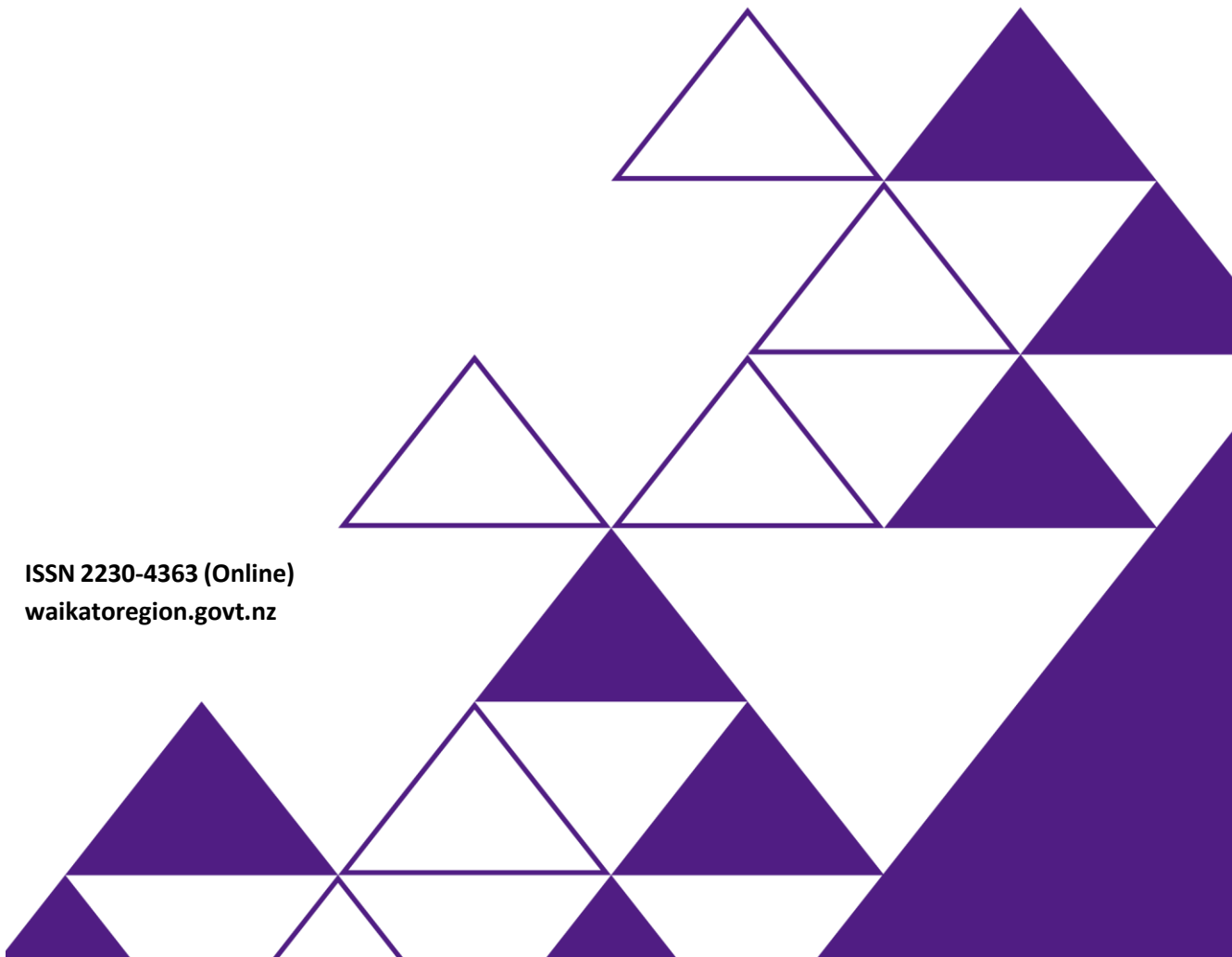


Flow requirements for the Piako River

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Executive summary

Water takes from streams and aquifers supply irrigation, industry and towns. Deciding how much water should be allocated, and when restrictions should come into force, will require information on flows required to sustain stream ecosystems. Oxygen is vital for the animals and plants living in streams. Lower flows can reduce oxygen in low-gradient streams, like the Piako River, where monitoring to date demonstrates low oxygen levels and high temperatures. Therefore, oxygen and temperature should be considered when setting limits on water use in this catchment.

Options were developed to inform the setting of minimum flows and allocations limits in the Piako catchment. This report builds on the previous reports by NIWA (commissioned by council), focussing on oxygen and temperature and how these respond to flow. The same data were re-processed using additional quality controls and supplemented with newer data. The previous authors decision to base the study on observational data increases our dependence on capturing oxygen levels during periods of extreme low flow. Fortunately, data were collected in 2013 and 2021, which turned out to be some of the driest years on record.

The data revealed a decline in oxygen with flow for most sites, including Piako at Paeroa-Tahuna Rd, Piako at Kiwitahi, Waitoa at Waharoa and Waitoa at Puketutu. The previous NIWA study already demonstrated that the higher energy headwaters (Piakonui Stream) sustained high oxygen levels, regardless of flow. Another site where oxygen showed little response to flow was the Waitoa River at Mellon Rd. For this site, I expect that oxygen would decline at flows less than that observed.

Water temperature was found to show little or no response to flow at most sites. For several sites, temperature improved at lower flows, which may reflect an increasing portion of groundwater as surface flows recede. Other land management, including riparian shading, must change to achieve cooler temperatures and improved ecosystem health.

Three options were developed for setting minimum flows in the regional plan, including:

- Option 1 – minimum flow at a target oxygen level, with 3 targets to choose from
- Option 2 – minimum flow allowing for a 10% reduction in oxygen
- Option 3 – minimum flow allowing pre-existing water use

The resulting flows for each option at each site are detailed in Table 5. From the many options presented, I recommend revised minimum flows for the Piako catchment, including:

1. ***A minimum flow of 0.50 m³/s, or 70% of Q5nat (0.71 m³/s), set at Paeroa-Tahuna Rd on the Piako River (749_15).***
2. ***A minimum flow of 0.14 m³/s, or 70% of Q5nat (0.20 m³/s), set at Waharoa on the Waitoa River (1249_38).***
3. ***A minimum flow of 0.7 m³/s, or 63% of Q5nat (1.12 m³/s), set at Mellon Rd on the Waitoa River, but with water use restrictions triggered at Waharoa (1249_38) using a correlated flow of 0.14 m³/s***

These minimum flows are generally lower than the minimum flows that were specified in the regional plan (typically 90% of Q5) but fall short of allowing for all the water already allocated. The river would still be over-allocated.

The final decision on setting minimum flows and allocation limits for the Piako will be made as part of the review of the Waikato Regional Plan. There are a range of issues to consider when setting minimum flows, with Policy 1 setting out those matters we *should have particular regard to*. This report addresses a subset of those issues, including stream ecology and water quality. It is one step, rather than the final step, in deciding limits on water use for this catchment.

1 Introduction

A review of the Waikato Regional Plan is underway, triggered by the National Policy Statement for Freshwater Management 2020. Prior to this, a review of the minimum flows was already planned for the Piako and Waihou rivers.

The regional plan has minimum flows specified for most rivers, including the Piako which ranges from 70% to 95% of the Q5¹ flow. The limit of 90% of Q5 applies to most water takes in the catchment (from [Table 3-5](#) in the regional plan). The magnitude of Q5 is calculated outside the plan, enabling it to be updated periodically (e.g. in response to climate change). The primary water allocation is then based on Q5 minus the minimum flow (from [Table 3-5](#) in the regional plan). In addition to the primary allocation, the plan allows an additional secondary allocation of water that has a lower reliability (SW-D priority, Policy 18) and, by default, brings the total allocation to 30% of Q5 (Policy 2). The allocation limits for some catchments were scheduled for review, with [Method 3.3.4.9](#) specifically nominating the Piako catchment for investigation.

A series of previous investigations were completed by NIWA scientists for the Piako River (see Section 2), and the last report brings that information together (Graham et al. 2018). The present study builds on that work, revisiting the same datasets and adding more recent data.

Oxygen and temperature are key issues for the Piako River. For example, the state of oxygen was assessed for the Waikato region, with some Piako sites in the worst band for oxygen (D Band) and many sites in C Band for temperature (Figure 1). This is relevant for setting limits on water use because flow increases reaeration through turbulent mixing (Cox, 2003; Demars and Manson, 2013; Ulseth et al. 2019, Hall and Ulseth, 2020). The low gradient of the Piako River exacerbates this (see Section 3 and 5).

There are a range of issues to consider when setting minimum flows, with [Policy 1](#) setting out those matters *we should have particular regard to*. This report addresses a subset of those issues, including stream ecology and water quality. It is one step, rather than the final step, in deciding limits on water use for this catchment.

The objective of this report is to develop recommended options for setting limits on water use in the Piako catchment, based on the information provided in the NIWA reports and subsequent monitoring. This report is primarily intended to support limit setting for abstractive water use. Changes to high flows (e.g. from water storage and river regulation) are not covered. Run of river takes typically do not have the capacity to alter high flows, and the impacts of dams and water harvesting are covered by other rules in the plan.

¹ Q5 is the 7-day annual low flow with a 1 in 5, or 20%, chance of occurring in any given year. It is a drier-than-usual year. Each annual low flow is calculated for the July to June water year to avoid splitting a single summer across two calendar years. The use of a 7-day moving average improves certainty, compared to the use of instantaneous flows or 1 day means.

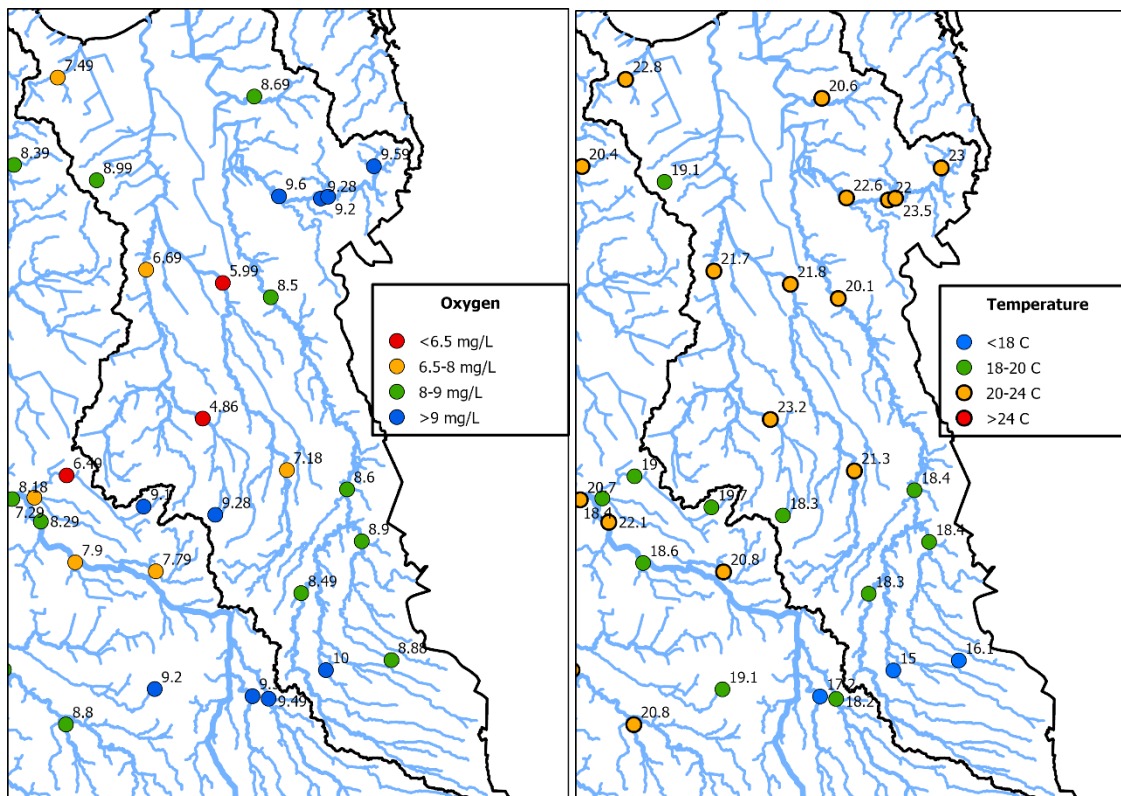


Figure 1 Oxygen and temperature attributes for the Piako catchment and broader Hauraki area. The oxygen attribute is the 10th percentile of spot measurements over 5 years to 2017. Likewise for temperature, except using the 90th percentile. Red dots are D band attributes, representing the most stressful conditions. Methods are as described in Wilding (2024).

2 Previous Investigations

Catchment investigations for the Piako River were scheduled in the regional plan (Plan Table 3-4A), triggering the original NIWA investigations. An investigation of the oxygen-flow and temperature-flow relationships was completed in 2014 (Franklin, 2014). This provided flows “that approximate... oxygen” for ecosystem health, based on the observed relationship between flow and oxygen concentrations measured over two summers. However, the report recommended additional monitoring be completed to increase certainty for limit setting. In response, additional oxygen monitoring was funded by Waikato Regional Council (Graham et al. 2018).

Armed with additional data, the subsequent report provided updated estimates of flows “that approximate... oxygen” (Table 1). The report stopped short of labelling these as flow requirements, stating “it is not possible to provide robust minimum flow limits from current data”. That report recommended further investigation, including:

- Modelling flow requirements in the tidal section of the river
- Additional monitoring higher in the catchment to understand the role of high flows

This report is then the third in the series, with more than 10 years now elapsed since council initiated minimum flow investigations for the Piako. As demonstrated in this report, uncertainty has been substantially reduced with the collection of more data and by applying a higher standard of quality control to the previously collected data.

The NIWA reports provided flows associated with oxygen concentrations as specified in the NPSFM (Davies-Colley et al. 2013). However, the NPSFM only adopted oxygen as a limit setting

attribute in rivers downstream of point discharges (NPSFM Table 7). I therefore interpret the compulsory attribute for oxygen as intended to regulate point discharges, rather than water takes. There is a second oxygen attribute that applies to all rivers (NPSFM Table 17), but it is not a compulsory attribute for limit setting (instead triggering action plans). These thresholds therefore provide relevant and useful guideline values for the purpose of setting limits on water use, rather than compulsory targets.

Table 1 Flows associated with oxygen levels for the 6 sites in the Piako catchment, reproduced from Table 7 in Graham et al. (2018). Flow is in m³/s and sites are as listed in Table 1. The oxygen levels represented by the “NOF band” A/B, B/C and C/D are 8, 7 and 5 mg/L.

Site	NOF band		
	A/B	B/C	C/D
Kiwitahi	-	-	0.25
Mellon Rd	-	-	-
P-T Rd	-	1.4	0.5
Piakonui	-	-	-
Puketutu Rd	0.8	0.5	0.3
Waharoa	-	0.6	0.25

3 Hydrology of the Piako River

Water resources in the Piako catchment are limited, compared to the neighbouring Waihou River, which has higher specific discharge (Figure 2). The mean annual low flow for the Piako is about 1.7 m³/s (below Waitoa-Piako confluence), compared to 23 m³/s for the Waihou River at Tirohia, despite similar catchment areas (948 km² and 1190 km² respectively).

The Waihou River benefits from more rainfall captured by the Kaimai Ranges, plus rain in the Mamaku Ranges that soaks deep into pumice soils, recharging large ignimbrite aquifers (Hemmings et al. 2022). In contrast, the Piako catchment has few mountains high enough to catch more rain (Figure 3). In the hill country feeding the Piako River, a higher proportion of the rain that does fall on the clay soils and shallow greywacke will discharge rapidly via shallow groundwater pathways (Stenger, 2022).

The small baseflow of the Piako River limits its ability to support both stream ecosystems and water takes (e.g. irrigation, industry, town supply). The amount of water already allocated from the Piako River exceeds the primary and secondary allocation limit specified in the regional plan (see Figure 31 in Koh and Jenkins 2022).

To demonstrate the realised flow alteration from this consented use, measured flow was compared to naturalised flows, which were estimated by adding back in metered water use² during the 2020 drought period (Figure 4). There is one reservoir in the Piako catchment which supplies Morrinsville. This water take required special treatment for reconstructing naturalised flows. The difference between reservoir inflows and outflows was used to provide a more accurate estimate of flow-regime alteration than the metered rate of take from the reservoir (see Appendix 1 in Section 13).

The flow at Paeroa-Tahuna Rd is reduced more by water use than the Kiwitahi site (Figure 4), because most of the consented water use occurs downstream of Kiwitahi. In both cases, the

² Note, the location and quantity of return flows were not included in this calculation.

flow reduction is most pronounced under low-flow conditions, while the flood disturbance regime is left largely intact (Figure 4).

Upstream of the Kiwitahi site, most of the water allocation is permitted use (e.g. stock drinking water). These takes are not metered, so I do not know how much water is taken at any point in time. Council uses an estimate of *peak* summer use that was developed for water allocation purposes (Brown et al. 2007). This method was not developed for reconstructing a flow time-series. For example, it does not account for the likely drop off in use during cooler weather (Section 2 in Brown et al. 2007). I have plotted the total of permitted takes separate to metered use, shown as a green line in Figure 4. The green line should be treated as an upper bound on potential effect of permitted use, rather than a naturalised time series.

Understanding the consequence of water use for river flow can benefit from an understanding of the hydrogeology of the catchment. For example, oxygen reaeration is more likely to be a limiting factor in low gradient streams. Because the plains are a sinking [rift valley](#), the rivers here have a low gradient and lack the energy to carry sediment. The pre-historic flow path of the Waikato River deposited sediment in this rift valley, building up the Hauraki Plains, before returning to its present-day path in the neighbouring catchment. The Piako and Waihou rivers were then left to rework this sediment, with the Waihou having incised through these deposits more rapidly. For example, the Waitoa is now perched some 20 m above the neighbouring Waihou channel at Gordon. The recurrent layers of peat in bore logs also reveal the past comings and goings of wetlands on the plains, like the modern day Kopuatai peat dome. Peat naturally accumulates in the absence of oxygen that would otherwise fuel decomposition of the plant matter.

The low relief of the rift valley also allows the tidal influence to extend well inland, with the highest tides pushing more than 40 river km up the Piako River (tide detected at Paeroa-Tahuna Road). The northern area of the plains was inundated when sea levels were higher, depositing layers of marine clays that now cap the Hauraki Northern Aquifer and limit surface water - groundwater interaction. These marine clays were deposited by a Holocene incursion (Hemmings et al. 2022) that correspond with the light-coloured area in Figure 5.

Coarse sediments were deposited by rivers upstream of the marine incursion, forming the Southern Hauraki Aquifer. High class soils developed here (LUC 1-2) that now support intensive agriculture and associated industry (e.g. dairy factories). With higher temperatures and lower rainfall, agriculture on the Hauraki Plains is more dependent on water resources to offset days of soil moisture deficit (Chappel, 2014).

Those alluvial deposits also allow the Southern Hauraki Aquifer to contribute more to river flow here than the Northern Hauraki Aquifer, as predicted by the groundwater flow model³ that was developed for the Hauraki Plains (Hemmings et al. 2022). Within the Piako catchment, most of the Southern Hauraki Aquifer is drained by the Waitoa tributary (Figure 5). The Waitoa produced more than double the flow per catchment area under low-flow conditions, compared to hill country tributaries upstream of the Waitoa confluence (see Section 9).

The Southern Hauraki Aquifer produces younger water, that feeds the Waitoa River (Stenger, 2022). Water from the Waitoa was aged as younger than both the Piako (upstream of the Waitoa confluence) and the Waihou rivers, under low-flow conditions (mean transit of 20, 32 and 28 years respectively, Stenger et al. 2022). The younger age indicates that the Southern Hauraki Aquifer is a smaller aquifer than the deep ignimbrite aquifer feeding the Waihou River, hence the higher baseflow of the Waihou River.

³ Hemmings et al. (2022) developed the Hauraki groundwater model and reported the *probability* of gain or loss across the catchment. Sung Soo Koh re analysed the model output for the predicted *magnitude* of gain or loss. These predictions are considered suitable for identifying where the potential exists for greater gains.

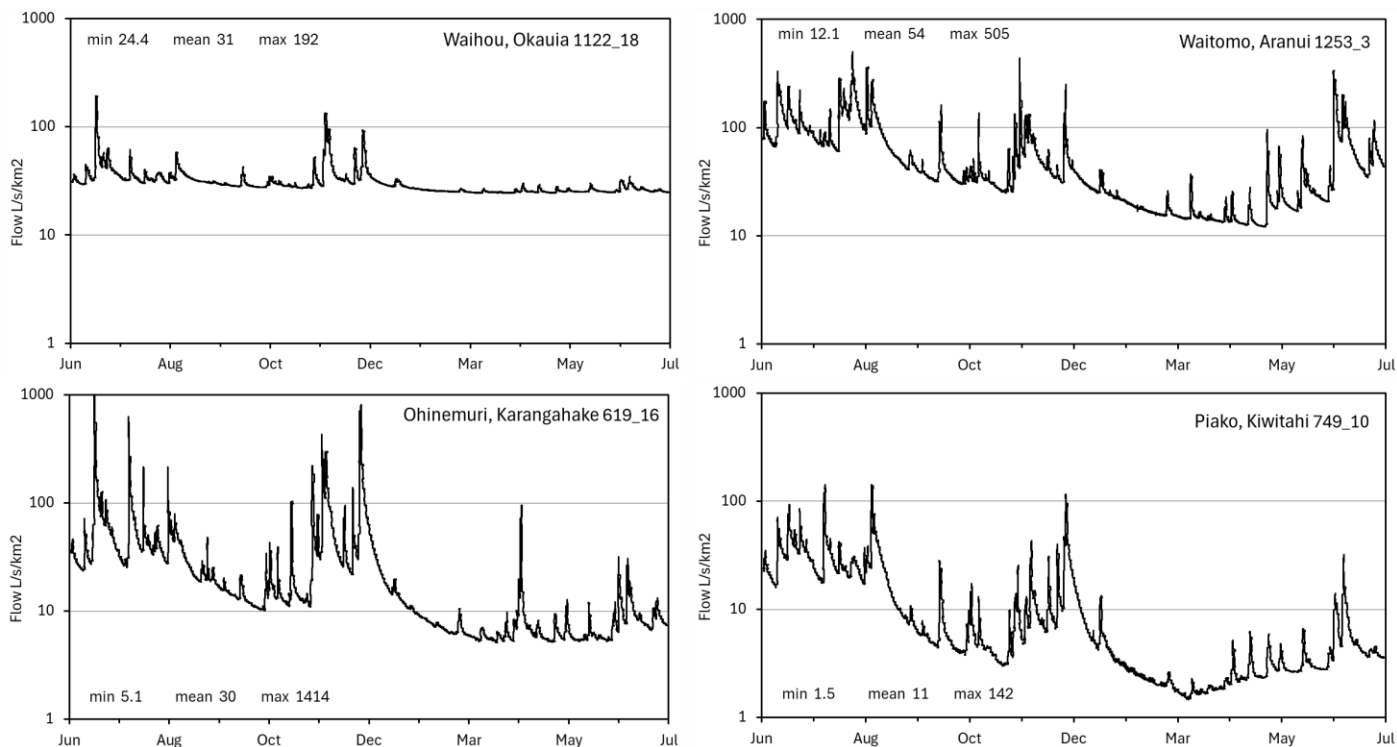


Figure 2 The contrast in flow regimes between the Piako (bottom right) and other rivers draining different climates and rock types. For direct comparison, all sites are plotted over the same 2018-2019 water year (x-axis), chosen for having typical rainfall, and flow is standardised per unit catchment area (L/s/km²) on the same log-scale (y-axis). This displays instantaneous flow (i.e. not a daily mean or 7-day mean flow) from rated water-level recorders.

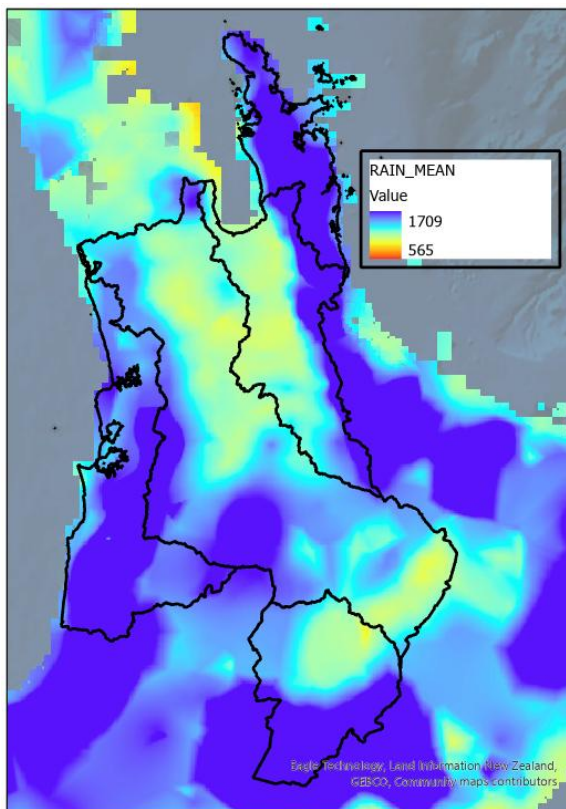


Figure 3 Rainfall in the Waikato region (mm/year). The Piako catchment drains the west side of the Hauraki Plains, which is drier than the ranges (e.g. 1063 mm/year at Maukoro Landing Rd [749-12](#)).

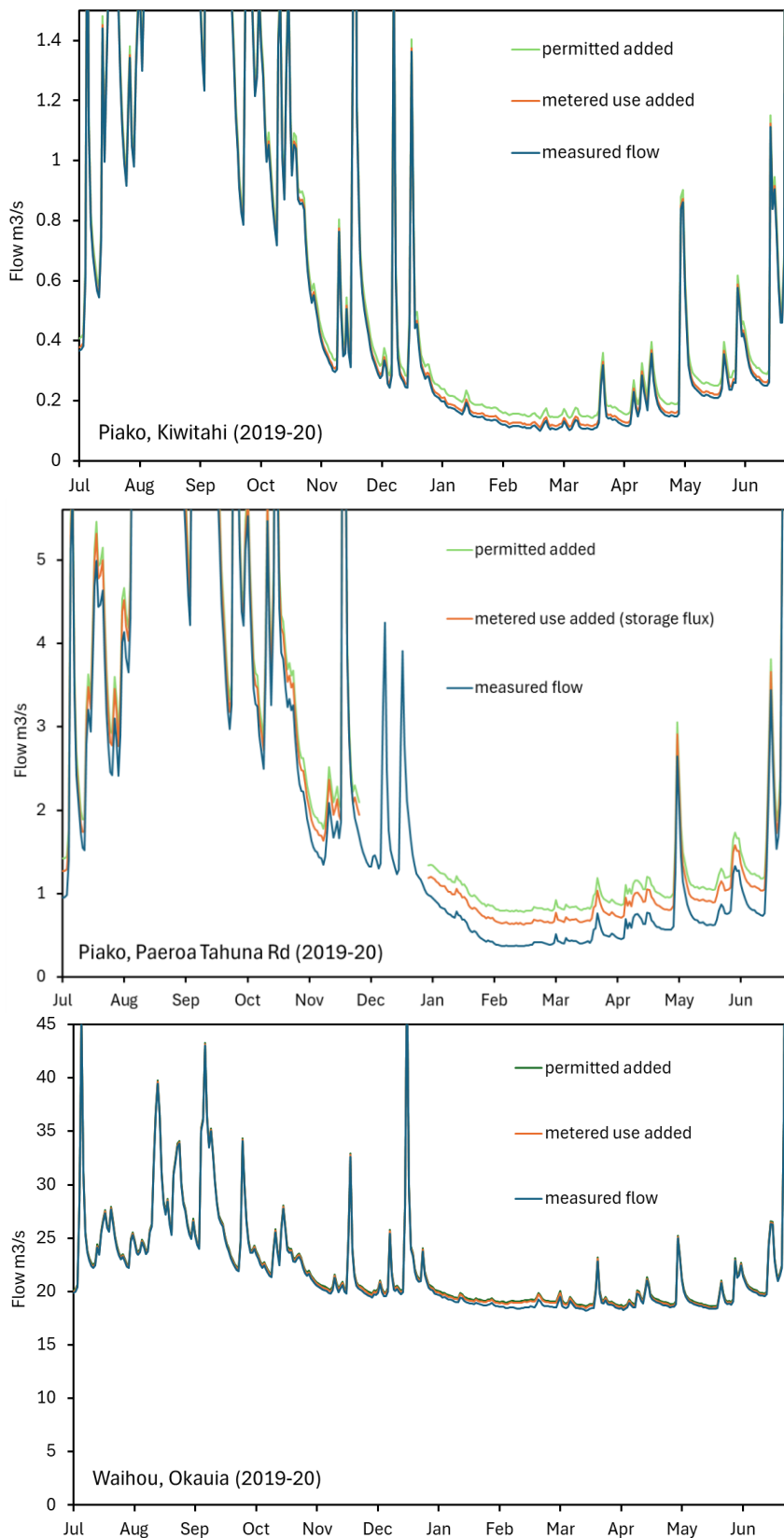


Figure 4 The effect of water use on river flows was estimated by adding back the metered water takes for each day (orange line) during the drought of 2019-2020. Permitted allocation is plotted separately (green line) because it is not a measured time series. Instead, estimated peak annual use was applied to all days. The y-axis is scaled to twice the median flow for each site (m³/s), which is a different scale to **Figure 2**.

