Dissolved Oxygen Thresholds and Management

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Executive summary

Dissolved oxygen is a key component of water quality with critical effects on ecosystem health. Many aquatic organisms require oxygen above a specific threshold to survive. The Horizons Regional Council Regional Plan (One Plan) currently specifies a minimum DO threshold criteria for each different management zone within the region. The aim of this project was to support a review of the current dissolved oxygen criteria in the One Plan for the maintenance of native aquatic biota. This was accomplished via three components: a literature review of current knowledge on dissolved oxygen requirements and potential thresholds for New Zealand native fish, trout, and invertebrates, an analysis of a six-year time series of continuous dissolved oxygen data from six Horizons Regional Council (HRC) monitoring sites, and an exploratory analysis of potential drivers of dissolved oxygen focusing on periphyton.

The analyses were also repeated using the National Objectives Framework (NOF) guidelines for minimum dissolved oxygen levels (MfE 2014) as a comparison to the One Plan limits. This comparison was of interest because the One Plan targets are specified in terms of dissolved oxygen percent saturation values, whereas the NOF guidelines use dissolved oxygen concentration. This is a key distinction because the same saturation can occur at different temperatures with different dissolved oxygen concentrations. Additionally, if HRC is considering revising their regional targets, they may want to consider adopting the national limits instead.

The daily minimum dissolved oxygen saturation was above the One Plan target 90% of the time at all six monitoring sites, but only above the NOF A/B guideline 75% of the time. Under current NOF implementation, however, which uses the lowest daily minimum or 7-day mean daily minimum dissolved oxygen concentration recorded over an extended summer period (1 Nov – 30 April), four sites were in the C band and two were in the D band. The dissolved oxygen saturation dropped below both types of limit most frequently in autumn and summer, when water temperatures are warmest and periphyton growth is highest.

Maximum daily water temperature and periphyton biomass (measured as chlorophyll-a), were selected as the best explanatory variables driving dissolved oxygen levels in a linear mixed effects modelling analysis. Periphyton was also selected as a driver of primary production and respiration, although there was not a strong correlation between either pair of variables.

Understanding the drivers of dissolved oxygen and the influence of seasonality on dissolved oxygen levels will enable Horizons Regional Council to manage their streams and to revise the One Plan targets, if necessary, to ensure the protection of New Zealand native fish, trout, and invertebrates.

1 Introduction

The One Plan sets out how the natural resources of the Manawatu-Wanganui region, including air, water, and land, will be managed by Horizons Regional Council (HRC). The One Plan establishes water quality targets to ensure the provision of ecosystem, recreational, cultural values, social, and economic values (Horizons Regional Council 2016). Dissolved oxygen (DO) is a key component of water quality with critical effects on ecosystem health. Many aquatic organisms require oxygen above a specific threshold to survive. The One Plan currently specifies a minimum DO threshold criteria for each different management zone within the region.

The aim of this project was to inform a review of the current dissolved oxygen criteria in the One Plan for the maintenance of native aquatic biota and trout. This was addressed in three parts:

1. A literature review was conducted to summarize known information on dissolved oxygen requirements and potential DO thresholds for New Zealand native fish and invertebrate species, as well as trout.
2. Continuous DO data recorded over the past six years from six HRC monitoring sites were analysed to determine whether current One Plan minimum DO targets are being exceeded, and if so, how often and for how long. The DO data were also compared to the dissolved oxygen limits recommended under the National Objectives Framework (NOF) for the protection of ecosystem health to determine which set of limits was more conservative. This comparison was of interest because the NOF guidelines are specified in terms of dissolved oxygen concentration (mg L^{-1}), which decreases with increasing water temperature, while the One Plan target limits are defined in terms of dissolved oxygen percent saturation. Less oxygen dissolves in water at higher temperatures, and therefore percent saturation can remain high or increase in warmer water, even as the concentration of oxygen declines. Therefore, standards expressed in terms of percent saturation have a higher risk of being under-protective for aquatic organisms. Additionally, the majority of studies reported in the literature on dissolved oxygen thresholds for New Zealand species investigated changes in oxygen concentration, rather than percent saturation.
3. Periphyton cover and biomass data from the six monitoring sites were analysed to investigate potential causal relationships between periphyton and photosynthetic production, respiration, and DO levels within sites. This analysis also incorporated flow and temperature as additional drivers of DO.

NOF guideline values are currently not applied everywhere at all times. Instead they are to be applied downstream of point source discharges, and only during the summer period (defined as 1 November to 30th April). However, given the consistency of the current NOF limits with the proposed protection levels for fish in Franklin (2014b), it would be justifiable to adopt the NOF guidelines and apply them to all locations year-round. This would also provide consistency with the national standard.

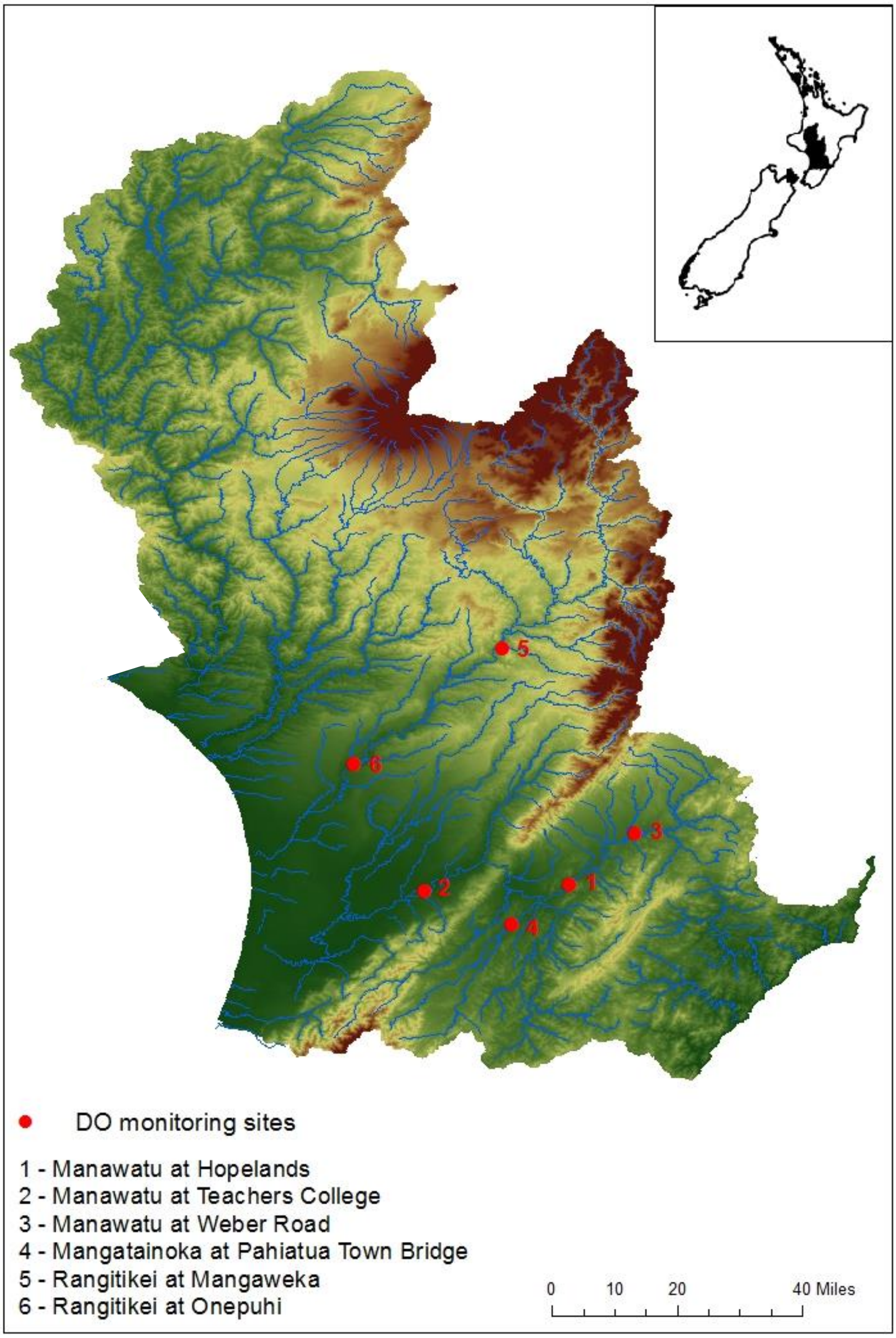

Figure 1-1: Horizons Regional Council dissolved oxygen monitoring sites. Continuous (every 15 minutes) dissolved oxygen measurements were recorded for these six sites between 2011-2017.

2 Methodology

2.1 Literature review

Published journal papers from New Zealand and overseas, along with past NIWA research and reports, were summarised regarding available information on DO requirements of New Zealand native fish species, trout, and aquatic invertebrates.

2.2 Analysis of continuous DO data

Continuous dissolved oxygen data were collected every 15 minutes for six years, from 2011-2017, at six Horizons Regional Council monitoring sites (Figure 1-1). Time series of percent saturation and concentration of dissolved oxygen were plotted for each site, along with calculated summary statistics including daily mean DO, daily minimum DO, and rolling seven-day average mean and minimum DO.

The time series data were also used to calculate the total time and percentage of days that dissolved oxygen levels dropped below relevant management targets that are specified in the One Plan, as well as those set out in the NOF. The current One Plan targets specify a water quality target (measured as minimum percentage saturation) for dissolved oxygen for relevant management zones (HRC 2014; Table 2-1). The recommended NOF attributes differ from the One Plan targets, and specify an attribute state that is measured by two criteria: a 7-day mean minimum (where the mean value is calculated from 7 consecutive daily minimum values), and a 1-day minimum (i.e. the lowest daily minimum) (MfE 2014; Table 2-2). Both the 7-day and 1-day NOF attributes apply only during the summer period of 1 November to 30th April.

Duration curves were plotted to characterise the influence of seasonality on low DO levels.

Table 2-1: One Plan management zones for each monitoring site and associated One Plan targets for dissolved oxygen (% saturation).

Site	Management sub-zone at site	Management sub-zone from monitoring site to bottom of sub-zone	One Plan DO target (% sat.)
Manawatu at Hopelands	Mana_5a - Tamaki-Hopelands	Mana_5a - Tamaki-Hopelands	80
Manawatu at Teachers College	Mana_11a - Lower Manawatu	Mana_10a - Middle Manawatu	70
Manawatu at Weber Road	Mana_1a - Upper Manawatu	Mana_1a - Upper Manawatu	80
Mangatainoka at Pahiatua Town Bridge	Mana_8c - Lower Mangatainoka	NA (middle of sub-zone)	80
Rangitikei at Mangaweka	Rang_3a - Lower Rangtikei	Rang_2b - Pukeokahu - Mangaweka	80
Rangitikei at Onepuhi	Rang_4a - Coastal Rangitikei	Rang_3a - Lower Rangitikei	70 and 80

Table 2-2: NOF dissolved oxygen guidelines for ecosystem health from the NPS for Freshwater (MfE 2014).

Attribute State	7-day mean minimum[1] DO (mg L^{-1})	1-day minimum[2] DO (mg L^{-1})	Attribute State
A	$\geq$ 8.0	$\geq$ 7.5	No stress caused by low DO on any aquatic organisms that are present at matched reference (near pristine) sites.
B	$\geq$ 7.0 and < 8.0	$\geq$ 5.0 and < 7.5	Occasional minor stress on sensitive organisms caused by short periods (a few hours each day) of lower DO. Risk of reduced abundance of sensitive fish and macroinvertebrate species.
C	$\geq$ 5.0 and < 7.0	$\geq$ 4.0 and < 5.0	Moderate stress on a number of aquatic organisms caused by DO 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 local integrity.

1. The mean value of 7 consecutive daily minimum values (Summer Period: 1 November to 30th April).
2. The lowest daily minimum across the whole summer period (Summer Period: 1 November to 30th April).

2.3 Evaluation of possible causal relationships between periphyton and DO

Monthly periphyton percent cover and biomass (measured as chlorophyll-a) data from the same six monitoring sites were used to investigate the influence of periphyton on dissolved oxygen levels. Linear mixed effects models were used to determine whether periphyton cover, periphyton type, or biomass were significant drivers of dissolved oxygen. Periphyton, mean daily flow (m^3 s^{-1}), and maximum daily water temperature (C) were included in the models as fixed effects, and site and season were included as crossed random effects. Fixed effects are variables which are constant across individuals (or sites or other unit of interest), whereas random effects represent underlying variability in the population (Kreft and De Leeuw 1998, Gelman 2005). The same model formulation was also used to test the relationships between periphyton cover or biomass and gross primary production and ecosystem respiration, the processes which produce and consume oxygen, respectively, in streams. Models were compared using the Akaike Information Criterion (AIC). A lower AIC score indicates better model fit, or explanatory power (Burnham and Anderson 2002).

3 Dissolved oxygen requirements of aquatic organisms

3.1 Native fish

Information on the dissolved oxygen requirements of New Zealand's native fish species is limited to a relatively small number of laboratory experiments. Moreover, the few studies which have been done used different methods to assess impacts of low dissolved oxygen, making direct comparison of results difficult (Franklin 2014a). For example, some studies measure the time it takes for 50% mortality of organisms at a given constant dissolved oxygen concentration, whereas others progressively decrease dissolved oxygen concentrations and report the concentration at which 50% mortality occurs (Davies-Colley et al. 2013). Most studies focus on lethal effects, although some have examined sub-lethal impacts on behaviour and growth (Davies-Colley et al. 2013).

Dean and Richardson (1999) investigated the acute tolerances of seven New Zealand native fish species and rainbow trout to low dissolved oxygen concentrations by holding them for 48 hours in the laboratory at constant dissolved oxygen levels of 1, 3, and 5 mg L^{-1} at 15°C. The species most sensitive to low dissolved oxygen were juvenile and adult common smelt (*Retropinna retropinna*), with 50% mortality at 1 mg L^{-1} after 0.6-0.7 hrs, juvenile common bullies (*Gobiomorphus cotidianus*), with 50% mortality at 1 mg L^{-1} after 0.6 hrs, and juvenile rainbow trout (*Oncorhynchus mykiss*), with 50% mortality at 1 mg L^{-1} after 1 hr. All sensitive species had 100% mortality within four hours at 1 mg L^{-1} dissolved oxygen. Juvenile banded kokopu (*Galaxias fasciatus*) were slightly less sensitive, with 50% mortality occurring in less than 8 hours at 1 mg L^{-1} and 100% mortality occurring by twelve hours. Juvenile torrentfish (*Cheimarrichthys fosteri*), on the other hand, survived 24 hrs but had 100% mortality by 48 hrs. Juvenile inanga (*Galaxias maculatus*) were more sensitive than adults, with 61% mortality after 48 hrs at 1 mg L^{-1} compared to 38% mortality, respectively. Only juvenile trout showed a response at the 3 mg L^{-1} of dissolved oxygen level; fish moved to the surface to breathe, an indication of stress, although mortality was only 5% after 48 hrs. Shortfin (*Anguilla australis*) and longfin (*Anguilla dieffenbachii*) eels had no response under any of the conditions tested.

Landman et al. (2005), on the other hand, varied the dissolved oxygen concentration to determine at what level 50% mortality occurred over 48 hrs at 15°C. The aquariums used had clear plastic lids to prevent aquatic surface respiration (ASR), a behaviour used by some fish species, such as inanga, banded kokopu, and smelt, to overcome low oxygen levels (Dean and Richardson 1999; Urbina et al. 2011). In the Landman et al. (2005) study, juvenile inanga were the most sensitive species, with 50% mortality occurring after 48 hrs at a dissolved oxygen concentration of around 2.6 mg L^{-1}. Common smelt and juvenile trout showed 50% mortality after 48 hrs at dissolved oxygen concentrations of 1.8 mg L^{-1} and 1.6 mg L^{-1}, respectively. Shortfin eels and common bullies were the most tolerant species; both had lethal thresholds of less than 1 mg L^{-1}. Shrimp (50% mortality over 48 hrs at 0.82 mg L^{-1} DO) and freshwater crayfish (50% mortality over 48 hrs at 0.77 mg L^{-1} DO) were also found to be tolerant to low dissolved oxygen in this experiment. The outcomes of these two studies highlight how differences in experimental methodology can impact results, as well as the need to interpret results carefully for management applications. In the Landman et al. (2005) study, adult inanga had 50% mortality after 48 hrs at 2.6 mg L^{-1} whereas in the Dean and Richardson (1999) study, inanga showed only 38% mortality after 48 hours at a lower dissolved oxygen concentration of 1 mg L^{-1}. The difference is likely due to the restriction on ASR in the Landman et al. (2005) study. The smaller difference in mortality results for smelt (50% mortality in 0.7 hrs at 1 mg L^{-1} (Dean and Richardson 1999) compared to 50% mortality in 48 hrs at 1.8 mg L^{-1} (Landman et al. 2005) suggests that ASR is less important as an avoidance strategy for this species.

It is also important to note that both of these studies used fish which were acclimated to a constant temperature of 15°C, a temperature which is significantly lower than summer water temperatures in many lowland streams throughout New Zealand (Wilcock et al. 1998). Because the metabolism, and therefore oxygen demand, of fish varies with temperature, oxygen tolerance thresholds increase with temperature. For example, Downing and Merkins (1957) reported that lethal dissolved oxygen concentrations for several fish species increased by a mean of 2.6 mg L^{-1} over a temperature range of 10-20°C, whereas stream water temperatures regularly reach 20-25°C in summer in some regions (Michael Patterson, HRC, personal communication). Thus, oxygen thresholds based on the data from the Landman et al. (2005) and Dean and Richardson (1999) studies are likely to be under-protective at higher water temperatures.

Low dissolved oxygen concentrations can also have sub-lethal effects on some New Zealand fish species. Sub-lethal effects include behavioural and physiological responses. Richardson et al. (2001) investigated avoidance behaviour of smelt, inanga, and common bully under low dissolved oxygen conditions. Fish were acclimated at 20°C and placed in a fluvarium in which one half was held at 2 mg L^{-1} DO and the other at 8.5 mg L^{-1}, with free access between the two sides. The behaviour of fish was then monitored over a 15 minute trial period. Smelt avoided the low dissolved oxygen water, inanga showed no significant response, and adult bullies significantly preferred the low dissolved oxygen side. The authors did not suggest an explanation for the low oxygen preference of bullies, although this species has been shown to have a high tolerance to low dissolved oxygen (Dean and Richardson 1999).

Bannon and Ling (2003) tested the effects of low dissolved oxygen and temperature on sustained swimming capability of both inanga and rainbow trout parr. They conducted swimming trials at 10°C, 15°C, and 20°C under both normoxic (>96% saturation of DO; approximately 11.3, 10.1, and 9.1 mg L^{-1}, respectively) and mildly hypoxic (75% saturation of DO; approximately 8.5, 7.6, and 6.8 mg L^{-1}, respectively) conditions. Fish were acclimated to the trial temperatures prior to testing. The sustained swimming capability of inanga juveniles was temperature dependent; maximum swimming speed occurred between 15°C and 20°C under normoxic conditions, whereas under mild hypoxia no effect was observed at 10°C, but swimming capability was significantly reduced at 15°C and 20°C. Trout parr showed maximum sustained swimming speeds at 15°C under normoxic conditions, but decreased swimming speeds at lower and higher temperatures. In the mild hypoxia trial, no effect on swimming speed was observed at 10°C or 15°C, but at 20°C swimming capability was significantly reduced. These results indicate that the effect of dissolved oxygen on sustained swimming speed varies with water temperature, although it remains unclear whether this is due to increased metabolic demands for oxygen at higher temperatures or because fish are responding to dissolved oxygen concentrations, which decrease with increasing temperature even though percentage saturation remains constant (Franklin 2014a).

Urbina et al. (2011) also investigated behavioural and physiological responses of inanga under progressive hypoxia. They reported significant changes in swimming activity when dissolved oxygen concentration declined below 7.3 mg L^{-1}. They also found that inanga spent more time performing ASR as dissolved oxygen concentrations declined from normoxia (9.7 mg L^{-1}), but the increase was only significant when dissolved oxygen reached 1.9 mg L^{-1}. Avoidance behaviour, defined as jumping out of the water, was observed in 70% of fish at 1.9 mg L^{-1} and 94% of fish at 1.5 mg L^{-1}, the lowest dissolved oxygen concentration tested.

In general, the ability of fish to survive in low oxygen environments depends on the duration and timing of exposure, the level and constancy of dissolved oxygen, the species, life stage and health status of the fish, as well as on other environmental conditions, e.g., water temperature. Most fish species are capable of adapting their behaviour to compensate for short-term exposure to depressed dissolved oxygen levels (Kramer 1987). However, as the severity and duration of low dissolved oxygen conditions increase, the costs in terms of energy expenditure and vulnerability to predation also increase (Franklin 2014a). Such chronic sub-lethal effects are also likely to contribute to overall changes in community composition, due to varying tolerance levels between species.

3.2 Trout

Much more data is available on the effects of low dissolved oxygen on the salmonid species (trout and salmon) present in New Zealand compared to New Zealand's native fish, including several detailed reviews (Doudoroff and Shumway 1970, Davis 1975, Alabaster and Lloyd 1982, USEPA 1986). Both acute (lethal) and chronic (sub-lethal) effects of low dissolved oxygen have been studied on all life stages (eggs, larval, juvenile, and adult) of salmonids. Low dissolved oxygen has been show to delay egg development (Coble 1961, Côte et al. 2012, Ingendahl 2001, Malcolm et al. 2011, Shumway et al. 1964, Silver et al. 1963), reduce growth and alter behaviour of larvae and juvenile life stages (Jones 1952, Remen et al. 2012, Roussel 2007, Whitworth 1968) and influence the growth, behaviour, and habitat use of adults (Bushnell et al. 1984, Plumb & Blanchfield 2011, Poulsen et al. 2011). Dean and Richardson (1999) found that the most sensitive of New Zealand's native fish species display similar acute tolerances to trout, suggesting that it is reasonable to predict similar effects of low dissolved oxygen on New Zealand native fish to those that have been observed for salmonids.

Low dissolved oxygen has been associated with increased median time to hatching and decreased size at hatching for steelhead trout (Silver et al. 1963) and Chinook salmon (Shumway et al. 1964). Atlantic salmon eggs have also been observed to have delayed hatching and reduced survival under hypoxic conditions (4.5 mg L^{-1}). Brown trout in the Rhine were found to hatch only when dissolved oxygen concentrations were greater than 7 mg L^{-1} (Ingendahl 2001). Embryonic hypoxia (3 mg L^{-1}) was also reported to affect emergence and survival of brown trout alevin (Roussel 2007). Alevins that were subjected to hypoxia during development had delayed emergence, reduced swimming activity, and greater predation mortality than those that developed under normoxic conditions (10.3 mg L^{-1}), suggesting that early exposure to hypoxia can have carry-over effects in later stages of the life cycle. Reduced feeding and growth has also been observed in Atlantic salmon exposed to cyclical hypoxia of 40-70% saturation (Remen et al. 2012).

