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Assessment of dissolved oxygen and flow dynamics in the Piako catchment

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August 2017

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Executive summary

The Waikato Regional Council (WRC) is responsible for managing the status of water resources in the Waikato Region, including flow and allocation limits in the Piako catchment. The aim of this project was to characterise the dissolved oxygen dynamics in the Piako catchment with a view to identifying potential preventative limits on water abstraction to maintain aquatic biota and ecosystem health.

Dissolved oxygen time series collected from six sites around the Piako catchment showed that dissolved oxygen levels were generally above the National Objectives Framework (NOF) guidelines for protection of ecosystem health. However, dissolved oxygen concentrations at two of the Waitoa sites, Mellon Rd and Puketutu Rd, fell below the NOF national bottom line for both dissolved oxygen attributes on multiple occasions during the summer of 2017.

Maximum water temperatures (measured mid-water column in representative flow) exceeded the preferred temperatures of inanga, bullies, and smelt at all sites. No robust relationships were identified between maximum water temperatures and flow at any of the sites, but there was some evidence of negative associations at some sites in early summer months.

Non-linear relationships were observed between dissolved oxygen concentrations and flow at four of the six sites, consistent with patterns observed in the 2012/2013 monitoring data. These relationships were used to identify the flows that approximate to the attribute boundaries for the NOF guidelines for dissolved oxygen. The approximate flows can then be used to inform minimum flow limits to avoid stress on aquatic organisms due to dissolved oxygen concentrations falling below the guideline protection levels for ecosystem health.

Dissolved oxygen depletion was also observed to occur immediately following high flow events. This suggests that event-based depletion can disrupt the low flow – DO relationship, which has implications for the limit-setting process. Therefore, it is recommended that further monitoring be conducted to investigate event-based dissolved oxygen depletion versus low baseflow-related depletion, and the role of small flushing flows in restoring oxygen during prolonged low flow periods.

The zone of dissolved oxygen depletion, or sag, first identified in the lower river in 2012/2013 was confirmed. Dissolved oxygen concentrations in the sag zone were below the NOF bottom line, indicating significant stress on aquatic organisms was likely. The temporal and spatial extent of the sag appeared to be driven by complex interactions between turbidity, saline intrusion, and freshwater flows. Detailed understanding of the processes driving the observed patterns is needed to enable WRC to make more informed decisions about the allocation of upstream water resources, including minimum flow limits.

Introduction

Background

Waikato Regional Council (WRC) is currently in the process of reviewing the status of water resource availability and allocation in the Piako catchment. Defining water resource use limits that effectively balance both in and out-of-stream water uses, whilst also protecting ecosystem health and aquatic organisms, is a significant challenge for water resource managers. Water use limits are most justifiable if they are developed using scientific tools and transparently linked to clear objectives for both environmental outcomes and water use (Snelder, Rouse et al. 2014).

NIWA has recently carried out studies of the current status of water allocation in the Piako catchment (Franklin, Diettrich et al. 2014) and investigated relationships between flow and dissolved oxygen in the catchment (Franklin 2014a). This has been supported by ongoing ecological monitoring studies in the Piako and Waihou catchments (Franklin, Smith et al. 2013; Franklin, Croker et al. 2014; Graham, Franklin et al. 2015; Graham, Franklin et al. 2016). Building on this initial work, WRC requested that NIWA undertake further work to assist with the process of evaluating water quantity limits in the Piako catchment. The aim of this project was to characterise the dissolved oxygen and water temperature dynamics in the Piako catchment over summer and corroborate the results from an initial investigation conducted in 2012 and 2013.

Project scope

Main stem

The aim of the main stem component of the project was to empirically evaluate the interactions between dissolved oxygen (DO), temperature, and flow in the Piako catchment, with a particular focus on how they may impact instream ecology.

This was to be achieved through the following programme of work:

- Repeating measurements of dissolved oxygen dynamics at the same six sites surveyed during the summers of 2012 and 2013 for Franklin (2014a).
- Analysing the interactions between dissolved oxygen, temperature, and flow.
- Comparing dissolved oxygen concentrations to relevant ecological limits.

The purpose of this work is to support the development of holistic water resource use limits for protecting instream values.

Tidal

The aim of the tidal component of the project was to determine the temporal and spatial dynamics of the dissolved oxygen sag in the tidally affected lower Piako River and how it is influenced by freshwater flows.

This was to be achieved through the following programme of work:

Measuring longitudinal profiles of dissolved oxygen concentrations in the Piako River between the mouth of the river near Pipiroa and the confluence of the Piako and Waitoa Rivers near Maukoro Landing.

Deployment of DO loggers at two sites and an ExoSonde logger at one site in the main stem of the lower Piako downstream of the Paeroa-Tahuna Road for a minimum of two weeks, covering a range of tide heights under summer low flow conditions and to characterise the DO sag in the lower river.

• Methodology

○ Main stem

D-Opto loggers were calibrated and deployed by NIWA and used to collect temperature (°C) and dissolved oxygen (% saturation and mg L^{-1}) data at six sites within the main stem of the Piako and Waitoa Rivers (**Table** Error! No text of specified style in document.**-1**, **Figure** Error! No text of specified style in document.**-1**, from Franklin 2014a). The D-Opto loggers were deployed in early summer on the 6th of January and remained in place until the 26th of March to ensure the full range of summer low flow conditions were captured. The Paeroa-Tahuna (P-T) Road logger was unable to be retrieved on 26/03/2017 due to high water levels, but was recovered on the 13th of June, with complete data recorded for the duration of its deployment. The D-Opto loggers were downloaded, cleaned, and re-calibrated in the field every 2-5 weeks over the course of the summer using 0% and 100% DO saturated standards.

Table Error! No text of specified style in document.**-1: Location of dissolved oxygen monitoring and flow gauging sites from Franklin (2014a).** Piakonui and Puketutu Rd sites do not have flow recorders, therefore flow data from the nearest flow recorder (749_10 and 1249_38, respectively) was used.

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	✓	✓		

Following quality checking of the DO data, time series were plotted and summary statistics derived from the continuous dissolved oxygen measurements at each site. Summary statistics were compared against the current National Objectives Framework (NOF) guidelines (**Table** Error! No text of specified style in document.**-2**) for protection of ecosystem health from the National Policy Statement for Freshwater Management (MfE 2014). The NOF guidelines reflect differing protection levels for aquatic ecosystem health based on the known information about acute and chronic effects of varying levels of dissolved oxygen (Dean and Richardson 1999; Davies-Colley, Franklin et al. 2013; Franklin 2014b). The 7-day mean daily minimum dissolved oxygen concentration was calculated as a rolling 7-day average of the daily minimum dissolved oxygen concentration. The 1-day minimum is equivalent to the daily minimum dissolved oxygen concentration.

Each dissolved oxygen statistic was plotted against mean daily flow to assess the relationships between dissolved oxygen concentrations and flow at each site. The relationship between flow and the dissolved oxygen reaeration coefficient (k_2) was also analysed, because concentration of dissolved oxygen in water has been linked to hydraulic properties (O'Connor and Dobbins 1958). Reaeration coefficients were estimated using the night-time regression method (Hornberger and Kelly 1975; Wilcock, Young et al. 2011) as described in (Franklin 2014a). Only regressions with an $r^2 \geq 0.4$ were used in the analysis of the relationship between k_2 and flow.

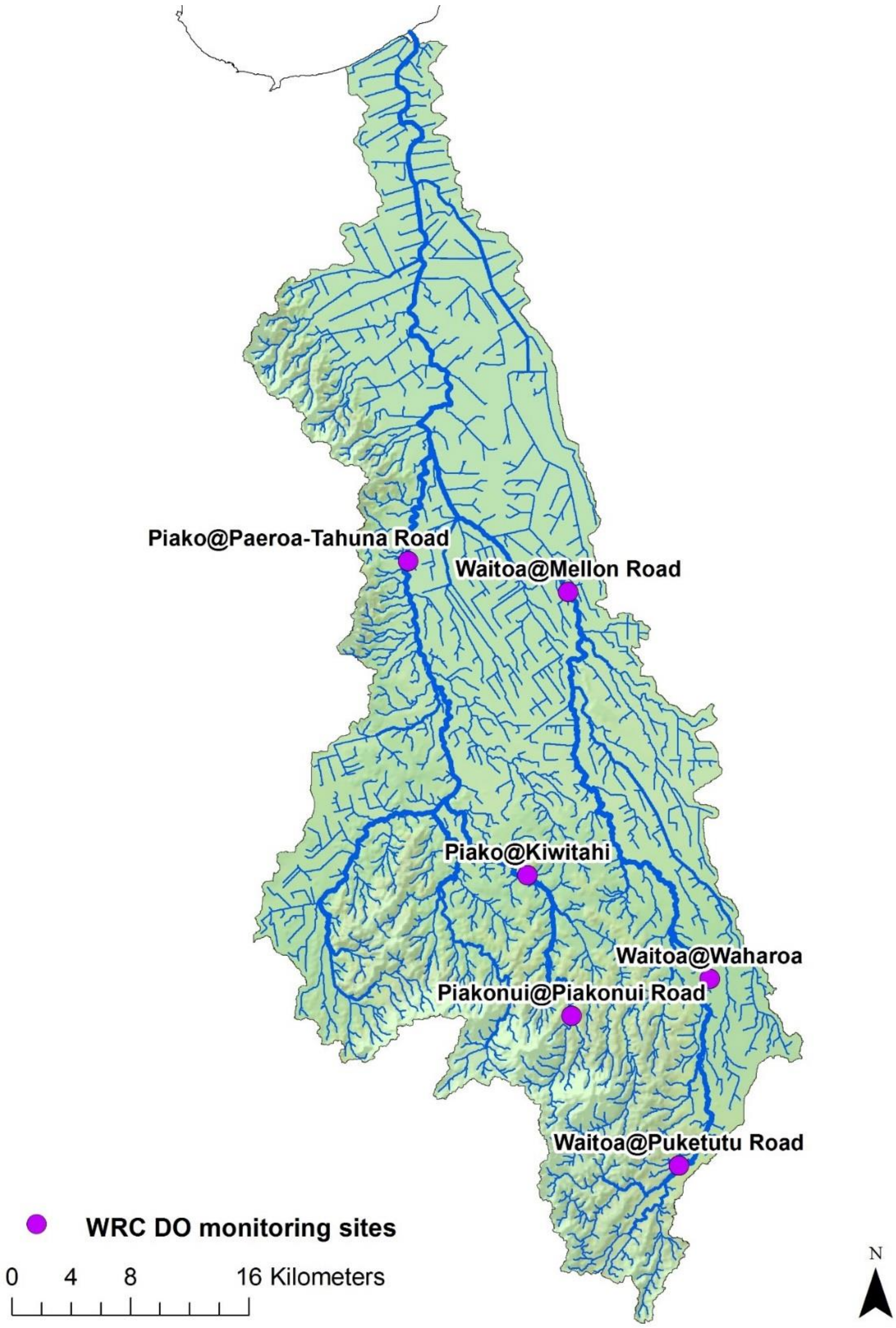

Figure Error! No text of specified style in document.**-1: Location of dissolved oxygen monitoring sites in the Piako catchment.**

Table Error! No text of specified style in document.**-2: National Objectives Framework (NOF) dissolved oxygen guidelines for ecosystem health (MfE 2014).**

Attribute State	7-day mean minimum DO (mg L^{-1})	1-day minimum DO (mg L^{-1})	Attribute State
A	$\geq$ 8.0	$\geq$ 7.5	No stress
B	$\geq$ 7.0 and < 8.0	$\geq$ 5.0 and < 7.5	Occasional minor stress
C	$\geq$ 5.0 and < 7.0	$\geq$ 4.0 and < 5.0	Moderate stress
National bottom line	5.0	4.0	Moderate stress
D	< 5.0	< 4.0	Persistent stress

○ Tidal

Longitudinal profiles of dissolved oxygen concentrations, water temperature, salinity, turbidity, and chlorophyll-a were measured on site using an ExoSonde data logger deployed just below the water surface at 26 locations in the Piako River between the river mouth near Pipiroa in the Piako and the confluence of the Piako and Waitoa Rivers near Maukoro Landing, 37 km upstream of the river mouth (**Figure** Error! No text of specified style in document.**-2**). A total of six profiles were completed, with all surveys beginning at the river mouth near the time of high tide. Surveys encompassed a range of tide and flow conditions.

Additionally, two D-Opto loggers and one EXOsonde logger were deployed between the end of February and the beginning of June in the estuarine zone of the lower Piako to collect high-resolution temporal data. The EXOsonde was placed closest to the mouth of the estuary, at transect site #12, approximately 14 km upstream of the river mouth. The two D-Opto loggers were located at transect sites #15, 18 km upstream, and #19, 25 km upstream.

