Waikato Regional Council Technical Report 2014/53

Dissolved oxygen dynamics in the Lower Waihou River

www.waikatoregion.govt.nz
ISSN 2230-4355 (Print)
ISSN 2230-4363 (Online)

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May 2014

Document #:3137330

Peer reviewed by:
Edmund Brown Date August 2016

Approved for release by:
Tracey May Date August 2016

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NIWA Client Report No:	HAM2014-017
Report date:	May 2014
NIWA Project:	EVW13210

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Reviewed by

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Executive summary

The Waikato Regional Council (WRC) is responsible for managing the status of water resources in the Waikato Region. WRC is currently undertaking a scheduled review of flow and allocation limits in the Waihou catchment. The aim of this project was to empirically evaluate the interrelationships between freshwater flows and the spatial and temporal dynamics of dissolved oxygen in the Waihou River.

Dissolved oxygen time series collected at a range of sites in the catchment during the summers of 2012 and 2013 showed that the majority of sites met the recommended thresholds for ecosystem protection for the majority of the time. The main exceptions were the sites in the lower, tidal part of the river at Turua and Wharf Road where the 7-day mean daily limit of 7.0 mg L^{-1} was not met. The time series also showed that dissolved oxygen is depleted in the river during flushing flow events. This is most likely a consequence of the mobilisation of decaying organic matter with a high biochemical oxygen demand.

In the lower river, downstream of Paeroa, the presence of a dissolved oxygen sag was reaffirmed. During summer low flows, the location of the dissolved oxygen minima varied from the mouth of the river at Thames at low tide to nearly 20 km inland at high tide.

No statistically significant relationships were found between dissolved oxygen concentrations and flow over the range of flows observed. In general, the variance in daily minimum dissolved oxygen concentration was limited to ≤2 mg L^{-1} across the majority of flows observed during the surveys. The main exception was the site in the Ohinemuri River, where the variance in daily minimum dissolved oxygen was greater at lower flows. Attempts to estimate the value of the reaeration coefficient k_2 using the night-time regression method were unsuccessful at the majority of sites.

Analyses of the long-term dissolved oxygen monitoring data within the Waihou catchment indicate that, in general, dissolved oxygen is not likely to be a limiting factor for aquatic ecology in the main river upstream of Paeroa. However, it has been shown previously that there may be problems caused by low dissolved oxygen in some of the smaller, lowland tributaries of the Waihou River. The presence of a dissolved oxygen sag in the lower river downstream of Paeroa, where dissolved oxygen minima are below those recommended for the protection of aquatic ecosystems, is also of concern in setting allocation limits for the catchment.

If the degree of hydrological alteration associated with water resource use is expected to be low, the risk of significant deleterious effects on dissolved oxygen in the main stem of the Waihou upstream of Paeroa is likely to be low. However, there is some evidence to suggest that dissolved oxygen concentrations in the Ohinemuri River may be more sensitive to flow changes. A more precautionary approach to setting water allocation limits is therefore advised for the Ohinemuri sub-catchment. It is also recommended that a more conservative approach to setting limits be taken in the smaller lowland tributaries where dissolved oxygen is identified as being a limiting factor on aquatic communities.

It is likely that the dissolved oxygen sag in the lower river will be the main limiting factor on the determination of upstream water resource use limits. Over the range of flows observed during this study, no significant relationships were found between flow and either the magnitude or location of the dissolved oxygen minima in the lower river. However, evidence from other systems suggests freshwater flows (over a broader range than those that were possible to cover in this study) are likely to be an important driver of the sediment and water quality dynamics in this part of the catchment.

The potential importance of low flow duration was highlighted for managing the effects of flushing flows on dissolved oxygen depletion.

1 Introduction

1.1 Background

The Waikato Regional Council (WRC) is responsible for managing 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).

WRC is currently undertaking a scheduled review of flow and allocation limits in the Waihou catchment. Work contributing to the review has included monitoring of instream ecological values (Franklin & Booker 2009, Franklin et al. 2011, Franklin et al. 2013), evaluation of minimum flow requirements for fish habitat (Jowett 2008), characterisation of flow regime variability (Franklin & Booker 2009) and analyses of dissolved oxygen dynamics (Franklin 2010a, 2010b, Vant 2011). The assimilative capacity of the lower Waihou River (i.e. the ability of the river to absorb and process contaminants) has subsequently been identified as a potential bottleneck for water resource use. The Kerepehi water intake is at times already compromised by reduced water quality (Ed Brown, WRC, personal communication) and preliminary monitoring undertaken by WRC indicates the presence of a natural dissolved oxygen sag in the lower river (Vant 2011). It is hypothesised that the location, duration and magnitude of the dissolved oxygen sag will be influenced by flow in the Waihou and tide height. WRC has requested that NIWA undertakes a targeted study of dissolved oxygen dynamics in lower Waihou River to try and establish the nature of dissolved oxygen dynamics and their dependence on freshwater flows and tidal fluctuations.

1.2 Project scope

The aim of this project was to empirically evaluate the interrelationships between freshwater flows and the spatial and temporal dynamics of dissolved oxygen in the Waihou River. This was to be achieved through the following programme of work:

- Measurement of longitudinal profiles of dissolved oxygen concentrations in the Waihou River between the Puke and Kopu bridges under varying flow and tide conditions.
- Measurement and characterisation of dissolved oxygen temporal dynamics at a range of sites in the main stem of the Waihou River during summer low flow conditions.
- Analysis and interpretation of the monitoring results with respect to flow, tide levels and the known tolerances of aquatic organisms.

2 Methodology

2.1 Longitudinal profiles

Longitudinal profiles of dissolved oxygen concentrations were measured in the Waihou River between the Puke and Kopu bridges following the method of Vant (2011). Measurements of dissolved oxygen, water temperature and salinity were made by boat using a calibrated YSI Professional Plus handheld multi-parameter instrument at 23 sites along the river (Figure 2-1). Dissolved oxygen measurements were automatically corrected for salinity. All profiles were measured during the morning between January and April 2013 (i.e., during summer low flows) and encompassed a range of flow and tide conditions (Table 2-1).

Table 2-1: Flow and tide conditions for the six longitudinal profiles. Tide height is the high/low limit predicted by the NIWA Tide Forecaster (http://www.niwa.co.nz/services/online-services/tide-forecaster) for the mouth of the Waihou River (175 31 20 E, 37 09 30 S). Flow is the mean daily flow at Te Aroha.

Date	Tide height (m)	Tide time	Flow ($m^3\ s^{-1}$)
14/01/2013	1.92	09:59	26.98
01/03/2013	1.66	10:41	23.72
14/03/2013	1.64	09:59	23.86
21/03/2013	-0.93	09:03	26.40
05/04/2013	-1.27	09:35	23.69
12/04/2013	1.48	08:30	23.37

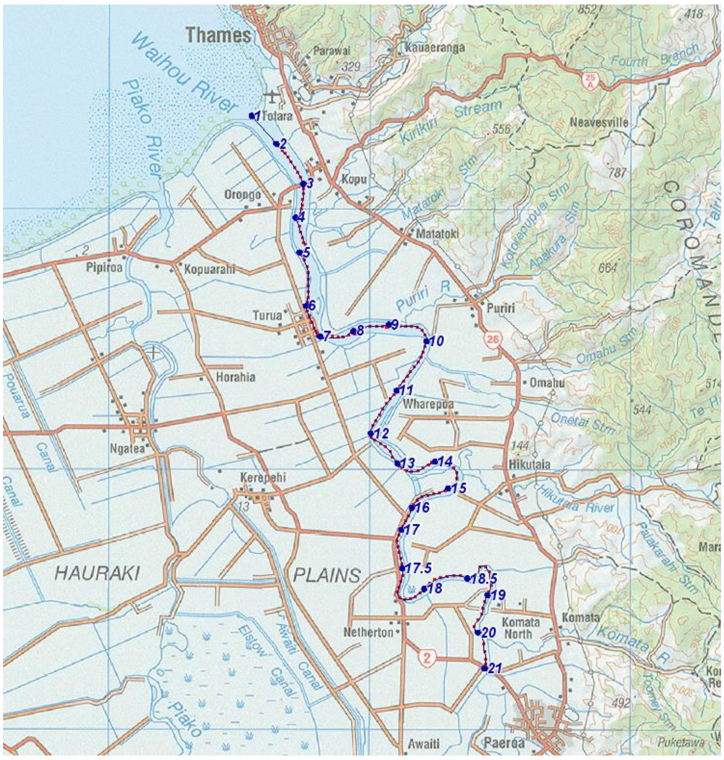


Figure 2-1: Sampling locations for the long profile measurements in the lower Waihou River.

2.2 Continuous dissolved oxygen monitoring

Continuous dissolved oxygen measurements were taken during the summer low flow periods of 2012 and 2013. Where possible, monitoring was carried out close to flow or water level recording sites. The seven sites monitored in 2012 covered the main stem of the Waihou between Tirau (Oraka) and Pekapeka Road (Table 2-2; Figure 2-2). In 2013, monitoring focussed on the lower reaches of the Waihou with loggers being deployed at nine sites between Matamata (Okauia) and Turua (Table 2-2; Figure 2-2).

Calibrated D-Opto loggers were deployed to collect water temperature (°C) and dissolved oxygen (% saturation and mg L^{-1}) records at all sites in 2012 and the seven upstream sites in 2013. The two downstream sites monitored during the summer of 2013 (Turua and Wharf Road) are located within the influence of the saline wedge in the lower river. Due to the effects of salinity on dissolved oxygen saturation potential, a combination of Eureka Manta2 Multiprobes and Hydrolab DataSonde DS5x Multi parameter Sondes which also record and account for the influence of salinity were deployed at these sites. Loggers were deployed at these two sites from mid-January to early-April. The D-Opto loggers use a solid-state optical sensing system to measure dissolved oxygen and are considered highly stable over long periods of time. Spot samples of dissolved oxygen and temperature were taken at the time of logger deployment and retrieval using a YSI Professional Plus handheld multi-parameter instrument to identify any instrument drift that may have occurred.

Table 2-2: Location of continuous dissolved oxygen monitoring sites in 2012 and 2013. *Subject to saline influence. **Logger failed.

Site	River	Easting	Northing	2012	2013	Flow/water level site
Oraka	Oraka Stream	1843225	5796380	✓		Pinedale
Mangawhero	Mangawhero Stream	1848914	5812451	✓		Okauia
Okauia	Waihou River	1850066	5813931	✓	✓	Okauia
Shaftesbury	Waihou River	1844749	5831778	✓	✓	Shaftesbury
Te Aroha	Waihou River	1839643	5841025	✓	✓	Te Aroha
Tirohia	Waihou River	1833500	5853150		✓	Tirohia
Ohinemuri	Ohinemuri River	1836964	5858987	✓	✓**	Karangahake
Puke Bridge	Waihou River	1834561	5862337		✓	Puke Bridge
Pekapeka	Waihou River	1831163	5867228	✓	✓	Pekapeka
Wharf Road*	Waihou River	1832306	5874826		✓	Pekapeka
Turua*	Waihou River	1827757	5875792		✓	Pekapeka