Behavioural changes have also been observed in salmonid species under low dissolved oxygen conditions. Poulsen et al. (2011) conducted a choice chamber test to investigate rainbow trout response to progressive hypoxia. Reduced swimming speed was observed at 60% saturation (approximately 5.7 mg L^{-1}) compared to normoxic conditions (approximately 9.5 mg L^{-1}). Avoidance behaviour, namely reduced average residence time per trip, was observed once 50% saturation (approximately 4.7 mg L^{-1}) was reached, and the number of trips to hypoxia declined when dissolved oxygen was reduced to 30% saturation (approximately 2.8 mg L^{-1}). These results suggest that behavioural responses to low dissolved oxygen may be hierarchical, with a wider range of responses occurring as hypoxia increases.

3.3 Exotic fish

Cyprinid species, several of which have been introduced to New Zealand, typically have a higher tolerance for low dissolved oxygen concentrations than salmonid species (Doudoroff and Shumway 1970, USEPA 1986), with acute thresholds of <1 mg L^{-1}. Exotic cyprinids in New Zealand include goldfish (*Carassius auratus*), carp (*Cyprinus carpio*), tench (*Tinca tinca*), perch (*Perca fluviatilis*), and mosquito fish (*Gambusia affinis*). Carp have been reported to have 50% mortality only after 24 hrs under 0.4 mg L^{-1} at 10°C and 0.8 mg L^{-1} at 20°C, while tench did not show 50% mortality until 0.2 mg L^{-1} at 10°C (Downing and Merkens 1957). McNeil and Closs (2007) found that both goldfish and carp were highly tolerant of hypoxia under laboratory conditions and used ASR to survive in extremely hypoxic (<1 mg L^{-1}) habitats for sustained periods of time.

3.4 Aquatic invertebrates

Macroinvertebrate responses to low dissolved oxygen are extremely variable (Davis 1975, USEPA 1986). In general, lethal thresholds for macroinvertebrates have been found to range from <1 mg L^{-1} to >8 mg L^{-1} (Davis 1975, USEPA 1986). Therefore, some macroinvertebrate species are more sensitive to low dissolved oxygen than fish. Oxygen tolerance of macroinvertebrates has been observed to be correlated with habitat: individuals normally found in well-oxygenated habitats, such as riffles, are less tolerant of low dissolved oxygen than those that only encounter it periodically (Davis 1975). Correspondingly, mayflies, which typically inhabit faster flowing streams, have been identified as the most sensitive group of aquatic invertebrates (Gaufin et al. 1974).

Although the New Zealand macroinvertebrate community index (MCI) used to determine stream health is largely based on the differing sensitivities of macroinvertebrate species to low dissolved oxygen conditions associated with organic pollution (Chapman 1996, Stark and Maxted 2007), there have been few studies on the dissolved oxygen tolerances of New Zealand macroinvertebrates. Dean and Richardson (1999) tested freshwater shrimp (*Paratya curvirostris*) and found mean mortality of 26.7% after 48 hrs at 1 mg L^{-1}, with the first deaths occurring after 2 hrs. Landman et al. (2005) reported 50% mortality after 48 hrs at 0.82 mg L^{-1} for *Paratya* and 0.77 mg L^{-1} for freshwater crayfish (*Paranephrops planifrons*).

An Australian study using tropical stream macroinvertebrates reported that while most taxa tolerated all but very low dissolved oxygen levels (<10% saturation), sub-lethal effects occurred at intermediate levels, including reduced emergence, particularly of chironomid midges and mayflies (Connolly et al. 2004). A drift response was also observed when oxygen concentrations approached lethal levels (<10% saturation), indicating that sub-lethal effects are likely to occur before organisms leave a low oxygen environment. Because higher water temperatures would be expected to exacerbate hypoxia effects due to increased metabolic rates, the authors suggest that their results can be generalized to predict responses of temperate biota as well. Moreover, studies conducted in temperate regions have also reported sub-lethal effects such as reduced feeding and growth for mayflies in low dissolved oxygen conditions (Winter et al. 1996, Lowell and Culp 1999).

The effects of low levels of dissolved oxygen on aquatic invertebrates have also been studied in the context of anthropogenic flow reductions. Lower water levels result in increased temperatures and, therefore, typically also lower dissolved oxygen (although increased surface to volume ratio and increased turbulence can sometimes mean this isn’t the case). Two European studies, one conducted in a large river which has recently experienced reduced groundwater inputs (Graeber et al. 2013) and the other in small lowland streams in which flow was experimentally reduced (Pardo and Garcia 2016), both found that reduced flow and dissolved oxygen were associated with community compositional shifts from rheophilic to limnophilic taxa and decreased abundance of filter feeders.

4 Analysis of Horizons Regional Council DO data

Dissolved oxygen percent saturation levels ranged from 21% to 217% across all six monitoring sites over the six-year period. Dissolved oxygen percent saturation levels were higher and displayed greater diel variability during the summers, and lower and less variable over the winter (Figure 4-1).

Dissolved oxygen concentration ranged from 2.5 to 22.5 mg L^{-1} across all sites over the six years. Dissolved oxygen concentrations were highest in winter, lowest in summer, and most variable during spring and autumn (Figure 4-1).

4.1 One Plan target limits

Daily minimum dissolved oxygen values dropped below the One Plan target limits at least once at all sites during the six years (Table 4-1). Manawatu at Hopelands was below the 80% saturation target for its management zone the most out of the six sites, for a total of 164.6 days between 2011 and 2017. The percentage of days on which DO percent saturation dropped below the limit was 25.5%. This site also had the greatest number of consecutive days on which DO percent saturation dropped below the limit (59 days). Mangatainoka at Pahiatua Town Bridge was below the limit on 18.5% of days, with 110.3 total days below the threshold over the six years. There were also four periods of more than 30 consecutive days on which DO saturation dropped below the limit. Rangitikei at Onepuhi, which spans two management zones with different targets, was below the upper limit (80%) for 60.5 days, or 6.8% of days, but only went below the lower 70% saturation limit on 3.8% of days, or 22.9 days. There were two long periods of consecutive days on which DO percent saturation dropped below the 80% limit (41 and 47 days). Manawatu at Weber Road was below the 80% saturation limit 7.7% of days, or 19.5 days in total. The longest period of consecutive days on which DO percent saturation dropped below the limit at this site was 18 days. Rangitikei at Mangaweka was rarely below the 80% saturation limit, only 3.1 days in total, or 0.7%, out of the six years. Manawatu at Teachers College also dropped below its limit, 70% saturation, 0.6% of days, or less than 2 days in total. These two sites only had short periods of less than one week of consecutive days on which DO percent saturation levels fell below the One Plan targets.

As expected, the majority of occasions when dissolved oxygen percent saturation levels dropped below the limit were in summer or autumn (Figure 4-2, Figure 4-3), when flows tend to be lower and water temperatures higher. Rangitikei at Onepuhi also appeared to have dissolved oxygen saturation drop below the One Plan targets in winter, however, this is possibly due to errors in the dataset. The dissolved oxygen time series plot shows two occasions where DO levels dropped sharply with no associated decline or low values in the surrounding days, which is unusual and may indicate a logger malfunction where erroneous very low values of DO were recorded.

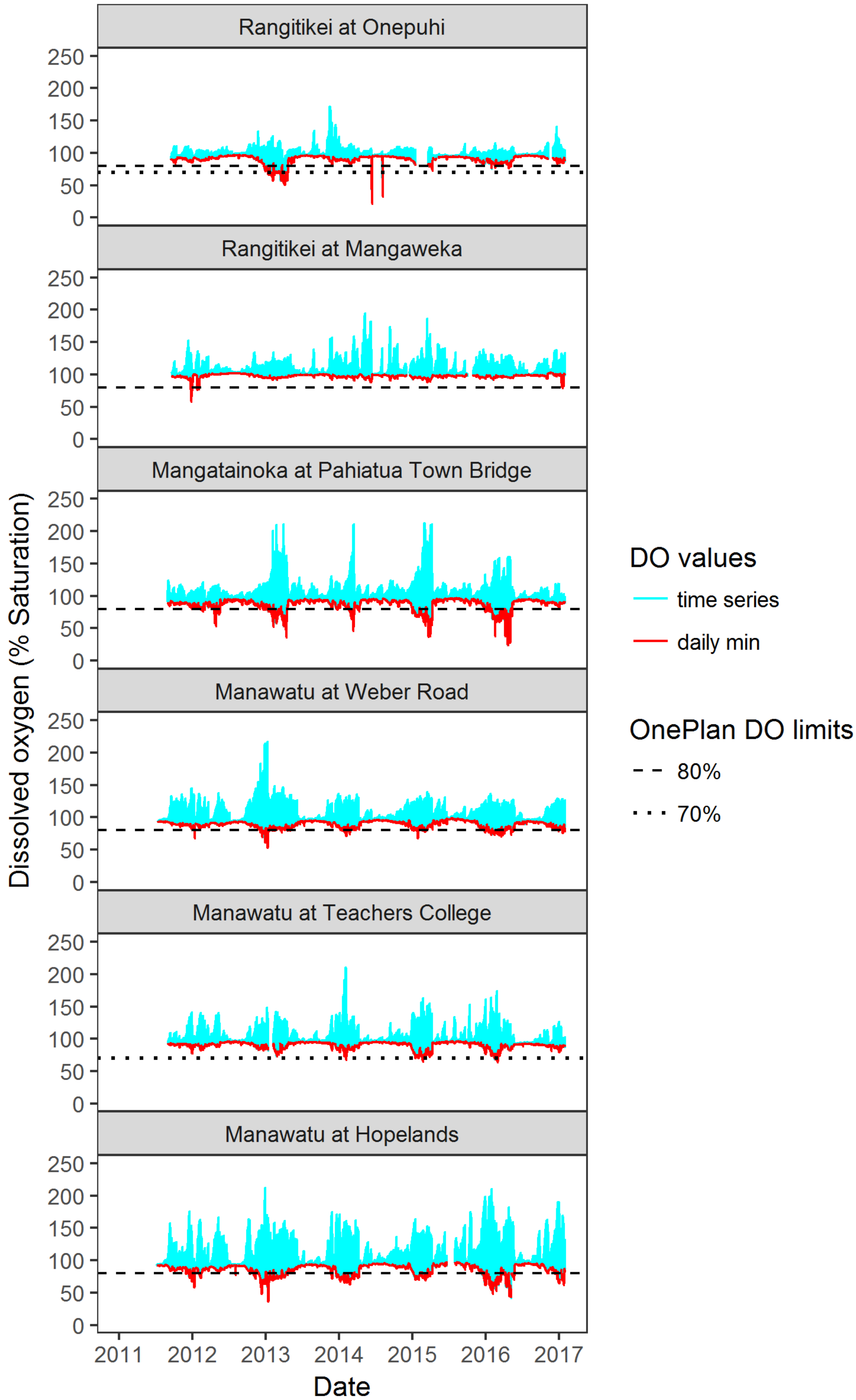

Figure 4-1: Dissolved oxygen time series of dissolved oxygen percent saturation for each site over the six-year monitoring period. The corresponding One Plan minimum dissolved oxygen targets (% saturation) for each site are indicated by the horizontal lines on each plot. Larger individual plots for each site are included in Appendix A.

Table 4-1: Total time, percentage of days, and number of consecutive days below One Plan minimum dissolved oxygen targets (% saturation). The percent saturation limit for each site's management zone is listed. Rangitikei at Onepuhi spans two management zones with different targets, thus two limits are listed.

Site	Limit (%)	Total time below limit (days)	Percentage of time below limit	Percentage of days daily minimum below limit	Number of consecutive days below limit
Manawatu at Hopelands	80	164.6	8.1	25.5	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 17, 21, 29, 33, 37, 39, 59
Manawatu at Teachers College	70	1.2	0.1	0.6	2, 7
Manawatu at Weber Road	80	19.5	1.0	7.7	2, 3, 4, 5, 6, 7, 9, 10, 13, 18
Mangatainoka at Pahiatua Town Bridge	80	110.3	5.6	18.5	2, 3, 5, 6, 9, 15, 23, 27, 30, 31, 32, 49
Rangitikei at Mangaweka	80	3.1	0.2	0.71	2, 3, 4
Rangitikei at Onepuhi	80	60.5	3.1	6.8	2, 3, 5, 28, 41, 47
	70	22.9	1.2	3.8	2, 3, 4, 5, 9, 12, 15, 16

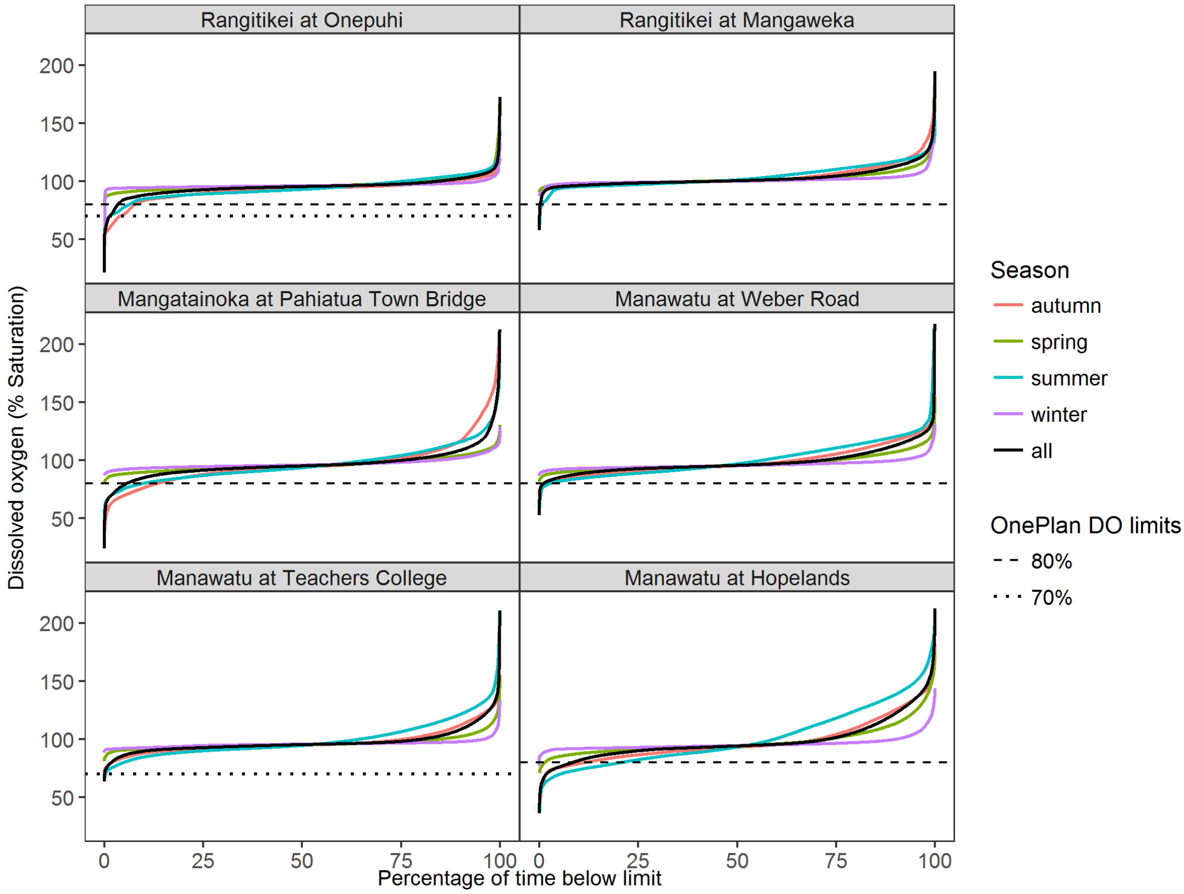

Figure 4-2: Percentage of time dissolved oxygen saturation was below the One Plan target. The percentage of time is indicated by the point where the duration curve crosses below the minimum limit line. Seasons are indicated by colour.

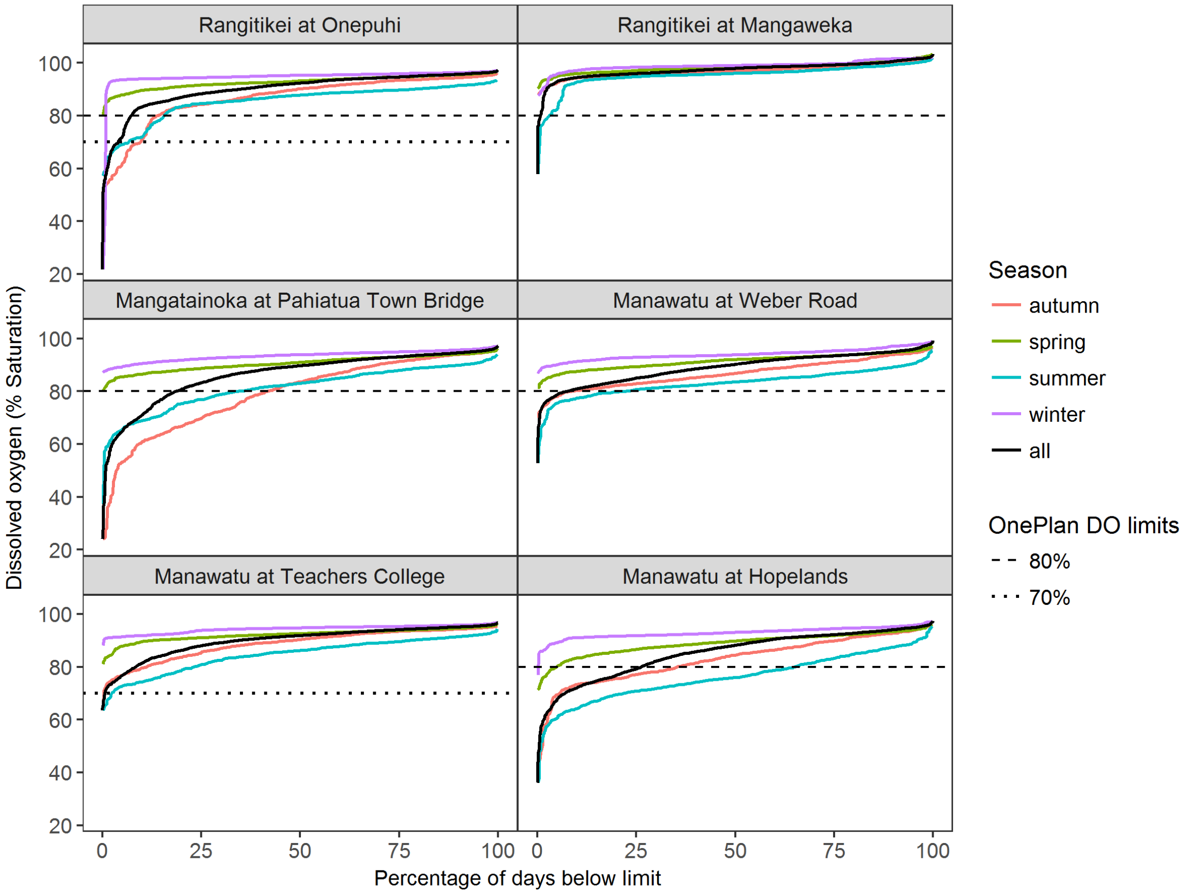

Figure 4-3: Percentage of days dissolved oxygen saturation was below the One Plan target. The percentage of days is indicated by the point where the duration curve crosses below the minimum limit line. Seasons are indicated by colour.

4.2 NOF guideline limits

Although current proposed implementation of the NOF guidelines is to determine the overall attribute site for a given site using only dissolved oxygen levels from during the summer period (defined as 1st November to 30th April), a proportion of time approach was also taken for comparison with the One Plan target analysis. Overall, two sites, Manawatu at Teachers College and Rangitikei at Mangaweka, were in the B band for daily minimum dissolved oxygen concentration, but in the C band for 7-day mean daily minimum dissolved oxygen concentrations. The B band indicates occasional minor stress on aquatic organisms, whereas the C band represents moderate stress on aquatic organisms due to low DO. Two sites, Manawatu at Weber Road and Rangitikei at Onepuhi, were in the C band for both daily minimum and &-day mean daily minimum DO. The final two sites, Manawatu at Hopelands and Mangatainoka at Pahiatua Town Bridge, were in the D band for both dissolved oxygen attributes. The D band is below the national bottom line, indicating significant and persistent stress on aquatic organisms.

However, under the proportion of time approach using the full data record, daily minimum dissolved oxygen concentrations were in the NOF A band, which means there is no stress caused by low dissolved oxygen levels on aquatic organisms, over 75% of days at all six monitoring sites over the six years (Table 4-2). The 7-day mean minimum dissolved oxygen concentration was in the A band 67.9% of days at Manawatu at Hopelands, but the other five sites were also in the A band over 75% of days for 7-day mean daily minimum dissolved oxygen concentration. Correspondingly, all sites were in the B band less than 25% of all days for both NOF attributes, daily minimum and 7-day mean daily minimum, over the six-year monitoring period. The B band represents occasional minor stress on aquatic organisms caused by short periods of low dissolved oxygen. Manawatu at Hopelands was in the C band for 7-day mean daily minimum DO concentration, which represents moderate stress on aquatic organisms due to low dissolved oxygen levels, 13.6% of days, while Mangatainoka at Pahiatua Town Bridge had 7-day mean daily minimum DO concentration in the C band 11.7% of days. All other sites were in the C band less than 6% of days for either NOF dissolved oxygen metric.

The C/D band limit represents the national bottom line, below which significant stress on aquatic organisms is expected. The national bottom line is <4 mg L^{-1} for daily minimum DO and <5 mg L^{-1} for 7-day mean daily minimum DO. Mangatainoka at Pahiatua Town Bridge had dissolved oxygen concentrations less than the national bottom line for 12 days, or 0.6% of total days, for both NOF dissolved oxygen metrics. Three sites, Manawatu at Teachers College, Manawatu at Weber Road, and Rangitikei at Mangaweka, never dropped below the national bottom line during the six-year monitoring period. Manawatu at Hopelands and Rangitikei at Onepuhi were below the national bottom line less than 0.2% of the time, and for the latter site this appears to be a possible error in the data, as concentrations dropped sharply on two occasions with no pattern of low or decreasing oxygen during the surrounding days (Figure 4-4).

The number of consecutive days that sites had dissolved oxygen concentrations below the national bottom line was also low. Mangatainoka at Pahiatua Town Bridge was below for only three and six days consecutive days out of the six years for the daily minimum DO concentration and 7-day mean daily minimum DO concentration, respectively, and Manawatu at Hopelands was only below for two and three consecutive days for the two metrics.

Similarly to the saturation results, the occasions on which dissolved oxygen concentrations did fall below the NOF guidelines were primarily in autumn and summer (Figure 4-5). All sites except Rangitikei at Mangaweka had daily minimum and 7-day mean daily minimum dissolved oxygen concentrations were in the B band 25-50% of the time in summer and autumn. Spring and winter dissolved oxygen concentration levels mostly remained in the A band in all sites, with the notable exception of daily minimum dissolved oxygen concentration at Rangitikei at Onepuhi. There does not appear to be any missing data or zero data in the dataset, thus it is likely that this anomaly is related to the possible outliers mentioned above, perhaps due to a logger malfunction which has resulted in a period of incorrect low data (Figure 4-5).