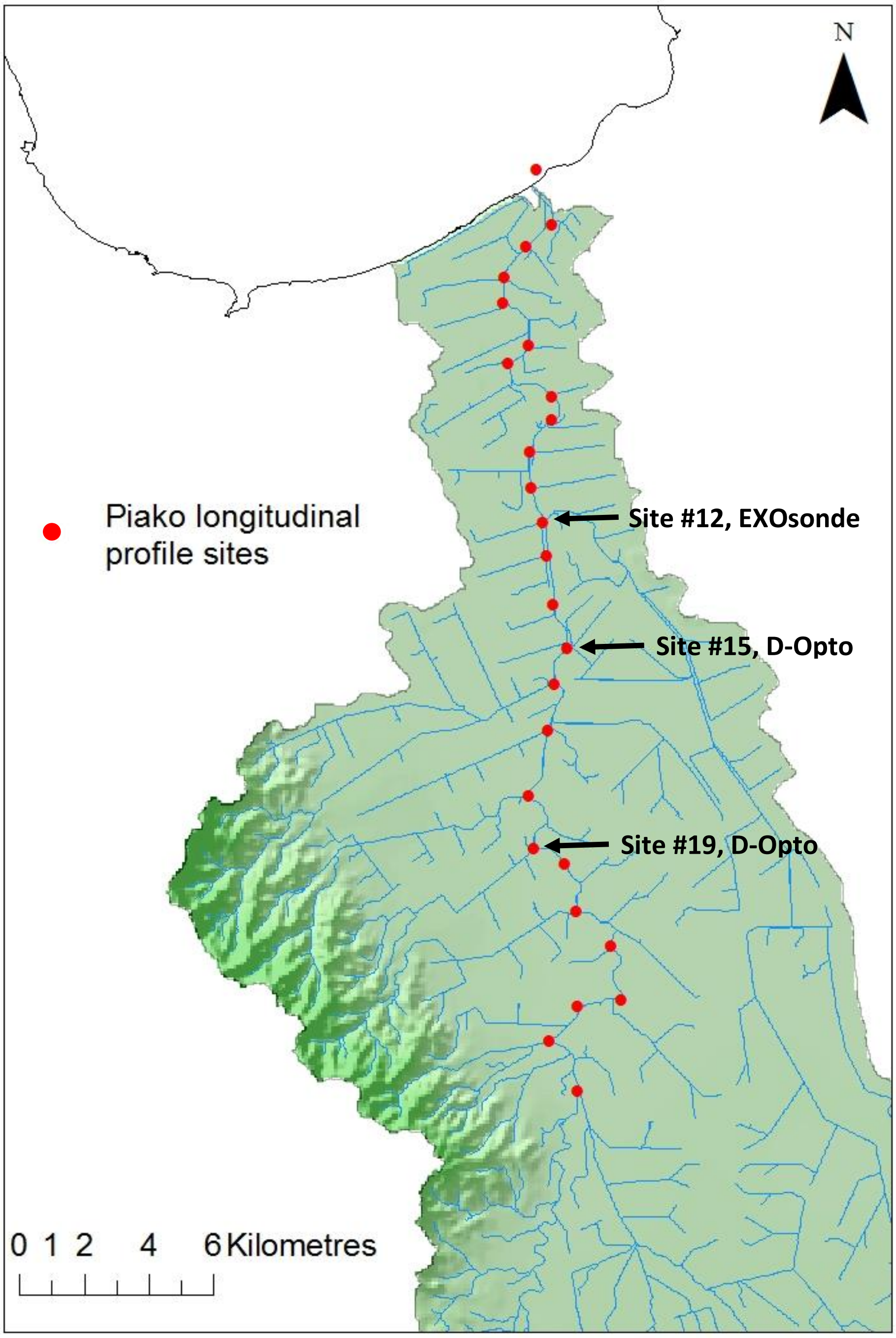

Figure Error! No text of specified style in document.**-2: Location of longitudinal profile sites in the lower Piako River.** The three sites at which high resolution temporal data was also collected via D-Opto or EXOsonde loggers are indicated by arrows.

- # Main stem

  - ## Results

    - ### Flow conditions

River flows were low and stable at all six sites between January and mid-March, when a small flow event occurred (Figure 3-1). A second small flow event occurred in late March, followed by two high flow events in early and mid-April. The second high flow event was an extremely large flood, with the largest flows ever recorded at the Paeroa-Tahuna (P-T) Rd gauging site. Maximum flows during that event ranged between 36 $m^3 s^{-1}$ and 172 $m^3 s^{-1}$ across sites, compared to average baseflows of 0.5 – 1.5 $m^3 s^{-1}$ (**Table** Error! No text of specified style in document.**-3**).

Table Error! No text of specified style in document.**-3: Average baseflow and maximum flow at the six dissolved oxygen monitoring sites during summer 2017.** Piakonui and Puketutu Rd sites do not have flow recorders, therefore flow data from the nearest flow recorder (Kiwitahi and Waharoa, respectively) was used.

Site	Average Baseflow (m^3s^{-1})	Maximum flow (m^3s^{-1})
Kiwitahi	0.5	35.8
Mellon Rd	1.2	136.5
Paeroa-Tahuna Road (P-T Rd)	1.5	171.6
Piakonui	0.5	35.8
Puketutu Rd	0.5	51.3
Waharoa	0.5	51.3

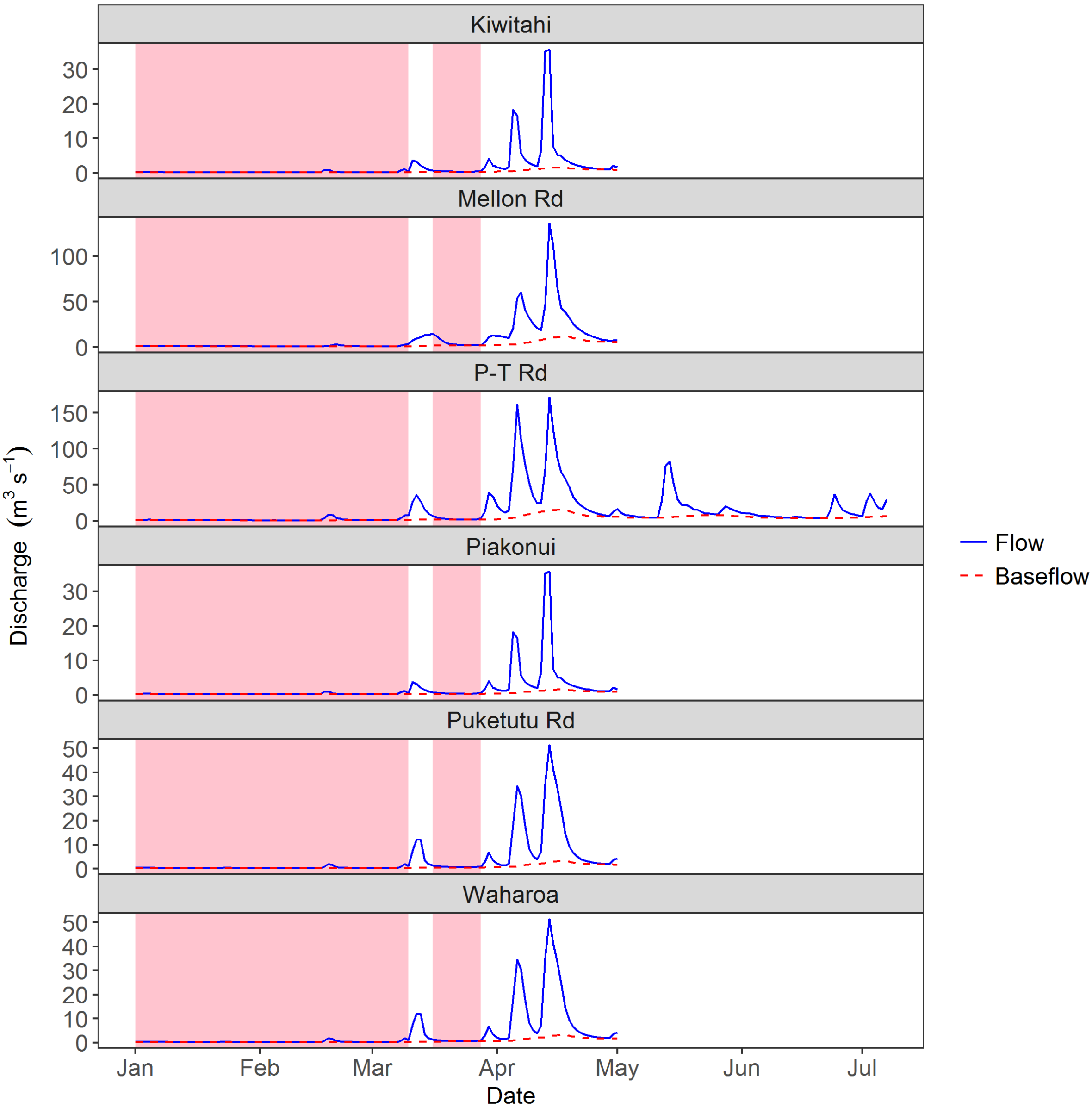

Figure Error! No text of specified style in document.**-3: Flow time series at the six dissolved oxygen monitoring sites over summer 2017.** Low flow periods are shaded in pink; the first low flow interval was between January 1 and March 10, the second low flow interval was between March 16 and March 28.

▪ Water temperature dynamics

Water temperatures during the summer period ranged from a maximum of 25°C in February to a minimum of 13°C in April[1] (**Table** Error! No text of specified style in document.**-4**, **Figure** Error! No text of specified style in document.**-4**). Water temperatures were highest in February and began a seasonal decline in March. Summer maxima were between 23°C and 25°C across all six sites, which exceeds the temperature preferences of most native fish, with the exception of eels (**Table** Error! No text of specified style in document.**-5**). The mean diel variation in summer water temperatures was

[1] If the extended temperature record between April and June from the Paeroa-Tahuna (P-T) Rd is included, the lowest temperature recorded was 9°C in June.

approximately 2°C. Diel variation decreased towards the end of the summer in all sites, and into the winter at the P-T Rd site, due to seasonal effects and the larger volume of water in all sites following the April high flow events. The 2017 temperatures were approximately 1°C warmer than those recorded in summer 2012-2013, when the summer maxima was between 22°C and 24°C across the six sites. The largest difference in temperatures between the 2012-2013 and 2017 measurements was at the Piakonui site, where temperatures generally did not exceed 17°C in 2012-2013, but were regularly above this temperature in 2017. Consequently, in 2017 they fell outside the preferred water temperature ranges of inanga, banded kokopu, and smelt (**Table** Error! No text of specified style in document.**-5**), all of which are known to occur within the Piako catchment (Franklin, Smith et al. 2013; Franklin, Croker et al. 2014; Graham, Franklin et al. 2015; Graham, Franklin et al. 2016). The cause of the increase in water temperature at this site, which was substantially cooler than other sites in summer 2013, is unclear.

Table Error! No text of specified style in document.**-4: Range of temperature values at the six dissolved oxygen monitoring sites in January-April 2017.**

Site	Minimum Temp. (°C)	Mean Temp. (°C)	Maximum Temp. (°C)
Kiwitahi	14.1	19.9	25.2
Mellon Rd	16.1	20.3	23.1
P-T Rd	14.8	19.8	24.2
Piakonui	14.0	18.5	24.1
Puketutu Rd	13.4	19.3	24.2
Waharoa	14.2	18.8	23.2

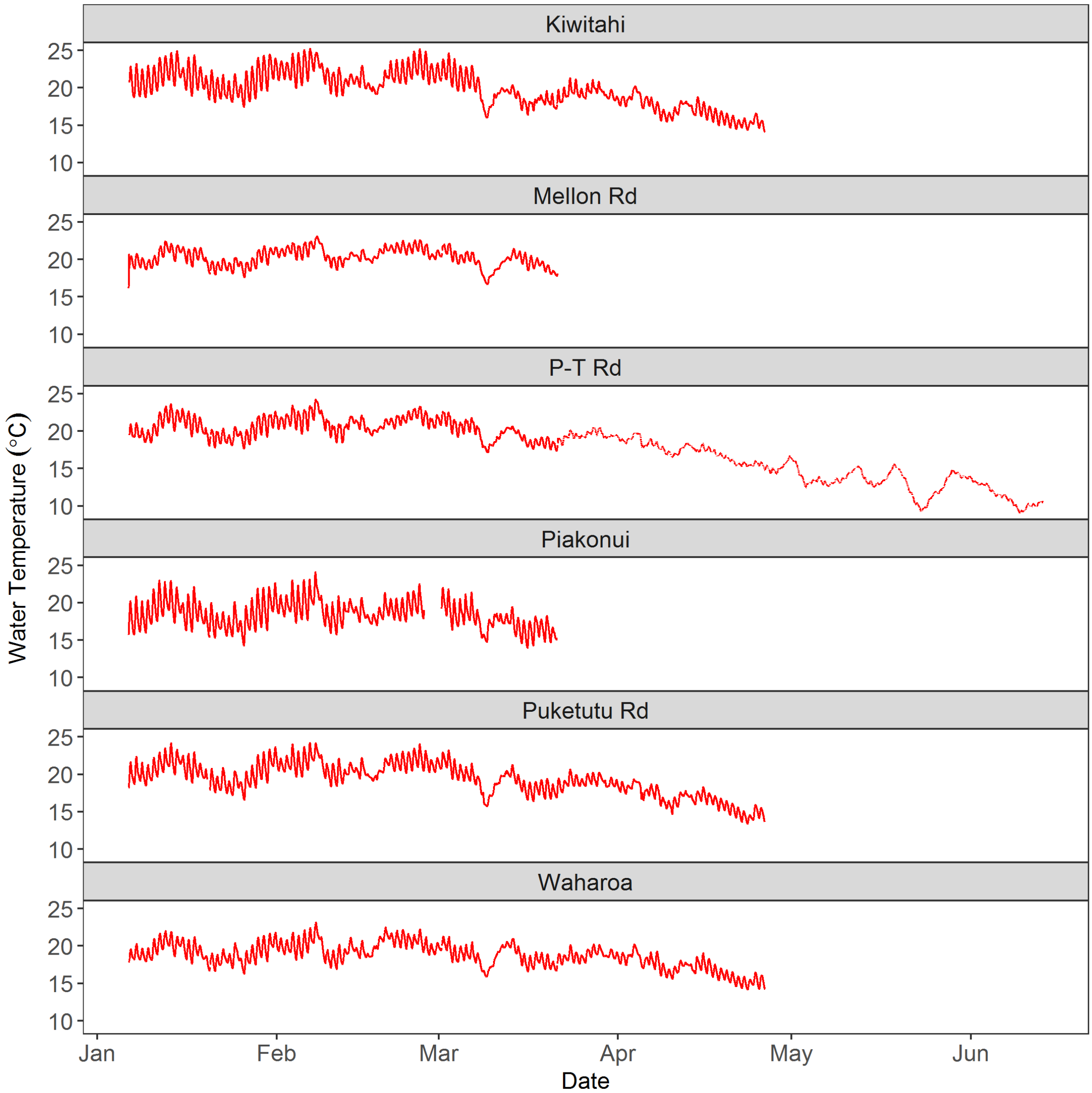

Figure Error! No text of specified style in document.**-4: Water temperature time series at each dissolved oxygen monitoring site over summer 2017 (and through winter 2017 for P-T Rd site).**

Table Error! No text of specified style in document.**-5: Preferred water temperatures of selected native fish species typical of the Piako River system.** From Franklin (2014a), original source Richardson, Boubée et al. (1994).