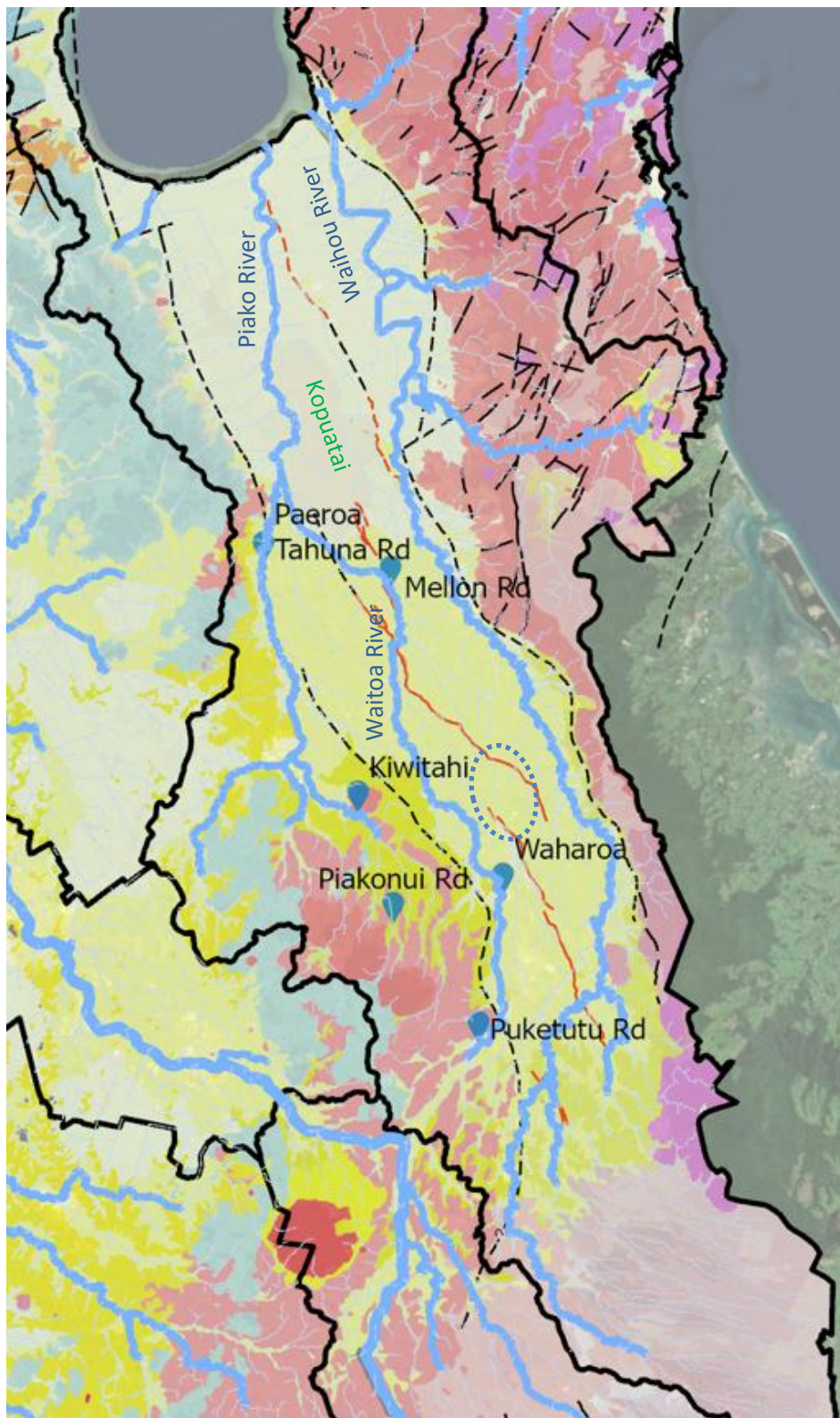


Figure 5 The Piako River flows across the sinking rift valley that is bounded by fault lines (dashed lines concealed faults, orange lines active faults). Marine clays separate the river from the Northern Hauraki Aquifer where the rivers are tidally influenced (light coloured area north of Mellon Rd). Land units are delineated from QMAP geology. Oxygen monitoring sites are mapped that are included in this study (excluding tidal sites). The dotted circle between faults is where concentrated groundwater inflows were detected (Waihekau Stream, Section 9).

4 Ecology of the Piako River

Aquatic plants are important both in terms of the causes and consequences of low oxygen. Plants are widespread in the Piako catchment and typically covered 20% to 90% of the stream bed in 2021 surveys for this study, which is consistent with previous studies (Matheson and Wells, 2017). The seasonal growth of aquatic plants can influence oxygen levels in rivers by consuming oxygen night and day (respiration) and producing oxygen by day (photosynthesis).

Plants can only reach high biomass where the disturbance regime allows it. Disturbance is a product of both flow and slope, with more flow needed to achieve the same shear velocity in low-gradient streams. For example, floods three times the median flow can dislodge algae in streams steep enough to support benthic algae (Clausen and Biggs, 1997), compared to flows seven times the median flow associated with disturbance in streams gentle enough to support aquatic plants (Riis and Biggs 2001). The low gradient of the Piako is expected to limit the ability of the flashy floods to dislodge plants. This can allow aquatic plants to reach a higher biomass, especially where a lack of shade allows rapid regrowth between disturbance events (Rutherford et al. 2021, Wilding 2016). This then provides a feedback loop, where the low gradient allows the development of a high biomass of aquatic plants that increases channel roughness, further increasing depth and reducing velocity (Madsen et al. 2001, Champion and Tanner 2004).

Aquatic plants recorded for this study in 2021 were *Ceratophyllum*, *Myriophyllum*, *Potamogeton*, *Egeria* and *Elodea*. Emergent plants included reed sweet grass, watercress, water piper and water speedwell, plus floating duck weed. The native charophyte *Nitella* was observed in Piakonui Stream and detected in eDNA samples from Paeroa-Tahuna Rd (Appendix 1).

Aquatic plants increase oxygen levels by photosynthesis during daylight hours, increasing oxygen supply when fish need it most, given their oxygen requirements increase with temperature (Clarke and Fraser, 2004). Plants themselves need oxygen to survive (Crawford 1992, Jampeetong and Brix 2009, Parveen et al. 2017, Zahra et al. 2021). Inadequate reaeration can then trigger a collapse of the plant biomass, which can then result in anoxia that is fatal to fishes (Wilding 2016). Bacteria continue consuming oxygen at levels too low to support plant respiration (Edwards and Rolley 1965, Morris and Schmidt 2013).

The Piako River and tributaries support diverse fish communities, which benefit from clear migratory pathways to the Firth of Thames. There are no waterfalls or engineered structures limiting access through the tidal section of the river. The first notable barrier on the mainstem is more than 60 km inland (upstream of Kuranui Rd, Morrinsville), where a 1 metre waterfall is expected to limit the distribution of inanga and smelt.

From the NIWA surveys (Franklin et al. 2013), fishes include tuna (shortfin and longfin eel), inanga and Cran's bully in the mainstems, plus banded kōkopu and torrentfish in some tributaries. Common smelt were reported in other studies (Meredith 1990, Robb 2011). Common bully were more often recorded in the lower catchment, with non-migratory Cran's bully in the upper catchment (note, these two species are often confused). Additional fishes recorded in the New Zealand Freshwater Fish Database since 2014 (accessed 18/12/2025) include a single giant kōkopu and several redfin bully caught in a forested tributary (Mangakahika Stream).

Environmental DNA (eDNA) samples were collected by Mike Lake (Tonkin+Taylor) for this study, including 9 sites in March 2021 (see Appendix 1). The samples confirmed that previously recorded fishes were still present in 2021, including common smelt. In addition to confirming torrentfish occur in the tributaries, they were also detected in the mainstem from eDNA samples collected in May (not in January, February or March samples from Paeroa-Tahuna Rd).

New species were detected in 2021 using eDNA that were previously unrecorded, including shortjaw kōkopu and kōaro in one tributary (Piakonui tributary at Piakonui Rd), plus speckled longfin eel in the mainstem (Piako at Paeroa-Tahuna Rd). However, the eDNA detection rates were low for these 3 species, so represent unconfirmed records. Our budget limited the replication to 3 samples, which is less than the 6 replicates recommended by Smith et al. (2024). Joshua Smith was able to confirm the presence of kōaro, having previously caught one upstream⁴ of the Piakonui site where eDNA was sampled.

Detection of grey mullet in eDNA samples from the Paeroa-Tahuna Rd site (March to May samples) extends their recorded distribution into wholly freshwater parts of the Piako. Previous reports of grey mullet were limited to saline areas, together with yellow-eye mullet, yellow-belly flounder and parore (Meredith 1990). These marine wanderers can move up and down the river with the tide. Their predators will sometimes follow, including a pod of [dolphins seen in 2020](#) as far upstream as Kerepehi (some 15 km inland). Fur seals were reported even further up the Piako, with [sightings in 2021](#) some 90 km inland, and are known to [feed on tuna](#).

Other notable fauna detected in eDNA samples were kōura (freshwater crayfish), freshwater jellyfish, shrimp, sponge and kākahi (freshwater mussel), with the latter visibly abundant in the mainstem at Paeroa-Tahuna Rd (Figure 6).

Macroinvertebrate communities were described by Pingram et al. (2023). The Piako catchment had a high proportion of stream length below the national bottom line for macroinvertebrates (as set in the NPSFM 2020). Low oxygen and high temperature likely contribute to stress on macroinvertebrates (Haidekker 2016).

Koi carp were introduced to the Piako River at least ten years ago (Bartels, 2015) and are now common. Koi were detected in 2021 eDNA samples at the lowest sites (Piako at Paeroa-Tahuna Rd and Waitoa at Hapai Rd), along with other introduced species, including brown bullhead catfish. Goldfish and *Gambusia* dominated eDNA readings, from samples collected January to May 2021 at Paeroa-Tahuna Rd (followed by native shortfin eel). The eDNA results also detected birdlife, with introduced mallard dominating the bird signature at Paeroa-Tahuna Rd (followed by native pūkeko, white-faced heron and black shag).

Introduced rudd and tench were detected in some eDNA samples with a low number of reads. Rudd have been caught in the Topehahae Stream downstream of the Te Miro reservoir, along with perch (New Zealand Freshwater Fish Database, accessed 18/12/2025).

Trout were *not* detected in any eDNA samples from the Piako, despite their abundance in the neighbouring Waihou River. Of the many possible constraints, high temperature and frequent flood disturbance likely prevent rainbow trout from forming self-sustaining populations in the Piako River (see Fausch et al. 2001).

The Kopuatai wetland is located in the Piako catchment. Kopuatai includes New Zealand's largest restiad bog and is listed under the RAMSAR convention because of its international significance (Cromarty and Scott 1995). Raised peat domes are defined by the lack of river influence, instead fed by rainfall. The Piako River skirts around the peat dome (Figure 5), with tidal sections of the Piako receiving outflows from some 86 km² of bog. The load of dissolved organic carbon draining from the peat dome contribute to the oxygen demand in the receiving river (Abell and Doucet 2024, Hicks and Bell 2018).

The eastern fringes of Kopuatai transition to some 17 km² of swamp habitat that are distinguished from the bog by direct river influence. This allows different plants to grow, with the swamp area dominated by introduced crack willow, in contrast to the manuka and endemic jointed rush of the restiad bog (Cromarty and Scott 1995). Black mudfish are found around

⁴ 80 mm kōaro caught 3 March 2016 in Piakonui tributary about -37.826953 175.625697.

Kopuatai, with most records from swamp habitats (New Zealand Freshwater Fish Database, accessed 18 Dec 2025). There are also four records of mudfish from the wider Piako catchment (mostly wetland drains).



Figure 6 Freshwater mussel (*Echyridella menziesii*) were abundant in sandy substrates at the Paeroa-Tahuna Rd site, on the Piako River (photo February 2021).

5 A focus on oxygen and temperature for minimum flows

Flow is necessary, but not sufficient, to support stream ecosystems. The Waikato Regional Plan integrates the management of waste discharges and water use. Additionally, council's catchment management programme provides incentives for fencing and planting. Together, this provides integrated management to protect stream ecosystems from land use activities. In achieving more integrated management, it is necessary to set limits on specific activities and water use is one of those activities. This report therefore contributes to that broader management of stream ecosystems by informing the limits set on water use in the Piako catchment.

When setting limits on water use, the natural flow regime requires protection to support ecosystem health (Poff et al. 1997). That is why the regional plan contains rules to protect both high flows (e.g. from damming and water harvesting) and low flows (e.g. from run of river water takes). This report focuses on the effects of water use on low flows. Existing water use in the Piako catchment has a greater effect on low flows than high flows (Figure 4). The frequency, magnitude, duration and timing of high-flow events is largely intact.

In addition to the importance of high flows (e.g. spawning cues, sediment transport), there are many ways by which reduced low flows can impact stream ecosystems, not limited to:

- Habitat area for drift feeding fish and bioenergetics

- Depth required for migratory access/connectivity
- Spawning habitat requirements
- Dilution of pollution discharges
- Oxygen reaeration

Rather than delay decisions indefinitely while all possible methods are applied, it is necessary to make an informed decision on water allocation limits based on the best attainable information. Previous investigations by NIWA focussed on oxygen and temperature to inform minimum flows for the Piako River. In my opinion, NIWA exercised good judgement in focussing on oxygen and temperature. This opinion is based on 25 years' experience investigating flow requirements of ecosystems using many different methods in many different settings, from Rocky Mountain streams to Bay of Plenty springs and braided rivers in the Hawke's Bay. The mechanism by which stream ecosystems are constrained by flow is best informed by the flow regime and channel forming processes of the streams in question, together with the animals and plants that live there (Sanderson et al. 2012).

Oxygen is a key issue for the Piako River (Figure 1) and this is relevant for setting limits on water use because flow increases reaeration through turbulent mixing (Cox, 2003; Demars and Manson, 2013; Ulseth et al. 2019, Hall and Ulseth, 2020). The low reaeration rates of the deep and slow-flowing water increase the dependence on flow in lowland rivers. The low gradient and limited shading of the Piako can also increase respiration (e.g. more aquatic plants, more deposition of organic matter). The formation of peat bogs (existing, drained and ancient peat layers) demonstrates the potential for low oxygen conditions to develop in this hydrogeomorphic setting, given the absence of oxygen necessary for peat to accumulate over time.

Salt water from the Firth of Thames pushes some 4 to 17 km upstream of the mouth (Graham et al. 2018). An estuarine turbidity maximum occurs where salt meets freshwater, flocculating the finest fractions and placing the water column in a holding pattern of tidal inflow and outflow (Carlin et al. 2015). A sag in oxygen occurs in the Piako River at about this point (Vant, 2011; Graham et al. 2018). The salt wedge and turbidity maxima are expected to be more pronounced at lower flows that have less energy to break up the salt wedge (Carlin et al. 2015).

Additionally, the freshwater high tide slows the river for tens of kilometres upstream of saltwater influence, further reducing reaeration at high tide (Wilding et al., 2012). Drainage from Kopuatai peat dome enters the tidal section of the river (Figure 5), and catchments draining large wetlands have a higher risk of anoxia (Błaszczak et al. 2023, Abell and Doucet 2024). Upstream of the tidal section, aquatic plants consume oxygen, which is offset only during daylight hours by their photosynthetic oxygen production.

These features create a river environment that is more sensitive to land use effects. Agricultural, urban and industrial discharges contribute organic matter to the Piako (Vant, 2023), which is more likely to settle to the bottom when velocity is low. The organic matter increases oxygen demand as it is decomposed by bacteria. Aquatic plants add to the oxygen demand in these low-gradient streams (see Section 4). The reaeration capacity of the river is not sufficient to offset that higher oxygen demand.

The consequence of low oxygen for aquatic life is exacerbated at high temperatures. Metabolic demand for oxygen increases with temperature (Clarke and Fraser, 2004), and eventually a temperature is reached where the increase in oxygen supply to an organism is exceeded by the increase in demand (Verberk and Bilton, 2013). The result is increasing risk of suffocation of aquatic life at higher temperatures, despite oxygen supply increasing with temperature (Verberk et al. 2011).

A lack of shade can increase water temperature, especially during summer when solar radiation is greater. Flow is expected to have a secondary effect on temperature, which can increase at

lower flows because cool water flowing from high elevations can reach equilibrium with local conditions over a shorter distance when travel times are longer. Cool groundwater inflows can decrease stream temperatures during summer. This can reverse the temperature-flow response if the cool inflows occur downstream of warm surface inflows (Wilding, 2018).

The distribution of fishes in the catchment demonstrates that migratory access is not a critical issue, especially for flow limits in the mainstem (Section 4). Protecting the stream bed from structures that create a barrier is important. But it is unlikely that streams will become too shallow for whitebait to swim through before the stream goes anoxic, given the low gradient of the channel creates deeper water at low flows (compared to high gradient streams). It is important that depths and velocities are suitable for feeding. But optimising food production for growth (i.e. bioenergetic methods) is secondary to having enough oxygen to breath. Oxygen is a fundamental requirement of stream ecosystems. The severe consequence of low oxygen provides certainty to regulators that restrictions on water use are required to avoid significant adverse effects.

6 Methods

6.1 Site details

Sites included in the NIWA study are listed in Table 2 and mapped in Figure 5. Flow statistics are summarised in Table 3, as calculated by Koh and Jenkins (2022). Observed streamflow includes the effect of water takes occurring at the time. For allocation decisions, it is preferable to use flow estimates that represent conditions without abstraction, so that the effect of proposed or existing water takes is not already embedded in the baseline. Koh and Jenkins (2022) therefore derived 'naturalised' Q5 estimates after accounting for water takes (run-of-river and groundwater takes).

The only site not covered by their hydrology report was the Piako River at Paeroa-Tahuna Rd. There is a reservoir upstream of Paeroa-Tahuna Rd, and accounting for the effects of reservoir operation was out of scope of that report. Therefore, flows were naturalised to account for reservoir operations in this report, and the methods are described in Appendix 2.

Table 2 Sites included in the NIWA study of the Piako catchment, reproduced from Table 1 in Graham et al. 2018. The years in which monitoring was undertaken is also indicated.

Site	Easting	Northing	2017	2013	2012	Flow
Piako @ Paeroa-Tahuna Rd (749_15)	1821514	5845214	✓	✓	✓	✓
Piako @ Kiwitahi (749_10)	1829552	5824019	✓	✓	✓	✓
Piakonui @ Piakonui Rd (753_4, flow from 749_10)	1832535	5814545	✓	✓		
Waitoa @ Mellon Rd (1249_18)	1832321	5843131	✓	✓		✓
Waitoa @ Waharoa (1249_38)	1841868	5817036	✓	✓		✓
Waitoa @ Puketutu Rd (1249_25, flow from 1249_38)	1839787	5804427	✓	✓		

Table 3 Flow statistics for study sites in the Piako catchment (1990-2020). Methods are described in Koh and Jenkins (2022) for removing the effect of water takes (estimated actual use) to produce 'naturalised' Q5 estimates. The Paeroa-Tahuna Rd* flows were estimated in this report (Appendix 1). Modelled MALF estimates were accessed via the [NIWA River Maps](#), with methods described by Booker & Woods (2014).

	Piako at Paeroa-Tahuna Rd	Piako at Kiwitahi	Waitoa at Waharoa	Waitoa at Puketutu	Waitoa at Mellon Rd	Piako inflow to tidal
Located ID	749_15	749_10	1249_38 (1249_15)	1249_25	1249_18	749_15 + 1249_18
REC Reach ID	3054261	3059826	3062720	3069125	3054693	
Catchment area km ²	539	108	123	68	409	948
Measured MALF m ³ /s	0.647*	0.182	0.220		1.023	1.67
Measured Q5 m ³ /s	0.450*	0.138	0.150		0.788	1.24
Naturalised Q5 m³/s	0.713*	0.172	0.197		1.12	1.83
Mean flow m ³ /s	7.12	1.70	1.49		4.86	10.98
Modelled MALF m ³ /s	1.01	0.24	0.28	0.21	0.97	1.98
Elevation m (2021 LiDAR, 2016 datum)		28.3	45.4		5.7	
Distance to sea km	46.4	80.4	99.5	120	50.5	
ALF Trend 1990-2020	-14% per decade	-10% per decade				
Total water allocated m ³ /s (at 28/3/2024)	0.353	0.046	0.117		0.313	
Limit on primary allocation (WRP Table 3-5)	10% of Q5nat	5% of Q5nat	5% of Q5nat		10% of Q5nat	30% of Q5nat
Secondary allocation	20% of Q5nat	25% of Q5nat	25% of Q5nat		20% of Q5nat	0% of Q5nat
Width m (3/2021)	13.2	6.5	3.6			
Depth m (3/2021)	0.75		0.29		>1 m	
Slope m/km (LiDAR)	0.4	1.3	1.5		0.7	
Submerged plant cover (3/2021)	27%		9%		1%	
Emergent plant cover (3/2021)	19%		19%		12%	

6.2 Monitoring

Oxygen and temperature data were collected by NIWA for Waikato Regional Council during the period 2012 to 2017 (Graham et al. 2018).

Additional data were collected by Tonkin + Taylor in 2021 for Waikato Regional Council. A YSI Exosonde (optode sensor) was deployed at Paeroa-Tahuna Rd, which was the only site where the intention was to capture seasonal variability. Shorter deployments of D-Opto loggers were made at other sites to capture short-term variability (typically 2 weeks). On the Waitoa River, one logger was deployed at Lansdowne Rd (1249_15), which was treated as an equivalent location to the site monitored by NIWA at Waharoa control (1249_38), (the Lansdowne site is 600m upstream of Waharoa control).

Methods are described here for the Tonkin and Taylor monitoring (see NIWA reports for the methods NIWA used). The instruments were calibrated in the lab using a two-point calibration before the initial deployment (0% and 100%). For the 0% calibration, NaSO₄ was dissolved into water and the sensor allowed to temperature stabilise for more than 1 hour before re-calibrating if necessary. The sensor was rinsed and soaked several times to remove residual NaSO₄ before being left for at least 12 hours for temperature stabilisation of both the 100% solution and the sensor. The 100% calibration was then completed with barometric correction. The calibration was then double-checked after re-saturating the same solution using 20 tips

from bucket to bucket. A single point calibration check at 100% was completed prior to any re-deployments with the same instrument.

The optode field meter used for validation checks was likewise calibrated using 2-point calibration at the start of the deployment season, then a single point calibration check at 100% in moist air on each day of use. Validation measurements were completed during site checks. To ensure temperature stabilisation of the field meter, the sensor was placed in the stream at the start of the site visit, and measurements taken at the end of the site visit in the main flowing part of the channel. This provides a check of the deviation between logger measurements and oxygen in the flowing part of the channel. Any deviation is therefore the combined error of any calibration drift and sensor fouling. Additional validation data was also provided from the monthly river monitoring completed by Waikato Regional Council for Paeroa-Tahuna Rd (Bates, 2021).

D-Opto loggers were also deployed for 1-week periods in 2019 and 2022 as part of the stream metabolism monitoring program (Pingram et al. 2020). These data were used to extend the record for Waitoa at Mellon Rd, Piako at Kiwitahi and Paeroa-Tahuna Rd.

Recovered instruments were downloaded and quality checks completed on the data. These quality checks included:

- Compare oxygen validation measurements from portable meters
- Identify sudden changes in oxygen associated with field visits (sensor checks and flow gaugings)
- Identify 'noisy' data that changed to a smooth trace after a site visit
- Days when the logger was not recording at the appropriate time to include minima or maxima (e.g. if the logger was deployed in the afternoon, the daily minima would have been missed)

Any suspect data were omitted from further analysis.

The effect of temperature change was removed by using oxygen saturation, rather than oxygen concentration, and the effect of barometric pressure changes also removed. This helps isolate the effect of flow reductions from air pressure fluctuation and seasonal changes in temperature.

The question of where to monitor minimum flows is better informed by understanding how flows are distributed throughout the catchment. Same-day flow measurements were completed at multiple sites in February 2025 by Environmental Monitoring Scientists from Waikato Regional Council (Table 4). Sites were chosen for flow surveys to investigate the distribution of groundwater inflows, targeting the Hauraki Southern Aquifer. Previous work had demonstrated that one tributary in particular - the Waitoa River - contributed disproportionately to the flow of the Piako River (relative to catchment area). Sites with an existing gauging record were the first choice, to help build up a sample size over time. Survey dates were chosen to target times of stable flow. Comparability between sites is improved if there is little change in flow over the course of the day.

Table 4 Sites used for concurrent gauging surveys in 2025. The first survey on 4 February 2025 extended to 17 sites in the Piako catchment, and the second focussed in on the Waitoa sub-catchment to better define areas of concentrated groundwater inflows, notably the Waiheke Stream.

Site # (LocatedID)	Stream	Site	Catchment area km ²	Flow m ³ /s 4/2/2025	Flow m ³ /s 27/2/2025
1249_38	Waitoa	Waharoa	122.5	0.187	0.131
1249_28	Waitoa	SH26	251.3	0.506	0.426
1113_5	Waiheke	SH26 Curtains Bridge	80.5	0.318	0.230
776_1	Piraunui	Bailey Rd	50.4	0.072	0.083
1249_18	Waitoa	Mellon Rd	408.0	0.988	0.852
617_1	Ohine	Wiseman Rd	34.2	0.061	0.042
1249_22	Waitoa	Paeroa-Tahuna Rd	480.2	1.130	0.884
3146_1	North Rd Drain	North Rd	4.5	0.009	
1275_1	Whakahoro Canal	Paeroa-Tahuna Rd	26.2	0.043	
1249_32	Waitoa	North Rd Bridge	519.1	1.460	
363_2	Mangahaumia	US Piako confluence	31.9	0.003	
749_5	Piako	Haumia Rd	432.5	0.463	
1111_7	Waiharakeke West	Horrell Rd	53.1	0.034	
1832_5	Riuohauraki	1351 Morrinsville- Tahuna Rd	3.8	0.002	
749_15	Piako	Paeroa-Tahuna Rd	538.7	0.614	
807_1	Pukenamu	Pioneer Rd	5.9	0.008	
749_21	Piako	SH27 West Rd	557.5	0.559	
1113_5	Waiheke	SH26 Curtains Br	80.5		0.230
1113_8	Waiheke	Waiheke Rd	64.9		0.200
1113_3	Waiheke	Diagonal Rd	59.8		0.181
1113_9	Waiheke	Wairere Rd	45.6		0.100
1113_10	Waiheke	Wardville Rd	20.7		0.045
1113_4	Waiheke	Mowbray Rd	15.2		0.031

6.3 Data analysis

To better understand how water use affects oxygen levels, this report attempts to isolate the response to low flows from other drivers, including:

- temperature - by using oxygen saturation instead of concentration
- solar cycle – by using oxygen daily minima to capture the period when photosynthesis is less likely to conceal reduced reaeration
- rainfall runoff events - by excluding periods of rapidly changing flow

Flow recommendations were developed, including flow requirements to achieve NPSFM attribute grades. The oxygen attribute included in the NPSFM is not a limit setting attribute for water takes, so provides a relevant guideline for the risks to ecosystem health, rather than a required standard or limit for water takes. Because these oxygen attributes are expressed as a concentration, oxygen bands were converted from concentration to saturation. A temperature of 20 °C was used in the conversion of concentration bands to saturation. Of the temperatures nominally used to specify water quality measures (e.g. 15, 20 or 25 °C), 20 °C was used for the Piako to approximate overnight temperatures in summer when oxygen stress is greatest (e.g. 20

°C was the 90th percentile of daily minima for Paeroa-Tahuna Rd, and 83rd percentile for KIWITAHĪ).

