean	0.59	0.01	0.04	0.02	95	70	7.1	5.4	1.2	13.7	1243
			Median	0.52	0.01	0.03	0.02	95	70	7.2	3.8	1.2	13.6	420
			stdev	0.26	0.02	0.03	0.00	3	6	0.2	7.0	0.5	2.8	5393
			CV	45	121	71	26	3	8	3	130	38	21	434
			Min	0.25	0.01	0.02	0.01	83	55	6.5	1.2	0.3	7.7	120
			Max	1.31	0.13	0.29	0.04	105	84	7.5	68.0	2.7	19.9	58000
			Range	1.06	0.13	0.27	0.03	22	29	1.0	66.8	2.5	12.2	57880
			n	116	116	116	116	115	116	116	116	115	116	116
				NNN	NH4-N	TP	DRP	DO-%	EC	pH	Turbidity	Bdisk	WT	E. coli
1239_32	Waitekauri River	U/S Ohinemuri Conflu	Mean	0.15	0.01	0.01	0.00	103	111	7.2	1.4	3.5	15.9	296
			Median	0.13	0.01	0.01	0.00	103	108	7.2	0.7	3.8	15.4	110
			stdev	0.12	0.01	0.01	0.00	4	27	0.3	2.5	1.4	3.8	735
			CV	79	93	86	128	4	25	4	182	39	24	249
			Min	0.00	0.01	0.00	0.00	96	61	6.5	0.1	0.2	8.2	3
			Max	0.49	0.06	0.05	0.04	119	196	7.8	19.1	8.0	23.8	4500
			Range	0.49	0.05	0.05	0.03	23	135	1.3	19.0	7.8	15.6	4497
			n	103	112	112	112	111	112	112	112	110	112	111
				NNN	NH4-N	TP	DRP	DO-%	EC	pH	Turbidity	Bdisk	WT	E. coli
1249_15	Waitoa River	Landsdowne Rd Br	Mean	1.57	0.02	0.06	0.02	88	170	7.1	7.1	1.8	15.1	1248
			Median	1.48	0.01	0.05	0.02	88	170	7.1	4.2	1.4	15.6	610
			stdev	0.61	0.02	0.04	0.01	11	24	0.2	8.8	1.3	3.6	1954
			CV	39	112	70	57	12	14	3	125	74	24	157
			Min	0.24	0.01	0.01	0.00	56	128	6.5	0.5	0.2	6.8	60
			Max	3.00	0.14	0.19	0.06	127	229	7.8	42.0	7.5	22.8	16000
			Range	2.76	0.13	0.18	0.06	71	101	1.3	41.6	7.3	16.0	15940
			n	116	116	116	116	115	116	116	116	114	116	115
				NNN	NH4-N	TP	DRP	DO-%	EC	pH	Turbidity	Bdisk	WT	E. coli
1249_18	Waitoa River	Mellon Rd Recorder	Mean	1.99	0.07	0.13	0.06	73	309	7.3	10.9	1.1	15.6	1447
			Median	1.96	0.05	0.12	0.05	75	297	7.4	7.5	0.9	15.9	520
			stdev	0.85	0.08	0.06	0.02	10	75	0.3	9.2	0.6	3.9	4173
			CV	43	102	48	43	14	24	4	84	56	25	288
			Min	0.36	0.01	0.05	0.02	40	200	6.5	1.7	0.2	6.6	30
			Max	4.20	0.34	0.40	0.14	87	627	8.1	52.0	3.0	23.0	42000
			Range	3.84	0.34	0.35	0.11	47	427	1.6	50.3	2.8	16.4	41970
			n	116	116	116	116	115	116	116	116	114	116	116

				NNN	NH4-N	TP	DRP	DO-%	EC	pH	Turbidity	Bdisk	WT	E. coli
169_2	Hikutaia River	Old Maratoto Rd	Mean	0.08	0.01	0.01	0.00	95	81	7.1	2.4	3.0	14.5	722
			Median	0.04	0.01	0.01	0.00	95	82	7.1	1.4	2.8	13.9	260