Species	Life stage	Preferred temperature and quartiles (°C)
Shortfin eel (*Anguilla australis*)	Elver	26.9 (25.6 – 28.5)
Longfin eel (*Anguilla dieffenbachii*)	Elver	24.4 (22.6 – 26.2)
Cran's bully (*Gobiomorphus basalis*)	Mixed	21.0 (19.6 – 22.1)
Common bully (*Gobiomorphus cotidianus*)	Mixed	20.2 (18.7 – 21.8)
Inanga (*Galaxias maculatus*)	Whitebait	18.8 (18.0 – 19.8)
	Juvenile	18.7 (17.3 – 20.0)
	Adult	18.1 (17.2 – 19.1)
Banded kokopu (*Galaxias fasciatus*)	Whitebait	16.1 (14.8 – 17.7)
	Adult	17.4 (16.3 – 18.3)
Common smelt (*Retropinna retropinna*)	Adult	16.1 (15.1 – 17.4)

There was a slight negative correlation between both the daily mean and daily maximum water temperature and flow (**Figure** Error! No text of specified style in document.**-5**). To test for confounding by the co-variation of flow and water temperature with season (i.e., both higher water temperatures and lower flows tend to occur earlier in the summer), regression relationships between maximum daily water temperature and mean daily flow were calculated for each month using un-logged data. (**Table** Error! No text of specified style in document.**-6**). There were no statistically significant correlations between maximum water temperature and daily flow in any month at three of the six sites (Mellon Rd, Piakonui, and Waharoa). Statistically significant negative correlations occurred in January at Puketutu Rd, in February at Kiwitahi, and in both January and February at P-T Rd. The slopes of the negative statistically significant relationships ranged from -8.9 to -3.9 °C/$m^3 s^{-1}$. Significant positive correlations occurred in autumn and winter (April and June) at P-T Rd. This suggests that there may be a seasonal association between flow and water temperature, but the low number of significant correlations is inconclusive.

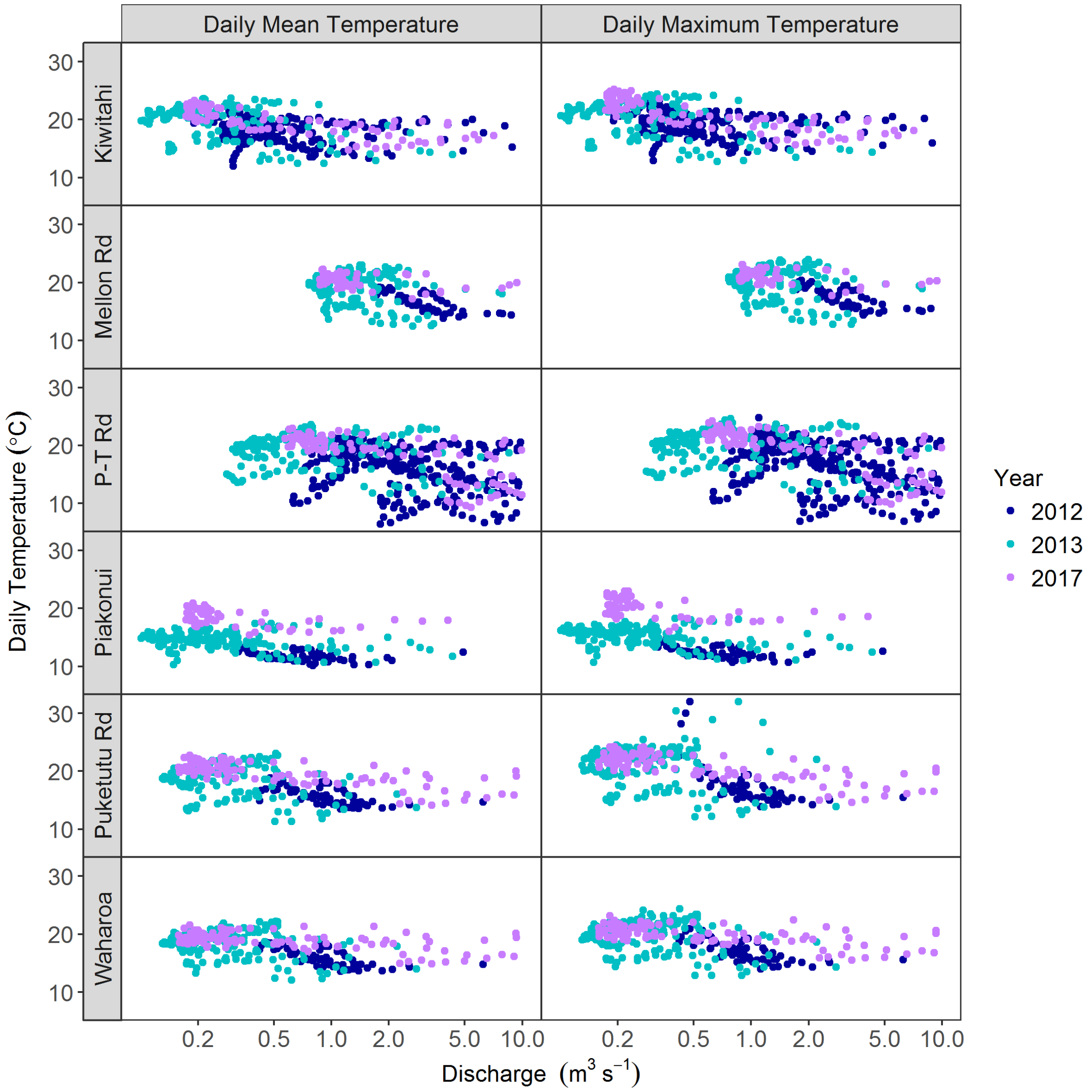

Figure Error! No text of specified style in document.**-5: Daily mean and maximum water temperatures (°C) versus mean daily flow (m^3s^{-1}) at the six dissolved oxygen monitoring sites in both summer 2017 and summers 2012/2013.** Although discharge is presented on a log scale, correlations were tested using non-transformed data.

Table Error! No text of specified style in document.**-6:** **Statistical significance and slope of monthly correlations between maximum water temperature and mean daily flow in 2017.** NS = Not significant; * = p<0.05; **= p<0.01; *** = p<0.001, + = positive correlation, - = negative correlation.

Site	January	February	March	April	May	June
Kiwitahi	NS	** (-5.0)	NS	NS		
Mellon Rd	NS	NS	NS			
P-T Rd	** (-3.9)	* (-0.2)	NS	* (+0.01)	NS	*** (+0.5)
Piakonui	NS	NS	NS			
Puketutu Rd	* (-8.9)	NS	NS	NS		
Waharoa	NS	NS	NS	NS		

Dissolved oxygen time series

Dissolved oxygen time series were plotted relative to the NOF guidelines for protection of ecosystem health (**Table** Error! No text of specified style in document.**-2**) given in the National Policy Statement for Freshwater Management (MfE 2014; **Figure** Error! No text of specified style in document.**-6** and **Figure** Error! No text of specified style in document.**-7**). The dissolved oxygen measurements from summer 2012 and summer 2013 presented in Franklin (2014a) were also replotted relative to the NOF guidelines for comparison (**Figure** Error! No text of specified style in document.**-6** and **Figure** Error! No text of specified style in document.**-7**).

The 2017 dissolved oxygen time series at the Piakonui, Puketutu Rd, and Waharoa sites followed a similar pattern to that observed in the same sites in summer 2013. DO concentrations fluctuated, but were relatively constant on average, with a slight decline over January and February, and subsequent slight increase beginning in March or April. Dissolved oxygen time series at the other three sites had different patterns in 2017 than 2013. At Kiwitahi in summer 2013 dissolved oxygen concentrations declined sharply over the entire summer monitoring period (January-March), but a similar decline was not observed in 2017. P-T Rd also showed a decline in dissolved oxygen concentration between January and March 2013, followed by a prolonged period of very low concentrations in April and May. Again, this trend was not repeated in 2017, when the flows were not as low as in 2013. Instead, dissolved oxygen concentrations remained fairly constant over most of the summer, with one short period of low DO in April. Dissolved oxygen concentrations at Puketutu Rd, on the other hand, were relatively stable over summer 2013 but declined sharply beginning in March 2017.

The daily minimum dissolved oxygen concentration was primarily in the NOF B band at four of the six monitoring sites (Kiwitahi, Mellon Rd, P-T Rd, and Waharoa) in January and February 2017, indicating low stress on aquatic organisms (**Figure** Error! No text of specified style in document.**-6**). However, daily minimum oxygen concentrations dropped into the C and D bands at these sites in March and April 2017 (**Figure** Error! No text of specified style in document.**-6**), coinciding with the occurrence of high flow events (**Figure** Error! No text of specified style in document.**-3**). The 7-day mean daily minimum dissolved oxygen concentrations, on the other hand, indicated greater impairment in 2017, with concentrations falling primarily into the C band at Kiwitahi, Mellon Rd, P-T Rd, and Waharoa (**Figure** Error! No text of specified style in document.**-7**). At Piakonui concentrations were higher and largely fell in the B band, while at Puketutu Rd the 7-day mean daily minimum DO concentrations were mostly in the D band, below the national bottom line, indicating significant and persistent stress on aquatic organisms.

At the Kiwitahi site, both the daily minimum DO and the 7-day mean daily minimum DO concentration remained fairly constant and largely within a single NOF band (B and C, respectively) in 2017. In contrast, in summer 2012 the daily minimum dissolved oxygen concentrations at Kiwitahi were in the C and D bands early in the summer (December-January), but rose into the B band in February and March. In 2013 the daily minimum dissolved oxygen concentration at Kiwitahi was primarily in the D band, below the NOF national bottom line for the duration of the summer.

Daily minimum dissolved oxygen concentrations at Mellon Rd also fell below the national bottom line for a period in February 2017 and again in March 2017, whereas in 2013 dissolved oxygen concentrations largely remained in the D band for the duration of the summer.

Daily minimum dissolved oxygen concentrations at P-T Rd remained mostly in the A band in summer 2012, but declined sharply over the course of summer 2013, from the B band in January and February to the D band in March and April, indicating significant stress on aquatic organisms occurred during late summer and early autumn. In 2017, on the other hand, daily minimum dissolved oxygen concentrations only fell into the D band briefly in April, then rose into the A band during May and June.

Piakonui had daily minimum dissolved oxygen concentrations and 7-day mean daily minimum dissolved oxygen concentrations around 7.5, the dividing line between the NOF A and B bands, for the duration of the 2017 monitoring period (January-April). However, in summer 2013 dissolved oxygen concentrations at this site remained well above the A band limit.

At Puketutu Rd, daily minimum dissolved oxygen concentrations often fell into the D band, below the national bottom line, indicating significant ecological impairment at this site during summer 2017. Conditions at this site were better in summer 2013, when daily minimum dissolved oxygen concentrations were primarily in the B band over the entire monitoring period.

Daily minimum dissolved oxygen concentrations at Waharoa were mostly in the NOF B band during both 2017 and 2013, indicating little stress on aquatic organisms due to dissolved oxygen levels.

In general, daily minimum and 7-day mean daily minimum dissolved oxygen concentrations were in the C and D bands more often in 2017 than in 2013 at the Waitoa River sites Mellon Rd, Puketutu Rd, and Waharoa, suggesting that low dissolved oxygen concentrations may be a significant stressor on aquatic organisms at these sites, particularly following high flow events. This is opposite to the pattern observed in summer 2013, where elevated flows in autumn resulted in an improvement in dissolved oxygen concentrations, suggesting that flushing flows could help maintain dissolved oxygen concentrations (Franklin 2014a). The difference between studies is likely linked to the magnitude of flows observed; the high flows in 2017 were approximately four times greater than those which occurred in early autumn 2013.

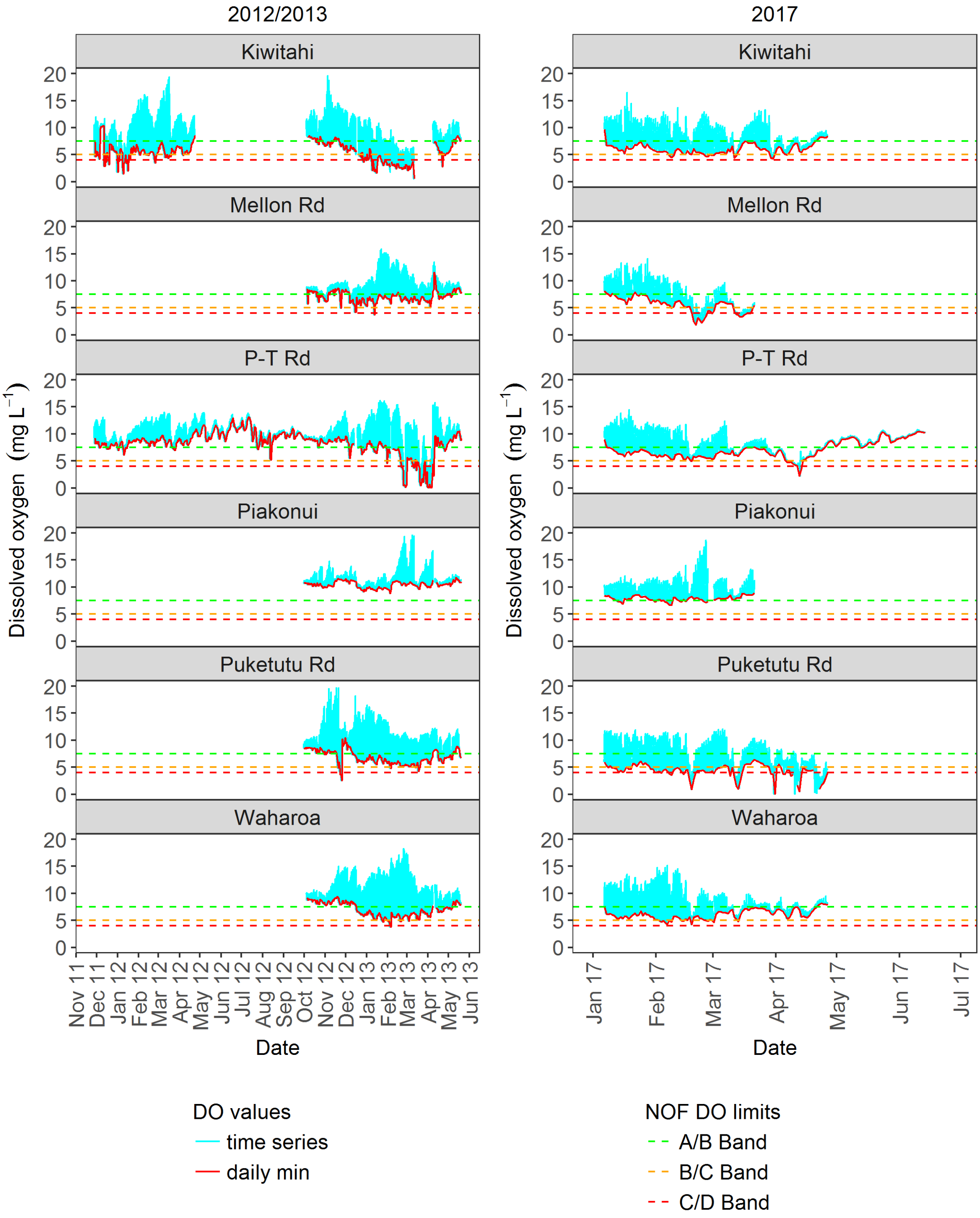

Figure Error! No text of specified style in document.**-6:** **Daily minimum dissolved oxygen time series at each monitoring site over summer 2017 and summer 2012/2013.**

