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Dissolved oxygen and temperature dynamics in the Piako catchment

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Prepared by:
Paul Franklin
National Institute of Water & Atmospheric Research Ltd

For:
Waikato Regional Council
Private Bag 3038
Waikato Mail Centre
HAMILTON 3240

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Authors/Contributors:
Paul Franklin

For any information regarding this report please contact:

Dr Paul Franklin
Scientist
Freshwater Ecology
+64-7-859 1882
paul.franklin@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road
Hillcrest, Hamilton 3216
PO Box 11115, Hillcrest
Hamilton 3251
New Zealand

Phone +64-7-856 7026
Fax +64-7-856 0151

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Reviewed by

B. Wilcock

Approved for release by

D. Rowe

Formatting checked by

Executive summary

The Waikato Regional Council (WRC) is responsible for managing the status of water resources in the Waikato Region. WRC is preparing for a scheduled review of flow and allocation limits in the Piako catchment. The aim of this project was to characterise the dissolved oxygen and water temperature dynamics in the Piako catchment during summer low flow conditions with a view to identifying potential limits on the assimilative capacity of the waterway.

Dissolved oxygen time series collected from six sites around the Piako catchment showed that in the Waitoa River sub-catchment, dissolved oxygen levels were generally maintained at or above the recommended protection levels for maintaining ecosystem health. However, in the Piako River at Kiwitahi and at the Paeroa-Tahuna Road site, dissolved oxygen concentrations fell below recommended protection levels for several weeks during the summer of 2012-13.

Water temperatures reached levels that were above the preferred temperatures of inanga and smelt at all sites except the Piakonui Stream. 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 for some months of the year that may merit further investigation for the limit setting process.

Threshold responses were observed between dissolved oxygen concentrations and flow at four of the six sites. These relationships were used to identify the flows that approximate to the lower class boundaries for the proposed National Objectives Framework (NOF) limits for dissolved oxygen (Table 1-1). Based on the observed correlations between flow and dissolved oxygen concentrations, it is recommended that minimum flow limits be set at a level sufficient to avoid dissolved oxygen concentrations falling below the recommended protection levels for ecosystem health.

Table 1-1: Flows that approximate to the proposed NOF dissolved oxygen attribute state class boundaries for ecosystem health. Flow values are for the corresponding on-site hydrological gauging station with the exception of the Waitoa at Puketutu Road where the flow values are those recorded at Waharoa, the nearest gauging station.

Site	Proposed NOF class – 7-day mean minimum dissolved oxygen		
	Class C (5.0 mg L^{-1})	Class B (7.0 mg L^{-1})	Class A (8.0 mg L^{-1})
Piako @ Paeroa-Tahuna Road	>0.5 $m^3 s^{-1}$	>0.8 $m^3 s^{-1}$	>1.0 $m^3 s^{-1}$
Piako @ Kiwitahi	>0.3 $m^3 s^{-1}$	>0.4 $m^3 s^{-1}$	>0.5 $m^3 s^{-1}$
Waitoa @ Puketutu Road	>0.2 $m^3 s^{-1}$	>0.5 $m^3 s^{-1}$	>1.0 $m^3 s^{-1}$
Waitoa @ Waharoa	>0.25 $m^3 s^{-1}$	>0.5 $m^3 s^{-1}$	>1.0 $m^3 s^{-1}$

It is emphasised that these flow thresholds are based on monitoring results from only one or two summer periods. It is recommended that continuous dissolved oxygen and temperature monitoring be implemented in at least one location on the Waitoa River and one on the Piako River to better refine these thresholds over multiple years and differing flow conditions. This will be required to increase WRC's ability to confidently define limits that meet the likely NOF dissolved oxygen and temperature requirements for protecting ecosystem health.

In the lower river, downstream of the confluence with the Waitoa River, a zone of dissolved oxygen depletion has been identified where dissolved oxygen concentrations drop below recommended protection levels for aquatic ecosystem health. A similar phenomenon has been observed in the lower Waihou River. From the data available, the magnitude and spatial extent of the zone of depletion appears to be greatest during summer and associated with the development of a zone of high turbidity under summer low flows. This may act as a constraint on upstream water resource use and it is recommended that more detailed monitoring of this feature be undertaken to better elucidate the temporal and spatial extent of the oxygen depletion zone. Enhanced understanding of the processes driving the observed patterns will allow WRC to make more informed and transparent decisions about the management of upstream water resources.

1 Introduction

1.1 Background

The Waikato Regional Council (WRC) is responsible for managing the status of water resources in the Waikato Region. WRC's approach to the protection, allocation and use of water resources is set out in the Waikato Regional Plan: Variation No. 6 – Water Allocation, which became operative on 10 April 2012 (Waikato Regional Council 2012). As required by the National Policy Statement for Freshwater Management (MfE 2011), the Plan defines minimum flows and allocation limits for all catchments in the region (Table 3-5, Waikato Regional Council 2012).

A review of the flow and allocation limits in the Piako catchment is scheduled for July 2014 (Table 3-4A, Waikato Regional Council 2012). In preparation for this, WRC have initiated a number of investigations to support and inform the review process. The aim of this project was to characterise the dissolved oxygen and water temperature dynamics in the Piako catchment during summer low flow conditions with a view to identifying potential limits on the assimilative capacity of the waterway.

1.2 Project scope

The aim of this project was to empirically evaluate the interrelationships between flow and dissolved oxygen and water temperature dynamics in the Piako catchment. This was to be achieved through the following programme of work:

- Characterisation of the temporal dynamics of dissolved oxygen and water temperature at a range of sites in the Piako catchment during summer low flow conditions.
- Analysis and interpretation of the results with respect to flow and the known tolerances of aquatic organisms.

During the course of the project, WRC carried out longitudinal surveys of dissolved oxygen concentrations in the lower reaches of the Piako River (Vant 2013). WRC subsequently requested that the results of those surveys be added to this report (Ed Brown, WRC, pers. com.).

2 Methodology

D-Opto loggers calibrated and deployed by WRC were used to collect continuous dissolved oxygen and water temperature data at six sites around the Piako catchment during the summer low flow period of 2013 (Table 2-1). The location of the six monitoring sites are shown in Figure 2-1. The loggers were also deployed during the summer of 2012 at two of the sites. Four of the sites are also flow gauging sites and flow data for the relevant monitoring periods were provided by WRC (Table 2-1).

Table 2-1: Location of dissolved oxygen and temperature monitoring sites in summer 2012 and 2013.

Site	Easting	Northing	2012	2013	Flow
Piako@Paeroa-Tahuna Road	1821514	5845214	✓	✓	✓
Piako@Kiwitahi	1829552	5824019	✓	✓	✓
Piakonui@Piakonui Road	1832535	5814545		✓	
Waitoa@Mellon Road	1832321	5843131		✓	✓
Waitoa@Waharoa	1841868	5817036		✓	✓
Waitoa@Puketutu Road	1839787	5804427		✓	

Following data checking, time series were plotted and summary statistics derived describing the dissolved oxygen dynamics at each site. Summary statistics were compared against the limits for ecosystem protection proposed by Franklin (2013) (Table 2-2). All summary statistics were calculated from continuous dissolved oxygen measurements. The 7-day mean dissolved oxygen concentration was calculated as a rolling 7-day average of the mean daily dissolved oxygen concentrations. The 7-day mean daily minimum dissolved oxygen concentration was calculated as a rolling 7-day average of the daily minimum dissolved oxygen concentration and the instantaneous minimum is equivalent to the daily minimum dissolved oxygen concentration.

Table 2-2: Proposed dissolved oxygen levels for protection of New Zealand freshwater fish communities (Franklin 2013). Imperative protection level is the minimum recommended protection level for adult fish. Guideline protection level should be the target protection level or minimum for salmonids and the early life stages of all species. For salmonid spawning redds or embryonic stages of fish, this should be the interstitial concentration.

Summary statistic	Protection level	Dissolved oxygen concentration (mg L^{-1})
7-day mean (mg L^{-1})	Guideline	8.0
	Imperative	7.0
7-day mean daily minimum (mg L^{-1})	Guideline	6.0
	Imperative	5.0
Instantaneous minimum (mg L^{-1})	Guideline	5.0
	Imperative	3.5

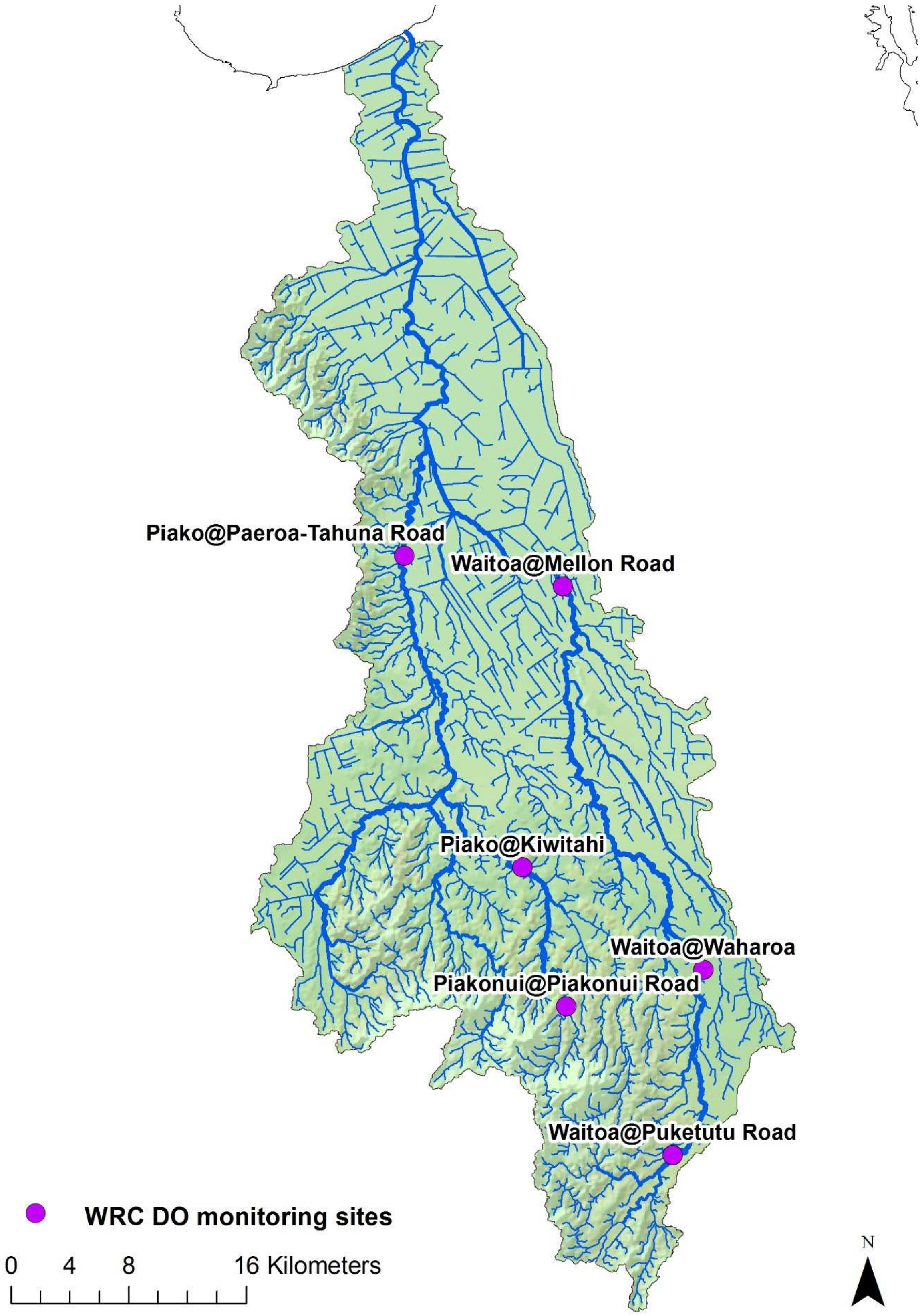


Figure 2-1: Location of dissolved oxygen monitoring sites in the Piako catchment.

Flow dependent relationships with dissolved oxygen were analysed using linear regression and Pearson correlation coefficients. The concentration of dissolved oxygen in water has also been linked to the influence of different hydraulic properties on the dissolved oxygen reaeration coefficient (k_2) (e.g., O'Connor & Dobbins 1958). A range of methods are available to estimate the value of k_2 (Aristegi et al. 2009, Chapra & Di Toro 1991, Hornberger & Kelly 1975, Thyssen & Erlandsen 1987), but the relative performance of different methods when transferred between systems is variable (Aristegi et al. 2009, Thyssen & Erlandsen 1987). Both Aristegi et al. (2009) and Young, in Wilcock et al. (2011), recommended the night-time regression method of Hornberger and Kelly (1975) as being suitable for estimating the value of k_2 from continuous dissolved oxygen measurements under stable flow conditions. This method relies on the fact that plant photosynthesis stops at night and so any changes in oxygen concentration are due to either uptake by respiration within the river or exchange of oxygen with the atmosphere at the river surface. This relationship is represented in the following equation:

$$\frac{dO}{dt} = -R + k_2 D$$

Where *O* is the dissolved oxygen concentration, *t* is the time of day, *R* is the rate of oxygen uptake by respiration, k_2 is the stream reaeration coefficient and *D* is the dissolved oxygen deficit such that $D=O_{sat} - O$ where O_{sat} is the saturation concentration of dissolved oxygen at the monitoring site. The rate of change of the oxygen concentration (*dO/dt*) and *D* are known from the oxygen record. The slope of the regression line on those data collected at night is used to estimate k_2 and the intercept to estimate mean *R*. The r^2 value of the regression line gives an indication of the confidence in the estimation, with little confidence given to values when r^2 is <0.4 (Aristegi et al. 2009, Wilcock et al. 2011).

The value of k_2 was estimated for each site using the night-time regression method. Only regressions with an $r^2 \geq 0.4$ were used in the analysis of the relationship between k_2 and flow.

3 Results

3.1 Flow conditions during sampling

River flows over the sampling period were characterised by a spring time recession of the hydrograph interspersed with two high flow events in late October 2012 and early December 2012, followed by an extended period of base flow where flows were at or below Q_5 until mid-April 2013 (Figure 3-1). Dissolved oxygen loggers were also deployed at Kiwitahi and the Paeroa-Tahuna Road bridge for the 2011-12 summer period (Figure 3-1). River flow during this period was characterised by frequent summer flood events, including two large floods in late December 2011 and early January 2012. Flow did not fall below Q_5 for the whole of this period. Monitoring at the Paeroa-Tahuna Road bridge site was also continued throughout the winter period of 2012 (Figure 3-1).

