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A2E Two Loops Catchment Group

Review of existing catchment data to inform development of action plan

Report 1630-01 R1

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March 2024

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DOCUMENT ACCEPTANCE

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EXECUTIVE SUMMARY

- Data and information on freshwater quality and land-to-water contaminant transfers in the Two Loops Catchment Group area and the wider Piako River catchment largely originate from two sources, monitoring by Waikato Regional Council (WRC, since 1994) and research in the Critical Pathways Programme (CPP) led by Lincoln Agritech (2018 – 2023).
- WRC data demonstrate typically low concentrations of various contaminants (e.g., nitrogen, phosphorus, E. coli, sediment) at the Piakonui Stream site high up in the catchment on the slope of Maungakawa, but already substantially increased concentrations less than 20 km downstream at the Piako River at Kiwitahi site, and further increases on the way to the river mouth at the Firth of Thames in the north.
- Concentration – discharge relationships illustrate that Nitrate-Nitrite-Nitrogen (NNN) concentrations and turbidity increase with increasing stream flow, while Total Phosphorus (TP) and Dissolved Oxygen (DO) show more complex behaviour that can also be affected by point-source discharges (e.g. wastewater treatment plant).
- CPP research highlighted the value of exploring the relevant water and contaminant pathways, their associated lag times, and any transformation processes that may occur during transfer.
- Applying a modelling technique called Bayesian chemistry-assisted hydrograph separation (BACH) suggested that near-surface flows (surface runoff, interflow, artificial drainage) of very young water contributed 42% of the Piako at Kiwitahi streamflow, young shallow groundwater 40%, and old deep groundwater 17% (long-term average 2008 – 2022).
- Crucially, these pathway contributions vary substantially with flow. While deep groundwater almost exclusively sustains flow under dry summer and autumn conditions, shallow groundwater is a key source of the substantially higher flows typically observed in winter and spring. Near-surface flows can episodically become important during storms all year around, but more frequently so during winter and spring).
- Age-dating of stream water revealed substantial spatial variation under low-flow conditions (16 to >100 years), but young water with Mean Transfer Times below 10 years dominates at the high flows when most contaminants get exported from the catchment.
- High-frequency monitoring revealed the highly dynamic behaviour of nitrate nitrogen concentrations in Piakonui and Piakoiti Streams in response to flow dynamics. While concentrations were low (largely < 0.5 mg l^{-1}) and relatively stable during low-flow periods in summer and autumn, they became very dynamic in late autumn and winter, reaching peak concentration of > 4 mg l^{-1} during some events, particularly in Piakoiti Stream.
- Incidentally, this degree of temporal variation cannot be captured accurately by routine monthly monitoring programmes, which therefore tend to underestimate pollution levels in highly dynamic streams.
- Peak nitrate nitrogen concentrations tended to decrease during winter in Piakonui Stream, but much less so in Piakoiti Stream. This could indicate that the Piakonui sub-catchment contained a smaller stock of nitrate nitrogen at the onset of the leaching period, which was gradually depleted during winter, while a greater stock at Piakoiti took longer to flush out of the catchment.
- Integrated surface water/groundwater modelling for the Piako headwater catchment suggested relatively modest nitrate nitrogen losses from the Piakonui and Piakoiti sub-catchments (16 and 22 kg ha^{-1} yr^{-1}, respectively) and delivered loads at the stream monitoring sites that were in both sub-catchments only 35% of the source loads (6 and 8 kg ha^{-1} yr^{-1}, respectively).
- Given that hydrologic lags can be considered negligible, this very high 65% discrepancy is likely to be due to natural denitrification occurring during transfer and/or any biogeochemical lags that would arise should organic nitrogen be accumulating in the soil zone. It is currently unknown if this process is occurring under NZ land use conditions.
- While not necessarily representative for the entire catchment, snapshot samples from 14 farm supply wells suggest low nitrate nitrogen concentrations in groundwater (0 – 2.5 mg l^{-1}), with nine samples < 1 mg l^{-1}. Typically somewhat higher concentrations of up to 7 mg l^{-1} were detected in four of six shallow groundwater monitoring wells (1 – 9 m depth) that better reflect recent land use intensity.
- Reduced redox status was indicated for some samples in both datasets, reinforcing that natural nitrate attenuation via microbial denitrification is likely to occur in the groundwater system underlying the catchment.

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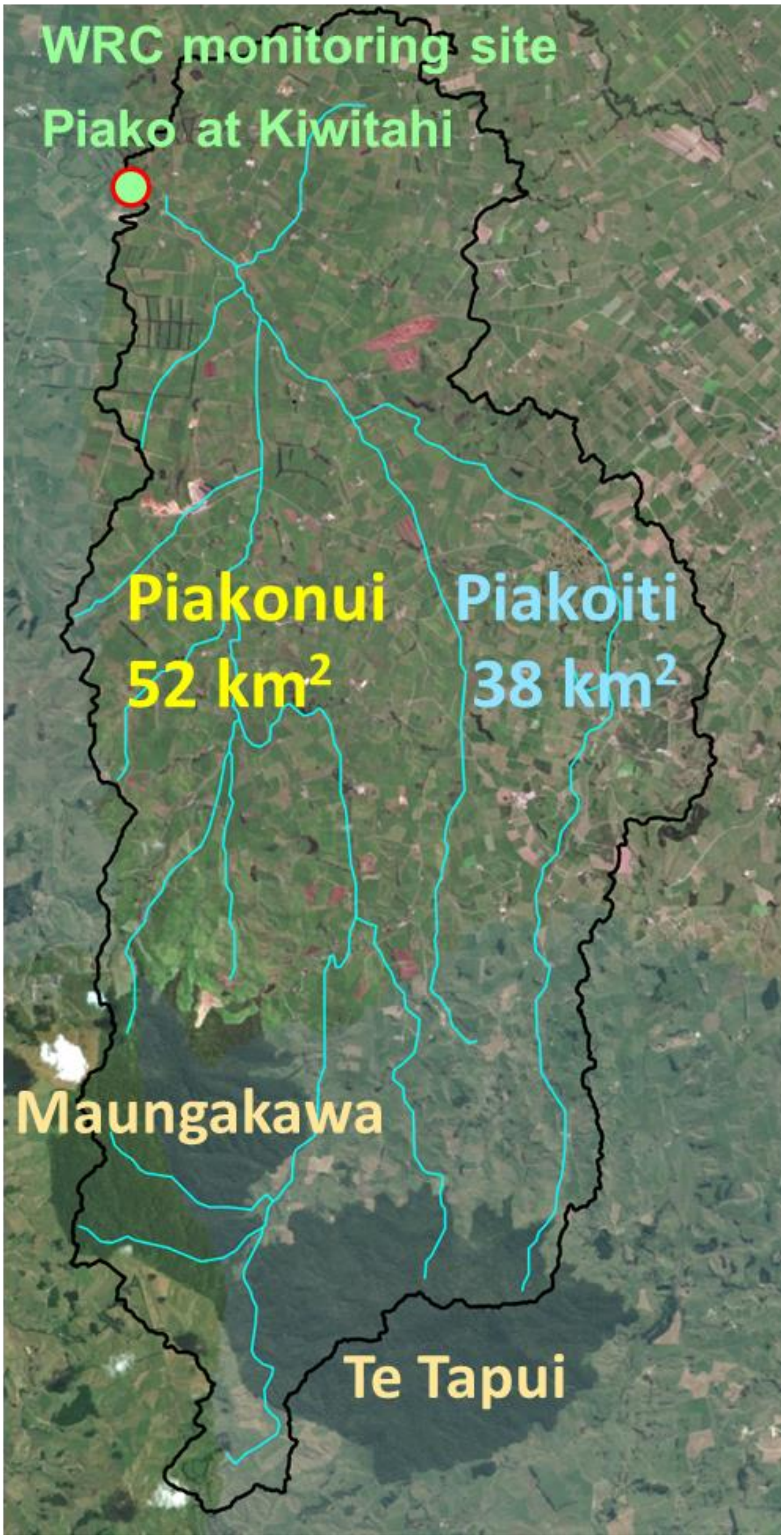
- It is important to recognise that the largely bush-clad peaks of Maungakawa and Te Tapui exert a very beneficial influence on the catchment's water quality. This is most evident in Piakonui Stream but extends throughout the entire Piako River system to the Firth of Thames. Accordingly, any land use intensification in the headwater areas should be prevented.
- Any measure to reduce or intercept near-surface flows will have multiple water quality benefits as surface runoff, interflow, and artificial drainage play a major role in transferring phosphorus, E. coli, sediment, and to a lesser degree nitrogen from land to water.
- Given that transfer controls often get overwhelmed during the high-flow periods (mainly during winter) when the entire catchment is near saturation, source controls that minimise the stock of contaminants that potentially can get mobilised should concurrently be introduced. Source control is anyway crucial for nitrogen, as a high fraction of it travels on the shallow groundwater pathway that cannot be effectively intercepted by transfer control measures.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION



This Access to Experts (A2E) project is being carried out on request by the newly formed Two Loops Catchment Group concerned about the impacts of their farming operations on water quality and ecosystem health.

The project comprises an initial review of existing water quality data and other relevant information, a farm walkover, and a workshop to develop potential remedial actions.

The catchment concerned encompasses the Piakoiti and Piakonui Streams that join to form the Piako River near the long-term water quality monitoring site 'Piako at Kiwitahi' run by Waikato Regional Council (WRC) since 1994 (Figure 1).

The purpose of this report is to provide the catchment group members with a compilation of existing water quality data and relevant other information (e.g. modelling results). This will then help the group to prioritise remedial measures in their action plan. By compiling information from multiple sources, and presenting it graphically in numerous maps and charts, this report will also facilitate the interaction between the catchment group and other landowners in the area.

Figure 1: Piako headwater catchment, as defined by the Waikato Regional Council (WRC) monitoring site Piako at Kiwitahi.

2. EXISTING DATA AND INFORMATION

There are two principal sources of data and information to be considered. Firstly, the long-term monitoring programme carried out across the region by the Waikato Regional Council, which provides monthly concentration data for a range of water constituents, typically starting in 1993/94. Secondly, the Critical Pathways research programme lead by Lincoln Agritech (2018-2023).

2.1 Long-term monitoring sites operated by Waikato Regional Council

The area of particular interest to the Two Loops Catchment Group forms part of the Piako River headwater catchment, and water leaving this area ultimately discharges into the Firth of Thames and the wider Hauraki Gulf. Accordingly, the discharges into this highly valued marine environment need to be considered additionally to the ecological, recreational, and cultural values of the Piako River itself. Calculations by WRC suggested that the Piako River contributes 18% of the flow of all Hauraki Rivers discharging into the Firth of Thames, but 35% of the nitrogen, and 43% of the phosphorus (WRC, 2016).