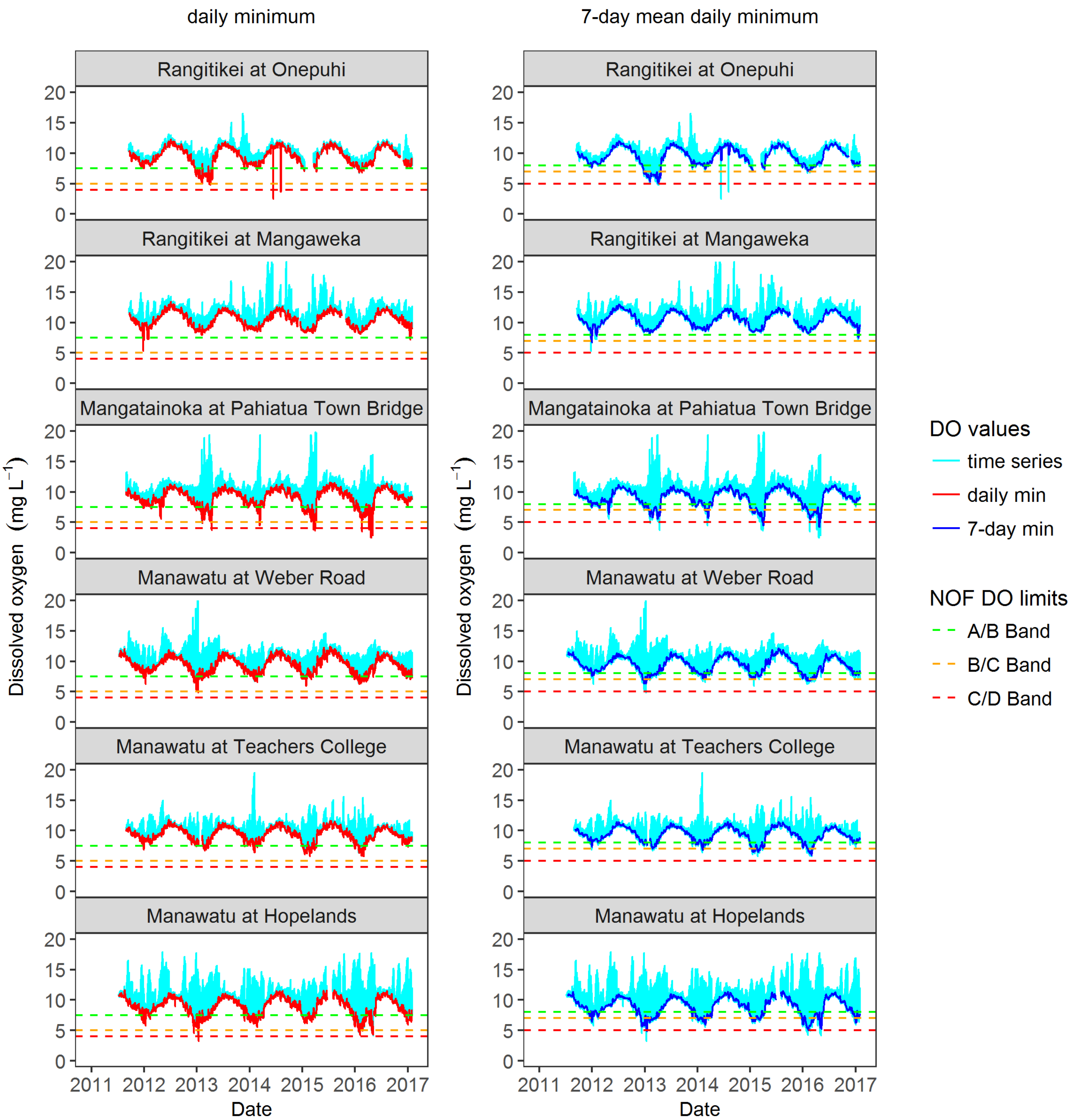

Figure 4-4: Dissolved oxygen time series for dissolved oxygen and concentration (mg L^{-1}) for each site over the monitoring period. The NOF guidelines for each attribute (daily minimum and 7-day mean daily minimum) are indicated by the horizontal lines on each plot. Larger individual plots for each site are included in Appendix A.

Table 4-2: Total days and percentage of days dissolved oxygen concentrations fall within each NOF band for the daily minimum and 7-day mean daily minimum criteria. The number of consecutive days dissolved oxygen concentration went below C, the national bottom line, is also given. The lowest attribute values across the extended summer period (1 November to 30 April) are also listed along with the associated overall NOF band for the site.

Site	NOF attribute	Total days in NOF band				Percent of days in NOF band				Number of consecutive days	Overall NOF band
		A	B	C	D	A	B	C	D (below bottom line)	D (below bottom line)	
Manawatu at Hopelands	daily min	1538	436	10	2	77.4	22.0	0.5	0.1	2	D (3.3)
	7-day min	1358	366	272	3	67.9	18.3	13.6	0.2	3	D (4.9)
Manawatu at Teachers College	daily min	1778	172	0	0	91.2	8.8	0.0	0.0		B (5.8)
	7-day min	1668	217	74	0	85.1	11.1	3.8	0.0		C (6.0)
Manawatu at Weber Road	daily min	1862	170	1	0	91.6	8.3	0.1	0.0		C (4.9)
	7-day min	1641	346	40	0	81.0	17.0	2.0	0.0		C (6.3)
Mangatainoka at Pahiatua Town Bridge	daily min	1649	315	6	12	83.2	15.9	0.3	0.6	3, 4	D (2.5)
	7-day min	1495	239	232	12	75.6	12.1	11.7	0.6	6	D (4.3)
Rangitikei at Mangaweka	daily min	1904	13	0	0	99.3	0.7	0.0	0.0		B (5.4)
	7-day min	1909	16	3	0	99.0	0.8	0.2	0.0		C (6.8)
Rangitikei at Onepuhi	daily min	1683	159	4	2	91.1	8.7	0.1	0.1		C (4.8)*
	7-day min	1583	189	113	0	84.0	10.0	6.0	0.00		C (5.1)

*The daily minimum dissolved oxygen concentration dropped below the national bottom line outside of the summer period designated in the NOF guidelines, therefore this site remains in the C band.

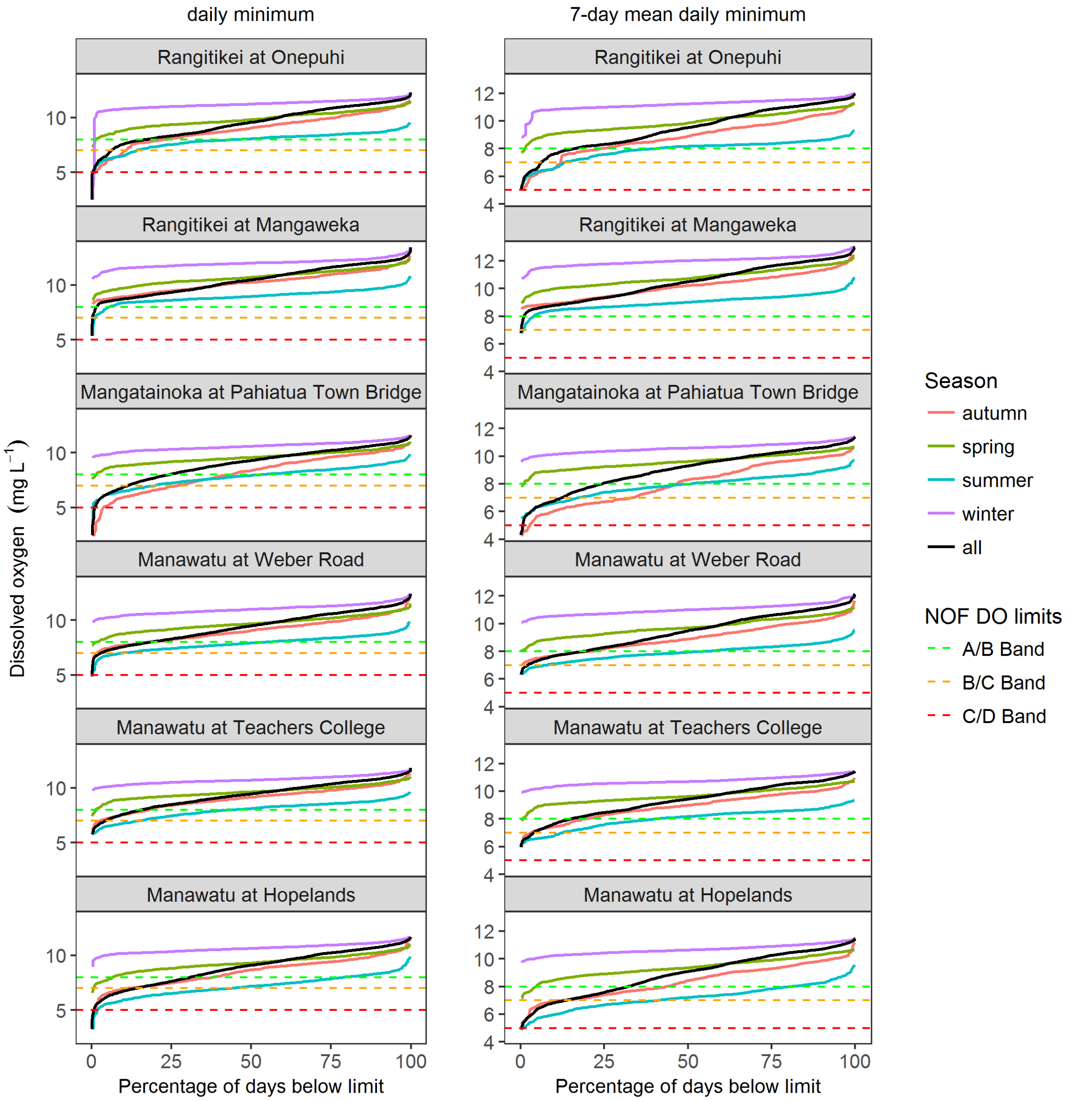

Figure 4-5: Percentage of days the dissolved oxygen concentration was below the NOF guidelines. The percentage of days is indicated by the point where the duration curve crosses below the limit line. Seasons are indicated by colours.

4.3 Potential drivers of dissolved oxygen

4.3.1 Flow

Flow was typically low and stable during the summer period in each site, with the majority of high flow events occurring in winter and spring. However, there was also inter-annual variability within sites; fewer high flow events occurred in 2012 and 2016 compared to other years (Figure 4-6).

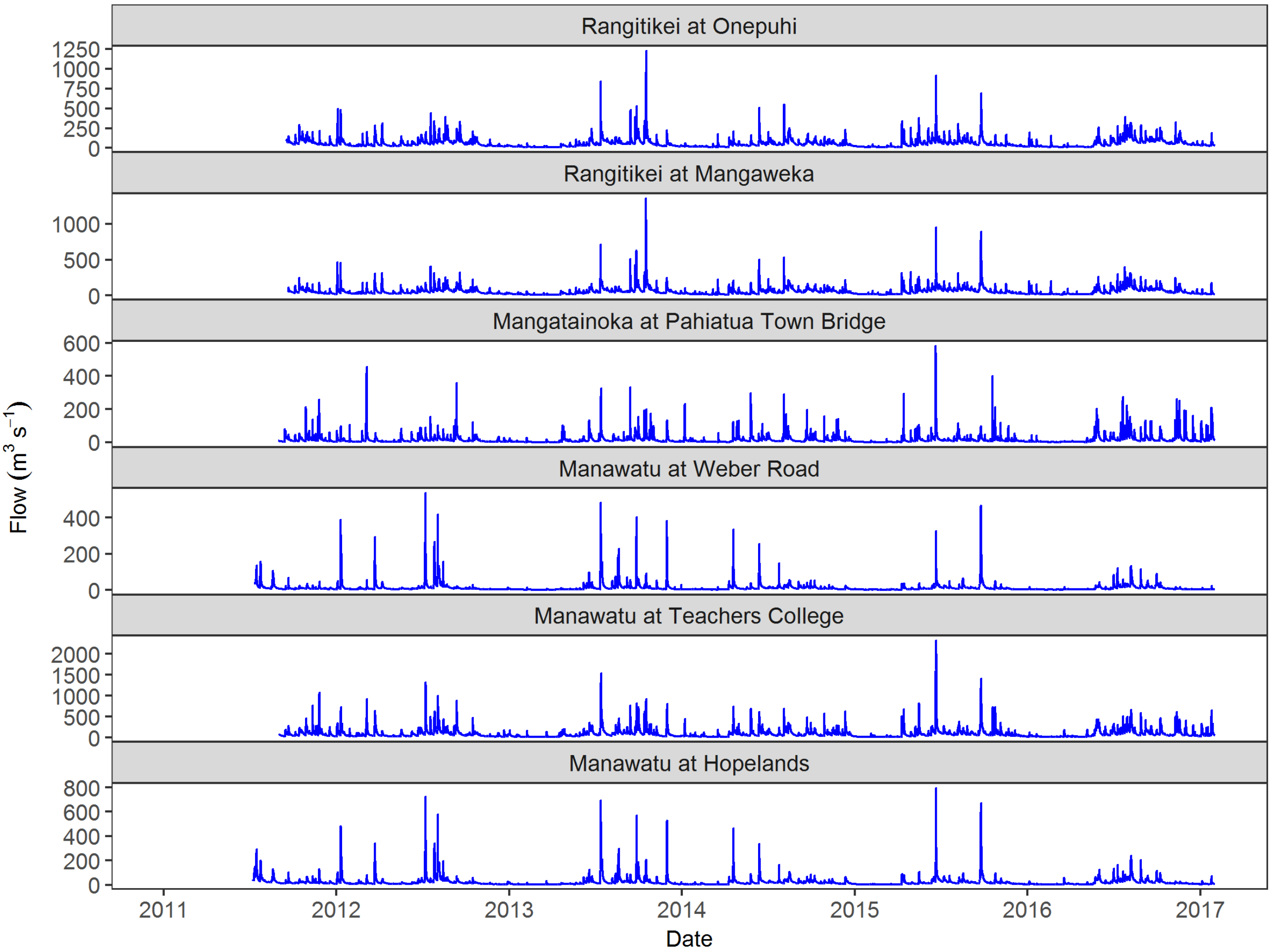

Figure 4-6: Flow time series for each of the six HRC monitoring sites between 2011 and 2017. Note the different y-axis scale for each site.

Dissolved oxygen percent saturation was not strongly correlated with flow at any of the monitoring sites (Figure 4-7), although at several sites (Rangitikei at Onepuhi, Manawatu at Teachers college, Manawatu at Hopelands) the highest daily mean dissolved oxygen percent saturation occurred at intermediate flows, possibly due to high soluble inorganic nitrogen (SIN) associated with run-off in high flow conditions. Conversely, Mangatainoka at Pahiatua Town Bridge had highest percent saturation at low flows. This could be due to increased temperatures which are also likely to occur at low flows, particularly in shallow rivers. On the other hand, dissolved oxygen concentrations were also higher at this site at low flows, which would not be the case if water temperatures were very warm. However, this river is strongly influenced by groundwater and SIN remains high even during low flows, resulting in high periphyton growth (Michael Patterson, HRC, personal communication). Interestingly, another site, Rangitikei at Onepuhi, had its lowest values of daily mean percent saturation (and concentration) of DO at low flows. SIN drops below detection limit in low flows at this site, resulting in less respiration by periphyton and thus less fluctuation in DO values (HRC, personal communication). All sites had greater variability in DO percent saturation values at low-mid flows and less variability at high flows. This effect could be partially due to increased reaeration keeping DO levels near 100% saturation during high flow events, or because photosynthesis also tends to be low during high flow events due to little sun, increased turbidity, and increased scouring of periphyton. Additionally, groundwater and nutrient inputs may have a larger influence on periphyton growth and respiration at low flows, making it difficult to determine the flow-DO relationship.

Dissolved oxygen concentration, on the other hand, tended to increase with increasing daily mean discharge across all sites and then level off at high flows (100-1000 $m^3 s^{-1}$). The increase in DO concentrations with discharge occurred due to increased mixing and reaeration at high flows. As mentioned above, Rangitikei at Onepuhi had lower concentrations at low flows and Mangatainoka at Pahiatua Town Bridge had high concentrations at low flows. The other four sites had fairly constant variability in dissolved oxygen concentrations across the range of flows.

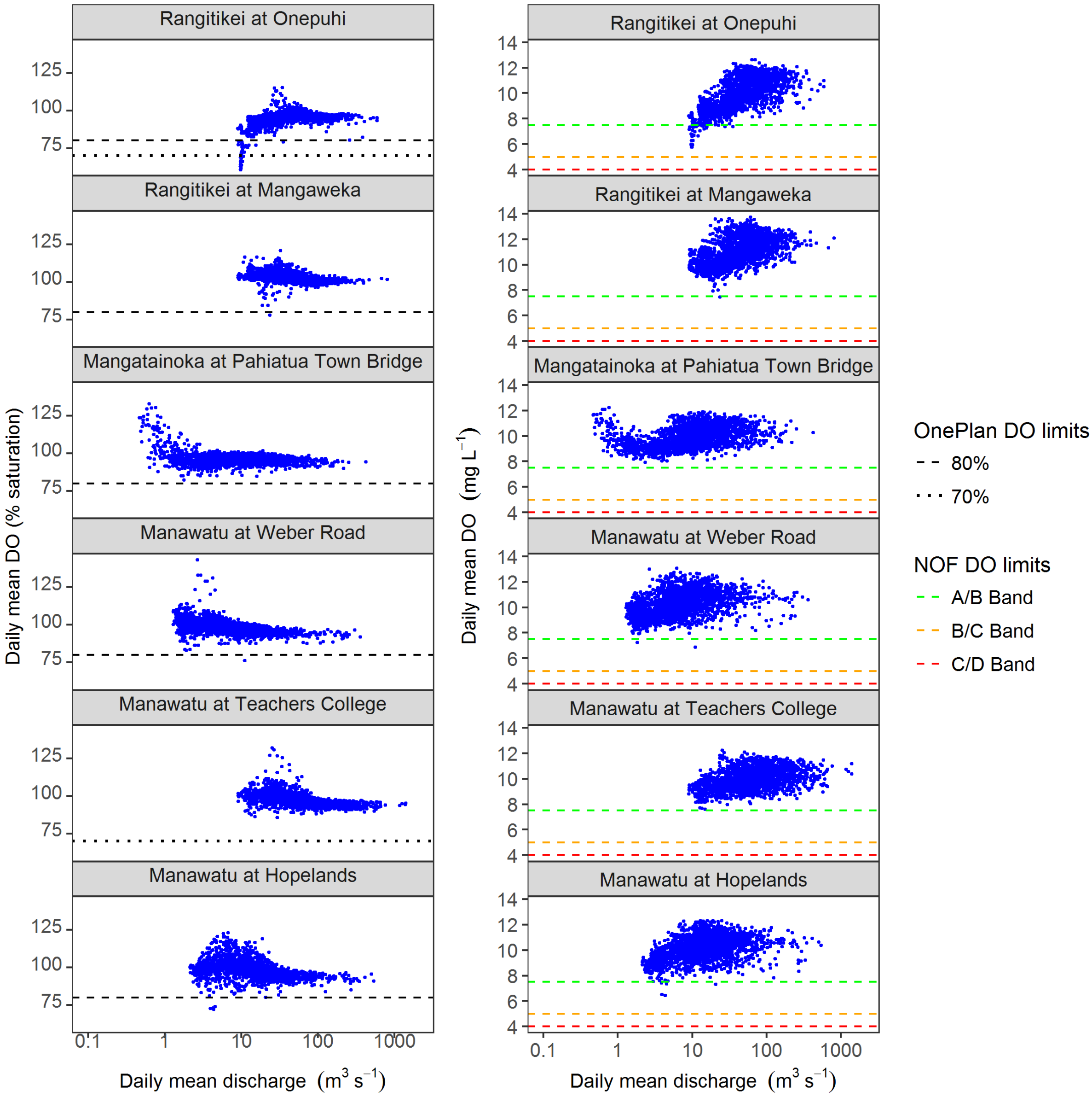

Figure 4-7: Scatter plots of dissolved oxygen levels (% saturation or mg L^{-1}) against daily mean discharge (m^3 s^{-1}) with One Plan targets and NOF limits for daily minimum DO concentrations. Note the logarithmic x-axis.

4.3.2 Temperature

Water temperature had a regular sinusoidal pattern across all sites, with maximum daily temperatures ranging between 3°C in the winter months and up to 28°C over summer (Figure 4-8). Lower daily minimum dissolved oxygen saturation values occurred on days with higher maximum water temperatures. The variability in DO percent saturation was greatest at medium to high water temperatures (e.g., 15-25°C), particularly at Rangitikei at Onepuhi and Mangatainoka at Pahiatua Town Bridge. The difference at the Mangatainoka site is likely due to high abundance of macrophytes at this site; the large diel variation and very high saturation during daylight hours is consistent with macrophyte growth, which is greatest in summer when temperatures are also highest. Daily minimum dissolved oxygen concentrations were strongly negatively correlated with daily maximum water temperature across all sites (Figure 4-9).

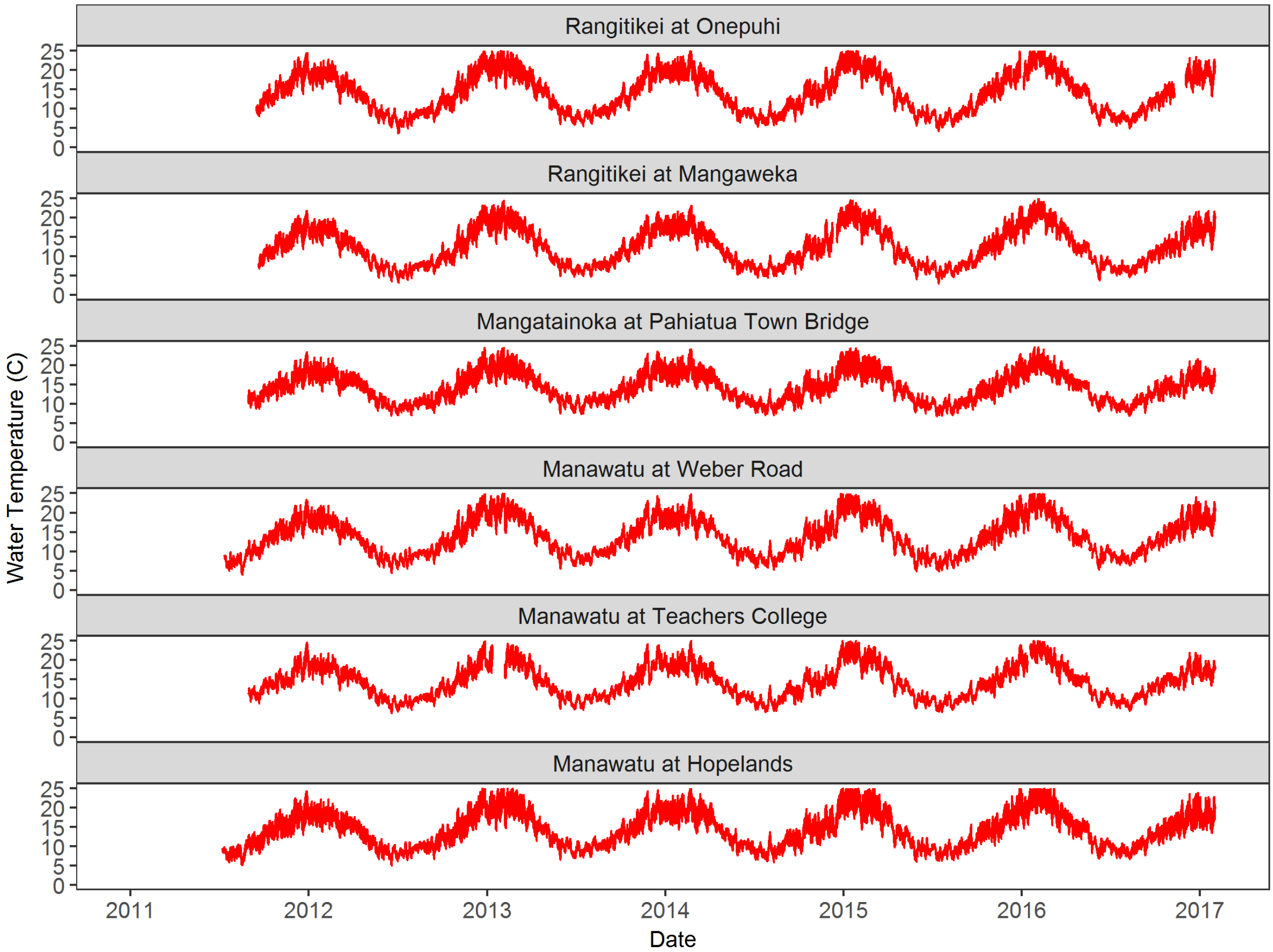

Figure 4-8: Temperature time series for each of the six HRC monitoring sites between 2011 and 2017.