Investigating the relationship between oxygen and flow focussed on the minimum oxygen value for each day. This represents the time of oxygen stress for stream ecosystems and is consistent with the NPSFM oxygen attributes. The use of daily minima also helps isolate the flow effect on reaeration, from photosynthesis that contributes oxygen later in the day. The oxygen minima were compared to daily mean flow calculated from flow monitoring by Waikato Regional Council.

Days with rapid changes in flow were omitted from further analysis because the effect of sudden *rises* in flow associated with rainfall is a separate matter not under investigation (e.g. blackwater events). The focus here is instead setting limits on water use, which should be informed by the effect of *reductions* in flow associated with abstraction. Rapid changes in flow also introduce ambiguity in what flow measurement is associated with what oxygen value, given the time and distance required for oxygen to reach equilibrium with prevailing reaeration conditions. Data were excluded if flow doubled in the 3 days up to, and including, each day of measurement. For this calculation, a flow time-series of daily maxima and minima were generated for each site using WISKI software (version 7.4.13). A flow variability ratio was then calculated for each date in excel:

$$\text{Flow variability} = \max(3 \text{ daily maxima}) / \min(3 \text{ daily minima})$$

Flow variability ratios greater than 2 were classified as rapid fluctuations in flow (i.e. flow doubling or halving), and those days omitted from further analysis. Streams characterised by flashier flows require a higher ratio to reliably distinguish rapid changes in flow associated with rainfall events from gradual baseflow recession, and a ratio of 2 achieved this for the Piako River.

The equation used to describe the relationship between daily minimum oxygen and daily mean flow is the same as that used for low-gradient streams in Hawke's Bay. This provided an adequate fit for the Piako sites:

$$\text{Oxygen} = \text{upperbound} - a \cdot \text{EXP}(\text{flow} \times b)$$

The parameters 'a' and 'b' in this exponential function were solved using RStudio software (Version 2024.04.02 Build 764; package: QuantReg; function: "nlrq"), (Koenker et al. 2023). The 'upperbound' describes how high oxygen minima can go for a given site. This constant was selected by trial and error because the software was unable to solve the upperbound, as well as 'a' and 'b'. The above equation was rearranged when calculating the flow for a given oxygen level (e.g. estimating flow to meet NPSFM targets):

$$\text{flow} = (\text{Log}_e((\text{upperbound} - \text{Oxygen})/a))/b$$

Flow is an important driver of oxygen reaeration. Therefore, taking more water can reduce oxygen levels. But limiting water use does not guarantee a specific oxygen target will be met because other factors can further constrain oxygen (e.g. pollution discharges, increased plant biomass). Consequently, there is a distribution of possible oxygen levels for a given flow. Quantile regression was used to describe those times when flow constrained oxygen to low levels (Milous and Bartholow, 2005). The 25th quantile was fitted to describe oxygen levels that were exceeded by 75% of daily minima, following the methods I used in similar investigations in Hawke's Bay ([Wilding, 2015](#)). In that investigation, the 25th quantile gave a better approximation of the response predicted by a process model used to isolate the effect of flow on oxygen levels.

7 Oxygen results

7.1 Piako at Paeroa-Tahuna Rd 749-15

I was able to reproduce the NIWA results for Piako at Paeroa-Tahuna Rd using data archived in the Wiski database (Figure 7). This was achieved by plotting all daily minima without any quality control.

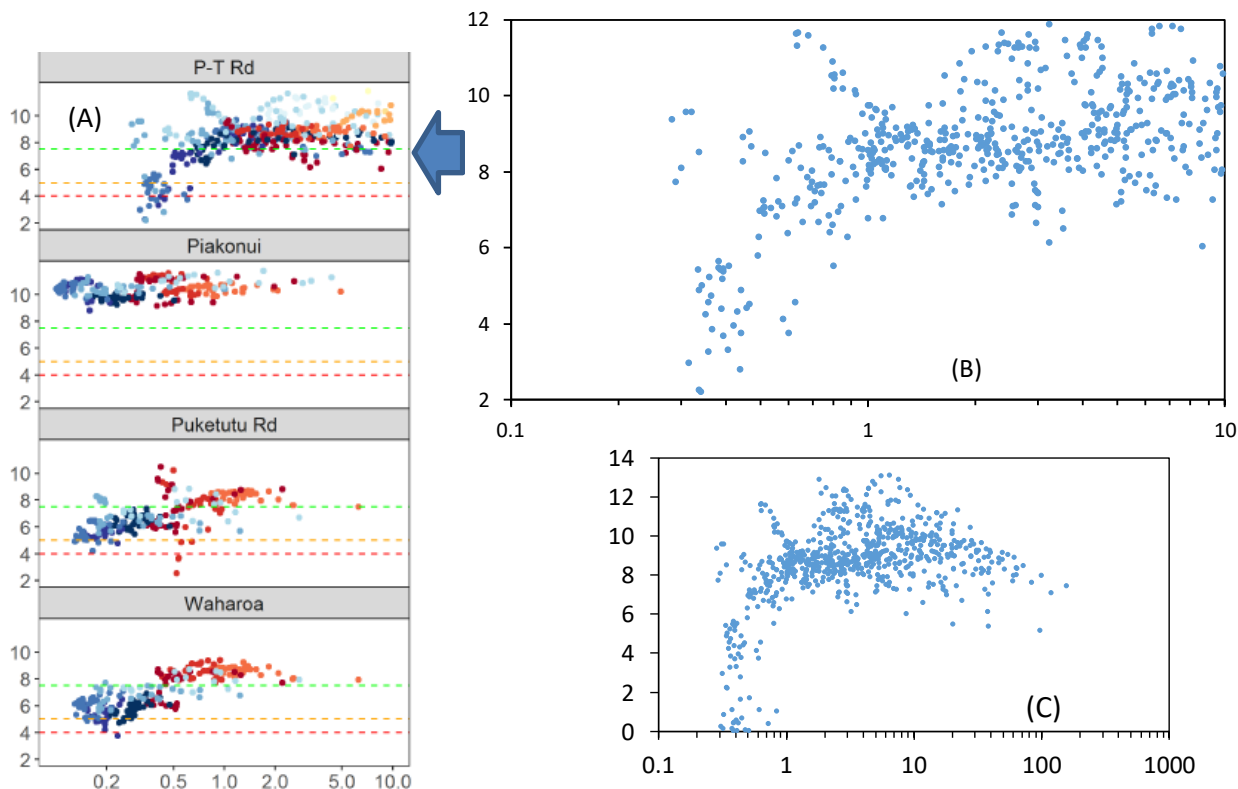


Figure 7 The relationship between oxygen concentration (mg/L) versus flow for the **Paeroa-Tahuna Rd** site (P-T Rd), confirming I was able to reproduce the plot on the top left (A) from Graham et al. (2018) using data archived in councils' Wiski database (right plots). A match was achieved in the top right plot (B) by including all measured data and setting axis bounds as per the NIWA report (oxygen > 2 mg/L and < 12 mg/L, flow < 10 m³/s). The smaller plot (C) displays the same data with axis limits extended to show all data. Oxygen daily minima are plotted against daily mean flow for the monitoring period 28 November 2011 to 14 November 2013.

The data were then put through additional quality control checks, as described in the Methods (Section 6.2). The resulting data set lacked any oxygen values less than 50% saturation (Figure 8). The important point of difference between the pre and post processing is the exclusion of data collected from 17 February 2013 to 10 April 2013 (Figure 9). A sudden rise in measured oxygen values at the time of site visits indicate the sensor was fouled and then cleaned upon inspection (e.g. clearing weed wrapped around the instrument). The jump in oxygen values was pronounced on 28/2/2013, 12/3/2013 and 9/4/2013 (Figure 9).

Removing that period of data when the sensor was fouled also omitted some of the lowest flows during the 2013 drought (flows < 0.5 m³/s). This is a problem because the empirical assessment of low flow effects relies on having oxygen data that represents those low-flow conditions.

Additional monitoring was commissioned by Waikato Regional Council, after the NIWA report. These data were collected by Tonkin+Taylor in 2021 and fill an important gap in the dataset at low flows, shown as orange dots in Figure 8. The updated dataset therefore improves certainty in the response of oxygen to low flow. Flows greater than 1 m³/s provided oxygen levels near

saturation, and there is a steady decline in oxygen at lower flows. This decline demonstrates the importance of placing limits on water use to protect stream ecosystems from low oxygen. Additionally, the steep decline in daily *maxima* (upper plot, Figure 8) at flows less than about 0.5 m³/s indicates that plant photosynthesis is also becoming limited at insufficient flow. Plants require both oxygen and carbon dioxide supplied by reaeration (Jones et al. 2000).

The 25th quantile was fitted to describe oxygen levels that were exceeded by 75% of daily minima, following the methods used in a similar investigation in Hawke's Bay (see Section 10.1). The flow requirements for oxygen were revised based on the 25th quantile presented in Figure 12

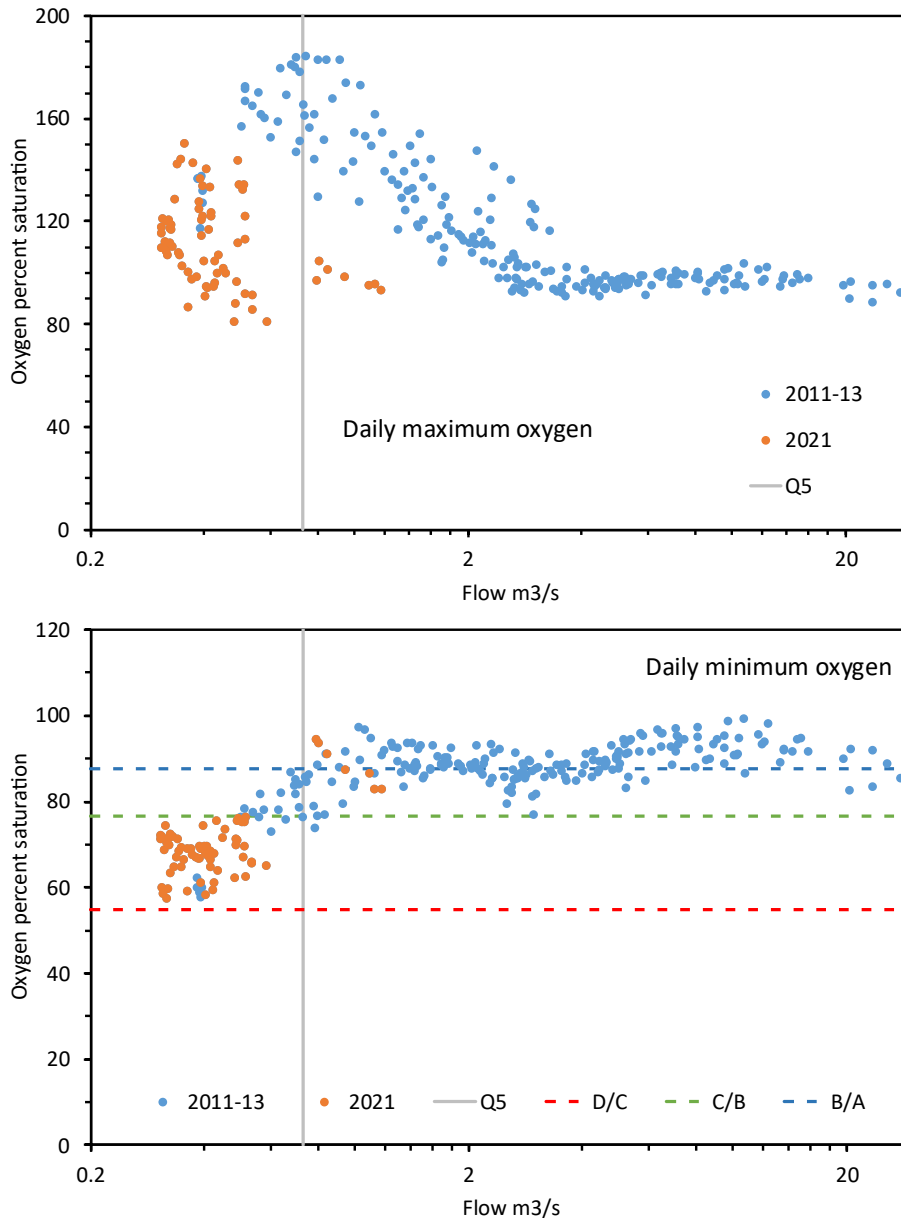


Figure 8 Paeroa-Tahuna Rd oxygen, as per Figure 7, after removing data that failed quality control checks listed in the methods. The blue points are for the same period as used in the NIWA report. The orange points are from monitoring completed in 2021 after the NIWA report.

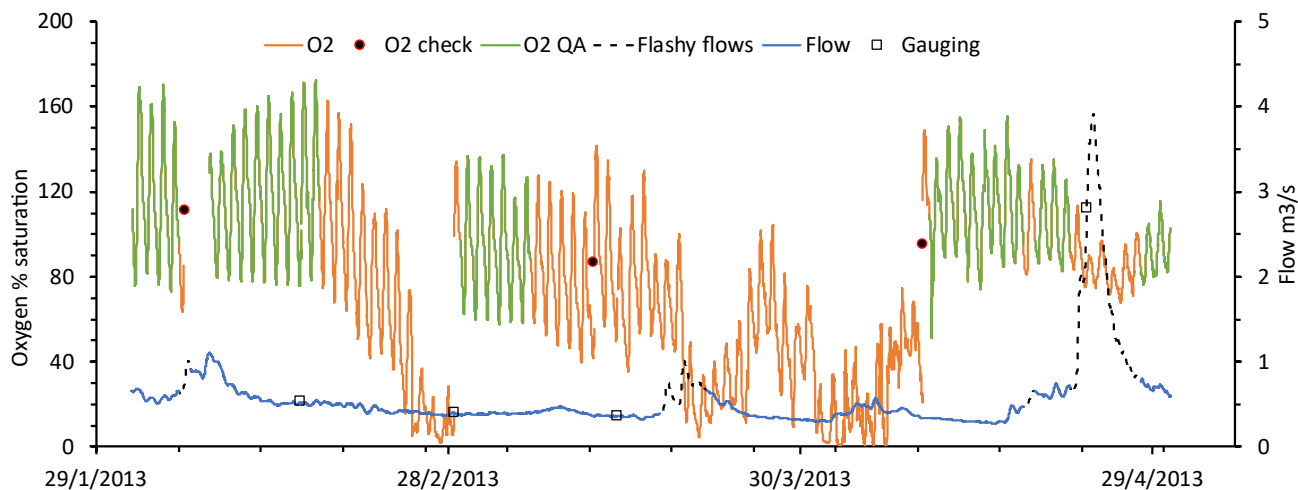


Figure 9 Periods of oxygen data excluded from Figure 8 are plotted as an orange line. These periods account for all the values when oxygen was less than 50% saturation. Sudden changes in oxygen at the time of field visits (indicated by dots, squares and gaps in record) are consistent with sensor fouling. Oxygen data were also excluded during periods of rapid flow change, indicated by a dashed segment on the hydrograph (blue line).

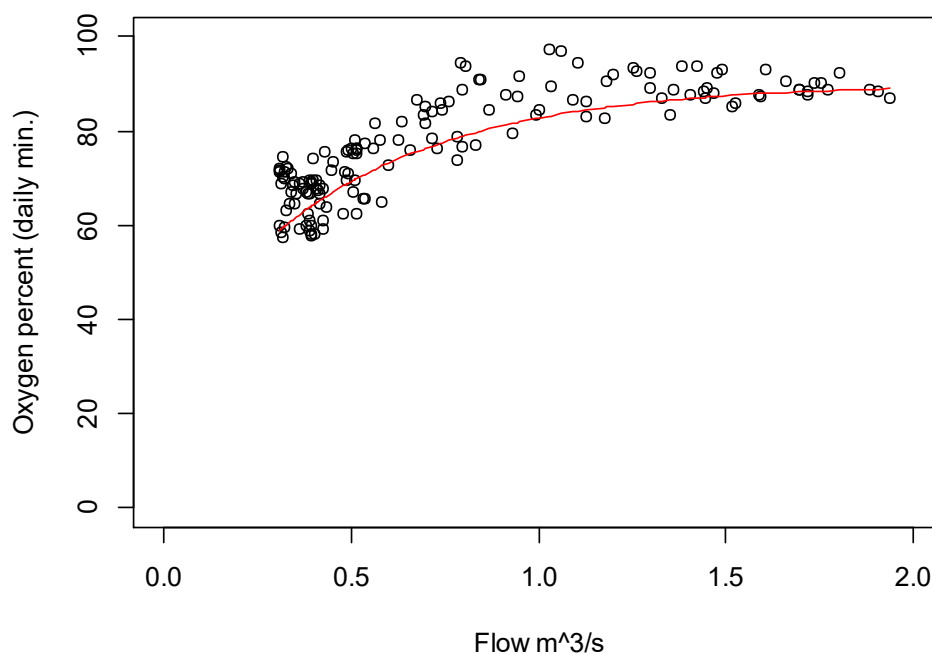


Figure 10 Fitting a quantile regression line to describe the relationship between oxygen daily minima and flow for Piako at **Paeroa-Tahuna Road**. Flows greater than 2 m³/s were excluded to improve model fit over the flow range more relevant to minimum flows (note the linear scale for flow in this plot differs from the log scale used in **Figure 7**). The red line was fitted using quantile regression, with 75% of values exceeding this value. Oxygen = 90 – 59.490 * exp(Flow * -2.1067).

7.2 Piako at Kiwitahi 749-10

Data quality checks were applied to the oxygen data from the Piako River at Kiwitahi. There were step changes at times of site visits that are consistent with fouling of the sensor (e.g. detached weed wrapping around the sensor). Additionally, there were some spikes in the data at the time of site visits, approaching saturation. Those could be explained by sensor continuing to log data while the sensor was out of the water for cleaning.

Using the quality-controlled data demonstrates a decline in oxygen levels at flows less than 0.6 m³/s at KIWITAHU (Figure 11). The monitoring period included low-flow conditions and are adequate to quantify the relationship between oxygen and flow at this location (Figure 12).

A series of flow increases occurred at this site that were not detected by the a priori method (28/12/2012 to 1/1/2013, circled in Figure 12). Excluding those days from the dataset would decrease the predicted flow requirements, more so if considering flow requirements for higher oxygen levels. For example, the flow required for 77% oxygen would decrease by 112 L/s if excluding those outliers. But flow would only decrease by 7 L/s for 40% oxygen. Aiming for higher oxygen levels therefore comes with more uncertainty in the flow required.

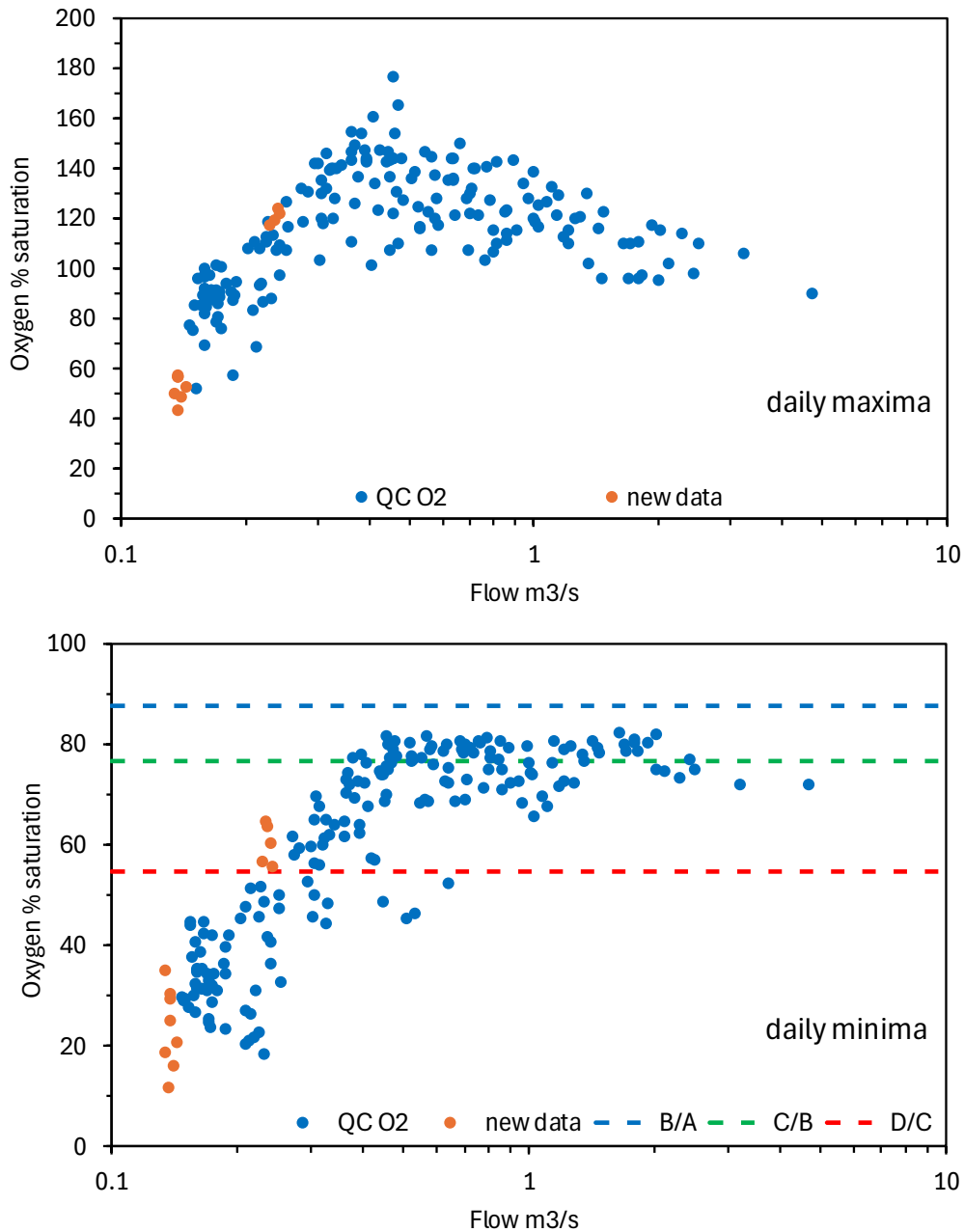


Figure 11 Oxygen versus flow for Piako at KIWITAHU, after removing data that failed quality control checks listed in the methods. Daily maxima are presented in the top plot and minima in the lower plot. Attribute band cut-offs are also plotted as dashed lines. The blue points are for the same period as used in the NIWA report. The orange points are from monitoring completed subsequent to the NIWA report. Periods of rapidly changing flow are excluded.

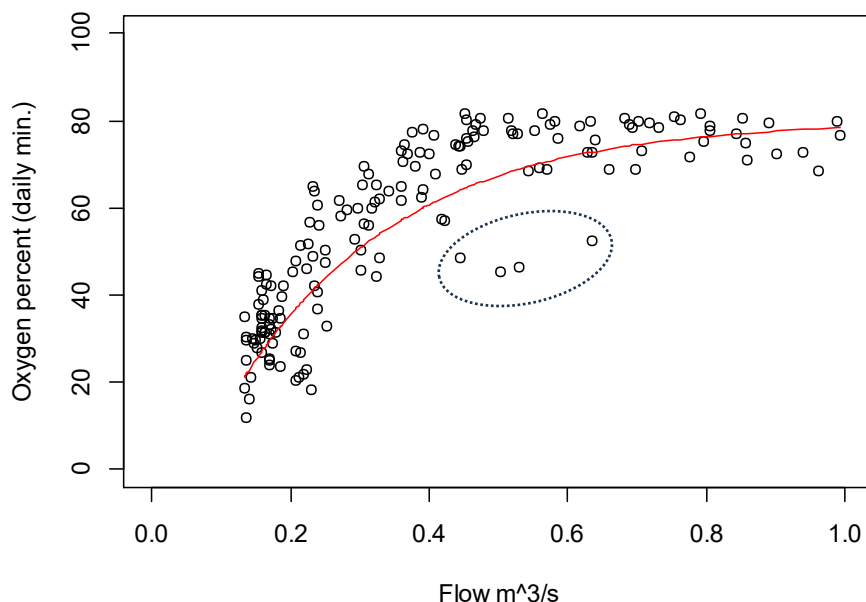


Figure 12 Fitting a quantile regression line to describe the relationship between oxygen minima and flow for Piako at **Kiwitahi**. Flows greater than 1 m³/s were excluded to improve model fit over the flow range more relevant to minimum flows (note the linear scale for flow in this plot differs from the log scale used in Figure 11). The red line was fitted using quantile regression, with 75% of values exceeding this value. $Oxygen = 80 - 102.87 * \exp(Flow * -4.1906)$. The circled points experienced a pronounced change in flow that did not meet the a-priori threshold for rapid flow change. Excluding them changes the equation ($Oxygen = 80 - 120.8 * \exp(Flow * -5.077)$).

Oxygen at Kiwitahi was lower than same-day measurements at the Paeroa-Tahuna Rd site located further downstream (Figure 13). Presumably less flow at Kiwitahi contributes to this⁵. But it is also possible the lower oxygen levels were an artefact of the weir. The water level at Kiwitahi is controlled by a weir that was installed by Waikato Regional Council to improve flow monitoring. The weir is intended to raise the hydraulic control above the influence of aquatic plants, reducing the impact of seasonal growth on the relationship between water level and flow (i.e. for more accurate stage to flow rating). Accurate flow data is important for a monitoring site that is used to trigger restrictions on water use. A weir can reduce reaeration by increasing depth and reducing velocity (Cox, 2003). The backwater created by the monitoring weir was at least 200 m long at the time of the 2021 LiDAR flights (Figure 14).

Oxygen data from two sites located some 5 km upstream of Kiwitahi, beyond the influence of the weir, indicated higher oxygen levels for a given flow (Piakonui Stream upstream of Milliken Rd, 753_17, Piakoiti Stream at Milliken Rd, 751_1). The monitoring was during a period of extreme low flows (March 2021). The data from these upstream sites are more consistent with Waitoa at Waharoa than with Piako at Kiwitahi, in terms of the oxygen response to flow (Figure 15).

The change in oxygen upstream of the weir was further investigated under low flow conditions (28 February 2025). Higher oxygen levels were observed upstream of weir's influence on water level (Figure 16). This survey was timed just after dawn when daily minimum oxygen levels were expected⁶. At this time, oxygen at Hutchinson Rd was double that at the weir (Figure 16). Hutchinson Rd oxygen were in closer agreement with oxygen levels at Waharoa, for both observed oxygen (Figure 15) and predicted oxygen levels for Waharoa (Figure 16). This is further evidence that oxygen observed at Kiwitahi is not representative of the oxygen response to flow for the upper Piako River.

⁵ Flows are typically 5 times higher at Paeroa-Tahuna Rd. However, the channel is steeper and narrower at Kiwitahi (slope 1.3 m/km, cf. 0.4 m/km at Paeroa-Tahuna Rd).

⁶ From past oxygen logger data at this site, daily oxygen minima occurred about 7:45 am in the last weeks of February, compared to the 2025 survey time of 06:36 to 07:42 am NZST.

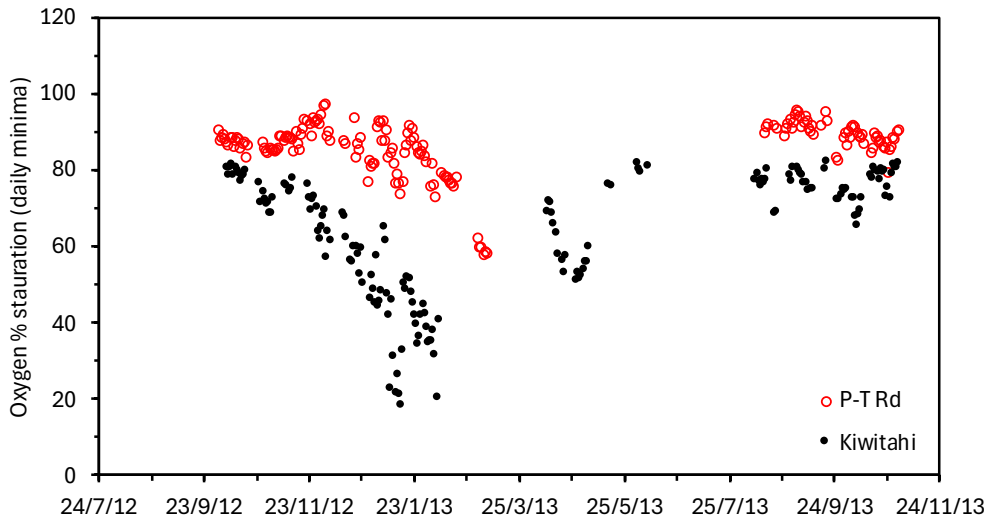


Figure 13 Comparing daily minima oxygen from Piako at Kiwitahi (black dots) to those measured the same day at Paeroa-Tahuna Rd (red circles). Data are included that passed the quality control checks.