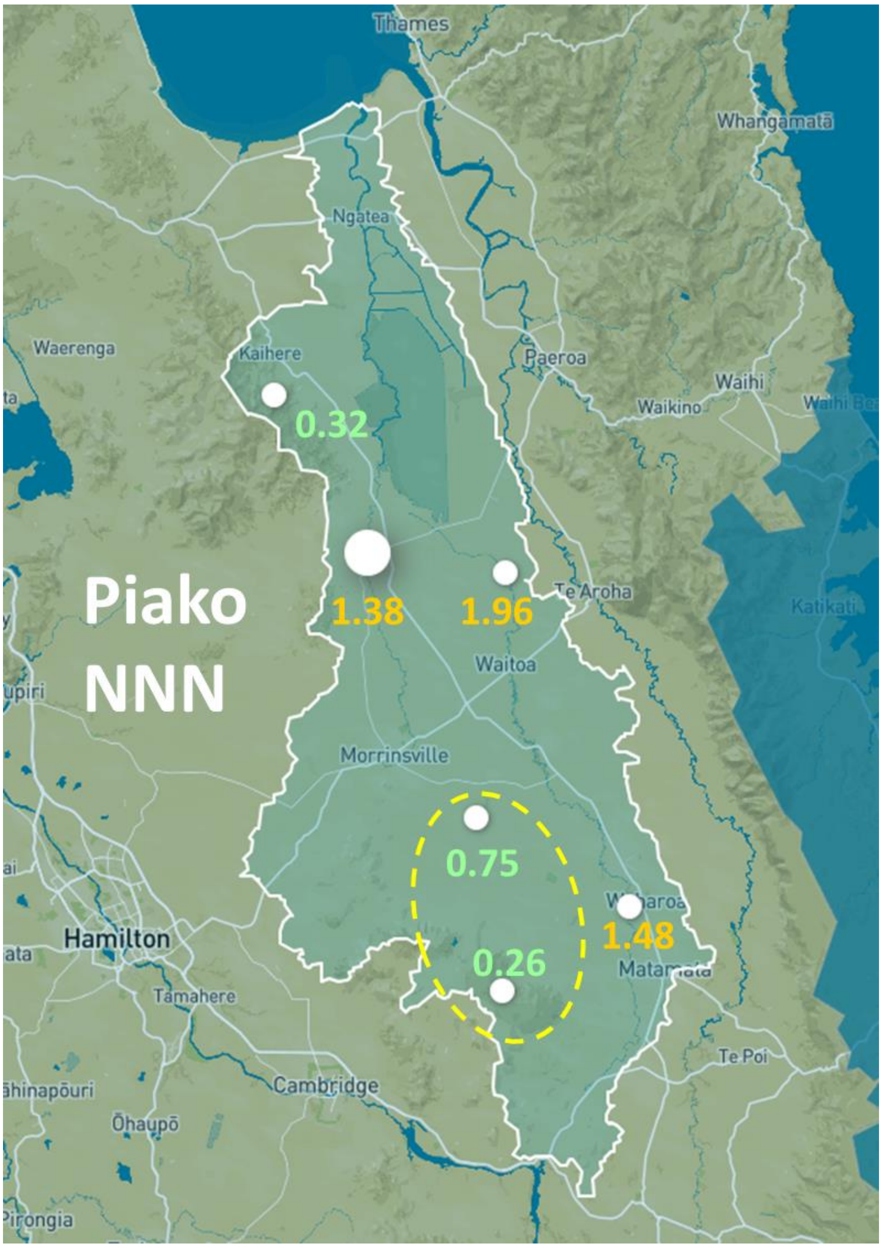
2.1.1 Spatial variation

Figure 2: Waikato Regional Council long-term stream monitoring sites in the Piako River catchment. Background map copied from https://www.lawa.org.nz/explore-data/waikato-region/river-quality/.

There are two monitoring sites within the Piako headwater area, the Piakonui Stream site high up in the catchment and the Piako at Kiwitahi site at the northern boundary; with a further Piako site downriver at the Paeroa-Tahuna Road (P-T Rd). Mangawhero Stream at Mangawara Road is a small tributary to the Piako River in the north-western part of the catchment. Furthermore, there are two monitoring sites on the Waitoa River, which joins the Piako River north of the Paeroa-Tahuna Road (Figure 2).

To illustrate the typical spatial variation of contaminant concentrations within the Piako River catchment, the median concentrations of Nitrate-Nitrite-Nitrogen (NNN), Escherichia coli (E. coli), and Total Phosphorus (TP) are presented in Figures 3 – 5 for the 10-year period 2014 – 2023.

The data presented here were sourced directly from WRC, but interested parties can also use the Land, Air, Water Aotearoa (LAWA) website (https://www.lawa.org.nz) to obtain some information on monitoring sites and overall water quality.

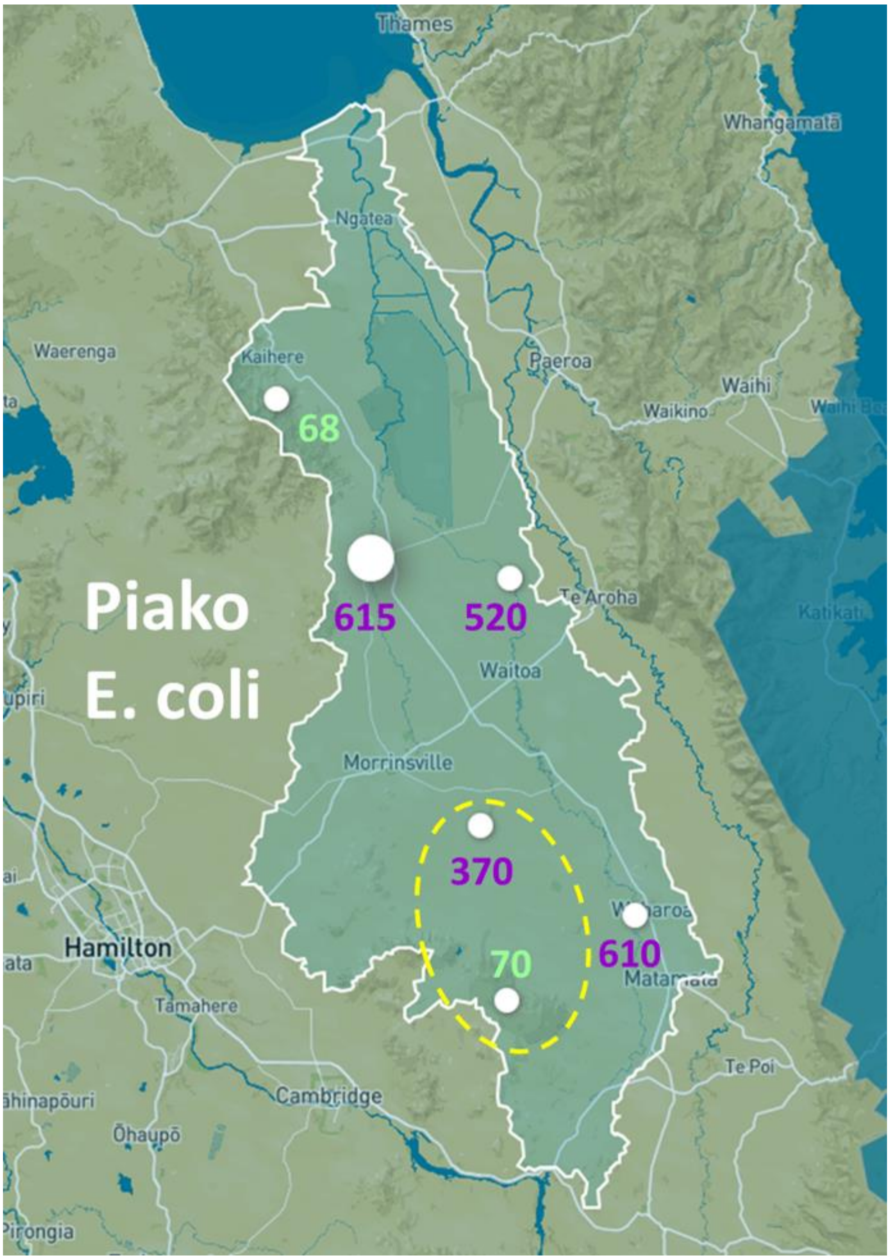


The colour-coding of the median nitrate-nitrite-nitrogen (NNN) concentrations presented in Figure 3 shows that both monitoring sites within the Two Loops Catchment area would have fallen into the Band A (green colour) of the now defunct National Objectives Framework (NOF) of the National Policy Statement for Freshwater Management (NPS-FM). The same positive rating applies to Mangawhero Stream further north.

Both Waitoa Stream sites and the Piako River site at the Paeroa – Tahuna Road had elevated concentrations (Band B, orange); particularly Waitoa at Mellon Road approaching the national bottom-line concentration of 2.4 mg l^{-1}.

It is important to note that the NNN bands and bottom line only refer to toxicity; more stringent criteria would be required to protect overall ecosystem health.

Figure 3: Median Nitrate-Nitrite-Nitrogen (NNN) concentrations (mg l^{-1}) at the WRC monitoring sites in the Piako River catchment (2014 – 2023).

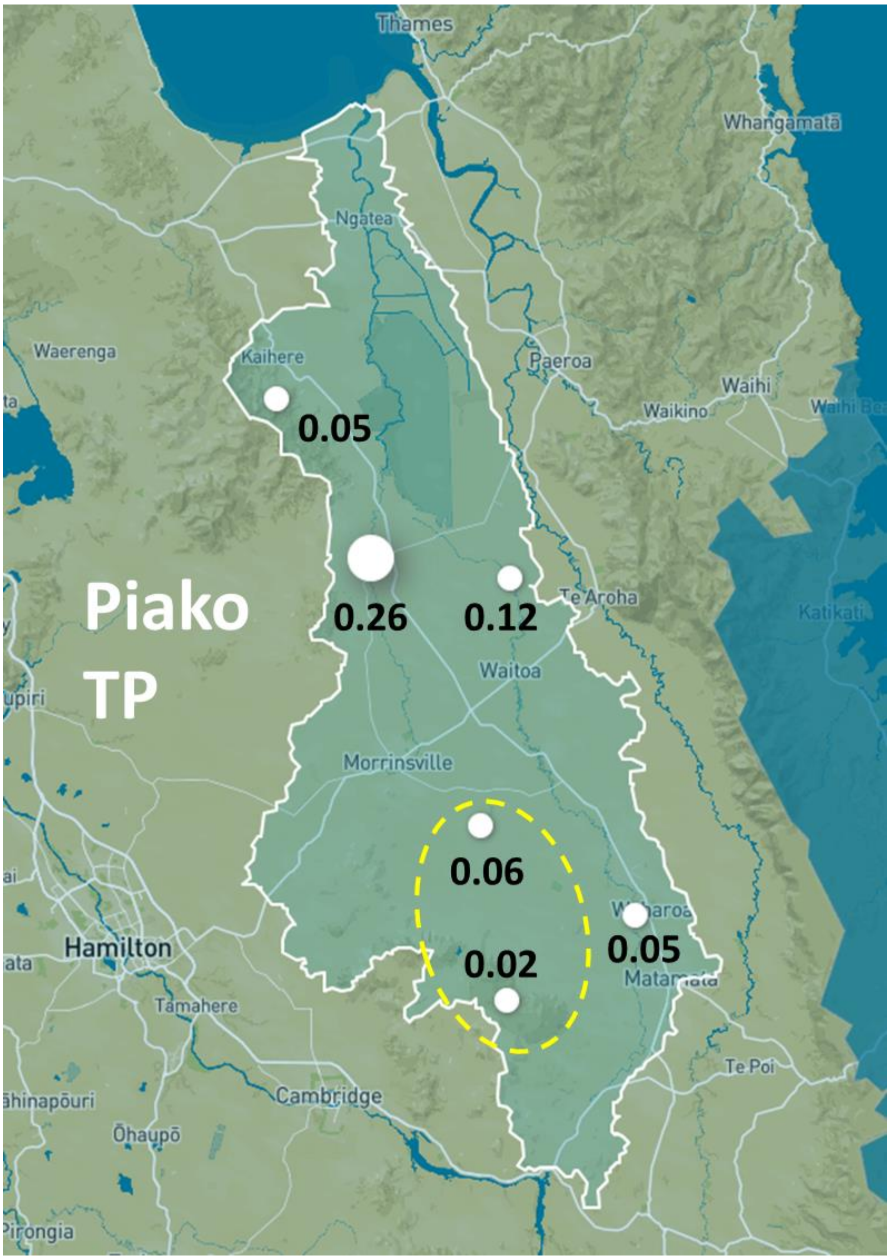


Escherichia coli (E. coli) is monitored in lakes and rivers as an indicator of the risk of a swimmer attracting a Campylobacter infection.

The 5-fold concentration increase from the Piakonui (70 Cfu 100 ml^{-1}) to the Piako at Kiwitahi monitoring site (370 Cfu 100 ml^{-1}) highlights how fast concentrations can reach concerning levels already within the headwater catchments.

All four lowland monitoring sites would presumably have fallen into Band E, the worst category of the National Objectives Framework.

Figure 4: Median Escherichia coli (E. coli) concentrations (Cfu 100 ml^{-1}) at the WRC monitoring sites in the Piako River catchment (2014 – 2023).



In contrast to lakes, Total Phosphorus (TP) concentrations did not form part of the National Objectives Framework for rivers, but they are reported in Figure 5 as the Piako River discharges a disproportionally high TP load into the Firth of Thames (WRC, 2016).

While increasing TP concentrations from headwater to lowland areas are partly due to diffuse agricultural pollution, several point-source discharges also add to the load (e.g. Morrinsville wastewater treatment plant, Waitoa dairy factory and meatworks).

Figure 5: Median Total Phosphorus (TP) concentrations (mg l^{-1}) at the WRC monitoring sites in the Piako River catchment (2014 – 2023).