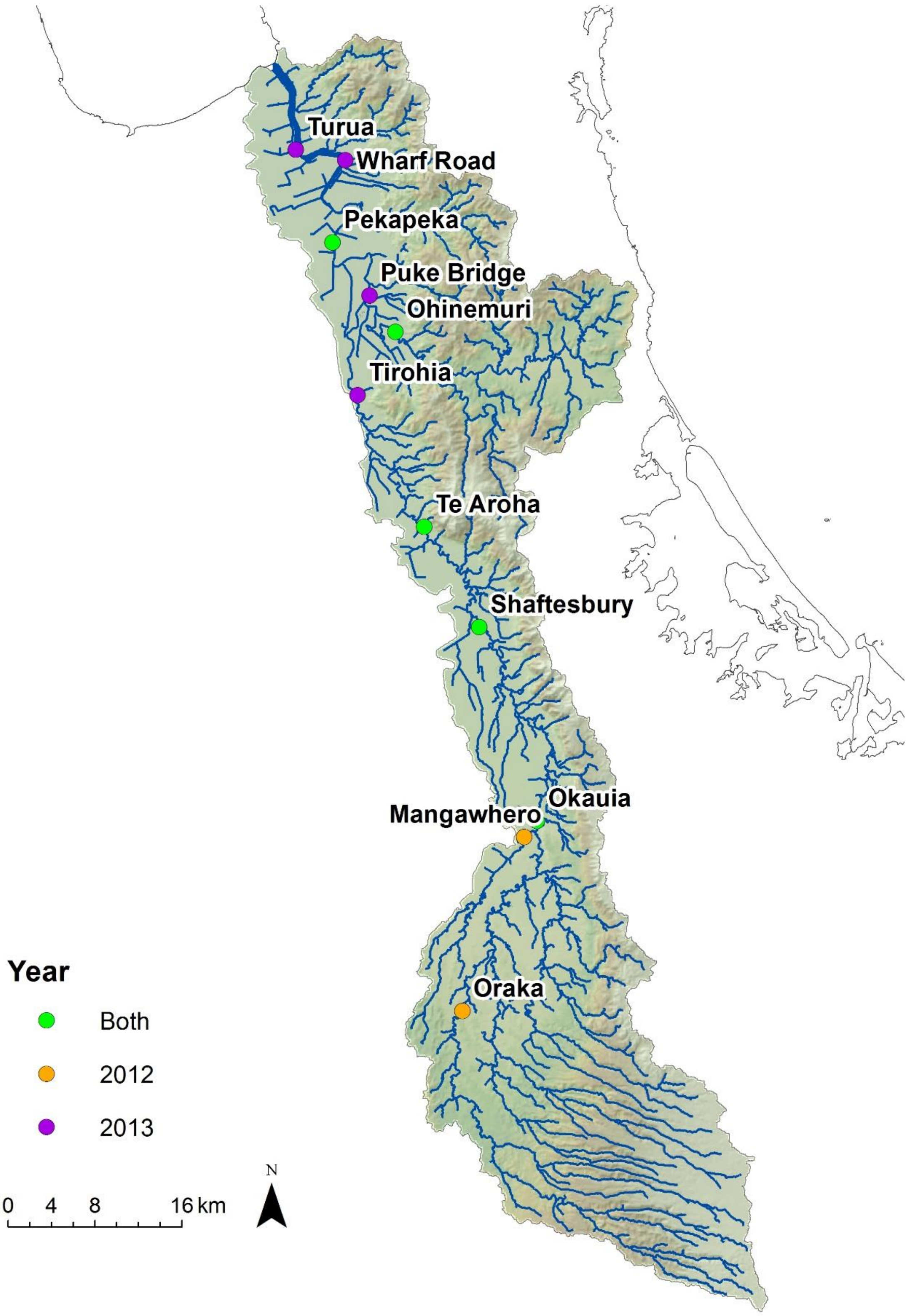


Figure 2-2: Location of dissolved oxygen temporal monitoring sites in 2012 and 2013.

2.3 Flow data

Mean daily flow or water level data were supplied by WRC for the gauging sites in Table 2-3. Water level data were also obtained from Hauraki District Council for the Pekapeka recording site.

Table 2-3: Location of flow and water level recording sites in the Waihou catchment used in this study.

Site	Easting	Northing	Flow	Water level
Pinedale	1846121	5783025	✓	
Okauia	1849977	5814047	✓	
Shaftesbury	1844646	5831847		✓
Te Aroha	1839127	5841042	✓	
Tirohia	1833404	5853237		✓
Puke Bridge	1834488	5862243		✓
Pekapeka	1831177	5867839		✓

2.4 Data analyses

Following data checking, time series were plotted and summary statistics derived describing the dissolved oxygen dynamics at each site. Summary statistics were compared with the limits for ecosystem protection proposed by Franklin (2013) (Table 2-4) These limits also provide the basis of the recently proposed dissolved oxygen limits under the National Objectives Framework (Appendix A; MfE 2013). All summary statistics are 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 2-4: 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 standard	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

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 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 diffusion of oxygen through the river surface. This relationship is represented in the following equation:

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

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. 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. This analysis was restricted to the 2013 data collected prior to 16/04/2013 when flows were stable. Only regressions with an $r^2 \geq 0.4$ were used in the analysis of the relationship between k_2 and flow as recommended by Young in Wilcock et al. (2011).

3 Results

3.1 Dissolved oxygen time series

3.1.1 Flow conditions during sampling

Figure 3-1 shows the periods during which the dissolved oxygen loggers were deployed relative to the mean daily flow at Te Aroha. The 2012 sampling period coincided with a relatively wet summer with regular flushing flow events and higher than average summer base flows. In 2013, flow was at or below the 7-day mean annual low flow (MALF) for about two thirds of the sampling period as a result of a very dry summer, with no significant flushing flows until late April. The 2013 sampling period therefore provided ideal conditions for characterising dissolved oxygen dynamics under summer low flows and subsequent analyses focus on these data.

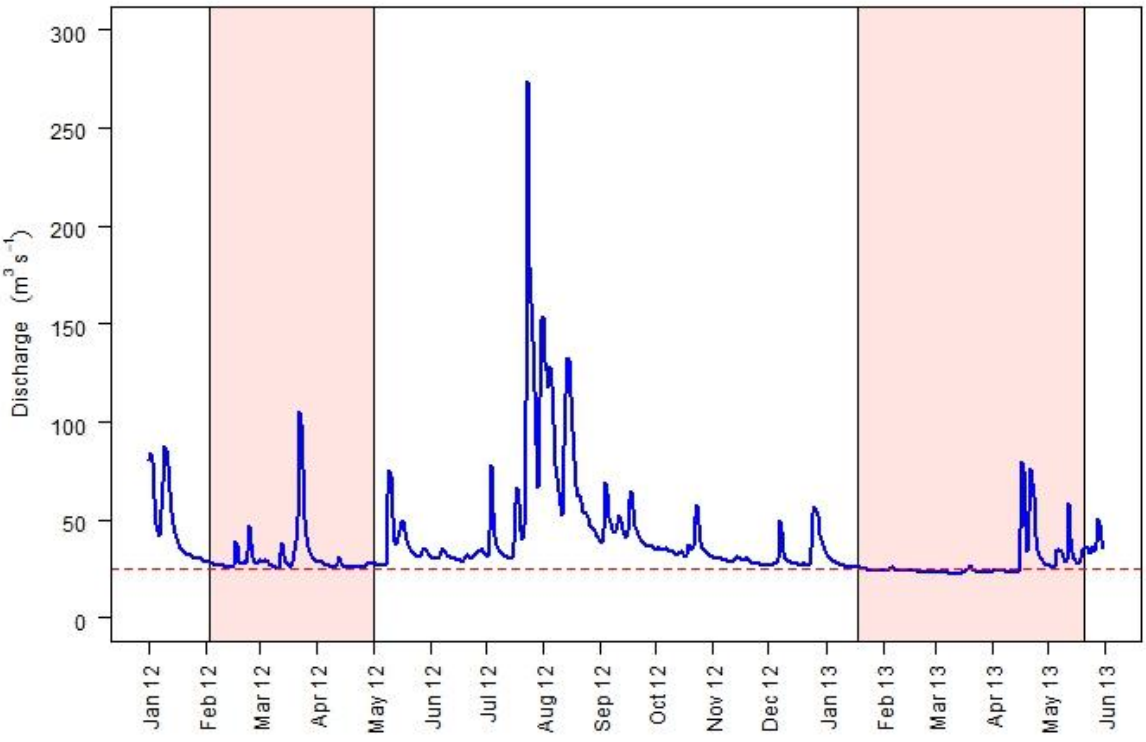


Figure 3-1: Dissolved oxygen sampling periods relative to mean daily flow in the Waihou at Te Aroha for 2012 and 2013. Pink shaded boxes indicate the dissolved oxygen sampling periods. Dashed red line indicates the estimated 7-day mean annual low flow.

3.1.2 Dissolved oxygen dynamics

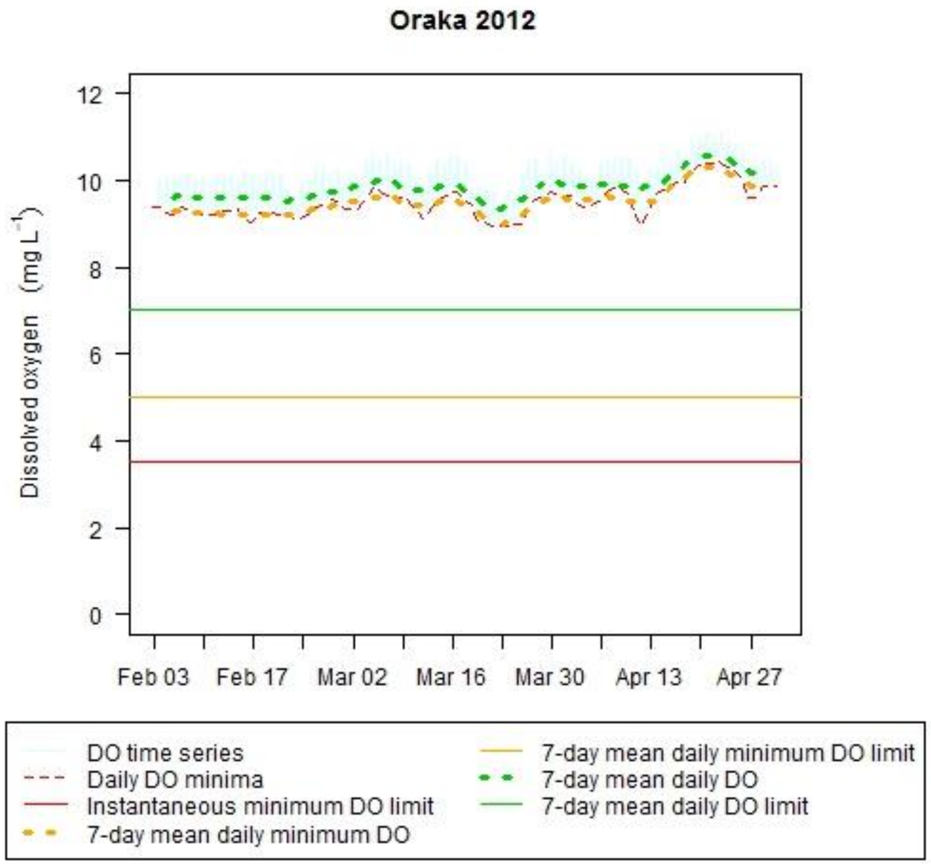
The dissolved oxygen times series collected in both 2012 and 2013 are shown relative to the imperative dissolved oxygen limits for ecosystem protection proposed by Franklin (2013) in Figure 3-2 to Figure 3-9. The imperative protection levels are used, as opposed to the guideline levels, because the majority of sites where monitoring took place were downstream of the main areas of trout habitat. Where trout are considered the main value, the guideline protection levels should be used. It can be seen that for the majority of sites the 7-day mean daily dissolved oxygen limit of 7 mg L^{-1} was met throughout the sampling period providing adequate protection for aquatic ecosystem values. The only exceptions to this were the sites in the lower river at Wharf Road and Turua (Figure 3-8) which were below the limit for the majority of the 2013 sampling period and the site at Shaftesbury (Figure 3-4), where there were two relatively short periods in 2013 when the 7-day mean daily dissolved oxygen concentration was below the limit.

The 7-day mean daily minimum dissolved oxygen limit of 5 mg L^{-1} was exceeded for a short period at the Puke Bridge site on the Waihou in late January 2013 (Figure 3-6) and in the Ohinemuri River near Paeroa in late February 2012 (Figure 3-9). The exceedance of the recommended limit in the Ohinemuri River was associated with the first flushing flow following a period of low rainfall, when the instantaneous minimum dissolved oxygen limit of 3.5 mg L^{-1} was also not met. At Turua, the 7-day mean daily minimum limit was not met from early-February to mid-March 2013 (Figure 3-8). The risk of ecosystem impairment associated with reduced dissolved oxygen concentrations is therefore highest in the vicinity of the Turua sampling site.

Large diel variation in dissolved oxygen concentrations were observed at the Mangawhero Stream site (Figure 3-2) as a result of the high abundance of aquatic macrophytes at this site. Relatively high diel variations in dissolved oxygen were also observed at times at the Shaftesbury (Figure 3-4), Tirohia (Figure 3-6), Puke Bridge (Figure 3-6) and Pekapeka (Figure 3-7) sites which are also likely to be associated with the growth of aquatic macrophytes.

At all sites where sampling was carried out in both 2012 and 2013, mean dissolved oxygen concentrations over the total sampling period were slightly lower in 2013. The greatest difference was at Shaftesbury where mean dissolved oxygen concentration was 9.8 mg L^{-1} in 2012 and 7.7 mg L^{-1} in 2013. The average difference between 2012 and 2013 at the other three sites (Okauia, Te Aroha and Pekapeka) was -0.4 mg L^{-1} over the entire sampling period.

It is noted that flushing flow events in both 2012 (e.g., 20/03/2012) and 2013 (e.g., 6/04/2013) caused a temporary reduction in dissolved oxygen concentrations at most sites. It is hypothesised that this is associated with a mobilisation of decaying organic matter (e.g., from macrophyte beds that are beginning to die back) which causes an elevation in the biological oxygen demand.