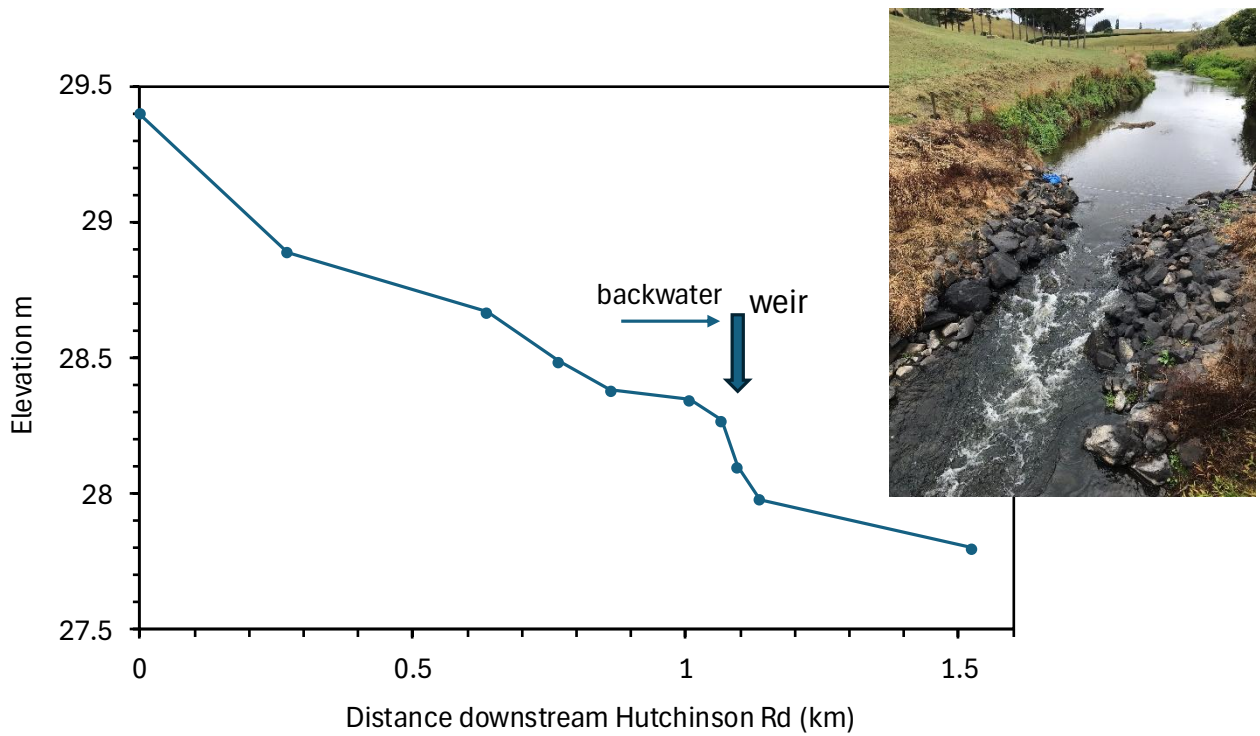


Figure 14 Elevation profile for the Piako River showing the backwater upstream of the monitoring weir. Water surface elevation was derived from the LiDAR digital elevation model (2021 flight). The most upstream point is below the [Hutchinson Road](#) bridge. The overall water surface slope was 1.3 m/km.

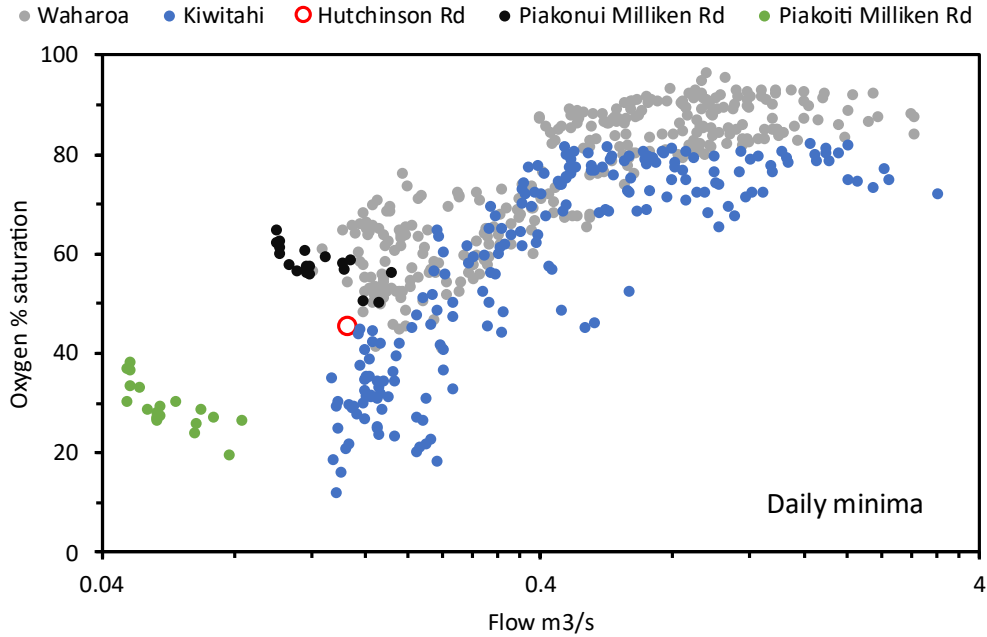


Figure 15 Daily minima from two sites upstream of the Kiwitahi weir (black and green dots) are more consistent with the Waharoa flow response (grey dots), compared to the Kiwitahi response (blue dots). The two upstream sites are Piakonui at Milliken Rd (753_17, black dots) and Piakoiti at Milliken Rd (751_1, green dots). The Hutchinson Rd measurement taken from Figure 16 is also plotted as a red circle.

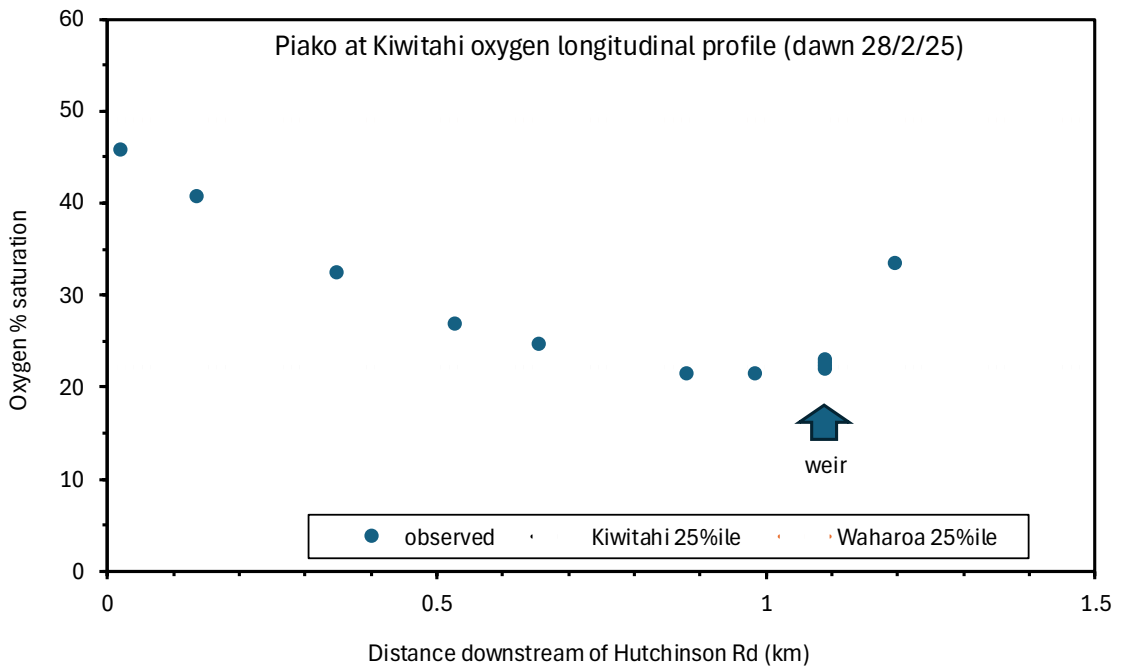


Figure 16 Longitudinal profile of oxygen saturation, demonstrating the increase in oxygen upstream of the Kiwitahi weir (arrowed at 1.1 km on the x-axis). Spot measurements were taken after dawn on 28 February 2025 to represent daily minimum oxygen under low flow conditions (rated flow 0.145 m³/s). Based on previous logger deployments, photosynthesis was not expected to produce a rise in oxygen levels until after the last measurement. Stable oxygen conditions were confirmed by repeat measurements at the weir (21.9% at the start of the survey 06:36, and 22.3% at the end 07:35 standard time). The most upstream site was by [Hutchinson Road](#) bridge. Overplotted are the predicted oxygen levels at the observed flow using equations for Kiwitahi and Waharoa (black and orange dotted lines).

7.3 Waitoa River at Waharoa 1249-38

Data quality checks were applied to oxygen data from the Waitoa River at Waharoa. There were step changes at times of site visits for validation checks (Figure 17). Most changes revealed sensor fouling, so data were omitted up to the site visit. But, for some days, the data after the visit were deleted because a better match to check data was achieved prior to the site visit (see lower plot). This is consistent with calibration error of the newly deployed instrument.

Data used in subsequent analysis excluded periods that were likely affected by sensor fouling or calibration error. Periods of rapidly changing flows were also excluded from the analysis (see methods).

Daily minimum oxygen declined at flows less than $1 \text{ m}^3/\text{s}$ (Figure 6). The more extreme maxima and minima at lower flows is consistent with reduced reaeration rate. The relationship between oxygen minima and flow was represented using quantile regression (Figure 19). Following the methods used in a similar investigation in Hawke's Bay, the 25th quantile was fitted to describe oxygen levels that were exceeded by 75% of daily minima. The flow requirements for oxygen were revised based on the 25th quantile presented in Figure 19 (see Section 10.1).

There is a monitoring weir associated with this site (Figure 20). From LiDAR data, this small weir produced a minimal backwater effect (some 150 m on a section of stream with slope $1.5 \text{ m}/\text{km}$), so is not expected to influence the 2021 data collected 600 m further upstream at Lansdowne Rd. And that data collected at Lansdowne Rd in 2021 is consistent with the earlier data. The weir is therefore not expected to have increased the flow requirements for oxygen.

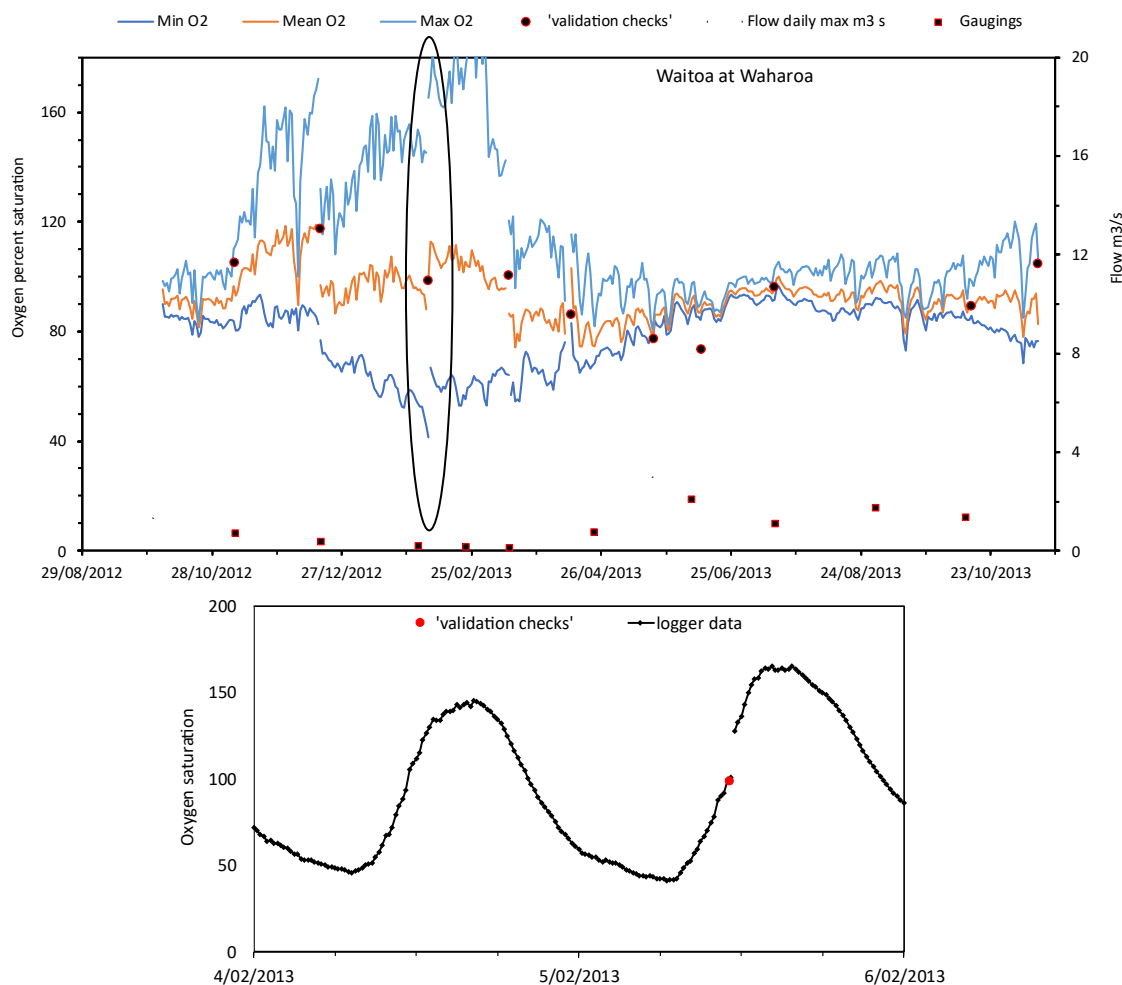


Figure 17 Quality checks on oxygen data for Waitoa River at **Waharoa**. Problems with the oxygen data are revealed when step changes in oxygen coincide with site visits. The upper plot shows daily minima, mean and maxima for each day of oxygen monitoring (continuous data not used to improve clarity) over the period December 2012 to March 2013. Validation check points are not directly comparable to these extrema, so only indicate the timing of the site visit. The lower plot shows the full time-series data for just two days in February (period circled in the top plot). Note the increase in oxygen after the site visit (orange dot), when the logger recorded values (back dots) that were 30% higher than the validation measurement.

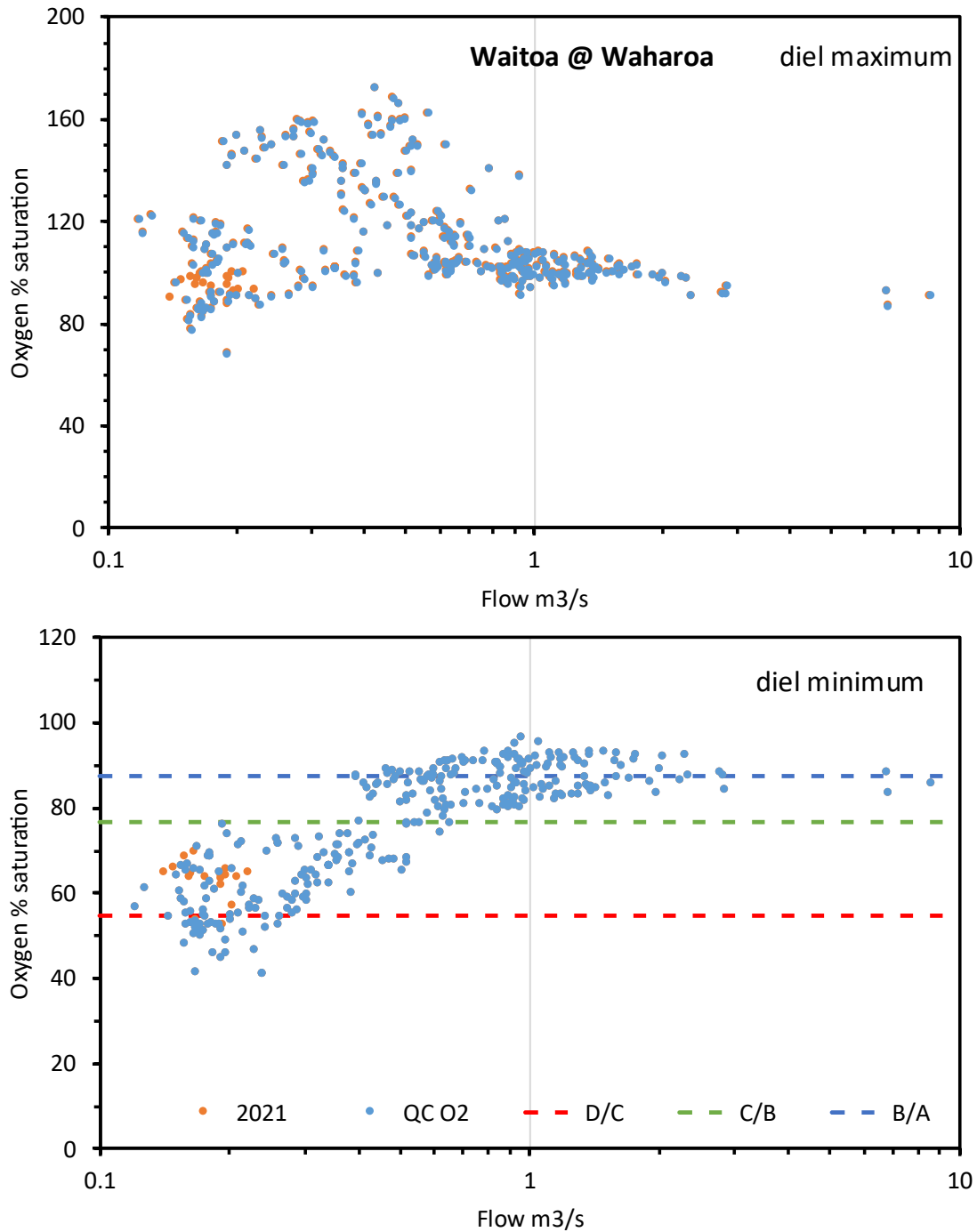


Figure 18 Oxygen versus flow for Waitoa at Waharoa, after removing data that failed quality control checks listed in the methods. The blue points are for the same period as used in the NIWA report. The orange points are from monitoring completed subsequent to the NIWA report (in 2021 at the nearby Lansdowne Rd bridge). Periods of rapidly changing flow are excluded from both. Daily maxima are presented in the top plot and minima in the lower plot. Attribute band cut-offs are also plotted as dashed lines.

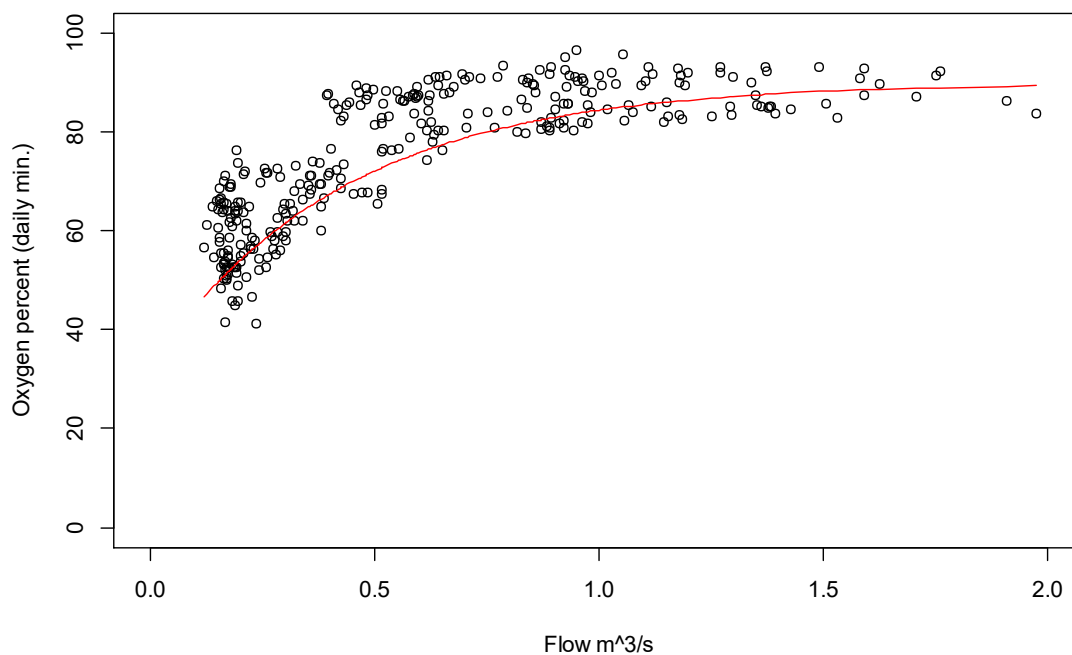


Figure 19 Fitting a quantile regression line to the data from Figure 18, to describe the relationship between oxygen minima and flow for Waitoa River at **Waharoa**. Flows greater than 2 m³/s were excluded to improve model fit over the flow range more relevant to minimum flows (note the linear scale for flow in this plot differs from the log scale used in Figure 18). The red line was fitted using quantile regression, with 75% of values exceeding this value. Oxygen = 90 – 57.46 x exp(Flow x -2.34).



Figure 20 Flow monitoring weir on the Waitoa River at Waharoa. This photo was taken May 2022 after the weir was rebuilt (photograph Kane Lynn).

7.4 Waitoa River at Puketutu 1249-25

The most upstream site on the Waitoa River also demonstrated a decline in oxygen at lower flows (Figure 21). There were several challenges in quantifying the flow requirements for this site. Firstly, most of the data record did not pass the quality checks. Second, flow is not monitored at this site, posing a challenge for implementing any water use restrictions that are specific to this section of river.

Oxygen saturation at Puketutu was similar to same-day measurements at the Waharoa site further downstream (Figure 22). So, it is reasonable to assume that limiting water use to meet flow requirements at Waharoa would also provide adequate flow at Puketutu. Therefore, no additional flow requirements are recommended for the Waitoa River at Puketutu.

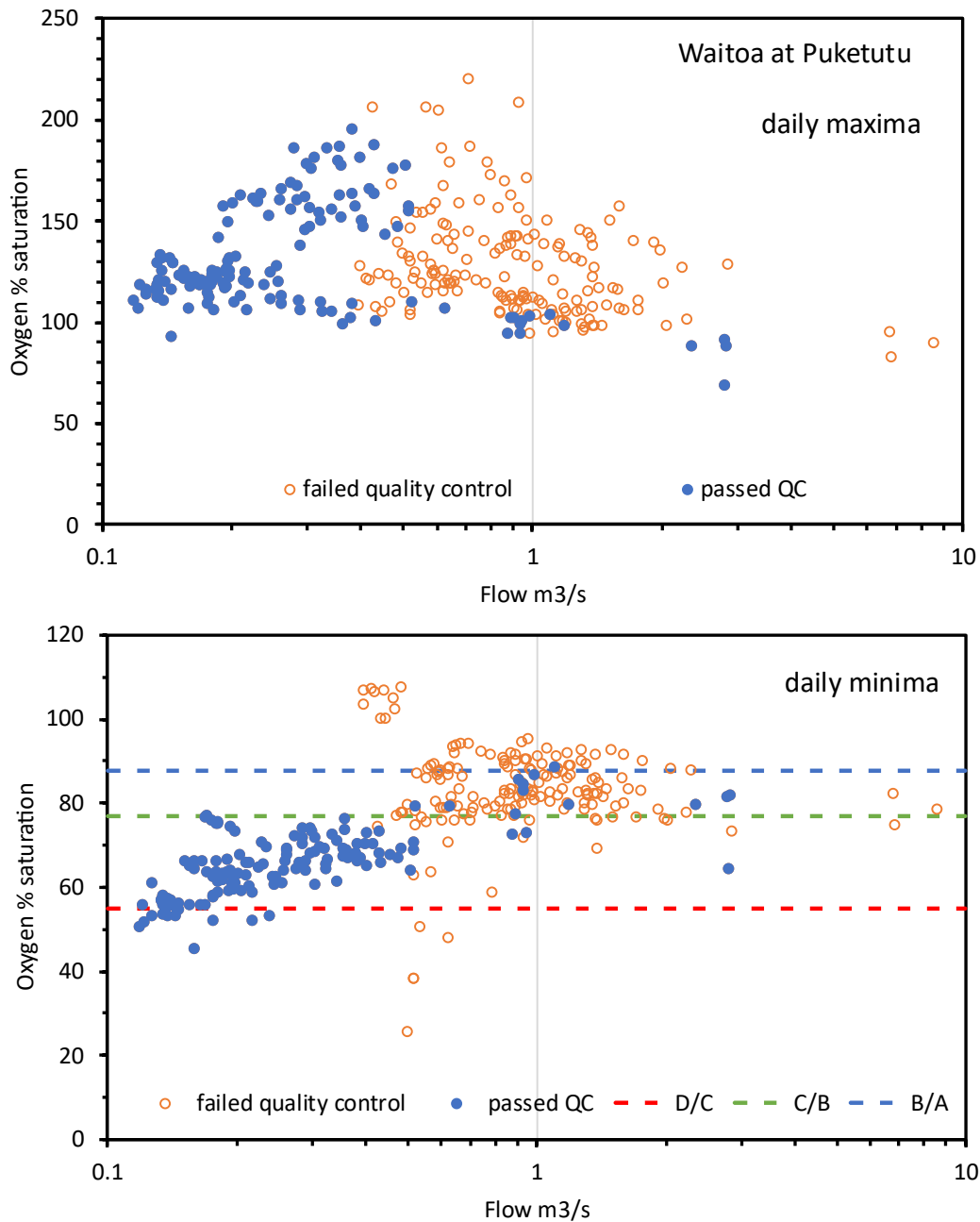


Figure 21 Oxygen for Waitoa at **Puketutu**, using flow from the nearest recorder (Waharoa). The blue points passed quality checks (removing periods of suspected sensor fouling or calibration problems), while the orange dots did not. Periods of rapidly changing flow are excluded from both datasets. The upper plot shows daily maxima and the lower plot are daily minima. Attribute band cut-offs are also plotted as dashed lines.

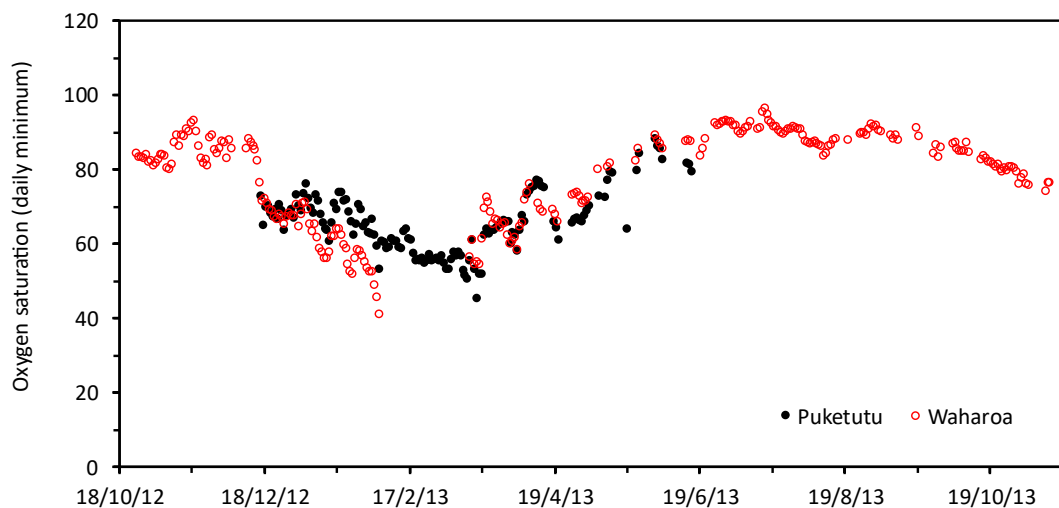


Figure 22 Comparing daily minimum oxygen levels from **Waitoa** at **Puketutu** to those measured the same day at Waharoa. Data are included that passed the quality control checks.

7.5 Waitoa River at Mellon Road 1249-18

Graham et al. (2018) found “no discernible relationship between oxygen and flow” for the Waitoa at Mellon Road. Revisiting the same data with quality control applied supports this conclusion. The data is sufficient to demonstrate that abstraction is unlikely to reduce oxygen at the Mellon Rd site, at least across the measured flow range (Figure 23). Data from the other sites demonstrate the potential for oxygen to decline rapidly at lower flows. The Mellon Road data are consistent with the decline in oxygen at flows less than 1 m³/s observed at Paeroa-Tahuna Rd (Figure 24).