2.1.2 Temporal variation

This section focusses on the variation of concentrations with time (1994 – 2023), specifically for the three monitoring sites of greatest relevance to the Two Loops catchment group. Note that a small number of very high outliers are not shown on the charts in this section, so that the dynamics of most measurements can more easily be illustrated. All concentrations are reported in mg l^{-1}, unless specified otherwise. Note that concentration trends are typically not visually detectable in catchments as dynamic as the Piako River system (and require analysis using sophisticated statistical methods). While time series of concentration data are presented here, the relationship between concentrations and flow rate will be discussed in Section 2.1.3.

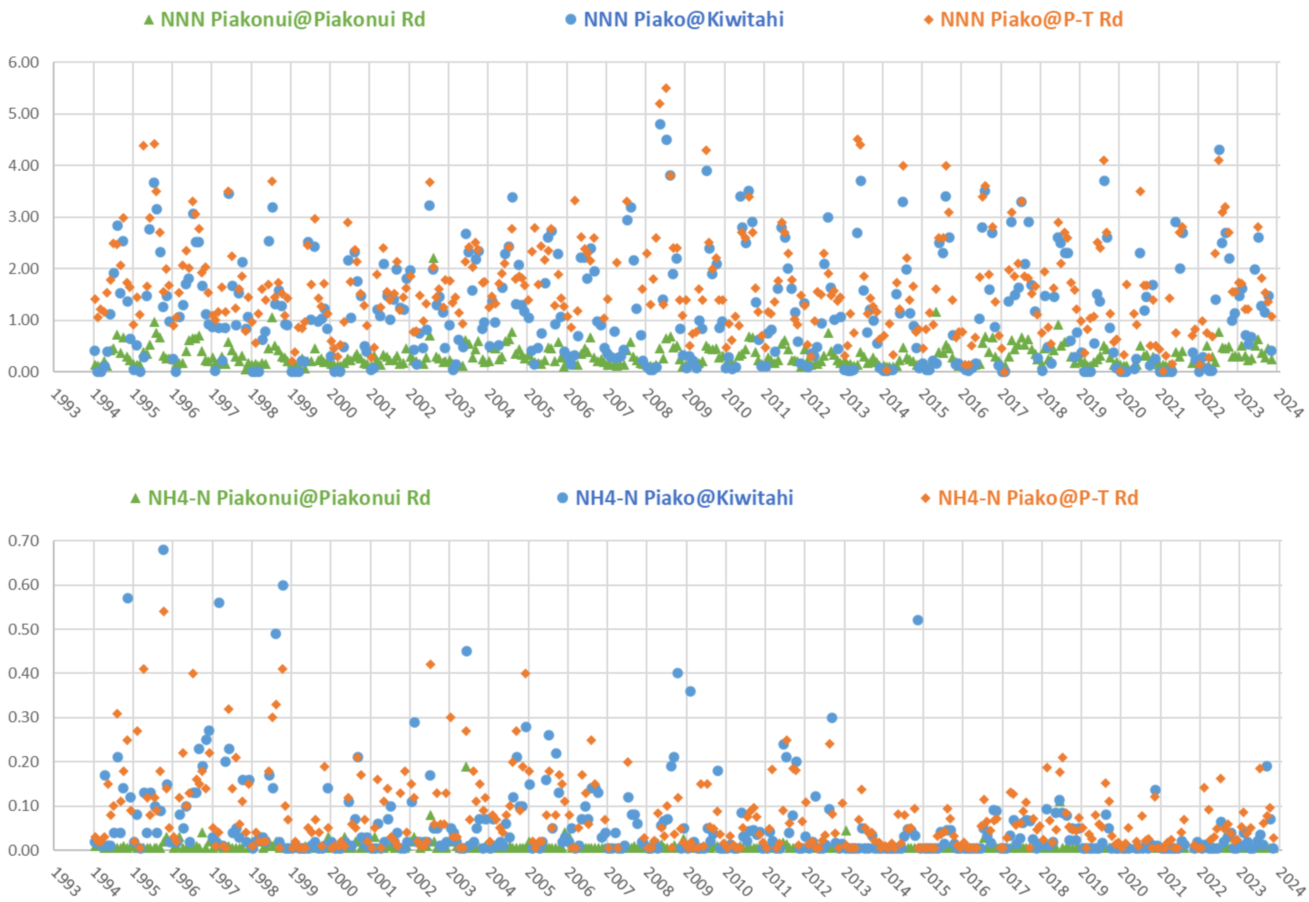
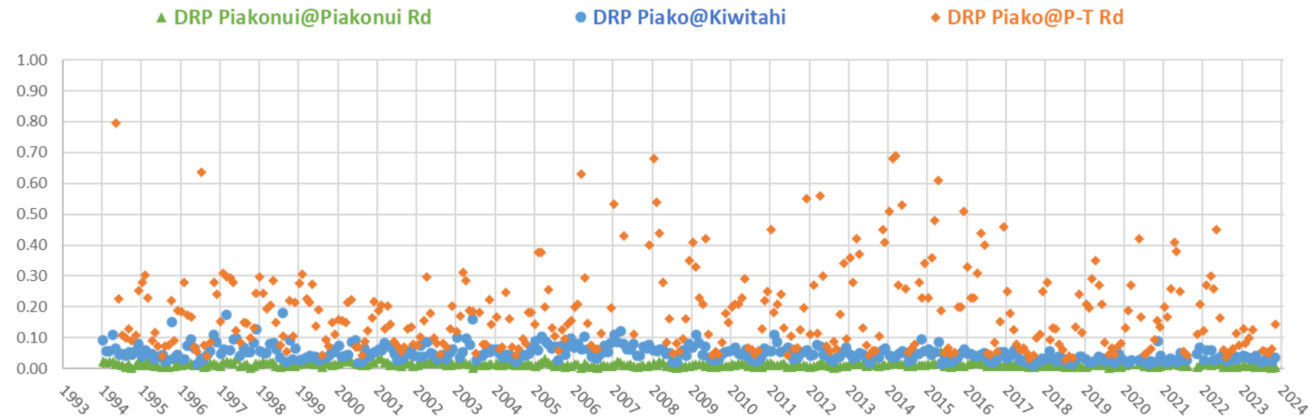


Figure 6: Nitrate-Nitrite-Nitrogen (NNN, top) and Ammonia-Nitrogen (NH4-N, bottom) measured monthly, 1994 to 2023 (mg l^{-1}).

Concerning NNN concentrations, three points are worth noting. Firstly, they were consistently lowest and showing little temporal variation at the Piakonui site (green triangles in Fig. 6), which has only a relatively small fraction of agricultural land in its catchment area. Secondly, NNN concentrations were already much more dynamic and at an elevated level at Piako at Kiwitahi (blue dots), less than 20 kilometres downstream of the Piakonui site. NNN minima tended to occur during summer and maxima in winter. Thirdly, maximum concentrations at the Paeroa-Tahuna site (orange diamonds) were relatively similar to the Kiwitahi site, but the Paeroa-Tahuna site does not reach summer minima as low as observed at the Kiwitahi site (see also Fig. 10).

Ammoniacal nitrogen concentrations were generally one order of magnitude lower than NNN concentrations, which reflects that the positively charged ammonium ion (NH_4^+) is strongly held by negatively charged soil particles, while the negatively charged nitrate ion (NO_3^-) is repelled by soil particles and therefore highly mobile. The decreasing frequency of measured elevated concentrations over time could be related to improved effluent management, stream fencing, and other measures introduced to prevent animal excreta from reaching a waterway.



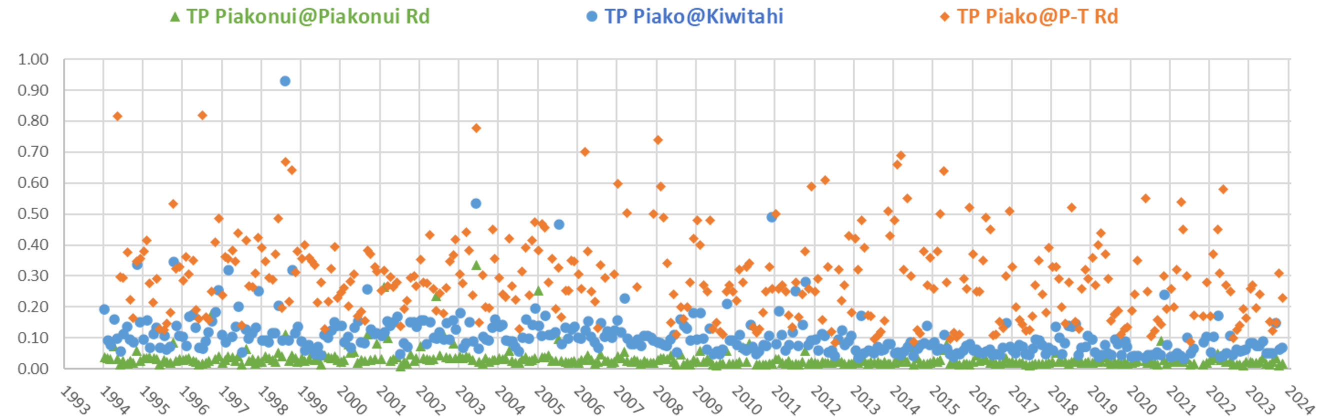


Figure 7: Dissolved Reactive Phosphorus (DRP, top) and Total Phosphorus (TP, bottom) measured monthly, 1994 to 2023 (mg l^{-1}).

DRP, which is the main dissolved and mobile fraction of TP, increases between the Piakonui and the Piako at Kiwitahi sites, but not as strongly as TP (Fig. 7). This indicates that particulate phosphorus, which is largely transferred from land to water via erosion of soil material, accounts for a high fraction of the TP increase between these sites. As mentioned earlier, point-source discharges from wastewater treatment plants (Morrinsville, Tahuna) and factories (Morrinsville) contribute to the strong concentration increases between the Kiwitahi and Paeroa – Tahuna Road sites.

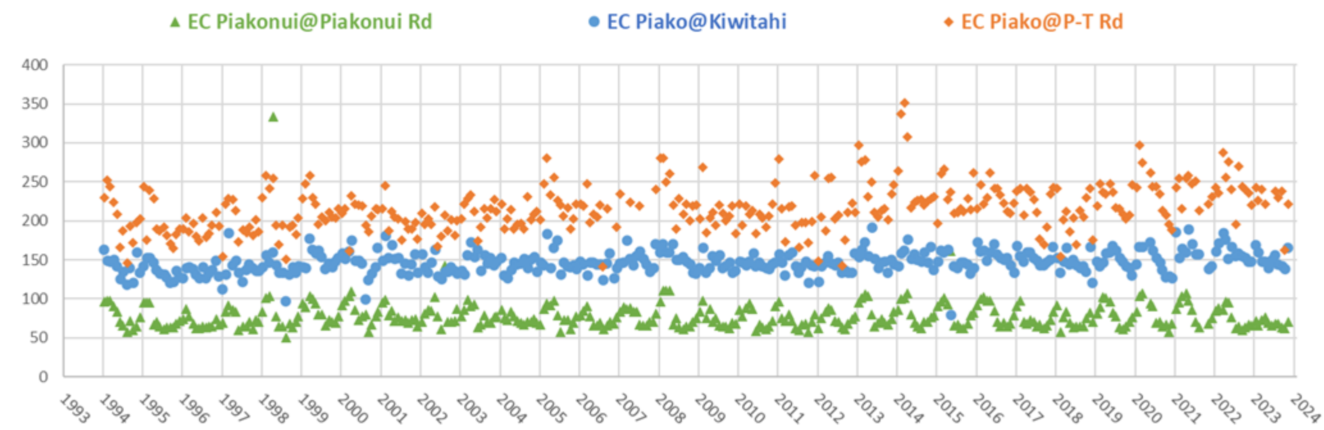
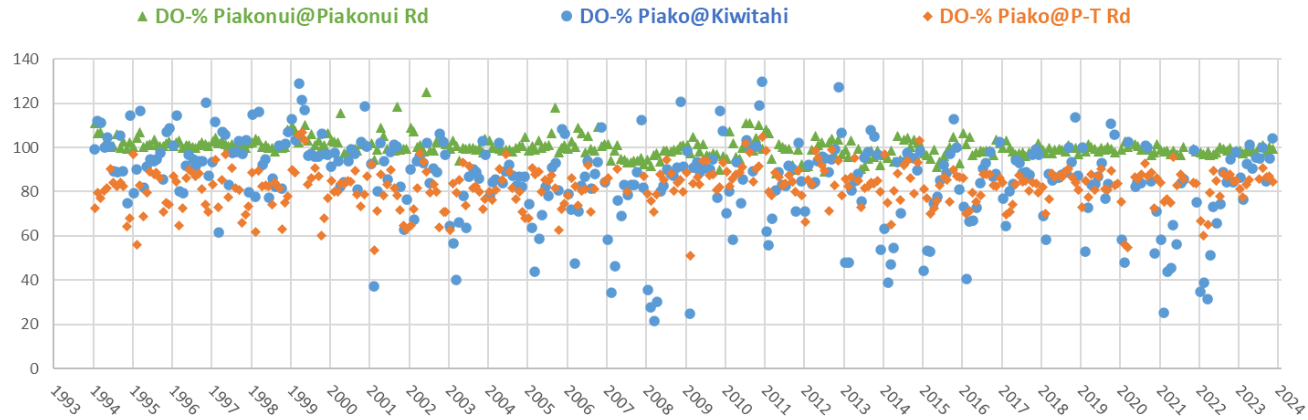


Figure 8: Electrical Conductivity (EC in µS cm^{-1} at 25°C) measured monthly, 1994 to 2023.