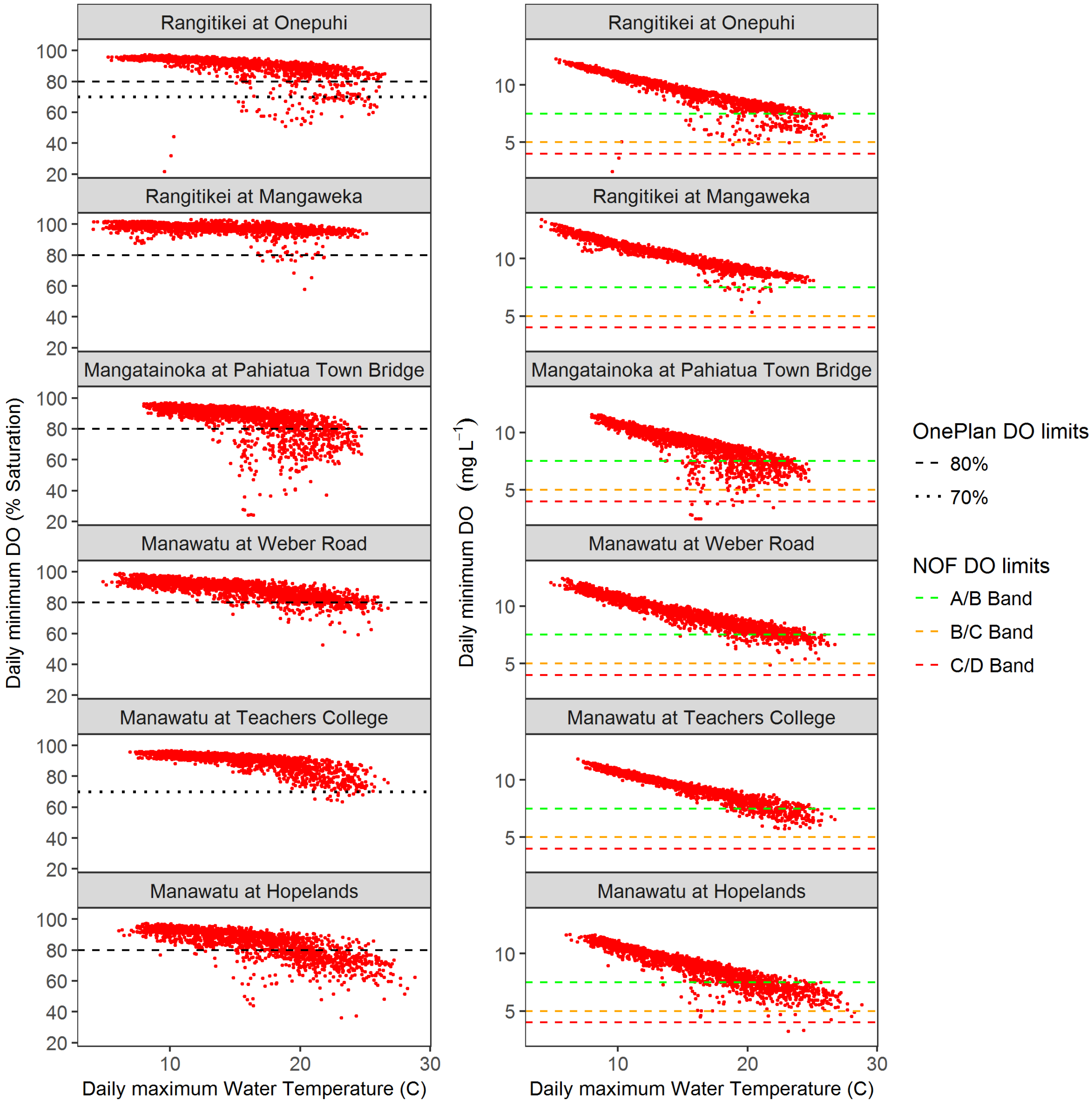

Figure 4-9: Scatter plots of dissolved oxygen levels (% saturation or mg L^{-1}) against daily maximum temperature (°C) with One Plan targets and NOF limits for daily minimum DO concentrations.

4.3.3 Periphyton

Periphyton was measured in two ways, as percent cover of various algal types (film, mat, sludge, slimy filamentous, and coarse filamentous) or as chlorophyll-a, an estimate of total algal biomass. Film was the most common type of periphyton present, and typically covered 50-100% of the stream bed. Sludge was rarely present, and mats, slimy filamentous, and coarse filamentous algae typically covered only 0-25% of the stream bed.

As would be expected, total percent cover of periphyton and algal biomass (chlorophyll-a) were positively correlated (Spearman rank correlation, ρ= 0.61); algal biomass increased as percent algal cover increased (Figure 4-10). The contribution to biomass varied considerably between cover types. Mats and slimy filamentous algae often had higher chlorophyll-a at 0-25% cover than films had at close to 100% cover (Figure 4-10). Both percent cover and chlorophyll-a tended to be greatest in autumn and winter, followed by summer (Figure 4-10).

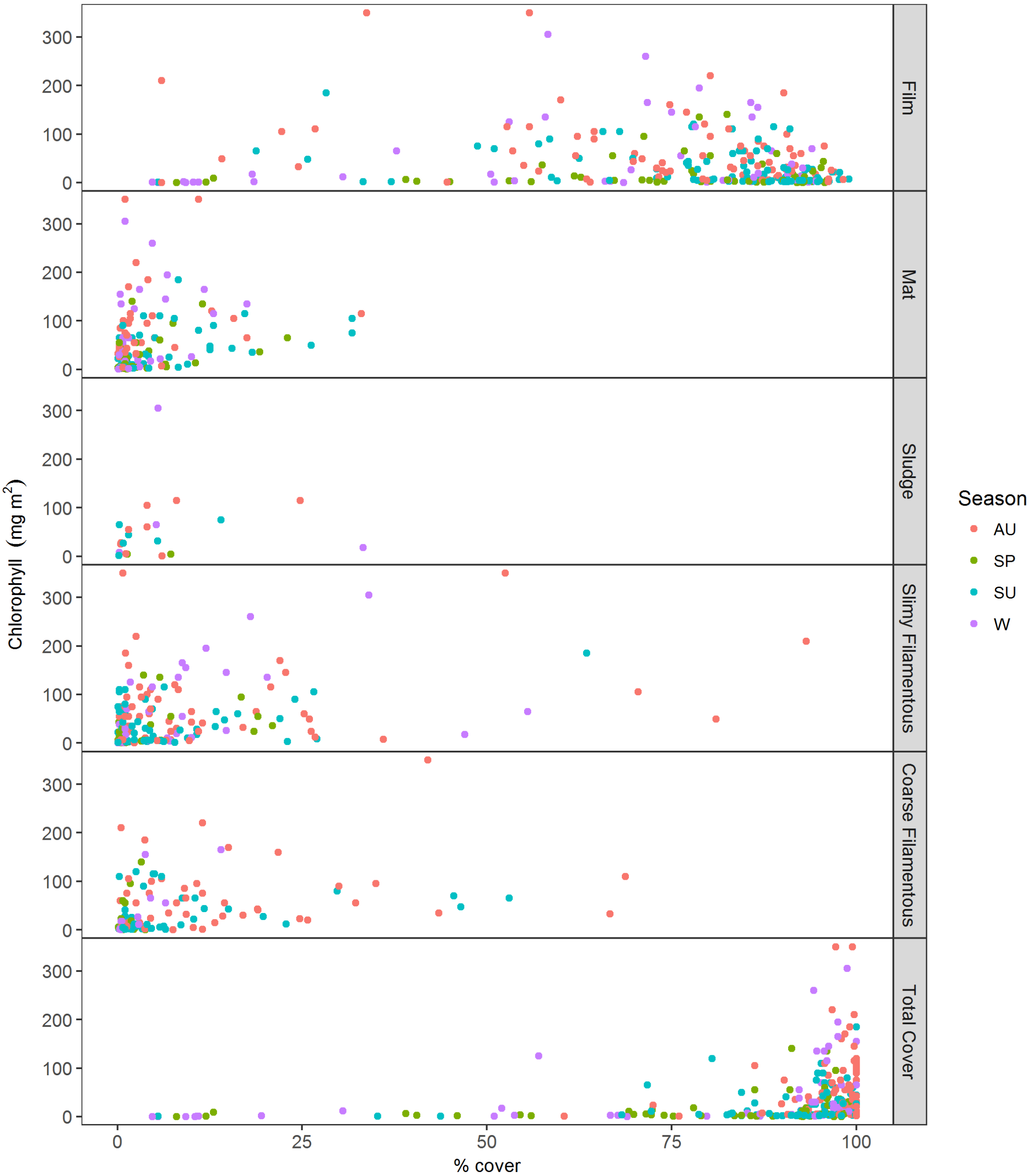

Figure 4-10: Scatterplots of percent cover of various algal types and total percent cover against algal biomass (chlorophyll-a, mg m^{-2}) across all monitoring sites. Season is indicated by colour. Individual plots for each site are included in Appendix A.

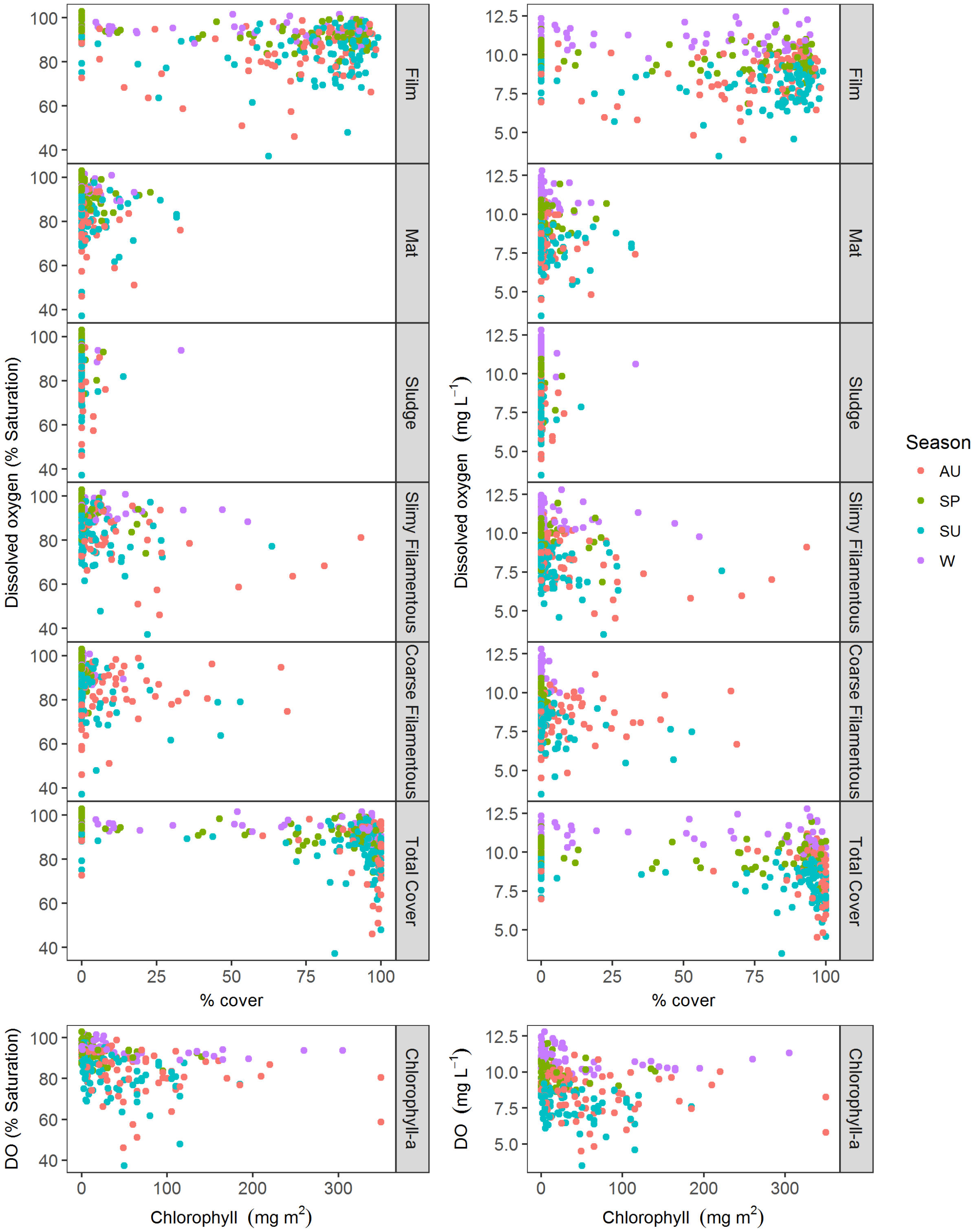

Figure 4-11: Scatterplots of algal percent cover and algal biomass (chlorophyll-a, mg m^{-2}) against daily minimum dissolved oxygen (% saturation or mg L^{-1}) for all monitoring sites. Season is indicated by colour.

As periphyton percent cover and biomass increased, lower values of both daily minimum dissolved oxygen percent saturation and concentration became more frequent, particularly in summer and autumn (Figure 4-11), when algal growth rates are high. In winter, when algal growth rates are reduced due to low temperatures, high dissolved oxygen saturation and concentration occurred even at 100% cover. It is important to note that because both periphyton growth and dissolved oxygen levels vary seasonally with water temperatures, it is difficult to determine whether the observed correlation between periphyton and daily minimum dissolved oxygen levels is a causal relationship or an artefact of other seasonal effects. Moreover, the cover type can also have a strong influence on the periphyton-DO relationship; for example 100% cover of a thin diatom mat will not impact DO as much as 100% thick cyanobacteria layer, or long filamentous algae.

Total percent cover of periphyton and chlorophyll-a were both weakly negatively correlated with primary production (spearman correlations, cover: ρ=0.05, chlorophyll-a: ρ =0.16, Figure 4-12) but positively correlated with respiration (cover: ρ =0.33, chlorophyll-a: ρ =0.37, Figure 4-12).

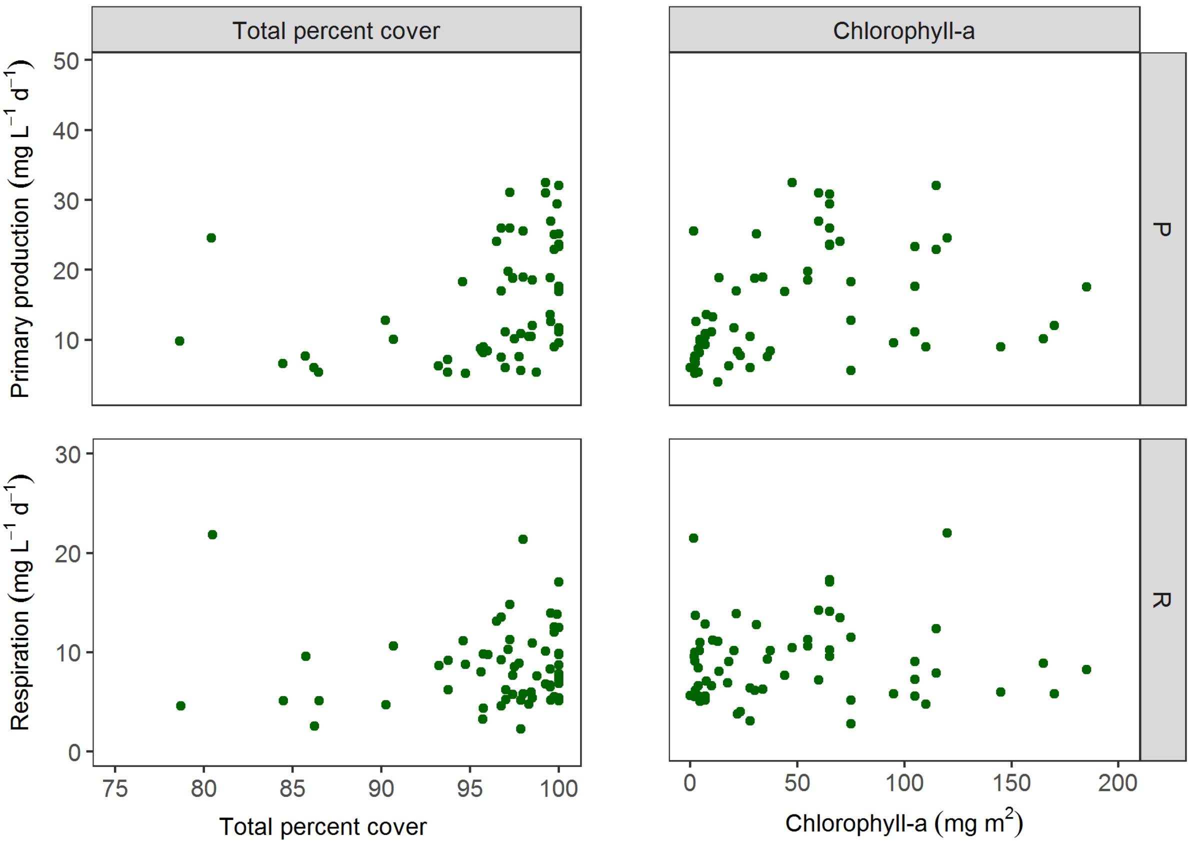

Figure 4-12: Scatterplots of algal percent cover and biomass (chlorophyll-a, mg m^{-2}) against primary production (mg L^{-1} d^{-1}) and respiration (mg L^{-1} d^{-1}) across all monitoring sites.

4.3.4 Dissolved oxygen modelling

The mixed effects modelling indicated that maximum daily temperature and chlorophyll-a were the strongest predictors of dissolved oxygen levels. The best model for dissolved oxygen percent saturation was the model with maximum daily temperature and chlorophyll-a as the fixed effects, while the second-best model also included flow (Table 4-3). However, because the difference in AIC scores between the top two models was less than two, they are considered to have equally good fit (Burnham and Anderson 2002). The best model for dissolved oxygen concentration was the model with maximum daily temperature, chlorophyll-a, and flow, but again the second-best model, which did not include flow, had a difference in AIC score less than two. The third and fourth best models for both dissolved oxygen measures were those with temperature, total periphyton cover, and flow.

Table 4-3: AIC scores, ∆ AIC, and rank of dissolved oxygen models with varying fixed effects. ∆ AIC is the difference between the AIC score of the current model and the best model. ∆ AIC<2 is considered to be an equally good model fit. The red numbers indicate the lowest AIC score/best model fits (as the top two models were tied). The top five models are ranked accordingly.

Fixed effects	AIC score Saturation (%)	∆ AIC	Rank	AIC score Concentration (mg L^{-1})	∆ AIC	Rank
Null model	582.8	153.4		256.1	226	
Temperature (daily maximum)	501.3	71.9		44.5	14.4	5
Flow (daily mean)	570.7	141.3		246.4	216.3	
Chlorophyll-a (mg m^2)	469.8	40.4		193.8	163.7	
Percent cover * Cover type	524.5	95.1		240.3	210.2	
Total cover	525.9	96.5		209.2	179.1	
Temperature + Flow	506.9	77.5		54.9	24.8	
Temperature + Chlorophyll-a	429.4	0	1	30.4	0.3	2
Temperature + Total cover	439.3	9.9	4	38.6	8.5	3
Temperature + Percent cover * Cover type	447.3	17.9		88.2	58.1	
Flow + Chlorophyll-a	474.4	45		199.8	169.7	
Flow + Total cover	517.3	87.9		197.5	167.4	
Flow + Percent cover * Cover type	517.7	88.3		231.4	201.3	
Temperature + Flow + Chlorophyll-a	430.9	1.5	2	30.1	0	1
Temperature + Flow + Total cover	435.2	5.8	3	42.5	12.4	4
Temperature + Flow + Percent Cover * Cover type	443.9	14.5	5	92.6	62.5	

Although there was not a strong correlation between either measure of periphyton and primary production, the modelling analysis showed that including any of the periphyton measures improves the model’s predictive power compared to a null model (no explanatory variables). The model with total cover was the best-fitting model for primary production (Table 4-4). The best-fitting model for respiration was the model with the interaction between percent cover and cover type. However, the AIC scores only indicate the relative performance between models, they do not indicate whether the explanatory variables in the best-fitting model are significant.

Table 4-4: AIC scores, ∆ AIC, and rank of primary production and respiration models with varying measures of periphyton as fixed effects. ∆ AIC is the difference between the AIC score of the current model and the best model. ∆ AIC<2 is considered to be an equally good model fit. The red numbers indicate the lowest AIC score/best model fits. The top three models are ranked accordingly.

Fixed effects	AIC score Production (mg L^{-1} d^{-1})	∆ AIC	Rank	AIC score Respiration (mg L^{-1} d^{-1})	∆ AIC	Rank
Null model	2121.6	63.7		5323.8	182.1	
Chlorophyll-a	2066.9	9	2	5157.2	15.5	2
Total cover	2057.9	0	1	5181.3	39.6	3
Percent cover * Cover type	2117.2	59.3	3	5141.7	0	1

5 Discussion

5.1 Dissolved oxygen management

Dissolved oxygen saturation levels in all sites remained above the One Plan targets 90% of the time over the six-year monitoring period. However, one site, Manawatu at Hopelands, had a daily minimum dissolved oxygen saturation value below the One Plan limit 25.5% of all days. Another, Mangatainoka at Pahiatua Town Bridge, had a daily minimum dissolved oxygen saturation value below the limit 18.5% of all days. The remaining four sites, on the other hand, had daily minimum dissolved oxygen saturation values below the limit on less than 10% of all days. Perhaps most concerning for fish, several sites had prolonged periods of consecutive days where the daily minimum dropped below the One Plan target. There were several periods of thirty consecutive days at Manawatu at Hopelands and Mangatainoka at Pahiatua Town Bridge, as well as two periods of forty consecutive days at Rangitikei at Onepuhi. While less is known about chronic effects of sub-lethal low dissolved oxygen conditions on fish than about acute lethal effects, it is predicted that the duration of low oxygen events can affect both fish recruitment and growth (Davies-Colley et al. 2013).