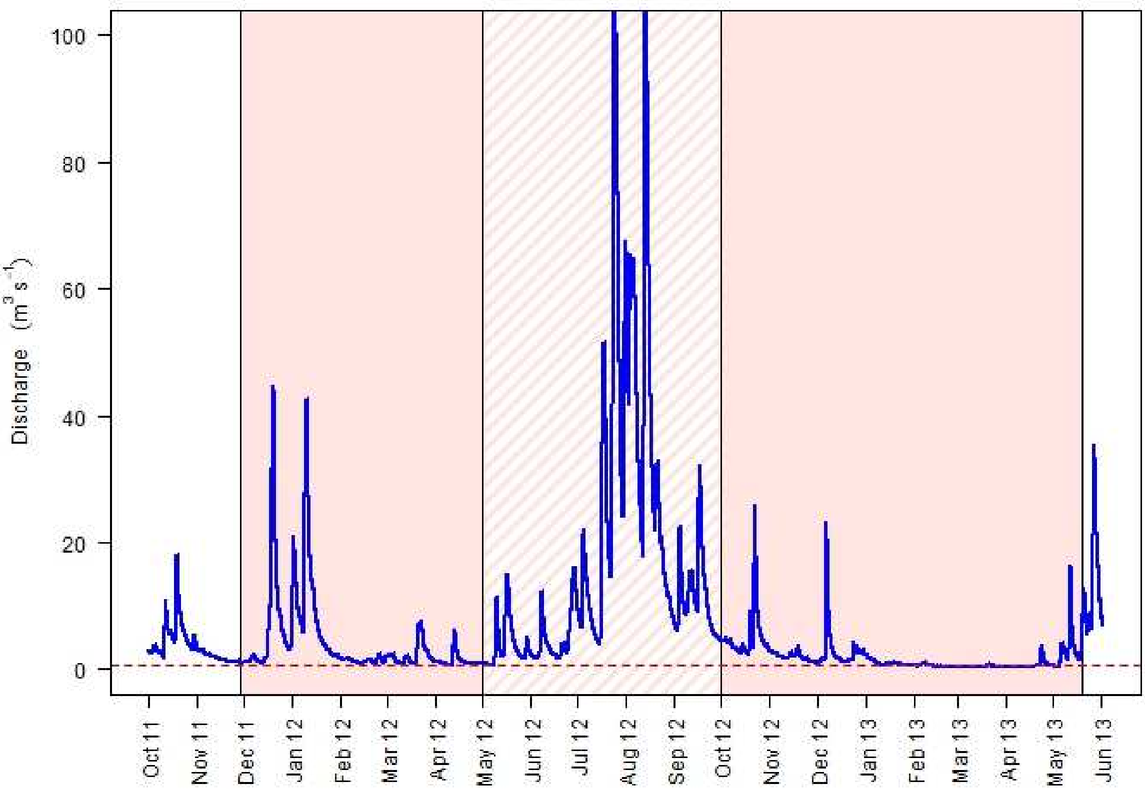


Figure 3-1: Flow time series for the Piako River at the Paeroa-Tahuna Road gauging site showing the dissolved oxygen sampling periods. The solid shaded areas represent the duration of the 2011-12 and 2012-13 monitoring periods. Monitoring also continued over the winter period (striped shading) at the Paeroa-Tahuna Road bridge monitoring site. Horizontal dashed line is the estimated Q_5 flow.

3.2 Water temperature dynamics

3.2.1 Water temperature time series

Water temperature time series for each of the six monitoring sites are shown in Figure 3-2 to Figure 3-5 and are strongly correlated with ambient air temperature. Water temperature was recorded in the Piako River at the Paeroa-Tahuna Road bridge from October 2011 to April 2013 (Figure 3-2). Summer maxima were around 22°C and 24°C for the 2011-12 and 2012-13 summer periods respectively. The lowest recorded temperature was 6°C in May 2012. During summer a diel variation in water temperatures was observed of around 2°C. Summer water temperatures at this site exceed the thermal preferences of both inanga and smelt (Table 3-1), both of which would be expected to occur in this part of the Piako River. Summer water temperatures in the Piako River at Kiwitahi were very similar to those recorded at the Paeroa-Tahuna Road bridge and again exceed the preferred temperature of both inanga and smelt (Figure 3-3). Summer water temperatures in the Piakonui Stream generally did not exceed 17°C during 2012-13 (Figure 3-4). This is within the temperature preference range for the main fish species (longfin and shortfin eel, Cran's bully and banded kokopu) that occur in this stream (Franklin & Bartels 2012). The lower water temperatures at this site reflect its location higher in the catchment and the greater proportion of stream shading in many of the nearby tributaries.

Water temperatures in the three Waitoa River monitoring sites are relatively similar with summer maxima during 2012-13 of around 24°C (Figure 3-4 & Figure 3-5). The main difference is that diel variability is slightly higher (c. 3°C) at the Puketutu Road site, compared to c. 2°C at the other two sites. At all three sites summer water temperatures (December to February) are generally in excess of those preferred by both smelt and inanga (Table 3-1). Both species would be expected to occur at these sites based on their location in the catchment and the habitat available (Franklin & Bartels 2012).

Table 3-1: Preferred water temperatures of selected fish species typical of the Piako River system. Source: Richardson 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)

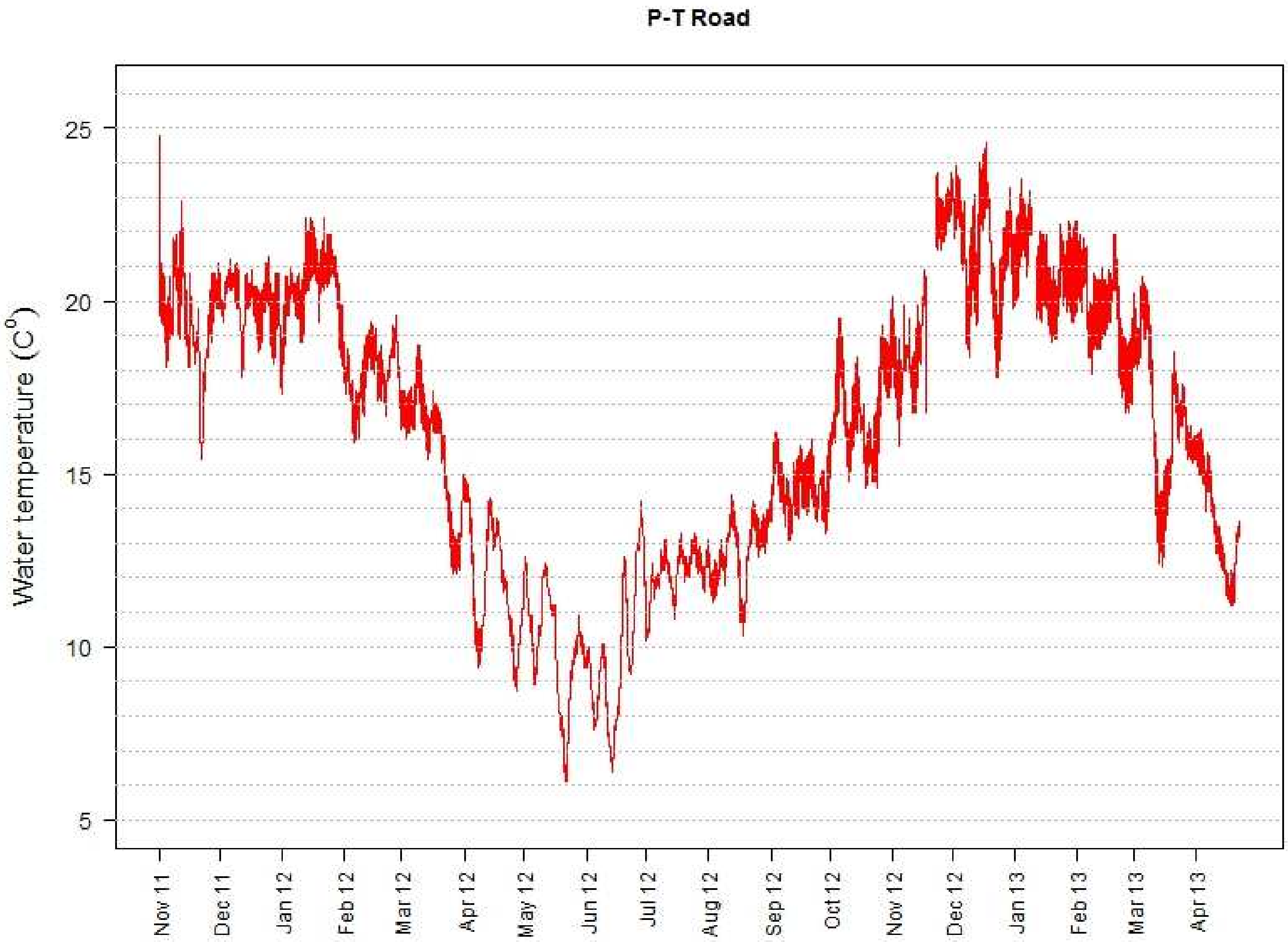


Figure 3-2: Water temperature time series from October 2011 to April 2013 for the monitoring site on the Piako River at the Paeroa-Tahuna Road bridge.

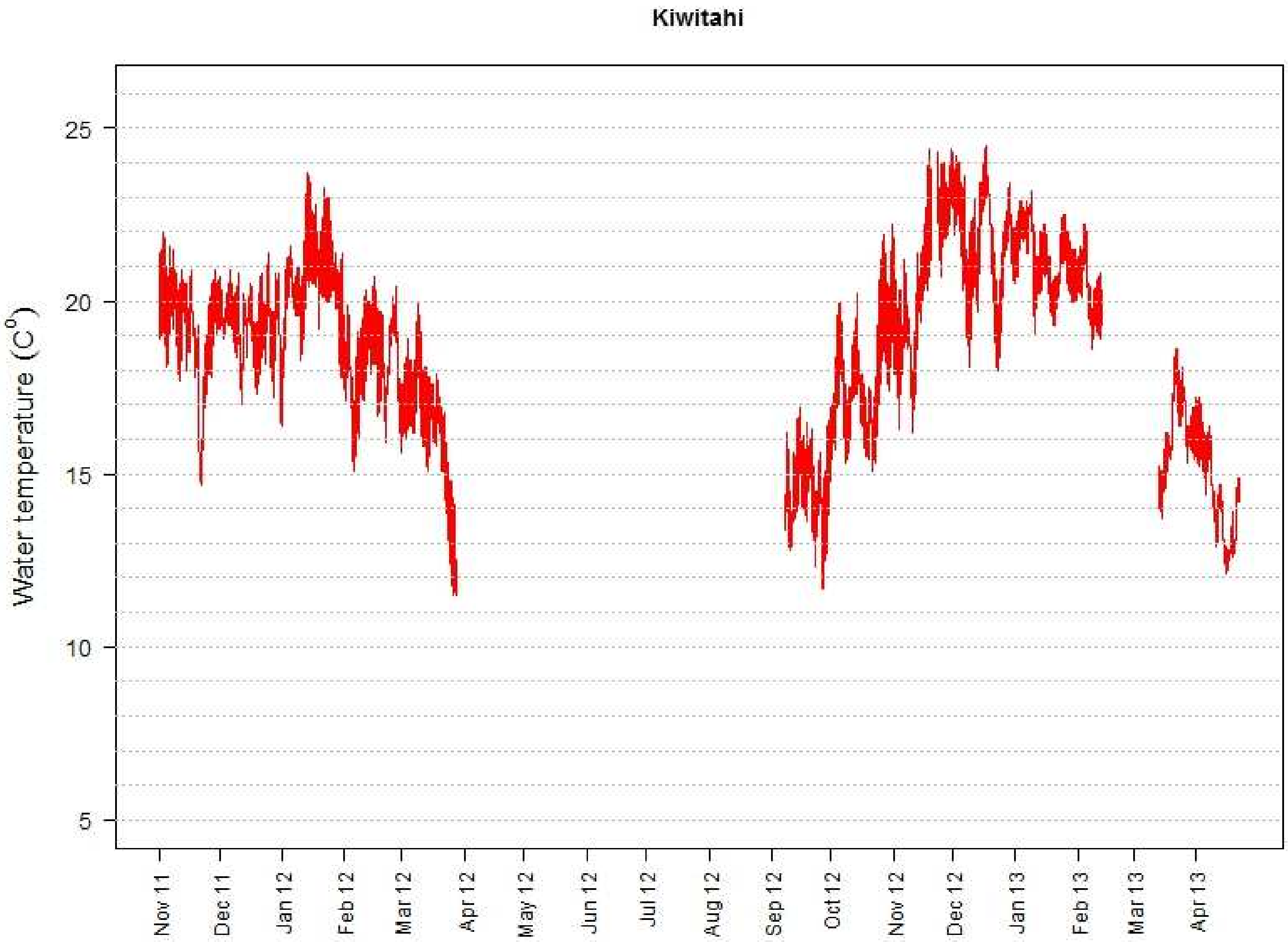


Figure 3-3: Water temperature time series from the 2011-12 and 2012-13 sampling periods for the monitoring site on the Piako River at the Kiwitahi.

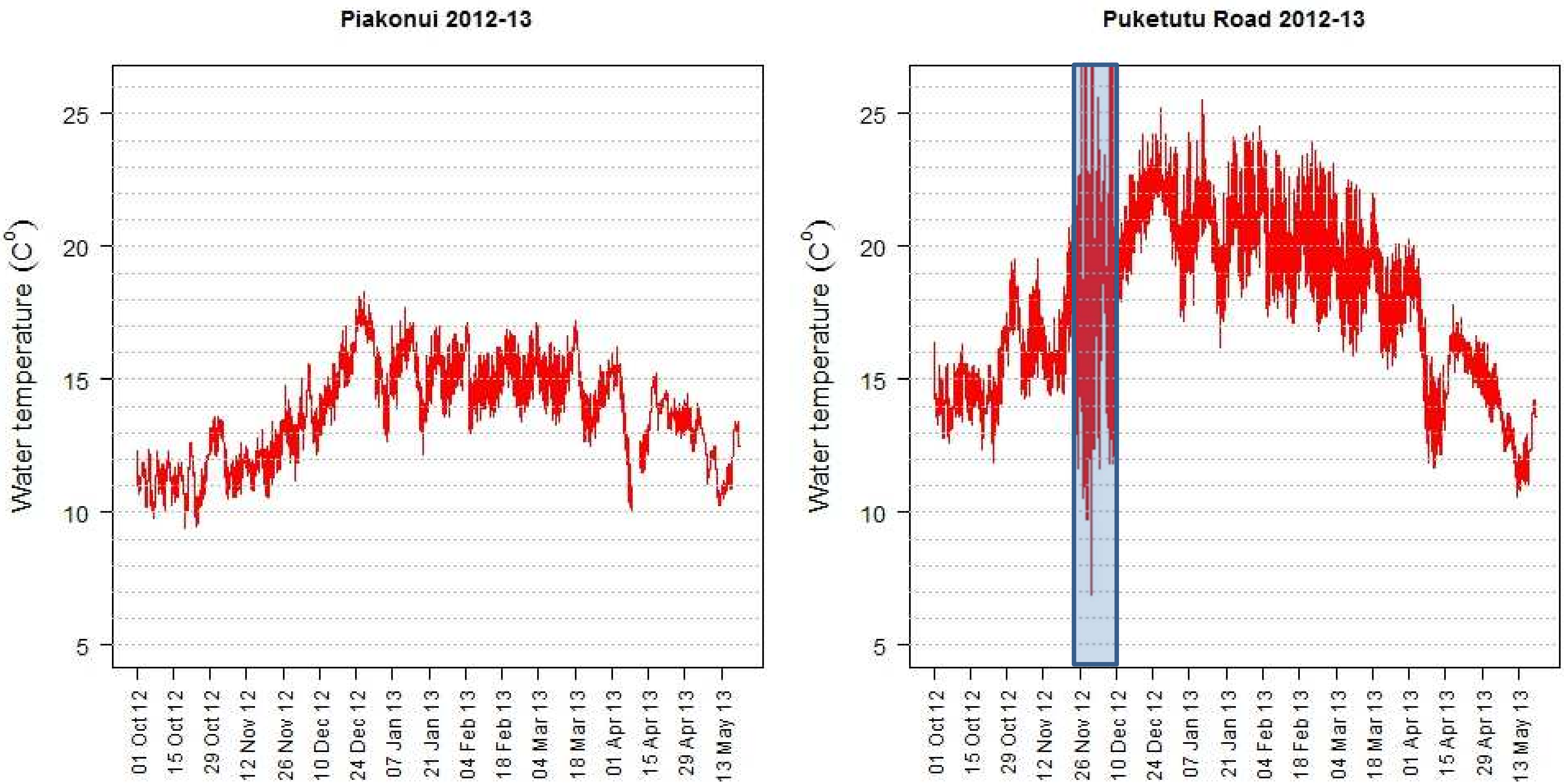


Figure 3-4: Water temperature time series for the 2012-13 low flow period for the Piakonui Stream and the Waitoa at Puketutu Road. The large diel variations in water temperature at the Puketutu Road site during November 2012 (blue box) are thought to be a result of the logger being exposed rather than real water temperatures and should be treated with caution (Mark Hamer, WRC, pers. com.).