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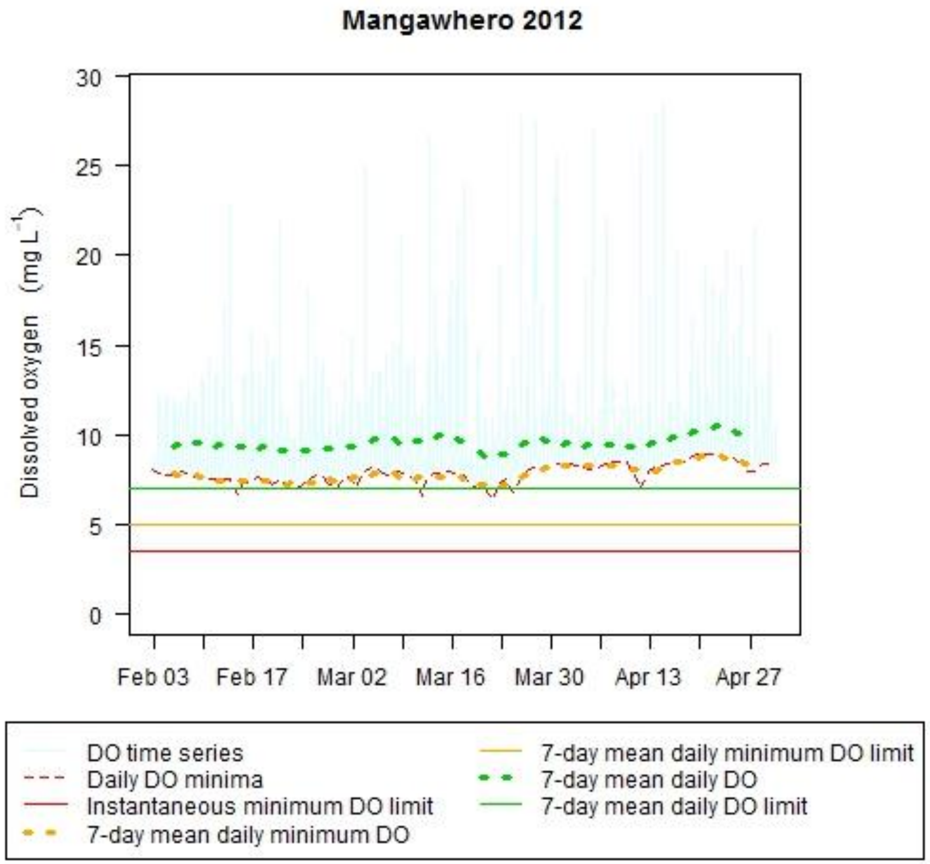
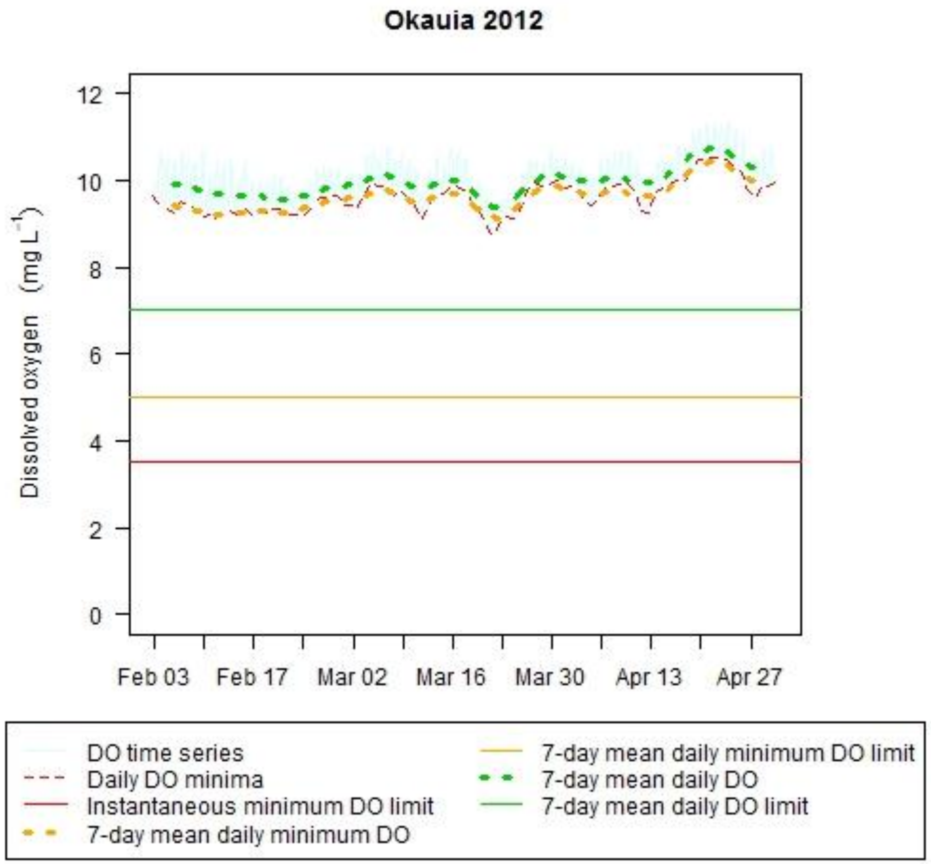


B.

Figure 3-2: Dissolved oxygen time series for: A. Oraka Stream 2012; B. Mangawhero Stream 2012. Dissolved oxygen limits indicated by solid horizontal lines are the imperative limits from Franklin (2013) proposed for protection of aquatic ecosystem values. Note that the limits are not visible on the graph for the Oraka Stream because dissolved oxygen concentrations are well above the limits.



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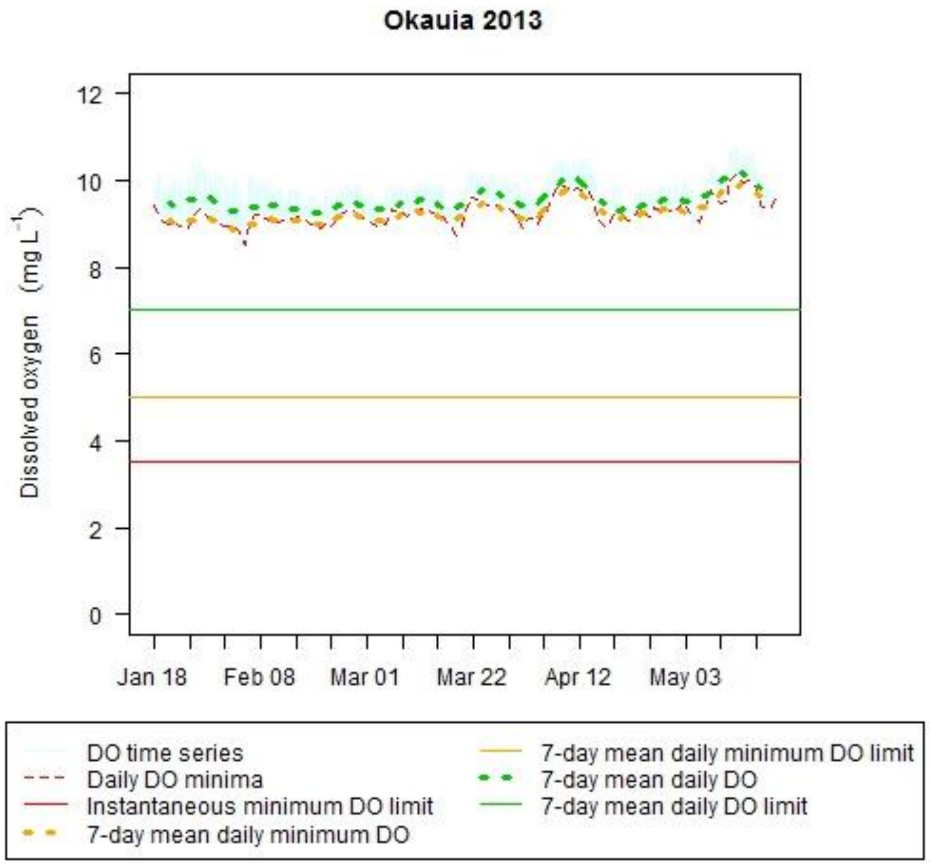
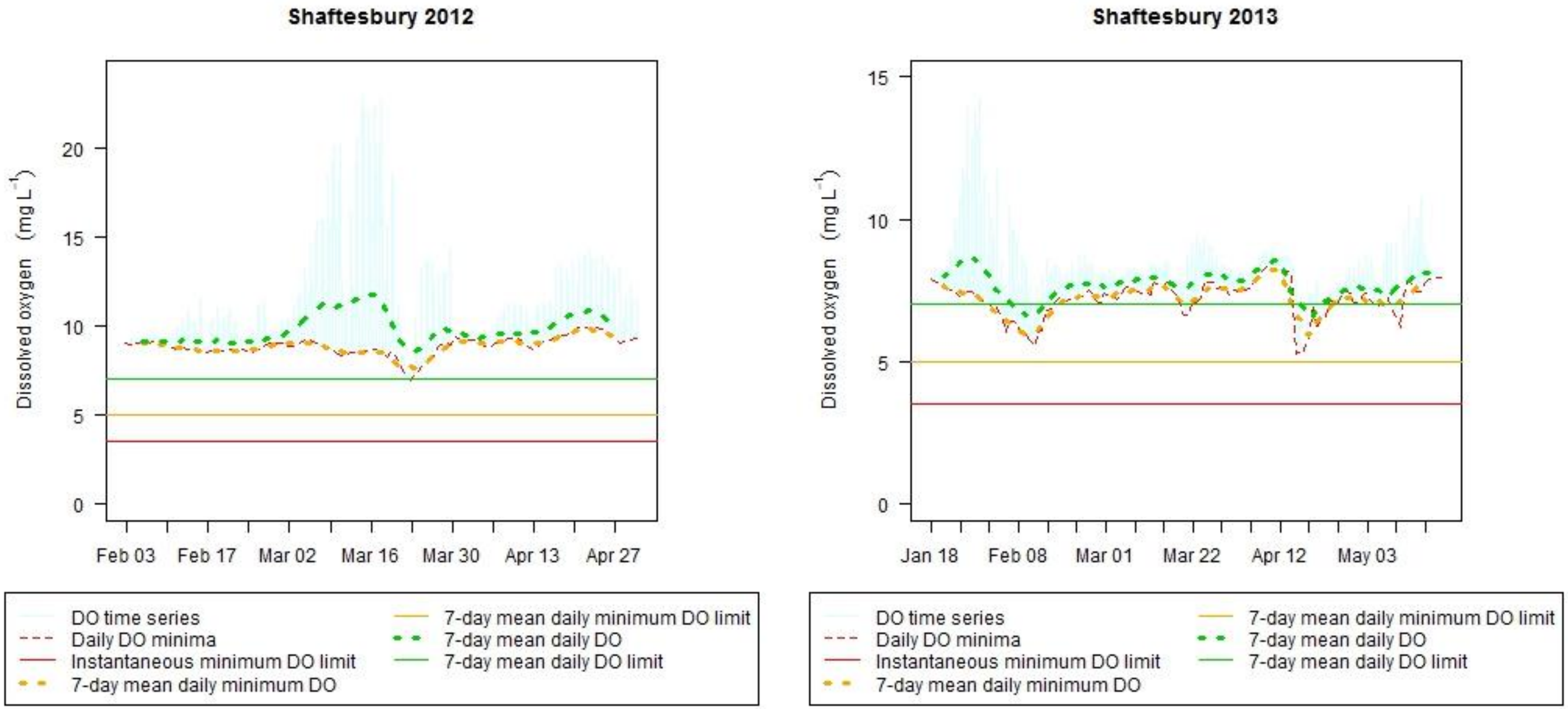


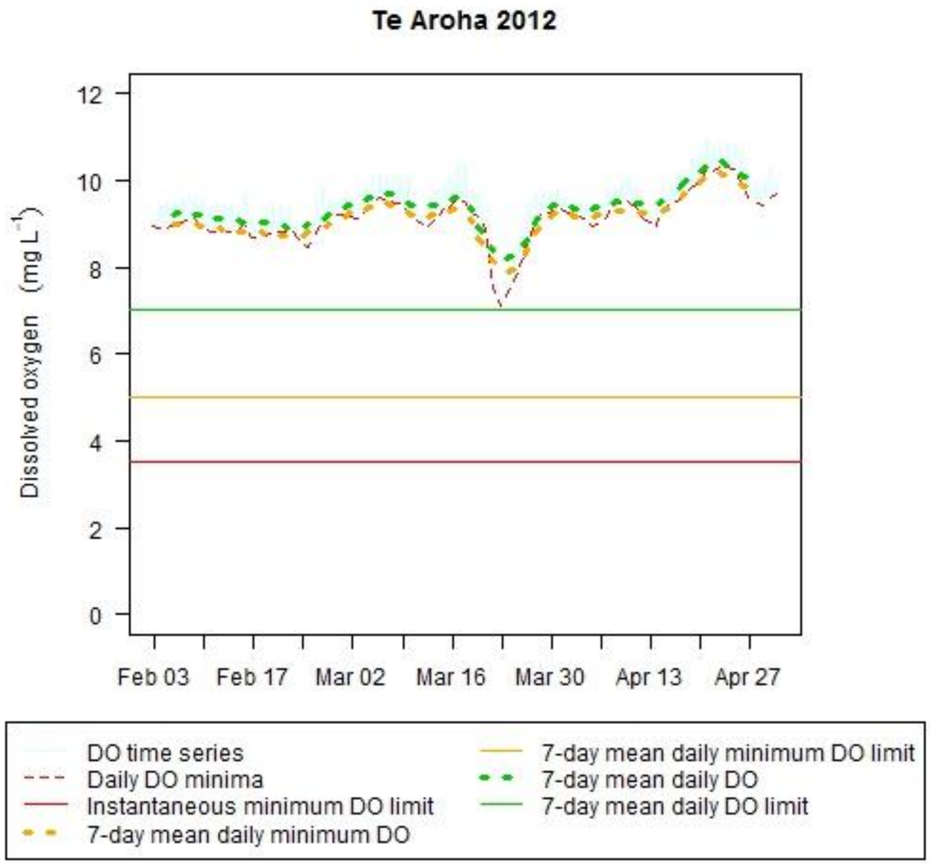
B.