Electrical Conductivity (EC) is a summary parameter that provides an integral measure of all ions contained in the water (Fig. 8). While rainwater infiltrating the soil has a very low conductivity, it increases in the subsurface environment due to interaction with human-made substances (e.g. fertilisers providing nitrate) and rocks (e.g. providing calcium and magnesium). The longer the contact time, the higher the EC typically becomes until a saturation level is reached. The seasonal concentration dynamics very evident for the Piakonui site can therefore be interpreted as follows: The EC peaks typically observed in late summer reflect that the sampled water had more time to pick up ions during its longer travel time through the catchment than the low EC water sampled in winter. The latter contains a higher fraction of water that moved quickly on near-surface pathways (surface runoff, interflow, artificial drainage) to the monitoring site under wet winter conditions, while flow during summer is predominantly provided by groundwater discharge. This seasonal dynamic is less obvious at the two Piako River sites, as land use effects (e.g. fertiliser, wastewater) become more important with increasing catchment size than natural water/rock interaction.



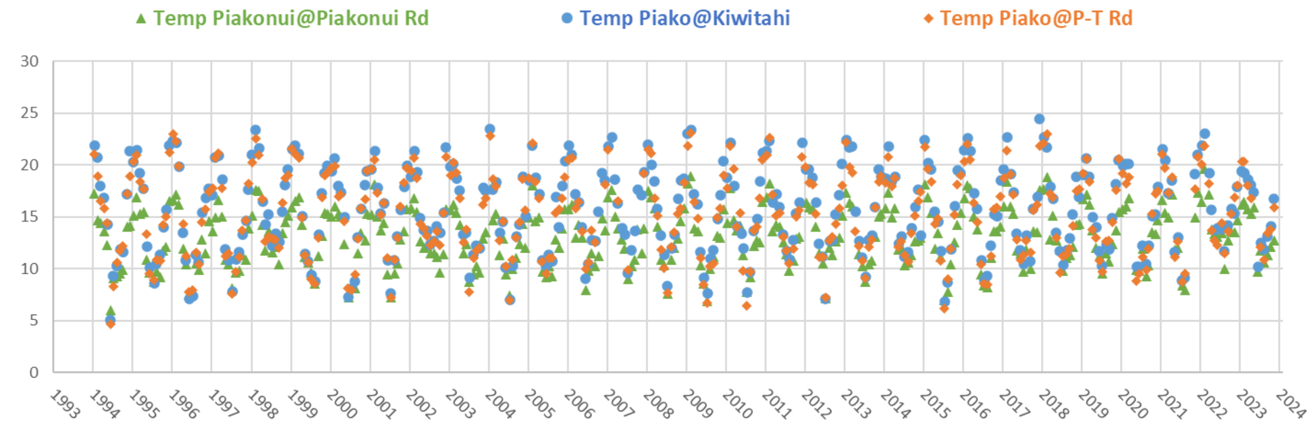


Figure 9: Dissolved Oxygen saturation (DO%, top) and water temperature (Temp in °C, bottom) measured monthly, 1994 to 2023.

Dissolved oxygen (DO) concentrations are very important to aquatic life and ideally should not fall below 80%; below 20% would be fatal for most aquatic life. The water sampled at the Piakonui monitoring site at the edge of bush on Maungakawa consistently has near 100% DO saturation (Fig. 9). However, DO saturation at the Piako at Kiwitahi site shows substantial temporal variation, with levels as low as 20% recorded for a few sampling dates, with minima typically occurring in mid to late summer. It should be noted that lower than recorded DO concentrations will occur during the nighttime, as DO shows a diurnal pattern. Concentrations increase during daylight hours when photosynthesis is occurring (generating DO) and decreases at night when respiration continues (consumption of DO) but photosynthesis does not.

DO saturation levels are less dynamic at the Paeroa – Tahuna Rd site, with most measurements ranging from 80 to 100%. The temperature time series indicate the smallest amplitude and lowest maxima for the Piakonui site and greater amplitudes and highest temperature maxima for the two Piako River sites, with Piako at Kiwitahi tentatively recording the highest maxima. These high temperatures are considered one of the reasons for the frequently observed DO minima in mid to late summer. Shading of the shallow stream could help to alleviate the DO minima. The greater depth of the stream at the Paeroa – Tahuna Road site could explain the typically slightly lower maximum temperatures recorded there.

2.1.3 Concentration – Discharge Relationships (CDRs)

The temporal variation of measured concentrations presented in the previous section is often related to changes in stream flow (also called 'discharge'). Graphing measured concentrations (y-axis) against the discharge at the time of sampling (x-axis) produces charts that depict the concentration – discharge relationship (CDR) for a particular water constituent at a given site. In this section, CDRs for NNN, TP, Black Disk visibility, and DO saturation are presented for both Piako River sites for which discharge measurements exist. Note that conventionally log-log axes are used in CDRs to make it easier to display data that may spread across several orders of magnitude (see gridlines in figures).

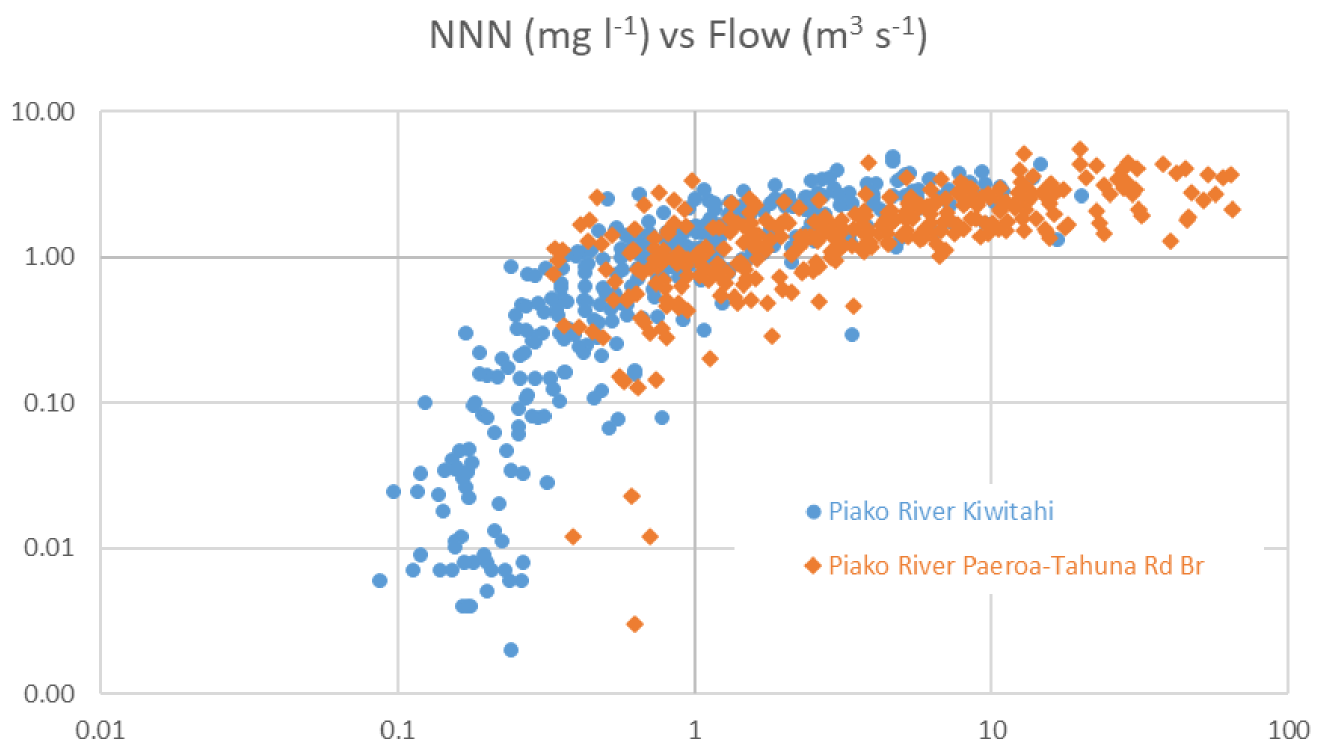


Figure 10: Concentration – Discharge Relationship (CDR) for NNN at both Piako River monitoring sites (1994 – 2023).

As observed for many other waterways (Stenger et al., 2024), NNN concentrations at both Piako River sites tended to increase with increasing flow (Fig. 10). This behaviour is interpreted as being due to increasingly strengthening hydrologic connectivity between zones in the catchment where NNN is available and local waterways as catchments wet up and water tables rise in late autumn or winter. NNN is in pastoral catchments largely generated within the root zone (from animal excreta, applied fertiliser, and soil organic matter). Rainfall exceeding evapotranspiration, as typical for autumn and winter, can result in NNN being leached out of the root zone. A concurrently rising water table facilitates lateral movement of shallow groundwater towards the nearest stream; any existing artificial drainage (drainpipes or surface ditches) further accelerate this NNN transfer. Consequently, highest NNN concentrations are often observed during or shortly after the first major rainfall events in early winter, after the catchment has wetted up in late autumn. Year-to-year variation in weather patterns obviously can substantially modify this generalised pattern (See Fig. 15).

While the overall CDRs are relatively similar for both monitoring sites, there is a noteworthy difference at the lowest flows. NNN concentrations at the Paeroa – Tahuna Road site rarely drop below 0.10 mg l^{-1}, while many samples below this value were recorded at the Kiwitahi site. Such extremely low NNN concentrations can result from one of three processes, or a combination of those (Morgenstern et al., 2010; Woodward et al., 2013). Firstly, the groundwater that sustains streamflow during prolonged dry conditions was typically recharged decades ago, when NNN concentrations may have been much lower due to lower overall land use intensity. Secondly, NNN leached from the root zone may have been denitrified during its slow travel through deeper parts of the groundwater system towards the waterway.

Finally, under very low flow conditions and good growing conditions in summer, NNN uptake by plants growing in a stream or on its banks can further reduce NNN concentrations of the stream water. Circumstantial evidence suggests that the groundwater sustaining flow at Kiwitahi at the lowest flows is older than at Paeroa – Tahuna Road (see next section). Moreover, plant uptake will have a greater effect on the relatively small stream at Kiwitahi compared to bigger stream at Paeroa – Tahuna Road.