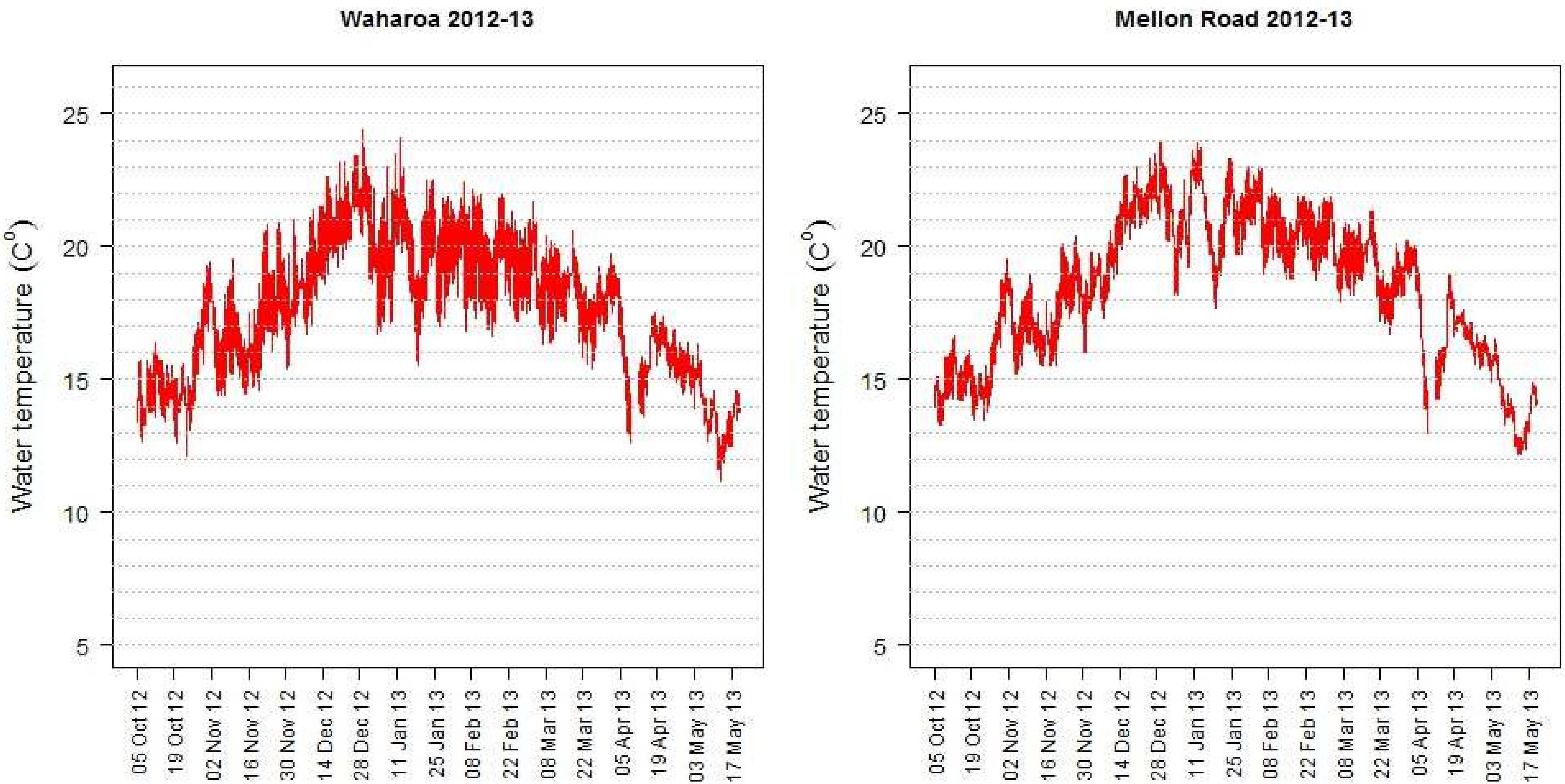


Figure 3-5: Water temperature time series for the 2012-13 low flow period for the Waitoa at Waharoa and Mellon Road.

3.2.2 Interaction between water temperature and flow

The scatter plots of mean daily water temperature against flow showed some evidence of a slight negative correlation between the variables (Figure 3-6 to Figure 3-8). However, this correlation is confounded by the co-variation between flow and water temperature with season (i.e., higher water temperatures and lower flows both occur in summer). To account for the potential temporal co-variation, regression relationships between maximum daily water temperature and mean daily flow were calculated on a monthly basis for each site (based on the assumption that within each month average temperature and flow are similar).

At all sites, for the majority of months there was a negative correlation between maximum water temperature and mean daily flow. However, in most cases this correlation was not statistically significant ($p>0.05$; Table 3-2). At the Piakonui site, there were no statistically significant correlations in any month. Statistically significant negative correlations were most common in November 2012, but this also coincides with the steepest recession of the hydrograph and increase in water temperatures associated with the end of spring and thus is likely to be an artefact of the natural seasonal changes during this month. The sites on the Waitoa River at Waharoa and Mellon Road have the greatest frequency of significant relationships between flow and water temperature. However, the slope of the statistically significant correlations ranges from -14.9 to 11.9 at Waharoa and -9.8 to 3.2 at Mellon Road. This lack of consistency makes it difficult to provide any robust characterisation of any potential causal relationship between water temperature and flow.

Table 3-2: Statistical significance of monthly correlations between maximum water temperature and mean daily flow for the 2012-13 monitoring period. All significant correlations were negative except where indicated (+ive). NS = Not significant; * = $p<0.05$; ** = $p<0.01$; *** = $p<0.001$.

Site	October	November	December	January	February	March	April	May
Kiwitahi	NS	***	**	NS	* (+ive)	NS	NS	NS
Paeroa-Tahuna Road	NS	**	NS	NS	NS	NS	NS	NS
Piakonui	NS	NS	NS	NS	NS	NS	NS	NS
Puketutu Road	NS	***	NS	NS	NS	**	NS	NS
Waharoa	NS	***	**	NS	** (+ive)	**	NS	NS
Mellon Road	NS	**	*	NS	** (+ive)	***	NS	***

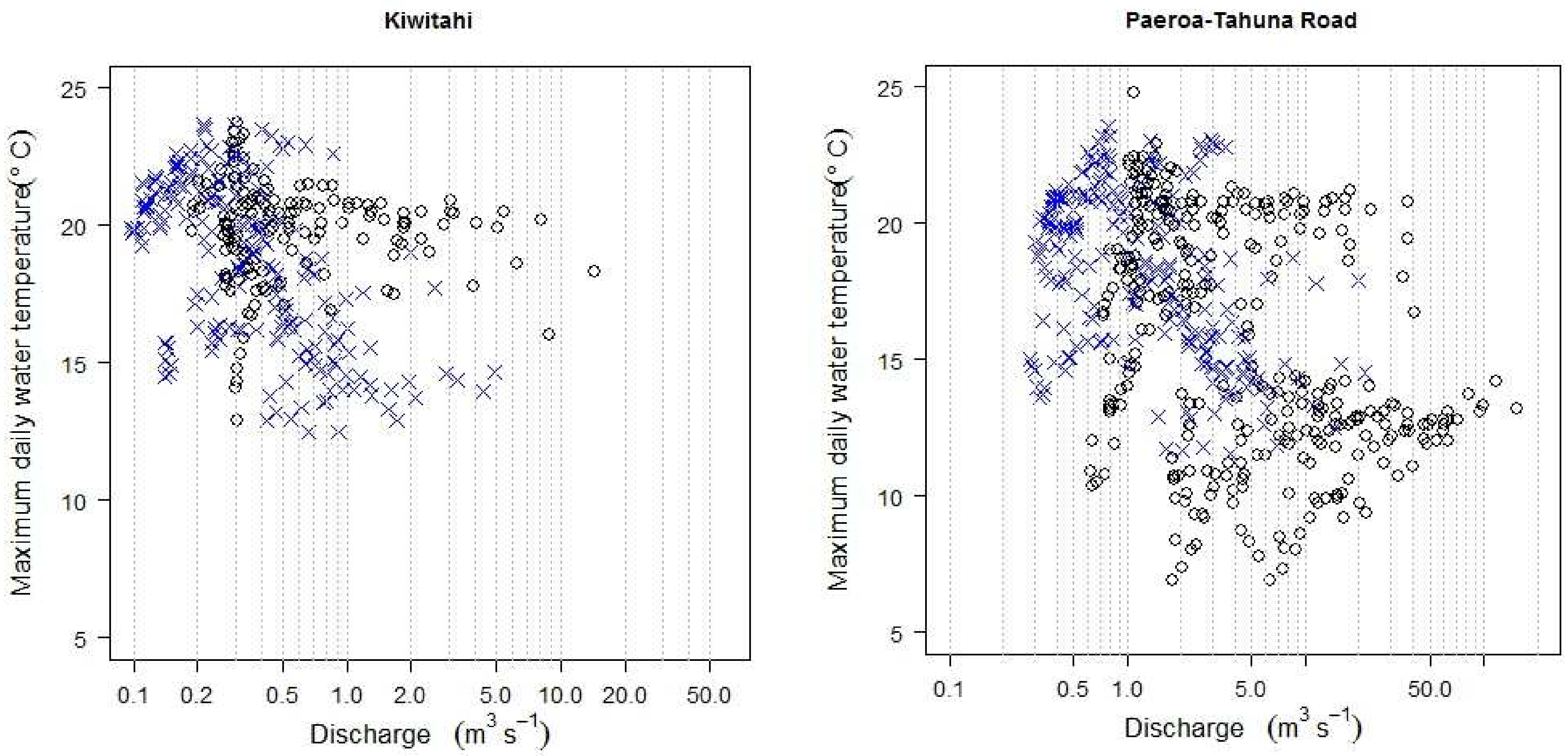


Figure 3-6: Scatter plots of maximum daily water temperature against mean daily flow for the Piako River at Kiwitahi and the Paeroa-Tahuna Road bridge. Circles represent data from 2011-12 and crosses 2012-13 sampling periods. Note that the x-axis is a logarithmic scale.

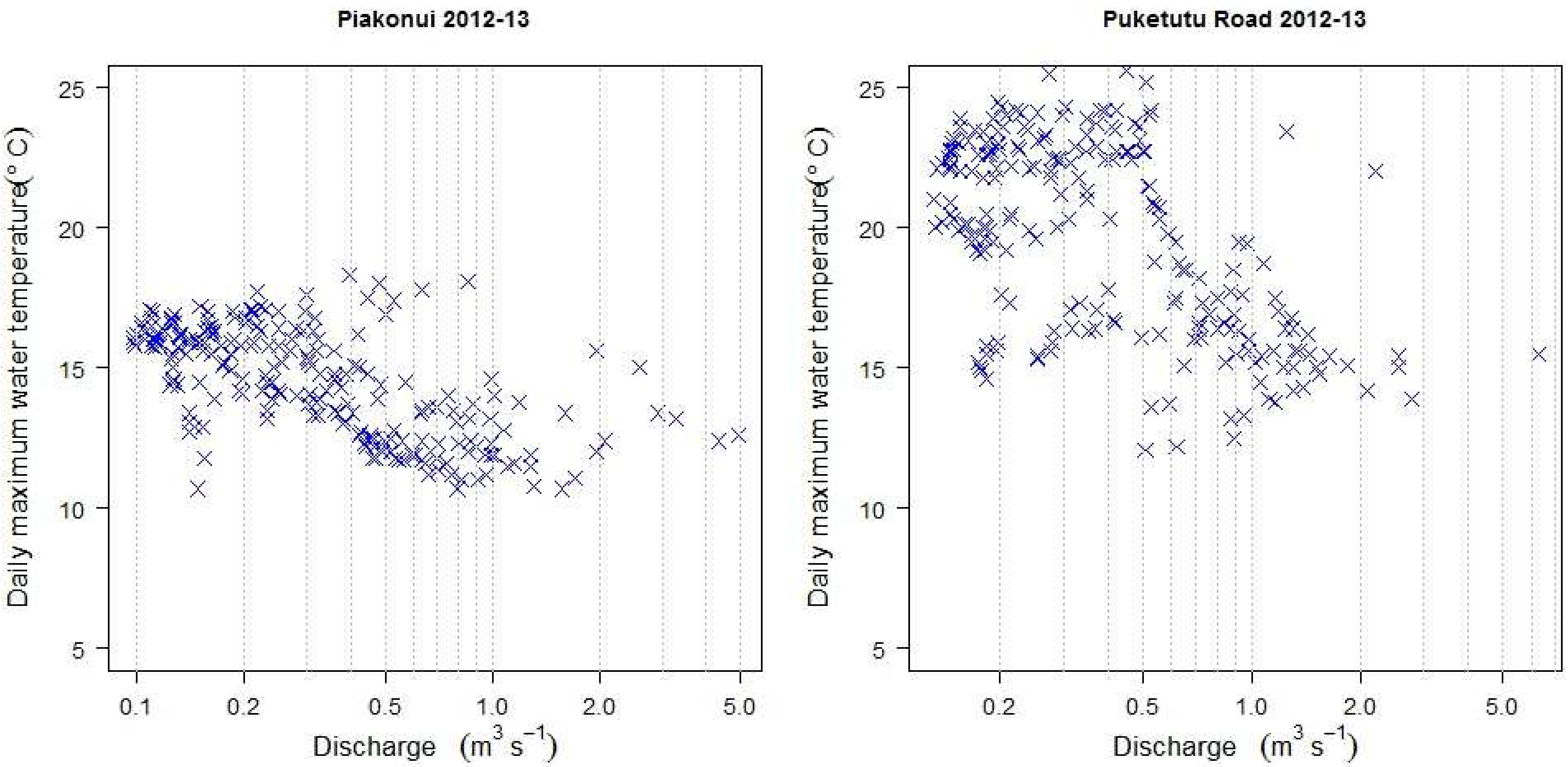


Figure 3-7: Scatter plots of maximum daily water temperature against mean daily flow for the Piakonui Stream and the Waitoa River at Puketutu Road. Note that the x-axis is a logarithmic scale.