There is more flow at this Mellon Rd site, compared to the Piako mainstem (see Section 9). Hence Mellon Rd did not experience flows less than 0.6 m³/s during the monitoring period.

At flows greater than 1 m³/s, there was a wide scatter of oxygen values that does not appear related to flow (Figure 23). Some 3% of daily minima were in D band. These D band values could not be explained by flow or climatic factors, and there were no indications of oxygen sensors being fouled on those occasions (e.g. 12/1/2013). The occurrence of low oxygen conditions, even at high flows, suggests that the reaeration rate may not increase at flows greater than 1 m³/s. This can happen if water depth increases more than water velocity as flow rises.

A monitoring weir is located at Mellon Rd (Figure 25) and this improves the accuracy of flow data by limiting the effects of weed growth on water level (i.e. a more stable stage-flow rating curve). But this also reduces water velocities over the length of the backwater created by the weir. The 0.6 m increase in water level by this weir is enough to create a backwater some 1,000 m long (Figure 26), exacerbated by the low gradient at this site (0.6 m/km). The combination of increased depth and reduced velocity is expected to reduce oxygen reaeration over this length of stream.

Regardless of flow dependence, oxygen levels are a problem in this section of river and will require management of key pressures (e.g. point discharges).

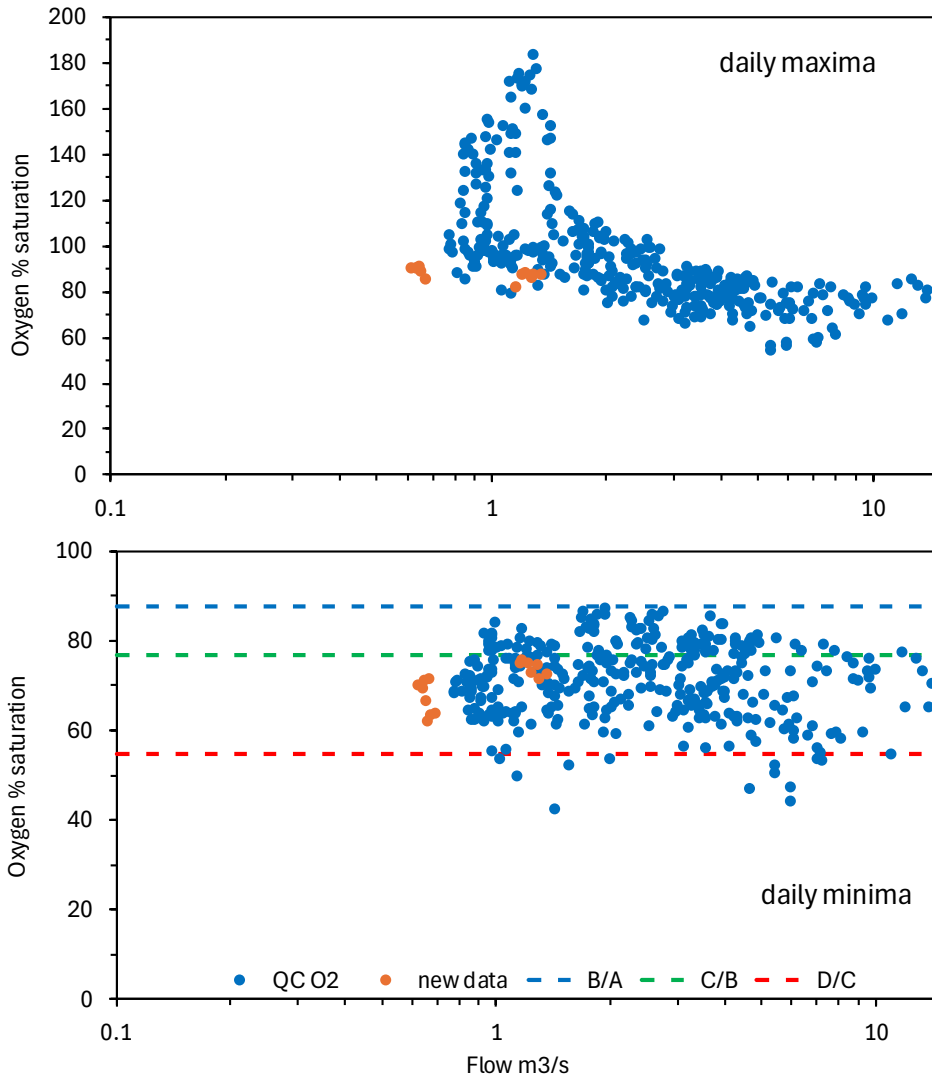


Figure 23 Oxygen for Waitoa at **Mellon Rd** versus flow at the same site. The blue dots are as used in the NIWA report (Graham et al. 2018) with more recent data included as orange points. Periods of rapidly changing flow are excluded from both datasets. The upper plot shows daily maxima and the lower plot are minima. Attribute band cut-offs are also plotted as dashed lines.

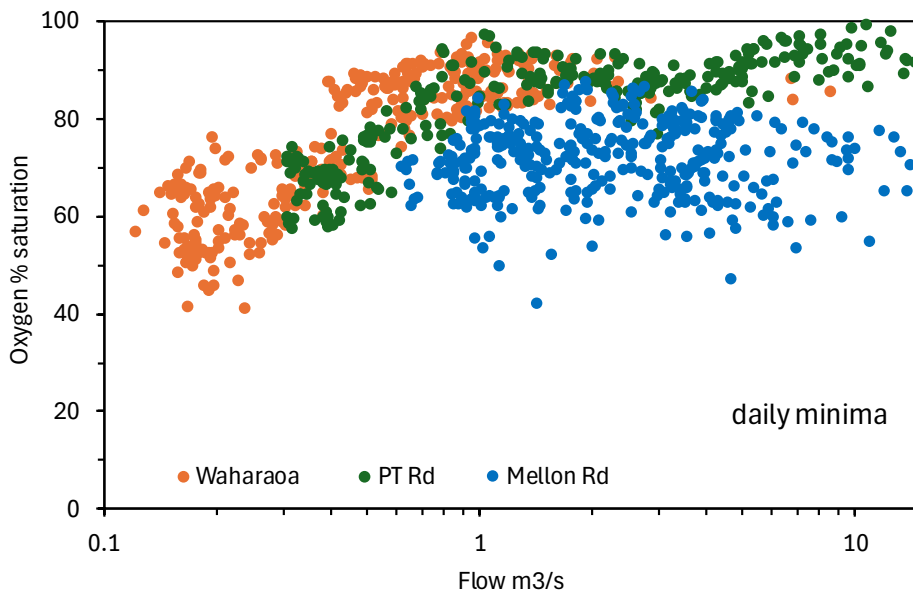


Figure 24 Comparing Mellon Rd to other sites for the response of oxygen daily minima to flow.



Figure 25 Water falling over the weir downstream of **Mellon Rd** on the Waitoa River (file photo, 1996).

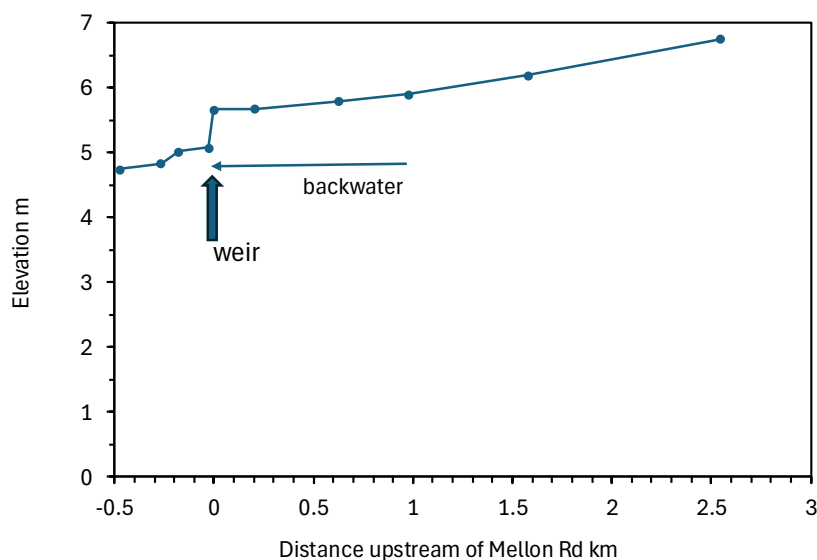


Figure 26 Elevation profile of the Waitoa River at **Mellon Rd**. From LiDAR elevation data, the weir lifts water level about 0.6 m and, with a stream gradient of 0.6 m/km, is expected to create a backwater extending some 1,000 m upstream.

7.6 Tidal section

As part of the NIWA study, oxygen was sampled along the length of the tidal section on 10 occasions between 2011 and 2017 (Table 8 in Graham et al. 2018). This identified a length of river with lower oxygen, known as an oxygen sag, located some 4 to 17 km inland of the mouth (Graham et al. 2018). Changes in freshwater outflow is one of several processes that can contribute to the local sag in oxygen.

The limit of salt-water intrusion extended further inland at lower flows (Figure 27). The turbidity maxima occurred about the same location as the salt wedge, as did the lowest oxygen concentration. This association held at low flows, but broke down at flows greater 10 m³/s. There was an oxygen sag about the salt wedge at higher flows, but slightly lower oxygen levels were observed further upstream, hence a different location is plotted. Different processes presumably act at high flows to extend the zone of low oxygen, and these high-flow processes are less relevant to the setting of minimum flows.

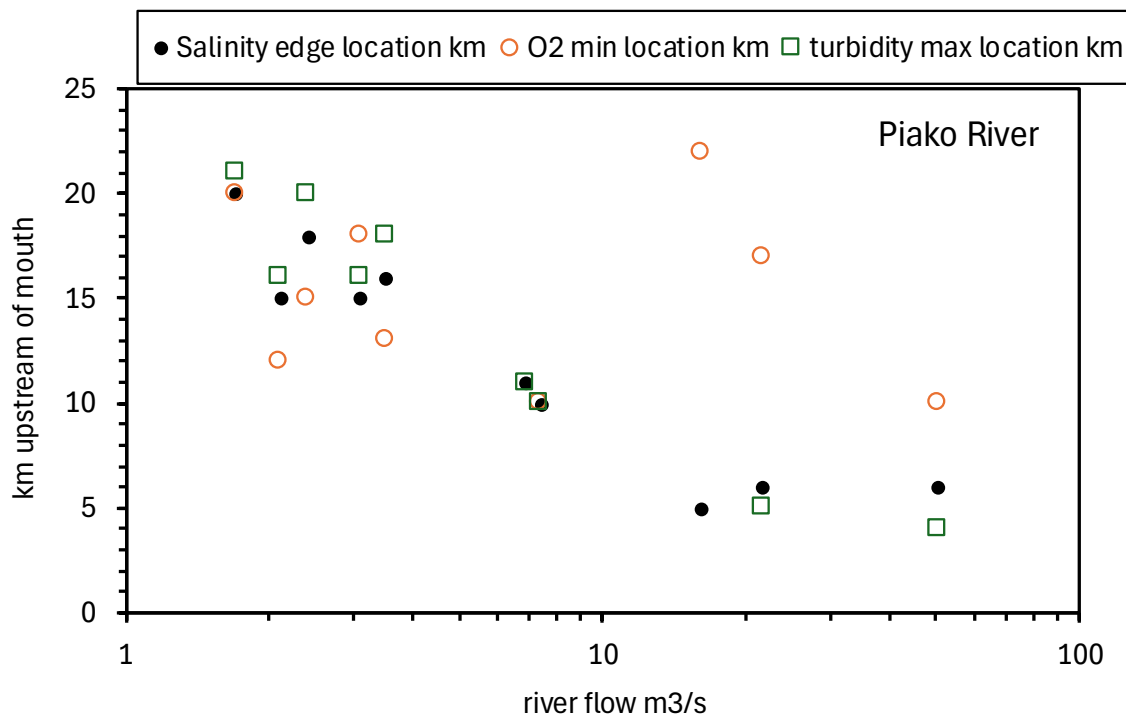


Figure 27 Upstream penetration of salt water at high tide (black dots) versus freshwater flow in the Piako River. Values were read off the plots in Graham et al. (2018) (their Figure 12), selecting the point at which salinity dropped to near-zero. The location of lowest oxygen value is also plotted (orange circles) together with the highest turbidity (green squares). Each point is from a longitudinal survey conducted in 2011/12 and 2017 (dates given in Table 8 in Graham et al. 2018). Freshwater flow is the sum of data from Paeroa-Tahuna and Mellon Rd on the day of each survey.

In addition to the *location* of the oxygen sag, the *magnitude* of oxygen depletion was also related to flow (Figure 28). The non-linear response demonstrates this is not a simple case of more flow providing more oxygen. Peak oxygen was observed at some 8 m³/s, declining at higher and lower flows. The lowest oxygen concentrations were observed at the highest flows. Further complicating this pattern, several of the surveys were conducted after rain, experiencing rapidly changing flows (black dots in Figure 28).

The flow response derived from the same-day longitudinal surveys (Figure 28) was also supported by continuous monitoring data at sites located about 14 km to 25 km upstream the mouth (typically upstream of the salt wedge). This deployment of oxygen loggers enabled the calculation of daily minima by Graham et al. (2018), which also peaked at intermediate flows (about 10 to 20 m³/s from their Figure 17). The oxygen minima declined at higher and lower flows, which is consistent with the longitudinal surveys.

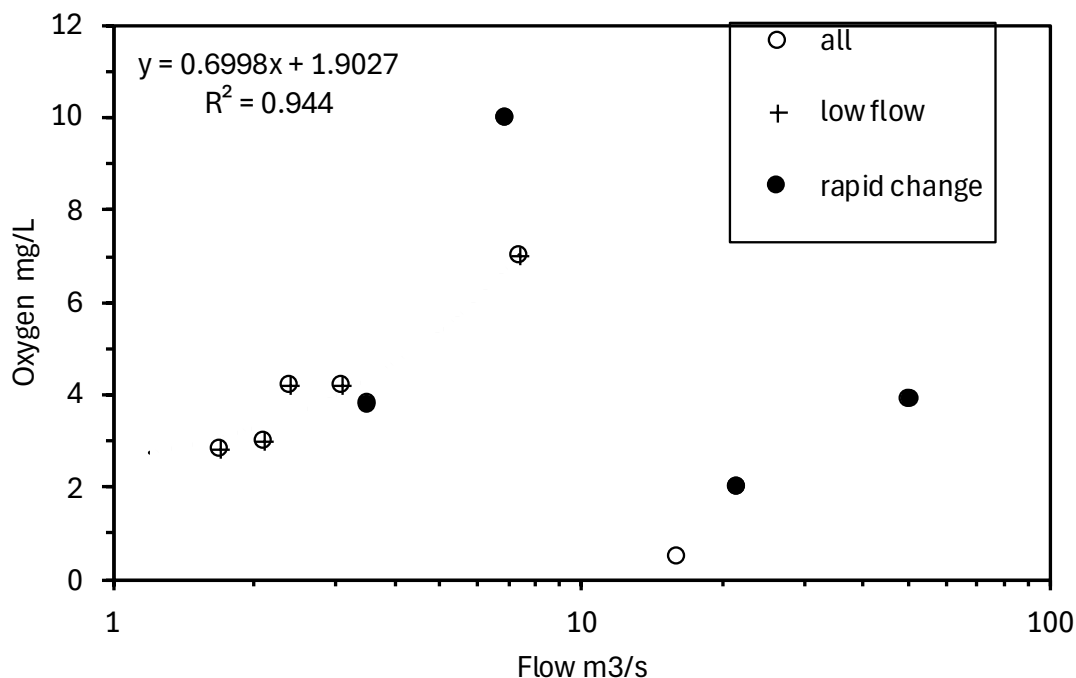


Figure 28 The lowest oxygen concentrations from each longitudinal survey plotted against flow. Values were read off the plots in Graham et al. (2018) (their Figure 12). These were measured during daytime surveys about high tide. The exponential trendline was fitted only to flows less than 10 m³/s that did not experience rapidly changing flows (+ point symbol). Note, the x-axis is on a log-scale.

As discussed in the NIWA report, flow is one of many factors contributing to oxygen dynamics in the tidal reach. To give an indication of the magnitude of oxygen response to water takes during low flows, a trendline was fitted to flows less than 10 m³/s that did not coincide with rapidly changing flows (Figure 28). Setting limits on water use should be informed by the effect of reductions in flow associated with abstraction. The effect of sudden rises in flow associated with rainfall is a separate matter not under investigation.

The resulting equation predicts an oxygen reduction from 3.2 to 2.8 mg/L if flow is reduced from 1.8 to 1.2 m³/s (naturalised vs observed Q5 respectively, by summing Paeroa-Tahuna Rd and Mellon Rd). This oxygen decline of 0.4 mg/L was estimated using methods intended to describe the worst-case observed, representing the combined effect of all existing water takes on the worst affected section of river at the time of high tide.

8 Temperature results

Climate is the dominant driver of how temperature changes over time at a site (e.g. higher solar radiation in summer). Detecting the effect of changing flow over time therefore requires some method for isolating the climate signal (Booker and Whitehead, 2021). To this end, the NIWA reports looked at temperature-flow response within each calendar month (see page 18 in Graham, et al. 2018). Building on that investigation, I analysed the relationship between the range in daily temperature with flow for three sites (Kiwitahi, Paeroa-Tahuna Rd, Waharoa). In the absence of continuous data to represent the climate signal (e.g. nearby ground temperature), I have used the daily minima of water temperature to provide some level of climate normalisation (e.g. overnight temperatures are warmer in summer), and this is subtracted from the daily maxima. In this way, using the range of daily temperature (max - min) helps isolate the flow effect on temperature from the dominant climate signal.

Starting with the Paeroa-Tahuna Road site, higher temperature ranges are possible at lower flows (Figure 29). This is consistent with a cool water source from upstream (e.g. mountains, shaded reach, groundwater inflow) reaching equilibrium over a shorter length of stream when flows are lower. There is a wide envelope of possible temperatures for a given flow. Lower flows

allow the stream to fluctuate to greater maxima, as described by the upper bound of the dataset (Figure 30).

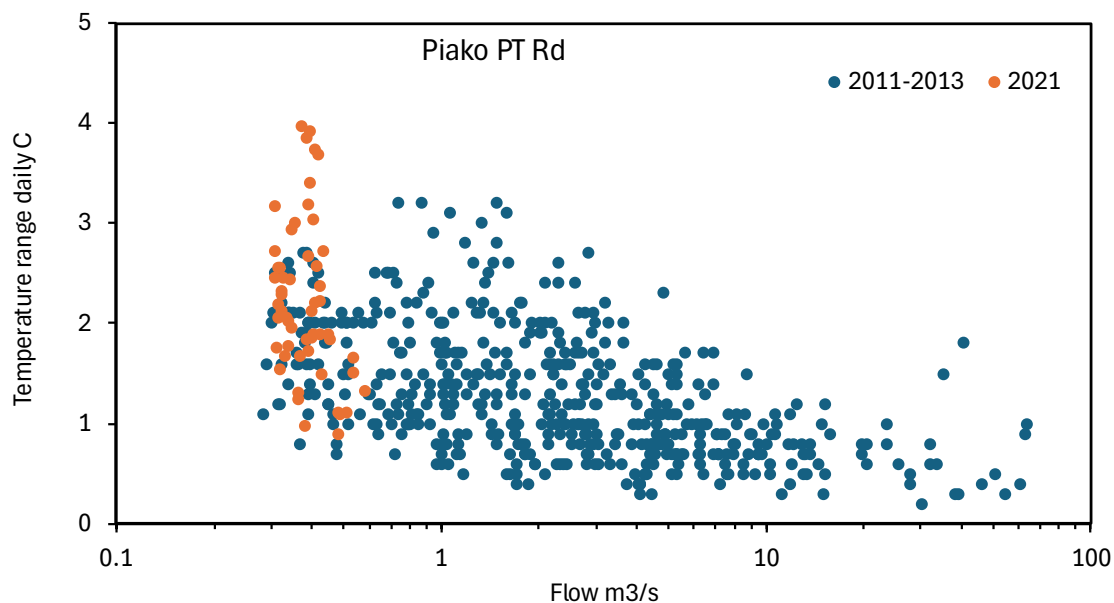


Figure 29 The relationship between daily **range** in temperature and flow for the Piako River at **Paeroa-Tahuna Road** (749-15). Daily range (max – min) for temperature is plotted against daily mean flow. The orange points are data collected in 2021, subsequent to the data used in the NIWA reports. Periods of rapidly changing flow are excluded.

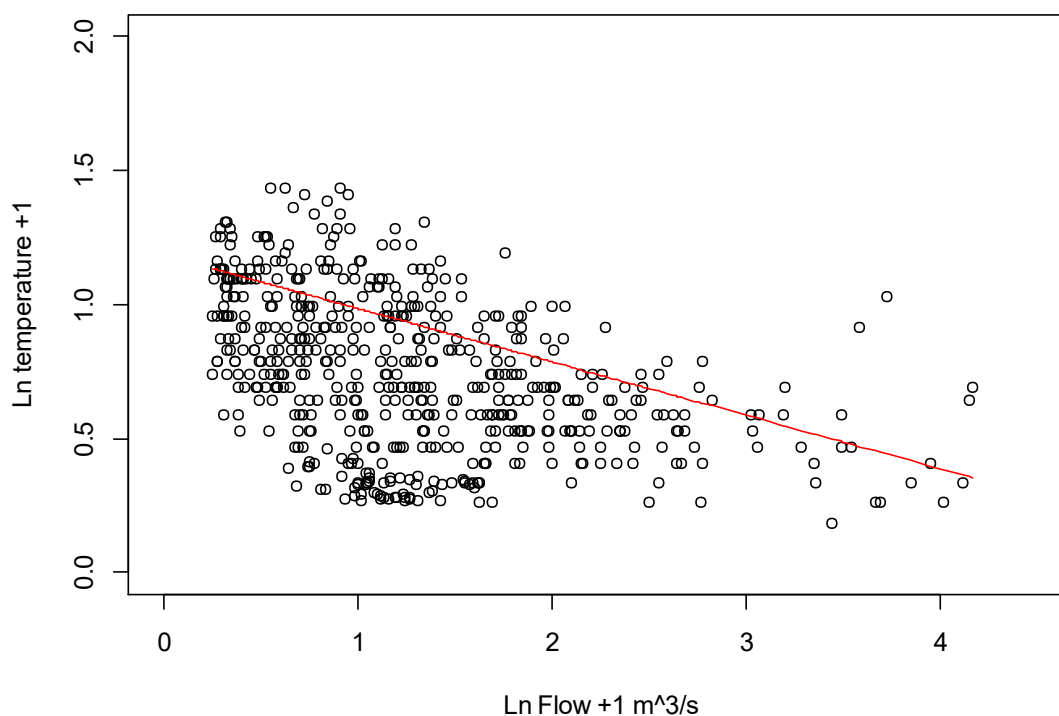


Figure 30 Temperature versus flow at Paeroa-Tahuna Rd, as per Figure 29, with the addition of a quantile regression line calculated as the 75th percentile. Both temperature range and flow were log transformed, and a linear trendline fitted ($\text{Log}_e(\text{temp_range} + 1) = -0.1991 \times \text{log}_e(\text{flow} + 1) + 1.1844$).

Stream flow is expected to play a subordinate role to climate (over time, at a site) and riparian shade (between sites) in driving stream temperature. This is consistent with the above results from Paeroa-Tahuna Rd. For example, the flow reduction expected from abstraction (from 0.713 to 0.450 m³/s at Q5) is expected to increase the daily range in temperature by 0.1 °C (using equation in Figure 30).

Temperatures at Kiwitahi produced a flow response (Figure 31) that differed to Paeroa-Tahuna Road. The daily range increased as flow decreased, down to flows of about $0.4 \text{ m}^3/\text{s}$, much like the response at Paeroa-Tahuna Rd. However, the response changed direction at lower flows, revealing a decline in temperature at flows less than $0.4 \text{ m}^3/\text{s}$ at Kiwitahi. This is consistent with an increasing portion of deep groundwater at lower flows. Therefore, water abstraction is not expected to increase water temperature at Kiwitahi, under low-flow conditions (naturalised Q5 is $0.172 \text{ m}^3/\text{s}$).

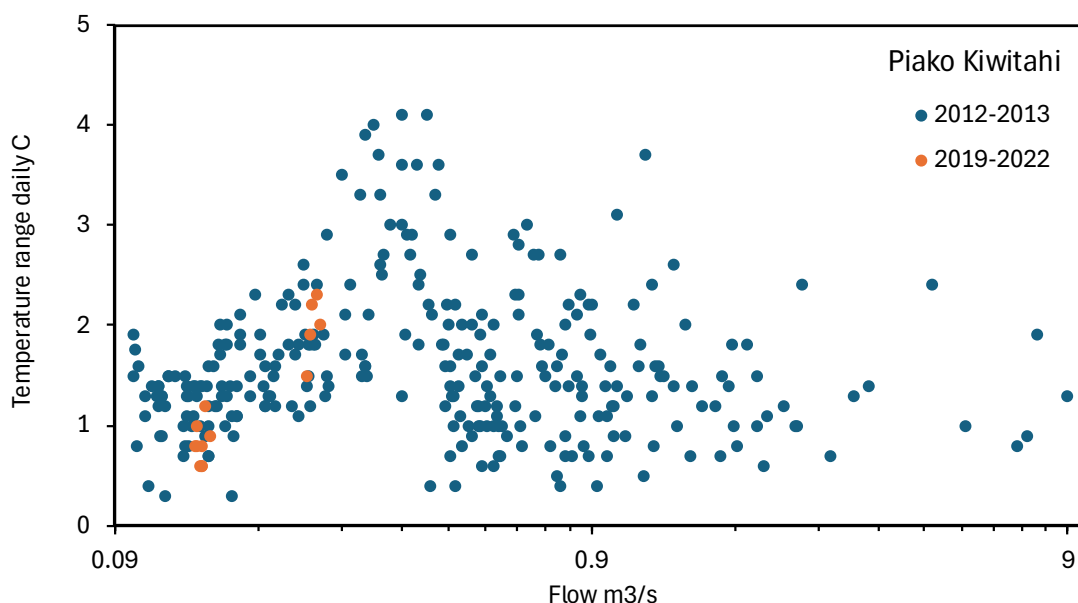


Figure 31 The relationship between temperature **range** and flow for the Piako River at **Kiwitahi** (749-10). Daily range (max – min) for temperature is plotted against daily mean flow. The orange points are data collected subsequent to the NIWA reports (2019 and 2022). Periods of rapidly changing flow are excluded.

The NIWA report did not detect a temperature response for the Waitoa River at Waharoa. Re-examining the data using daily range also demonstrates the wide scatter of data at flows less than $1 \text{ m}^3/\text{s}$ (Figure 32). However, the upper bound of the dataset does show a modal response, like Kiwitahi. Again, the upper bound increased as flow dropped to $0.4 \text{ m}^3/\text{s}$, then declined at flows less than $0.3 \text{ m}^3/\text{s}$. Again, water abstraction is not expected to increase water temperature at Waharoa, under low-flow conditions (naturalised Q5 is $0.197 \text{ m}^3/\text{s}$).