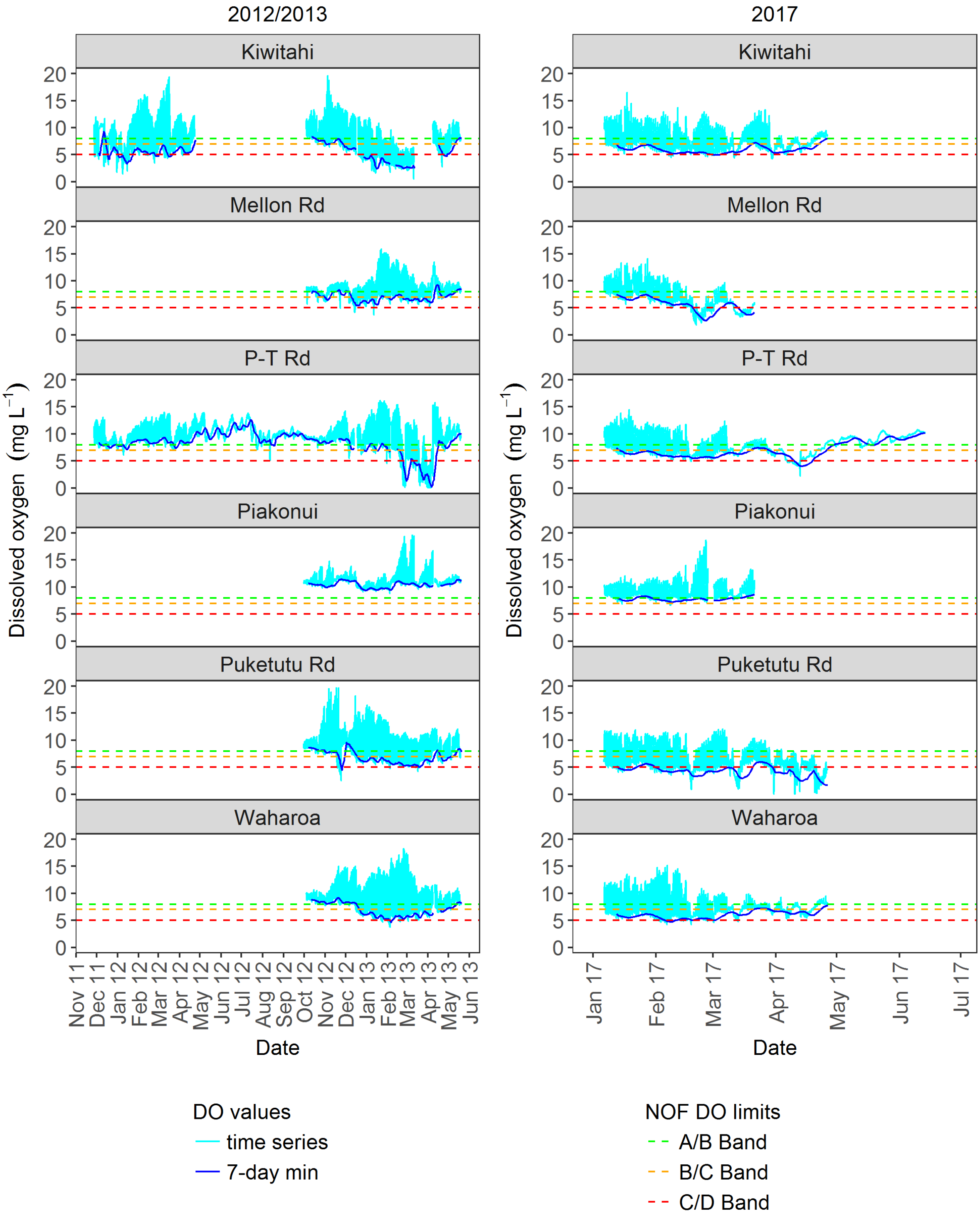

Figure Error! No text of specified style in document.**-7: 7-day mean daily minimum dissolved oxygen time series at each monitoring site over summer 2017 and summer 2012/2013.**

▪ Interactions between dissolved oxygen and flow

The 2017 data confirmed the 2012/2013 finding that relationships between dissolved oxygen and mean daily flow were non-linear at several sites, including Kiwitahi, P-T Rd, Puketutu Rd, and Waharoa. The non-linear relationships were caused by low dissolved oxygen values occurring at both the low and high ends of the flow range (**Figure** Error! No text of specified style in document.**-8** and **Figure** Error! No text of specified style in document.**-9**). There was no identifiable relationship between flow and dissolved oxygen at Piakonui or Mellon Rd in either 2017 or 2012/2013 (Franklin 2014a).

Only summer data were comparable between the two surveys, as no data were collected in winter 2017. However, in general, both flows and DO concentrations were higher in the autumn and winter months in 2012/2013 than in the summer months (Franklin 2014a).

At the Kiwitahi site, flows were less than 0.2 $m^3 s^{-1}$ and both daily minimum and 7-day average daily minimum dissolved oxygen concentrations were below the respective NOF bottom lines for the majority of the summer months in 2012/2013, indicating significant stress on aquatic organisms. In contrast, summer flows were largely above 0.2 $m^3 s^{-1}$ at Kiwitahi in 2017, and dissolved oxygen concentrations remained largely in the B band. An increase in dissolved oxygen concentrations in late summer (and into winter) was also observed in 2012/2013 with increasing flow up to 5 $m^3 s^{-1}$, at which point dissolved oxygen concentrations declined (Franklin 2014a).

Mellon Rd had similar low flows, between 0.5 and 1 m^3s^{-1}, in both 2017 and 2012/2013. Daily minimum dissolved oxygen concentrations were primarily in the NOF B band in both 2017 and 2012/2013, although there were also more observations in the A band in 2012/2013. However, there were several occasions when daily minimum dissolved oxygen concentrations dropped below the NOF bottom line at intermediate (1.0 – 2.0 m^3s^{-1}) flows in 2017. The 7-day mean daily minimum dissolved oxygen concentration was split between the C and D band (below national bottom line) in summer 2017, but had remained primarily in the C band during the summer months in 2012 and 2013. This indicates significant persistent stress to aquatic organisms at this site during the 2017 summer period.

Flows at P-T Rd in 2017 were higher than those observed in 2012/2013. Most notably, there were no flows <0.5 m^3s^{-1}, the range over which DO concentrations in 2012/2013 dropped into the NOF C or D band, indicating significant stress on aquatic organisms. However, outside of those low flow periods, daily minimum dissolved oxygen concentrations in 2012/2013 were largely in the A band. By contrast, daily minimum dissolved oxygen concentrations at P-T Rd in 2017 were mostly in the B band, indicating minor stress, although in autumn concentrations rose to in the A band, when flows were higher and water temperatures lower. In 2017, 7-day mean daily minimum oxygen concentrations remained primarily in the B band, except for the autumn measurements which were in the A band, similar to the pattern observed for daily minimum DO concentrations. Likewise, the 7-day mean daily minimum dissolved oxygen concentrations at P-T Rd in 2012/2013 were largely in the A and B bands, but fell into the C and D bands at flows < 0.5 m^3s^{-1}.

At Piakonui, both daily minimum dissolved oxygen concentrations and 7-day mean daily minimum dissolved oxygen concentrations were mostly in the A band during summer 2017, except during the lowest flows (approximately 0.2 m^3s^{-1}), when they were in the B band. This indicates slightly more stress on aquatic organisms than in 2012/2013, when dissolved oxygen concentration remained in the A band for the duration of the monitoring period.

Daily minimum dissolved oxygen concentrations at Puketutu Rd were primarily in the B band during the summer months in both 2017 and 2012/2013. The low flow ranges were also similar between the two surveys, with a flow minima of 0.2 $m^3 s^{-1}$. However, in 2017 there were several occasions when daily minimum DO concentrations were in the D band, below the national bottom line, both at low flows ~0.2 $m^3 s^{-1}$ and when flows exceeded 2.0 $m^3 s^{-1}$ during high flow events. In contrast, daily minimum dissolved oxygen concentrations rarely fell into the D band, and into the C band on only a few occasions during low flows (around 0.2 $m^3 s^{-1}$). The 7-day mean daily minimum DO concentrations at Puketutu showed a similar, but more pronounced, pattern. In 2017, 7-day mean daily minimum DO concentrations were in the B and C bands at low to intermediate flows, and in the D band at higher flows. In contrast, in 2012/2013, 7-day mean daily minimum DO concentrations were mostly in the B band, and lowest concentrations occurred during low flow conditions.

At Waharoa, daily minimum dissolved oxygen concentrations were primarily in the B band, indicating low stress on aquatic organisms, in both 2017 and 2012/2013, with some concentrations falling into the C band at flows around 0.2 $m^3 s^{-1}$. The 7-day mean daily minimum dissolved oxygen concentrations at this site, however, mostly fell in the C band during both surveys, indicating moderate stress on aquatic organisms due to low dissolved oxygen concentrations.

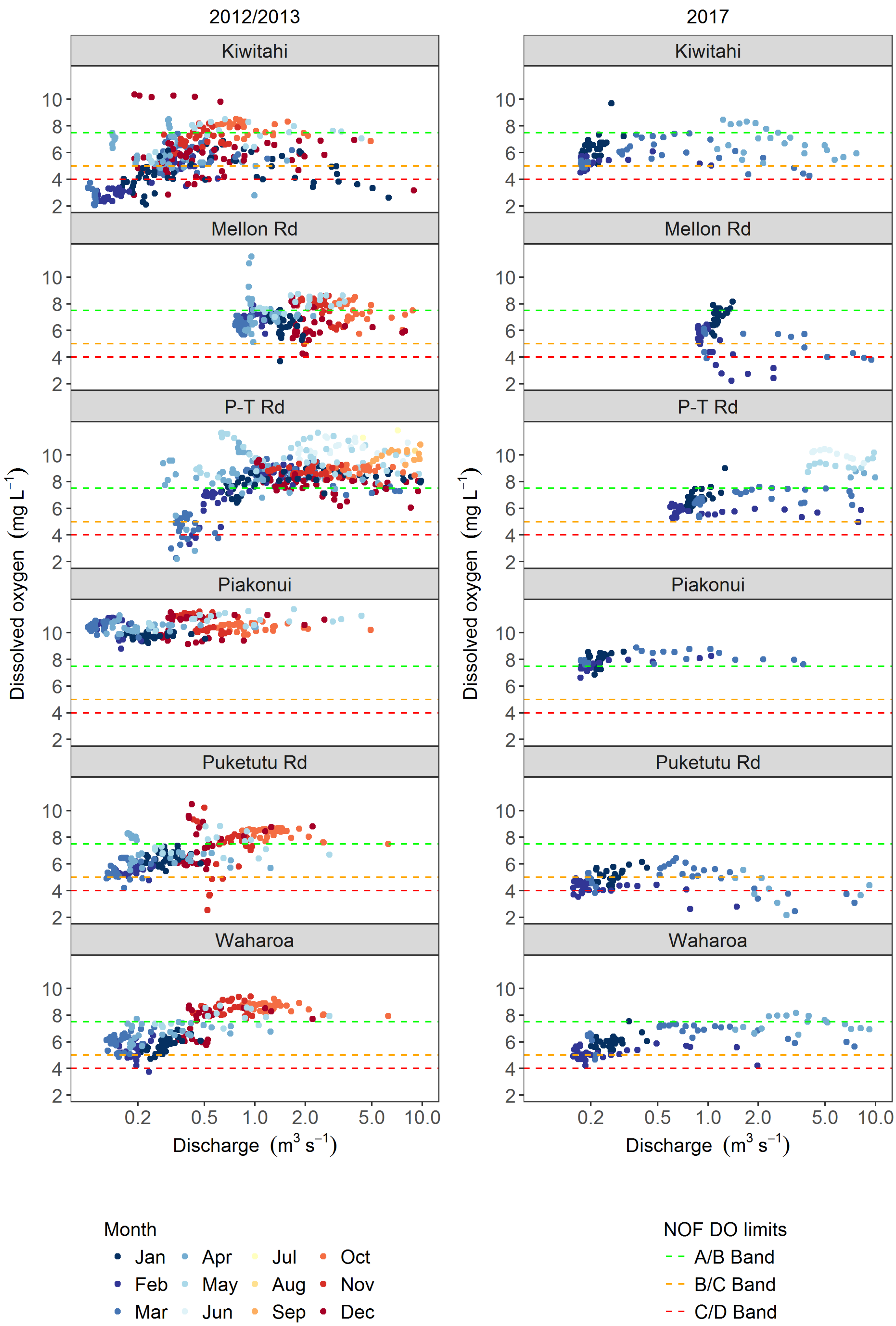

Figure Error! No text of specified style in document.**-8:** **Daily minimum dissolved oxygen concentrations (mg L^{-1}) versus mean daily flow (m^3 s^{-1}) during summer 2017 and summers 2012/2013.**