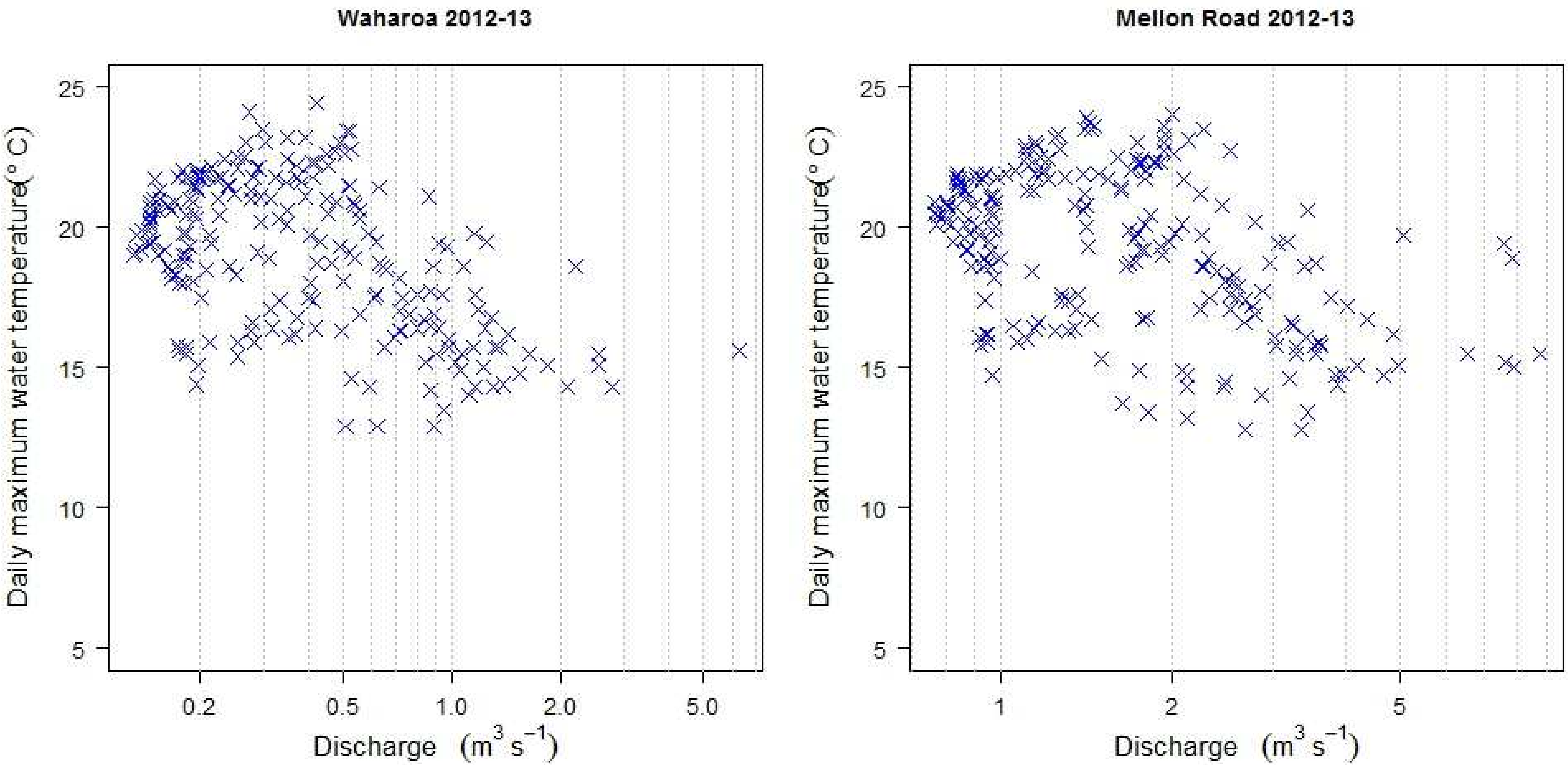


Figure 3-8: Scatter plots of maximum daily water temperature against mean daily flow for the Waitoa River at Waharoa and Mellon Road. Note that the x-axis is a logarithmic scale.

3.3 Dissolved oxygen dynamics

3.3.1 Dissolved oxygen time series

The dissolved oxygen time series for the Piako and Waitoa Rivers are shown relative to the imperative dissolved oxygen limits for ecosystem protection proposed by Franklin (2013) in Figure 3-9 to Figure 3-12. The longer time series recorded in the Piako River at the Paeroa-Tahuna Road bridge shows that both mean and minimum dissolved oxygen concentrations were higher than the proposed ecosystem protection levels throughout the summer of 2011-12 and winter 2012 (Figure 3-9). However, as flows dropped during the summer of 2012-13, dissolved oxygen concentrations fell below the recommended thresholds for all three measures of dissolved oxygen (7-day mean daily concentration, 7-day mean daily minimum concentration and daily minimum concentration) for several weeks. The dissolved oxygen minima recorded during this period at this site exceeded acute lethal levels for some species of fish (Dean & Richardson 1999) and thus, in combination with the duration of low dissolved oxygen concentrations, there is a high risk of ecological impairment at this site.

At the Kiwitahi monitoring site, the recommended ecosystem protection levels were not met for parts of both the 2011-12 and 2012-13 summer periods (Figure 3-10). In 2011-12, the period where limits were exceeded occurred during December, prior to the summer flood events, but were still of sufficient duration to increase the risk to aquatic ecosystem values. During the summer of 2012-13 when sustained low flows occurred, dissolved oxygen concentrations were below recommended protection levels from mid-December until beyond the middle of February when the logger failed (Figure 3-10). The risk of ecosystem impairment at this site is likely to be high as a result of this prolonged period of low dissolved oxygen concentrations, particularly in combination with additional stressors such as high water temperature and low flows.

Dissolved oxygen concentrations in the Piakonui Stream remained well above the recommended ecosystem protection levels throughout the monitoring period (Figure 3-11). The cooler water temperatures and riffle located upstream of this site will contribute significantly to this.

At all three monitoring sites on the Waitoa River, dissolved oxygen concentrations generally remained at or above the recommended limits for ecosystem protection for the entire monitoring period (Figure 3-11 & Figure 3-12). However, particularly at Puketutu Road and Waharoa, the 7-day mean daily and 7-day mean daily minimum dissolved oxygen concentrations frequently approached their respective limits during the January to March 2013 low flow period. At each of these sites, the diel variation in dissolved oxygen concentrations between January and March was typically very high, with dissolved oxygen concentration frequently varying by 5-10 mg L^{-1} between the daily minimum and maximum values. This is likely to be a consequence of high macrophyte abundance in these reaches.

At all six sites, the effect of the first significant rainfall event in early April 2013 is apparent in the dissolved oxygen time series. In all cases, the elevated flows result in an improvement in dissolved oxygen concentrations. This further emphasises the importance of flushing flows for maintaining dissolved oxygen concentrations, which was also observed in the summer of 2011-12.

Figure 3-9: Dissolved oxygen time series for the Piako River at the Paeroa-Tahuna Road bridge. Dissolved oxygen limits indicated by solid horizontal lines are those proposed by Franklin (2013) for the protection of aquatic ecosystem values.

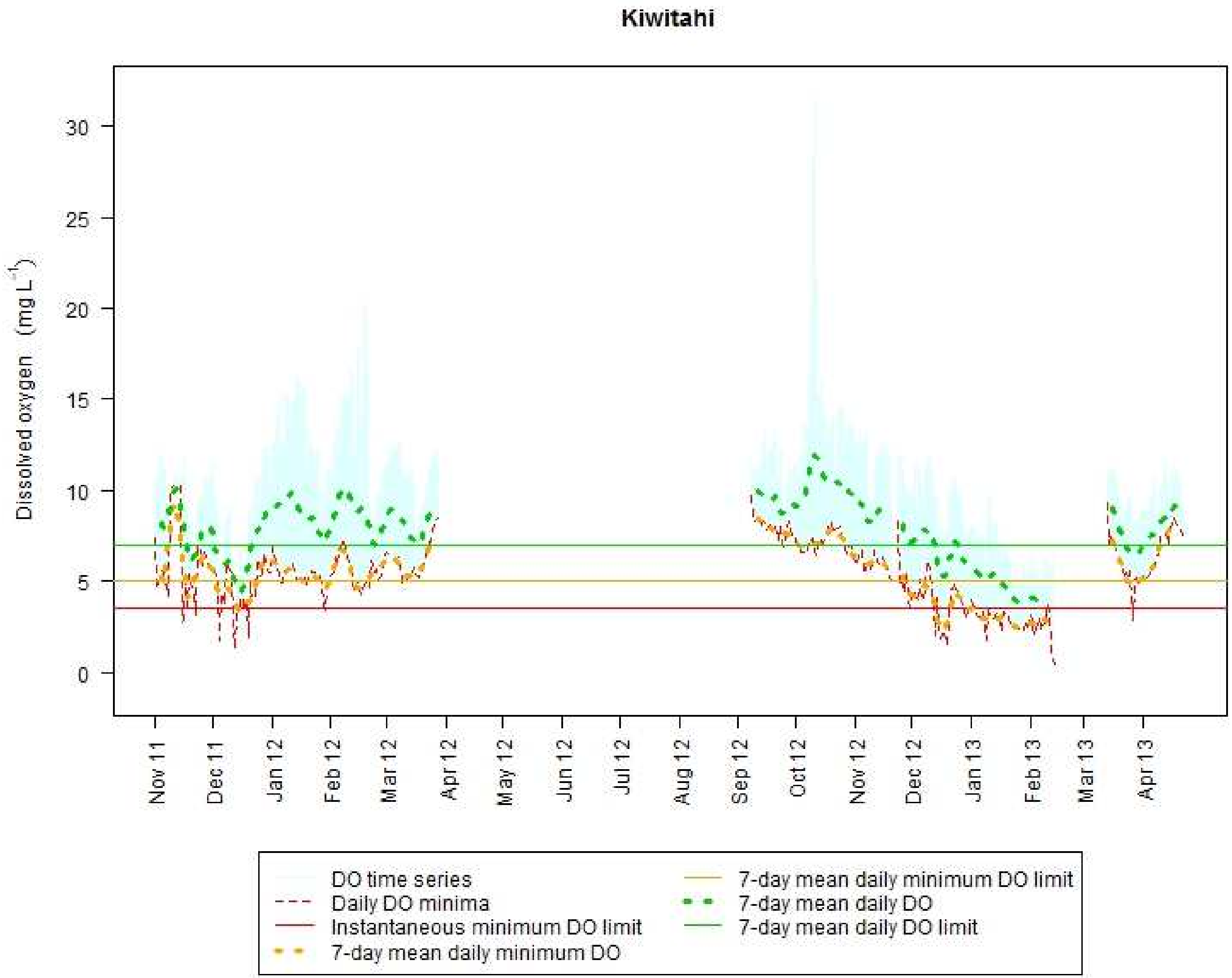


Figure 3-10: Dissolved oxygen time series for the Piako River at Kiwitahi. Dissolved oxygen limits indicated by solid horizontal lines are those proposed by Franklin (2013) for the protection of aquatic ecosystem values.

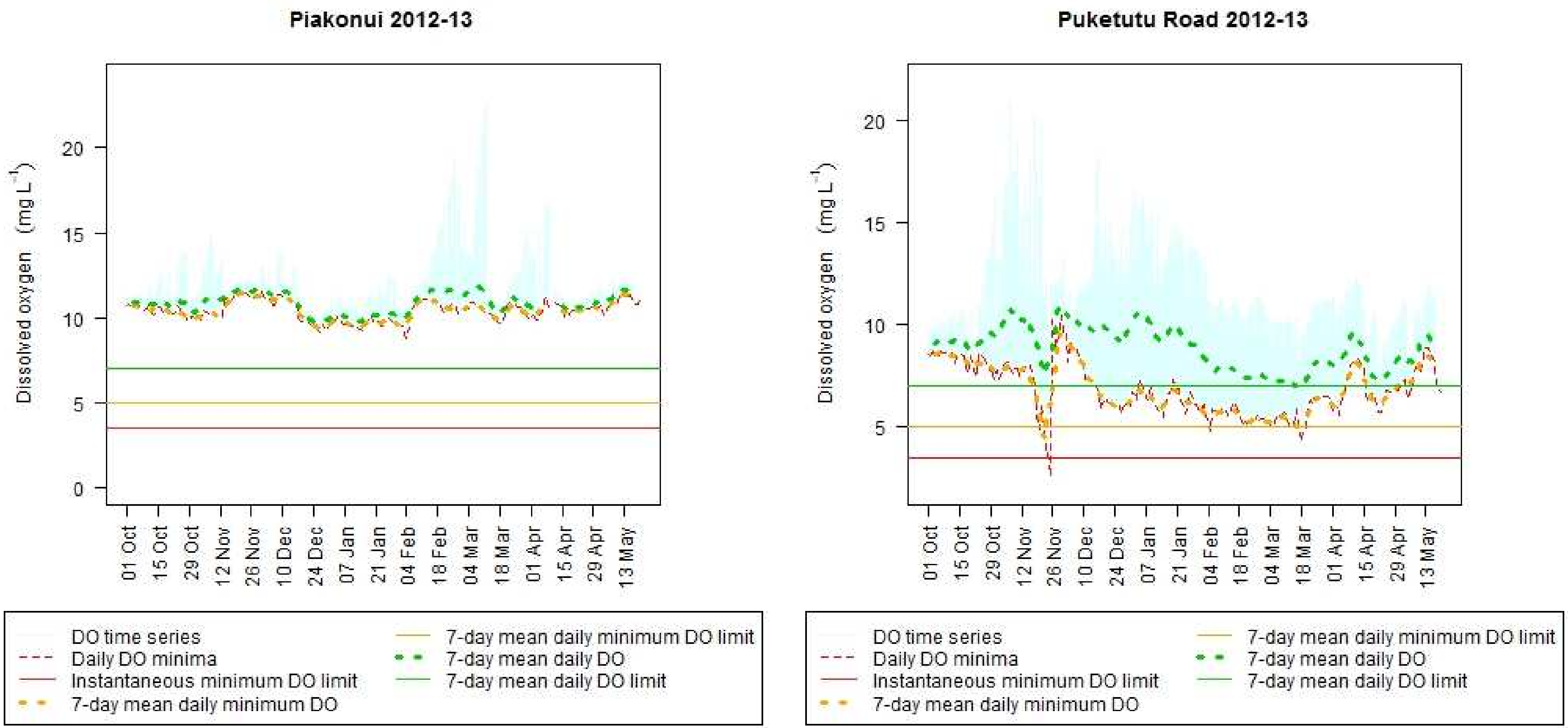
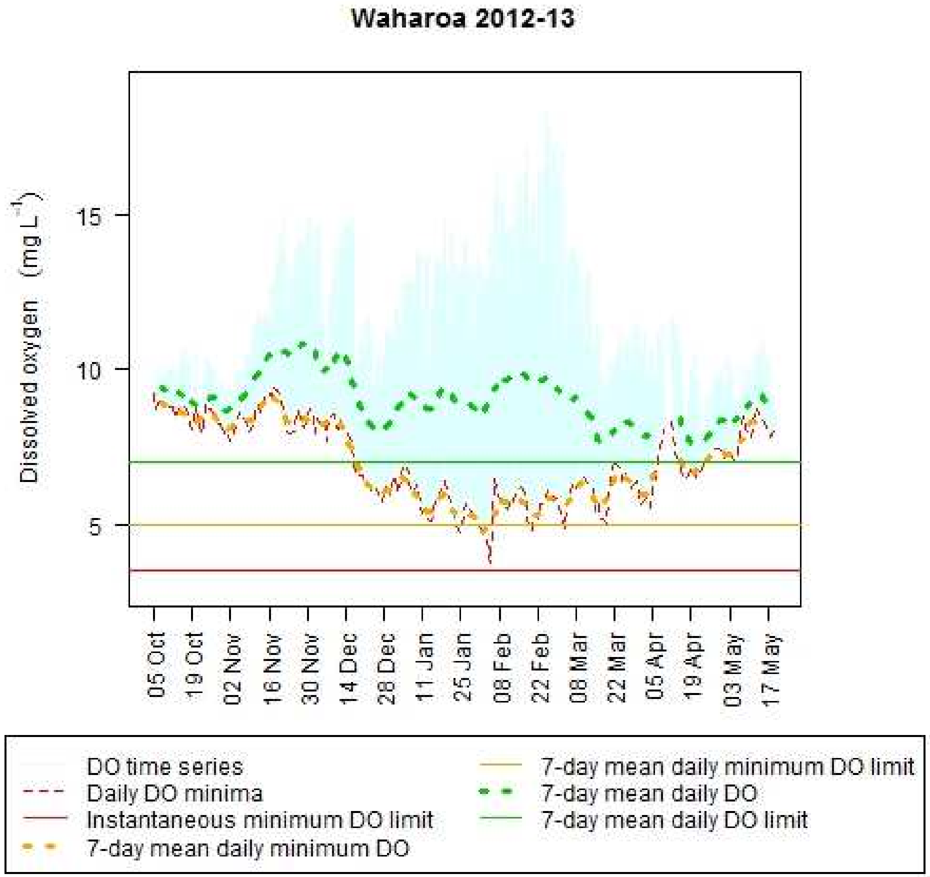


Figure 3-11: Dissolved oxygen time series for the Piakonui Stream and the Waitoa at Puketutu Road. Dissolved oxygen limits indicated by solid horizontal lines are those proposed by Franklin (2013) for the protection of aquatic ecosystem values. None of the limits are visible for the Piakonui site as they are below the range of dissolved oxygen concentrations observed at the site.