Figure 3-3: Dissolved oxygen time series for the Waihou River at Okauia in: A. 2012; B. 2013. Dissolved oxygen limits indicated by solid horizontal lines are the imperative limits from Franklin (2013) proposed for protection of aquatic ecosystem values.. Note that the limits are not visible on the graphs because dissolved oxygen concentrations are well above the limits.



A. B.

Figure 3-4: Dissolved oxygen time series for the Waihou River at Shaftesbury in: A. 2012; B. 2013. Dissolved oxygen limits indicated by solid horizontal lines are the imperative limits from Franklin (2013) proposed for protection of aquatic ecosystem values. Note that some of the limits are not visible on the graphs if they fall below the minimum value for the y-axis.



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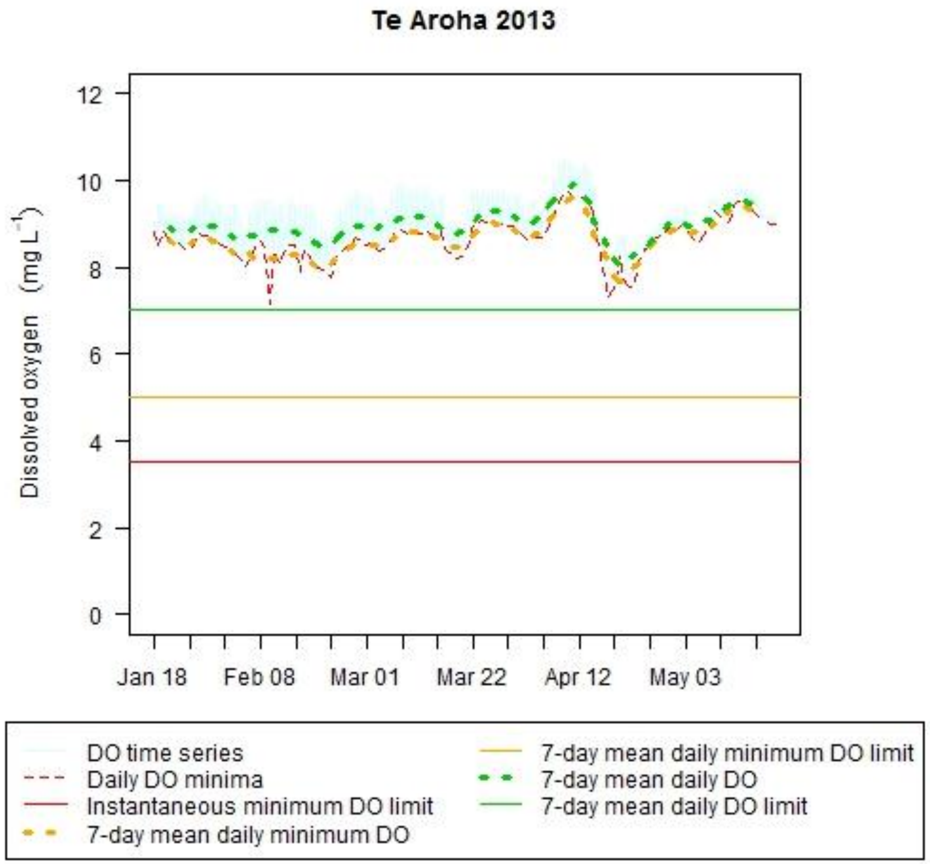
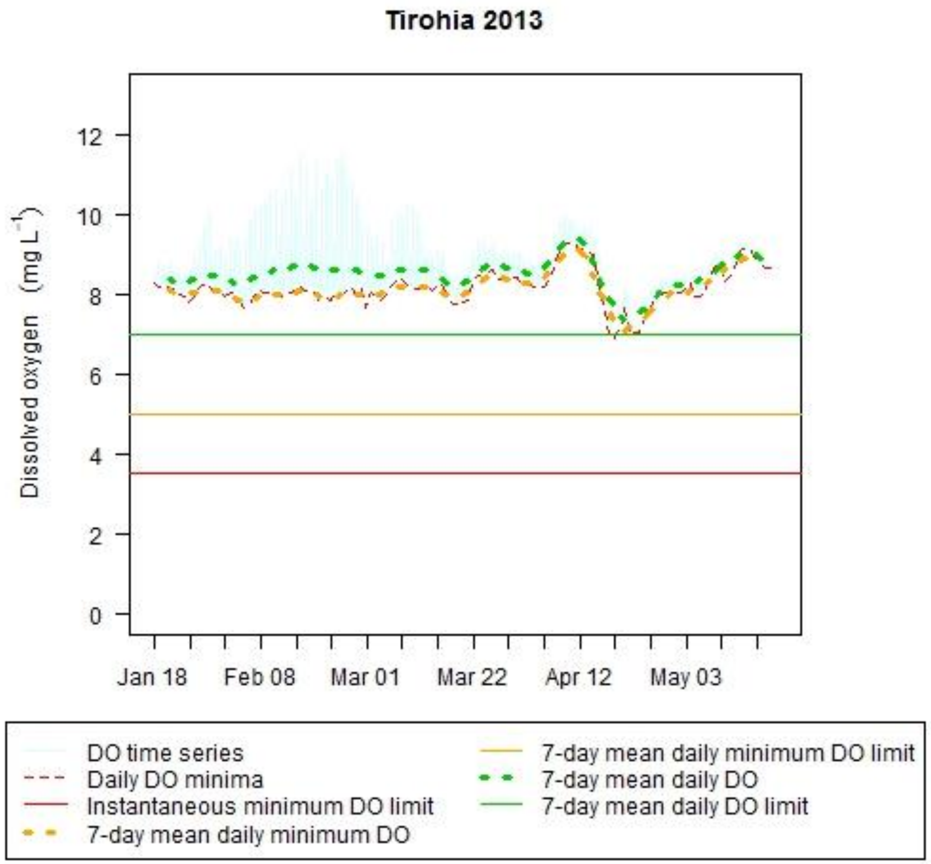


B.

Figure 3-5: Dissolved oxygen time series for the Waihou River at Te Aroha in: A. 2012; B. 2013. Dissolved oxygen limits indicated by solid horizontal lines are the imperative limits from Franklin (2013) proposed for protection of aquatic ecosystem values. Note that some of the limits are not visible on the graphs if they fall below the minimum value for the y-axis.



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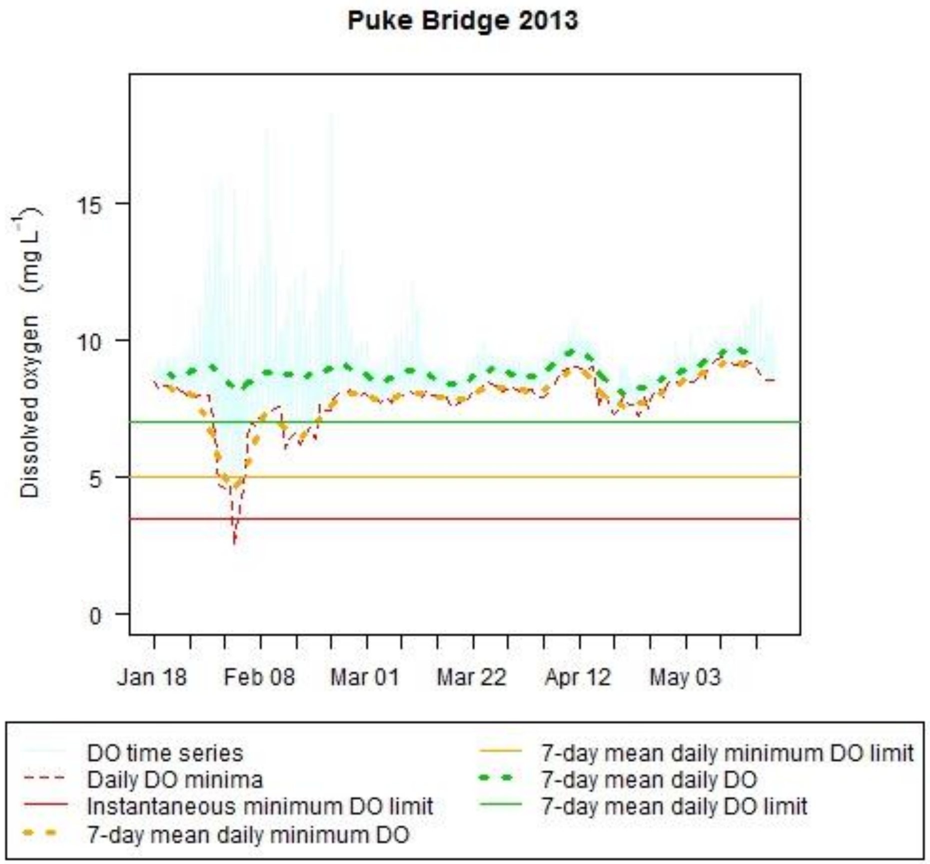
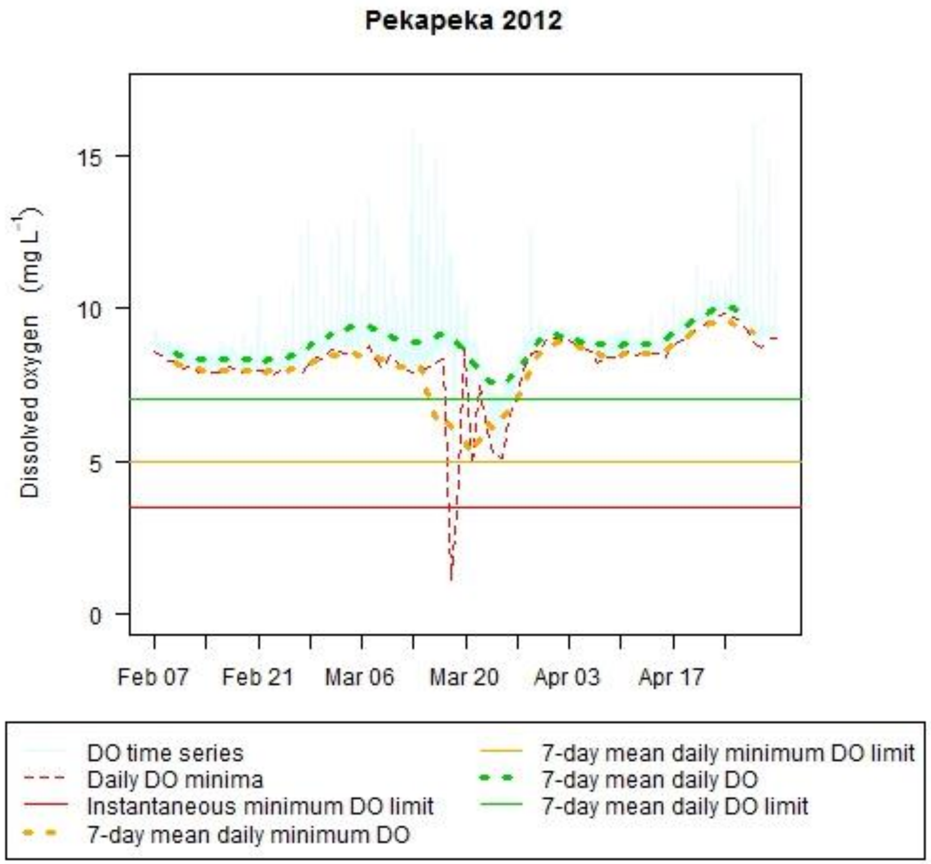


B.

Figure 3-6: Dissolved oxygen time series for the Waihou River at: A. Tirohia 2013; B. Puke Bridge 2013. Dissolved oxygen limits indicated by solid horizontal lines are the imperative limits from Franklin (2013) proposed for protection of aquatic ecosystem values. Note that some of the limits are not visible on the graphs if they fall below the minimum value for the y-axis.