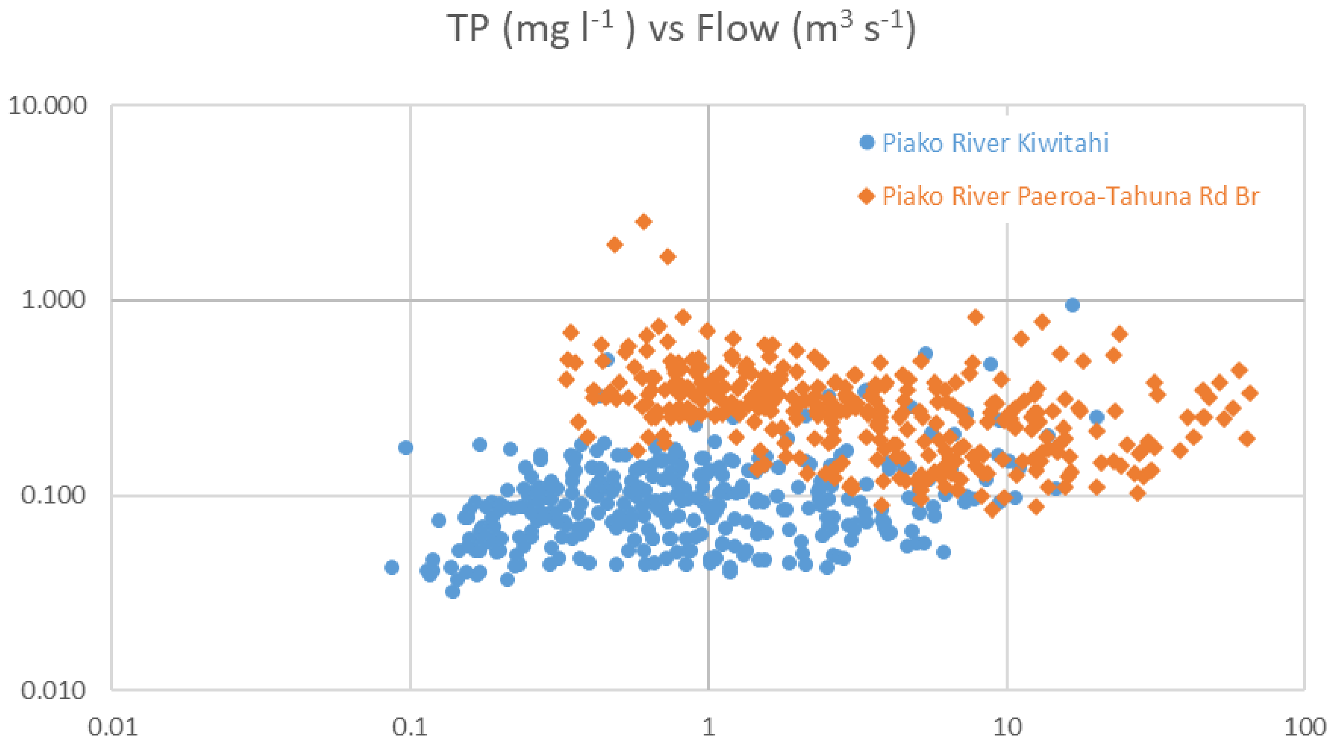


Figure 11: Concentration – Discharge Relationship (CDR) for TP at both Piako River monitoring sites (1994 – 2023).

A distinct difference in CDRs between the two sites was observed for Total Phosphorus (Fig. 11). While TP concentrations at Kiwitahi generally showed a modest increase with increasing flow, and a few very high concentrations at the highest flows, concentrations at Paeroa – Tahuna Rd showed a contrasting pattern. The tendency for decreasing concentrations from the lowest flows to the middle flow range indicates point-source discharges that have the greatest effect at the lowest flows and then get diluted as flows increase. As mentioned previously, the Morrinsville wastewater treatment plant and a few agricultural processing facilities are known TP point-sources in this catchment.

The Black Disc visibility is a measure of water clarity that describes how far away a black disc can be seen horizontally through water (Fig. 12). While there is substantial variation for any given flow, at both sites there is a clear tendency of decreasing water clarity with increasing flow.

DO saturation was high and relatively independent of flow at the Paeroa – Tahuna Road site, but low saturation levels were frequently observed at the Kiwitahi site at low flows (Fig. 13) that typically occur during warm summer periods (see Fig. 9).

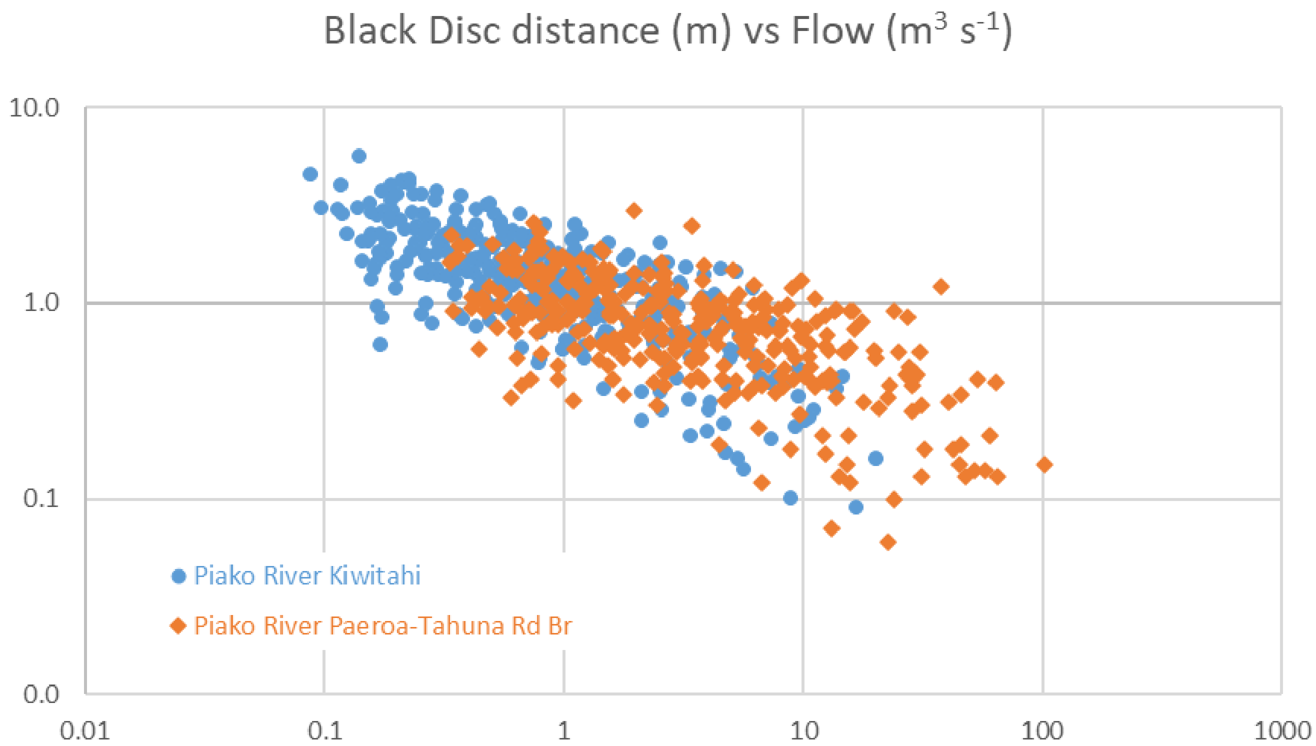


Figure 12: Concentration – Discharge Relationship (CDR) for Black Disc distance at both Piako River monitoring sites (1994 – 2023).

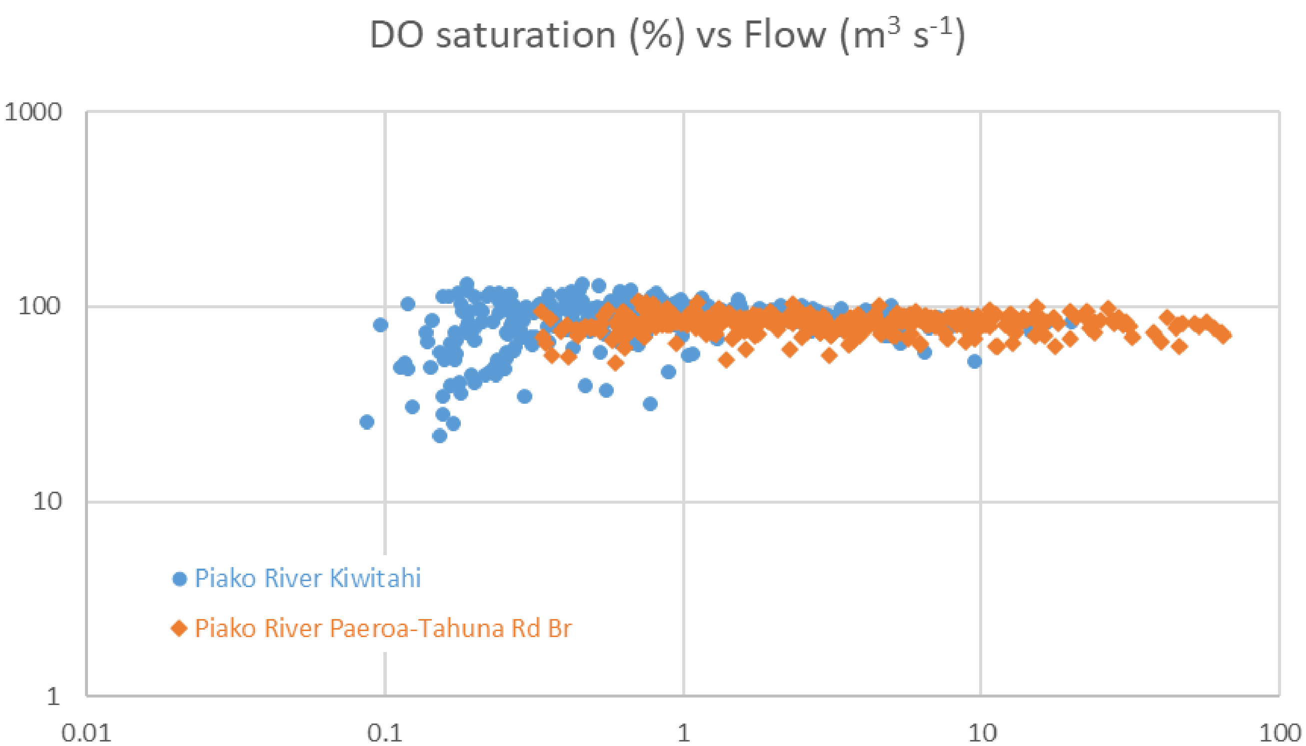


Figure 13: Concentration – Discharge Relationship (CDR) for DO saturation at both Piako River monitoring sites (1994 – 2023).

2.2 Data and information from 'Critical Pathways Programme'

From 2018 – 2023, Lincoln Agritech led the MBIE-funded Critical Pathways research programme that amongst other components involved intensive field research in the Piako headwater catchment (as defined by the Piako at Kiwitahi monitoring site). These in-depth investigations utilised several innovative techniques, such as airborne and ground-based geophysical surveys and high-frequency nitrate measurements, to elucidate water and contaminant flows through the catchment. This section reports on a few components of this research that are of direct relevance to the catchment group and wider farming community.

2.2.1 Three fundamental questions

Before delving into results of this research, it seems warranted to reiterate the three fundamental questions that need to be addressed when aiming to understand land-to-water contaminant transfers (Fig. 14).

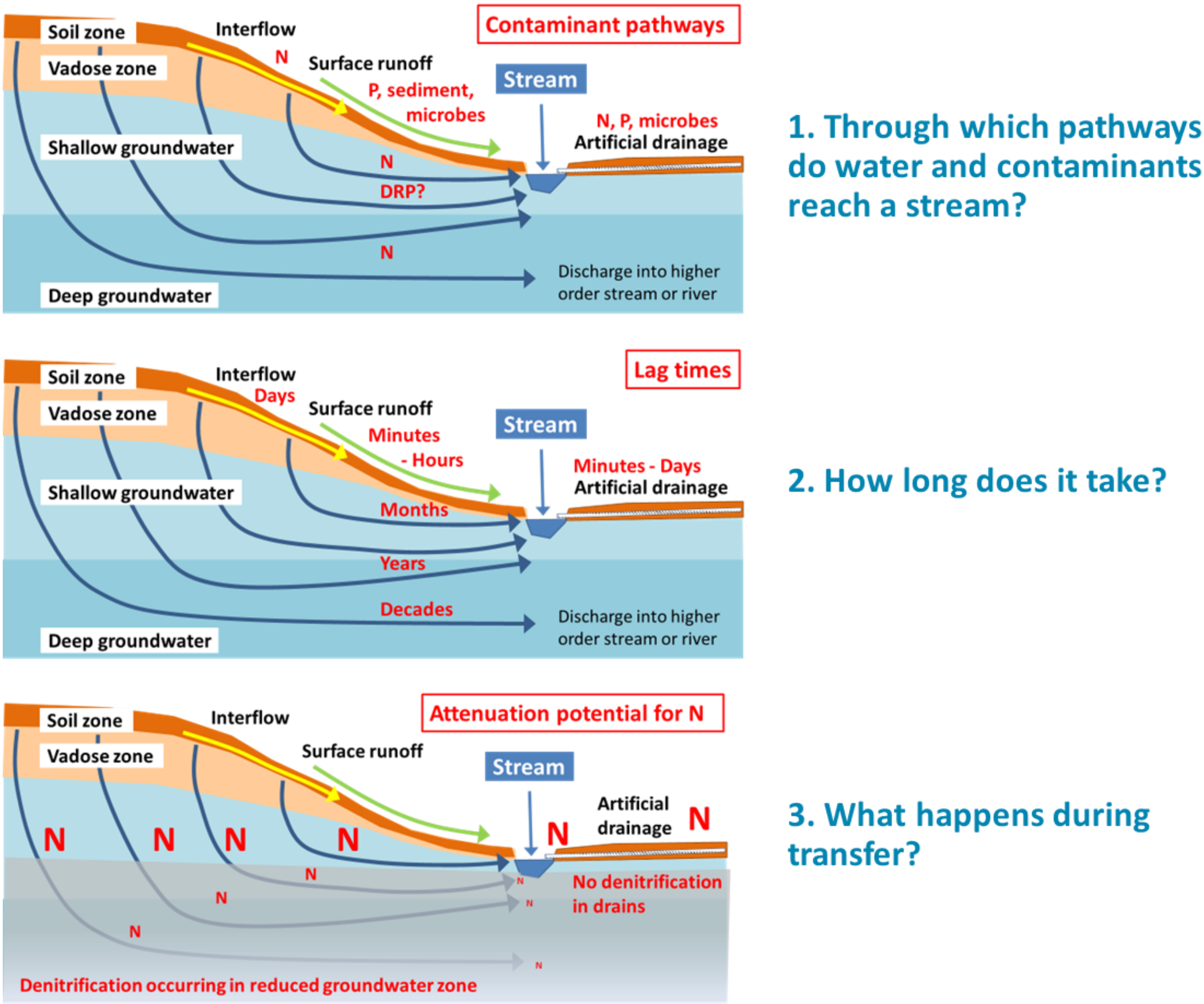


Figure 14: Schematics on three fundamental questions concerning land-to-water contaminant transfers.