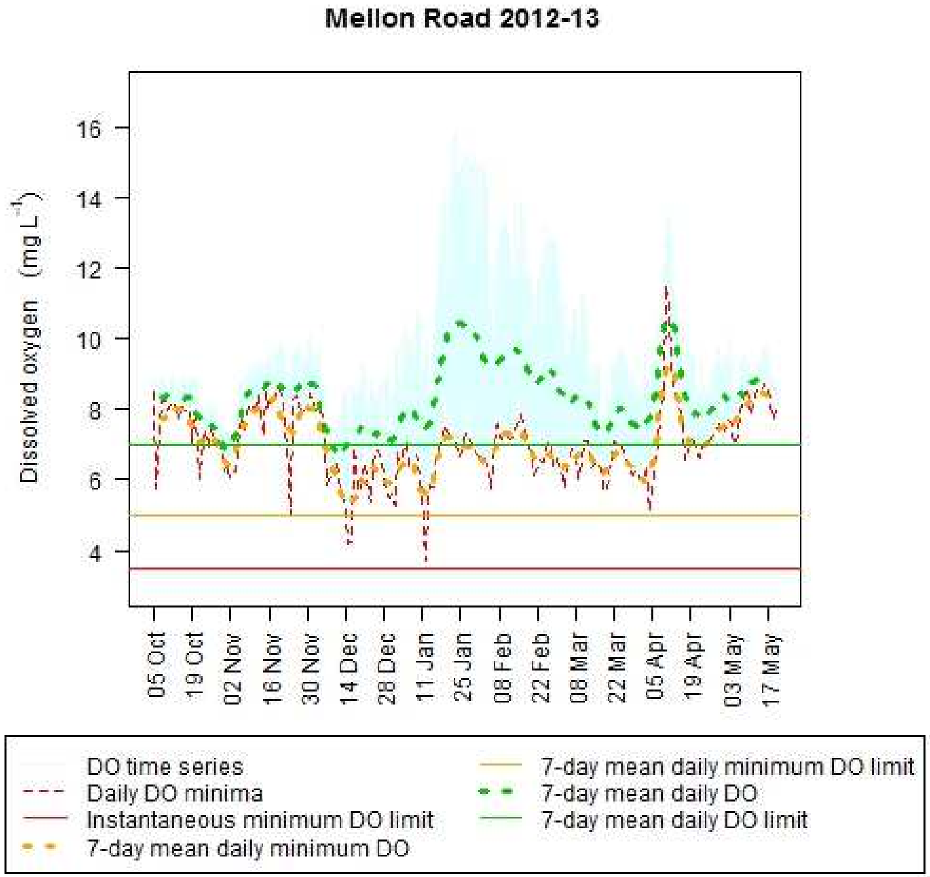


Figure 3-12: Dissolved oxygen time series for the Waitoa at Waharoa and Mellon Road. Dissolved oxygen limits indicated by solid horizontal lines are those proposed by Franklin (2013) for the protection of aquatic ecosystem values.

3.3.2 Interactions between dissolved oxygen and flow

A non-linear threshold response was identified between dissolved oxygen concentrations and mean daily flow at the Paeroa-Tahuna Road, Kiwitahi, Puketutu Road and Waharoa monitoring sites (Figure 3-13 to Figure 3-18). At the Piakonui and Mellon Road sites, no significant effect of flow on dissolved oxygen concentrations was identified.

At the Paeroa-Tahuna Road bridge site as flow drops below 1 $m^3 s^{-1}$, dissolved oxygen concentrations begin to decline (Figure 3-13). This decline accelerates rapidly as flow falls below 0.6 $m^3 s^{-1}$ such that at flows below 0.5 $m^3 s^{-1}$ the imperative dissolved oxygen limits for all three measures of dissolved oxygen are breached.

At Kiwitahi as flows fall below 0.5 $m^3 s^{-1}$, dissolved oxygen concentrations begin to decline. The flow threshold below which dissolved oxygen concentrations exceed the recommended imperative ecosystem protection limits is 0.3 $m^3 s^{-1}$ (Figure 3-14).

In the Piakonui Stream, no significant thresholds or correlations between flow and dissolved oxygen were observed (Figure 3-15).

In the Waitoa River at Puketutu Road the daily dissolved oxygen minima and 7-day mean daily minimum dissolved oxygen concentrations declined as flow fell below 1 $m^3 s^{-1}$ (Figure 3-16). However, the 7-day mean daily dissolved oxygen concentration remained stable until flow fell below 0.3 $m^3 s^{-1}$. The imperative ecosystem protection limits for the 7-day mean and 7-day mean minimum dissolved oxygen concentrations were exceeded as flow fell below 0.20 $m^3 s^{-1}$.

As flow falls below 1 $m^3 s^{-1}$ at the Waharoa site on the Waitoa River both the daily minimum and 7-day mean daily minimum dissolved oxygen concentrations decline (Figure 3-17). As flow declines below 0.25 $m^3 s^{-1}$ the recommended imperative protection levels for these measures of dissolved oxygen concentration are exceeded. For the 7-day mean daily dissolved oxygen concentration, no correlation is observed with flow.

Over the range of flows observed, no correlation was identified between flow and any of the measures of dissolved oxygen concentrations at the Mellon Road sampling site on the Waitoa River (Figure 3-18). However, dissolved oxygen did fall below the imperative 7-day mean limit on a number of days.

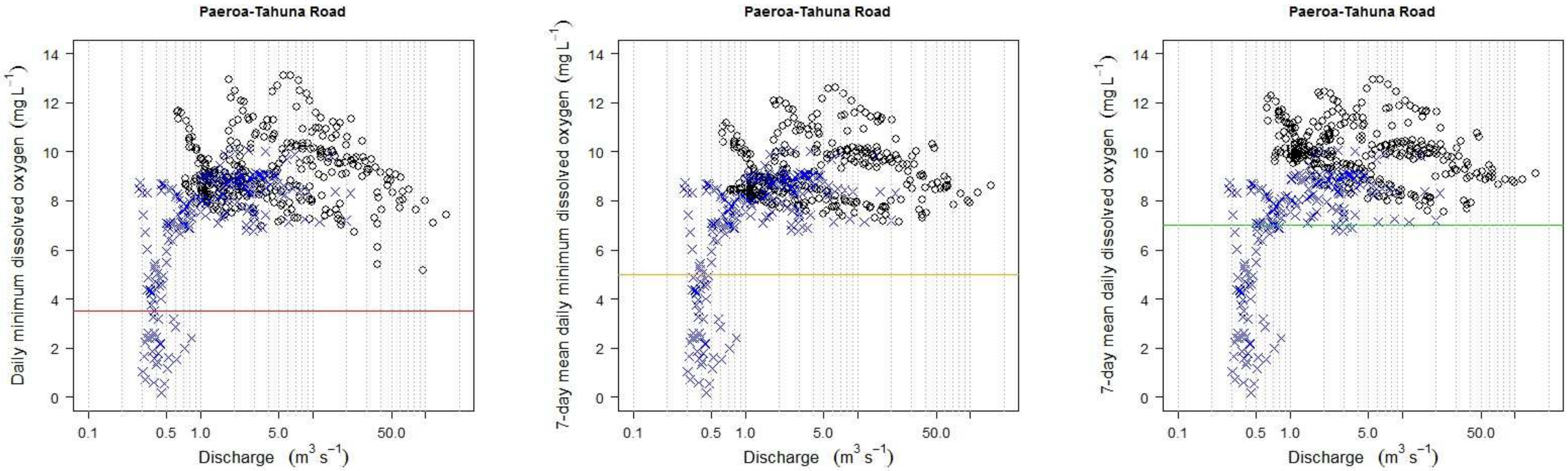


Figure 3-13: Scatter plots of daily minimum, 7-day mean daily minimum and 7-day mean daily dissolved oxygen concentrations against mean daily flow. Data are for the Piako at the Paeroa-Tahuna Bridge. Circles represent data from 2011-12 and crosses 2012-13 sampling periods. Note that the x-axis is a logarithmic scale. The recommended imperative ecosystem protection levels for each dissolved oxygen statistic are shown as solid horizontal lines.

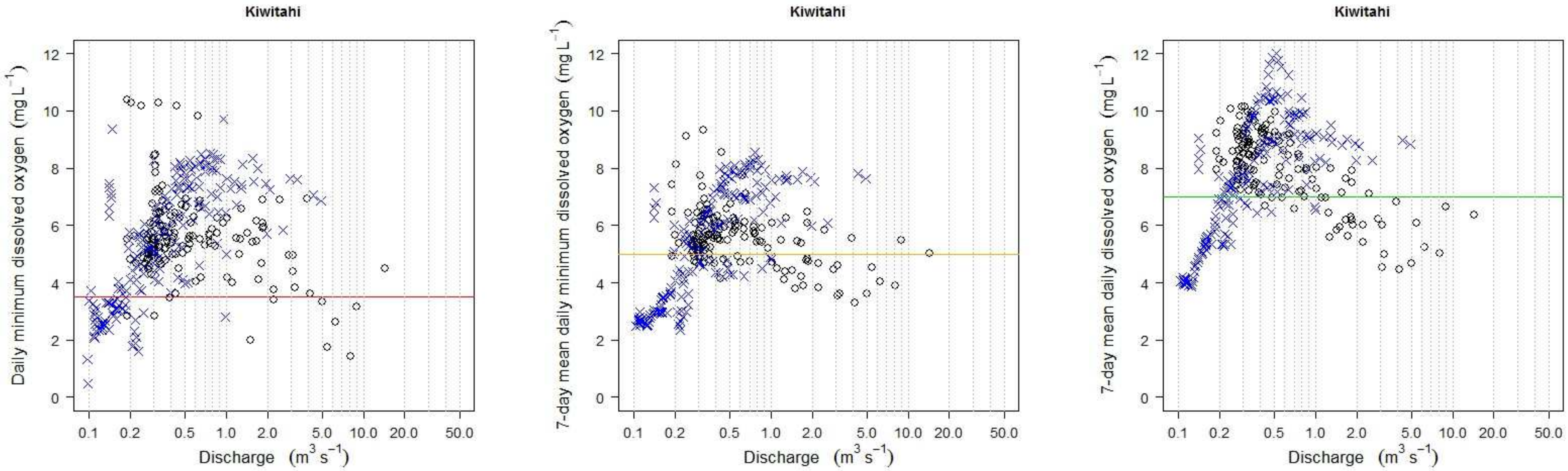


Figure 3-14: Scatter plots of daily minimum, 7-day mean daily minimum and 7-day mean daily dissolved oxygen concentrations against mean daily flow. Data are for the Piako at Kiwitahi. Circles represent data from 2011-12 and crosses 2012-13 sampling periods. Note that the x-axis is a logarithmic scale. The recommended imperative ecosystem protection levels for each dissolved oxygen statistic are shown as solid horizontal lines.

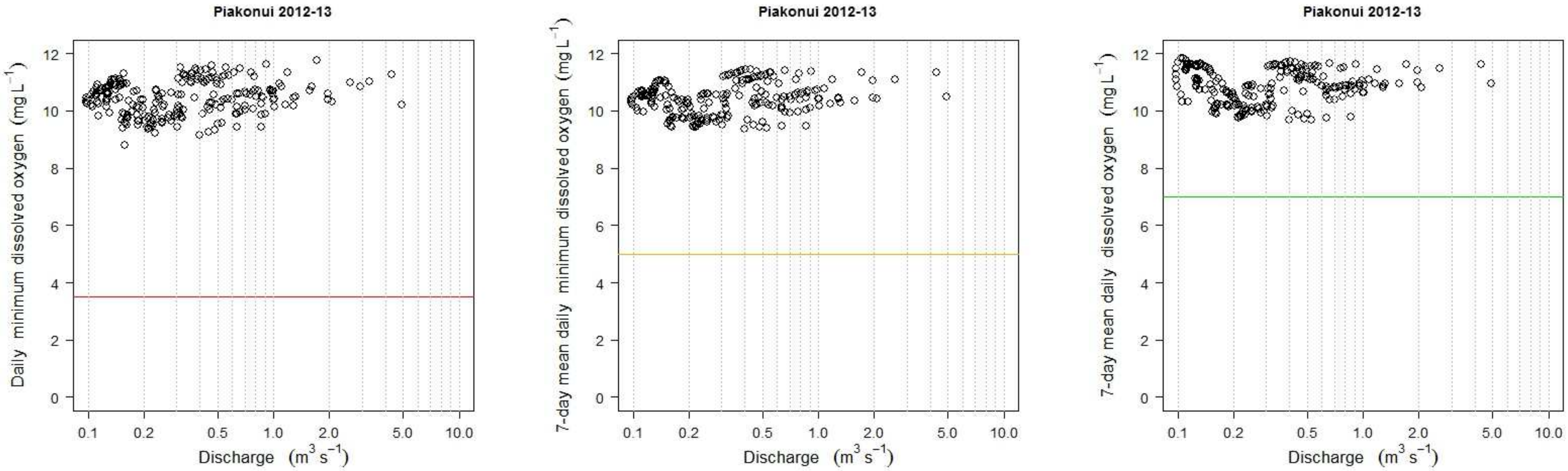


Figure 3-15: Scatter plots of daily minimum, 7-day mean daily minimum and 7-day mean daily dissolved oxygen concentrations against mean daily flow. Data are for the Piakonui Stream. Note that the x-axis is a logarithmic scale. The recommended imperative ecosystem protection levels for each dissolved oxygen statistic are shown as solid horizontal lines.