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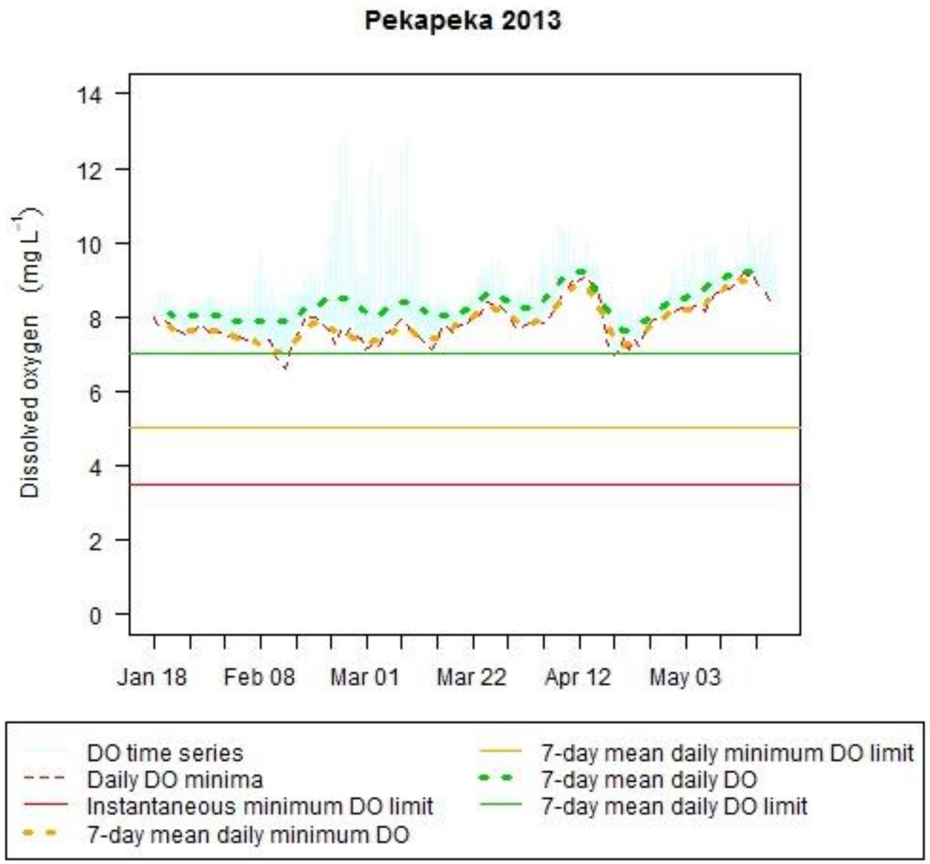
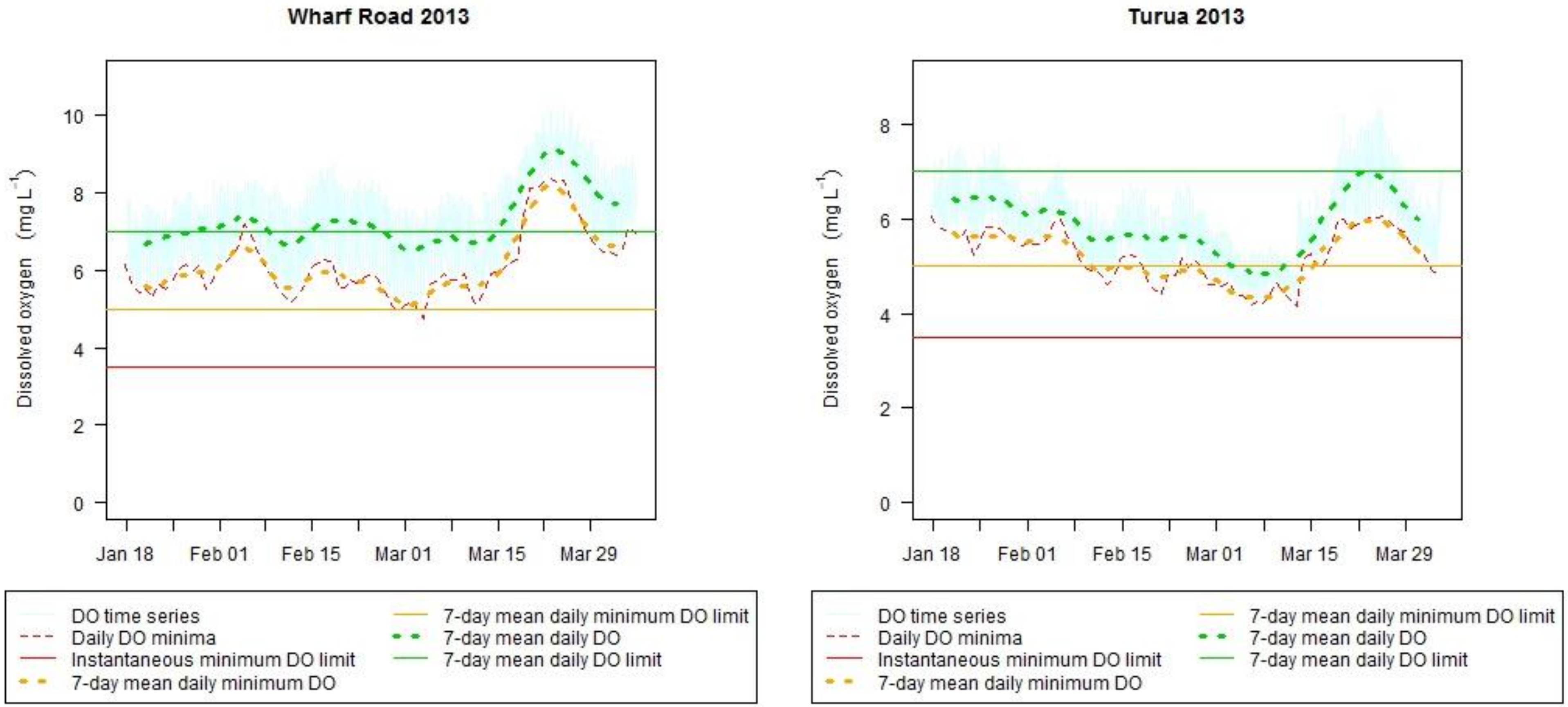


B.

Figure 3-7: Dissolved oxygen time series for the Waihou River at Pekapeka Road: A. 2012; B. 2013. Dissolved oxygen limits indicated by solid horizontal lines are the imperative limits from Franklin (2013) proposed for protection of aquatic ecosystem values. Note that some of the limits are not visible on the graphs if they fall below the minimum value for the y-axis.



A. B.

Figure 3-8: Dissolved oxygen time series for the Waihou River at: A. Wharf Road 2013; B. Turua 2013. Dissolved oxygen limits indicated by solid horizontal lines are the imperative limits from Franklin (2013) proposed for protection of aquatic ecosystem values. Note that some of the limits are not visible on the graphs if they fall below the minimum value for the y-axis.

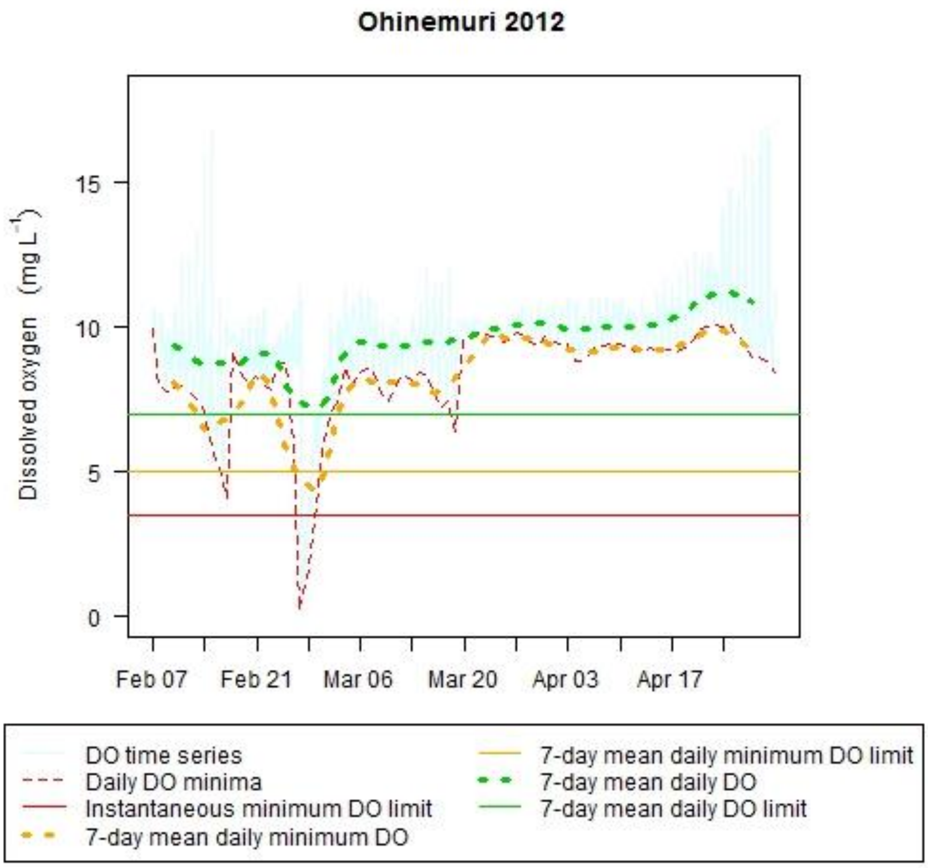


Figure 3-9: Dissolved oxygen time series for the Ohinemuri River in 2012. Dissolved oxygen limits indicated by solid horizontal lines are the imperative limits from Franklin (2013) proposed for protection of aquatic ecosystem values.

3.1.3 Interactions between dissolved oxygen and flow

Daily mean dissolved oxygen concentration was plotted against mean daily river flow or water level at the nearest gauging site for each of the sampling locations (Figure 3-10). Over the range of flows/water levels assessed there was no clear correlation between the two variables at any site. A few sites displayed evidence of a slight negative correlation (e.g., Shaftesbury), but this is largely a result of a small number of high flows/water levels associated with summer flood events which cause a temporary decline in dissolved oxygen. This is most likely caused by the mobilisation of organic matter (e.g., dead macrophytes) and an associated elevation in oxygen demand, rather than through a reduction in the reaeration rate. The only site where there was potential evidence of a higher occurrence of low dissolved oxygen minima with reduced flows was the site in the Ohinemuri River (Figure 3-10). Unfortunately, the dissolved oxygen logger failed at this site in 2013 limiting our ability to test this relationship at the lower flows experienced that summer.

A negative correlation between daily minimum dissolved oxygen concentration and water temperature was observed at all sites (Figure 3-11). To investigate whether this correlation may confound evidence of a relationship between dissolved oxygen concentration and flow, a linear regression between daily minimum dissolved oxygen concentration and water

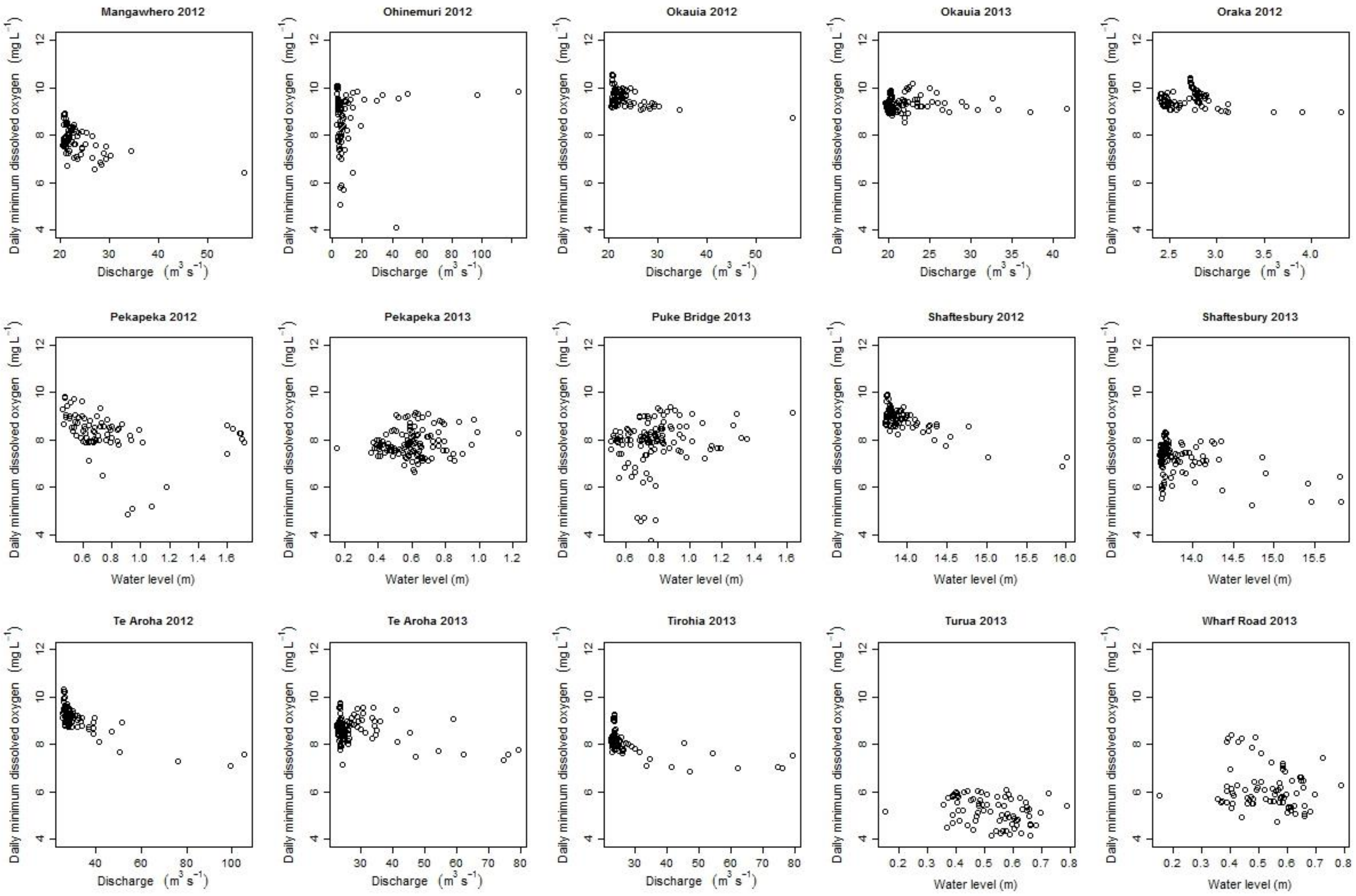


Figure 3-10: **Scatter plots of daily minimum dissolved oxygen concentration against flow.**