Under current implementation of the NOF guidelines for dissolved oxygen, four of the six sites fell in the NOF C band (Manawatu at Teachers College, Manawatu at Weber Road, Rangitikei at Mangaweka, and Rangitikei at Onepuhi) and two in the D band (Manawatu at Hopelands and Mangatainoka at Pahiatua Town Bridge), below the national bottom line. However, a proportion of time approach showed that concentrations this low were infrequent. In fact, dissolved oxygen concentrations were within the NOF A band, indicating no stress due to low dissolved oxygen, 75% or more of the time at all sites. DO concentrations were in the B band, which indicates occasional minor stress due to low dissolved oxygen, between 8.3-22% of the time at five of the six sites. DO concentrations at the sixth site, Rangitikei at Mangaweka, were in the B bank 0.7-0.8% of the time. Dissolved oxygen concentrations at four of the six sites were in the C band 6% of the time or less. DO concentrations at the other two sites, Manawatu at Hopelands and Mangatainoka at Pahiatua Town Bridge, were in the C band 13.6% and 11.7% of the time, respectively. The dissolved oxygen concentration never dropped below the national bottom line, under which significant stress on aquatic organisms is expected, at three sites, Manawatu at Teachers College, Manawatu at Weber Road, and Rangitikei at Mangaweka, during the six-year monitoring period. Dissolved oxygen concentrations at the other three sites were below the national bottom line less than 1% of the time, or 12 days over 6 years. This indicates that, fish in the six sites rarely experienced significant stress as a result of low oxygen levels during the six-year monitoring period.

However, the seasonal dissolved oxygen duration curves showed that it is much more likely for dissolved oxygen levels, both percent saturation and concentration, to exceed the relevant limits during summer and autumn, when water temperatures are warmest and algal growth rates are high. This suggests that HRC and other managers should consider setting more conservative targets for warm summer and early autumn periods. In fact, the NOF limits are currently only applied to summer dissolved oxygen levels, whereas this analysis found that low dissolved oxygen levels also occur frequently over the autumn.

While the One Plan targets were exceeded 8% of the time, dissolved oxygen levels remained above the NOF national bottom line 99% of the time. However, direct comparisons of the exceedance frequencies between the One Plan targets and the NOF guidelines are difficult, because the saturation capacity of water is reduced with increasing temperature and/or salinity (Franklin 2014b).

Thus, saturation can remain the same even as concentration changes with temperature. Consequently, standards expressed in terms of percent saturation have a higher risk of being under-protective for aquatic organisms. Furthermore, the One Plan and NOF national bottom-line thresholds are not intended to provide equivalent levels of protection.

A strength of the NOF guidelines is that they are explicitly designed to reflect differing protection levels for aquatic ecosystem health based on the known information about acute and chronic effects of varying dissolved oxygen levels (Franklin 2014b and other sources summarized in literature review section). Additionally, the multiple bands of the NOF provide greater resolution of degree of impact of different dissolved oxygen levels, and each band relates directly to consequences for ecosystem health. At the moment, the One Plan limits are simply above or below a threshold, but the meaning of that threshold with regard to fish health is less clear. If HRC wishes to keep the One Plan targets in terms of saturation, it is advised that the limits be expanded to include different targets at different temperatures or for different seasons, and that the targets be chosen based on potential ecological effects on fish and ecosystem health. Alternatively, while the NOF dissolved oxygen guidelines officially only apply downstream of point discharges during summer, it may be simpler to adopt the NOF guidelines and apply them to all locations year-round. Given the consistency of the current NOF limits with the proposed protection levels for fish in Franklin (2014b), it is considered that application of the NOF dissolved oxygen thresholds region-wide would be valid and justifiable. Furthermore, this would provide consistency with the national standard.

5.2 Drivers of dissolved oxygen

Daily maximum water temperature and chlorophyll-a (periphyton biomass) were identified as primary drivers of dissolved oxygen levels in the modelling analysis. The influence of both water temperature and periphyton on dissolved oxygen are likely responsible for the strong seasonal patterns observed in dissolved oxygen levels and probability of exceeding management targets.

Although flow was also correlated with dissolved oxygen levels, including it in the dissolved oxygen model did not substantially improve model fit. However, previous studies which investigated the effects of increasing duration of low flow periods on dissolved oxygen have reported that prolonged high/low flow events can have strong effects on dissolved oxygen dynamics (Franklin 2014b).

Periphyton cover and biomass also appeared to influence primary production and ecosystem respiration, respectively, although the correlations between each pair of variables were not strong. Nonetheless, a model with periphyton included was a better predictor of dissolved oxygen levels than a null model without periphyton.

6 Conclusions

Dissolved oxygen dynamics are complex because they are driven by multiple factors, several of which are correlated and/or vary seasonally, such as temperature, periphyton, and flow. Additionally, macrophytes, which were not included in this analysis, are also known to influence dissolved oxygen through their large contributions to primary production and respiration (Burrell et al. 2014). Further modelling and targeted field studies are needed to tease apart these influences on dissolved oxygen levels. Understanding drivers of dissolved oxygen dynamics, including the influence of seasonality, will enable Horizons Regional Council and other managers to continue to set appropriate DO limits for the protection of New Zealand native aquatic biota.

Laboratory experiments have shown that low dissolved oxygen can have both acute and chronic effects on New Zealand native freshwater fish and trout. The ability of fish to survive in low oxygen environments depends on the duration and timing of exposure, the level and constancy of dissolved oxygen, the species, life stage and health status of the fish, as well as on other environmental conditions, e.g., water temperature. Although most fish species are capable of adapting their behaviour to compensate for short-term exposure to depressed dissolved oxygen levels, long-term exposure can be lethal or result in chronic detrimental effects.

Analysis of HRC's dissolved oxygen data in comparison with the NOF guidelines for DO concentrations indicated that dissolved oxygen levels in the six HRC monitoring sites were generally sufficient to protect aquatic biota. However, dissolved oxygen percent saturation exceeded the One Plan targets primarily in summer and autumn at all sites. This could indicate that percent saturation levels may be under-protective during these periods, and that the current targets need to be reviewed and/or updated with concentration limits or more conservative saturation targets for warmer periods. However, the intended protection levels of the One Plan 70 and 80% dissolved oxygen saturation limits are unclear and so it may also reflect a higher intended protection level.

7 Acknowledgements

The assistance of several Horizons Regional Council staff, including Abby Matthews, Michaela Rose, Brent Watson, Manas Chakraborty, and Stacey Binsted, in obtaining the necessary data is gratefully acknowledged. The assistance of Kathy Walter in transferring FTP files was also much appreciated.

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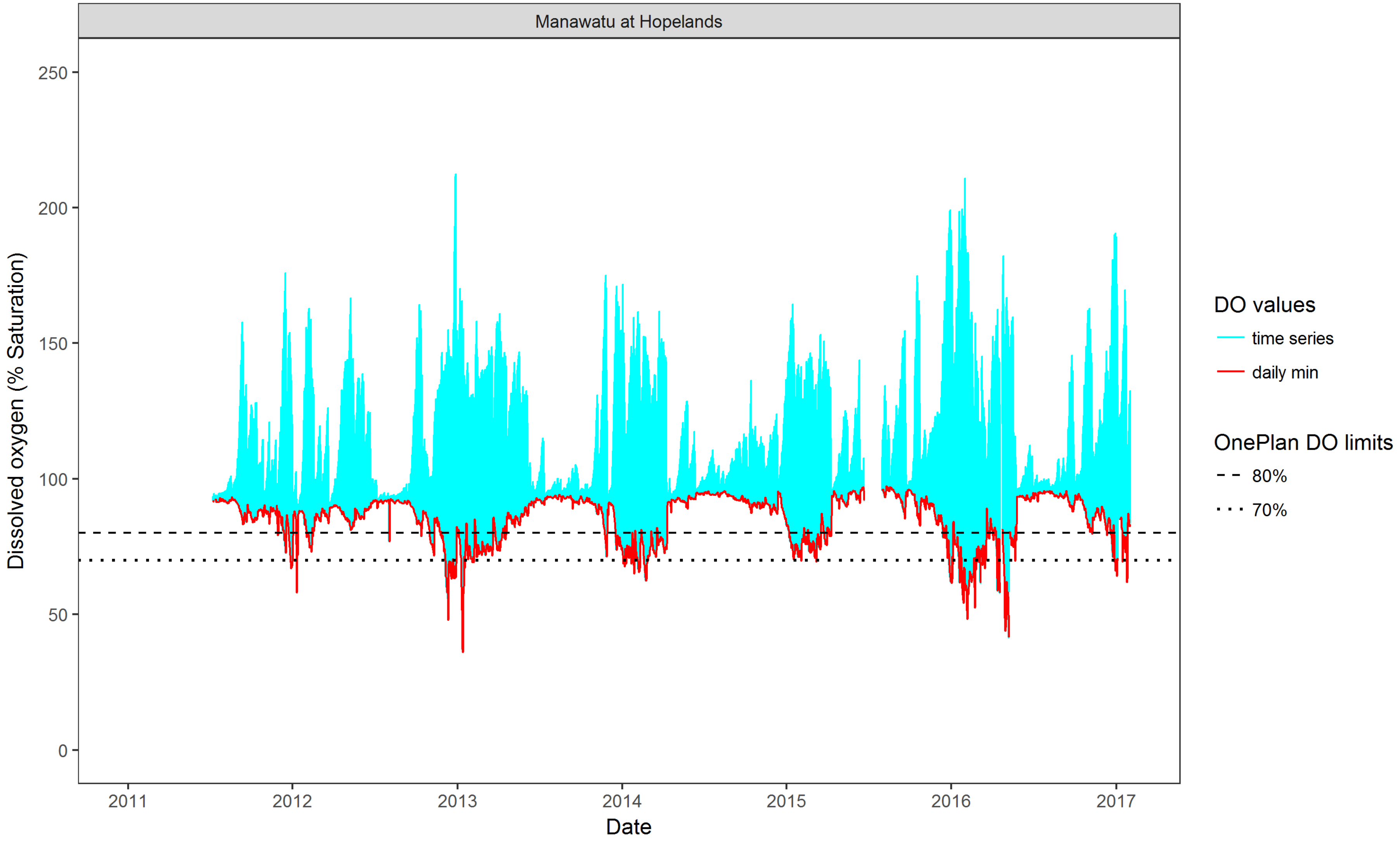
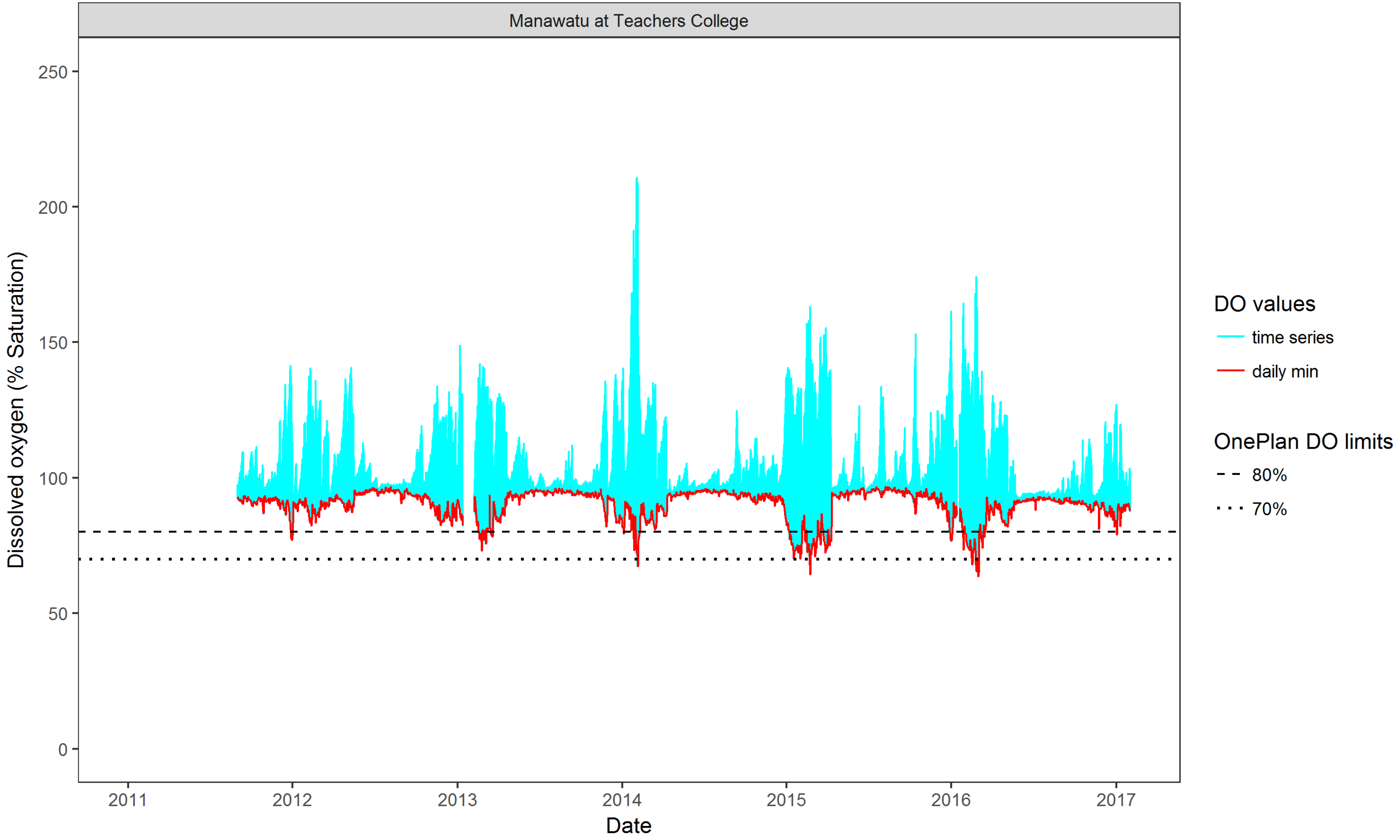
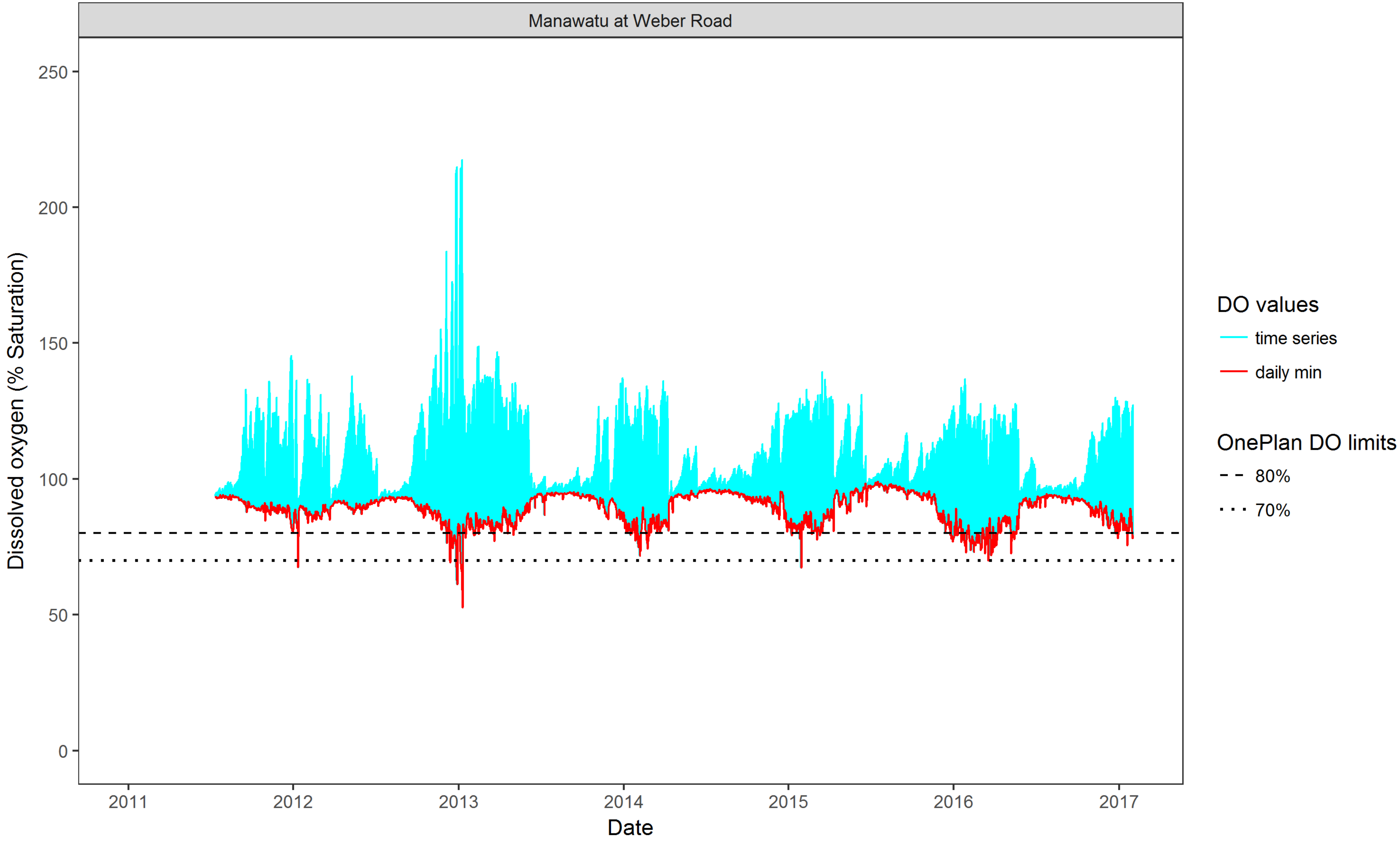
Appendix A Supplementary plots

Figure 4-1: Time series of dissolved oxygen percent saturation for each site over the six-year monitoring period with One Plan limits.

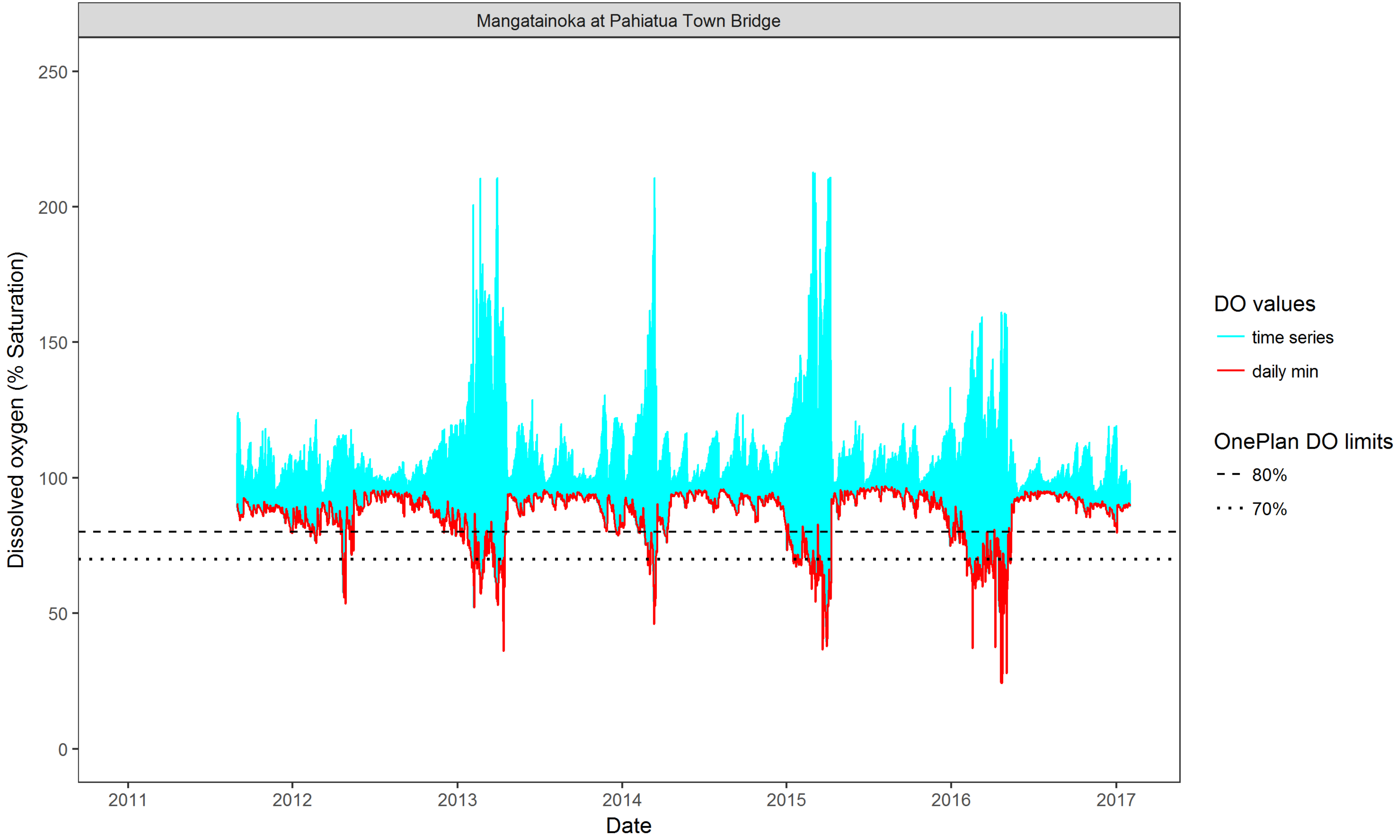


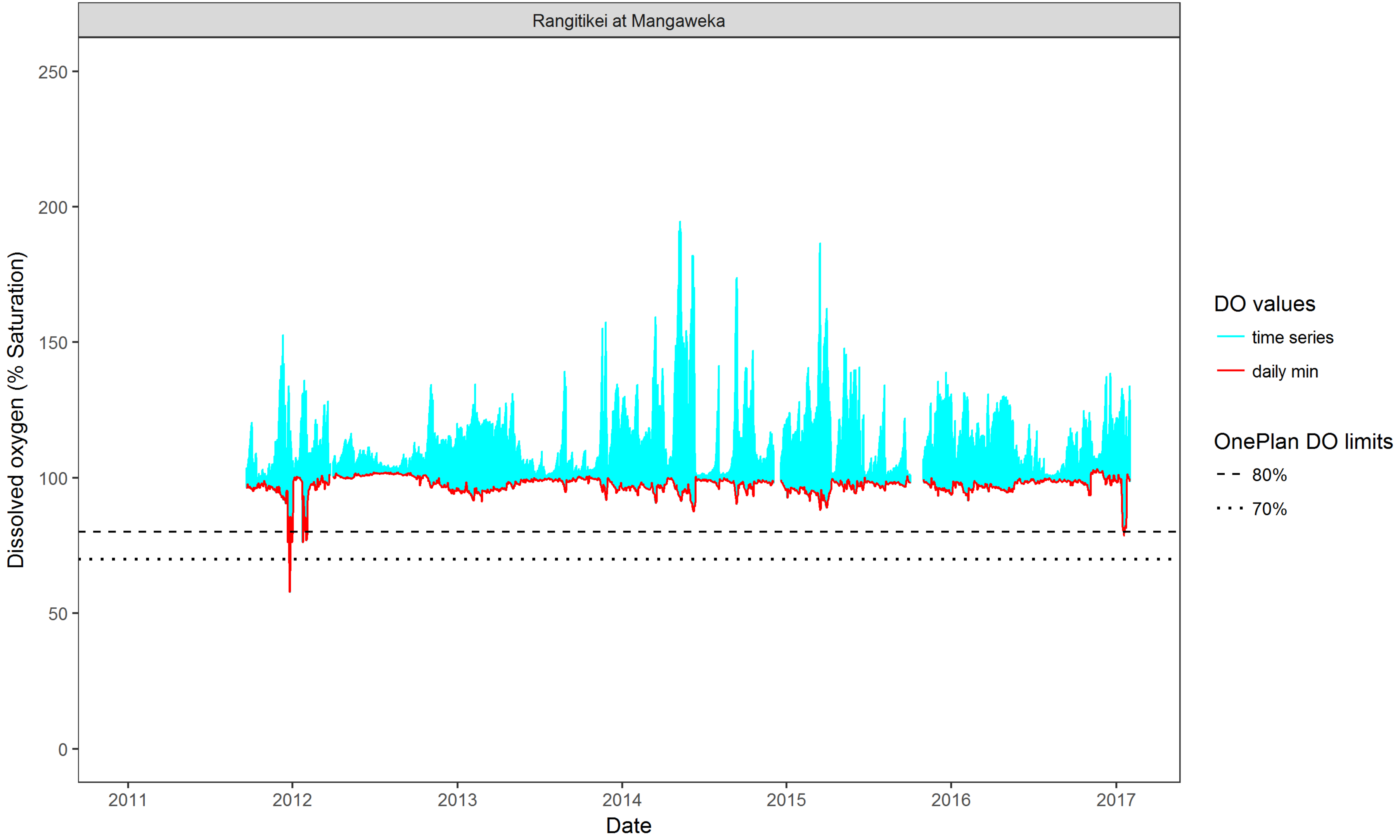


Manawatu at Teachers College
250
200
150
100
50
0
Dissolved oxygen (% Saturation)
2011
2012
2013
2014
2015
2016
2017
Date
DO values
time series
daily min
OnePlan DO limits
80%
70%