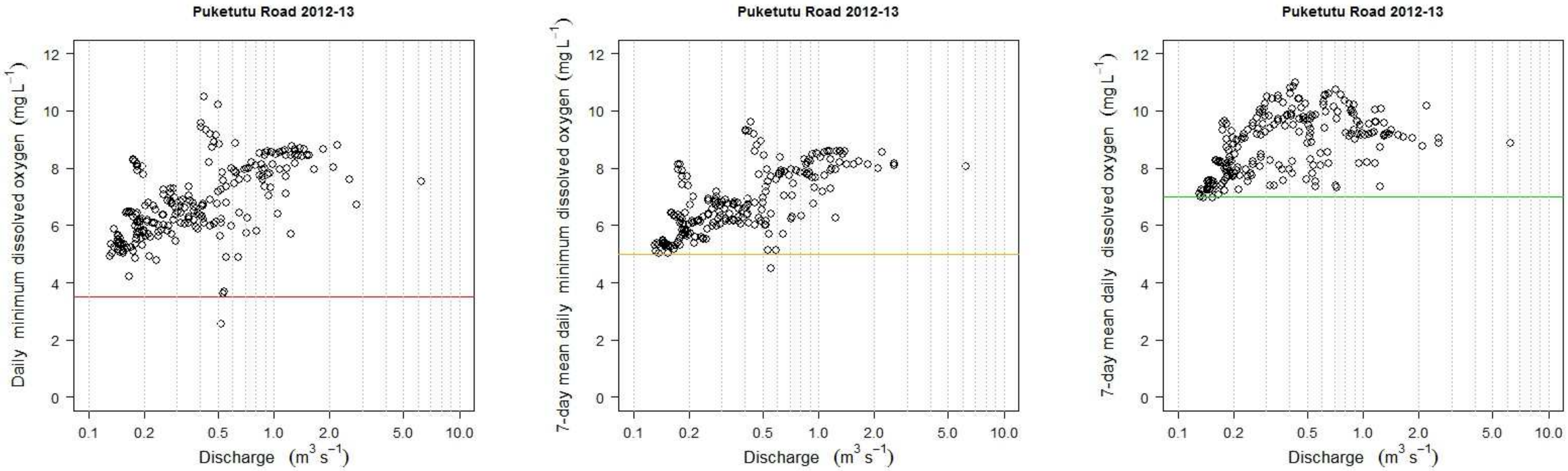


Figure 3-16: Scatter plots of daily minimum, 7-day mean daily minimum and 7-day mean daily dissolved oxygen concentrations against mean daily flow. Data are for the Waitoa Stream at Puketutu Road. Note that the x-axis is a logarithmic scale. The recommended imperative ecosystem protection levels for each dissolved oxygen statistic are shown as solid horizontal lines.

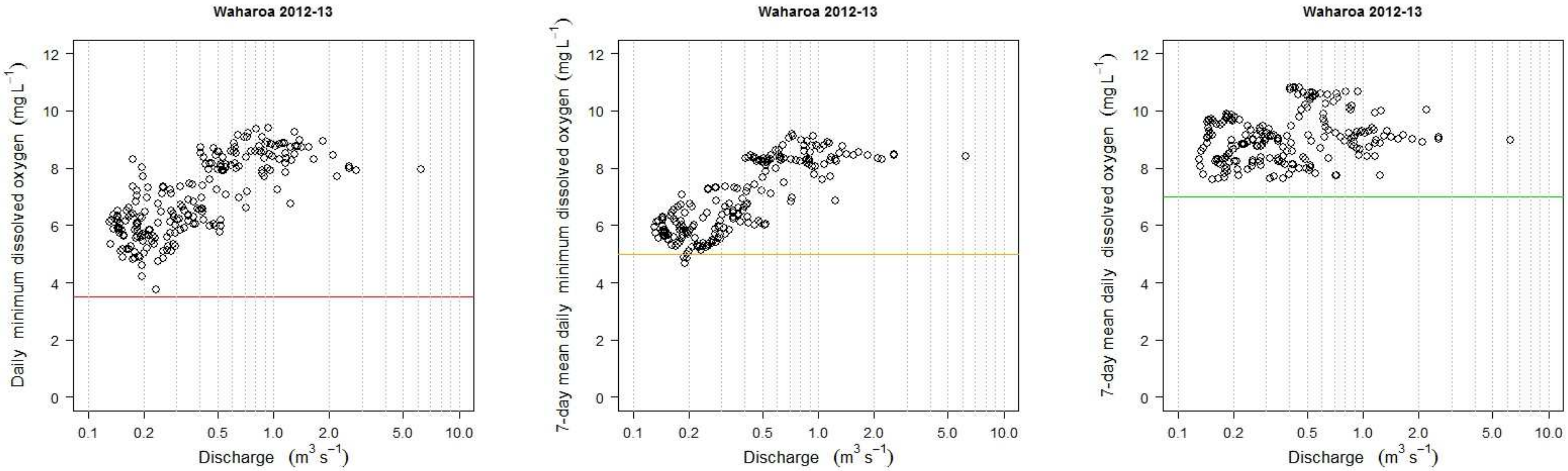


Figure 3-17: Scatter plots of daily minimum, 7-day mean daily minimum and 7-day mean daily dissolved oxygen concentrations against mean daily flow. Data are for the Waitoa Stream at Waharoa. Note that the x-axis is a logarithmic scale. The recommended imperative ecosystem protection levels for each dissolved oxygen statistic are shown as solid horizontal lines.

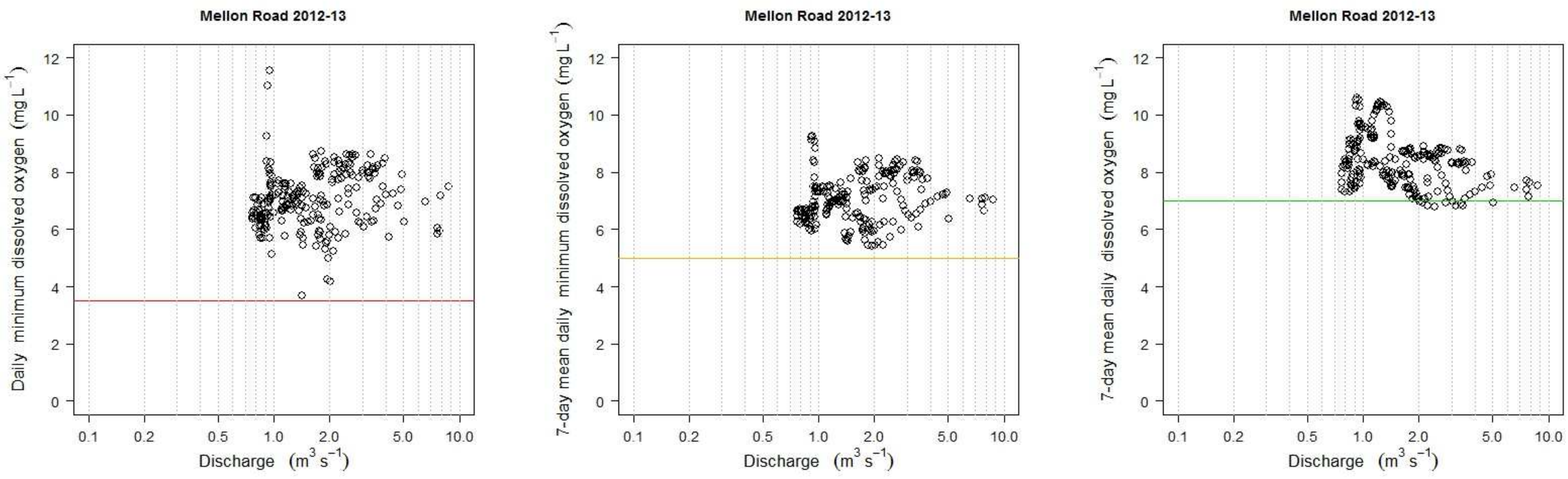


Figure 3-18: Scatter plots of daily minimum, 7-day mean daily minimum and 7-day mean daily dissolved oxygen concentrations against mean daily flow. Data are for the Waitoa Stream at Mellon Road. Note that the x-axis is a logarithmic scale. The recommended imperative ecosystem protection levels for each dissolved oxygen statistic are shown as solid horizontal lines.

3.3.3 Reaeration rates

Using the night-time regression method, robust estimates of the dissolved oxygen reaeration rate k_2 were calculated for the sites at Kiwitahi, Pareoa-Tahuna Road, Puketutu Road and Waharoa (Figure 3-19 & Figure 3-20). At all four sites the relationship between the estimate of k_2 and mean daily flow was heteroscedastic (i.e., as flow increased, the variance in the estimate of k_2 also increased). However, unlike the direct correlations between dissolved oxygen concentration and mean daily flow, the response was more linear and did not display the same threshold type responses. At all sites a downward trend in the average reaeration coefficient with decreasing flow was present. The implication of this is that as flow reduces, there is less capacity for dissolved oxygen concentrations to recover from night-time depletion of dissolved oxygen caused by respiration. It is likely this is an effect of reduced turbulence and possibly surface area associated with lower flows reducing the diffusion potential of oxygen across the air-water interface.

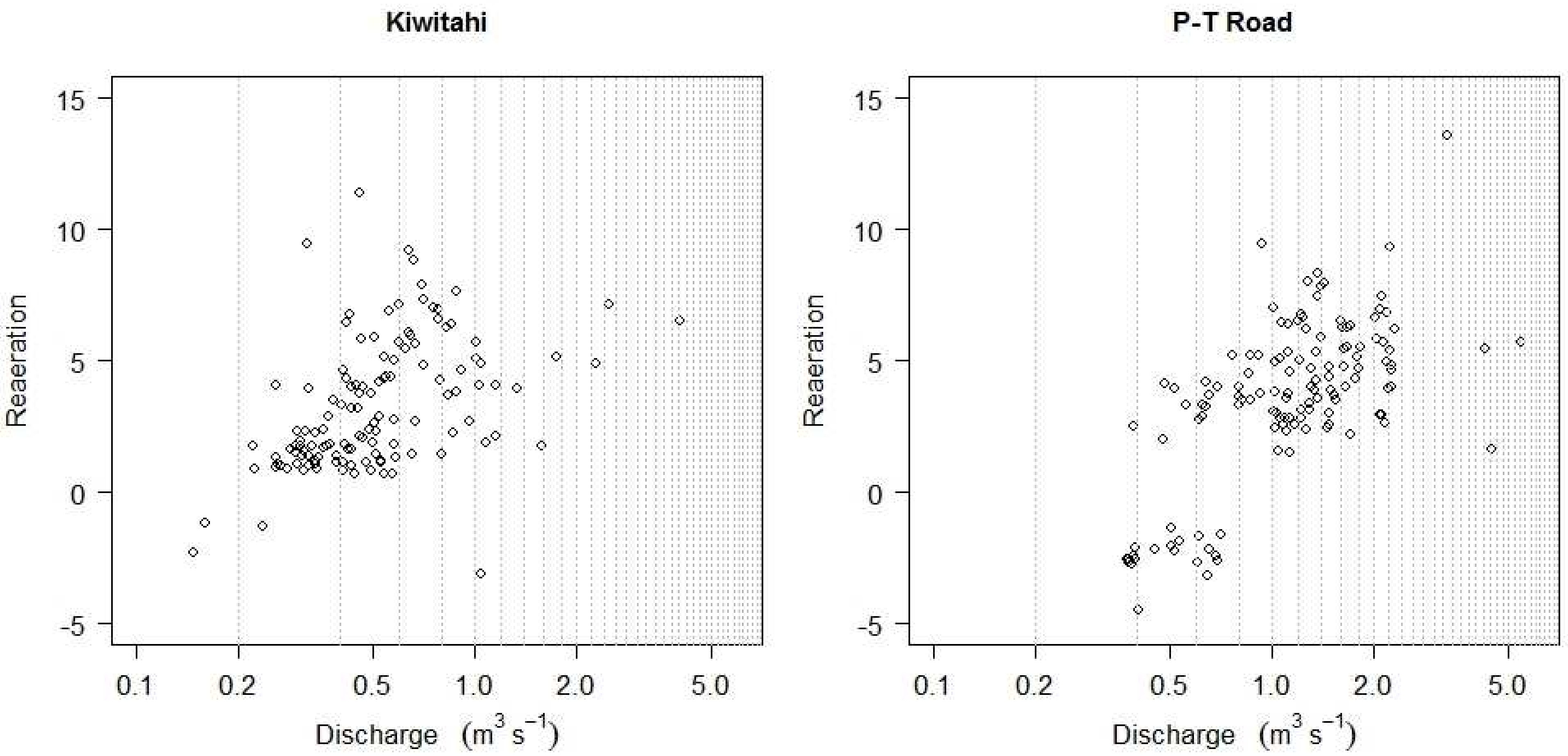


Figure 3-19: Scatter plots of the estimated reaeration coefficient (k_2) and river flow at the Kiwitahi and Paeroa-Tahuna Road sampling sites on the Piako River.

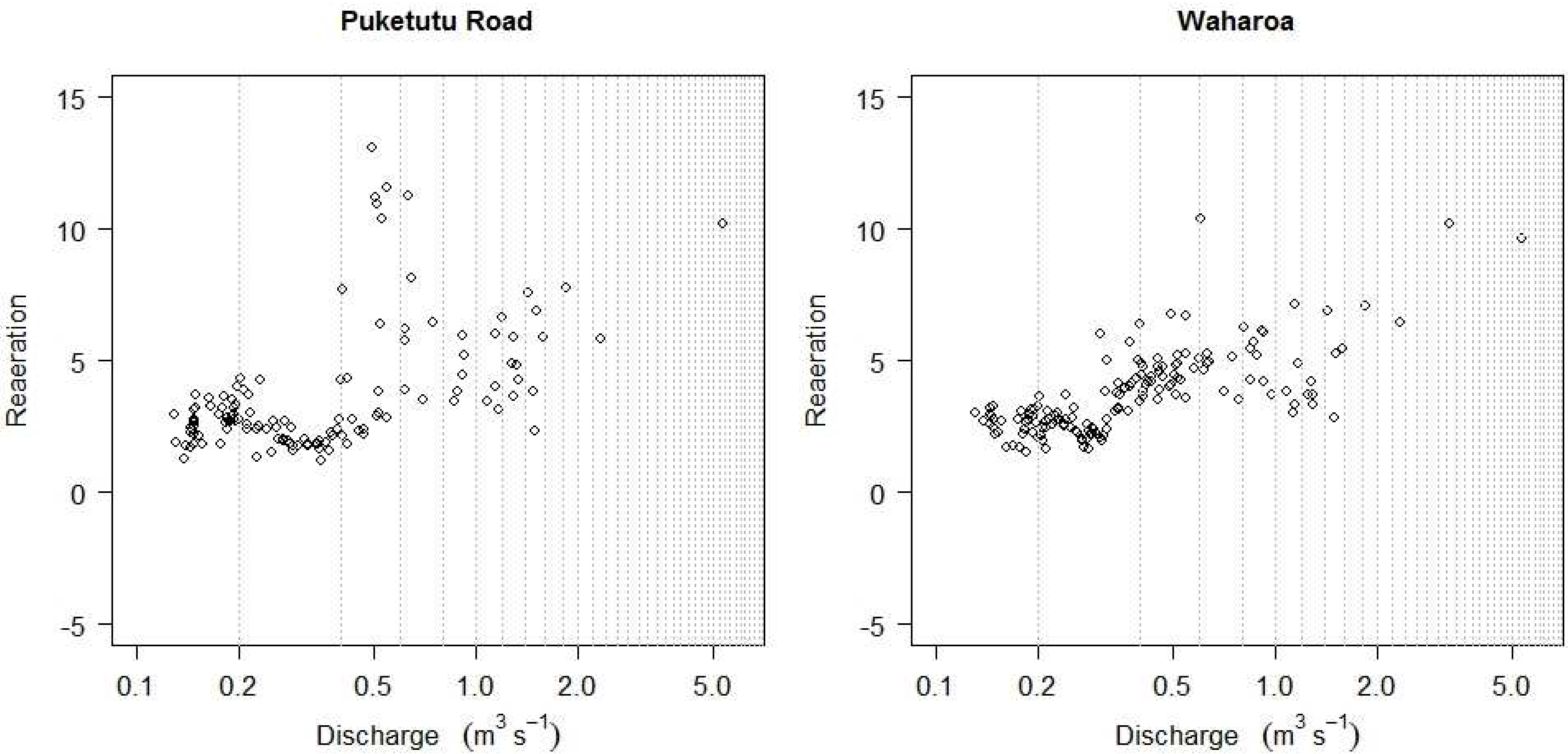


Figure 3-20: Scatter plots of the estimated reaeration coefficient (k_2) and river flow at the Puketutu Road and Waharoa sampling sites on the Waitoa River.