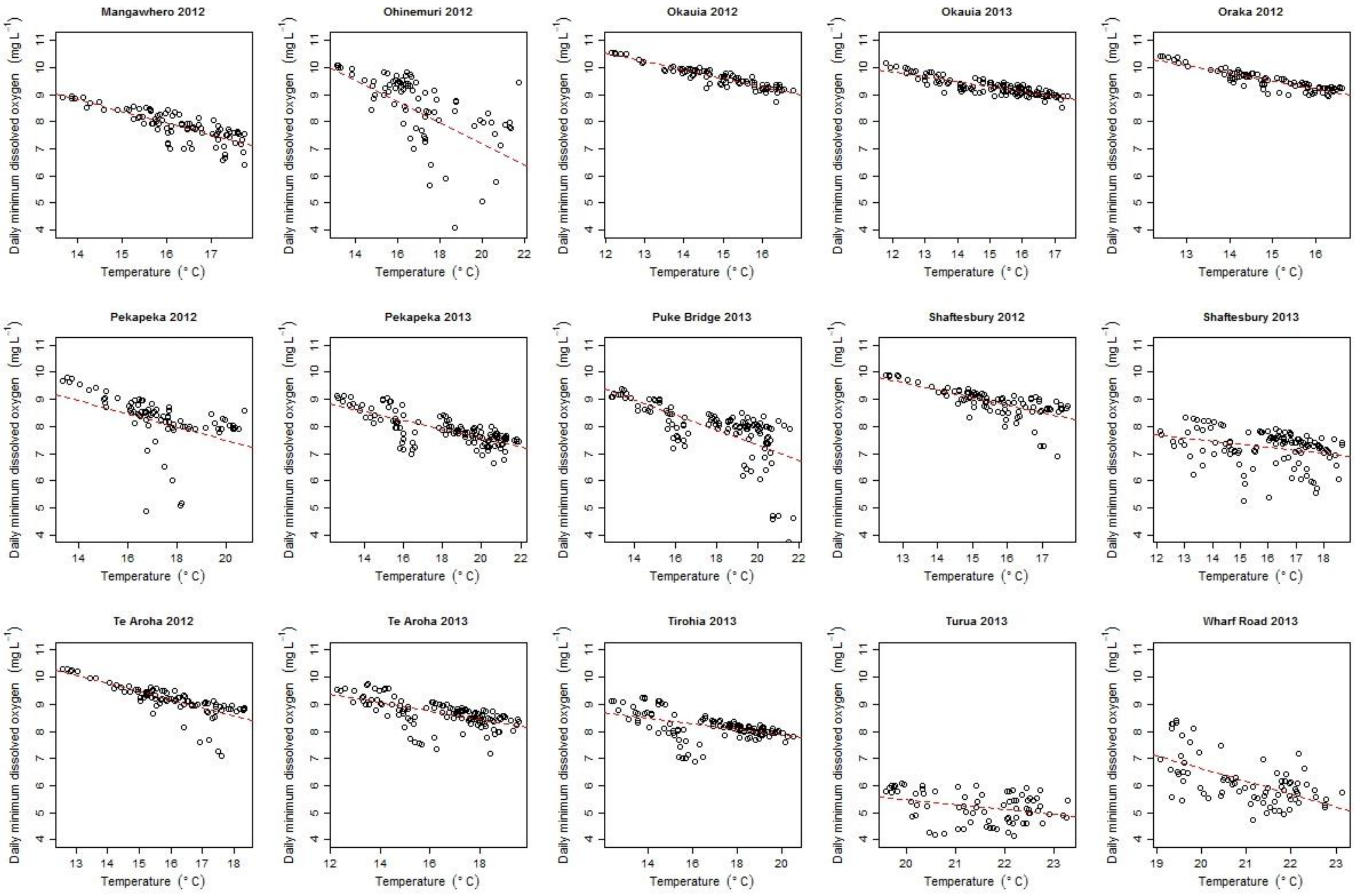


Figure 3-11: **Scatter plots of daily minimum dissolved oxygen concentration against temperature.**

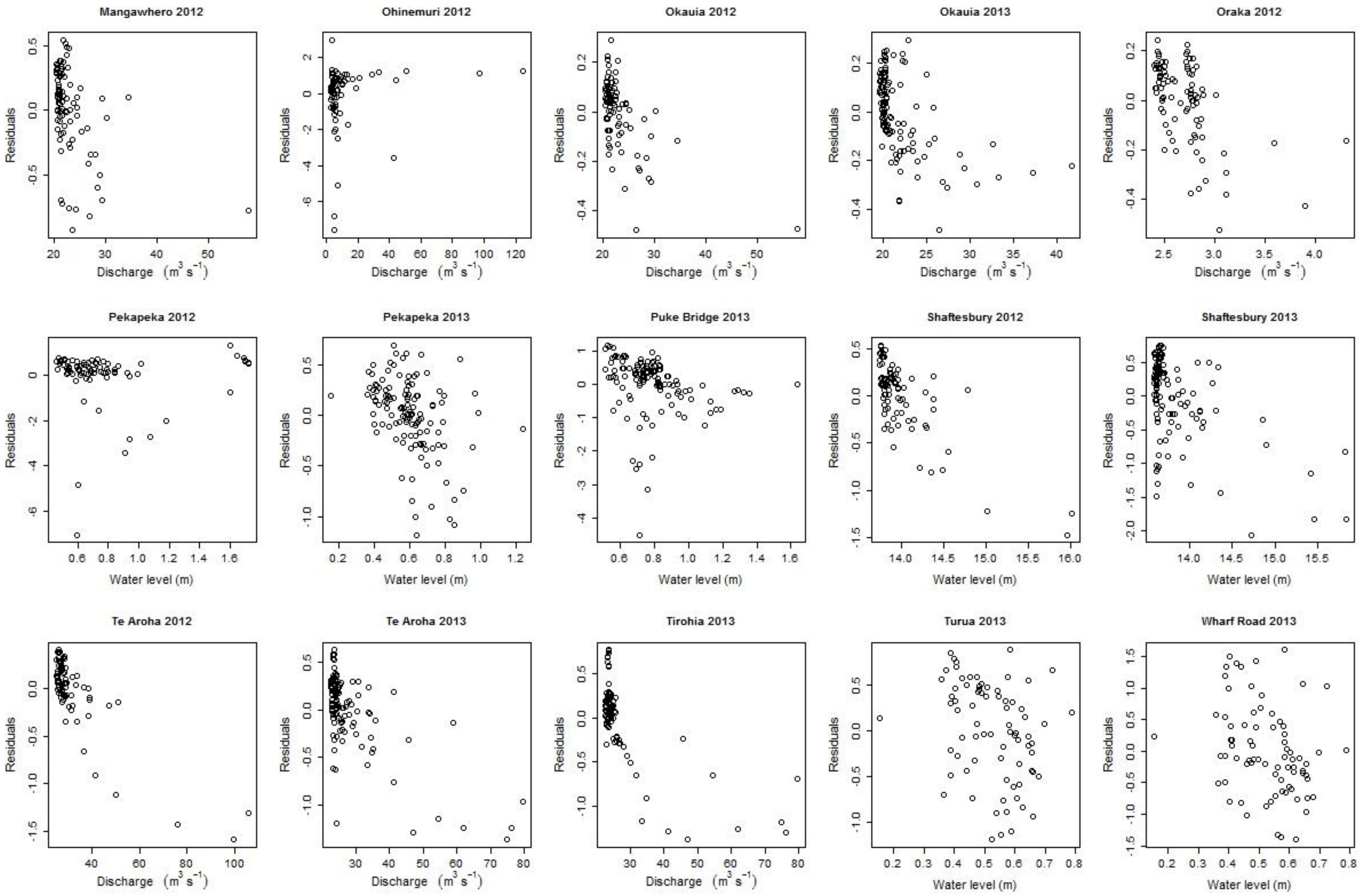


Figure 3-12: Residuals of a linear regression of daily minimum dissolved oxygen concentration and water temperature plotted against flow. The residuals represent the variation in daily minimum dissolved oxygen concentration that is not explained by the correlation with water temperature.

temperature was created for each site in each sampling year and the residuals of this relationship plotted against flow or water level (Figure 3-12). In effect, this allows an evaluation of whether the variation in dissolved oxygen that remains unexplained by changes in water temperature is correlated with flow/water level in any way. Broadly speaking the results show quite a broad scatter of points, reflecting the variance in daily dissolved oxygen minima across the range of low flows where monitoring occurred and weak or no correlation with flow. The only site where there may be some evidence of a relationship is in the Ohinemuri River, where there is a tendency for lower flows (<10 m^3 s^{-1}) to be associated with negative residuals, however, there remains a relatively high level of variance in the data.

The method for estimating the oxygen reaeration coefficient k_2 performed poorly at the majority of sites (Table 3-1). The reason for this is unclear and it was outside the scope of this study to investigate this further. Te Aroha was the only site where a sufficient number of robust estimates of k_2 are available for an analysis of the interactions with flow. No statistically significant correlation was present between k_2 and flow at Te Aroha ($p=0.28$, $r^2=0.009$; Figure 3-13). However, it should be noted that the flow range over which reliable estimates of k_2 were available was only 22.5 to 24.5 m^3 s^{-1} (Figure 3-13).

Table 3-1: Results from the night-time regression method for calculating reaeration.

Site	Number of nights where r^2 <0.4	Number of nights where r^2 ≥0.4
Okauia 2013	79	8
Shaftesbury 2013	87	0
Te Aroha 2013	61	26
Tirohia 2013	85	1
Puke Bridge 2013	83	4
Pekapeka 2013	85	2
Wharf Road 2013	69	8
Turua 2013	73	2

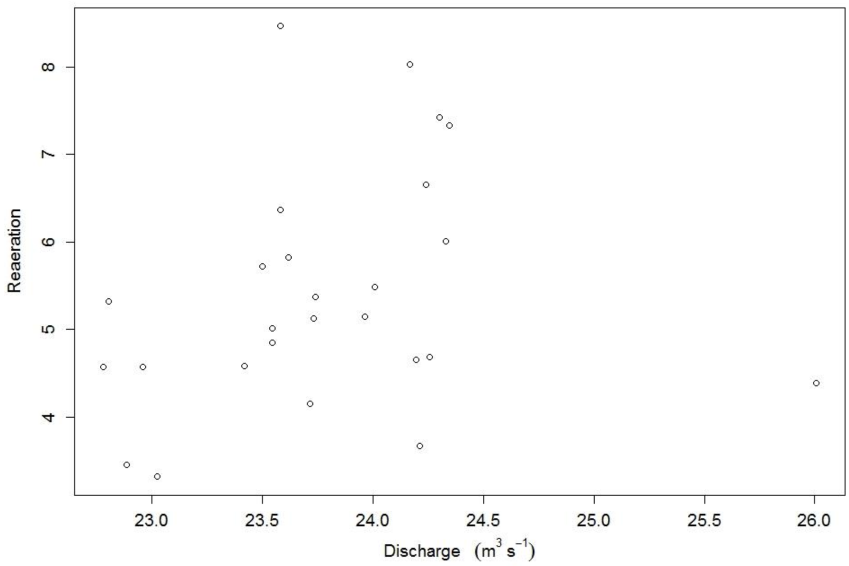


Figure 3-13:Scatter plot of reaeration (mg/L/day) against flow (m^3 s^{-1}) for the Te Aroha site.