Manawatu at Weber Road
250
200
150
100
50
0
Dissolved oxygen (% Saturation)
2011
2012
2013
2014
2015
2016
2017
Date
DO values
time series
daily min
OnePlan DO limits
80%
70%


Mangatainoka at Pahiatua Town Bridge
Dissolved oxygen (% Saturation)
250
200
150
100
50
0
2011
2012
2013
2014
2015
2016
2017
Date
DO values
time series
daily min
OnePlan DO limits
80%
70%



Rangitikei at Mangaweka
Dissolved oxygen (% Saturation)
250
200
150
100
50
0
2011
2012
2013
2014
2015
2016
2017
Date
DO values
time series
daily min
OnePlan DO limits
80%
70%

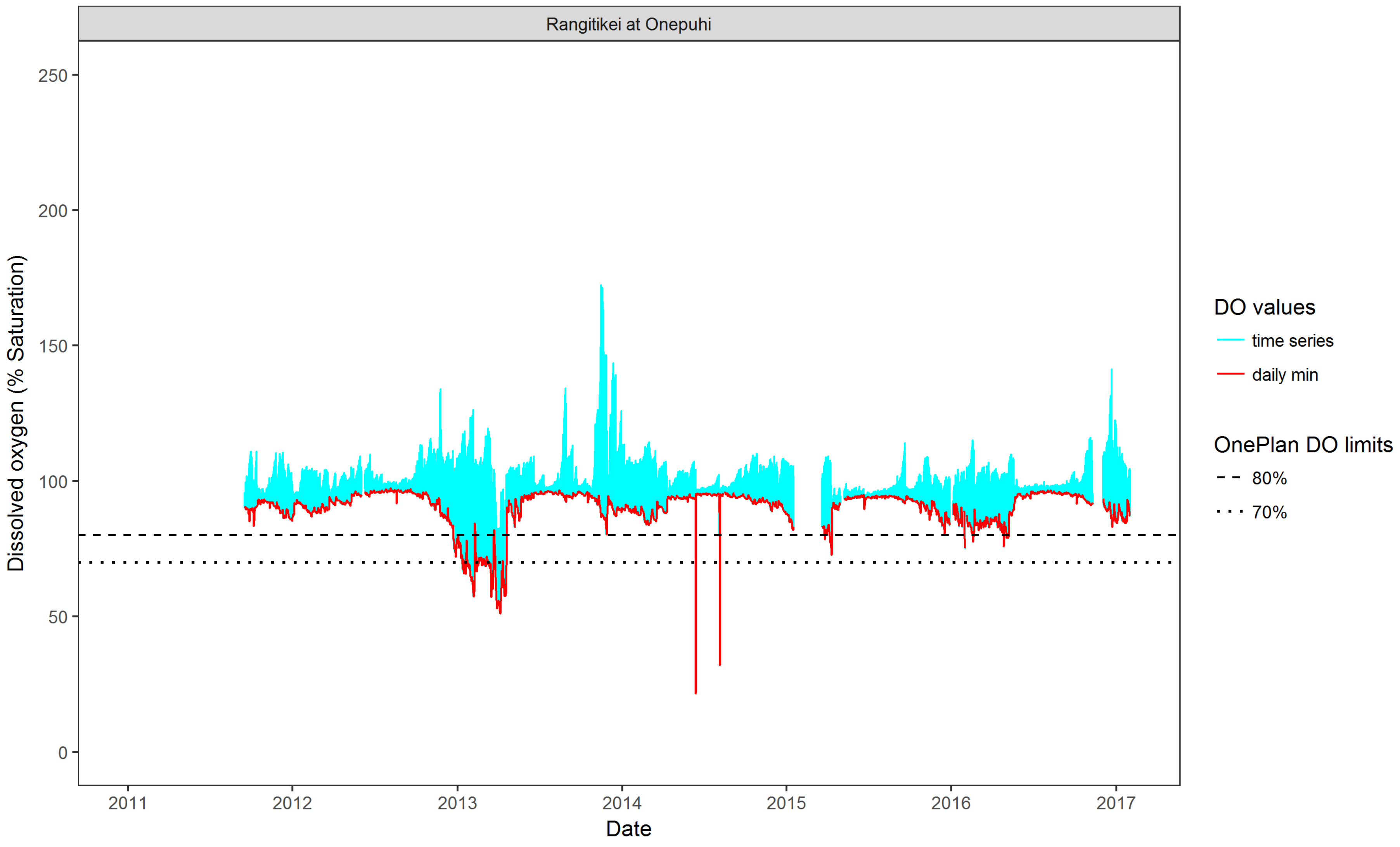
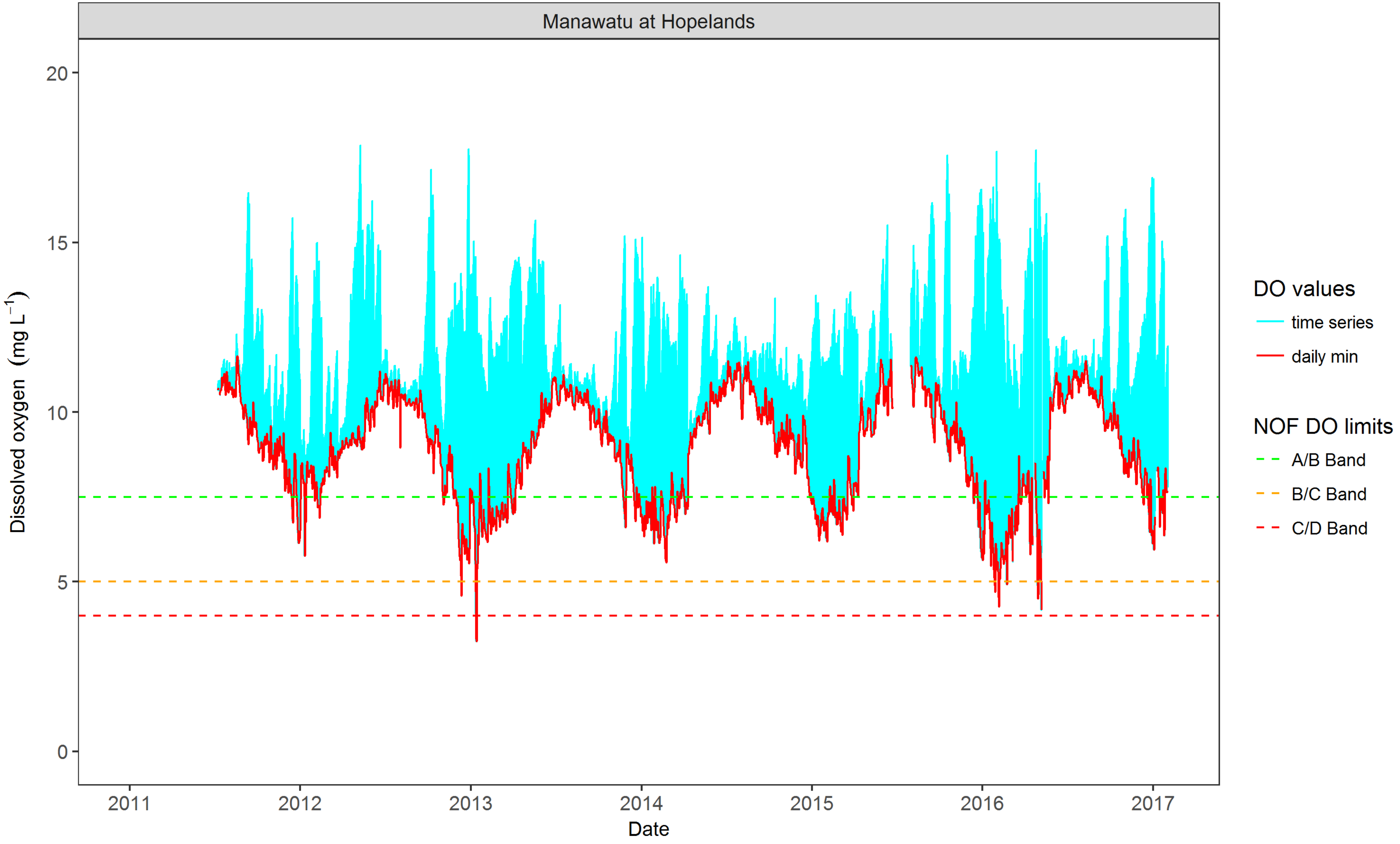
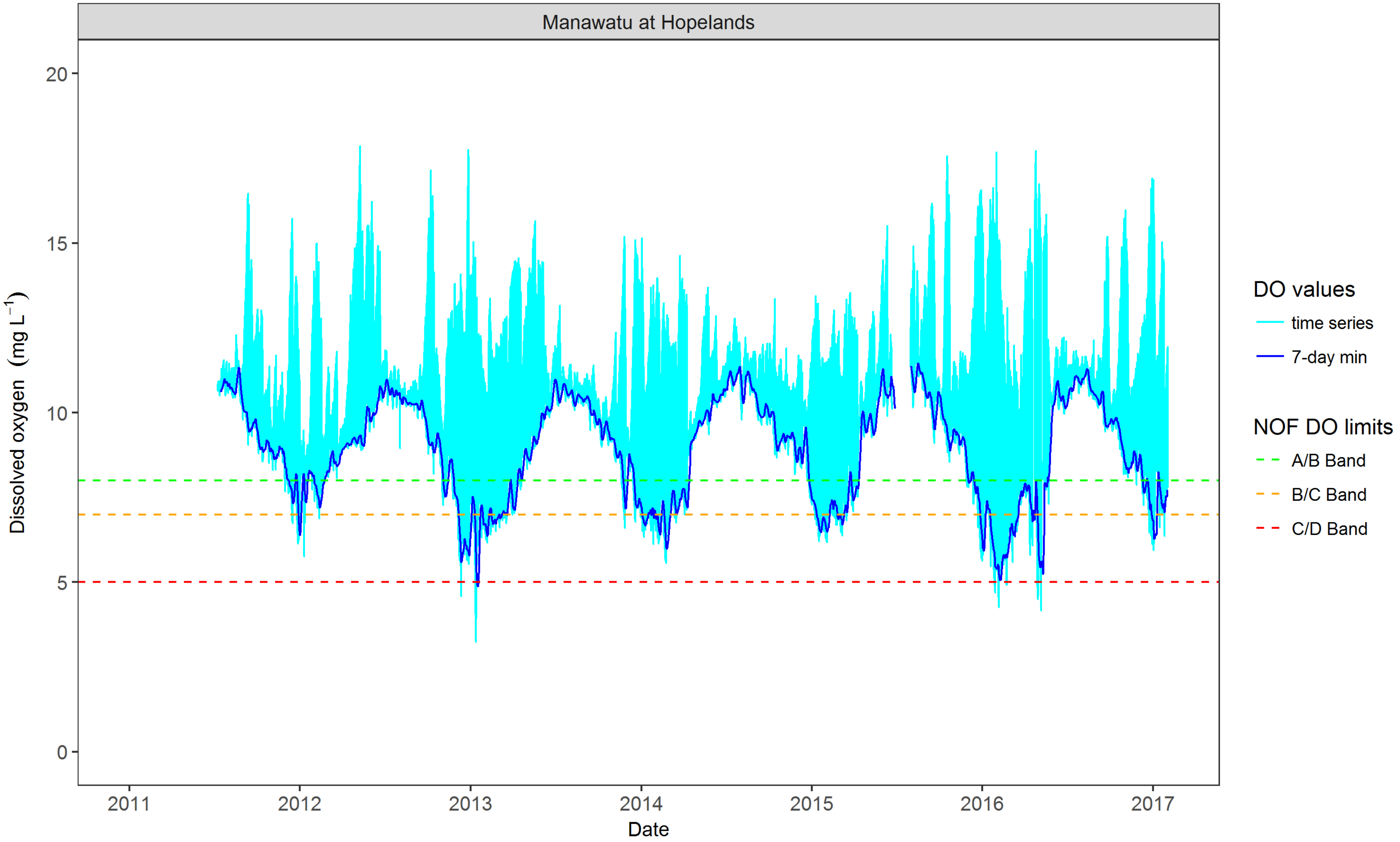
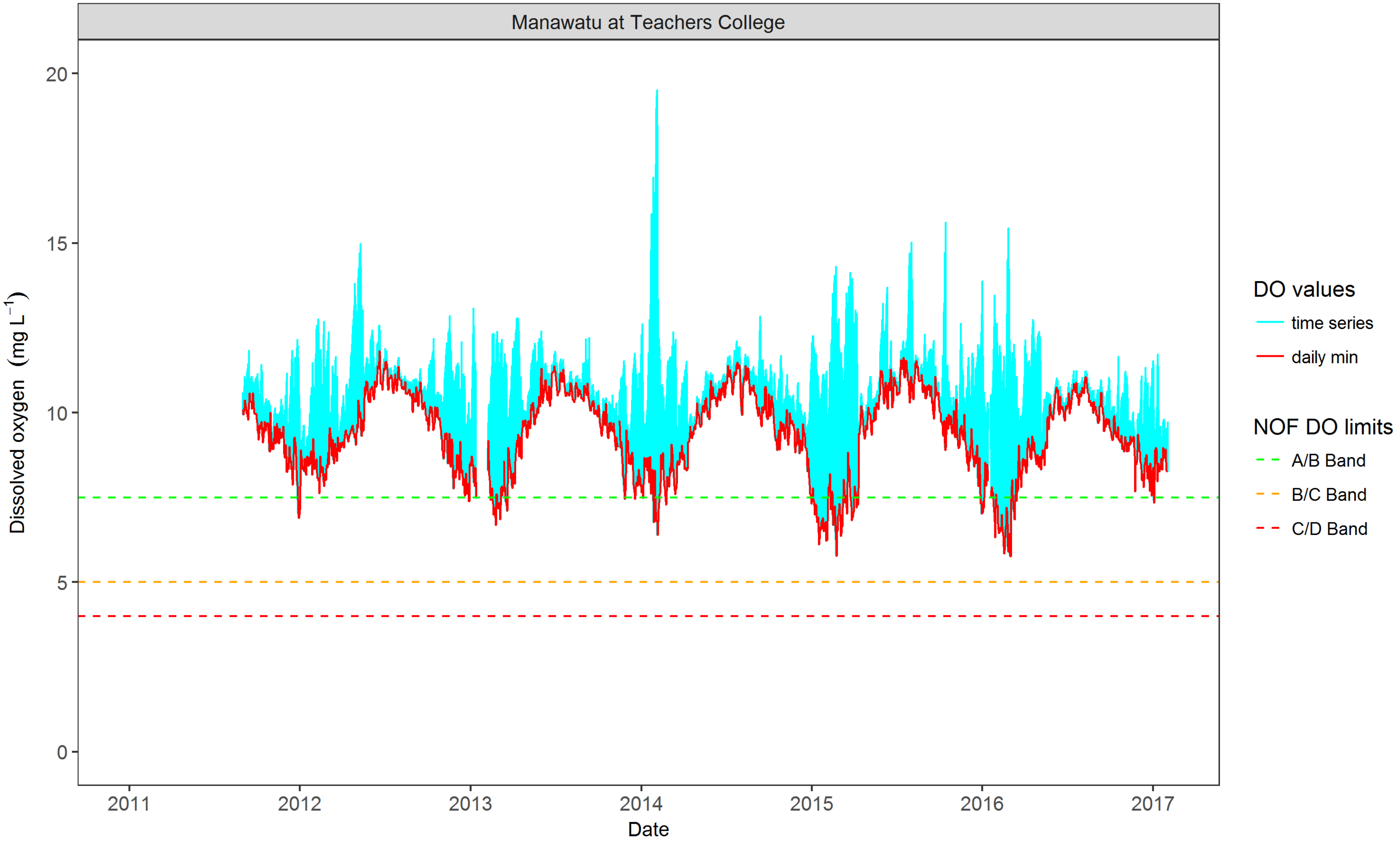

Rangitikei at Onepuhi
Dissolved oxygen (% Saturation)
250
200
150
100
50
0
2011
2012
2013
2014
2015
2016
2017
Date
DO values
time series
daily min
OnePlan DO limits
80%
70%

Figure 4-2: Dissolved oxygen time series for dissolved oxygen concentration (mg L^{-1}) for each site over the monitoring period with NOF limits.

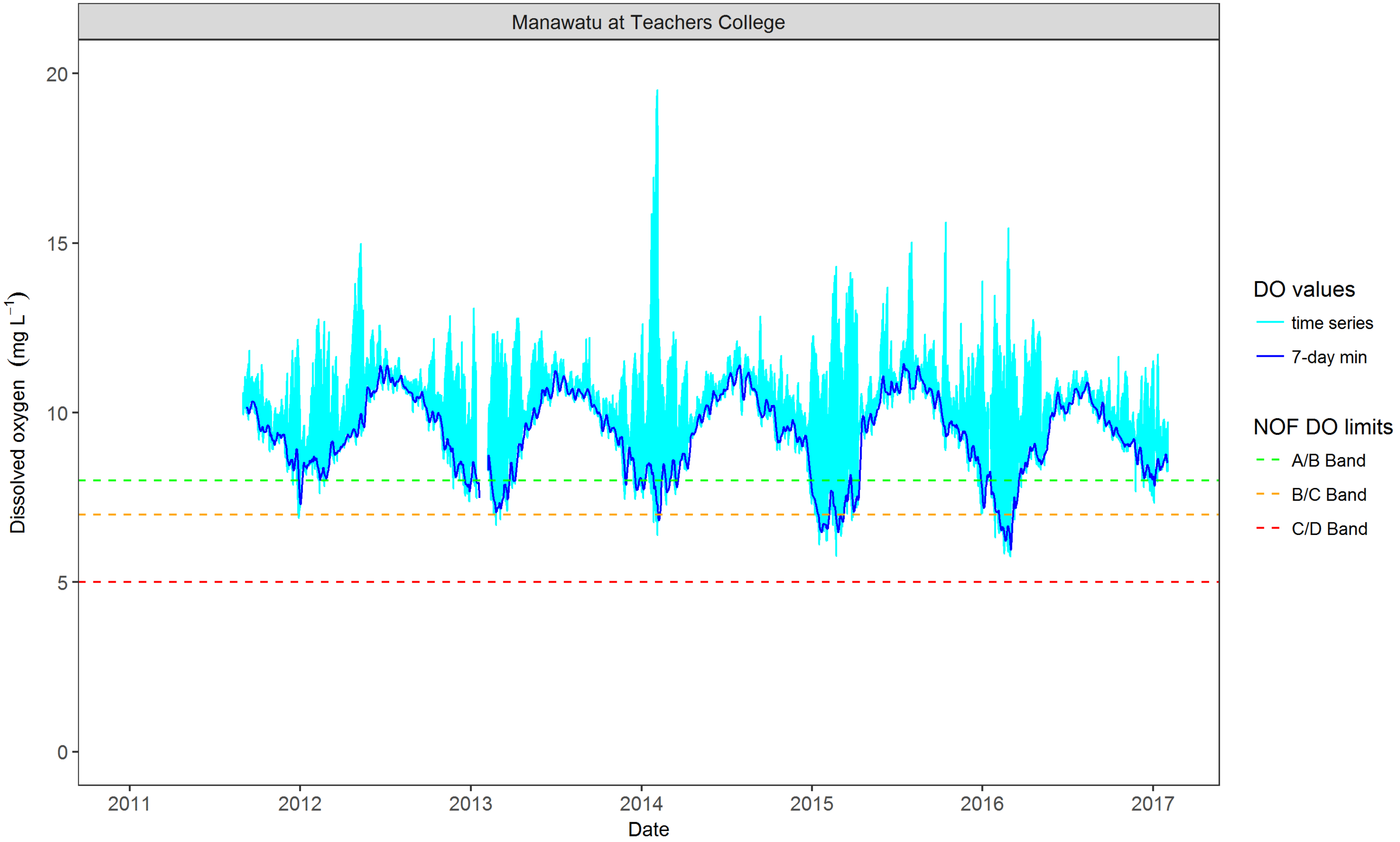




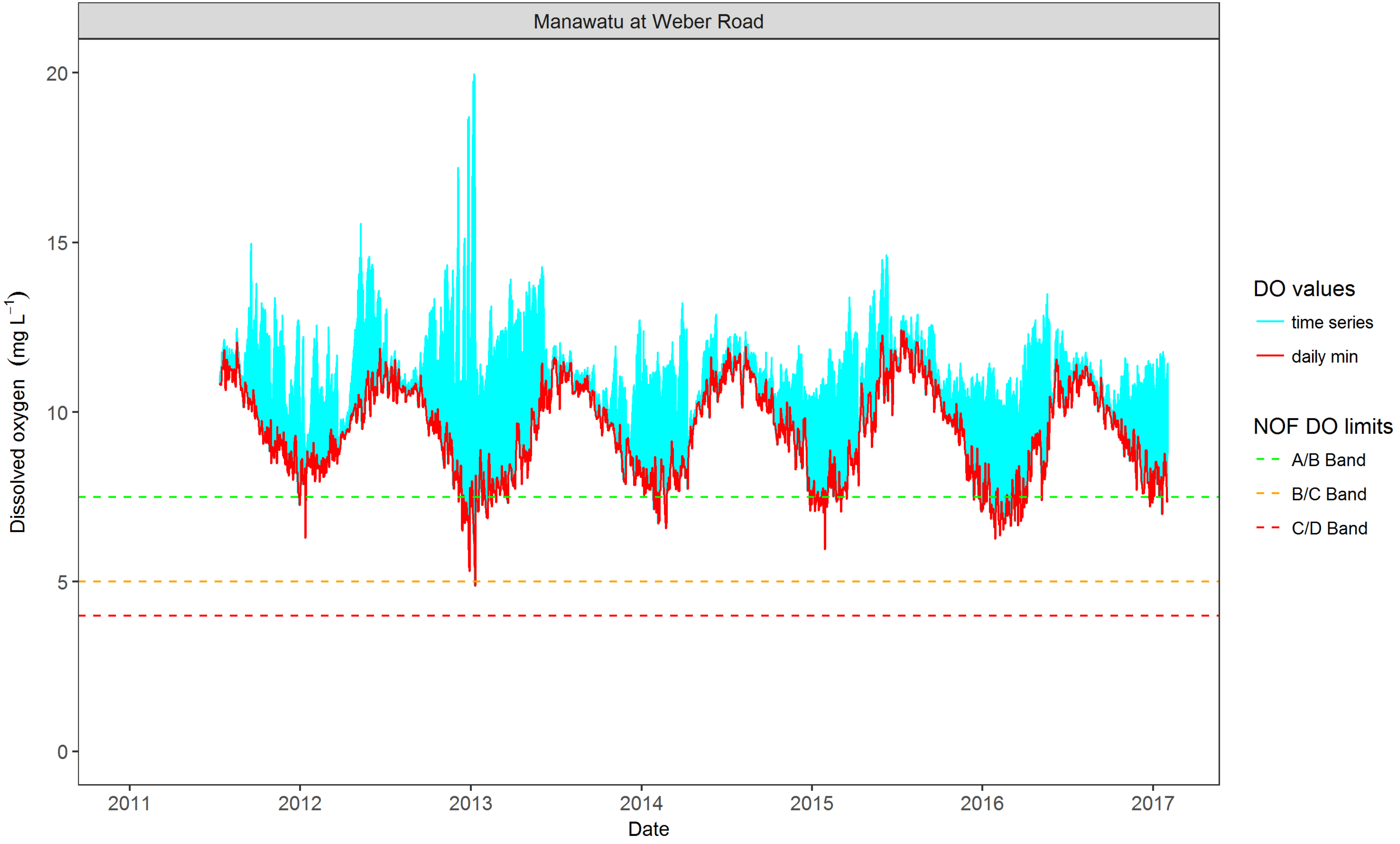
Manawatu at Hopelands
Dissolved oxygen (mg L⁻¹)
20
15
10
5
0
2011
2012
2013
2014
2015
2016
2017
Date
DO values
time series
7-day min
NOF DO limits
A/B Band
B/C Band
C/D Band