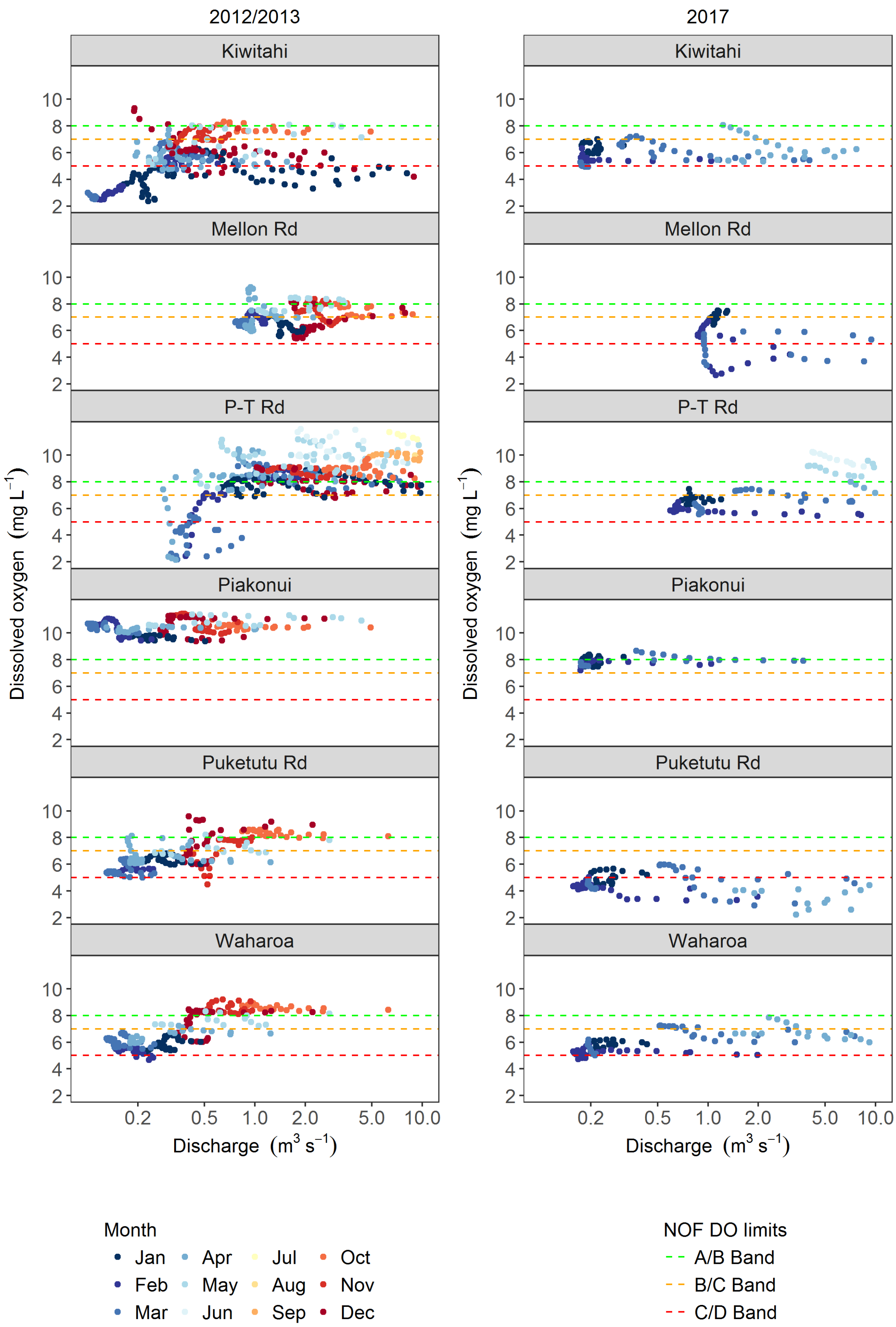

Figure Error! No text of specified style in document.-**9: 7-day mean daily minimum dissolved oxygen concentrations (mg L^{-1}) versus mean daily flow (m^3 s^{-1}) during summer 2017 and summers 2012/2013.**

Reaeration

The night-time regression method (Hornberger and Kelly 1975; Wilcock, Young et al. 2011; Franklin 2014a) was used to calculate estimates of the dissolved oxygen reaeration rate (k_2). Only regressions with an $r^2 \geq 0.4$ were retained; as a result it was only possible to obtain relationships between mean daily flow and reaeration coefficients for three sites in 2017 (and four sites in 2012/2013). The reaeration coefficient was positively correlated with flow across all sites, although the variance in the estimates also increased with flow (**Figure** Error! No text of specified style in document.**-10**). This indicates that there is less capacity for dissolved oxygen concentrations to recover from night-time depletion due to respiration at low flows, probably due to reduced turbulence and/or surface area reducing the diffusion of oxygen into the water column. By the same token, the high reaeration coefficients observed at higher flows in 2017, particularly at the Kiwitahi and Waharoa sites, suggest that increased turbulence may enhance the diffusion of oxygen. The positive correlation between flow and reaeration rates at these four sites is consistent with the observed reductions in dissolved oxygen with reduced flows at the same four sites in **Figure** Error! No text of specified style in document.**-8** and **Figure** Error! No text of specified style in document.**-9**.

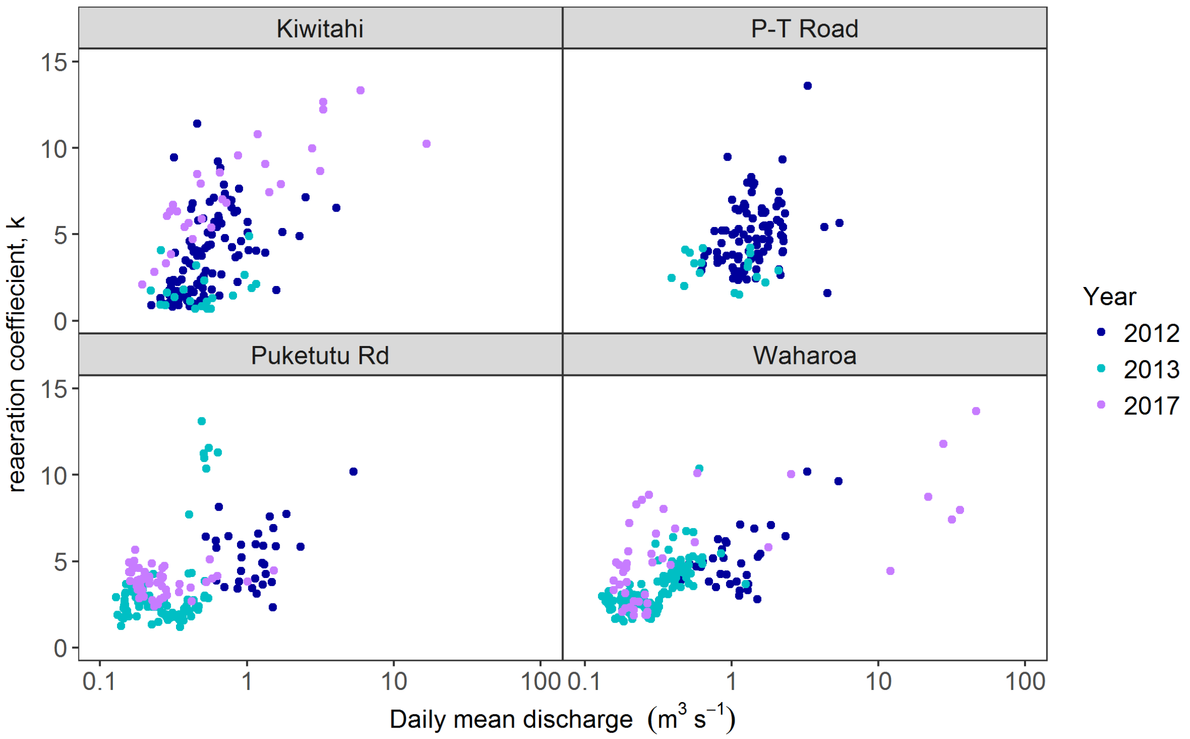

Figure Error! No text of specified style in document.**-10: Reaeration coefficient (k_2) versus mean daily flow ($m^3\ s^{-1}$).** Only three sites in 2017 and four sites in 2012/2013 had sufficient number of regressions with $r^2 \geq 0.4$ to enable calculation of reaeration coefficients.

Discussion

The 2017 summer sampling period was characterised by two very high flow events as well as several smaller flushing flows. The magnitude of the high flow events was more than twice as large as the peak flows that occurred during the 2012 and 2013 summer sampling seasons (Franklin 2014a). The large variation in flow conditions hindered validation of the 2012 and 2013 measurements, which were largely taken during periods of prolonged low flows.

Water temperatures in summer 2017 were on average 1°C warmer than in summer 2012 or 2013. Water temperatures exceeded the thermal preference of several key native fish species at all six sites, including Piakonui, which was several degrees cooler than the other five sites in 2012-2013, but not in 2017. Water temperature and mean daily flow were negatively correlated at some sites in some months, but no consistent relationship was detected across all sites that could be used to determine flow limits for maintenance of appropriate water temperatures for aquatic biota.

As in 2012/2013, dissolved oxygen concentrations in 2017 decreased over prolonged low flow conditions, resulting in non-linear relationships between dissolved oxygen and flow in four sites, Kiwitahi, P-T Rd, Puketutu Rd, and Waharoa, similar to the threshold relationships observed in 2012/2013. However, the occurrence of high flows in 2017 showed that dissolved oxygen concentrations are also often depleted immediately following high flow events.

Low dissolved oxygen concentrations at low flows is likely related to a decline in the dissolved oxygen reaeration coefficient (k_2) with decreasing flow. Similarly, it is expected that higher turbulence at high flows will be associated with larger reaeration coefficients. Loggers were generally deployed in glide-type habitats with U-shaped incised channels. The one exception was Piakonui, which is a smaller headwater stream with a steeper gradient and thus subject to higher local levels of turbulence characteristic of the stream. The loggers were deployed close to the bank in well-mixed areas representative of the broader conditions in each site. Consequently, the decline in dissolved oxygen concentrations in high flows is most likely unrelated to reaeration. Instead, it may be driven by biological oxygen demand from decomposition of increased inputs of organic matter, such as dead macrophytes and periphyton, which occur during high flow events. Additionally, high flows are also often associated with increased algal scouring and turbidity, both of which could temporarily reduce photosynthesis and thus oxygen production, following a high flow event.

It is also important to note that in both 2017 and 2012/2013, higher flows occurred more often later in the monitoring period, when water temperatures were lower due to seasonal effects. Therefore, there was also likely an influence of water temperature on the dissolved oxygen concentrations observed at high flows, particularly in 2012/2013 where the greatest flows were recorded during the winter months (**Figure** Error! No text of specified style in document.**-8** and **Figure** Error! No text of specified style in document.**-9**). Year to year variability is likely also associated with antecedent flow conditions prior to monitoring, because the recent flow regime will have affected macrophyte and periphyton growth, which in turn impacts oxygen dynamics.

At five of the six sites, dissolved oxygen concentrations in summer 2017 were primarily within the NOF B band for both attributes, daily minimum concentration and 7-day mean daily minimum concentration. The B band represents only minor occasional stress on aquatic organisms due to low dissolved oxygen. The sixth site (Piakonui) had concentrations mostly in the A band, indicating no stress on aquatic organisms. This difference may be because Piakonui is a smaller headwater site with a steeper gradient than the other sites. Sites located further downstream may also have more cumulative stressors than Piakonui, such as land use intensity and sedimentation. Overall, dissolved oxygen concentrations at all sites were lower in 2017 than in 2012/2013, when the majority of concentration values were in the A band. However, it is also important to note that many of the higher concentration values recorded in 2012/2013 were from winter measurements, when low water temperatures would have been positively influencing oxygen concentrations. Winter sampling was not included in the 2017 study, except inadvertently at the P-T Rd site where the logger was unable to be retrieved until several months after sampling was completed at the other sites.

The NOF national bottom line for both daily minimum dissolved oxygen concentrations and 7-day mean daily minimum dissolved oxygen concentrations was exceeded more often in 2017 than in 2012/2013 at two sites, Mellon Rd and Puketutu Rd. Three sites, Kiwitahi, P-T Rd, and Waharoa had greater frequency of dissolved oxygen concentrations below the bottom line in 2012/2013 than in 2017, largely because flows at these sites were much lower in 2012/2013 than in 2017. The sixth site, Piakonui, never had dissolved oxygen concentrations below the national bottom line during either sampling period. Dissolved oxygen concentrations below the NOF bottom line indicate that aquatic organisms are experiencing significant, persistent stress due to low oxygen availability.

The combined data from both surveys, which reflects the natural range of variability in flows between years, (**Figure** Error! No text of specified style in document.**-11**) was used to empirically estimate the lower boundary of the DO-flow relationship to identify the flow approximating to each NOF attribute boundary (**Table** Error! No text of specified style in document.**-7**).These estimates can then be used as a guide for setting precautionary minimum flow limits to prevent detrimental effects on aquatic organisms due to low dissolved oxygen concentrations. The 7-day mean daily minimum attribute was used because the bottom line is higher, and thus more conservative with regard to protection of ecosystem health. For some site/NOF band combinations it was not possible to estimate minimum flow limits from the data collected because the lower boundary did not cross the band threshold or because the scatter in the data was so great that the lower boundary crossed the band threshold at multiple values.

Table Error! No text of specified style in document.**-7: Flows that approximate to the NOF 7-day mean daily minimum dissolved oxygen guideline boundaries for ecosystem health.** '-' indicates that a clear boundary was not discernible.