3.3.4 Dissolved oxygen long profiles

WRC undertook an investigation of water quality in the estuarine section of the Piako River between September 2011 and June 2012. Longitudinal profiles of dissolved oxygen concentrations, water temperature and salinity were measured in the Piako River between the mouth of the river near Pipiroa and the confluence of the Piako and Waitoa Rivers near Maukoro Landing (Figure 3-21). A total of four 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 (Table 3-3).

Table 3-3: Flow and tide conditions for the four longitudinal profiles. Tide height is the high tide limit predicted by the NIWA Tide Forecaster for the mouth of the Piako River (175 29 5 2E, 37 11 13 S). Flows are estimated mean daily flow based on addition of measured flows in the Piako at the Paeroa-Tahuna Road and the Waitoa River at Mellon Road.

Date	Tide height (m)	Flow ($m^3 s^{-1}$)
29/09/2011	1.90	7.4
13/12/2011	1.49	3.1
12/03/2012	1.87	3.5
25/06/2012	1.27	6.9

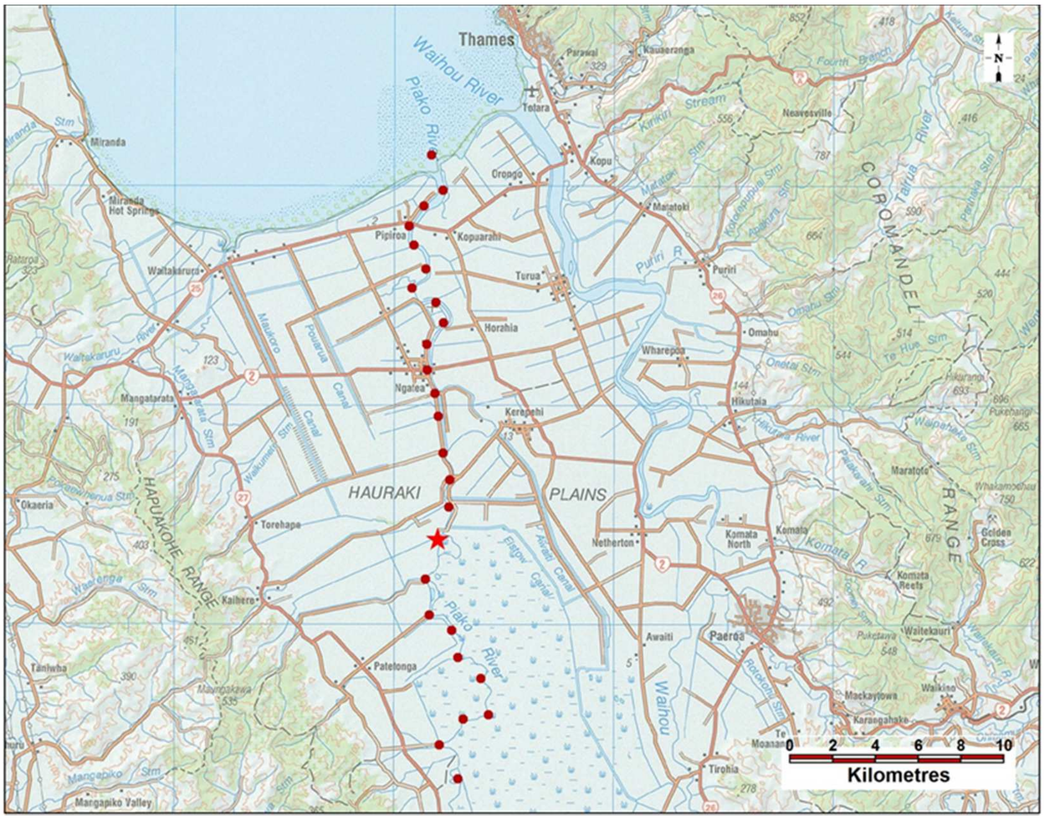


Figure 3-21: Sites on the lower Piako River where water quality was surveyed during 2011-12. The star shows the approximate upstream limit of salt water intrusion observed during this study (March 2012). Source: Vant (2013).

The long profiles of water temperature, salinity, dissolved oxygen concentration and turbidity collected from the lower Piako are shown in Figure 3-22. Water temperature was relatively consistent along the extent of the long profile and, as would be expected, varied with season. Mean temperature for the September 2011 profile was 13.6 °C, increasing to 20.5 and 19.2 °C for the December 2011 and March 2012 profiles respectively, and then lowering again to 11.1 °C for the June 2012 survey. This variation in water temperature had a strong influence on the mean dissolved oxygen concentration observed during each survey, with a negative correlation (r^2=0.84, p=0.05) between the two variables. It appears from the salinity profiles that saline intrusion into the freshwater zone is influenced by both tide height and flow (Figure 3-22). The tides on the September 2011 and March 2012 surveys were very similar (1.90 and 1.87 m respectively), but flow was more than double that in the March 2012 survey during the September 2011 survey (Table 3-3). Correspondingly, the limit of saline influence is 10 km further inland during the low flow conditions of March 2012 (Figure 3-22). A similar pattern is observed for the two surveys carried out at lower tide heights.

The dissolved oxygen profiles indicate the progressive development of a dissolved oxygen sag in the lower river from early spring through to the end of summer (Figure 3-22). However, this has disappeared by the time of the June 2012 survey. A similar dissolved oxygen sag has been recorded during summer in the lower Waihou River (Franklin & Smith 2014, Vant 2011). In the Waihou catchment, the location of the dissolved oxygen minima was strongly correlated with tide height over the range of flows that observations were made (Franklin & Smith 2014). However, in the lower Piako, this correlation does not exist. It is suggested that this may be a consequence of the broader range of flow and temperature conditions captured in the Piako surveys, thus reflecting their additional influence on dissolved oxygen concentrations. It was hypothesised that this would also be the case in the Waihou River if a wider range of flows were included in the surveys (Franklin & Smith 2014).

In the lower Piako, the location and magnitude of the dissolved oxygen minima during spring and summer appear to be associated with the occurrence of a turbidity maxima (Figure 3-22). Vant (2013) suggested that this turbidity maxima is probably due to a naturally occurring estuarine circulation cell operating in the low salinity zone of the lower river. The turbidity maxima appears to be most developed during summer low flow conditions and the location of the maxima moves up and down the river channel as tide height varies. Higher freshwater flows in spring and winter seem to be associated with a reduction in the spatial extent of the turbidity maxima from approximately 18 km during summer to about 5 km in spring and winter. This area is also associated with inputs of organic material from the Kopouatai wetland (Vant 2013). It is likely that oxidation of organic matter trapped within the turbidity maxima accounts for much of the observed oxygen depletion in this reach of the Piako. The higher rates of depletion that occur in summer compared to winter supports this hypothesis, with the decay rate for organic matter being temperature dependent. Lower temperatures reduce the decay rate of organic matter (Chapra 1997), thus reducing oxygen demand and therefore reducing the impact of the organic matter on dissolved oxygen concentrations.

Dissolved oxygen concentrations during the two summer long profile surveys were below recommended imperative 7-day daily mean (7.0 mg L^{-1}) and 7-day mean daily minimum (5.0 mg L^{-1}) protection limits for aquatic ecology through most of the reach and would not meet the proposed NOF bottom lines for dissolved oxygen, i.e., they would fall into Band D.

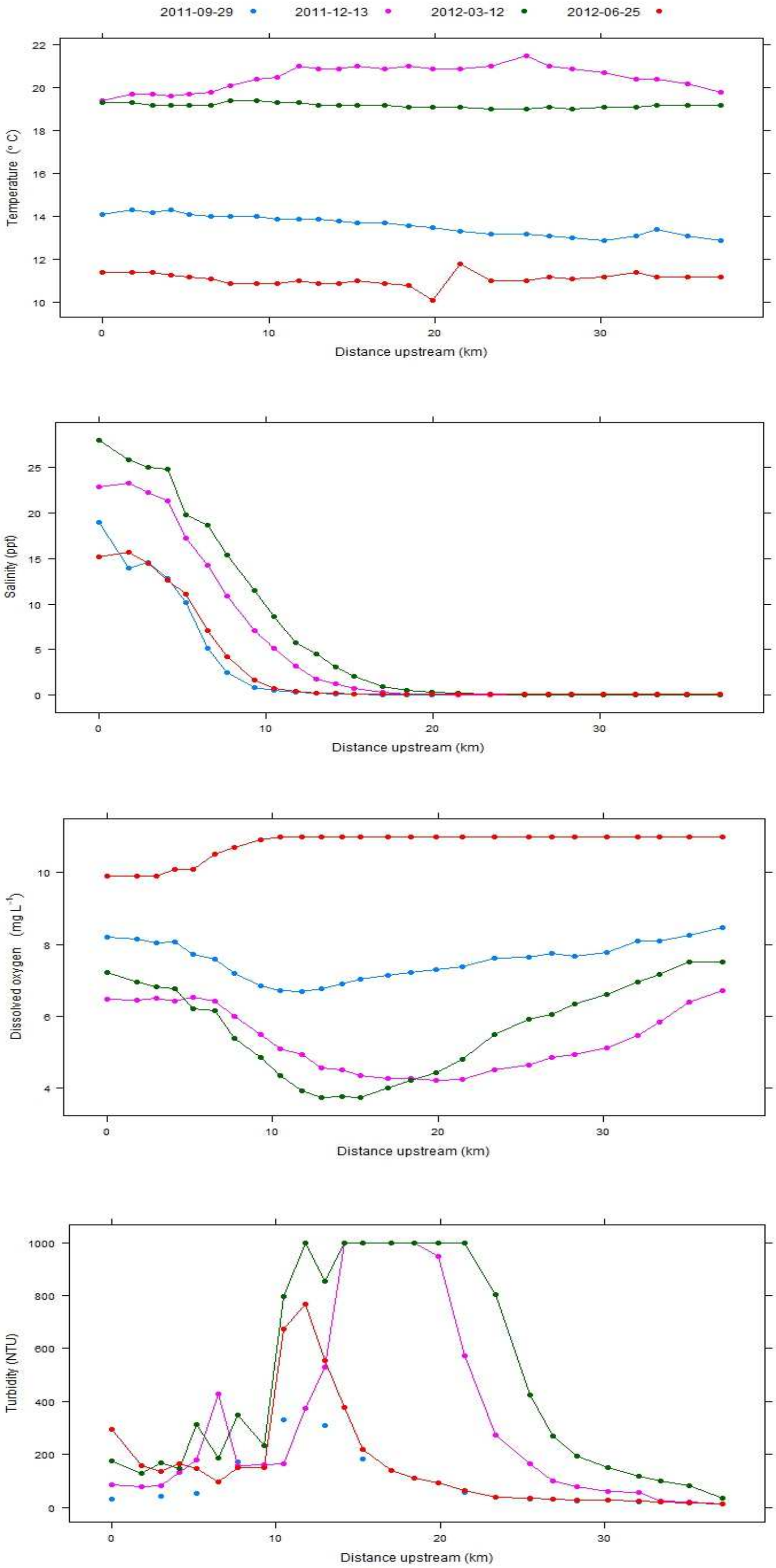


Figure 3-22: Long profiles of water temperature, salinity, dissolved oxygen and turbidity in the lower Piako. The maximum detection limit for turbidity was 1000 NTU.

In late summer 2013, WRC deployed a water quality data sonde (YSI model 660) for 3 weeks in the lower Piako River at Ngatea, approximately 13 km upstream from the river mouth. Conductivity, turbidity and dissolved oxygen were measured at 20 minute intervals throughout the deployment and results are presented in Figure 3-23.

The aim of the deployment was to provide supplementary high temporal resolution data on dissolved oxygen dynamics in one location coinciding with the approximate high tide location of the dissolved oxygen minima identified in the long profile surveys. Flow in the river at the time of the measurements was generally low, with two small flushing flow events towards the end of the first and third weeks of the deployment (Figure 3-23A). Tidal range varied from neap tides (small tides) in the first week, through spring tides (large tides) in the second week and back to neap tides in the third week of measurements (Figure 3-23B).

Conductivity was lowest during neap low tides and peaked during spring high tides, reflecting the influx of saline water during the tidal cycle (Figure 3-23C). It is interesting to note that the increases in conductivity associated with high tide were suppressed during the short periods of elevated freshwater flows (25-26 April) indicating the importance of freshwater flows in driving the hydrodynamics and associated water quality characteristics of the lower river.

Turbidity displayed more complex dynamics, with peaks occurring at the time of both high and low tide, and minima occurring at mid-tide, with the greatest reduction as the tide was going out (Figure 3-23D). Superimposed on this pattern, maximum turbidity was influenced by the shift between neap and spring tides, with the highest values of turbidity recorded under spring tide conditions. Elevated freshwater flows in also appear to reduce the magnitude of the turbidity maximum.

Dissolved oxygen dynamics were influenced by both salinity and the shift from neap to spring tides (Figure 3-23E). Dissolved oxygen saturation reduces as salinity increases with the incoming tide. It then recovers as the tide goes out and salinity reduces again. Additionally, daily mean oxygen saturation was lower during spring tides (c. 49% saturation), compared to neap tide conditions (c. 66% saturation). Assuming water temperatures were similar to those recorded during the March 2012 longitudinal surveys (19 °C), this equates to dissolved oxygen concentrations of approximately 4.5 and 6.1 mg L^{-1}, respectively. During spring tides, the dissolved oxygen concentrations therefore fall below the proposed NOF bottom lines for ecosystem protection. The highest dissolved oxygen saturation (c. 80%) occurred during the elevated flows in the last week of the measurements. It is likely this reflects increased reaeration associated with higher flows and the flushing of oxygen-demanding organic matter downstream (Figure 3-23E).

The fact that lower mean dissolved oxygen concentrations occur during the spring tide phase, when turbidity is also greatest, reinforces the observations from the longitudinal profiles that dissolved oxygen depletion appears to be coupled with the magnitude and spatial extent of the turbidity maxima. Elevated freshwater flows also coincide with reductions in the magnitude of the turbidity maximum and increases in dissolved oxygen concentration. This may have implications for how WRC wish to manage flows in the Piako, particularly given that currently dissolved oxygen levels in the lower river do not meet imperative protection levels for aquatic ecology and will not meet the proposed NOF bottom lines for dissolved oxygen.