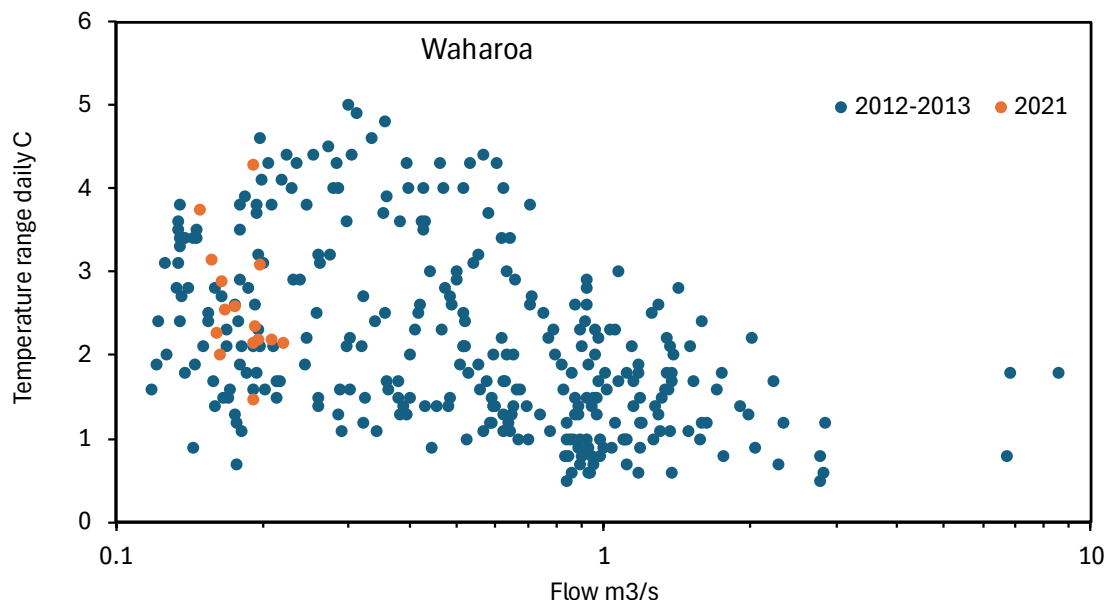


Figure 32 The relationship between temperature **range** and flow for the Waitoa River at **Waharoa** (1249-38). Daily range (max – min) for temperature is plotted against daily mean flow. The orange points are data collected in 2021, subsequent to the NIWA reports. Periods of rapidly changing flow are excluded.

Daily maxima are of concern as representing the period of highest temperature stress. However, daily minimum temperatures are also of concern because oxygen is lowest overnight (in the absence of photosynthesis). Aquatic life needs more oxygen to meet metabolic demand as temperature increases. Fortunately, daily minima did not show a response to flow at Paeroa-Tahuna Rd, after accounting for seasonal variability (Figure 33). Daily minima at Kiwitahi and Waharoa also did not show a response to flow, using the same method (not plotted).

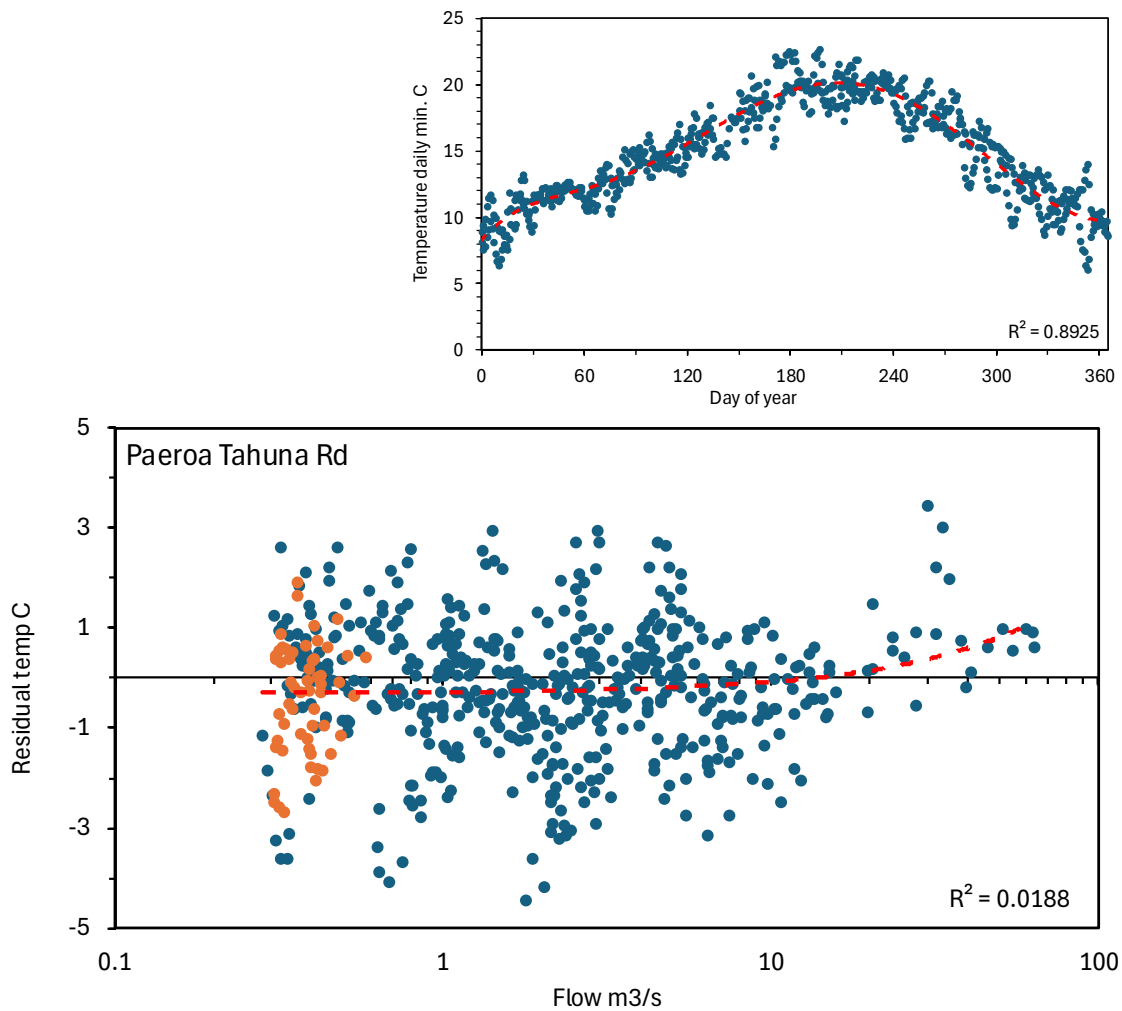


Figure 33 Temperature daily **minima** show little response to flow (lower plot), after accounting for seasonal variability (upper plot) at **Paeroa-Tahuna Rd**. The lower plot uses the temperature residuals from the upper plot (observed minus expected temperature). The orange dots are 2021 data, which were not used in generating the seasonal response.

9 Gauging results

Within the Piako catchment, the Waitoa tributary contributes more to summer low-flows than expected from the catchment area (Section 3). To better understand the groundwater inflows responsible for this, same-day gauging surveys were completed during a period of stable low-flow in February 2025. These gaugings again confirmed the Waitoa produces more baseflow than the Piako (Figure 34). Further, they revealed that the groundwater inflows responsible for higher flows are evenly spread across the Waitoa catchment. This was demonstrated by the gradual rise in flow as catchment area increased (Figure 34).

One notable exception to this gradual rise was the Waiheka tributary, which produced almost twice the flow per catchment area, compared to neighbouring tributaries (Figure 34). And, within the Waiheka, those inflows were concentrated over a 10 km section of stream that is circled in Figure 5 (between Wairere Rd and Waiheka Rd bridges). The Waiheka is a tributary of the Waitoa that runs along the toe of the Kerepehi surface fault (solid red line in Figure 5) before its confluence with the Waitoa located downstream of State Highway 26. Several features distinguish this gaining section of the Waiheka, notably the artificial straightening of the channel and its tributaries. Whether drainage caused the higher inflows of groundwater, or drainage was necessary because of the high groundwater inflows, was not resolved for this study.

This gaining section of the Waiheka also coincides with a discontinuity in the Kerepehi fault (i.e. the fault stops and starts at a different point). The 2021 LiDAR reveals several parallel ridge lines, consistent with unmapped surface faults, terminating at about the gaining section of stream. Fault lines can increase groundwater outflow by various mechanisms (Keegan-Treloar et al. 2022) and, in this case, may simply produce a low elevation area that intercepts the groundwater table.

The neighbouring Waihou River was not included in the gauging survey. However, rated flows for the Waihou were off the chart on both survey dates. The Waihou has a greater magnitude of flow and a greater flow per catchment area (Waihou Te Aroha specific discharge 19.5 L/s/km² on 4 Feb 2025, cf. 2.4 L/s/km² for Waitoa at Mellon Rd).

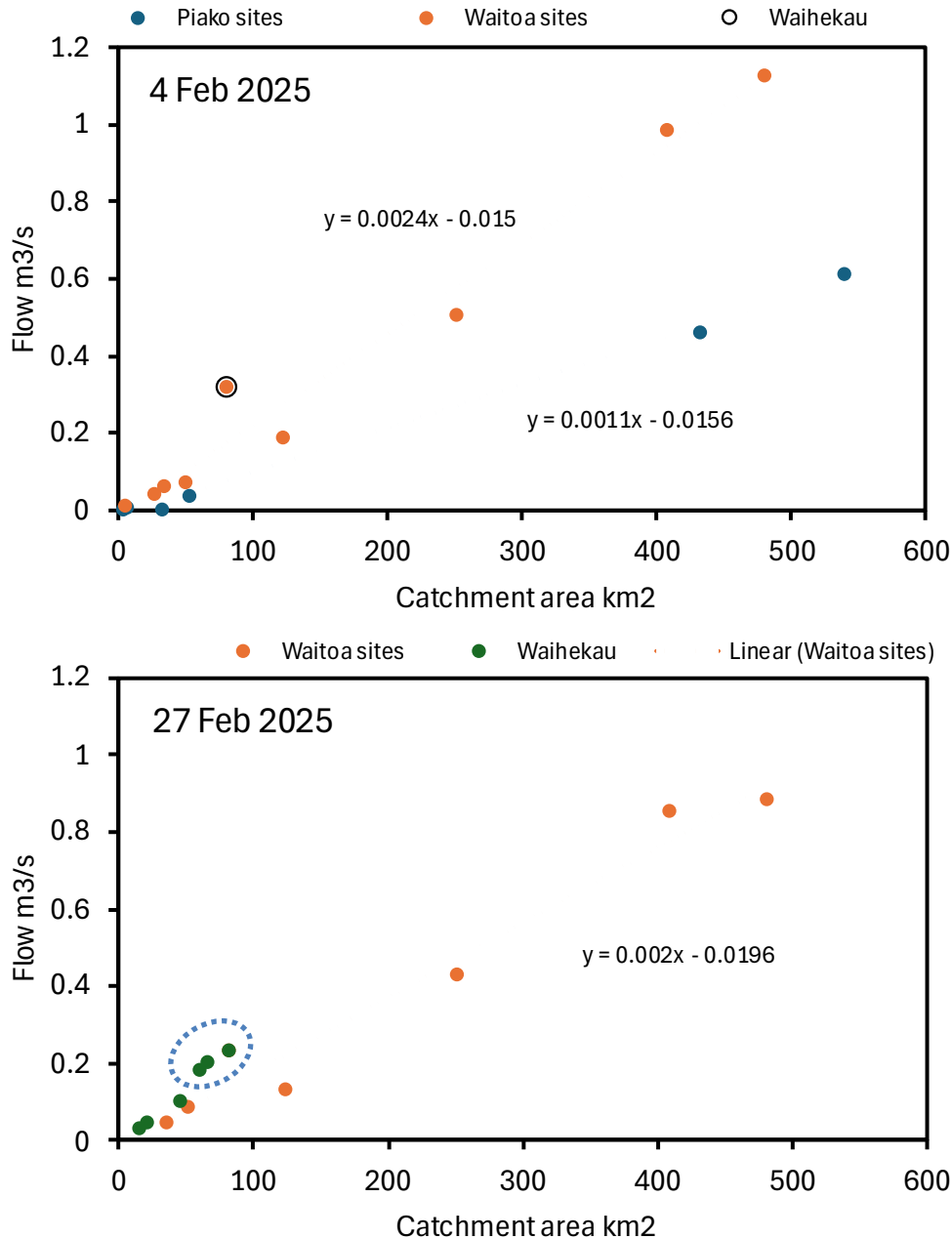


Figure 34 There was more flow in the Waitoa than the Piako, as demonstrated by these same day gauged flows plotted against catchment area. The upper plot is from gaugings conducted 4 Feb 2025 (sites on the mainstem and tributaries, Table 4). Note the Waiheka Stream produced more flow per catchment area (black circle). The lower plot revisits the Waitoa sites some weeks later, along with more sites on the Waiheka (27 Feb 2025). Note the higher discharge per catchment area in the lower Waiheka Stream (dashed circle).

10 Discussion and Recommendations

The Piako River supports a diverse range of plants and animals, but is falling short on several attributes for ecosystem health, including oxygen and temperature (Figure 1).

Previous NIWA reports examined how oxygen and temperature changed with flow (Franklin 2014, Graham et al. 2018). Flow recommendations presented here are a revision of what is presented in the earlier NIWA reports. This revision builds on the data collected by NIWA for the previous report, plus data collected subsequently for Waikato Regional Council. After reprocessing the data with quality control, the data were sufficient to provide robust limits on water use. Oxygen was measured under extreme low-flow conditions, including 2013 and 2021, which were the second and third driest years⁷ respectively since records began in 1973. This reduces uncertainty in what oxygen levels are expected during low flow conditions. It does not eliminate uncertainty altogether, and regulators must accept some level of risk when setting limits on water use - there is a risk of harm to irrigators and a risk of harm to stream ecosystems.

10.1 Oxygen

River flow is necessary, but not sufficient, to support stream ecosystems. A combination of activities will need to be managed to improve ecosystem health, including water use, point discharges and riparian shade. To inform better management of water use for adequate oxygen, this report attempts to isolate the water use signal from other drivers, including:

- temperature - by using oxygen saturation instead of concentration
- solar cycle – by using oxygen daily minima to capture the period when photosynthesis is less likely to conceal reduced reaeration
- rainfall runoff events - by excluding periods of rapidly changing flow
- water quality, plant growth and other unmeasured factors, by using quantile regression to define the relationship between oxygen and flow

A decline in oxygen with flow was confirmed for several sites in the Piako catchment, including:

- Piako at Paeroa-Tahuna Rd
- Piako at Kiwitahi
- Waitoa at Waharoa
- Waitoa at Puketutu

A general observation emerging from the results is the common response of oxygen to absolute flow *magnitude*, rather than percent flow *change*. The flow required to achieve a given oxygen level is of a similar magnitude across sites, despite the large difference in stream size (Table 5). For example, 0.210 m³/s to achieve band C at Waharoa, compared to 0.249 m³/s at Paeroa-Tahuna Rd, despite the much larger flows at Paeroa-Tahuna Rd. This is further supported by data from smaller streams, such as the Piakoiti (Figure 15). This pattern held for low gradient sites, but not for steeper streams flowing off the hills, like Piakonui Stream at Piakonui Rd, where oxygen was not flow dependent. This is consistent with a global study that reported hypoxia was more likely in warmer, smaller, and lower-gradient rivers (Błaszczak, et al. 2022) and higher reaeration is expected for the steep, turbulent streams (Ulseth et al. 2019). In Hawke's Bay, this interaction of flow and channel slope was brought together using Froude number (Wilding, 2016). Froude number⁸ generally increases with flow at a site, and increases with slope between sites, enabling scaling of flow requirements across catchments.

Oxygen-based flow recommendations are not included for the Piakonui Stream at Piakonui Rd (753_4). Graham et al. (2018) did not observe a relationship between oxygen and flow (reproduced in Figure 7), or between temperature and flow, for the Piakonui site, despite the

⁷ 7 day annual low-flows at Paeroa-Tahuna Rd were 2nd and 3rd lowest in 2013 and 2021 respectively, for period 1973 to 2023.

⁸ Froude number = velocity / square root(9.8 x depth)

wide range of flows monitored. Steep streams with cobble riffles, like this Piakonui site⁹, are expected to produce strong turbulent mixing and bubble entrainment (Hall, et al. 2019, Ulseth et al. 2019). So long as the oxygen reaeration exceeds the rate respiratory demand, oxygen will be maintained near saturation levels.

Recommendations are also omitted for the Waitoa at Puketutu. Oxygen did decline at lower flows at this site. However, specifying a separate minimum flow for this site is unnecessary because the next site downstream (Waharoa) provides adequate representation of the flow requirements at Puketutu (Figure 22).

Another site where a relationship between oxygen and flow was not observed was Waitoa at Mellon Rd. Other lines of evidence indicate that a decline in oxygen would occur at flows less than that monitored. For example, nearby sites experienced a similar lack of response across the range of flows observed at Mellon Rd, with declining oxygen occurring at lower flows than the Mellon Rd has experienced to date (Figure 24). In the absence of better information, I have used the oxygen-flow relationship from Paeroa-Tahuna Rd to estimate the relative reduction in oxygen at Mellon Rd at flows lower than that observed. This approach only enables the estimate of relative change in oxygen with flow (not oxygen magnitude) because the magnitude of oxygen differed between the two sites. This provides a conservative estimate of how much further oxygen may decline with future flow reductions, but it does not provide a robust estimate of absolute oxygen levels at Mellon Rd.

The complexities of the tidal reach are discussed by Graham et al. (2018). A correspondingly complex model would be required to predict oxygen at any point in time and space in the tidal reach. The NIWA observational data are presented in this report, and I consider the surveys adequate to demonstrate the relatively low sensitivity of oxygen in the tidal reach to existing levels of water use.

The concept of flow in the tidal reach is very much simplified for the purpose of this report. I have followed the NIWA report in using flow as measured at the two upstream recorders (Paeroa-Tahuna Rd plus Mellon Rd). In addition to ignoring the many tributaries entering the river downstream of these monitoring sites, this also ignores the complex flow patterns resulting from tidal influence. These vary from reverse flows closer to the mouth, to no flow at locations further upstream, to flow in both directions at sites where the heavier saltwater moves upstream beneath the freshwater outflow. And all of that swapping and changing over the tidal cycle. The freshwater inflow to the tidal reach from the recorder sites does not capture that complexity. The response is considered in terms of freshwater outflow simply because that is the variable being managed. Tidal height is not. The discharge of organic matter and nutrients may be more critical for the tidal reach than water allocation.

The NIWA study attempted to control for the tidal influence by conducting all longitudinal survey about high tide. Choosing high tide is more likely to capture oxygen at its worst. But it is low tide when freshwater outflow, and therefore water allocation, is likely to be the primary driver of oxygen reaeration (Wilding *et al.* 2012).

Given the quantified relationships between oxygen and flow, the next step is selecting minimum flows based on that relationship. Three options are considered in this report for setting minimum flows to protect stream ecosystems. These options are explained below, followed by Table 5 which summarises the minimum flows generated using each option, at each site.

10.1.1 Option 1 – Minimum flow at a target oxygen level

To meet targets for ecosystem health, one approach is to identify an oxygen target, then adopt a minimum flow that meets that oxygen target, regardless of the extent to which water use

⁹ Slope 5 m/km from 2019 LiDAR, compared to <2 m/km at other sites in Table 3.

contributes to low oxygen levels. If that approach is adopted, then the flows predicted to achieve each attribute band can be selected from Table 5. These were calculated using the oxygen-flow equations developed for each site (Figure 10, Figure 12, Figure 19, Figure 28).

The 2018 NIWA report offered flows associated with a given oxygen target (reproduced here in Table 1). Comparing the NIWA values to the revised flows presented here, the biggest difference is for Paeroa-Tahuna Rd where the flow required for B Band decreased from 1.4 m³/s, in the NIWA report, to 0.71 m³/s in this report. The NIWA reports do not describe how the flow requirements were derived, and presumably differed to those used here. However, I expect the difference in flow magnitude is mainly due to quality control undertaken for this report, which revealed extended periods when the oxygen sensors were not measuring water column oxygen, likely due to sensor fouling (see Figure 9). Omitting those periods raised the oxygen level expected for a given flow, resulting in less flow needed to meet a given target.

10.1.2 Option 2 – Minimum flow allowing for a 10% reduction in oxygen

In the same report that developed oxygen attributes for the NPSFM, Davies-Colley et al. (2013) recognised that some stream types may not be able to achieve the recommended oxygen levels due to natural constraints (e.g. low oxygen groundwater, high macrophyte abundance). This problem is not unique to New Zealand and the authors described the use of a minimum acceptable concentration of 90% of natural oxygen concentrations in such cases.

This problem of reduced natural potential was also acknowledged in the NPSFM (section 3.32 – *Naturally occurring processes*). The reduced oxygen potential for low-gradient streams, and irreversible human conditions, is often factored in during the implementation phase after national guidelines are set (e.g. UKTAG 2008; Washington Administrative Code [173-201A-260](#)). For water allocation, 10% is often used as a default level for flow and habitat reduction that provides a high level of protection to aquatic ecosystems (e.g. Beca 2008, Wilding 2018, Hay and Hayes 2025).

In applying the concept of natural potential, we can consider the scenario under which there is no water use as being the most natural condition that can be achieved by restricting water use alone. Oxygen achieved A Band (NPSFM criteria) at the naturalised Q5 flow for only one site – Piakonui Stream at Piakonui Rd. This was also the site where oxygen did not respond to flow. Clearly, the Piakonui is a stream that can naturally sustain high oxygen levels across a range of flow conditions. For the remainder of sites, moving to a more natural flow pattern (i.e. ceasing all consented water takes) would not achieve the NPSFM A Band.

Therefore, the Option 2 minimum flows were calculated as the flow providing 90% of the oxygen level provided by the naturalised Q5 flow. These are listed as Option 2 in Table 5, and were calculated using the oxygen-flow equations developed for each site (Figure 10, Figure 12, Figure 19, Figure 28).

10.1.3 Option 3 – Minimum flow allowing pre-existing water use

This option is simply the observed flow under the existing water use regime, together with the level of oxygen this provides (Table 5). It represents a status quo option in terms of existing water use. Note, this represents actual water use, which is less than the total allocation authorised by all resource consents. Water users rarely take their full allocation and are unlikely to use their full allocation at the same time as others.

Where Option 3 minimum flows are less than the minimum flow that is set in the regional plan (column 4), the river is over allocated. Setting minimum flows at existing allocation levels would reduce the frequency of water use restrictions, increasing reliability of supply. But it would also exacerbate the existing impact of water use on oxygen levels and the risk to stream ecosystems.

Table 5 Options for flow requirements (m³/s) to meet different oxygen targets. These were calculated using the oxygen-flow equations developed for each site (Figure 10, Figure 12, Figure 19, Figure 28). Flows denoted * are outside the observed flow range.

Site	Site ID	Q5nat	Existing min. flow (WRP Table 3-5)	Option 1a	Option 1b	Option 1c	Option 2	Option 3	comment
				Band A/B 87.7% O2 sat. (8 mg/L O2 conc. at 20 C)	Band B/C 76.7% O2 sat. (7 mg/L O2 at 20 C)	Band C/D 54.8% O2 sat. (5 mg/L O2 at 20 C)	Flow for 90% of O2 at Q5nat	Q5mod as at 2024	
Piako at Paeroa-Tahuna Rd	749_15	0.713 m ³ /s for 77% O2	0.64 m ³ /s (90% of Q5nat)	1.547 m ³ /s	0.713 m ³ /s	0.249 m ³ /s	0.505 m ³ /s for 69% O2	0.450 m ³ /s for 67% O2	High confidence
Piako at Kiwitahi	749_10	0.172 m ³ /s for 30% O2	0.16 m ³ /s (95% of Q5nat)	Not reached	0.824 m ³ /s	0.336 m ³ /s	0.158 m ³ /s for 27% O2	0.138 m ³ /s for 22% O2	Low confidence - weir effect
Waitoa at Mellon Rd	1249_18	1.12 m ³ /s for 66% O2	1.01 m ³ /s (90% of Q5nat)	Not reached	Not reached	< 0.6* m ³ /s (lowest observed)	0.673 m ³ /s for 59% O2	0.788 m ³ /s for 66% O2	Low confidence – flow range
Waitoa at Waharoa	1249_38	0.197 m ³ /s for 54% O2	0.187 m ³ /s (95% of Q5nat)	1.378 m ³ /s	0.627 m ³ /s	0.210 m ³ /s	0.138 m ³ /s for 48% O2	0.150 m ³ /s for 50% O2	Moderate confidence
Piako tidal (inflow)	749_15 + 1249_18	1.83 m ³ /s for 3.2 mg/L	1.28 m ³ /s (70% of Q5)	8.71 m ³ /s	7.28 m ³ /s	4.43 m ³ /s	1.38* m ³ /s for 2.9 mg/L O2	1.24* m ³ /s for 2.8 mg/L O2	Low confidence – tide changes flow response

10.2 Recommended minimum flows

The final decision on setting minimum flows and allocation limits for the Piako will be made as part of the review of the Waikato Regional Plan. There are a range of issues to consider when setting minimum flows, with [Policy 1](#) setting out those matters we *should have particular regard to*. This report addresses a subset of those issues, including stream ecology and water quality. It is one step, rather than the final step, in deciding limits on water use for this catchment.

This report presents options for flows to protect stream ecosystems that trigger restrictions on water use at selected sites the Piako River, and these are summarised in Table 5. From those many options, my recommendation for trigger flows to protect stream ecosystems are as follows:

1. A minimum flow of 0.50 m³/s, or 70% of Q5nat (0.71 m³/s), set at Paeroa-Tahuna Rd on the Piako River (749_15).

This adopts Option 2, which allows a 10% reduction, relative to the oxygen provided by Q5nat. At this flow, oxygen daily minima would exceed 50% saturation for 75% of days that flows are stable. I have a high degree of confidence in that prediction, given the narrow scatter of observed values and wide range of flows in the dataset used to calculate this flow. Monitoring at this site is expected to reflect the cumulative effect of surface water and groundwater takes upstream of this point. It is labour-intensive to maintain an adequate flow record at this site, where plant growth and freshwater tides affect the stage-flow ratings. In my opinion, that level of effort is justified, given the competing demands for water in this catchment.

2. A minimum flow of 0.14 m³/s, or 70% of Q5nat (0.20 m³/s), set at Waharoa on the Waitoa River (1249_38).

This adopts Option 2, which allows a 10% reduction, relative to the oxygen provided by Q5nat. At this flow, oxygen daily minima would exceed 50% saturation for 75% of days that flows are stable. I have a moderate degree of confidence in that prediction. The scatter of observed values was wider than Paeroa-Tahuna Rd. The range of flows captured in the dataset extends to extreme low flows. Monitoring at this site is expected to reflect the cumulative effect of surface water and groundwater takes upstream of this point. Data from a site further upstream at Puketutu, plus dawn surveys upstream of Kiwitahi, demonstrate that monitoring at Waharoa adequately represents the broader catchment. This site provides accurate flow data with a reasonable level of effort, and recent upgrades to the small weir on site increase reliability of flow monitoring data.

3. A minimum flow of 0.7 m³/s, or 63% of Q5nat (1.12 m³/s), set at Mellon Rd on the Waitoa River, but with water use restrictions triggered at Waharoa (1249_38) using a correlated flow of 0.14 m³/s

The Option 2 minimum flow was rounded up from 0.673 to 0.7 m³/s. Based on the lack of oxygen response to flow across the observed flow range (0.62 to 14 m³/s), I am confident that water use has a small effect on oxygen at flows greater than 0.7 m³/s. It is important to set an allocation limit at this site for two reasons. First, providing adequate freshwater inflows to the tidal reach requires adequate flow from Mellon Rd plus Paeroa-Tahuna Rd. Combined, the minimum flow of the two sites (0.7 + 0.5 = 1.2 m³/s) is expected to limit oxygen depletion to 0.4 mg/L in the worst section of the tidal reach of the Piako River. Second, the cumulative effect of groundwater use in the Southern Hauraki Aquifer is expected to be realised at Mellon Rd. But I do not recommend continued monitoring at this site for triggering restrictions on surface water use. Instead, the Waharoa site (located upstream) provides a more reliable record without the need for the Mellon Rd weir that creates a 1 km backwater, and any associated effects on oxygen levels. Restrictions for

surface takes affecting flows at Mellon Rd can be triggered when flows at Waharoa reach $0.14 \text{ m}^3/\text{s}$ ¹⁰.

Minimum flows for Option 2 are expected to be less sensitive to uncertainty than Option 1. The absolute oxygen level associated with a given flow varies more than the relative change in oxygen. Additionally, oxygen levels show little response to flow at high flows, at which point large increases in flow produce small increases in oxygen. For example, omitting a few outliers from the Kiwitahi data would decrease the flow required to achieve A Band by 112 L/s (Option 1a). The same outliers only change the flow requirements under Option 2 by 4 L/s (a 14% and 3% change, respectively).

This report focuses on oxygen and temperature for developing flow recommendations. The rationale for that focus is explained in Section 5. There is no end to the mechanisms by which flow can influence stream ecosystems, given that flow is a master variable. Oxygen is a critical issue for flow management in the Piako, given the overlap between the likely impact of low oxygen on stream ecosystems and the potential for water use to constrain oxygen. In comparison, temperature is likely to impact stream ecosystems but is less affected by water use.