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

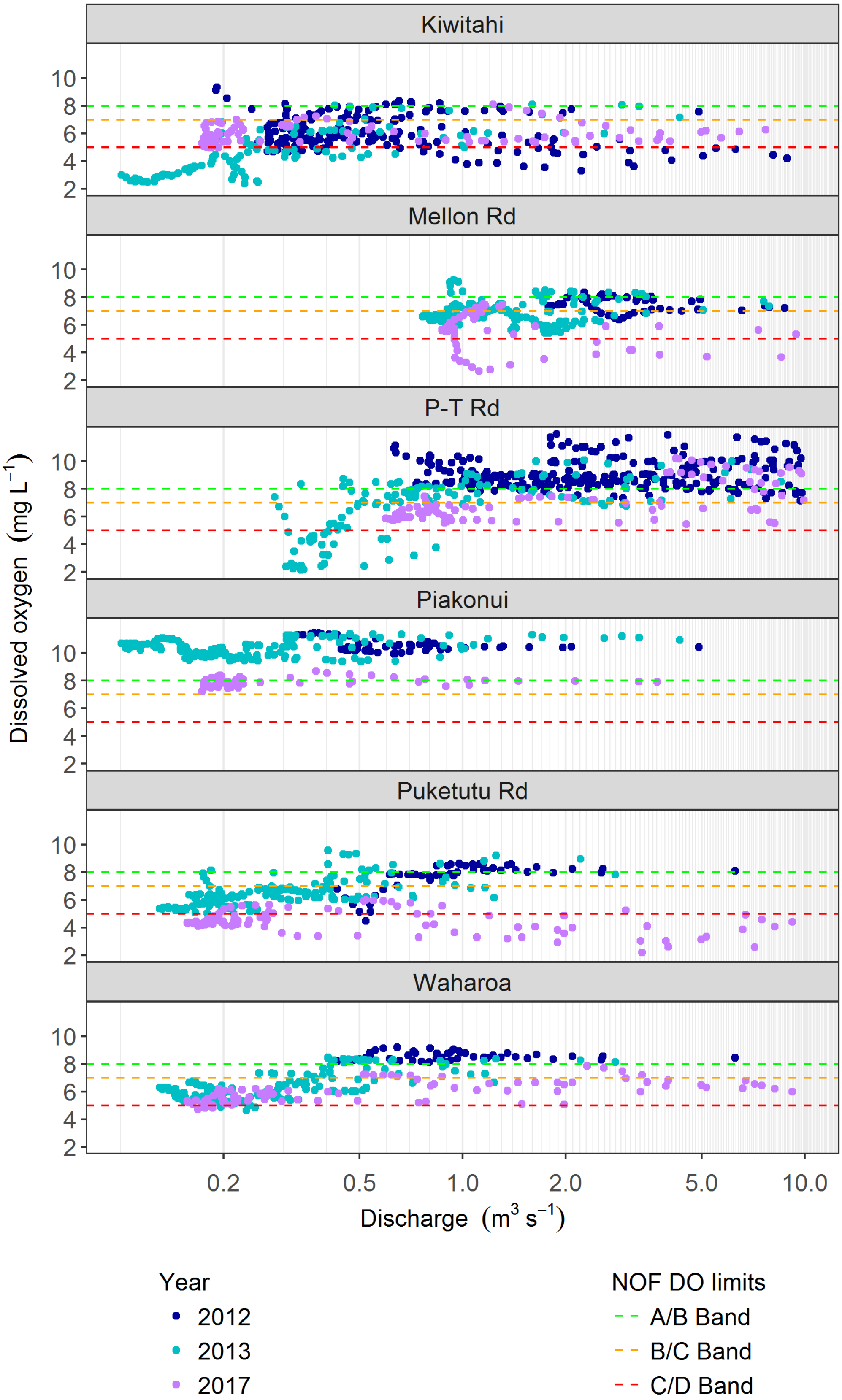

Figure Error! No text of specified style in document.**-11: 7-day mean daily minimum dissolved oxygen concentration versus Flow from the 2012, 2013, and 2017 summer monitoring periods.**

• Tidal

○ Results

▪ Longitudinal transects

Longitudinal profiles of temperature, salinity, dissolved oxygen, chlorophyll, and turbidity in the Piako River were taken on 6 occasions, approximately every two weeks, between the end of January and the end of April, 2017 (**Table** Error! No text of specified style in document.**-8**). All longitudinal surveys began at the mouth of the river near Pipiroa at high tide and extended 37 km upstream to the confluence of the Piako and Waitoa Rivers near Maukoro Landing (**Figure** Error! No text of specified style in document.**-2**).

Table Error! No text of specified style in document.**-8: Flow and tide conditions for the longitudinal surveys in 2017 and 2012.** Tide height is metres from mean sea level predicted by the NIWA Tide Forecaster for the mouth of the Piako River (75 29 52 E, 37 11 13 S). Flows are the mean daily value of combined flow measurements from the Piako River at P-T Road and the Waitoa River at Mellon Rd gauging stations.

Survey	Date	Flow ($m^3 s^{-1}$)	Tide height (m)
2017			
1	26/01/2017	2.4	1.3
2	10/02/2017	1.7	1.7
3	28/02/2017	2.1	1.8
4	16/03/2017	21.6	1.5
5	30/03/2017	50.4	1.9
6	27/04/2017	16.1	1.9
2012			
1	29/09/2011	7.4	1.9
2	13/12/2011	3.1	1.5
3	12/03/2012	3.5	1.9
4	25/06/2012	6.9	1.3

The longitudinal profiles from 2012 and 2017 are compared in Figure **Error! No text of specified style in document.**-12. However, it is important to note that the 2017 surveys were all conducted within a four-month summer period, whereas the 2012 surveys were conducted every three months over the course of a year. Consequently, some of the observed differences between the survey results may be the result of seasonal effects (particularly temperature) rather than inter-annual variation.

In 2017, the temperature was lower in the first 10 km and increased upstream, indicating a cooling tidal influence near the river mouth. This variation was not present in the last two surveys that occurred later in the season and following high freshwater flow events.

Salinity was highest in the downstream reaches earlier in the summer in 2017 and declined over time. The upstream extent of the saline intrusion also declined over time, from approximately 17 km upstream in the first three surveys to 4 km upstream in the last three surveys when freshwater flows were much higher. In contrast, the upstream length of the saltwater intrusion varied only between 10 and 17 km across the 2012/2013 surveys when the overall range of freshwater flows captured in the surveys was much smaller.

The 2017 profiles confirmed the identification of a dissolved oxygen sag in the lower Piako River, roughly coinciding with the upstream edge of the saltwater intrusion, around 17-18 km upstream of the river mouth. The sag developed progressively during the initial low flow period in January and February. The spatial extent of the DO sag increased from around 14 km of the lower river during the first survey to around 20 km during the third survey. Both the upstream and downstream extent of the sag increased over time. Dissolved oxygen concentrations within the sag were largely below 4-5 mg L^{-1}, the NOF national bottoms line for minimum DO attributes, indicating that aquatic organisms in the sag zone experienced significant stress due to low dissolved oxygen availability. A similar progressive DO sag was observed during low flow conditions in the 2012 longitudinal surveys (Franklin 2014a).

The sag was minimal by the 5th survey, conducted on the 30th of March. The river flow during the 30th of March survey was 50 $m^3\ s^{-1}$, twice as high as during any other survey (**Table** Error! No text of specified style in document.**-8**), suggesting that medium-sized flows can reduce the sag and 'reset' the dissolved oxygen, most likely by pushing the depleted DO water out to sea.

However, the lowest dissolved oxygen concentrations were recorded during the fourth and sixth surveys, when flows were moderate (~20 $m^3\ s^{-1}$) during the receding limb of a moderate and large flow event, respectively. Unlike the sag observed in the first three surveys, during the fourth and sixth surveys dissolved oxygen concentrations dropped below the national bottom line within 2-6 km of the river mouth, and fluctuated between 1-3 mg L^{-1} until 28 km upstream. Based on the dissolved oxygen depletion observed following high flow events at the upstream monitoring site, it is likely that the low DO concentrations in the last two surveys were associated with high flows, rather than the re-formation of the DO sag.

Chlorophyll-a was below 20 $\mu g\ L^{-1}$ in the first 20 km upstream from the river mouth in all 2017 surveys and for the entire length of the longitudinal profile in the last three surveys. In the first three surveys, chlorophyll increased between 20-30 km upstream of the river mouth and peaked at around 32-33 km.

Turbidity also varied longitudinally in the first three surveys, increasing between 13 and 20 km upstream of the river mouth, with a maximum around the same location as the dissolved oxygen sag. The highest turbidity values were recorded during the second survey, but turbidity was low in the last three surveys, which were conducted during or following elevated flow events. This suggests that elevated flows may reduce turbidity, which can in turn increase dissolved oxygen due to associated reduction in biological oxygen demand from decomposition of suspended particulate organic matter.

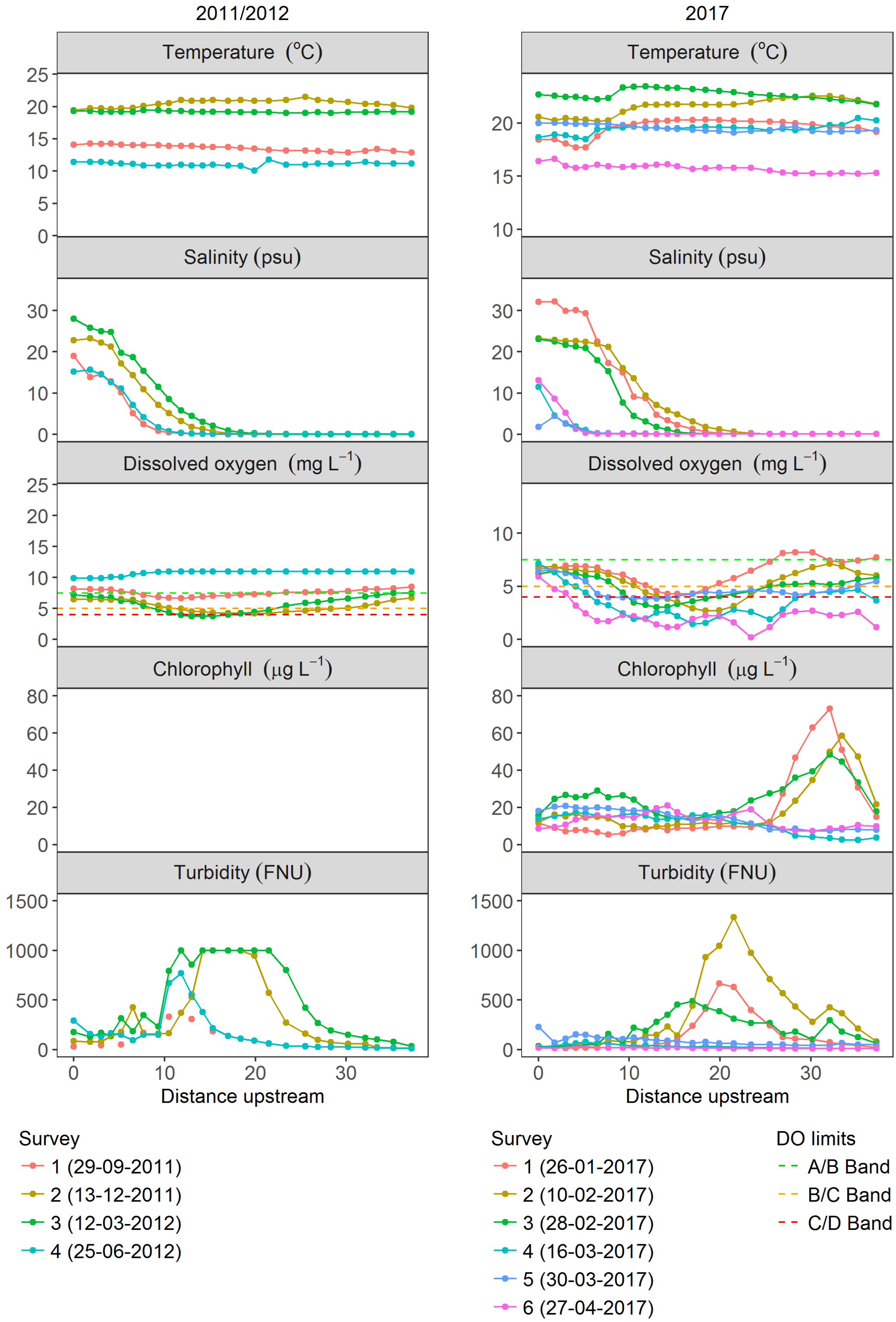

Figure **Error! No text of specified style in document.**-12: **Longitudinal profiles of water temperature, salinity, dissolved oxygen, chlorophyll, and turbidity in the lower Piako River in summer 2017 and spring – winter 2012**. DO limits are NOF attribute boundaries for daily minimum dissolved oxygen concentrations.

- ### High-resolution temporal sampling

Three additional data loggers were deployed in the estuarine zone of the lower Piako from the end of February to the beginning of June to collect high-resolution temporal data. D-Opto loggers were deployed at transect sites 19 and 15 (25 km and 18 km upstream of the river mouth, respectively), and an EXOSonde logger was deployed at transect site 12 (14 km upstream of the river mouth). The loggers were removed on April 28 and redeployed on May 10, resulting in a twelve day gap in the otherwise continuous time series (**Figure** Error! No text of specified style in document.**-13**).

Dissolved oxygen time series from the three loggers are displayed in **Figure** Error! No text of specified style in document.**-13**, along with river flow, calculated as the combined flow of the Piako and Waitoa rivers measured at P-T Rd and Mellon Rd, respectively (following Vant (2013)).

Dissolved oxygen concentration was initially highest at site 15, at around 7 mg L^{-1}. This concentration falls within the B band of the NOF guidelines, indicating little stress on aquatic organisms. However, dissolved oxygen concentrations declined at all three sites over the March low flow period to below 4 mg L^{-1}, the NOF national bottom line below which significant stress on aquatic organism occurs.

At site 19, the site located farthest upstream, dissolved oxygen was totally depleted for a week in mid-March, and again during a four-day period late in March. In the other two sites, dissolved oxygen concentrations were highly variable following the first small flow event in mid-March, and often approached zero for short periods of time, perhaps indicating strong diel variation and night-time oxygen depletion. Dissolved oxygen concentrations increased at all three sites in late March and early April. After the first high flow event in April, dissolved oxygen concentrations at all three sites initially increased by about 1-2 mg L^{-1}, but then quickly dropped to nearly zero.

At sites 12 and 19, dissolved oxygen concentrations increased between the two April flow events to approximately 4 mg L^{-1}, still below the NOF bottom line for protection of aquatic organisms and ecosystem health. At site 15, on the other hand, dissolved oxygen concentration only increased about 2 mg L^{-1} following the first high flow event and fell to zero following the second high flow event. Dissolved oxygen remained depleted at this site for the remainder of the sampling period, except for a brief return to initial values prior to the May flow event, after which concentrations once again remained near zero. Dissolved oxygen concentrations at sites 19 and 12 were higher than previously recorded following the May re-deployment, likely due to a corresponding seasonal decline in water temperatures. Dissolved oxygen concentrations at these two sites briefly increased further following the mid-May flow event before returning to pre-event levels (around 7.5 mg L^{-1}). This concentration is in the NOF A band, where no stress on aquatic organisms is expected. Variation in dissolved oxygen concentration also increased again over June, when flow was once again relatively low and stable.