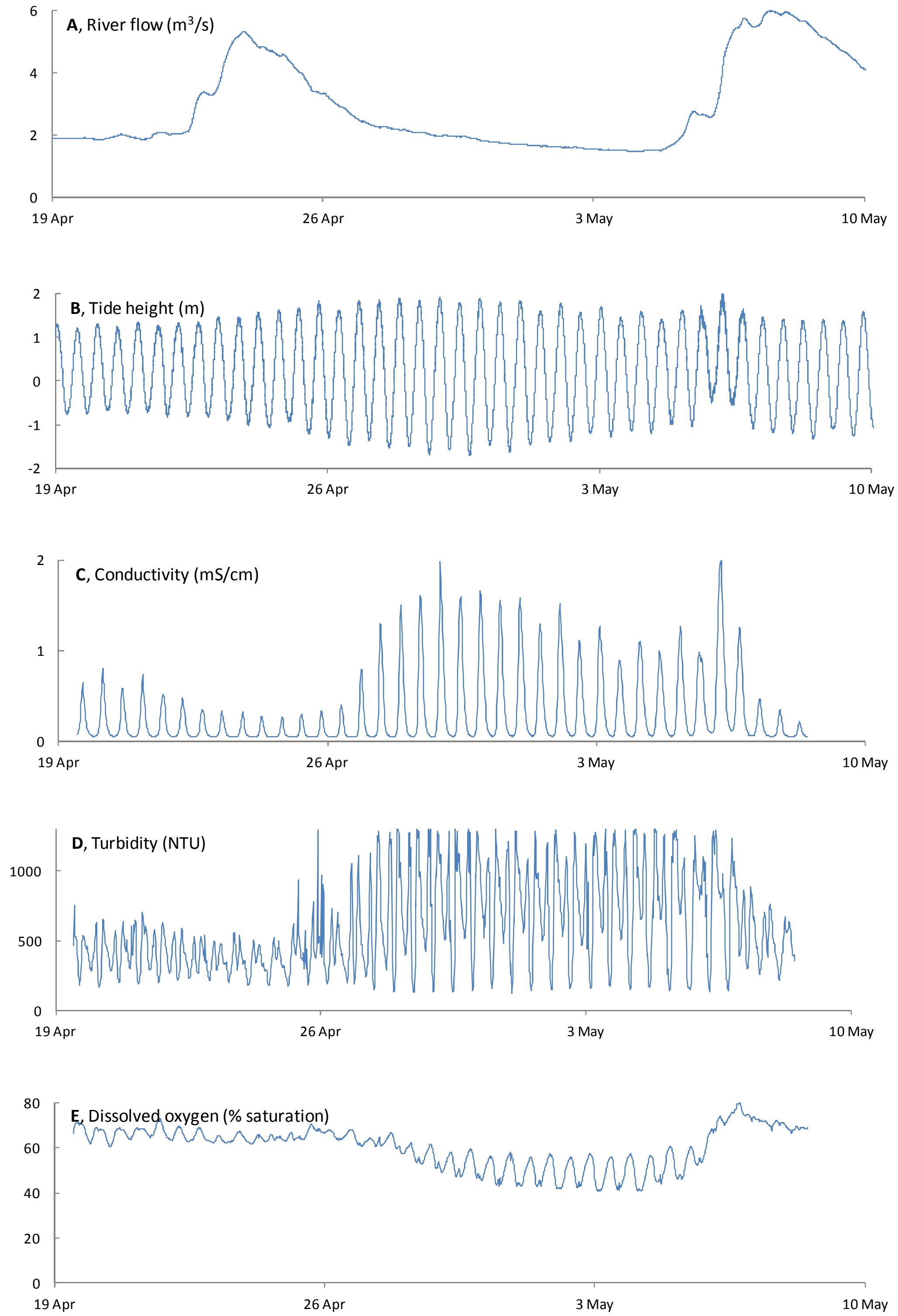


Figure 3-23: Provisional results from a survey of environmental conditions in the lower Piako River over a 3-week period in April-May 2013. A, combined flow of the Piako and Waitoa Rivers (as measured at Paeroa-Tahuna Rd and Mellon Rd, respectively); B, tide height in the Southern Firth of Thames (at Tararu); and C, conductivity; D, turbidity and E, dissolved oxygen as recorded by a datasonde deployed in the river at the SH2 bridge in Ngatea. Source: Vant (2013).

4 Discussion

4.1 Dissolved oxygen and flow

The 2011-12 summer sampling period was characterised by two relatively high summer rainfall events and regular summer flushing flows. In contrast the 2012-13 summer sampling period was characterised by a prolonged period of low base flows.

Summer water temperatures at five of the six sites exceeded the preferred water temperatures of several key fish species that are expected to occur at these sites. However, they did not exceed the lethal threshold for any fish species over the monitoring period. There was some evidence of a potential negative correlation between maximum water temperature and mean daily flow in some months at some sites, but the relationship between the two variables was inconsistent both between sites and between months within sites. It was therefore not possible to make any recommendations with respect to setting water resource use limits in relation to water temperatures.

At both sites where monitoring occurred during both summers (Paeroa-Tahuna Road & Kiwitahi), dissolved oxygen concentrations were noticeably lower during the low, stable flow conditions experienced in 2012-13 than in the higher flows that occurred in 2011-12. At four of the six monitoring sites, distinct threshold responses were identified between mean daily flow and dissolved oxygen concentrations over the range of flows observed during 2012-13. It is likely that this is related to a reduction in the dissolved oxygen reaeration coefficient (k_2) as flow declines at these sites.

In the recently proposed amendments to the National Policy Statement for Freshwater Management 2011 (MfE 2013), National Objective Framework (NOF) limits for maintaining ecosystem health were proposed for dissolved oxygen concentrations in rivers (Appendix A). Whilst it has been proposed that these limits are to apply only downstream of point sources (MfE 2013), the supporting documentation used to derive these limits recommended that the same limits are appropriate for and should apply to all locations on the river network (Davies-Colley et al. 2013).

Presently, the appropriate statistical measure for defining whether an attribute state (i.e., Class) is achieved or not has not been agreed (i.e., does the threshold have to be met, for example, 100% of the time or is 90% of the time adequate). An indication of the flows that approximate to the attribute state class lower boundaries for the proposed NOF are presented in Table 4-1 for those sites where clear threshold responses occur. These values are approximations made by eye from Figure 3-13 to Figure 3-18. More detailed statistical analyses based on longer time series are required to better characterise the flow thresholds that correspond to differing protection levels, but these flow thresholds can be used as a guide to the range of flows that must be considered in setting minimum flow limits for maintaining dissolved oxygen concentration at these sites.

For all sites it appears that the time between flushing flow events may have an important role in determining summer minimum dissolved oxygen concentrations. In the Piako catchment it appears that as the duration of low flows increases, the dissolved oxygen minima decreases. However, following flushing flow events (e.g., December 2011 and April 2013) the dissolved oxygen concentrations recovered significantly. Long-term monitoring of dissolved oxygen would be required to gain a better understanding of the role of flushing flows and low flow duration in controlling dissolved oxygen concentrations. For example, summer floods have also been observed to result in significant reductions in dissolved oxygen in some locations in the Piako River (Bob Wilcock, NIWA, pers. com.).

Table 4-1: Flows that approximate to the proposed NOF dissolved oxygen attribute state class boundaries for ecosystem health. Flow values are for the corresponding on-site hydrological gauging station with the exception of the Waitoa at Puketutu Road where the flow values are those recorded at Waharoa, the nearest gauging station.

Site	Proposed NOF class – 7-day mean minimum dissolved oxygen		
	Class C ($5.0\ mg\ L^{-1}$)	Class B ($7.0\ mg\ L^{-1}$)	Class A ($8.0\ mg\ L^{-1}$)
Piako @ Paeroa-Tahuna Road	$>0.50\ m^3\ s^{-1}$	$>0.80\ m^3\ s^{-1}$	$>1.00\ m^3\ s^{-1}$
Piako @ Kiwitahi	$>0.30\ m^3\ s^{-1}$	$>0.40\ m^3\ s^{-1}$	$>0.50\ m^3\ s^{-1}$
Waitoa @ Puketutu Road	$>0.20\ m^3\ s^{-1}$	$>0.50\ m^3\ s^{-1}$	$>1.00\ m^3\ s^{-1}$
Waitoa @ Waharoa	$>0.25\ m^3\ s^{-1}$	$>0.50\ m^3\ s^{-1}$	$>1.00\ m^3\ s^{-1}$

4.2 Lower Piako dissolved oxygen dynamics

The work carried out by WRC has demonstrated the existence of a dissolved oxygen sag in the lower reaches of the Piako River. This has also been observed for the Waihou River (Franklin & Smith 2014, Vant 2011). From the data available it appears that the dissolved oxygen sag progressively develops through spring to reach a maximum in late summer/early autumn. Whilst based only on spot measurements, during summer dissolved oxygen concentrations in the lower part of the river were below the 5.0 mg L^{-1} (7-day mean daily minimum) threshold set as the bottom line for the proposed NOF limits for up to 20 km. This implies a high risk of ecosystem health being impaired by dissolved oxygen in the lower river. The extent of the depletion is similar to that observed in the Waihou, but the minimum dissolved oxygen concentrations are lower than those seen in the Waihou (Franklin & Smith 2014, Vant 2011).

The evidence suggests that the development of the dissolved oxygen sag in the lower river may be associated with the concurrent development of a zone of high turbidity, or turbidity maxima, in the lower river. The likely mechanism for the depletion of oxygen is the oxidation of organic matter associated with the turbidity maxima. The extent and magnitude of the turbidity maxima was greatest during summer flows, and much reduced during higher freshwater flows in spring and winter. This suggests that freshwater flows may be an important control on this phenomenon, and therefore dissolved oxygen depletion, in the lower river. However, more data are required to confirm this association.

The high resolution temporal data collected at Ngatea in 2013 demonstrate the complexity of the interactions between freshwater inflows, tides, salinity, turbidity and dissolved oxygen in the lower river. Broadly speaking, neap tide conditions were associated with lower turbidity maxima and higher dissolved oxygen concentrations at Ngatea, whilst during spring tides turbidity was high and dissolved oxygen concentrations lower. Superimposed on this were the effects of freshwater inflows, with elevated flows apparently reducing turbidity and increasing dissolved oxygen.

The patterns observed in the high resolution data largely reinforce those identified in the long profile measurements and are similar to those observed in the Waihou (Franklin & Smith 2014) and other systems internationally (Mitchell et al. 1999, Uncles et al. 1998). Overall, it is clear that dissolved oxygen concentrations become depleted over an extended reach (c. 20 km) of the lower Piako, particularly during summer, and that they fall below recommended protection levels for aquatic ecosystems. It appears that the magnitude and extent of the oxygen depletion zone is greatest during the spring tide cycle and under low freshwater inflows during summer. This suggests that, as with the Waihou River, water quality in the lower reaches of the Piako may be a bottleneck for the management of upstream water resources. Consequently, it is recommended that WRC invest effort in better understanding the mechanisms and drivers of water quality in the lower reaches of the Piako (and Waihou) in order to provide transparency and confidence in setting constraints on upstream water resource use. This should include collecting data to understand the spatial and temporal variability in the extent, duration and magnitude of the oxygen depletion zone both seasonally and across the full tidal cycle. Higher resolution monitoring through the deployment of data sondes at fixed locations through the lower reach of the river is also recommended to help elucidate the mechanisms associated with oxygen depletion. These measurements should include water temperature, salinity, turbidity and dissolved oxygen as a minimum. Understanding the interactions between tides, freshwater inflows, the extent of the turbidity maxima and oxygen depletion is critical to being able to develop robust water resource use limits for the lower river.

5 Conclusions

Dissolved oxygen is an important water quality variable for maintaining ecosystem health. Concentrations of dissolved oxygen at Kiwitahi and the Paeroa-Tahuna Road on the Piako River fell below recommended imperative ecosystem protection levels for several weeks during the low flow summer of 2012-13. In combination with the high water temperatures, there is an elevated risk of ecosystem impairment at both of these sites. At all three monitoring sites in the Waitoa River, dissolved oxygen concentrations generally remained just above the recommended threshold for ecosystem protection. Only at the Piakonui Stream sampling site did dissolved oxygen concentrations remain well above the recommended thresholds. In the lower river, downstream of the confluence with the Waitoa River, there is an extended zone of dissolved oxygen depletion where concentrations are below recommended protection levels for ecosystem health.

Based on the observed correlations between flow and dissolved oxygen concentrations, it is recommended that minimum flow limits be set at a level sufficient to avoid dissolved oxygen concentrations falling below the recommended protection levels for ecosystem health. Indicative flow thresholds for differing protection levels were presented in Table 4-1 within the framework of the proposed NOF. It must be emphasised that these thresholds are based on monitoring results from only one or two summer periods and estimates of thresholds that are not statistically derived. Slow flowing rivers with high macrophyte cover like the Piako are complex systems making identification of spatially and temporally consistent relationships between flow, water temperature and dissolved oxygen challenging. It is recommended that continuous dissolved oxygen monitoring be implemented in at least one location on the Waitoa River and one on the Piako River to better refine these thresholds over multiple years and differing flow conditions. This will be required to increase WRC's ability to confidently define limits that meet the likely NOF requirements for protecting ecosystem health.

In the lower river, there are also indications that low flows may contribute to the development of a turbidity maxima and associated zone of oxygen depletion. However, further work is required in both the lower Waihou and Piako to elucidate the details of the complex interactions between flows, tide, temperature, salinity, turbidity and dissolved oxygen dynamics operating in this zone. It is possible WRC could decide that the low dissolved oxygen levels observed in these reaches may be a constraint on upstream water resource use due to the potential risk to aquatic ecosystem health.

It was not possible to identify any clear relationships between water temperature and flow. It is recommended that long term continuous monitoring of water temperature also be implemented in the catchment so that potential correlations over multiple years can be identified and characterised. Elevated water temperatures are a known stressor for many aquatic organisms (Olsen et al. 2012). Higher water temperatures also reduce the dissolved oxygen saturation potential of water and can therefore limit dissolved oxygen concentrations. Management of water temperatures may therefore be valuable for managing the dissolved oxygen concentrations in the catchment, potentially increasing the availability of water for out-of-stream use.

6 Acknowledgements

I would like to acknowledge WRC staff, particularly Mark Hamer, for maintaining and deploying the dissolved oxygen loggers and providing the data as required. Flow data were also provided by WRC and Hauraki District Council.

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Appendix A Proposed National Objectives Framework

Table A-1: Proposed NOF limits for dissolved oxygen concentrations for ecosystem health in rivers. Note: MfE (2013) proposes that these limits should apply only downstream of point sources.

Value	Ecosystem Health		
Freshwater Body Type	Rivers (below point sources)		
Attribute	Dissolved Oxygen		
Attribute Unit	mg/L (milligrams per litre)		
Attribute State	**Numeric Attribute State**		**Narrative Attribute State**
	7-day mean minimum (Summer Period: 1 November to 30th April)	**1-day minimum (Summer Period: 1 November to 30th April)**	
A	>8.0	>7.5	No stress caused by low dissolved oxygen on any aquatic organisms that are present at matched reference (near-pristine) sites.
B	7.0-8.0	5.0-7.5	Occasional minor stress on sensitive organisms caused by short periods (a few hours each day) of lower dissolved oxygen. Risk of reduced abundance of sensitive fish and macroinvertebrate species.
C	5.0-7.0	4.0-5.0	Moderate stress on a number of aquatic organisms caused by dissolved oxygen levels exceeding preference levels for periods of several hours each day. Risk of sensitive fish and macroinvertebrate species being lost.
National Bottom Line	**5.0**	**4.0**	
D	<5.0	<4.0	Significant, persistent stress on a range of aquatic organisms caused by dissolved oxygen exceeding tolerance levels. Likelihood of local extinctions of keystone species and loss of ecological integrity.