			stdev	0.12	0.01	0.01	0.00	5	8	0.3	4.5	1.2	3.7	2395
			CV	140	114	109	125	6	10	4	186	41	25	332
			Min	0.00	0.01	0.00	0.00	81	51	6.5	0.5	0.2	6.1	37
			Max	0.66	0.08	0.10	0.04	125	100	7.8	43.0	6.2	21.8	25000
			Range	0.66	0.07	0.10	0.04	45	49	1.3	42.5	6.0	15.7	24963
			n	102	114	114	114	114	114	114	114	113	114	113
				NNN	NH4-N	TP	DRP	DO-%	EC	pH	Turbidity	Bdisk	WT	E. coli
489_2	Mangawhero Stm	Mangawara Rd	Mean	0.33	0.01	0.05	0.03	98	115	7.4	13.5	0.9	15.0	213
			Median	0.32	0.01	0.05	0.03	98	117	7.4	6.8	0.9	14.5	68
			stdev	0.11	0.00	0.02	0.01	3	11	0.2	26.5	0.4	2.9	535
			CV	34	53	44	21	3	10	3	197	47	20	252
			Min	0.11	0.01	0.03	0.01	88	73	6.9	0.1	0.0	9.0	3
			Max	0.84	0.02	0.25	0.05	109	132	7.9	230.0	2.3	21.6	4100
			Range	0.73	0.02	0.22	0.04	21	59	1.0	229.9	2.3	12.6	4097
			n	109	109	109	109	109	109	109	109	108	109	109
				NNN	NH4-N	TP	DRP	DO-%	EC	pH	Turbidity	Bdisk	WT	E. coli
619_16	Ohinemuri River	Karangahake	Mean	0.49	0.02	0.01	0.00	105	163	7.5	2.0	3.0	16.1	313
			Median	0.54	0.01	0.01	0.00	104	140	7.4	1.0	3.1	15.8	70
			stdev	0.26	0.02	0.01	0.00	5	65	0.5	2.8	1.3	4.2	747
			CV	54	107	81	64	5	40	6	138	43	26	239
			Min	0.00	0.00	0.00	0.00	98	77	6.6	0.2	0.4	7.0	7
			Max	1.23	0.14	0.05	0.01	127	405	8.7	17.3	6.8	24.7	4600
			Range	1.23	0.14	0.04	0.01	29	328	2.1	17.1	6.4	17.7	4593
			n	112	113	113	113	113	113	113	113	112	113	70
				NNN	NH4-N	TP	DRP	DO-%	EC	pH	Turbidity	Bdisk	WT	E. coli
619_19	Ohinemuri River	Queens Head	Mean	0.93	0.09	0.01	0.00	105	271	7.2	1.7	3.5	16.7	479
			Median	0.99	0.06	0.01	0.00	104	236	7.1	1.0	3.6	16.4	80
			stdev	0.39	0.09	0.01	0.00	9	148	0.4	2.2	1.4	3.8	1289
			CV	42	103	85	80	9	55	5	129	39	23	269
			Min	0.07	0.01	0.00	0.00	68	99	6.5	0.3	0.3	9.4	10
			Max	1.96	0.43	0.08	0.02	137	890	8.9	16.6	6.0	24.4	9000
			Range	1.89	0.43	0.07	0.01	69	791	2.4	16.4	5.7	15.0	8990
			n	111	112	112	112	112	112	112	112	109	112	111
				NNN	NH4-N	TP	DRP	DO-%	EC	pH	Turbidity	Bdisk	WT	E. coli
619_20	Ohinemuri River	SH25 Br	Mean	0.49	0.01	0.01	0.00	108	77	7.1	1.5	3.4	16.8	340
			Median	0.48	0.01	0.01	0.00	108	76	7.2	1.1	3.2	16.4	150
			stdev	0.30	0.02	0.02	0.01	8	7	0.4	1.8	1.3	3.6	1042
			CV	62	195	136	241	8	9	5	122	37	22	306
			Min	0.01	0.01	0.00	0.00	95	55	6.4	0.3	0.4	9.3	12
			Max	1.19	0.05	0.07	0.02	138	91	8.4	14.8	6.1	24.4	6900