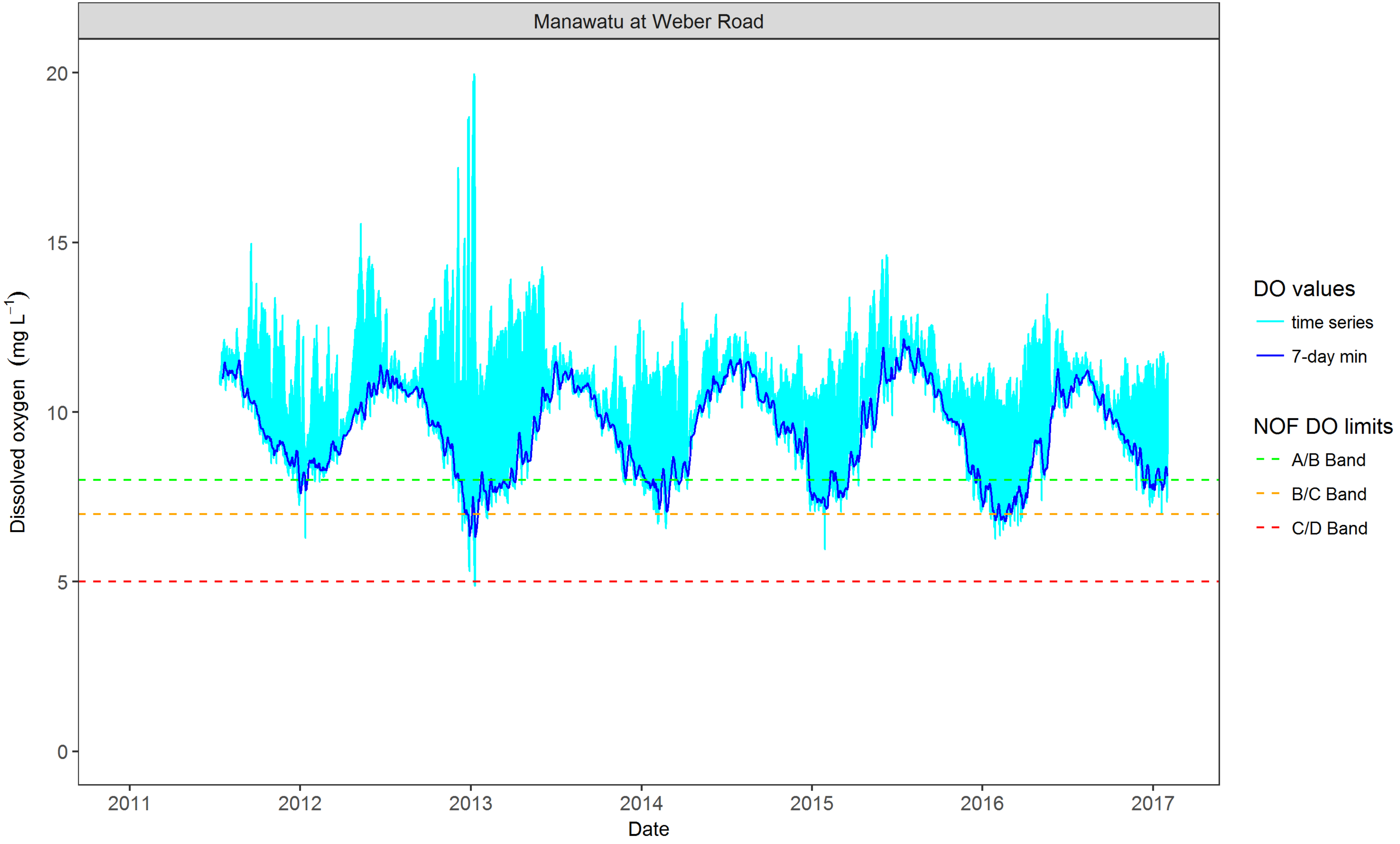
Manawatu at Teachers College
Dissolved oxygen (mg L^{-1})
20
15
10
5
0
2011
2012
2013
2014
2015
2016
2017
Date
DO values
time series
daily min
NOF DO limits
A/B Band
B/C Band
C/D Band



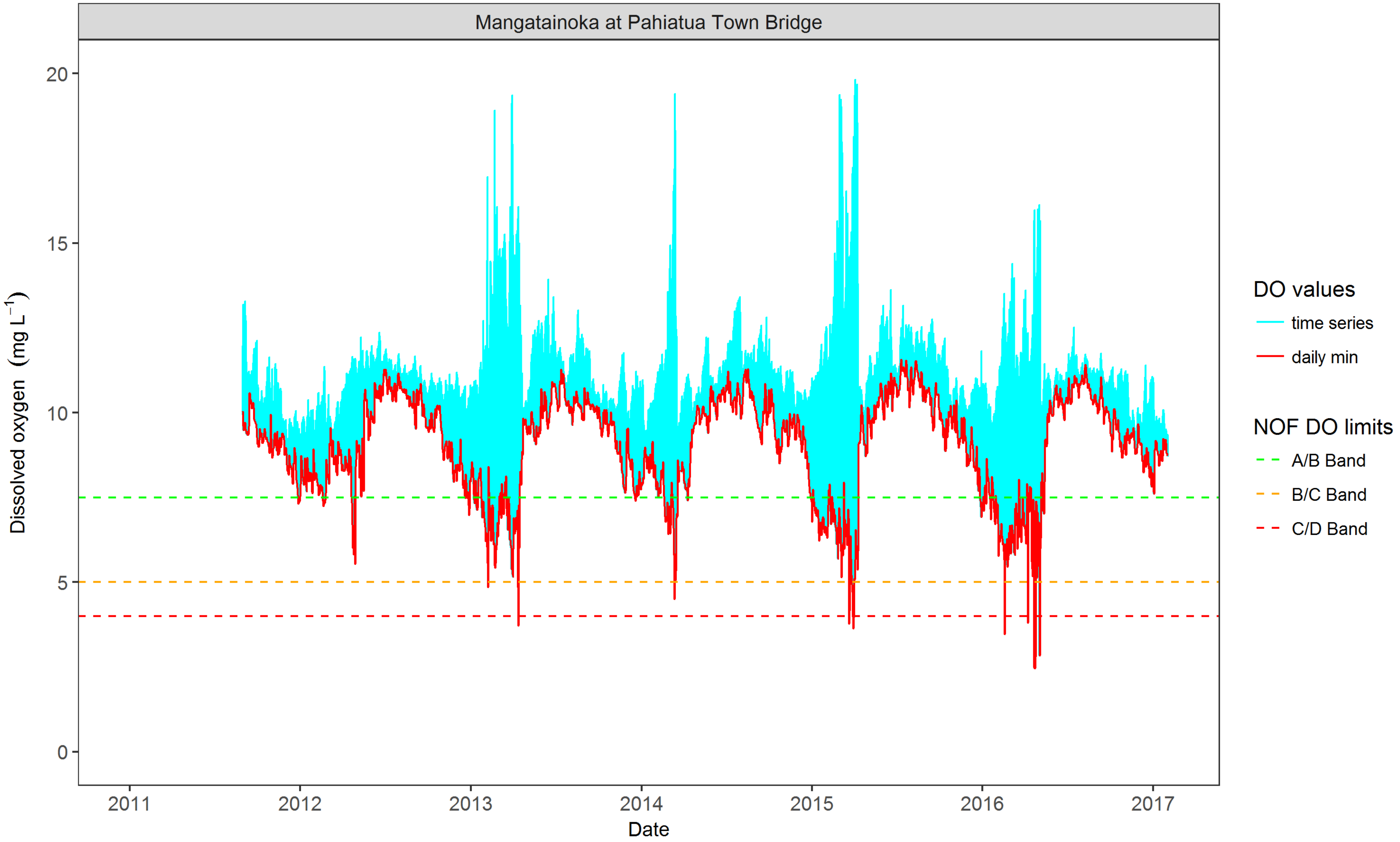
Manawatu at Teachers College
20
15
10
5
0
Dissolved oxygen (mg L^{-1})
2011
2012
2013
2014
2015
2016
2017
Date
DO values
time series
7-day min
NOF DO limits
A/B Band
B/C Band
C/D Band



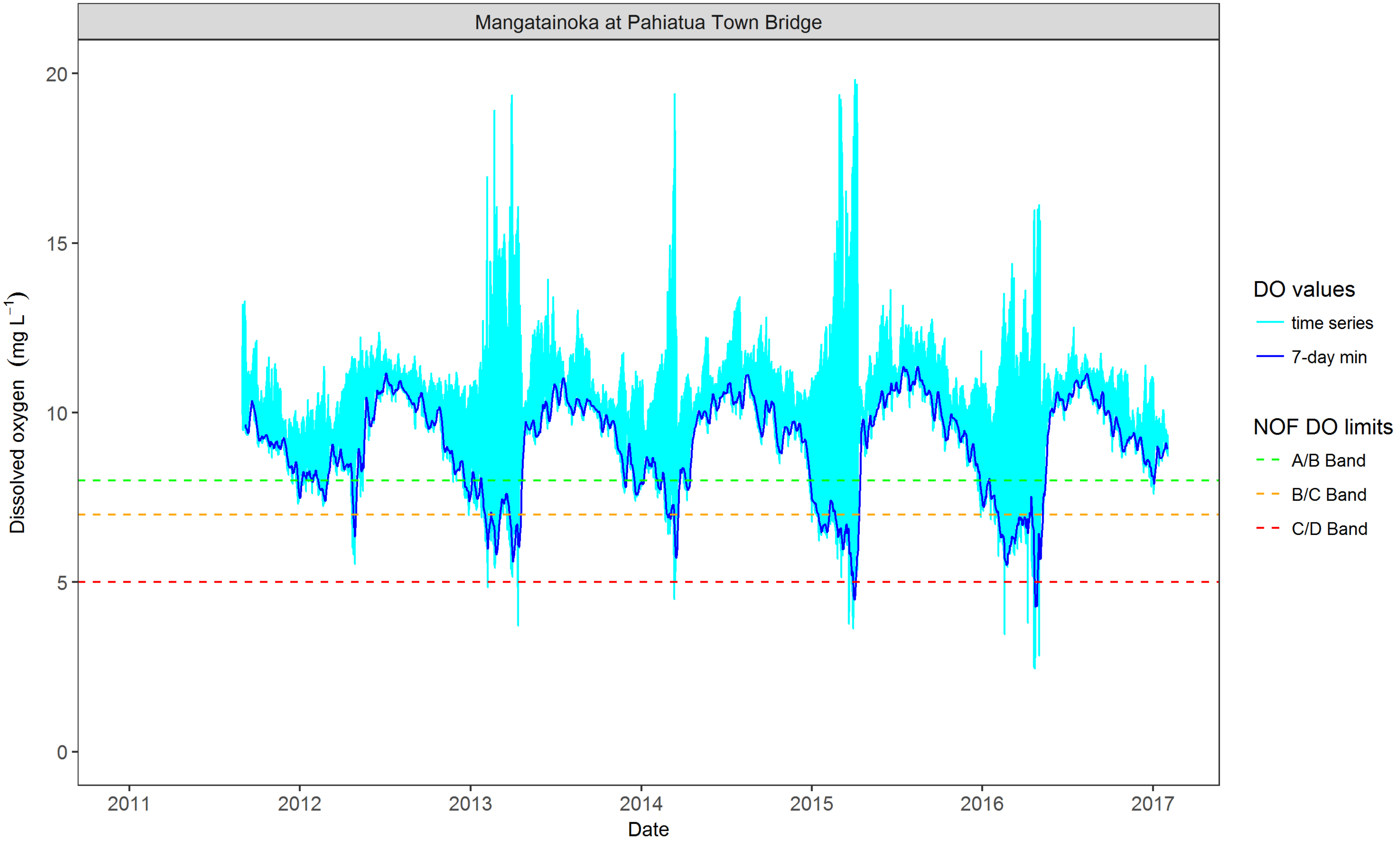
Manawatu at Weber Road
Dissolved oxygen (mg L^{-1})
20
15
10
5
0
2011
2012
2013
2014
2015
2016
2017
Date
DO values
time series
daily min
NOF DO limits
A/B Band
B/C Band
C/D Band

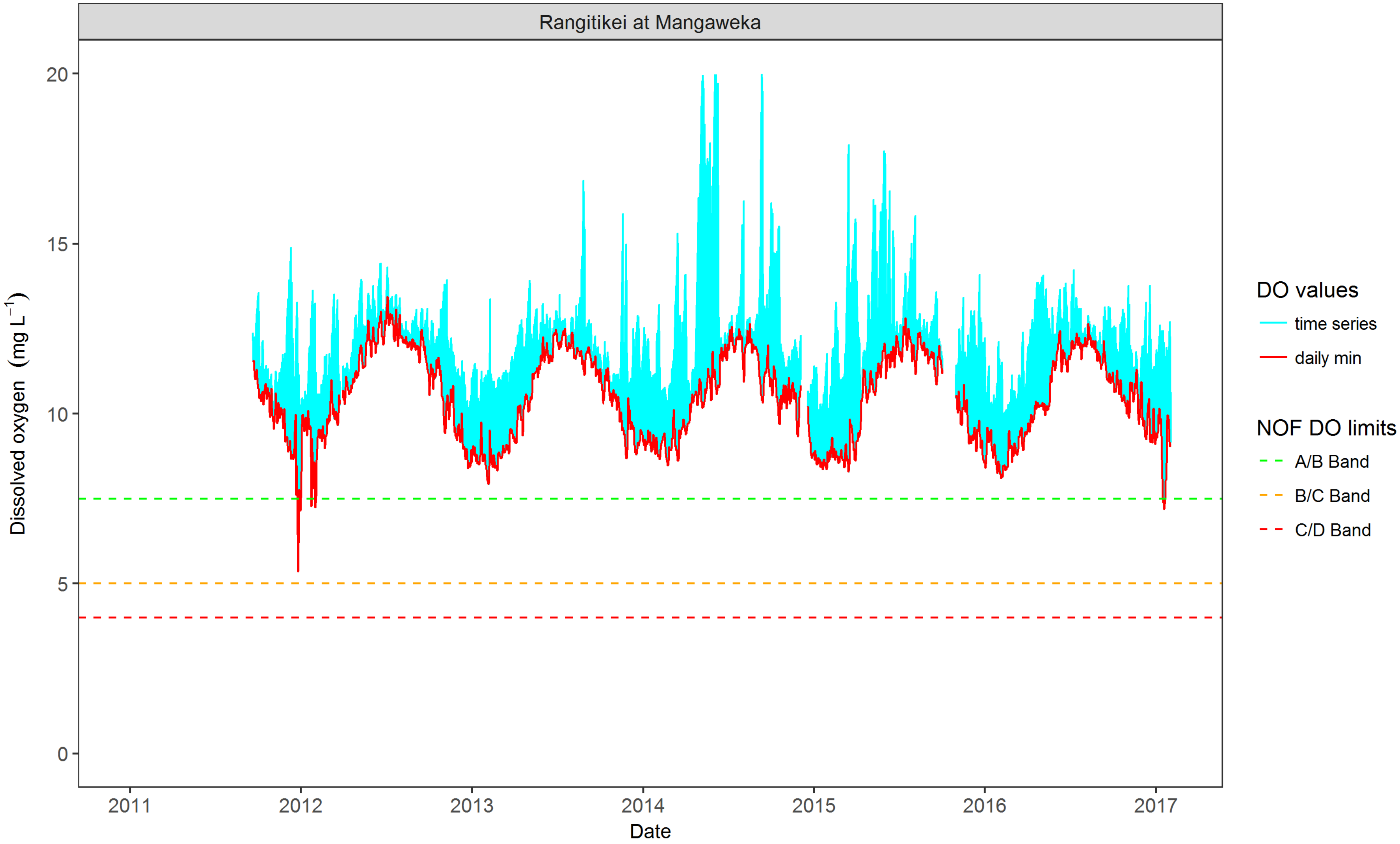


Manawatu at Weber Road
Dissolved oxygen (mg L^{-1})
20
15
10
5
0
2011
2012
2013
2014
2015
2016
2017
Date
DO values
time series
7-day min
NOF DO limits
A/B Band
B/C Band
C/D Band

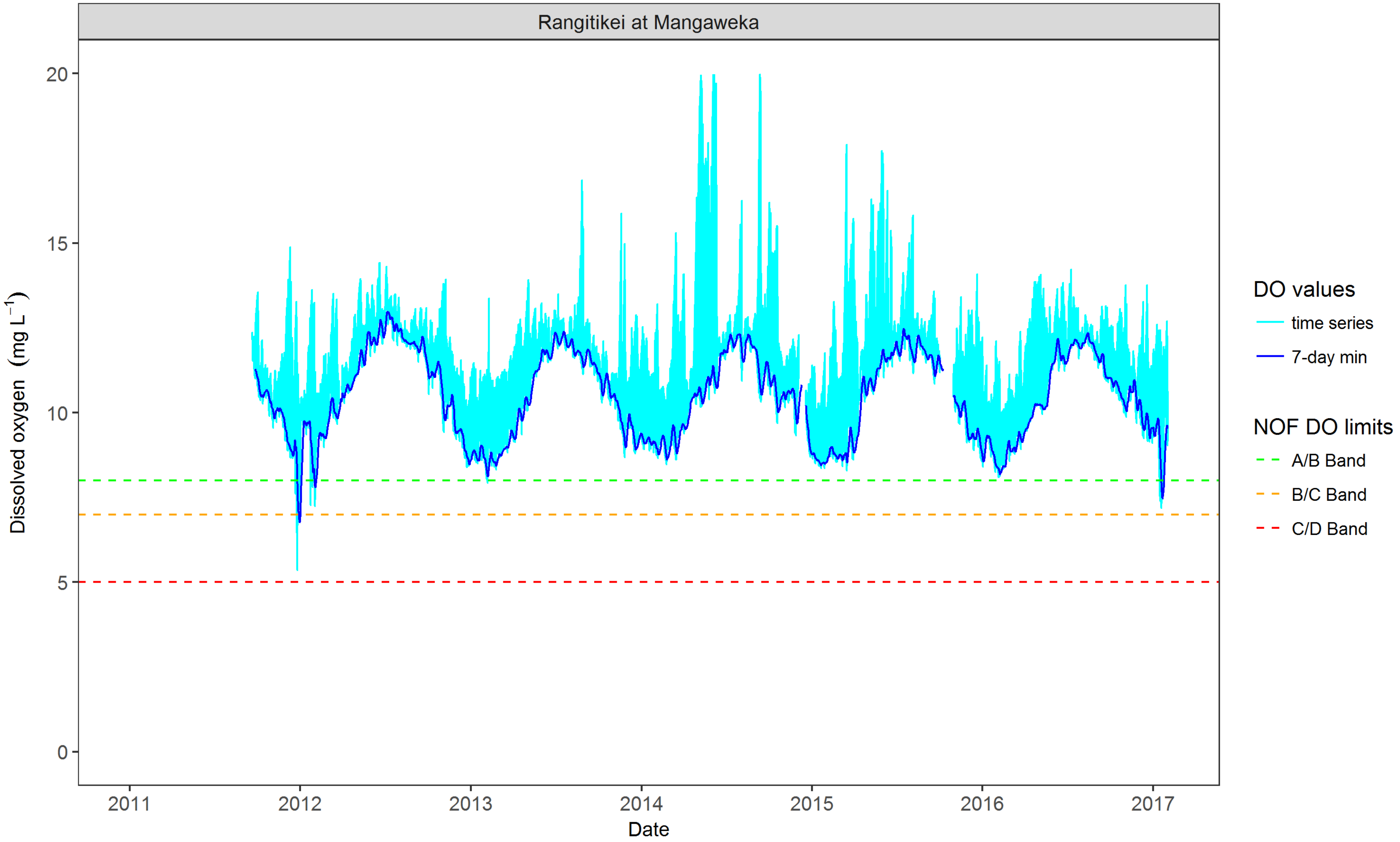


Mangatainoka at Pahiatua Town Bridge
20
15
10
5
0
Dissolved oxygen (mg L⁻¹)
2011
2012
2013
2014
2015
2016
2017
Date
DO values
time series
daily min
NOF DO limits
A/B Band
B/C Band
C/D Band