Water, and contaminants transported by it, can reach a stream via a range of pathways. Surface runoff, interflow, and artificial drainage 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) typically contributes seasonally to streamflow; it responds fast and is local. 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. 14, 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 also means that the water flowing in a stream does not have one unique age but consists of a number of components with differing ages (Fig. 14, middle).

Finally, it's important to recognise that not all contaminants leached from the root zone necessarily arrive at a stream, e.g. there can be substantial nitrogen attenuation occurring during transfer. In catchments underlain by oxygen-depleted, reduced groundwater zones, microbial denitrification can substantially reduce the nitrogen load discharged into streams (Fig. 14, bottom).

2.2.2 Dynamics of pathway contributions to streamflow

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 recorded at the Waikato Regional Council monitoring site Piako at Kiwitahi (Stenger et al., 2024).

Long-term average flow contributions (2008 – 2022) were estimated to be 42% near-surface flow, 40% shallow groundwater, and 17% deep groundwater. The three graphs shown in Fig. 15 for the calendar years 2020 – 2022 illustrate a common overall pattern, but also substantial variation between years due to differing weather conditions, particularly total rainfall amount and distribution. In all three years, stream flow was very low during the first half of the year and mainly sustained by deep groundwater discharge (grey colour). Near-surface flows (blue) occurred episodically in response to significant rainfall events. Shallow groundwater (orange) gradually starts building up in late autumn and, outside of rain events, becomes the main flow contributor during winter and spring. Near-surface pathways contribute most flow during very rainy periods once the catchment has wetted up in early winter.

Differences between years are evident for total flow, temporal distribution of flow, and the contributions made by the three pathways. Total flow was lowest in 2020, the 3-month period from late June to late September accounted for a very high fraction of it, and significant near-surface flows were relatively rare. In 2022, total flow was highest, elevated flows persisted from June until December (and beyond), and near-surface flows made substantial flow contributions during the second half of the year. Conditions in 2021 were in-between the other two years.

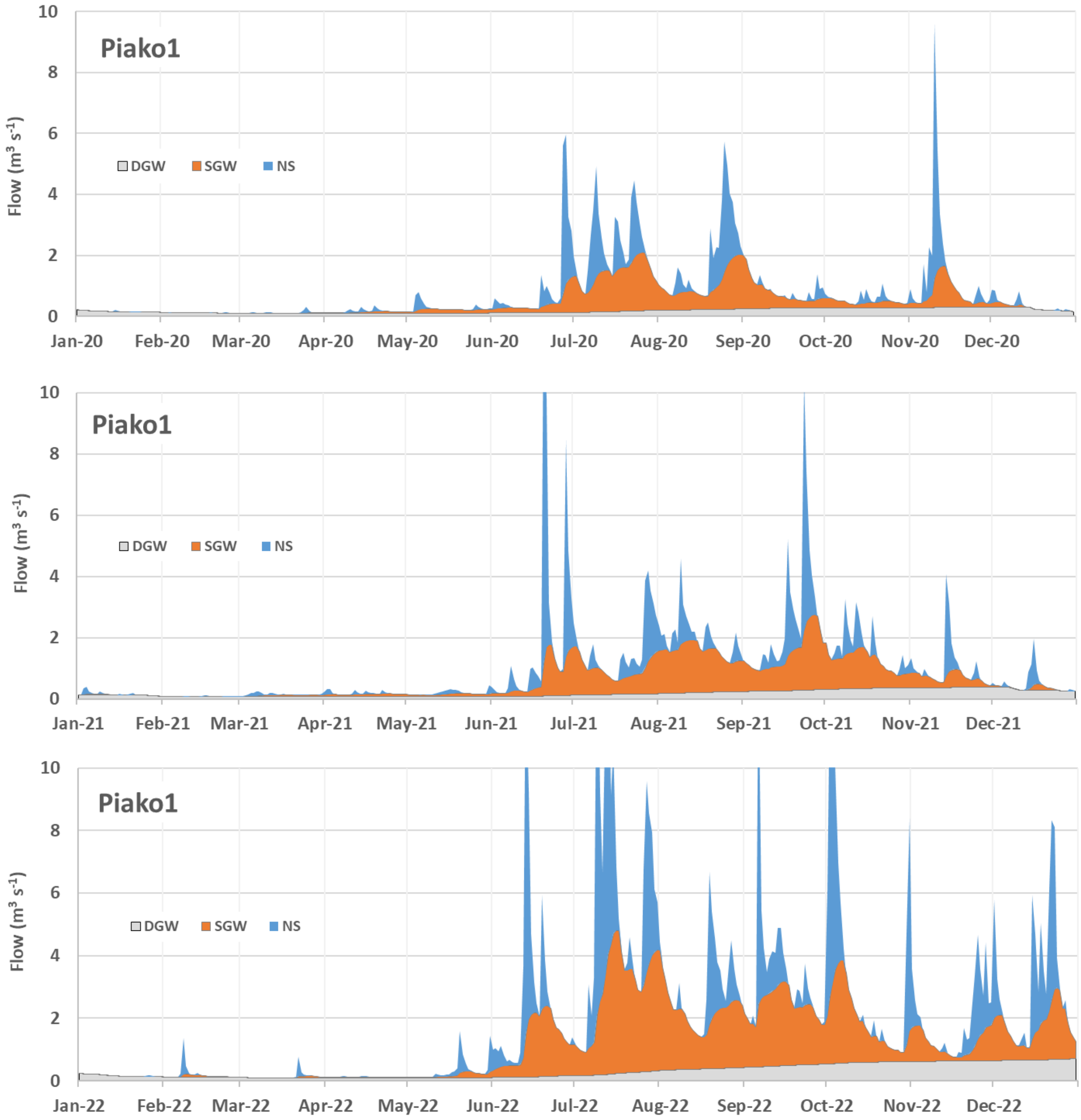


Figure 15: Estimated pathway contributions to flow in Piako River at Kiwitahi (2020 – 2022).

2.2.3 Spatiotemporal variation of stream water Mean Transit Times (MTTs)

As outlined in Section 2.2.1, the 'mean age' of the stream water sampled at any given date is determined by the fractions of water being contributed to streamflow by the various pathways at this point in time. Accordingly, MTTs vary between different parts of the catchment and change over time. This spatiotemporal variation is illustrated in Fig. 16 for the Piako headwater catchment with its two main tributaries, Piakonui Stream and Piakoiti Stream.

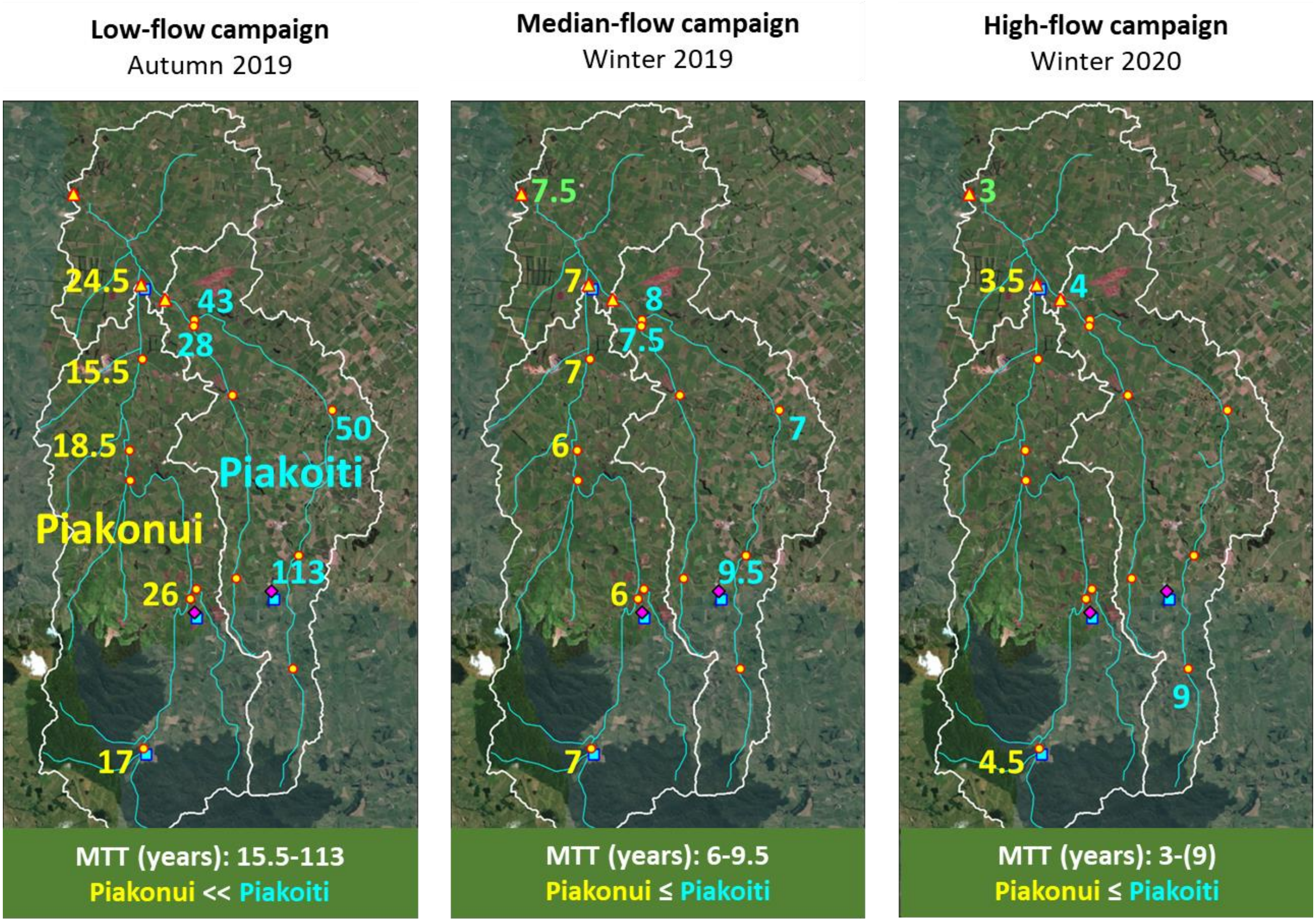


Figure 16: Spatiotemporal variation of stream water MTTs in the Piako headwater catchment.

Distinct differences between the two tributaries were evident during the low-flow sampling campaign carried out in the autumn of 2019. MTTs varied in the narrow range from 16 to 26 years in the Piakonui sub-catchment, but with 28 to 113 years were much higher in the Piakoiti sub-catchment (Fig. 16, left). These numbers suggest that the Piakonui sub-catchment is underlain by a sufficiently large groundwater reservoir to provide even under dry conditions stream flow with MTTs in the range of two to three decades. In contrast, the MTTs and their spatial distribution suggest that there is less groundwater storage available in the Piakoiti sub-catchment. Accordingly, flow in Piakoiti Stream is smaller and sustained by substantially older water. Here, water storage appears to increase from the headwater area towards the sub-catchment outlet, with MTTs in the main channel dropping from over 100 to 43 years. This difference between the two sub-catchments is thought to be due to two factors, some geological differences, but mainly different rainfall inputs. While Piakonui Stream receives substantial flow from the high-rainfall cones of Maungakawa and Te Tapui, Piakoiti Stream emerges within farmland at lower elevation.