Oxygen is less likely to be a critical issue in steeper tributaries of the Piako. The NIWA investigations that form the basis of this report did not consider habitat requirements for steeper tributaries, like the Piakonui (e.g. depth, velocity). However, flow requirements for oxygen at sites further downstream are expected to limit water allocation from the Piakonui sub-catchment, providing a level of protection for fish habitat in the Piakonui. And allocation limits have already been reached by water takes that are located downstream of this site (compare Kiwitahi and Paeroa-Tahuna Rd in Figure 4). Further investigations therefore risk delaying flow protections under the regional plan without any change to the water allocation decision.

Generally speaking, it is possible to over-allocate water from tributaries while remaining within the allocation limits at the minimum flow sites listed in the regional plan. For example, with a large take on a very small tributary. Franklin et al. (2014) provide a tool for estimating where in the catchment stress points could arise, and they tested that tool in the Piako catchment. The localised effects of individual takes are expected to be accounted for during the consenting process for each take (e.g. using default allocation limits), rather than through the limits on allocation that are specified in the regional plan for mainstem sites.

The minimum flow recommendations included in this report assume most of the allocation methods set in the regional plan will remain the same, along with the protections these afford. In particular, I assume the allocation will be limited to Q5 minus the minimum flow, thereby limiting cumulative effects of both surface water and groundwater takes (compared to, say, mean flow minus the recommended minimum flow). Likewise, it is assumed that these recommendations will be used to limit run of river takes. Any dams or water storage proposals would necessitate further investigation of the additional effects of changing the flow regime (e.g. reduced high flows, increased low flows).

Groundwater takes from the Southern Aquifer are expected to deplete river flows (Hemmings et al. 2022). I recommend any ambiguity in the policy wording be resolved to ensure the cumulative effect of these takes is managed by limiting the total allocation of groundwater as part of the surface water allocation. Minimum flow restrictions may be less effective in managing the instantaneous effects of groundwater use (due to lags), but allocation limits are appropriate for managing the cumulative effects of groundwater takes that persist through the time of greatest impact on stream ecosystems.

¹⁰ Based on a correlation of 87 same day gaugings, after omitting 6 pairs because of rapidly changing flows. This predicted a flow of $0.729 \text{ m}^3/\text{s}$ at Mellon Rd when flow at Waharoa was $0.14 \text{ m}^3/\text{s}$ (Mellon Rd = $3.6278 \times \text{Waharoa}^{0.816}$, $R^2 = 0.875$).

The recommended minimum flows were calculated relative to Q5nat – the annual low flow with a 1 in 5 probability of occurring in any given year, after adding back in estimated actual use by consented water takes. If these minimum flows are adopted for use in the regional plan, I recommend expressing them as a percent of Q5nat, as is done in the existing regional plan (see Table 3-5 in the regional plan). This better enables adaptation to climate change, compared to specifying minimum flows in absolute terms, as it avoids the delays created by a full plan change if the Q5 flow changes. The absolute flow will determine the resulting oxygen level, however the proportional change method (Option 2) recognises water use as a contributing factor to reduced river flows. Climate is the primary determinant of flow magnitude.

The location of minimum flows sites is sometimes disregarded as an operational matter. But it is an important decision. The number of staff and the financial resources limit the number of sites that council can monitor. Adding sites also adds complexity, which increases the likelihood of mistakes as new staff and new water users must understand the limits they are to operate under. Another important consideration is the accuracy of the data produced by a site. Unnecessary irrigation restrictions or unintentional impacts on stream ecosystems are the likely consequence of placing a minimum flow monitoring site in a location where available methods struggle to produce accurate data. It is also important that the sites relate to where people take water and where the impacts are felt (e.g. which groundwater takes affects which springs). In developing the minimum flow recommendations presented here, I have considered these factors, along with the certainty in the minimum flow estimates themselves.

10.3 Temperature, flow and riparian management

The consequence of low oxygen for aquatic life is exacerbated at high temperatures. Metabolic demand for oxygen increases with temperature (Clarke and Fraser, 2004), and eventually a temperature is reached where the increase in oxygen supply to an organism is exceeded by the increase in demand (Verberk and Bilton, 2013). The result is increasing risk of suffocation of aquatic life at higher temperatures, despite oxygen supply increasing with temperature (Verberk et al. 2011).

The effect of water use on temperature was relatively small (e.g. 0.1 °C at Paeroa-Tahuna Road), which is consistent with previous studies in Canterbury (Booker and Whitehead 2021). In contrast, temperature *decreased* to less stressful levels at lower flows at some sites. Such an improvement has been observed elsewhere, including the Ngaruroro River in Hawke's Bay (Wilding 2018, Grant 1977). For the Ngaruroro River, the mechanism of this improvement is likely an increasing portion of cool groundwater as river flows decline, as demonstrated by a 3-dimensional model of river-groundwater interactions that was able to reproduce a decline in temperature at lower flows (*unpubl. thesis*, Ben Tan Zhi Wen, Stanford University). For the Piako River, the critical pathway research demonstrated the increasing portion of deep groundwater at lower flows (e.g. Figure 21 in Stenger, 2022).

I have not provided flow recommendations based on water temperature because of the observed improvement in temperature at lower flows at most sites, and the relatively small effect on temperature at the one site where temperature did *increase* at reduced flow (0.1 °C at Paeroa-Tahuna Rd).

As well as daily *maxima*, the daily *minimum* temperatures are also of concern because daily minima are more likely to occur early morning when oxygen is lowest (no photosynthesis at night). Increased temperatures in the morning would increase the impact of low oxygen by raising oxygen demand for respiration in aquatic life (metabolism increases with temperature in ectotherms). For the study sites, I did not detect a relationship between overnight temperatures (daily minima) and flow (Figure 33). Therefore, the covariance of oxygen and temperature is not expected to exacerbate the effect of reduced flow on stream ecosystems.

This also demonstrates why using oxygen saturation, instead of oxygen concentration, performs better in teasing out the effect of water takes on stream ecosystems. Temperature changes the oxygen concentration by reducing solubility. Therefore, using observed¹¹ oxygen concentrations to examine flow response introduces variability unrelated to water use (in this case, temperature variability).

Restricting run-of-river water use is not an effective way of lowering temperatures for the sites examined. But the management of water temperature is critical to achieving ecosystem health targets for the Piako River and to improving ecosystem resilience at extreme low flows.

Riparian management should be prioritised where flow management alone cannot achieve adequate oxygen supply. Shade is important for reducing temperature, which reduces oxygen demand in fishes. This will be particularly important in streams that experience low oxygen in the afternoon when the temperature is highest (see oxygen maxima plots, e.g. Figure 11).

Riparian shade can also improve oxygen supply by reducing aquatic plants. Reducing the plant biomass can reduce the respiratory demand on oxygen, in addition to increased oxygen supply by allowing the water to move faster. I investigated the interaction between riparian and flow management for streams of the Heretaunga plains (Wilding 2016). For example, sites with more than 70% shade averaged 10-15% more oxygen, for a given depth and velocity.

The [predictions from climate models](#) are uncertain for rainfall. Will it get wetter, drier, or both at different times? But not for temperature. We can reasonably expect temperature will increase over and above the significant increases to date. Reducing stream temperature is critical for ecosystem resilience to climate change for streams in the Waikato region, on top of the effects of discharges and water use.

Reduced stream temperature was one of the few realised benefits of riparian management in a [paired catchment study](#) in Whatawhata (Waikato tributary), and contributed to the observed improvements in macroinvertebrate communities there. The length of stream that requires planting for the purpose of shading is shorter than the length of stream that delivers contaminants during storm runoff, given that stream length contracts at lower flows (Sidle et al. 2000, McGlynn & McDonnell 2003, Godsey & Kirchner 2014, Wilding and Parkyn 2006).

Smaller streams are easier to shade, such as the headwater streams included in the Whatawhata study. As a rule of thumb, Rutherford, et al. (2021) suggested that trees of a height that are similar to the width of the stream will provide ecological benefits. Therefore 15 m wide streams can realistically be shaded with native plants in New Zealand, where many species reach 15 m high (McGlone et al. 2010). Within this limit, canopy closure would occur more rapidly after planting beside narrower streams. Oxygen was typically more depressed in smaller streams in the Piako catchment (for low gradient sites), given the apparent response of oxygen to absolute flow (Section 10.1). For wider mainstem sections of the Piako, the benefit of riparian shading might be limited to providing mobile species (e.g. fish) a refuge in shaded tributaries.

10.4 Other matters

I have refrained from recommending Kiwitahi as a minimum flow site. Various lines of evidence point to the backwater behind the weir being responsible for lower oxygen than expected for a given flow. Oxygen was higher, for a given flow, from continuous data collected at sites upstream of the Kiwitahi weir backwater (Figure 15). And oxygen was higher from spot measurements immediately upstream and downstream of the Kiwitahi weir backwater about dawn (Section 7.2). Kiwitahi was also an outlier in a region wide survey of oxygen state, sharing

¹¹ This is more of a problem for observational studies, given most oxygen models hold temperature constant.

the distinction of less than expected oxygen with other monitoring sites associated with impoundments (Wilding, 2024). A Hawke's Bay study also found low oxygen levels at sites with weirs (Wilding, 2016). There, the reduction in oxygen level was consistent with the increase in depth, and decrease in channel slope produced by the weir (section 2.3 in Wilding, 2016).

The mechanism for the effect of a weir on oxygen is clear, with many previous studies describing the drop in reaeration rate as depth increases and velocity decreases (Cox 2003), and the Kiwitahi weir achieves both over an extended length of river.

Reduced shear velocities in the weir backwater also allow accrual of more organic matter in the sediment. The larger pool of water can also support a greater biomass of aquatic plants, adding to respiratory demand. The contribution of organic matter and plant growth was demonstrated by the anomalous high rates of respiration and photosynthesis for Piako at Kiwitahi reported by Clapcott and Doehring (2015). The multiple lines of evidence, including the recovery of oxygen levels both upstream and downstream of the weir backwater (Figure 16), indicates that reduced reaeration and increased respiration are mechanisms of the weir effect rather than a competing explanation.

The Kiwitahi site is therefore not representative of the upper Piako River, and results from this site should not be used to set flow limits for the river. Ecosystem metabolism estimates based on Kiwitahi weir data are also unlikely to be representative of the Piako River. Given the importance of oxygen for other variables (e.g. pH, speciation of nitrogen compounds), it also brings into question the representativeness of the state of the environment data collected from this site.

Point discharges of organic matter may be contributing to the suppression of oxygen levels at some sites (over and above diffuse discharges to all sites). Notably, the Waitoa River at Mellon Rd experienced rapid drops in oxygen at times that could not be explained by flow changes or sensor problems. Elevated respiration rates were confirmed for the Waitoa at Mellon Rd by Clapcott and Doehring (2015), second only to Kiwitahi in the Piako catchment. The weir at Mellon Rd may be exacerbating accrual of organic matter and reducing reaeration. This is in addition to any effect of point discharges that better explain the rapid drops in oxygen, regardless of flow.

The occurrence of low oxygen conditions, even when flows are high at Mellon Rd, suggests that the reaeration rate is not adequate at high flows. Dilution of organic matter will improve at high flows, but reaeration does not increase enough to offset the extra oxygen demand caused by increased organic matter. Higher flows can *reduce* reaeration rates in special cases where water depth increases more than water velocity (Cox, 2003). This brings into the question the practice of allowing more point discharges to the Waitoa during periods of high flow. Direct measurement of reaeration (e.g. using gas tracers) would help resolve whether reduced reaeration or increasing organic matter is the cause of low oxygen at high flows.

11 Conclusion

Options are presented to inform the setting of minimum flows and allocations limits in the Piako catchment. This study builds on the previous reports by Graham et al. 2018 and Franklin 2014, focussing on oxygen and temperature and their response to flow. The same data were re-processed using additional quality controls and supplemented with newer data. The previous authors' decision to base the study on observational data increases our dependence on capturing oxygen levels during periods of extreme low flow. The data collected in 2013 and 2021 were particularly useful in describing the oxygen levels under extreme low flow conditions. This sufficed for most sites, and exceptions are noted (e.g. Mellon Rd).

I have provided recommendations for which options adequately protect stream ecosystems from the effects of water use on reduced oxygen levels. Other land use practices must also be managed if ecosystem health is to improve. For example, reducing water use may do little to improve water temperature, compared to riparian shading.

12 References

- Abell, J., Doucet, C., 2024. *Hypoxic events in freshwater ecosystems: A literature review to inform regional management and policy*. Technical report series 2024/19. Hamilton: Waikato Regional Council.
<https://www.waikatoregion.govt.nz/services/publications/tr202419/>
- Bartels, B., 2015. *Upper Piako catchment ecological surveys June 2015*. Kessels Ecology report WRC.00265. Hamilton: Waikato Regional Council. Discover Doc ID 3723999.
- Bates, N., 2021. *Waikato River water quality monitoring programme: Data report 2020*. Technical report series 2021/23. Hamilton: Waikato Regional Council.
<https://www.waikatoregion.govt.nz/services/publications/tr202123/>
- Beca, 2008. Draft guidelines for the selection of methods to determine ecological flows and water levels. Report prepared by Beca Infrastructure Ltd for [Ministry for the Environment](#), Wellington.
- Blaszczak, J.R., Koenig, L.E., Mejia, F.H., Gómez-Gener, L., Dutton, C.L., Carter, A.M., Grimm, N.B., Harvey, J.W., Helton, A.M. and Cohen, M.J., 2023. Extent, patterns, and drivers of hypoxia in the world's streams and rivers. *Limnology and Oceanography Letters*, 8(3), pp.453-463. [DOI 10.5066/P99X6SIR](https://doi.org/10.5066/P99X6SIR)
- Booker, D.J. and Woods, R.A., 2014. Comparing and combining physically-based and empirically-based approaches for estimating the hydrology of ungauged catchments. *Journal of Hydrology*, 508, pp.227-239. [DOI 10.1016/j.jhydrol.2013.11.007](https://doi.org/10.1016/j.jhydrol.2013.11.007)
- Carlin, J.A., Dellapenna, T.M., Strom, K. and Noll IV, C.J., 2015. The influence of a salt wedge intrusion on fluvial suspended sediment and the implications for sediment transport to the adjacent coastal ocean: a study of the lower Brazos River TX, USA. *Marine Geology*, 359, pp.134-147. [DOI 10.1016/j.margeo.2014.11.001](https://doi.org/10.1016/j.margeo.2014.11.001)
- Champion, P.D. and Tanner, C.C., 2000. Seasonality of macrophytes and interaction with flow in a New Zealand lowland stream. *Hydrobiologia*, 441(1), pp.1-12. [DOI 10.1023/A:1017517303221](https://doi.org/10.1023/A:1017517303221)
- Chappell, P.R., 2014. 2nd ed. *The climate and weather of Waikato*. NIWA science and technology series No. 61. [Wellington]: National Institute of Water & Atmospheric Research Ltd (NIWA). <https://webstatic.niwa.co.nz/static/Waikato%20ClimateWEB.pdf>
- Clapcott, J. and Doehring, K., 2015. *Temporal variation in ecosystem metabolism in relation to water quality in the Piako River*. Technical report series 2015/04. Hamilton: Waikato Regional Council. <https://www.waikatoregion.govt.nz/services/publications/tr201504/>
- Clarke, A. and Fraser, K.P.P., 2004. Why does metabolism scale with temperature? *Functional ecology*, 18(2), pp.243-251. [DOI 10.1111/j.0269-8463.2004.00841.x](https://doi.org/10.1111/j.0269-8463.2004.00841.x)
- Clausen, B. and Biggs, B., 1997. Relationships between benthic biota and hydrological indices in New Zealand streams. *Freshwater biology*, 38(2), pp.327-342. [DOI 10.1046/j.1365-2427.1997.00230.x](https://doi.org/10.1046/j.1365-2427.1997.00230.x)
- Crawford, R.M.M., 1992. Oxygen availability as an ecological limit to plant distribution. *Advances in Ecological Research*, 23, pp.93-185. [DOI 10.1016/S0065-2504\(08\)60147-6](https://doi.org/10.1016/S0065-2504(08)60147-6)

- Cromarty, P., Scott, D.A (eds) 1995. *A Directory of Wetlands in New Zealand* (see [Chapter 3](#)). Department of Conservation, Wellington.
- Cox, B.A., 2003. A review of dissolved oxygen modelling techniques for lowland rivers. *Science of the Total Environment*, 314, pp.303-334. [DOI 10.1016/S0048-9697\(03\)00062-7](https://doi.org/10.1016/S0048-9697(03)00062-7)
- Davies-Colley R, Franklin P, Wilcock B, Clearwater S, Hickey C 2013. *National Objectives Framework - Temperature, Dissolved Oxygen & pH: proposed thresholds for discussion*. NIWA Client Report HAM2013-056. Wellington: Ministry for the Environment. <https://environment.govt.nz/publications/national-objectives-framework-temperature-dissolved-oxygen-and-ph/>
- Demars, B.O.L. and Manson, J.R., 2013. Temperature dependence of stream aeration coefficients and the effect of water turbulence: A critical review. *Water Research*, 47(1), pp.1-15. [DOI 10.1016/j.watres.2012.09.054](https://doi.org/10.1016/j.watres.2012.09.054)
- Edwards, R.W. and Rolley, H.L.J., 1965. Oxygen consumption of river muds. *The Journal of Ecology*, pp.1-19. [DOI 10.2307/2257562](https://doi.org/10.2307/2257562)
- Fausch, K.D., Taniguchi, Y., Nakano, S., Grossman, G.D. and Townsend, C.R., 2001. Flood disturbance regimes influence rainbow trout invasion success among five holarctic regions. *Ecological Applications*, 11(5), pp.1438-1455. [DOI 10.1890/1051-0761\(2001\)011\[1438:FDRIRT\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2001)011[1438:FDRIRT]2.0.CO;2)
- Franklin, P.A., Smith, J. and Croker, G., 2013. *Waihou and Piako ecological monitoring 2013*. Technical report series 2014/06. Hamilton: Waikato Regional Council. <https://www.waikatoregion.govt.nz/services/publications/tr201406/>
- Franklin, P.A., 2014. *Dissolved oxygen and temperature dynamics in the Piako catchment*. NIWA Client Report HAM2014-016. Technical report series 2014/50. Hamilton: Waikato Regional Council. <https://www.waikatoregion.govt.nz/services/publications/tr201450/>
- Franklin, P.A., Diettrich, J. and Booker, D., 2014. *Evaluation of a tool for investigating water allocation scenarios: A test case for the Piako catchment*. NIWA Client Report HAM2013-111. Technical report series 2014/52. Hamilton: Waikato Regional Council. <https://www.waikatoregion.govt.nz/services/publications/tr201452/>
- Godsey, S.E. and Kirchner, J.W., 2014. Dynamic, discontinuous stream networks: Hydrologically driven variations in active drainage density, flowing channels and stream order. *Hydrological Processes*, 28(23), pp.5791-5803. [DOI 10.1002/hyp.10310](https://doi.org/10.1002/hyp.10310)
- Graham, E., Franklin, P., Williams, P., and Reeve, K., 2018. *Assessment of dissolved oxygen and flow dynamics in the Piako catchment*. NIWA Client Report 2017308HN. Technical report series 2018/05. Hamilton: Waikato Regional Council. <https://www.waikatoregion.govt.nz/services/publications/tr201805/>
- Grant, P.J., 1977. Water temperatures of the Ngaruroro River at three stations. *Journal of Hydrology (New Zealand)*, 16(2), pp.148-157. www.jstor.org/stable/43944413
- Haidekker, S., 2016. *Life supporting capacity in lowland streams: with a focus on the Karamu catchment*. HBRC Report No. RM16-05 – 4782. Napier: Hawke's Bay Regional Council (HBRC). <https://www.hbrc.govt.nz/assets/Document-Library/Publications-Database/4782-Life-Supporting-Capacity-in-Lowland-Streams-with-a-Focus-on-the-Karamu-Catchment-2016.pdf>

- Hall, R.O. and Ulseth, A.J., 2020. Gas exchange in streams and rivers. *WIREs Water*, 7(1), e1391. [DOI 10.1002/wat2.1391](https://doi.org/10.1002/wat2.1391)
- Hay, J., Hayes, J. 2025. Review of the Wairau River sustainable flow regime. Prepared for Marlborough District Council. Nelson: [Cawthron Report No. 2505](#).
- Hemmings, B.J.C., Cameron, S.G., White, J.T., Rawlinson, Z.J., 2022. In press. *Regional groundwater modelling in the Hauraki Plains, Waikato*. Technical report series 2022/36. Hamilton: Waikato Regional Council. Discover Doc ID 23666874.
- Hicks, B.J., Bell, D.G., 2018. *Boat electrofishing survey of the Awaiti and Bancrofts canals (Tee Head Canal), Piako River system*. Environmental Research Institute Report No. 110. The University of Waikato, Hamilton. <https://researchcommons.waikato.ac.nz/server/api/core/bitstreams/d547617d-b07b-416e-ad07-17f8e6b39f51/content>
- Jampeetong, A. and Brix, H., 2009. Oxygen stress in *Salvinia natans*: Interactive effects of oxygen availability and nitrogen source. *Environmental and Experimental Botany*, 66(2), pp.153-159. [DOI 10.1016/j.envexpbot.2009.01.006](https://doi.org/10.1016/j.envexpbot.2009.01.006)
- Jones, J.I., Eaton, J.W. and Hardwick, K., 2000. The effect of changing environmental variables in the surrounding water on the physiology of *Elodea nuttallii*. *Aquatic botany*, 66(2), pp.115-129. [DOI 10.1016/S0304-3770\(99\)00069-8](https://doi.org/10.1016/S0304-3770(99)00069-8)
- Jowett, I.G., 2010. *Minimum flow requirements for the Topehaehae Stream*. Ian Jowett Consulting Client Report IJ0902 prepared for Matamata Piako District Council. [Doc ID 1694602](#)
- Keegan-Treloar, R., Irvine, D.J., Solórzano-Rivas, S.C., Werner, A.D., Banks, E.W. and Currell, M.J., 2022. Fault-controlled springs: A review. *Earth-Science Reviews*, 230, p.104058. [DOI 10.1016/j.earscirev.2022.104058](https://doi.org/10.1016/j.earscirev.2022.104058)
- Koh, S.S. and Jenkins, B., 2022. *Trends in hydrology and water resources*. Technical report series 2022/06. Hamilton: Waikato Regional Council. <https://www.waikatoregion.govt.nz/services/publications/tr202206/>
- Koenker, R., Portnoy S, Ng PT, et al. 2023. Software Package: *quantreg: Quantile Regression*. R software package version: 5.97, Volume Built: R 4.3.3. [DOI 10.32614/CRAN.package.quantreg](https://doi.org/10.32614/CRAN.package.quantreg)
- Meredith, A., 1990. *Piako-Waitoa fisheries studies*. Hamilton: Waikato Regional Council. [Doc ID 1941264](#).
- Madsen, J.D., Chambers, P.A., James, W.F., Koch, E.W. and Westlake, D.F., 2001. The interaction between water movement, sediment dynamics and submersed macrophytes. *Hydrobiologia*, 444(1), pp.71-84. [DOI 10.1023/A:1017520800568](https://doi.org/10.1023/A:1017520800568)
- McGlone, M.S., Richardson, S.J. and Jordan, G.J., 2010. Comparative biogeography of New Zealand trees: species richness, height, leaf traits. *New Zealand Journal of Ecology* 34, p. 137-151. <https://newzealandecology.org/nzje/2915>
- McGlynn, B.L. and McDonnell, J.J., 2003. Quantifying the relative contributions of riparian and hillslope zones to catchment runoff. *Water Resources Research*, 39(11). [DOI 10.1029/2003WR002091](https://doi.org/10.1029/2003WR002091), 11

- Milhous, R.T. and Bartholow, J.M., 2006. Two analytical approaches for quantifying physical habitat as a limit to aquatic ecosystems. *International Journal of River Basin Management*, 4(3), pp.191-199. [DOI 10.1080/15715124.2006.9635288](https://doi.org/10.1080/15715124.2006.9635288)
- Morris, R.L. and Schmidt, T.M., 2013. Shallow breathing: bacterial life at low O₂. *Nature Reviews Microbiology*, 11(3), pp.205-212. [DOI 10.1038/nrmicro2970](https://doi.org/10.1038/nrmicro2970)
- NPSFM 2020. National Policy Statement for Freshwater Management 2020 – amended October 2024. Wellington: Ministry for the Environment.
- Parveen, M., Asaeda, T. and Rashid, M.H., 2017. Biochemical adaptations of four submerged macrophytes under combined exposure to hypoxia and hydrogen sulphide. *PLoS One*, 12(8), p.e0182691. [DOI 10.1371/journal.pone.0182691](https://doi.org/10.1371/journal.pone.0182691)
- Pingram, M.A., Clapcott, J.E., Hamer, M.P., Atalah, J. and Özkundakci, D., 2020. Exploring temporal and spatial variation in cotton tensile-strength loss to assess the ecosystem health of non-wadeable rivers. *Ecological Indicators*, 108, p.105773. [DOI 10.1016/j.ecolind.2019.105773](https://doi.org/10.1016/j.ecolind.2019.105773)
- Pingram, M., David, B., Squires, N., Smith, J. and Hamer, M., 2023. *Current ecological state of wadeable streams in the Waikato region 2018-2020*. Technical report series 2022/32. Hamilton: Waikato Regional Council. <https://www.waikatoregion.govt.nz/services/publications/tr202232/>
- Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegard, K.L., Richter, B.D., Sparks, R.E. and Stromberg, J.C., 1997. The natural flow regime. *BioScience*, 47(11), pp.769-784. [DOI 10.2307/1313099](https://doi.org/10.2307/1313099).
- Rutherford, J.C., Haidekker, S., Matheson, F.E., Hicks, A., 2021. Modelled effects of channel orientation and tree canopy shape on average shade in streams. *New Zealand Journal of Marine and Freshwater Research*, 57(1), pp. 22-46. [DOI 10.1080/00288330.2021.1950193](https://doi.org/10.1080/00288330.2021.1950193)
- Riis, T. and Biggs, B.J., 2001. Distribution of macrophytes in New Zealand streams and lakes in relation to disturbance frequency and resource supply—a synthesis and conceptual model. *New Zealand Journal of Marine and Freshwater Research*, 35(2), pp.255-267. [DOI 10.1080/00288330.2001.9516996](https://doi.org/10.1080/00288330.2001.9516996).
- Robb, M., 2011. *Fishery survey of the Lower Piako drainage scheme*. Kessels & Associates Report prepared for River Catchment Services, Waikato Regional Council. Hamilton: Waikato Regional Council. [Doc ID 2132010](https://www.waikatoregion.govt.nz/services/publications/tr2011010).
- Sanderson, J.S., Rowan, N., Wilding, T., Bledsoe, B.P., Miller, W.J. and Poff, N.L., 2012. Getting to scale with environmental flow assessment: the watershed flow evaluation tool. *River Research and Applications*, 28(9), pp.1369-1377. [DOI 10.1002/rra.1542](https://doi.org/10.1002/rra.1542)
- Sidle, R.C., Tsuboyama, Y., Noguchi, S., Hosoda, I., Fujieda, M. and Shimizu, T., 2000. Stormflow generation in steep forested headwaters: a linked hydrogeomorphic paradigm. *Hydrological Processes*, 14(3), pp.369-385. [DOI 10.1002/\(SICI\)1099-1085\(20000228\)14:3<369::AID-HYP943>3.0.CO;2-P](https://doi.org/10.1002/(SICI)1099-1085(20000228)14:3<369::AID-HYP943>3.0.CO;2-P)
- Smith, J., David, B., Hicks, A., Wilkinson, S., Ling, N., Fake, D., Suren, A. and Gault, A., 2024. Optimizing eDNA replication for standardized application in lotic systems in Aotearoa, New Zealand. *Environmental DNA*, 6(5), p.e70017. [DOI 10.1002/edn3.70017](https://doi.org/10.1002/edn3.70017)

- Stenger, R., 2022. *Nitrogen lag review*. Internal series 2022/06. Hamilton: Waikato Regional Council.
- UKTAG, 2008. *UK environmental standards and conditions (Phase 1)*. Water Framework Directive, United Kingdom Technical Advisory Group. [SR1-2006](#).
- Ulseth, A.J., Hall Jr, R.O., Boix Canadell, M., Madinger, H.L., Niayifar, A. and Battin, T.J., 2019. Distinct air–water gas exchange regimes in low-and high-energy streams. *Nature Geoscience*, 12(4), pp.259-263. [DOI 10.1038/s41561-019-0324-8](#)
- Vant, B., 2011. *Water quality of the Hauraki rivers and southern Firth of Thames, 2000–09*. Technical report series 2011/06. Hamilton: Waikato Regional Council. <https://www.waikatoregion.govt.nz/services/publications/tr201106/>
- Vant, B., 2023. *Sources of nitrogen and phosphorus in two major catchments in the Waikato Region, 2011–20*. Technical report series 2022/05. Hamilton: Waikato Regional Council. <https://www.waikatoregion.govt.nz/services/publications/tr202205/>
- Verberk, W.C., Bilton, D.T., Calosi, P. and Spicer, J.I., 2011. Oxygen supply in aquatic ectotherms: partial pressure and solubility together explain biodiversity and size patterns. *Ecology*, 92(8), pp.1565-1572. [DOI 10.1890/10-2369.1](#)
- Verberk, W.C.E.P and Bilton, D.T., 2013. Respiratory control in aquatic insects dictates their vulnerability to global warming. *Biology Letters*, 9(5), 20130473. [DOI 10.1098/rsbl.2013.0473](#)
- Wilding, T.K., Brown, E. and Collier, K.J., 2012. Identifying dissolved oxygen variability and stress in tidal freshwater streams of northern New Zealand. *Environmental monitoring and assessment*, 184(10), pp.6045-6060. [DOI 10.1007/s10661-011-2402-2](#)
- Wilding, T.K., Parkyn, S., 2006. *Small headwater streams of the Auckland Region. Volume 1: Spatial extent*. Technical Publication No. 313. Auckland: Auckland Regional Council. [https://webstatic.niwa.co.nz/library/1877416460\(v1\).pdf](https://webstatic.niwa.co.nz/library/1877416460(v1).pdf)
- Wilding, T.K., 2015. *Karamu catchment instream flows for oxygen*. HBRC Report No. 13/25 – 4559. Napier: Hawke’s Bay Regional Council (HBRC). <https://www.hbrc.govt.nz/assets/Document-Library/Publications-Database/4559-RM-1325-Karamu-catchment-instream-flows-for-oxygen-July-2015.pdf>
- Wilding, T.K., 2016. *Spatial oxygen-flow models for streams of the Heretaunga Plains*. HBRC Report No. RM 15/06 – 4744. Napier: Hawke’s Bay Regional Council (HBRC). <https://www.hbrc.govt.nz/assets/Document-Library/Publications-Database/Spatial-oxygen-flow-models-for-streams-of-the-Heretaunga-Plains.pdf>
- Wilding, T.K., 2018. *Addendum to fish habitat modelling for the Ngaruroro and Tutaekuri rivers*. HBRC Report No. 4990 – RM 18-09. Napier: Hawke’s Bay Regional Council (HBRC). <https://www.hbrc.govt.nz/assets/Document-Library/TANK/TANK-Key-Reports/4990-Addendum-Fish-Habitat-Modelling-Ngaruroro-Tutaekuri-010418.pdf>
- Wilding, T.K., 2024. *Developing monitoring attributes for oxygen and temperature in rivers*. Internal series 2023/28. Hamilton: Waikato Regional Council.
- Zahra, N., Hafeez, M.B., Shaukat, K., Wahid, A., Hussain, S., Naseer, R., Raza, A., Iqbal, S. and Farooq, M., 2021. Hypoxia and anoxia stress: plant responses and tolerance mechanisms. *Journal of Agronomy and Crop Science*, 207(2), pp.249-284. [DOI 10.1111/jac.12471](#)

13 Appendix 1 - Flow statistics for Piako River at Paeroa-Tahuna Rd

The observed flow in a stream includes any effect of the water takes. Deciding how much water to allocate starts with an estimate of flow magnitude that does not already include the effect of allocated flow takes. The effects of run-of-river and groundwater takes were estimated by Koh and Jenkins (2022) to derive 'naturalised' Q5 estimates. However, flow statistics for Paeroa-Tahuna Rd were omitted from that report because accounting for the effects of reservoir operation was out of scope. There is a reservoir upstream of Paeroa-Tahuna Rd, and flow alteration could be over-estimated if using abstraction rate alone when water stored in the reservoir is used to moderate the effect of water takes.