			Range	1.18	0.04	0.07	0.01	43	36	2.0	14.5	5.7	15.1	6888
			n	113	113	113	113	113	113	113	113	111	113	113
				NNN	NH4-N	TP	DRP	DO-%	EC	pH	Turbidity	Bdisk	WT	E. coli
669_6	Oraka Stm	Lake Rd	Mean	2.17	0.10	0.19	0.14	92	145	7.3	9.0	0.9	14.4	1745
			Median	2.20	0.03	0.13	0.08	92	132	7.3	5.7	0.9	14.3	500
			stdev	0.29	0.18	0.16	0.15	4	38	0.2	10.9	0.5	2.4	6140
			CV	13	177	86	106	4	26	2	121	51	17	352
			Min	1.22	0.01	0.06	0.03	74	84	6.8	0.8	0.2	9.2	9
			Max	3.30	1.21	0.94	0.86	101	262	7.7	71.0	3.4	19.6	60000
			Range	2.08	1.21	0.88	0.83	27	178	0.9	70.2	3.2	10.4	59991
			n	114	114	114	114	114	114	114	114	113	114	114
				NNN	NH4-N	TP	DRP	DO-%	EC	pH	Turbidity	Bdisk	WT	E. coli
749_10	Piako River	Kiwitahi	Mean	1.09	0.03	0.07	0.04	80	152	7.1	5.2	1.8	15.7	1188
			Median	0.75	0.01	0.06	0.03	85	151	7.1	3.5	1.5	15.6	370
			stdev	1.10	0.06	0.03	0.02	19	14	0.2	5.5	1.0	4.0	2289
			CV	101	192	46	43	24	9	3	107	57	25	193
			Min	0.00	0.01	0.03	0.01	25	79	6.4	0.3	0.2	6.8	40
			Max	4.30	0.52	0.24	0.10	114	189	7.8	28.0	5.7	24.4	17000
			Range	4.30	0.52	0.21	0.09	88	110	1.4	27.7	5.4	17.6	16960
			n	116	116	116	116	115	116	116	116	113	116	116
				NNN	NH4-N	TP	DRP	DO-%	EC	pH	Turbidity	Bdisk	WT	E. coli
749_15	Piako River	Paeroa-Tahuna Rd Br	Mean	1.51	0.05	0.27	0.18	82	231	7.3	13.9	1.0	15.3	1482
			Median	1.38	0.04	0.26	0.13	84	230	7.4	7.7	0.9	15.5	615
			stdev	1.02	0.05	0.14	0.15	8	30	0.3	22.7	0.5	3.9	2020
			CV	67	93	52	81	10	13	4	163	57	26	136
			Min	0.00	0.01	0.09	0.03	55	154	6.7	1.5	0.1	6.2	50
			Max	4.10	0.21	0.69	0.69	103	351	8.0	210.0	3.0	23.0	12000
			Range	4.10	0.21	0.60	0.66	48	197	1.3	208.5	2.9	16.8	11950
			n	114	114	114	114	114	114	114	114	107	114	114
				NNN	NH4-N	TP	DRP	DO-%	EC	pH	Turbidity	Bdisk	WT	E. coli
753_4	Piakonui Stm	Piakonui Rd	Mean	0.31	0.01	0.02	0.01	99	78	7.3	5.4	1.3	13.4	208
			Median	0.26	0.01	0.02	0.01	99	73	7.3	4.0	1.2	13.5	70
			stdev	0.19	0.01	0.01	0.01	2	16	0.2	4.9	0.5	2.8	353
			CV	63	159	51	54	3	20	3	91	40	21	170
			Min	0.10	0.01	0.01	0.00	91	57	6.3	1.4	0.2	7.0	3
			Max	1.16	0.11	0.09	0.05	107	161	7.8	41.0	3.1	19.6	2100
			Range	1.06	0.11	0.08	0.05	15	104	1.5	39.6	2.9	12.6	2097
			n	116	116	116	116	115	116	116	116	115	116	116

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