While low-flow samplings are informative with regard to understanding how these sub-catchments function, samplings under median- and high-flow conditions are crucial when considering contaminant exports. The stark MTT differences observed at low-flow had almost disappeared when the median-flow sampling was carried out in winter 2019. By that time, the entire catchment had wetted up, which led to the activation of short and shallow pathways leading to substantially younger MTTs in both streams (6-10 years), but particularly so in Piakoiti Stream. Consequently, MTTs there were at median flow only tentatively higher than at Piakonui Stream. Even less variation between sub-catchments was evident under high-flow conditions, where short and shallow pathways were dominant everywhere (Fig. 16, centre and right). This example illustrates that climatic factors like persisting rainfall excess during winter are often strong enough to nullify the effect the spatial variation of other relevant factors (e.g. geology) may have under drier conditions. As will become even clearer in the next section, most of the nitrate exports from the catchment occur in the period directly following the wetting up of the catchment, i.e. typically in early winter.

2.2.4 Spatiotemporal variation of nitrate nitrogen concentrations in streams

To obtain a better understanding of their variation with time, nitrate nitrogen concentrations in streams were measured in 15-min intervals in the Piakonui and Piakoiti Streams (Fig. 17 bottom). Comparison with concurrent flow measurements (Fig. 17 top) shows that concentrations were low (largely < 0.5 mg l^{-1}) and relatively stable during low-flow periods in summer and autumn. However, when flow became more dynamic in late autumn and winter, nitrate concentrations also became more dynamic, reaching peak concentration of > 4 mg l^{-1} at some events, particularly in Piakoiti Stream.

As measurements during high-flow events pose substantial challenges to optical nitrate sensors, the two 'polished' nitrate concentration time series shown in Fig. 17 have several obvious gaps and peak concentrations of up to 6 mg l^{-1} recorded in the raw data were filtered out. Data gaps were caused by instruments failing temporarily (e.g. due to flooding), the accurate measurement range being exceeded (occasionally at high flows), or poor data quality due to high turbidity (also mainly during high-flow events). These factors together mean that data gaps mainly occurred during periods where elevated nitrate concentrations must be expected. The polished time series are therefore likely to provide a visual impression biased towards the lower range of actual concentrations.

The substantial effect on nitrate dynamics of year-to-year variation in rainfall amount and distribution becomes clear when comparing the years 2021 and 2022. Streamflow in 2021 followed more closely the long-term average pattern with extended periods of low flows outside the wet season (approx. June to October). Nitrate concentrations increased sharply from < 1 mg l^{-1} to peak concentrations of approx. 4 mg l^{-1} with the onset of high-flow events in late autumn/early winter, although there were a few data gaps during this period, particularly at Piakoiti. At Piakonui, peak nitrate concentrations decreased markedly during winter, indicating that the stock of nitrate in the catchment was gradually depleted. This was less pronounced in Piakoiti Stream, where peak concentrations remained > 3 mg l^{-1} into spring, suggesting there might have been a greater stock of nitrate available than in the Piakonui sub-catchment. Flows and nitrate concentrations at both sites were low from mid-spring until the end of the year. Accordingly, the majority of nitrate exports took place within the relatively short period from July to October.

In contrast, generally higher flows and more frequent high-flow events persisted during the second half of 2022, and even into 2023. This also meant that elevated nitrate concentrations and therefore nitrate exports from the catchment occurred for a substantially longer period than in 2021. Again, this was more pronounced in Piakoiti Stream compared to Piakonui Stream. This example underlines that in order to minimise nitrate exports, one needs to minimise stocks of nitrate potentially available for mobilisation at the time the catchment gets wetted up, whenever that may occur during the year.

It is also noteworthy that regular monthly sampling schemes, as typically run by regional authorities, fail to accurately capture nitrate nitrogen dynamics in highly dynamic streams like the two monitored here. Due to their infrequent occurrence, concentration peaks tend to be underrepresented in such datasets, resulting in an underestimation of real loads leaving the catchment.

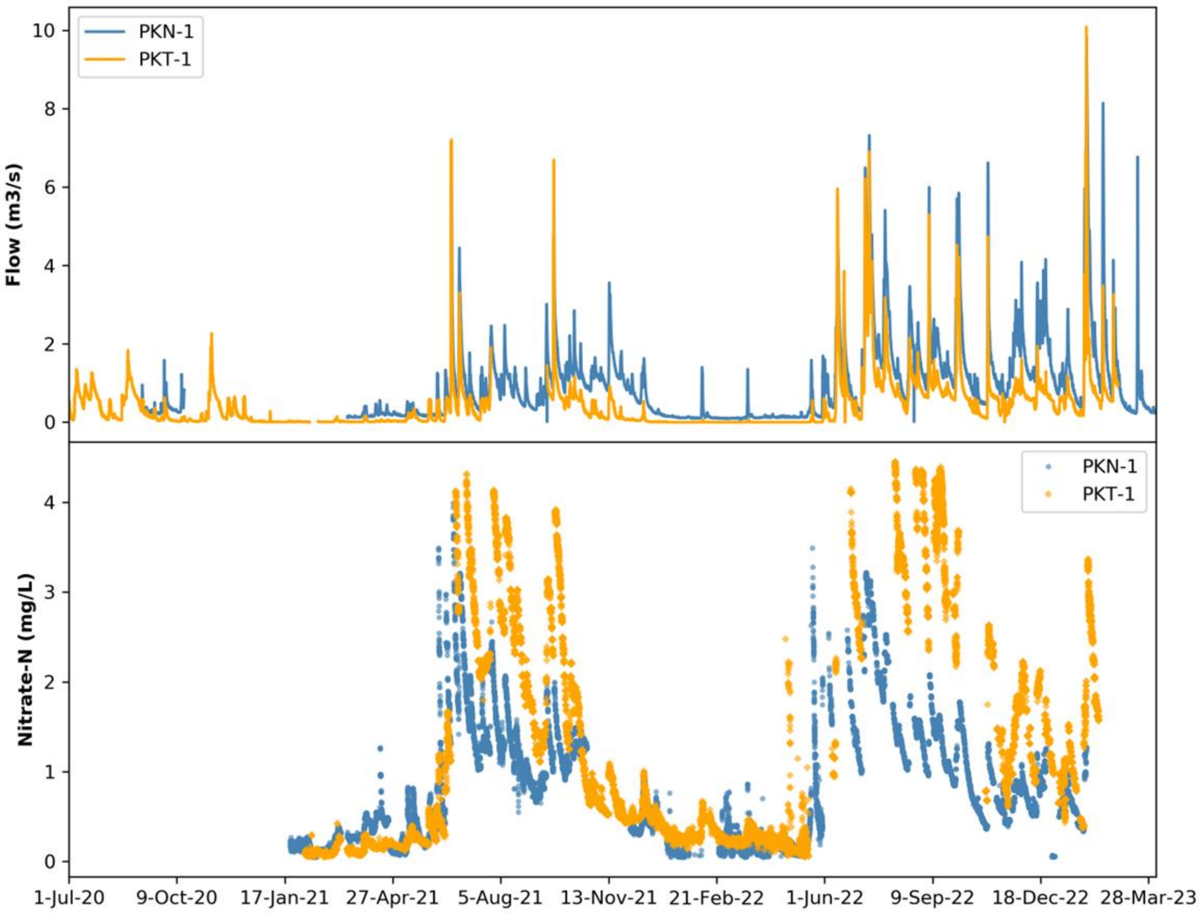


Figure 17: High-frequency stream flow (top) and nitrate nitrogen concentrations (bottom) at the Piakonui (PKN-1) and Piakoiti (PKT-1) Streams.

2.2.5 Integrated surface water/groundwater modelling

Modelling tools commonly applied in New Zealand have to date typically either focussed on surface waters or the groundwater system. The comparatively high data density achieved in the Critical Pathways programme enabled Lincoln Agritech scientists to set up an integrated surface water/groundwater model for the Piako headwater catchment (Durney, under review). The model structure was informed by the monitoring network established within the catchment, geophysical information (SkyTEM flights in 2019), and LiDAR surveys. The model was able to represent the spatial and temporal patterns of stream flow, nitrate concentrations, and groundwater elevations during the five-year simulation period from 2017 to 2022. Land management data was derived from SWAT routine procedures informed by local data from six farms collected for FARMAX/Overseer modelling by agricultural economist Phil Journeaux.

This modelling study suggested that average nitrate nitrogen source loads (i.e. losses from the land) amounted to 16.4 kg ha^{-1} yr^{-1} in the Piakonui sub-catchment and 21.8 kg ha^{-1} yr^{-1} in the Piakoiti sub-catchment. The difference between the sub-catchments is partly due to greater losses from Piakoiti sub-catchment farms, but also reflects that the Piakonui sub-catchment benefits from substantial flow of relatively clean water arising from the bush-clad Maungakawa and Te Tapui volcanic cones.

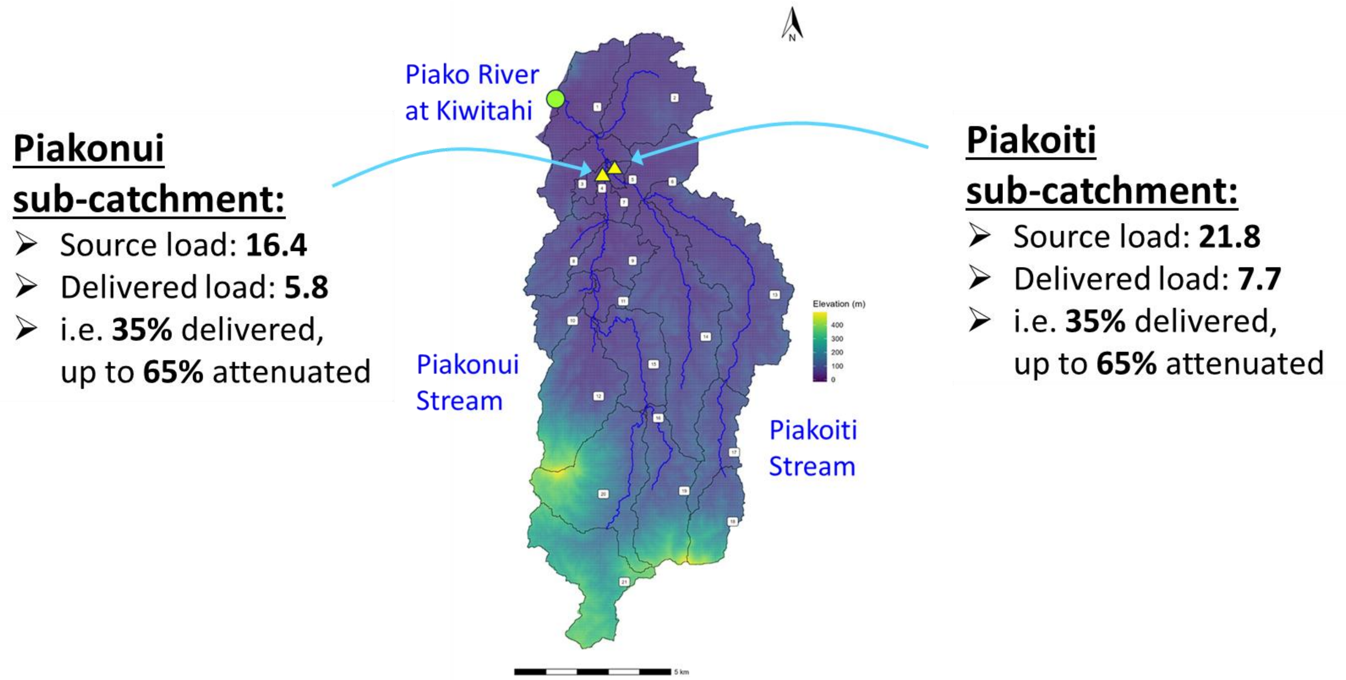


Figure 18: Nitrate loads estimated by integrated surface water/groundwater model (in kg NO_3-N ha^{-1} yr^{-1}).