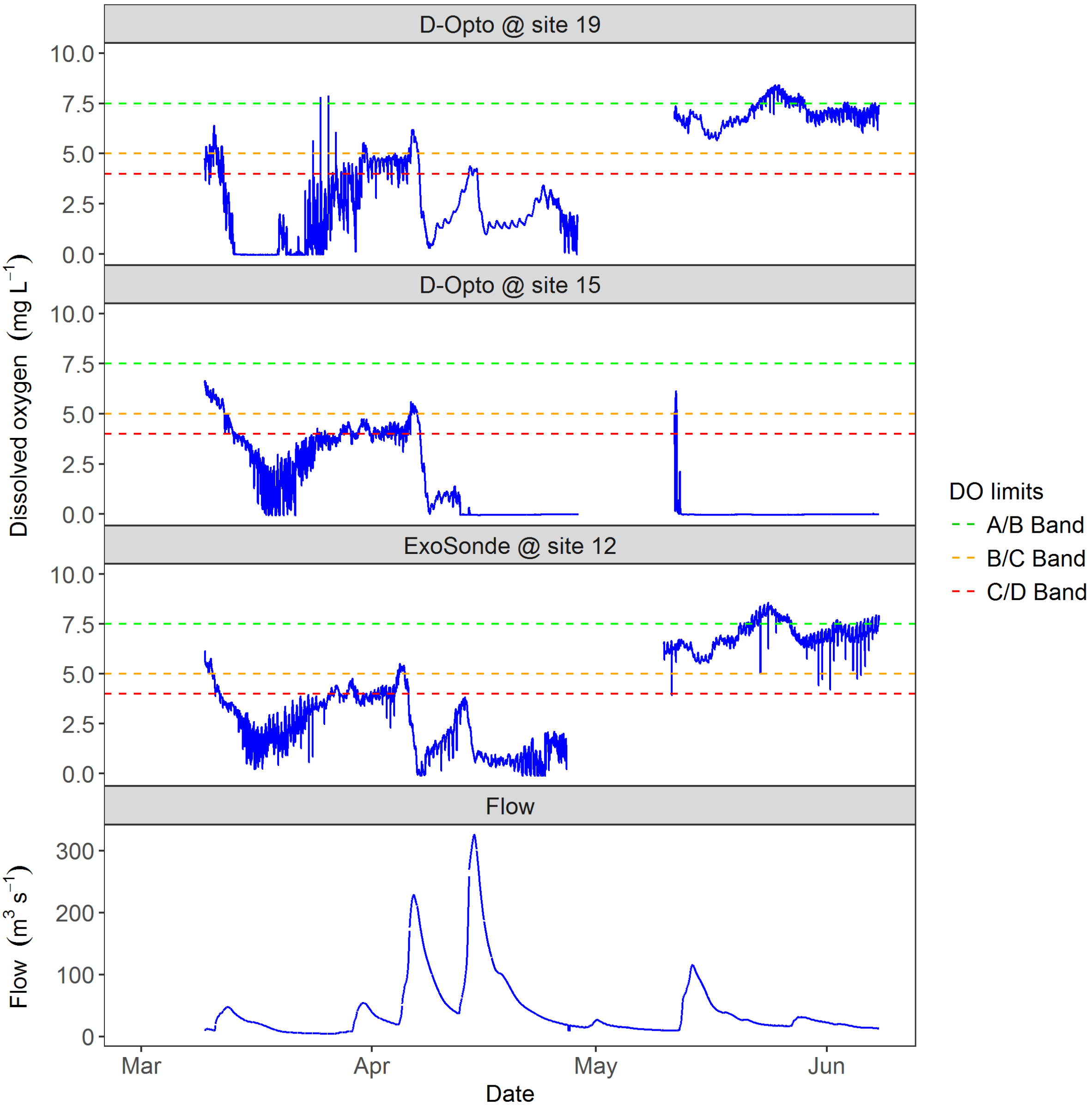

Figure Error! No text of specified style in document.**-13: High resolution time series of dissolved oxygen concentrations and flow at three sites in the lower Piako River during summer 2017.** Site 19 was located 25 km upstream of the river mouth, site 15 was located 18 km upstream of the river mouth, and site 12 was located 14 km upstream of the river mouth. DO limits are NOF attribute boundaries for daily minimum dissolved oxygen concentrations.

The EXOSonde logger at site 12 also measured several other parameters in addition to dissolved oxygen, including water temperature, conductivity, salinity, and turbidity. The time series for these parameters are shown in **Figure** Error! No text of specified style in document.**-15**, along with tide height data (metres from mean sea level) predicted by the NIWA Tide Forecaster for the mouth of the Piako River (75 29 52 E, 37 11 13 S) and combined flow of the Piako and Waitoa Rivers.

The tidal range varied from between 10 cm to 2 m between high and low tide over the sampling period.

The river flow was low, around 2-5 $m^3 s^{-1}$, and stable at the beginning of the monitoring period, with two small flow events with peak flow approximately 50 $m^3 s^{-1}$ in the first month. There were two large flow events with peak flows exceeding 200 $m^3 s^{-1}$ in the second month. The remainder of the monitoring period was stable at slightly higher flows around 10 $m^3 s^{-1}$, except for a mid-size flow event with peak flow of approximately 100 $m^3 s^{-1}$ in mid-May.

Water temperature remained between 17 and 22°C during March, but began to decline in April. Short-term declines in water temperature also occurred immediately following flow events.

Conductivity, salinity, and turbidity had almost identical temporal trends over the sampling period. Values of all three variables were highest at the end of March following a prolonged low-flow period, and substantially lower and less variable following the April high flow events.

Dissolved oxygen concentrations were initially around 5 mg L^{-1}, the boundary of the NOF bottom line, at the beginning of the sampling period, and dropped steadily to between 0 and 2.5 mg L^{-1} during the initial low flow period in March. Dissolved oxygen concentrations increased to above the bottom line and became more variable following the two small flow events in March, but dropped again following the large flow events in April and remained low for the rest of that month. The highest recorded dissolved oxygen concentration occurred in May following logger re-deployment.

The large variations in flow made it difficult to assess relationships between dissolved oxygen and other measured parameters. However, Franklin (2014a) noted that in 2013 dissolved oxygen concentrations were often higher following low tides, when there is less saline influence, and decreased following high tides, when turbidity was also the greatest. Unfortunately, the short periods of low flow data prevent robust inference of similar tidal patterns in 2017 (**Figure** Error! No text of specified style in document.**-15**).

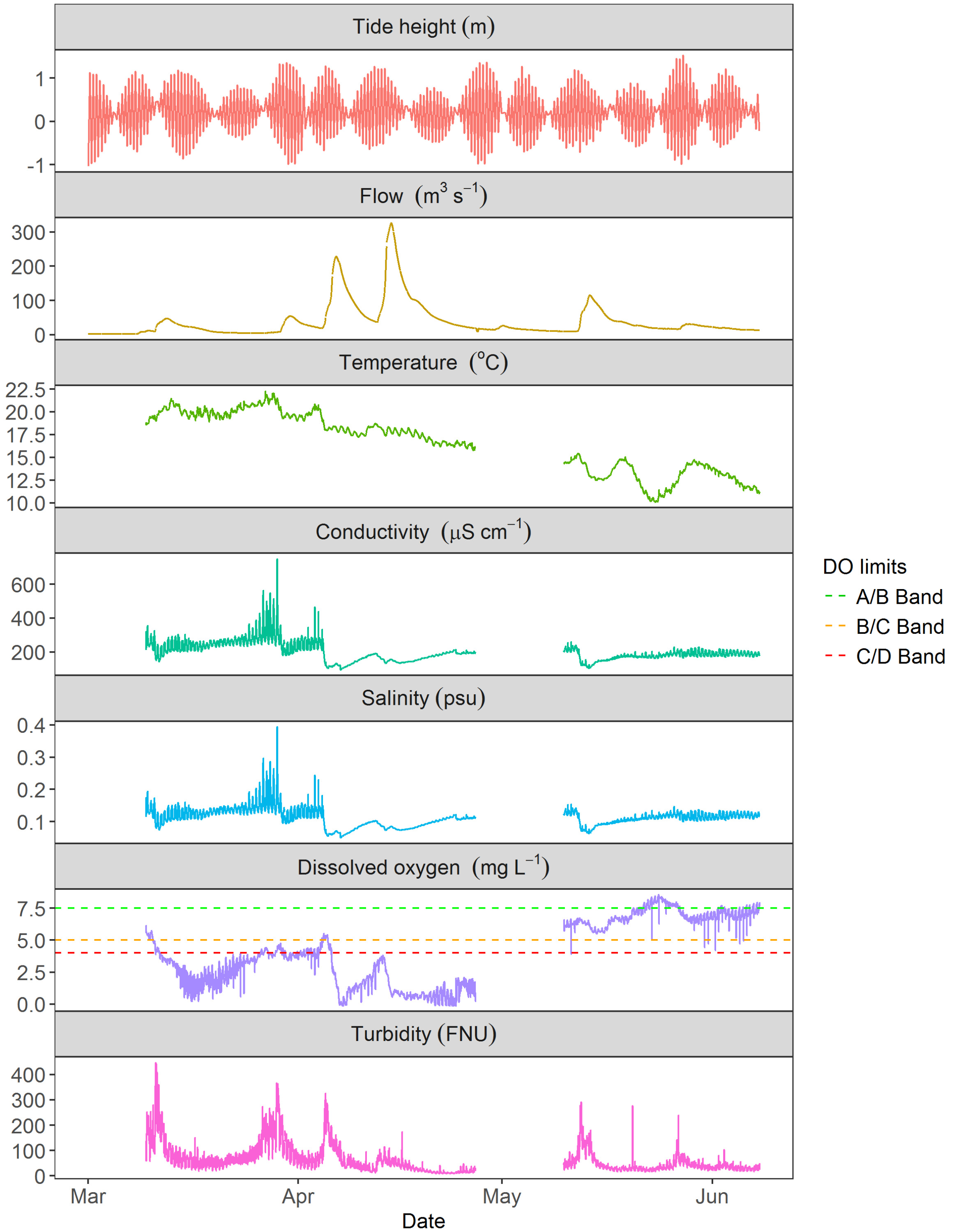

Figure Error! No text of specified style in document.**-14: High resolution time series of environmental conditions in the lower Piako River measured by the ExoSonde logger at longitudinal transect site 12, 14 km upstream from the river mouth.** DO limits are NOF attribute boundaries for daily minimum dissolved oxygen concentrations.

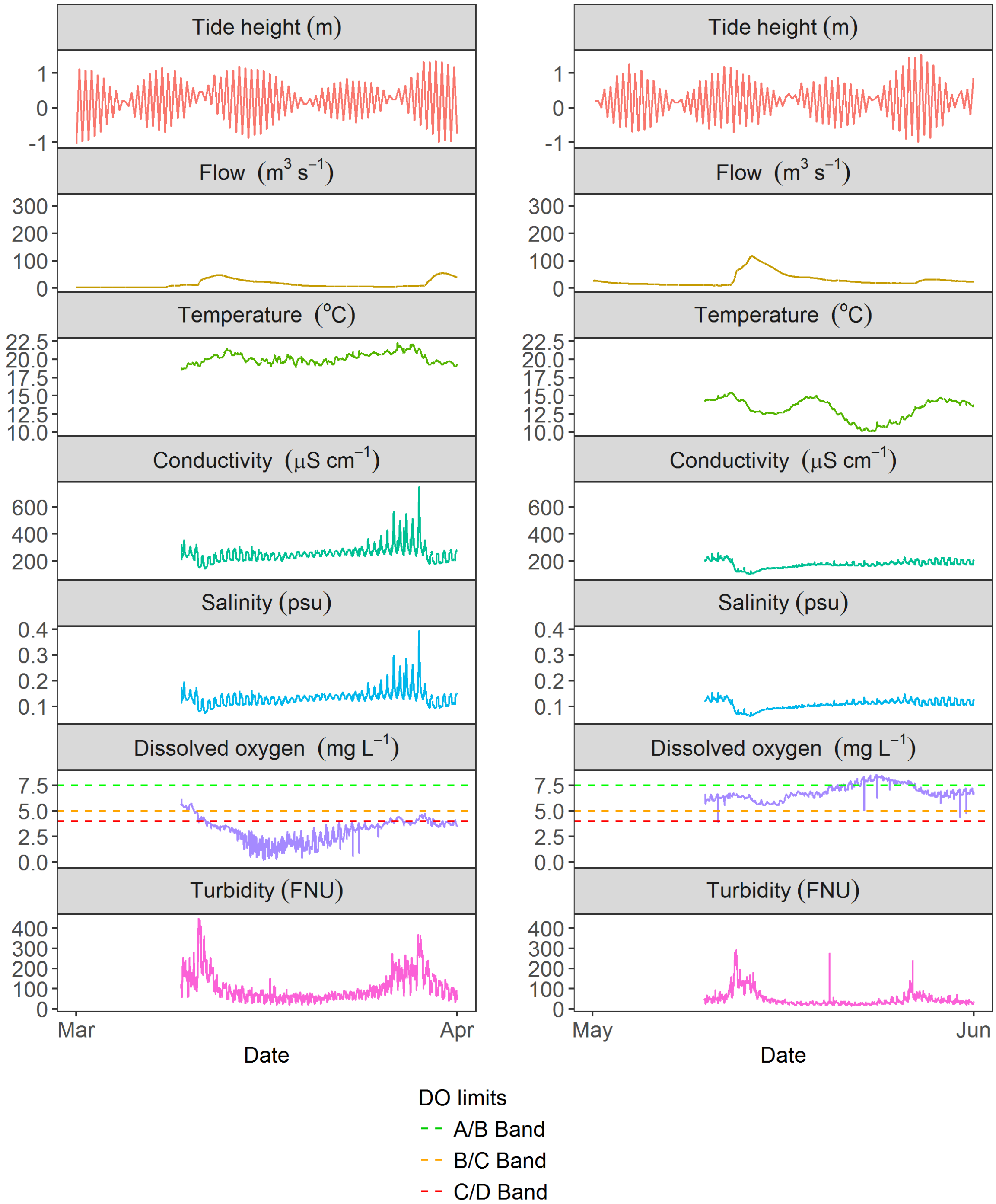

Figure Error! No text of specified style in document.**-15: High resolution time series of environmental conditions in the lower Piako River from low flow periods only.** DO limits are NOF attribute boundaries for daily minimum dissolved oxygen concentrations.

o Discussion

Longitudinal profile measurements were consistent with the complex relationships between flow, salinity, turbidity, and dissolved oxygen observed in the lower Piako River in summer 2012. A dissolved oxygen sag developed in the lower reaches of the river over the low flow period at the start of the summer, similar to that observed in summer 2012. The DO sag was greater at low flows across all longitudinal transects from both the 2011/2012 and 217 surveys (**Figure** Error! No text of specified style in document.**-16**). The sag occurred in the same location as the turbidity maximum at the upstream limit of the saltwater intrusion, approximately 18 km from the mouth of the river. Chlorophyll, on the other hand, peaked just upstream of the DO sag.

High turbidity can occur near the upstream limit of the salt wedge in estuaries due to the combination of tidal influences and density stratification resulting in the formation of a resuspendable pool of sediment particles near the salt limit (Sanford, Suttles et al. 2001; North and Houde 2003). Salinity can also enhance flocculation of sediment and organic material due to chemical-ionic interactions and/or turbulent shear at the interface of fresh and salt water (Manning, Bass et al. 2006).