Flow statistics were derived for Paeroa-Tahuna Rd for this report starting with the method described by Koh and Jenkins (2022) to correct for water takes. An additional correction was then needed for flow alteration for the reservoir operated by Matamata Piako District Council. The reservoir supplies water to Morrinsville and is located on the Topehahae Stream (a tributary of the Piako) at [Waterworks Rd](#) (Te Miro Mountain Bike Park). The sub-catchment upstream of the dam represents 3% of the total catchment area for the Piako River at Paeroa-Tahuna Rd (Table 6).

The resource consent ([Authorisation 120720.02](#)) sets conditions, including a maximum rate of take of 140 L/s (or 10,000 m³/day), dropping to 119 L/s if the flow at Paeroa-Tahuna Rd drops to less than 633 L/s. A minimum flow of 30 L/s is required to be released from the dam, or 7 L/s for up to 100 days per year. Note that minimum flows for the Topehahae Stream downstream of the dam are not covered in this report. Those were investigated in a separate report that informed the resource consent process ([Jowett, 2010](#)).

The difference between the reservoir outflow and inflow represents the effect of dam operation on river flows (i.e. combined effect of water abstraction and reservoir operation). For outflows, Matamata Piako District Council have a flow recorder downstream of the dam (1053_18) that provides measured flow over the period 2011 to 2023 (operated by [Scottech](#)). This site measures the combined outflow from the dam spillway together with water released as a compensation flow (*pers. comm.* Haley O'Donoghue, 21/6/2024).

To estimate the inflow to the reservoir, flow gaugings completed upstream of the reservoir (Topehahae Stream at Waterworks Rd 1053_9, 1053_13 and 1053_8) were correlated with flow gaugings from the Piako River at Kiwitahi (749_10), for which Waikato Regional Council monitors flow continuously. Of the three gauging sites on the inflow to the reservoir, a relationship was derived using site 1053_13 (Figure 35). Gauging from the other two historic sites were withheld from the correlation to provide a cross check (sites 1053_9, 1053_8). The equation was then used to calculate a continuous synthetic flow record for the upstream gauging site, predicted using the flow record from Kiwitahi. A correction was also made for the increase in catchment area between the upstream gauging site and the monitoring site downstream of the dam (9% increase, based on national hydrology models for mean annual low flow, Table 6).

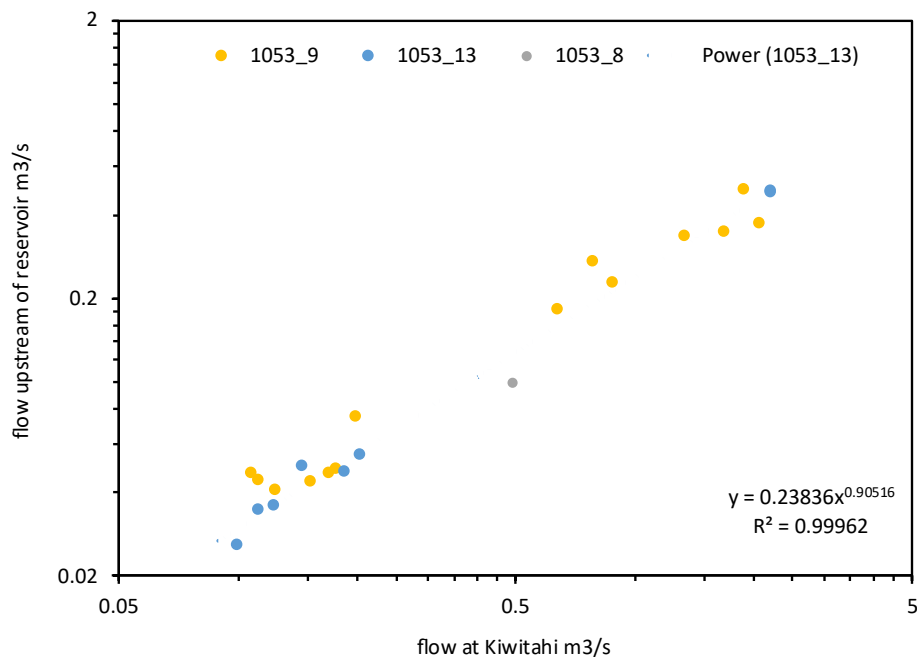


Figure 35 Correlation between flow gaugings on Topehahae Stream upstream of the reservoir and the flow monitoring site Piako at Kiwitahi (749_10). The trendline is fitted to the more recent data from site 1053_13 (blue dots), with older data from 1053_9 and 1053_8 over plotted as a cross check. Note the log scale for both axes. If necessary, a linear equation can provide a close approximation to the plotted power equation ($y = 0.21642.x + 0.01015$).

The impact on annual low flows was estimated using 7-day mean flows at the time of the observed annual low flow at Paeroa-Tahuna Road for the period of overlapping record (Figure 36). On these occasions, the difference between estimated dam inflows and dam outflows was -35 L/s on average (range -23 to -59 L/s). This reduction in flow was less than the measured rate of water abstraction (mean 62 L/s rate of take at that time). Therefore, reservoir operation was reducing the effect of water abstraction by drawing on stored volume, in addition to same day inflows.

A fixed correction of +35 L/s was then applied to all annual low flows used to estimate Q5 for the Piako River at Paeroa Tahuna Rd (1990-2020). A fixed correction was adequate for estimating Q5, in the absence of dam outflow monitoring prior to 2011. Although shorter, the period of outflow monitoring encompassed many dry years (9 years over the period 2011-2022 recorded flows less than observed MALF at Paeroa-Tahuna Rd), increasing confidence that 35 L/s is a suitable correction for estimating Q5. The travel time for water flowing from the dam to Paeroa-Tahuna Rd is expected to have small effect on Q5 estimation because it is based on 7 day mean flows.

Sung Soo Koh then estimated Q5 following the methods from Koh and Jenkins (2022, section 3.2.2), calculating the 20th percentile of the cumulative Weibull distribution curve fitted to the series of naturalised annual low flows from 1990-2020. The naturalised Q5 estimate of 0.713 m³/s is presented with other flow statistics in Table 6.



Figure 36 Time series of annual low flows for the **Piako River at Paeroa-Tahuna Rd** (blue dots), together with the estimated flow change for each year as a result of reservoir operation that supplies Morrinsville (orange dots). The period of dam outflow monitoring is limited to the period 2012¹² to 2022. The annual low flows corrected for all water takes are shown as green circles, which includes a fixed correction of 35 L/s for the Morrinsville supply dam.

Table 6 Hydrology statistics for the Piako River and Topehahae Stream used in this calculation (1990-2020 period of record). Flow statistics calculated here are denoted *. These are presented together with values from Koh and Jenkins (2022) and those modelled by Booker & Woods (2014). The latter were accessed via the [NIWA River Maps](#).

	Topehahae inlet	Topehahae outlet	Piako Kiwitahi	Piako Paeroa-Tahuna Rd
Located ID	1053_9	1053_18	749_10	749_15
REC Reach ID	3064141	3063858	3059826	3054261
Catchment area km ²	17.4	18.8	108	539
Measured MALF m ³ /s				0.647*
Naturalised MALF m ³ /s				0.885*
Measured Q5 m ³ /s			0.138	0.450*
Naturalised Q5 m³/s			0.172	0.713*
Modelled mean flow m ³ /s	0.342	0.368	1.631	8.06
Modelled MALF m ³ /s	0.0777	0.0846	0.236	1.01

¹² The 2011 outflow data was excluded because monitoring started a few days after the annual low flow. Rainfall produced non-steady flows at Kiwitahi and Paeroa-Tahuna Rd at the time monitoring started on Topehahae.

14 Appendix 2 – eDNA results from 2021 sampling

Samples of eDNA (environmental deoxyribonucleic acid) were collected once at each site, except for Piako at Paeroa-Tahuna Rd where sampling was repeated twice a month. Three replicate samples were collected on each occasion, with budget limiting replication below the 6 replicates recommended by Smith et al. (2024).

Samples were analysed by Wilderlab, and all sample results are available through their website. The table below lists the samples collected, including the sample number that you can use to search the [online database](#).

A subset of data collected from Piako at Paeroa-Tahuna Rd is reproduced in the subsequent table.

Sample Metadata:

UID	Site ID	By	Date	Latitude	Longitude	Volume Filtered mL	Site Name
504375	169.2	Tonkin & Taylor	24/03/2021	-37.28964992	175.671016	1000	Hikutaia River @ Old Maratoto Rd
504380	169.2	Tonkin & Taylor	24/03/2021	-37.28964992	175.671016	1000	Hikutaia River @ Old Maratoto Rd
504385	169.2	Tonkin & Taylor	24/03/2021	-37.28964992	175.671016	1000	Hikutaia River @ Old Maratoto Rd
504374	234.11	Tonkin & Taylor	23/03/2021	-37.1573657	175.5905224	1000	Kauaeranga River @ Smiths Cableway/Recorder
504383	234.11	Tonkin & Taylor	23/03/2021	-37.1573657	175.5905224	1000	Kauaeranga River @ Smiths Cableway/Recorder
504384	234.11	Tonkin & Taylor	23/03/2021	-37.1573657	175.5905224	1000	Kauaeranga River @ Smiths Cableway/Recorder
504389	489.2	Tonkin & Taylor	23/03/2021	-37.40080568	175.4243549	1000	Mangawhero Stm (Kaihere) @ Mangawara Rd
504395	489.2	Tonkin & Taylor	23/03/2021	-37.40080568	175.4243549	1000	Mangawhero Stm (Kaihere) @ Mangawara Rd
504400	489.2	Tonkin & Taylor	23/03/2021	-37.40080568	175.4243549	1000	Mangawhero Stm (Kaihere) @ Mangawara Rd
504398	749.15	Tonkin & Taylor	4/02/2021	-37.51345985	175.5063374	1000	Piako @ Paeroa-Tahuna Rd Bridge
504402	749.15	Tonkin & Taylor	4/02/2021	-37.51345985	175.5063374	1000	Piako @ Paeroa-Tahuna Rd Bridge
504403	749.15	Tonkin & Taylor	4/02/2021	-37.51345985	175.5063374	1000	Piako @ Paeroa-Tahuna Rd Bridge
504382	749.15	Tonkin & Taylor	11/02/2021	-37.51345985	175.5063374	1000	Piako @ Paeroa-Tahuna Rd Bridge
504391	749.15	Tonkin & Taylor	11/02/2021	-37.51345985	175.5063374	1000	Piako @ Paeroa-Tahuna Rd Bridge
504392	749.15	Tonkin & Taylor	11/02/2021	-37.51345985	175.5063374	1000	Piako @ Paeroa-Tahuna Rd Bridge
504393	749.15	Tonkin & Taylor	4/03/2021	-37.51345985	175.5063374	950	Piako @ Paeroa-Tahuna Rd Bridge
504394	749.15	Tonkin & Taylor	4/03/2021	-37.51345985	175.5063374	1000	Piako @ Paeroa-Tahuna Rd Bridge
504399	749.15	Tonkin & Taylor	4/03/2021	-37.51345985	175.5063374	950	Piako @ Paeroa-Tahuna Rd Bridge
505772	751.1	Tonkin & Taylor	25/03/2021	-37.72499955	175.630735	1000	Piakoiti twin creeks (Lincoln PKT-1)
505773	751.1	Tonkin & Taylor	25/03/2021	-37.72499955	175.630735	1000	Piakoiti twin creeks (Lincoln PKT-1)
505780	751.1	Tonkin & Taylor	25/03/2021	-37.72499955	175.630735	1000	Piakoiti twin creeks (Lincoln PKT-1)
504365	753.17	Tonkin & Taylor	25/03/2021	-37.72300462	175.6236195	1000	Piakonui Twin creeks (Lincoln PKN-1)
504387	753.17	Tonkin & Taylor	25/03/2021	-37.72300462	175.6236195	1000	Piakonui Twin creeks (Lincoln PKN-1)
504396	753.17	Tonkin & Taylor	25/03/2021	-37.72300462	175.6236195	1000	Piakonui Twin creeks (Lincoln PKN-1)
504358	753.4	Tonkin & Taylor	24/03/2021	-37.82535458	175.6282638	1000	Piakonui Stm Trib @ Piakonui Road
504359	753.4	Tonkin & Taylor	24/03/2021	-37.82535458	175.6282638	1000	Piakonui Stm Trib @ Piakonui Road

504367	753.4	Tonkin & Taylor	24/03/2021	-37.82535458	175.6282638	1000	Piakonui Stm Trib @ Piakonui Road
505771	1043.1	Tonkin & Taylor	25/03/2021	-37.70461548	175.5504641	1000	Toenepi at 1147 Tahuroa Rd
505774	1043.1	Tonkin & Taylor	25/03/2021	-37.70461548	175.5504641	450	Toenepi at 1147 Tahuroa Rd
505781	1043.1	Tonkin & Taylor	25/03/2021	-37.70461548	175.5504641	350	Toenepi at 1147 Tahuroa Rd
504388	1230.1	Tonkin & Taylor	23/03/2021	-37.27137048	175.3569684	1000	Waitakaruru River (Hauraki Plains) @ Coxhead Rd Br
504390	1230.1	Tonkin & Taylor	23/03/2021	-37.27137048	175.3569684	1000	Waitakaruru River (Hauraki Plains) @ Coxhead Rd Br
504397	1230.1	Tonkin & Taylor	23/03/2021	-37.27137048	175.3569684	1000	Waitakaruru River (Hauraki Plains) @ Coxhead Rd Br
504370	1249.12	Tonkin & Taylor	24/03/2021	-37.51668105	175.6015203	1000	Waitoa at Hapai Rd
504378	1249.12	Tonkin & Taylor	24/03/2021	-37.51668105	175.6015203	1000	Waitoa at Hapai Rd
504379	1249.12	Tonkin & Taylor	24/03/2021	-37.51668105	175.6015203	1000	Waitoa at Hapai Rd
504368	1249.15	Tonkin & Taylor	24/03/2021	-37.76485575	175.7413055	1000	Waitoa River@Landsdowne Rd Br
504369	1249.15	Tonkin & Taylor	24/03/2021	-37.76485575	175.7413055	1000	Waitoa River@Landsdowne Rd Br
504377	1249.15	Tonkin & Taylor	24/03/2021	-37.76485575	175.7413055	1000	Waitoa River@Landsdowne Rd Br
504372	749.15	Tonkin & Taylor	8/04/2021	-37.51345985	175.5063374	1000	Piako @ Paeroa-Tahuna Rd Bridge
504362	749.15	Tonkin & Taylor	8/04/2021	-37.51345985	175.5063374	1000	Piako @ Paeroa-Tahuna Rd Bridge
504401	749.15	Tonkin & Taylor	8/04/2021	-37.51345985	175.5063374	1000	Piako @ Paeroa-Tahuna Rd Bridge
504360	749.15	Tonkin & Taylor	20/04/2021	-37.51345985	175.5063374	1000	Piako @ Paeroa-Tahuna Rd Bridge
504366	749.15	Tonkin & Taylor	20/04/2021	-37.51345985	175.5063374	500	Piako @ Paeroa-Tahuna Rd Bridge
504373	749.15	Tonkin & Taylor	20/04/2021	-37.51345985	175.5063374	1000	Piako @ Paeroa-Tahuna Rd Bridge
504356	749.15	Tonkin & Taylor	6/05/2021	-37.51345985	175.5063374	800	Piako @ Paeroa-Tahuna Rd Bridge
504357	749.15	Tonkin & Taylor	6/05/2021	-37.51345985	175.5063374	900	Piako @ Paeroa-Tahuna Rd Bridge
504363	749.15	Tonkin & Taylor	6/05/2021	-37.51345985	175.5063374	1000	Piako @ Paeroa-Tahuna Rd Bridge
504371	749.15	Tonkin & Taylor	21/05/2021	-37.51345985	175.5063374	500	Piako @ Paeroa-Tahuna Rd Bridge
504381	749.15	Tonkin & Taylor	21/05/2021	-37.51345985	175.5063374	500	Piako @ Paeroa-Tahuna Rd Bridge
504361	749.15	Tonkin & Taylor	21/05/2021	-37.51345985	175.5063374	500	Piako @ Paeroa-Tahuna Rd Bridge

Piako River at Paeroa Tahuna Rd					date ->	4/2/21	4/2/21	4/2/21	11/2/21	11/2/21	11/2/21	4/3/21	4/3/21	4/3/21	8/4/21	8/4/21	8/4/21	20/4/21	20/4/21	20/4/21	6/5/21	6/5/21	6/5/21	21/5/21	21/5/21	21/5/21	21/5/21	21/5/21
Scientific Name	Rank	TaxID	Common Name	Group	4/2/21	4/2/21	4/2/21	11/2/21	11/2/21	11/2/21	4/3/21	4/3/21	4/3/21	8/4/21	8/4/21	8/4/21	20/4/21	20/4/21	20/4/21	6/5/21	6/5/21	6/5/21	21/5/21	21/5/21	21/5/21	21/5/21	21/5/21	
Anas platyrhynchos	species	8839	Mallard duck	Birds	414	492	163	870	162	600	520	358	0	1222	886	410	2023	1283	1035	1594	1843	1449	1765	2191	2278	1027		
Porphyrio melanotos	species	72013	Pukeko	Birds	29	28	0	20	17	87	77	0	0	211	34	95	181	31	97	349	653	329	97	11	125	118		
Ardea novaehollandiae	species	390973	White-faced heron	Birds	0	0	0	0	0	0	48	0	0	23	13	0	47	0	14	118	69	92	25	10	0	22		
Phalacrocorax carbo	species	9209	Black Shag	Birds	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	63	116	0	0	0	0	0		
Phasianus colchicus	species	9054	Pheasant	Birds	0	0	0	0	0	0	62	0	0	0	0	0	0	0	0	0	0	0	85	0	0	0		
Turdus	genus	9186	Thrush	Birds	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	74	0	0	0	0	0		
Anas chlorotis	species	75837	Brown teal	Birds	0	0	0	0	0	0	0	0	0	0	0	0	60	0	0	0	0	0	0	0	0	0		
Pavo cristatus	species	9049	Indian peafowl	Birds	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	7	0	40	0	5		
Cygnus atratus	species	8868	Black swan	Birds	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	69	15		
Zosterops lateralis	species	43581	Silveryeye	Birds	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	91	0	0	0	0	0		
Meleagris gallopavo	species	9103	Turkey	Birds	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	45	0	4		
Anserinae	subfamily	2068722	Swans and geese	Birds	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	34	3		
Hirundo neoxena	species	317132	Welcome swallow	Birds	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0		
Anatidae	family	8830	Ducks/Geese/Swan	Birds	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	1		
Todiramphus sanctus vagans	subspecies	497867	Sacred kingfisher	Birds	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0		
Plumatella	genus	34519	Plumatella	Bryozoans	36	20	23	154	0	53	5	13	0	0	12	5	8	0	0	14	17	13	7	0	17	19		
Hydra viridissima	species	6082	Hydra	Cnidarians	11707	1572	887	2809	1768	1590	113	509	0	108	10	22	118	4249	17	277	196	108	148	254	222	1271		
Astrohydra japonica	species	323341	Hydra	Cnidarians	160	398	163	588	295	342	436	929	0	79	33	45	33	12	10	62	51	12	55	70	0	180		
Hydra vulgaris	species	6087	Hydra	Cnidarians	142	506	444	303	390	172	40	16	0	33	21	15	38	0	7	44	17	38	38	12	12	109		
Craspedacusta sowerbii	species	128124	Freshwater jellyfish	Cnidarians	0	0	0	0	16	53	51	0	0	7	0	0	0	0	0	0	9	0	0	0	0	0		
Hydra	genus	6083	Hydra	Cnidarians	0	12	30	22	0	0	12	0	0	0	0	0	10	0	0	13	20	0	0	0	7	6		
Hexanauplia	class	72037		Crustaceans	4	257	82	0	225	14	7	0	0	5	0	5	13	51	13	51	13	51	13	51	13	51		
Paratya curvirostris	species	302712	Freshwater shrimp	Crustaceans	0	7	18	5	0	5	0	4	0	9	43	28	14	0	11	43	34	11	0	26	18	13		
Macrocyclus albidus	species	281258	Copepod	Crustaceans	0	0	0	0	0	81	111	0	0	0	65	0	47	0	0	0	0	0	0	0	0	9		
Malacostraca	class	6681		Crustaceans	0	23	6	0	0	0	7	10	0	0	0	0	0	0	7	10	0	0	6	7	5			
unclassified Macrothrix	no rank	2639238		Crustaceans	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1		
Carassius auratus	species	7957	Goldfish	Fish	518	1918	841	744	611	658	221	522	0	594	1561	3272	503	198	268	341	347	105	350	173	228	665		
Gambusia affinis	species	33528	Mosquitofish	Fish	293	258	42	241	264	362	117	135	0	606	971	835	1022	1405	2641	389	263	488	182	274	149	521		
Anguilla australis	species	7940	Shortfin eel	Fish	49	134	128	181	95	163	399	85	0	429	582	561	540	1778	683	1073	581	638	272	976	313	460		
Gobiomorphus	genus	86236	Bullies	Fish	77	163	199	120	47	216	352	87	0	256	138	158	425	11	126	494	570	379	369	83	275	216		
Cyprinus carpio	species	7962	Koi carp	Fish	17	218	21	152	138	138	660	284	0	37	0	0	0	0	0	0	40	55	0	83	54	23		
Galaxias maculatus	species	61620	Inanga	Fish	0	0	35	29	0	0	0	0	0	26	0	0	40	0	0	306	82	331	52	30	237			
Gobiomorphus basalis	species	432095	Crans bully	Fish	68	0	28	0	0	0	81	111	0	63	0	0	0	60	0	151	199	123	0	0	0	22		
Retropinna retropinna	species	170203	Common smelt	Fish	0	0	0	0	0	0	124	0	0	25	71	17	25	0	40	67	276	108	46	0	0			
Gobiomorphus cotidianus/basalis	species	10000038	Common or Crans bully	Fish	43	97	24	178	0	107	0	0	0	15	0	21	5	14	22	54	26	155	39	89	0			
Anguilla dieffenbachii	species	61127	Longfin eel	Fish	11	25	0	0	0	20	0	0	0	28	59	0	121	0	10	124	123	123	32	0	32			
Chemarrichthys fosteri	species	206139	Torrentfish	Fish	0	0	0	0	0	0	0	18	11	0	0	0	0	0	50	138	0	117	133	97	27			
Mugil cephalus	species	48193	Grey mullet	Fish	0	0	0	0	0	113	76	0	13	0	0	0	0	0	44	54	4	0	0	0	33			
Ameiurus nebulosus	species	27778	Brown bullhead catfish	Fish	0	28	0	0	0	0	69	0	0	0	0	0	37	0	0	0	0	0	0	65	0			
Anguilla reinhardtii	species	48165	Speckled longfin eel	Fish	0	11	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	37	0	0	0			
Osmeriformes	order	41711	Smelts and galaxiids	Fish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0			
Galaxias	genus	51242	Galaxiids	Fish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0			
Percomorphaceae	clade	1489872		Fish	0	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0			
Oxyethira albiceps	species	697957	Micro caddisfly	Insects	119	136	140	93	99	142	129	0	0	3	0	5	16	135	3	49	32	3	16	33	16			
Paroxyethira hendersoni	species	697996		Insects	38	67	85	59	38	88	124	60	0	10	0	0	0	0	21	0	8	3	5	10	29			
Austrosimulium australense	species	10000005	Sandfly	Insects	0	0	0	0	0	0	23	0	0	0	0	0	0	0	0	90	45	7	23	0	9			
Trichoptera	order	30263	Caddisflies	Insects	42	43	0	0	0	0	36	0	0	0	0	0	0	13	0	0	0	0	0	0	7			
Dasybasis bratrakii	species	1547350	Horsefly	Insects	0	0	0	0	0	0	0	53	22	0	0	0	0	0	0	0	0	0	0	0	0			
Ectoposocus briggsi	species	322492	Psoocopteran fly	Insects	0	0	0	0	17	0	0	0	0	0	7	0	0	0	4	58	0	0	6	33				
Limnophyes	genus	190098	Non-biting midge	Insects	0	0	0	0	12	0	0	0	0	0	0	4	102	3	0	0	0	0	0	0	6			
Simulini	tribe	44570		Insects	0	0	0	0	0	0	0	0	0	0	0	0	29	0	0	16	0	0	0	0				
Trichophyesis sp. ANIC1	species	1536083		Insects	0	0	0	0	0	0	0	0	0	5	0	16	28	0	0	0	0	0	0	0				
Lepidoptera	order	7088	Butterflies and moths	Insects	0	0	0	0	0	0	0	0	0	0	0	4	0	4	9	0	6	0	0	0	9			
Cecidomyiidae	family	33406	Gall midges	Insects	0	0	0	0	0	14	0	0	0	8	5	0	0	0	0	0	0	0	0	0				
Hemiptera	order	7524		Insects</																								