In both sub-catchments, the load delivered to the stream monitoring site equated to only 35% of the load estimated to have been lost from the land (Fig. 18). Two factors could potentially explain this 65% discrepancy: a long travel time between the land and the stream monitoring site and/or substantial attenuation (via denitrification) occurring during transfer. Denitrification is the microbial process of reducing nitrate and nitrite to gaseous forms of nitrogen, principally nitrous oxide and dinitrogen gas.

Long hydrologic lag times can be excluded as explanation (see Section 2.2.3), but biogeochemical lags are a possibility. They occur if immobile organic nitrogen accumulates in the soil zone during extended periods of nitrogen balance surpluses, and by doing so increases the pool of soil organic nitrogen. Gradual mineralisation of this accumulated relatively easily mineralisable pool releases mobile nitrate back into the soil solution, potentially providing significant amounts of nitrate even after nitrogen balance surpluses have been reduced. This process has been observed in North America and Europe, but it is currently not known if it is also relevant in New Zealand with a significantly differing history of land use intensities.

Assuming that neither hydrologic nor biogeochemical lags are significant, natural attenuation through microbial denitrification becomes the most likely explanation for the low delivered load. While 65% attenuation is a very high value, around 50% attenuation have previously been found in the neighbouring Toenepi Stream catchment (Woodward et al., 2013). Based on nation-wide modelling, an average of 65% denitrification has also been reported for Danish groundwater systems (Hansen et al., 2024). Moreover, groundwater sampling in the catchment showed that potential for denitrification does exist in the groundwater system (see next section). However, as no dedicated attempts to quantify groundwater denitrification were carried out, 65% should be considered an upper limit for natural attenuation in these two sub-catchments.

It is noteworthy that this percentage was identical for both sub-catchments. This indicates that the modest differences in land use and natural characteristics were not strong enough to cause a difference in sub-catchment scale attenuation rates.

2.2.6 Groundwater nitrogen concentrations

In February 2021, we sampled 14 farm supply wells and had the water analysed for a wide range of water constituents. The results were provided to the well owners at the time, and only well numbers are shown in Fig. 19 to maintain privacy.

Nitrate nitrogen concentrations ranged from near zero (6 wells) up to approx. 2.5 mg l^{-1}, i.e. well below the currently still valid maximum acceptable value (MAV) for drinking water of 11.3 mg l^{-1}. This long-established MAV relates to the prevention of infant death from methaemoglobinaemia ('blue baby syndrome'). However, emerging evidence suggests a link between nitrate exposure above 5 mg l^{-1} during pregnancy to preterm birth and low birth weight, and an even lower MAV (possibly as low as 0.87 mg l^{-1}) has been suggested to protect against colorectal cancer. It is noteworthy, that nearly two thirds of the sampled wells (nine out of 14) would even meet this stringent requirement.

While DO could not be reliably measured in these wells, the analysis of a few redox-sensitive analytes (Dissolved inorganic carbon, Fe, Mn) indicated that the groundwater with the lowest nitrate concentrations had a reduced redox status. Such oxygen-depleted conditions are a prerequisite for microbial denitrification to occur. Accordingly, it is to be assumed that the natural attenuation process of microbial denitrification has lowered the nitrate concentration of root zone leachate to the very low levels found in these wells.

Fig. 19 also illustrates that nitrate (NO_3-N) was the dominant form of nitrogen in the sampled groundwaters and ammoniacal nitrogen (NH_3-N) barely detectable. Organic nitrogen (estimated as Org-N = TN - NO_3-N – NH_3-N) was the dominant form of nitrogen in wells 1 and 3.

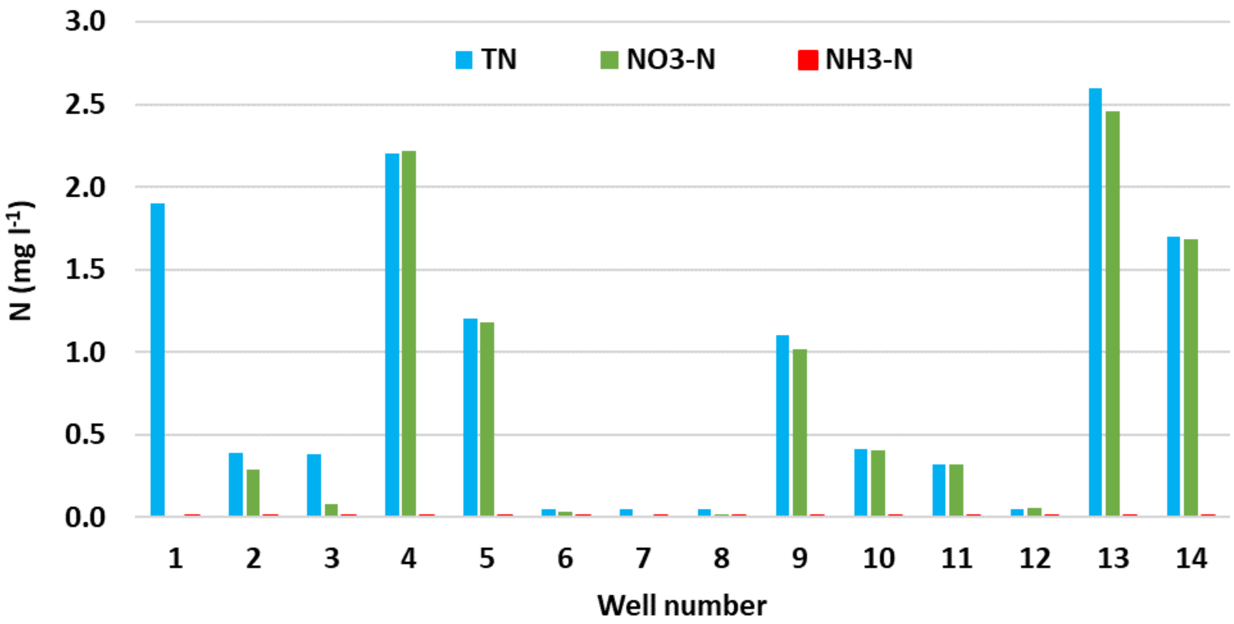


Figure 19: Total nitrogen (TN), nitrate nitrogen (NO_3-N), and ammoniacal nitrogen (NH_3-N) concentrations in farm supply wells (February 2021).

The fact that conditions inducing denitrification are not limited to relatively deep farm water supply wells is evident in data from a few dedicated shallow groundwater monitoring wells sampled in November 2022. The comparison of the nitrate nitrogen (Fig. 20, left) and dissolved oxygen (Fig. 20, right) concentrations illustrates very similar patterns (PM2-2 excepted). The data from wells PG3-1 and PB3-2 indicate that groundwater in less than 3 m below the ground surface can be oxygen-depleted, providing conditions suitable for microbial denitrification. Note that all three wells that were sampled at two depths showed a vertical gradient for decreasing nitrate and DO concentrations (apart from PM2-2 for DO). This suggests that sufficiently oxygen-depleted conditions to enable denitrification (approx. 2 mg l^{-1} DO) might also occur at these sites at greater depth.

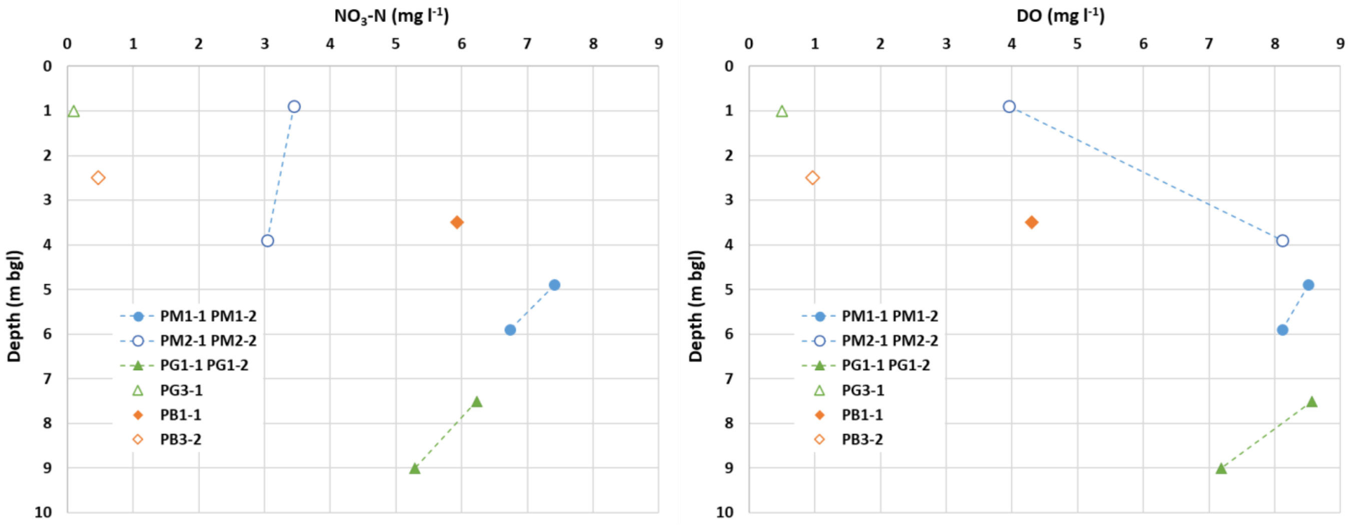


Figure 20: Nitrate nitrogen (NO_3-N) and dissolved oxygen (DO) concentrations in shallow groundwater monitoring wells (November 2022).

In summary, both types of groundwater sampling confirm that there is potential for nitrate reduction to occur within the groundwater system before the nitrate lost from the root zone is discharged into the Piakonui and Piakoiti Streams.

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.

This also applies to the area of particular interest to the Two Loops Catchment Group, although the non-agricultural land in its headwaters accounts only for 16% of the area. Nevertheless, the often-observed concentration differences between the Piakonui and Piakoiti streams reflect in parts the beneficial effect of substantial discharge of high-quality water from the largely bush-clad peaks of Maungakawa and Te Tapui into Piakonui Stream. In contrast, Piakoiti Stream receives very little water from Te Tapui and largely arises at lower elevation where rainfall is lower and therefore provides less dilution for agricultural contaminants. This means that 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 the Piako River catchment. 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. 21) 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).

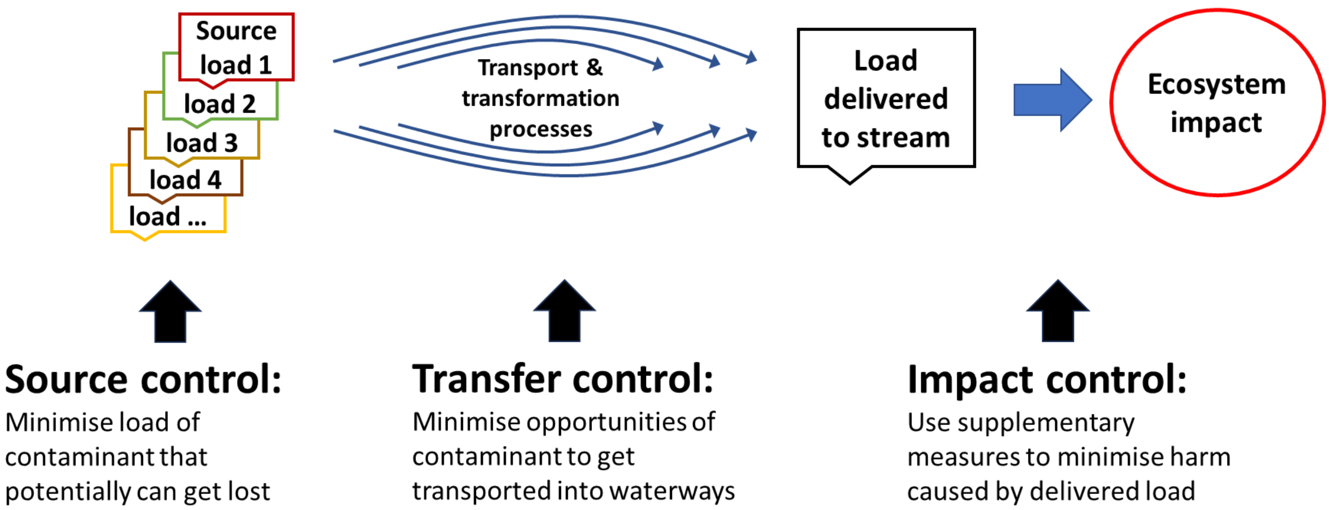


Figure 21: Schematic illustrating control options potentially available to reduce ecosystem impacts of water contaminants.

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