Turbidity and dissolved oxygen levels can be linked by a variety of mechanisms. First, high turbidity will reduce light availability for photosynthesis, thereby also reducing production of oxygen. Alternatively, if the turbidity is due to large amounts of small organic particles, low oxygen could be the result of increased decomposition. High algal growth can also increase turbidity, although in this case the chlorophyll peak was upstream, suggesting that any organic material present was more likely associated with runoff from nearby land or flushing of upstream drains and wetlands.

The spatial extent of the dissolved oxygen sag increased over the low-flow period between January and the beginning of March 2017. The minimum DO concentration within the sag also declined over this period. However, the moderately-sized flow events (~ 50 $m^3 s^{-1}$) that occurred in mid-March and late March improved dissolved oxygen conditions, likely by flushing turbid, low-DO water out to the estuary. The influence of such 'flushing' flows on dissolved oxygen levels is likely determined by antecedent flow conditions, which will affect macrophyte and periphyton growth, as well as build-up of particulates around the salt wedge/turbidity maximum. The large flow events (>100 $m^3 s^{-1}$) that occurred in April, on the other hand, appeared to exacerbate oxygen depletion, possibly related to increased inputs of organic matter from flushing of nearby drains, paddocks, and wetlands. However, full investigation of the drivers of DO depletion in the lower river following such extreme flow events was outside the scope of this study. The high-resolution temporal data corroborated the results from the longitudinal profile measurements; dissolved oxygen concentrations declined during low flow periods and increased following small 'flushing' flow events (approximately two times median flow). Similar patterns were observed in past years in both the lower Piako River (Franklin 2014a) and in the Waihou River (Franklin and Smith 2014). The largest dissolved oxygen depletion occurred in the middle downstream site, which is located near the upstream limit of the estuarine saltwater intrusion and the turbidity maxima, suggesting that turbidity and salinity were important factors affecting dissolved oxygen concentrations at this site, possibly due to either reduced light availability for photosynthesis or decomposition of large amounts of organic particles, as described above.

Summer dissolved oxygen concentrations in the lower part of the river often fell below 4 mg L^{-1}, the NOF national bottom line, when flows dropped below 10 $m^3 s^{-1}$ (**Figure** Error! No text of specified style in document.**-17**), indicating high risk of impaired ecosystem health and stress on aquatic organisms due to low dissolved oxygen availability. Dissolved oxygen concentrations were largely in the NOF B band when flows were between 10-20 $m^3 s^{-1}$, but once flows exceeded 20 $m^3 s^{-1}$ there was no clear relationship between DO and flow, probably due to oxygen depletion sometimes occurring at high flows. It is important to note, however, that the longitudinal transect data indicated that flow is not the only factor influencing dissolved oxygen in the lower river, but one of several interacting variables, including turbidity, salinity, and tidal effects. Dissolved oxygen levels spanned all NOF bands at elevated flows (defined as ten times the median baseflow, 1.8 $m^3 s^{-1}$, over the sampling period; **Figure** Error! No text of specified style in document.**-17**), likely due to the complex interactions between variables and the influence of antecedent flow conditions.

Dissolved oxygen concentrations below the national bottom line is a critical concern in the lower Piako river, as this area is the interface of marine and freshwater environments, and thus a biodiversity hotspot with high ecological value. Many native fish, including inanga, smelt, eels, and bullies migrate through or form resident populations in the lower reaches of the river. Inanga and smelt likely spawn in the area during March, April, and May. The lower river reaches also contain both marine and freshwater benthic invertebrates, and serves as important bird habitat.

Although outside the scope of this study, this year's data also indicated that dissolved oxygen concentrations decline substantially following some high flow events. In fact, large numbers of dead fish were observed during the oxygen depletion period following the April high flow events (Kathryn Reeve and Peter Williams, personal communication). This suggests that any proposed flow management in the catchment may want to consider the effects of high flows on dissolved oxygen levels as well as the effects of low flows.

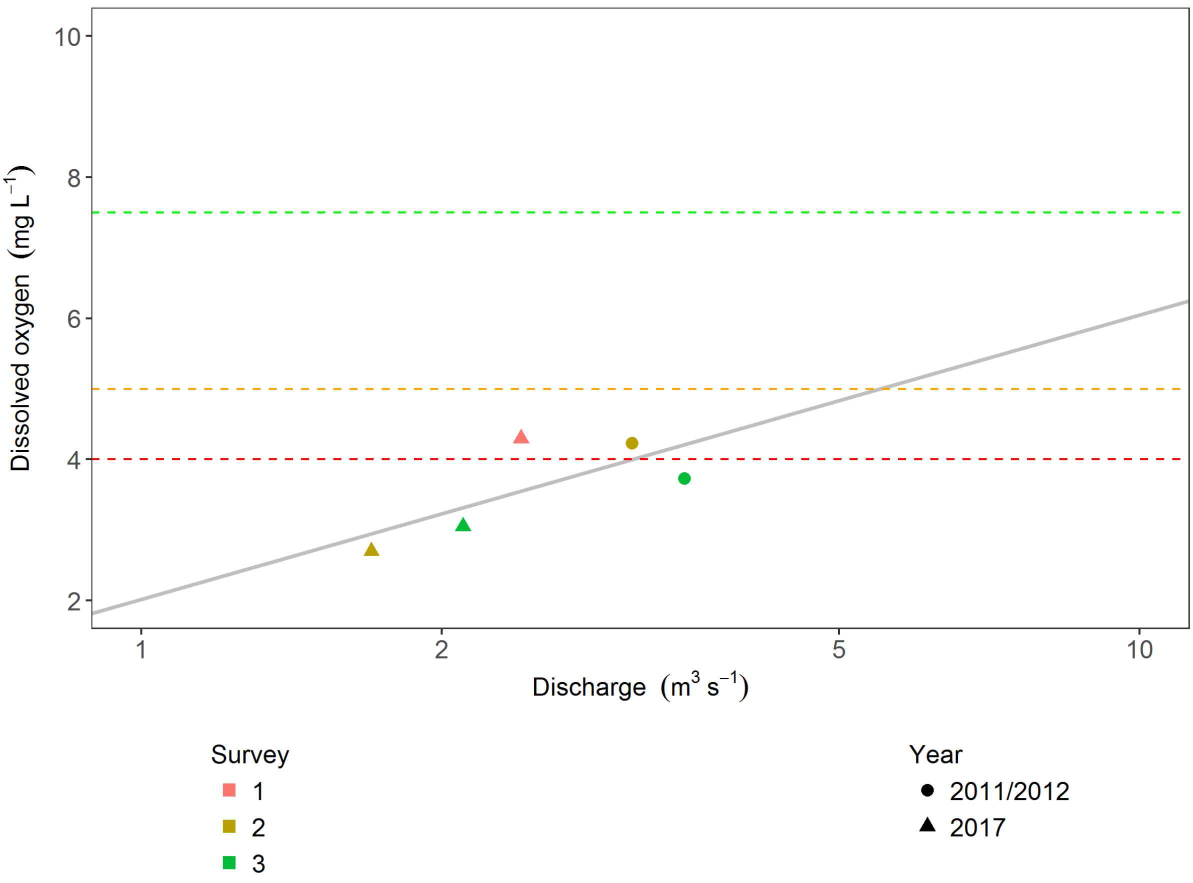

Figure Error! No text of specified style in document.**-16: Minimum dissolved oxygen concentrations (mg L^{-1}) from longitudinal transects versus mean daily flow (m^3 s^{-1}) in the lower Piako River in summers 2011/2012 and 2017.** Data from transects conducted during high flow (>10 m^3 s^{-1}) periods were excluded. The least-squares regression line between dissolved oxygen concentration and flow is shown in grey (R^2=0.36, p=0.17).

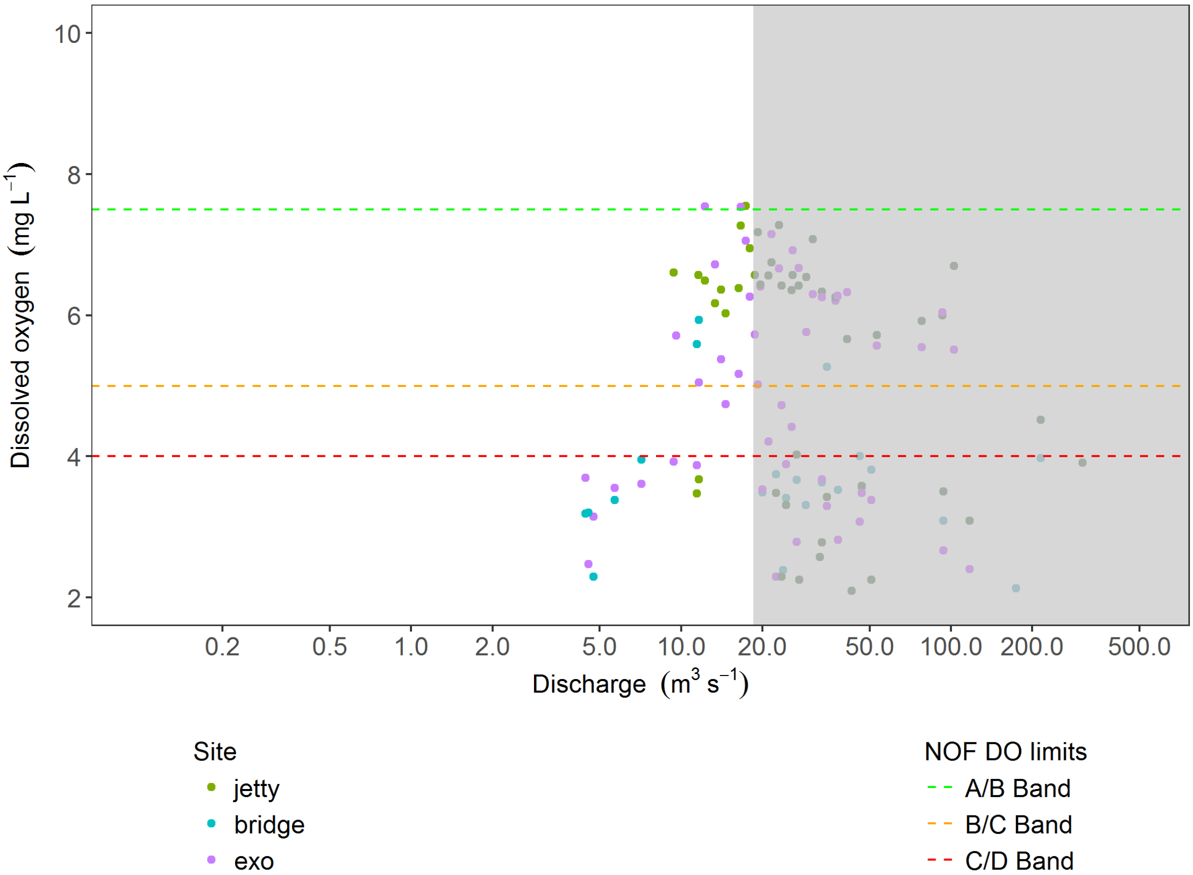

Figure Error! No text of specified style in document.**-17: Daily minimum dissolved oxygen concentrations (mg L^{-1}) from high resolution time series versus mean daily flow (m^3 s^{-1}) in the lower Piako River between March and June 2017.** It is important to note, however, that dissolved oxygen in the lower river is driven by complex interactions between flow and several other variables, including turbidity, salinity, and tidal influences. The grey shaded area indicates high flow conditions (i.e. discharges greater than ten times the median baseflow over the sampling period).

• Conclusions

The results of the 2017 dissolved oxygen monitoring are largely consistent with the relationships observed in 2012 and 2013 and reported in Franklin (2014a). However, validation of the initial results was complicated by differences in flow between the two monitoring periods. In particular, the very low flows which occurred in summer 2013 were not present during the summer 2017 monitoring period. Additionally, two very high flow events occurred during summer 2017, which also impacted dissolved oxygen dynamics, most likely via increased inputs and decomposition of organic matter associated with high turbidity. The oxygen depletion following high flows resulted in dissolved oxygen concentrations falling below the national bottom line for both NOF attributes (daily minimum DO concentration and 7-day mean daily minimum DO concentration). Significant and persistent stress on aquatic organisms occurs when dissolved oxygen concentrations remain below the bottom line.

The 2017 data also confirmed the presence of a dissolved oxygen sag in the lower Piako river first identified in Vant (2013) and provided further evidence of interactions between flow, turbidity, salinity, and dissolved oxygen. The sag occurred at the turbidity maxima, which was also the upstream limit of the saline intrusion. The influence of tide was less clear in 2017, but Franklin (2014a) found that tide height (most likely relative to freshwater inflows) can strongly influence the upstream extent of the saline intrusion.

Understanding the complex relationships between freshwater inflows, tides, turbidity, and oxygen depletion remains critical for development of robust water resource use limits to ensure ecosystem health of the lower river. The baseflow-dissolved oxygen relationship can be used to estimate minimum 'run of river' flow limits for maintenance of dissolved oxygen, but flushing flows superimpose on top of that relationship, and can either improve or further deteriorate dissolved oxygen conditions, depending on the magnitude of the event and antecedent flow conditions. For example, evidence suggests that small flushing events may restore oxygen during prolonged low flow periods. High water abstraction could reduce the number and magnitude of these small flushing flows, which could in turn influence the extent and duration of oxygen depletion during summer low flows.

Given the complexity of tidal effects and event-based flushing and depletion observed between differing flow conditions in this year's survey and the 2012/2103 surveys, it is not possible to provide robust minimum flow limits from current data. However, the consistency in the relationships between survey years indicate that the thresholds identified in **Table** Error! No text of specified style in document.**-7** relating to the D-band threshold are likely sensible working values with which to proceed with reviewing the current limits. It is recommended that continuous dissolved oxygen monitoring be implemented in the catchment to collect multiple years of data at different flow and tide conditions to further investigate the relative roles of flushing flows and high flow events on oxygen concentrations following low flows of varying duration. Monitoring should focus on the four sites in which non-linear relationships between dissolved oxygen and flow have already been observed, as thresholds can be used to identify minimum flows required to ensure adequate dissolved oxygen availability for protection of ecosystem health. An additional approach that could support understanding of the dissolved oxygen dynamics is to undertake process-based modelling of dissolved oxygen v. flow dynamics at key sites. It is recommended that any such modelling study should incorporate analyses of model uncertainty and the potential implications for the flow limit setting process.

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