3.2 Water temperature

Time series of water temperature are shown in Figure 3-14. In general, water temperatures were greater in the summer of 2013 compared to 2012, and maximum water temperatures increase with distance downstream (Figure 3-14). Maximum temperatures occurred close to the start of the monitoring period (i.e. mid-summer) and followed the seasonal changes in air temperature. Richardson et al. (1994) assessed the thermal tolerance and preferences of a range of native fish species acclimated to a water temperature of 15°C (Table 3-2). At most sites the preferred temperature of smelt and banded kokopu whitebait were exceeded for at least part of the summer and this was also the case for inanga at all sites downstream of Shaftesbury. In the lower reaches of the river (e.g., Wharf Road and Turua), only the preferred temperatures of the eel species were not exceeded (Table 3-2 & Figure 3-14).

Table 3-2: Preferred water temperatures of selected fish species typical of the Waihou River system. Source: [a] Richardson et al. (1994); [b] Paterson and Baker (2011).

Species	Life stage	Preferred temperature (quartiles) (°C)
Shortfin eel (*Anguilla australis*)	Elver	26.9 (25.6-28.5)[a]
Longfin eel (*Anguilla dieffenbachii*)	Elver	24.4 (22.6-26.2)[a]
Cran's bully (*Gobiomorphus basalis*)	Mixed	21.0 (19.6-22.1)[a]
Common bully (*Gobiomorphus cotidianus*)	Mixed	20.2 (18.7-21.8) [a]
Inanga (*Galaxias maculatus*)	Whitebait	18.8 (18.0-19.8) [a]
	Juvenile	18.7 (17.3-20.0) [a]
	Adult	18.1 (17.2-19.1) [a]
Banded kokopu (*Galaxias fasciatus*)	Whitebait	16.1 (14.8-17.7) [a]
	Adult	17.4 (16.3-18.3) [a]
Common smelt (*Retropinna retropinna*)	Adult	16.1 (15.1-17.4) [a]
Brown trout (*Salmo trutta*)	Adult	12.0-14.4[b]
Rainbow trout (*Onchorhynchus mykiss*)	Adult	16.5-21.1[b]

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 (based on the assumption that within each month average temperature and flow are similar) for each site. No consistent patterns were found in the monthly relationships between water temperature and flow at any of the sites.

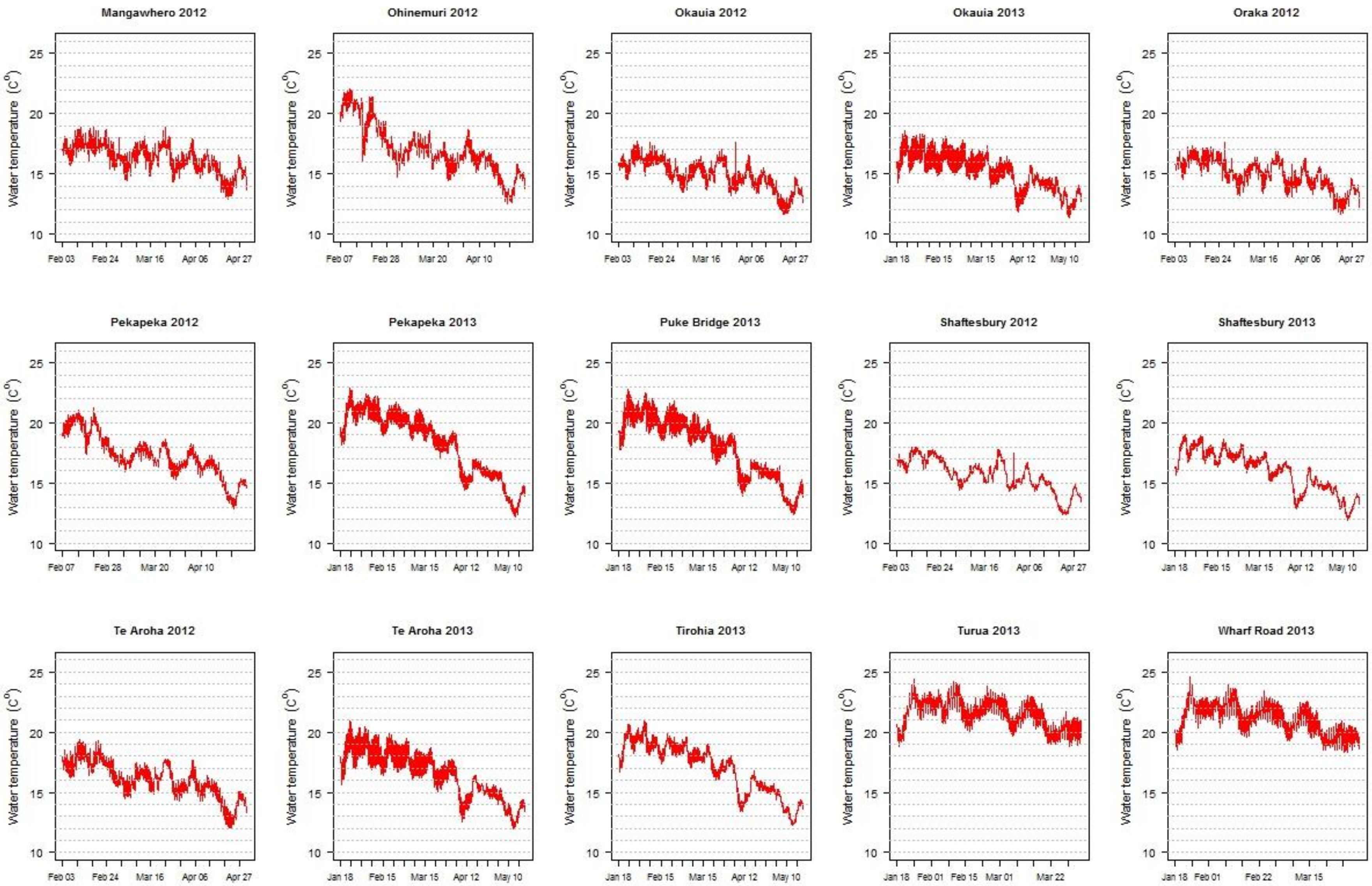


Figure 3-14: **Time series of water temperature at each site in the Waihou River.**

3.3 Lower river dissolved oxygen longitudinal profiles

A total of six long profiles were measured in the lower Waihou during 2013 (Figure 3-15). A clear dissolved oxygen sag occurs in the lower river, with the location of the dissolved oxygen minima associated with the limit of the saline influence. The location of the salinity gradient is driven by tide and therefore there is a strong correlation between the location of the dissolved oxygen minima and tide height at the time of the survey over the range of tides surveyed (Figure 3-16; $p=0.005$, $r^2=0.86$). After taking account of the variance in the location of the dissolved oxygen minima caused by tide height, no significant correlation was found with flow at Te Aroha (Figure 3-17). This suggests that the influence of flow on the location of the dissolved oxygen minima was low under the conditions the surveys were conducted.

Both mean and minimum dissolved oxygen concentration were correlated with mean water temperature ($p=0.004$, $r^2=0.88$ and $p=0.005$, $r^2=0.86$ respectively). After accounting for the influence of temperature, no correlation was identified between dissolved oxygen concentration and flow or tide height.

Mean temperature was not correlated with flow or tide height. However, the temperature range (i.e., the difference between the maximum and minimum temperature in a long profile) was correlated with tide height ($p=0.049$, $r^2=0.58$). This appears to reflect a difference in water temperature between the freshwater and saltwater inputs to the lower river as evidenced by relatively higher water temperatures being associated with more saline water (Figure 3-15).

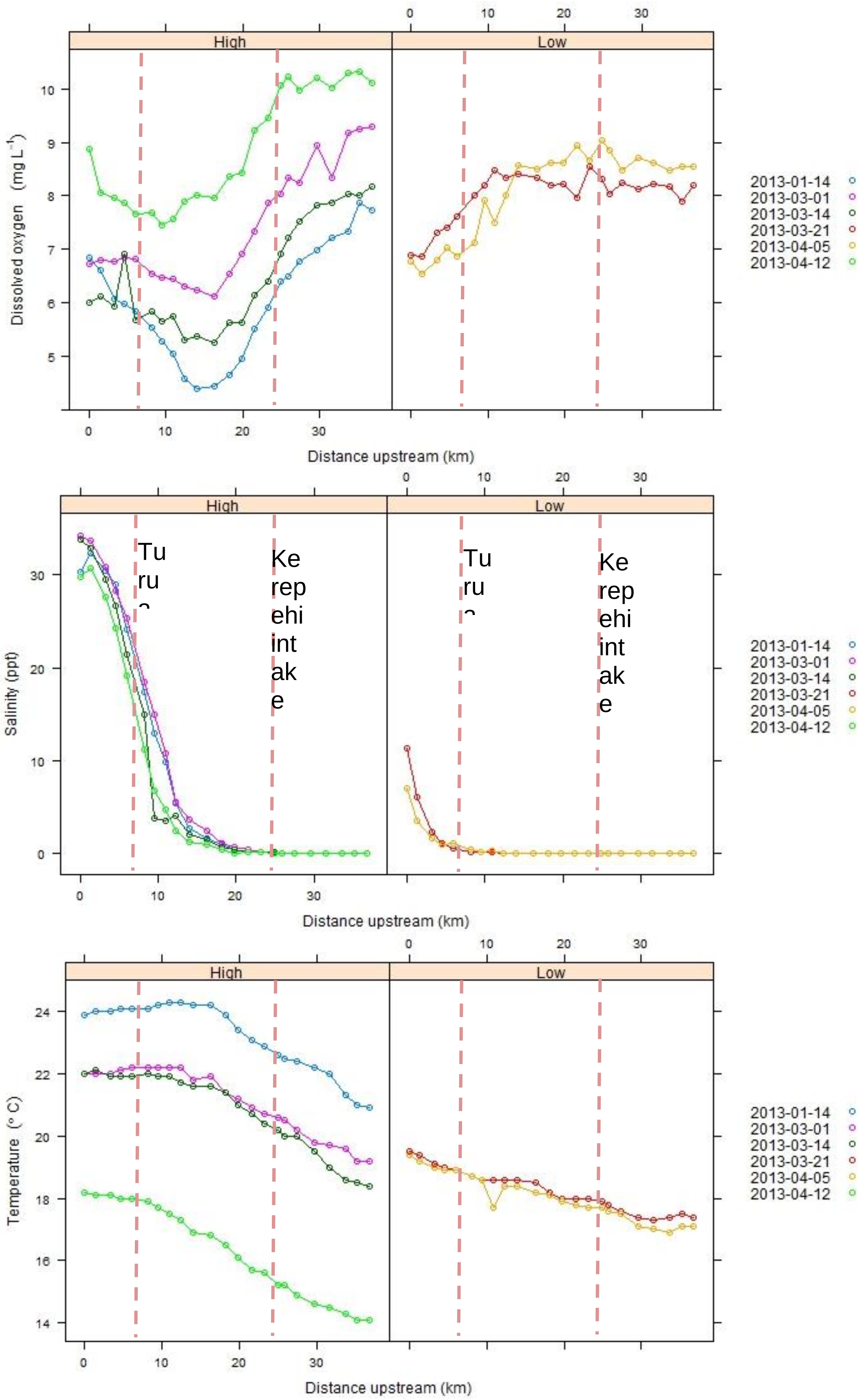


Figure 3-15: Long profiles of dissolved oxygen, salinity and water temperature in the lower Waihou River at high and low tide.

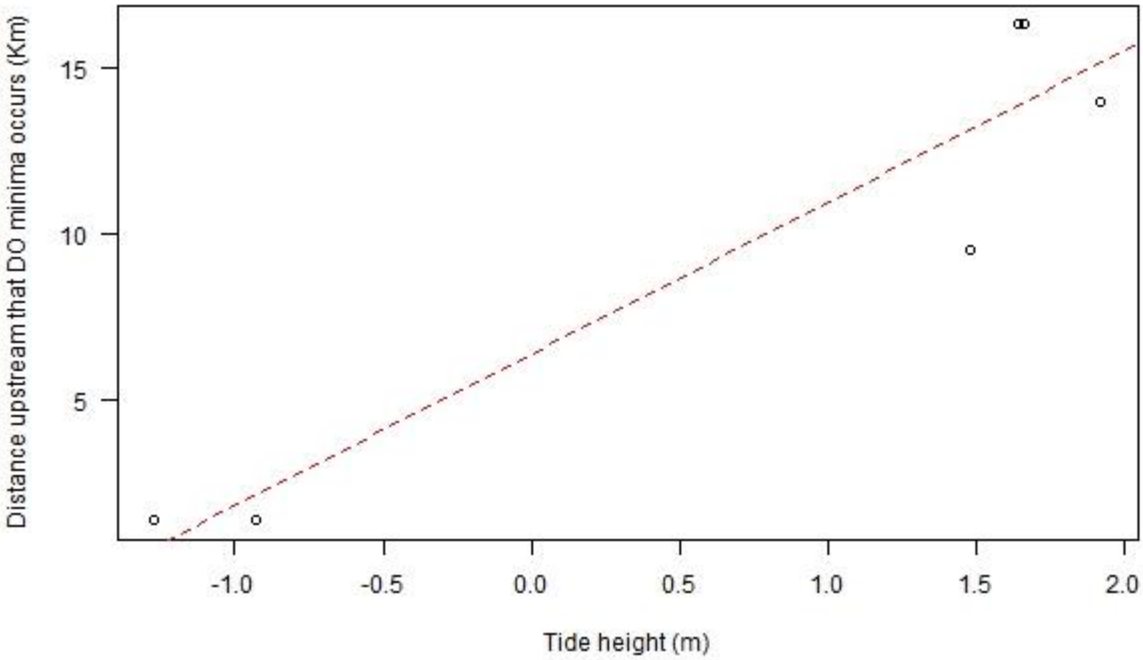


Figure 3-16: Correlation between the location of the dissolved oxygen minima and tide height at the time of survey in the lower Waihou at summer base flows.

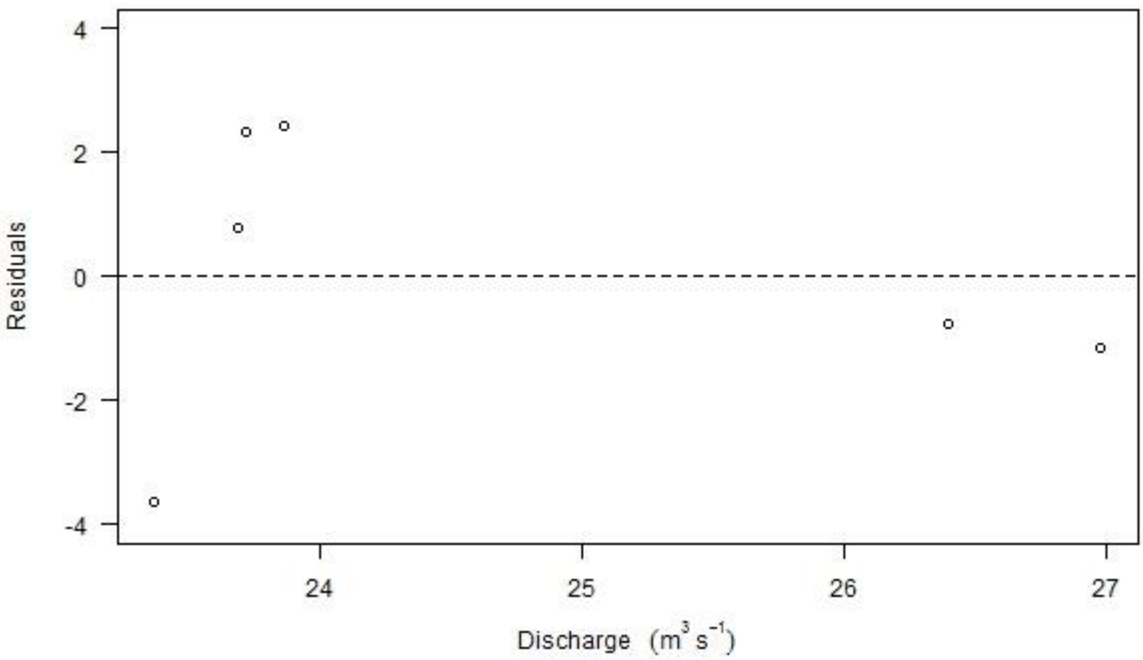


Figure 3-17: Residuals of the relationship between the location of the dissolved oxygen minima and tide height plotted against flow.

4 Discussion

The 2012 and 2013 sampling periods covered distinctly different summer flow conditions, with 2012 characterised by regular rainfall and associated flushing flow events, and 2013 characterised by a prolonged period of low summer base flows followed by autumn flushing flows. At all sites where monitoring was carried out in both years, mean dissolved oxygen concentrations were lower in 2013 when flows were on average lower, but this difference was not statistically different at any site. It is possible this was a result of warmer water temperatures in 2013. There were also no statistically significant relationships found between dissolved oxygen concentrations and flow, even after accounting for the influence of seasonal changes in water temperature on dissolved oxygen concentrations.

In general, the variance in daily minimum dissolved oxygen concentration was within 2 mg L^{-1} across the majority of flows observed during the surveys. The main exception was the site in the Ohinemuri River, where the variance in daily minimum dissolved oxygen was greater at lower flows. It is hypothesised that this may reflect the differences in hydrology and geomorphology of the Ohinemuri River compared to that of the Waihou River. The hydrology of the Ohinemuri River is driven strongly by rainfall, resulting in quite a flashy flow regime with low base flows. However, the hydrology of the Waihou River is more strongly influenced by groundwater inputs and is characterised by a more stable flow regime with higher base flows. The shape of the channel (steeper, rockier and shallower in the Ohinemuri compared to wider, deeper and lower gradient in the Waihou) also means that water depth is more sensitive to changes in flow in the Ohinemuri River. As a consequence, the dissolved oxygen reaeration coefficient (k_2) might be expected to be more sensitive to changes in flow in the Ohinemuri River, compared to the Waihou River. Unfortunately, the night-time regression method failed to provide robust estimates of k_2 for the majority of sites. In 2012, this was likely a consequence of the regular rainfall and lack of stable flows. However, it is unclear why the method failed for the majority of sites in 2013 when flows were stable and apparently good dissolved oxygen records were available at most sites. Investigating this further was outside the scope of this project, but other authors have found highly variable and site specific results from this and other methods for estimating k_2 from dissolved oxygen records, particularly where there are high abundances of macrophytes (Aristegi et al. 2009).

It was apparent from the dissolved oxygen time series that flushing flows associated with rainfall events result in a temporary drop in dissolved oxygen concentrations at the majority of sites. It is likely that this is associated with the mobilisation of decaying organic matter, such as dead macrophytes and periphyton. In 2012, such flushing flows were quite regular throughout the summer. As a consequence, there were relatively short accrual periods for organic matter (such as dead macrophytes and periphyton) to build up before being washed away, and therefore the decline in dissolved oxygen concentrations associated with these flushing flows was lessened. However, in 2013 base flows persisted from February through until April allowing a significant build-up of decaying organic matter. Consequently, following the first significant rainfall event in autumn there was quite a significant drop in dissolved oxygen concentrations. This phenomenon has also been observed at other sites in the Waihou catchment (Franklin 2010a, 2010b, Franklin & Hodges 2012), emphasising the potential significance of low flow duration in determining instream ecological responses.

As first identified by Vant (2011), a significant dissolved oxygen sag occurs in the lower Waihou River. A similar phenomenon has also now been observed in the lower Piako River

(Vant 2013). Over the range of freshwater flows observed during this survey (23-27 $m^3 s^{-1}$ at Te Aroha), the location of the dissolved oxygen minima was correlated strongly with tide height. It was observed that the location of the dissolved oxygen minima coincided with the limit of the saline wedge and a peak in turbidity. Whilst freshwater inflows were not identified as having a significant control on the location or magnitude of the dissolved oxygen minima, this is likely to be a result of the relatively small range of freshwater flows over which observations occurred in 2013. In a similar case in the upper Humber estuary in the UK, where observations were made over a greater range of freshwater inflows, flow was found to be an important driver of both the location and magnitude of the dissolved oxygen minima (Mitchell et al. 1999). In that case, suspended sediment and the associated sediment oxygen demand (SOD) were identified as being the main cause of the drop in dissolved oxygen. However, it was the interaction between tide height and freshwater inflows that determined the location and concentration of the suspended sediment maxima and hence dissolved oxygen minima (Mitchell et al. 1999). It is highly likely that the same functional processes are driving the dissolved oxygen dynamics of the lower Waihou and therefore that freshwater inflows (over a broader range than those measured) will have an important functional role in controlling the location and magnitude of the observed dissolved oxygen sag. It is also likely that high flow flood events will be important for periodically flushing sediment from the lower Waihou into the Firth of Thames. Longer term monitoring to help understand the dynamics driving this system may be beneficial for supporting future decision making.

At the majority of sites on the main stem of the Waihou River, the imperative dissolved oxygen protection levels for fish were met for the majority of the time. The only site where the thresholds were exceeded for an extended period was the downstream most site at Turua. This is associated with the dissolved oxygen sag that is known to occur in the vicinity of this site. At the remaining sites, exceedance was generally for short durations associated with flushing flow events. It is hypothesised that this is a consequence of the mobilisation of decaying organic matter, e.g. macrophytes and periphyton, which accrues over the summer low flow period. There is a risk that increased duration of summer low flows, thus allowing greater accrual of organic matter before mobilisation, could result in greater magnitude and duration of low dissolved oxygen events associated with flushing flows at the end of summer. This increases the risk of adverse effects on instream communities. The upper reaches of the Waihou River and its tributaries are known for being important trout fisheries. In these locations, the guideline dissolved oxygen protection limits are more appropriate. However, at sites representative of the main trout fisheries, e.g. Otaika and Okauia, these more stringent protection levels are also met.

5 Conclusions

Oxygen is essential for the process of respiration and therefore can be a limiting factor to many aquatic organisms. Analysis of the long-term dissolved oxygen monitoring data within the Waihou catchment indicates that, in general, dissolved oxygen is not likely to be a limiting factor for aquatic ecology in the main river upstream of Paeroa. However, it has been shown previously that there may be problems caused by low dissolved oxygen in some of the smaller, lowland tributaries of the Waihou River (Franklin 2010a, 2010b) and the presence of a dissolved oxygen sag in the lower river where dissolved oxygen minima are below those recommended for the protection of aquatic ecosystems is also of concern in setting allocation limits for the catchment.

In the main stem of the Waihou River above Paeroa, dissolved oxygen concentrations appear to be relatively insensitive to changes in flow over the flow range of 23-27 $m^3 s^{-1}$ (as measured at Te Aroha), with dissolved oxygen concentrations primarily influenced by water temperature and macrophyte/algal respiration and photosynthesis. If the degree of hydrological alteration associated with water resource use is expected to be low, it is expected that the risk of significant deleterious effects on dissolved oxygen in the main stem of the Waihou upstream of Paeroa will be low. However, there is some evidence to suggest that dissolved oxygen concentrations in the Ohinemuri River may be more sensitive to flow changes. Unfortunately, the failure of the dissolved oxygen logger at this site in 2013 means that this cannot be characterised robustly. Consequently, a more precautionary approach to setting water allocation limits is advised for the Ohinemuri sub-catchment with respect to maintaining dissolved oxygen. Based on the results of previous studies, it is also recommended that a conservative approach to setting minimum flow and allocation limits be applied for lowland tributaries subject to multiple stressors (see Franklin (2010a)).

The dissolved oxygen sag in the lower river may, however, be the main control on setting upstream minimum flow and allocation limits. Whilst over the range of flows that occurred during the 2013 sampling period, there was no significant effect of flow identified on either the location or magnitude of the dissolved oxygen minima, evidence from other river systems suggests that freshwater inflows are likely to have an important functional role in driving the dissolved oxygen dynamics in this part of the river through its influence on sediment dynamics. There is a reasonable risk that decreased magnitude and increased duration of summer low flows could lower the dissolved oxygen minima in the lower river. Lower minimum flows will also increase the probability of the dissolved oxygen minima, and associated saline wedge and turbidity maxima, penetrating further inland at high tide. It is recommended that a precautionary approach be taken to setting minimum flows for this part of the river due to existing conditions in the river already exceeding recommended protection levels for aquatic ecosystems. This could be supported by more intensive monitoring of dissolved oxygen concentrations in the lower river, including monitoring across the full tidal cycle and across a broader range of freshwater flow inputs.

The important role of flushing flows has also been highlighted in this study. During summer and autumn, high flow events appear to mobilise decaying organic matter, prompting a temporary decline in dissolved oxygen concentrations. Whilst most organisms are capable of coping with short term exposure to sub-optimal conditions (assuming acute thresholds are not exceeded), there is some evidence to suggest that the magnitude of the decline in dissolved oxygen may be linked to the duration of low flows and therefore the longer the duration of low flows, the more likely that acute thresholds may be exceeded. The occurrence of flushing flow events may also be an important control on the sediment dynamics, including fine particulate organic matter, that are likely to be driving the low dissolved oxygen in the lower river. The relative levels of the minimum flow and allocation limits with respect to the flow regime combine to determine the potential duration of low flows. It is therefore important that this is taken into consideration when determining appropriate water resource use limits for the catchment.

Whilst it has not been possible to identify a clear causative correlation between flow and dissolved oxygen concentrations in the main stem of the Waihou River, the proposed National Objectives Framework (NOF) includes dissolved oxygen as one of the primary attributes for maintaining ecosystem health (Appendix A; MfE 2013). The magnitude of the dissolved oxygen sag in the lower river is a consequence of multiple stressors, one of which is likely to be freshwater flows. Consequently, WRC could use dissolved oxygen concentrations in the lower river as a direct control for managing upstream takes during periods of low flow, with takes being restricted as dissolved oxygen concentrations drop below the NOF protection levels.

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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.