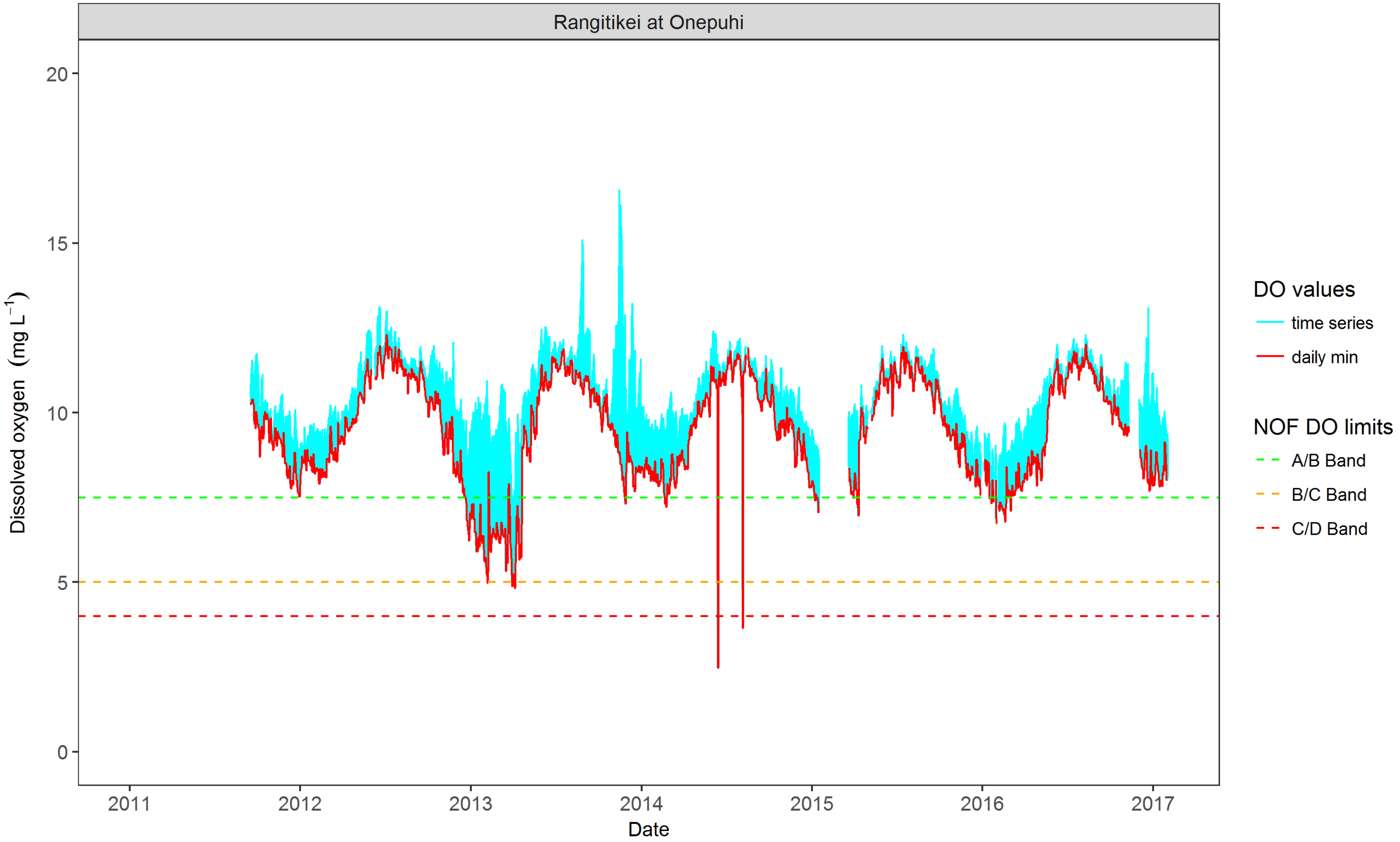

Mangatainoka at Pahiatua Town Bridge
Dissolved oxygen (mg L^{-1})
20
15
10
5
0
2011
2012
2013
2014
2015
2016
2017
Date
DO values
time series
7-day min
NOF DO limits
A/B Band
B/C Band
C/D Band



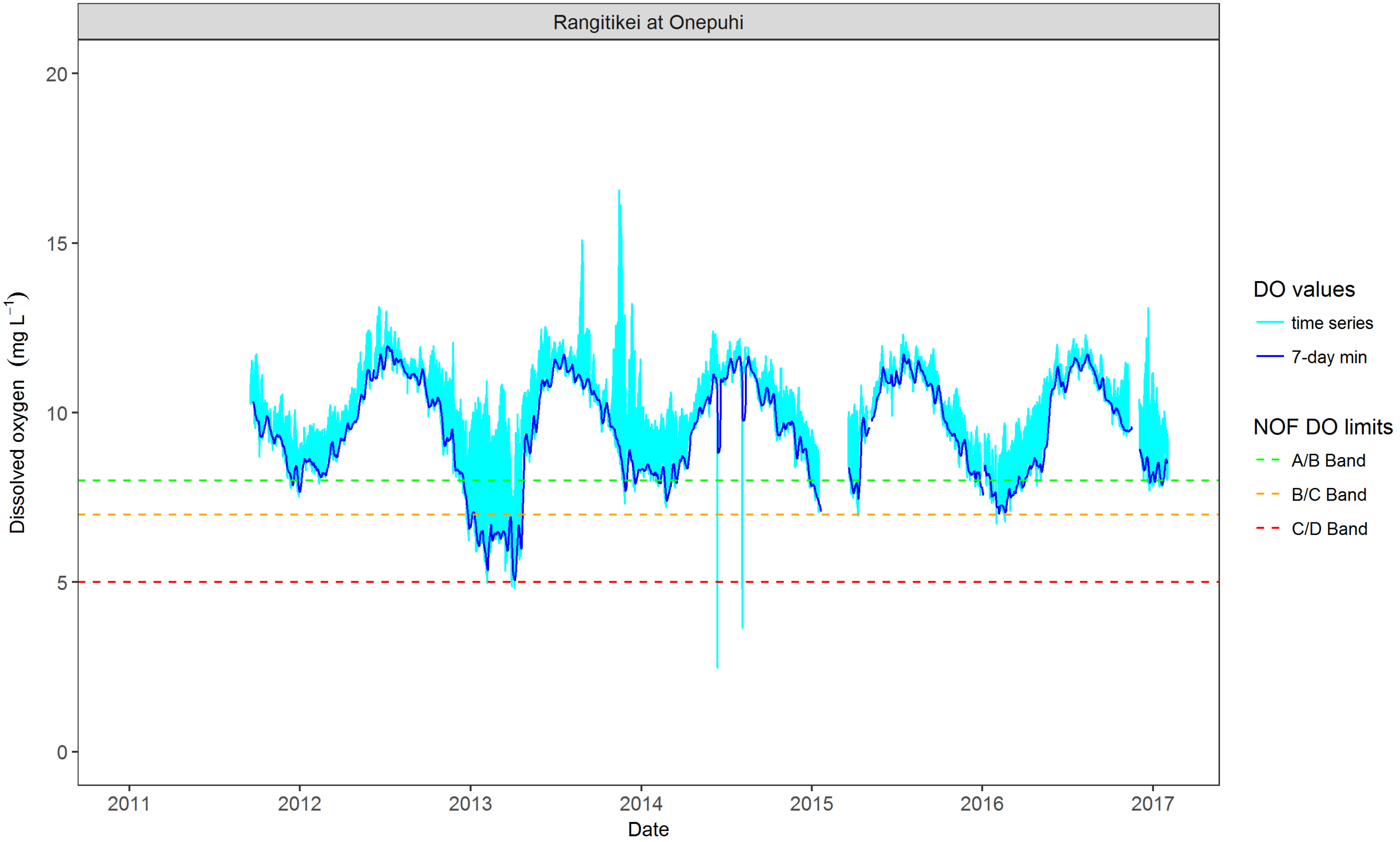
Rangitikei at Mangaweka
Dissolved oxygen (mg L⁻¹)
20
15
10
5
0
2011
2012
2013
2014
2015
2016
2017
Date
DO values
time series
daily min
NOF DO limits
A/B Band
B/C Band
C/D Band



Rangitikei at Mangaweka
Dissolved oxygen (mg L^{-1})
20
15
10
5
0
2011
2012
2013
2014
2015
2016
2017
Date
DO values
time series
7-day min
NOF DO limits
A/B Band
B/C Band
C/D Band

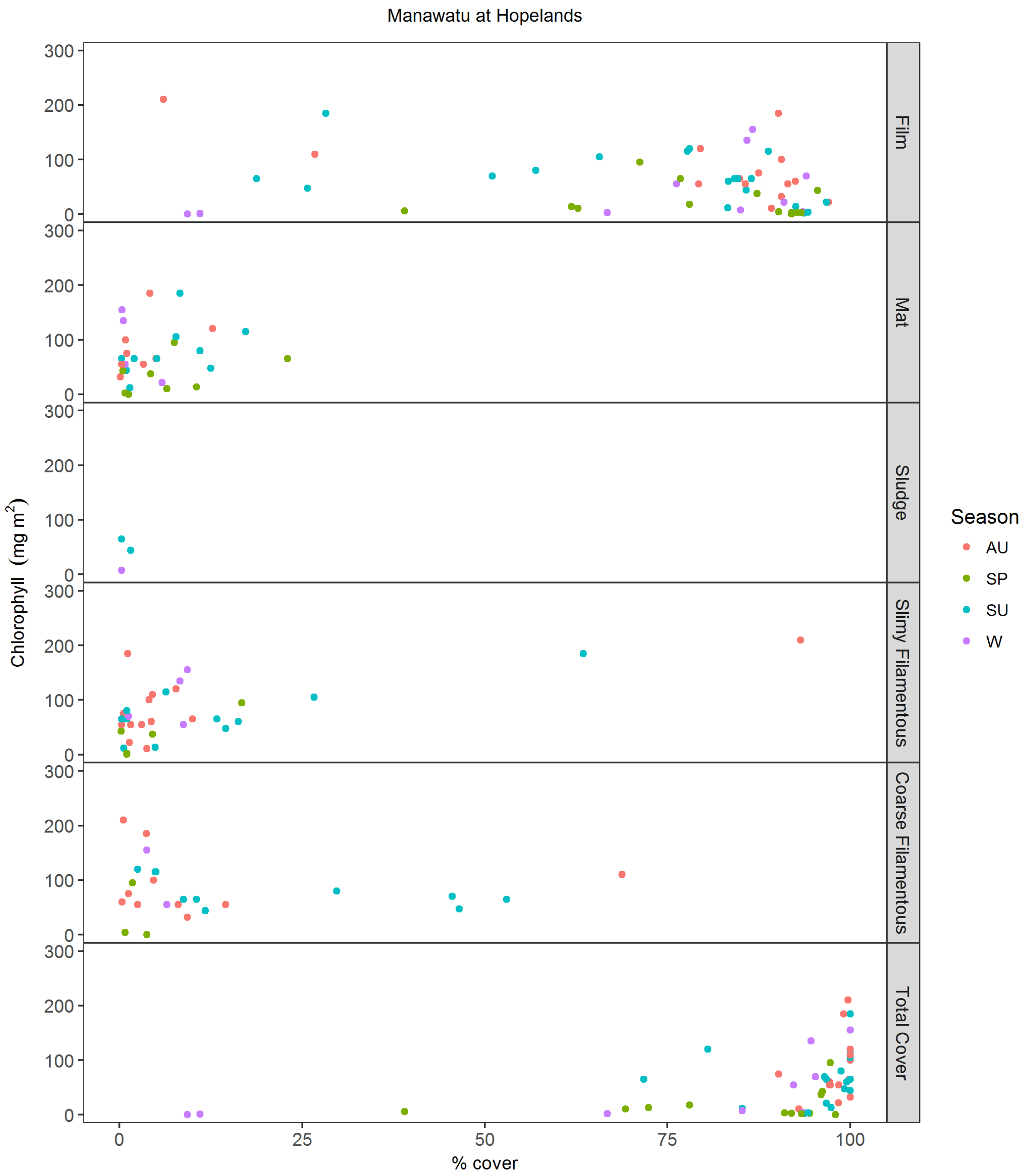


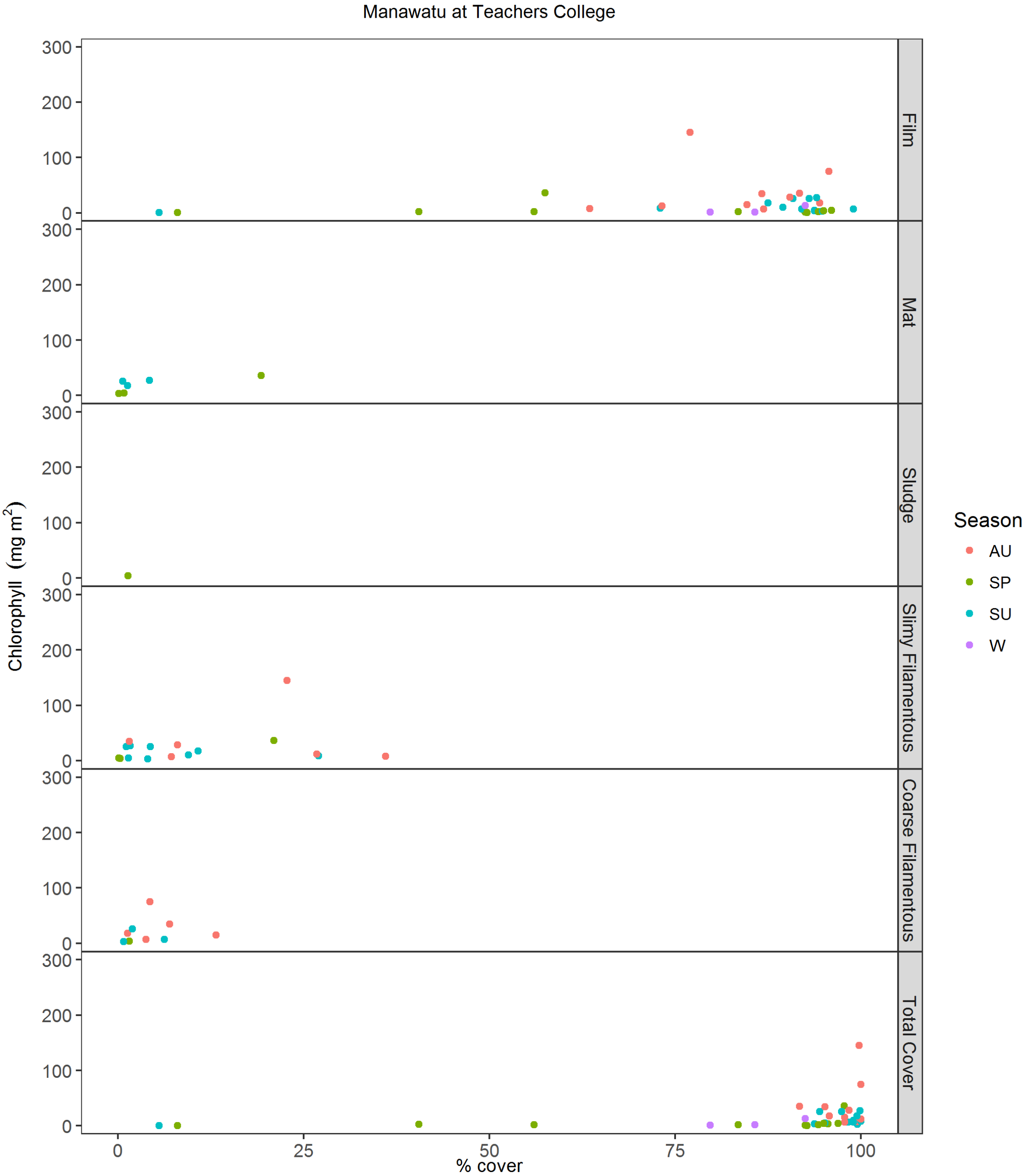
Rangitikei at Onepuhi
Dissolved oxygen (mg L^{-1})
20
15
10
5
0
2011
2012
2013
2014
2015
2016
2017
Date
DO values
time series
daily min
NOF DO limits
A/B Band
B/C Band
C/D Band



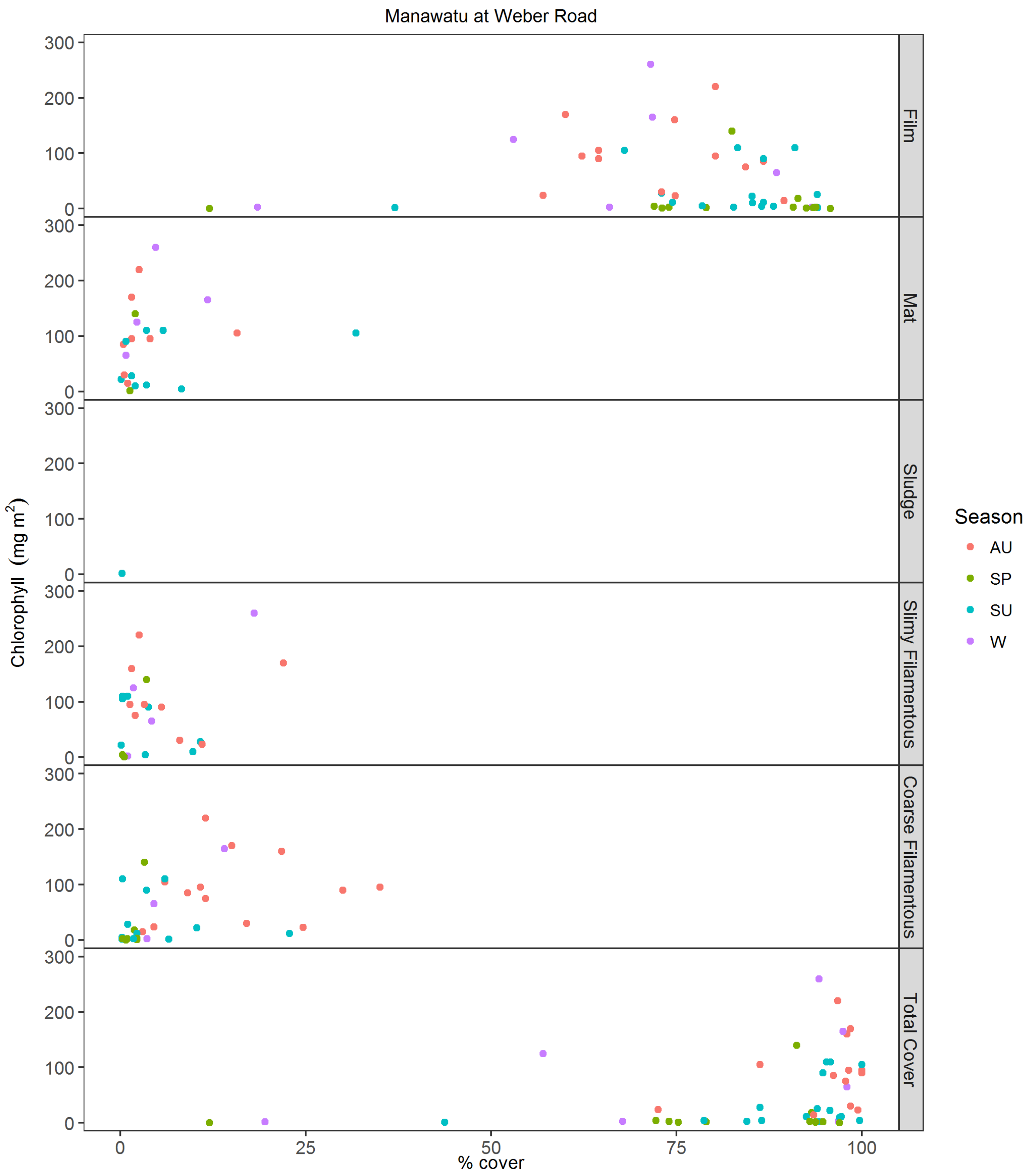
Rangitikei at Onepuhi
Dissolved oxygen (mg L-1)
20
15
10
5
0
2011
2012
2013
2014
2015
2016
2017
Date
DO values
time series
7-day min
NOF DO limits
A/B Band
B/C Band
C/D Band

Figure 4-10: Scatterplots of percent cover of various algal types and total percent cover against algal biomass (chlorophyll-a, mg m^{-2}).

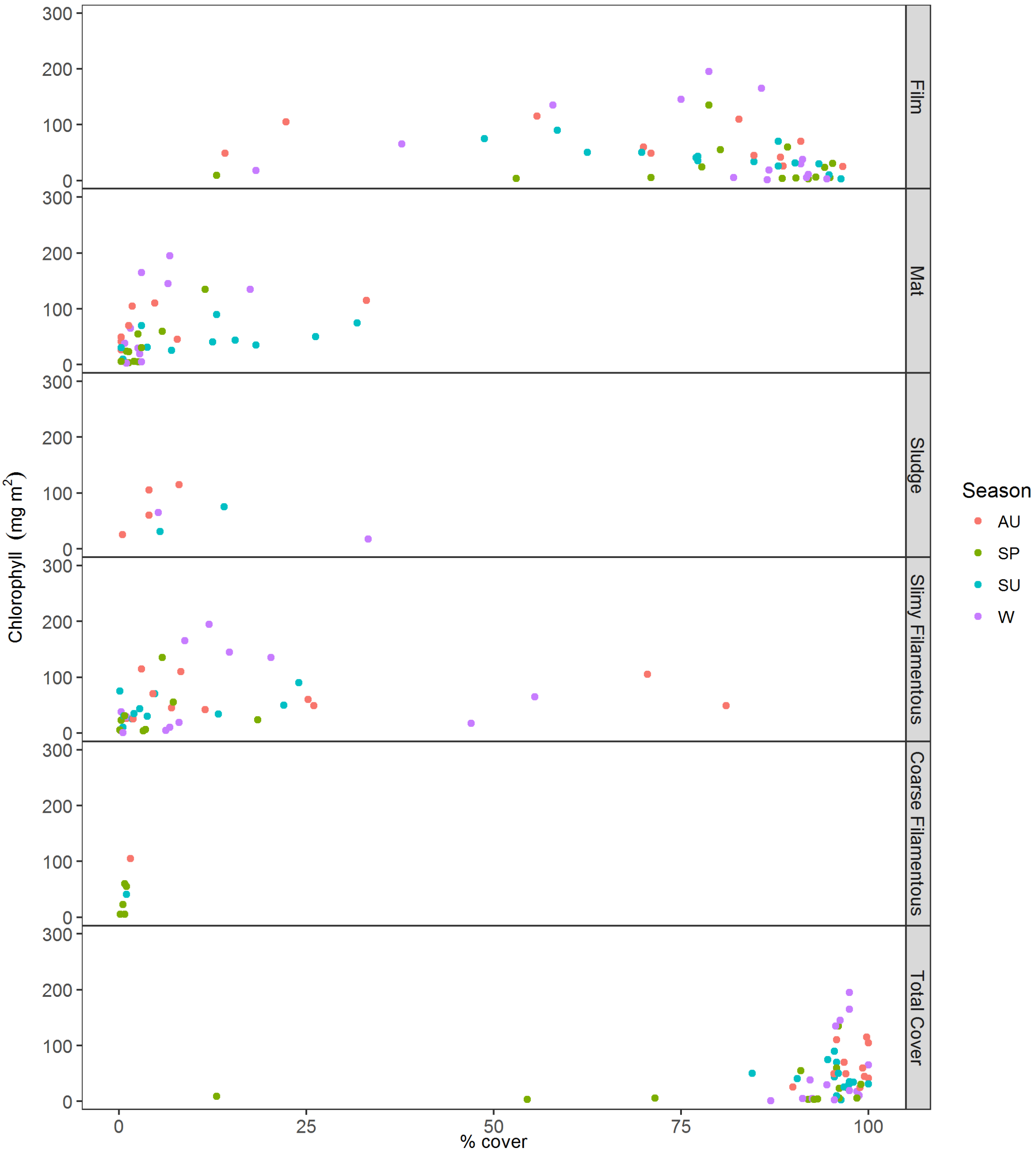


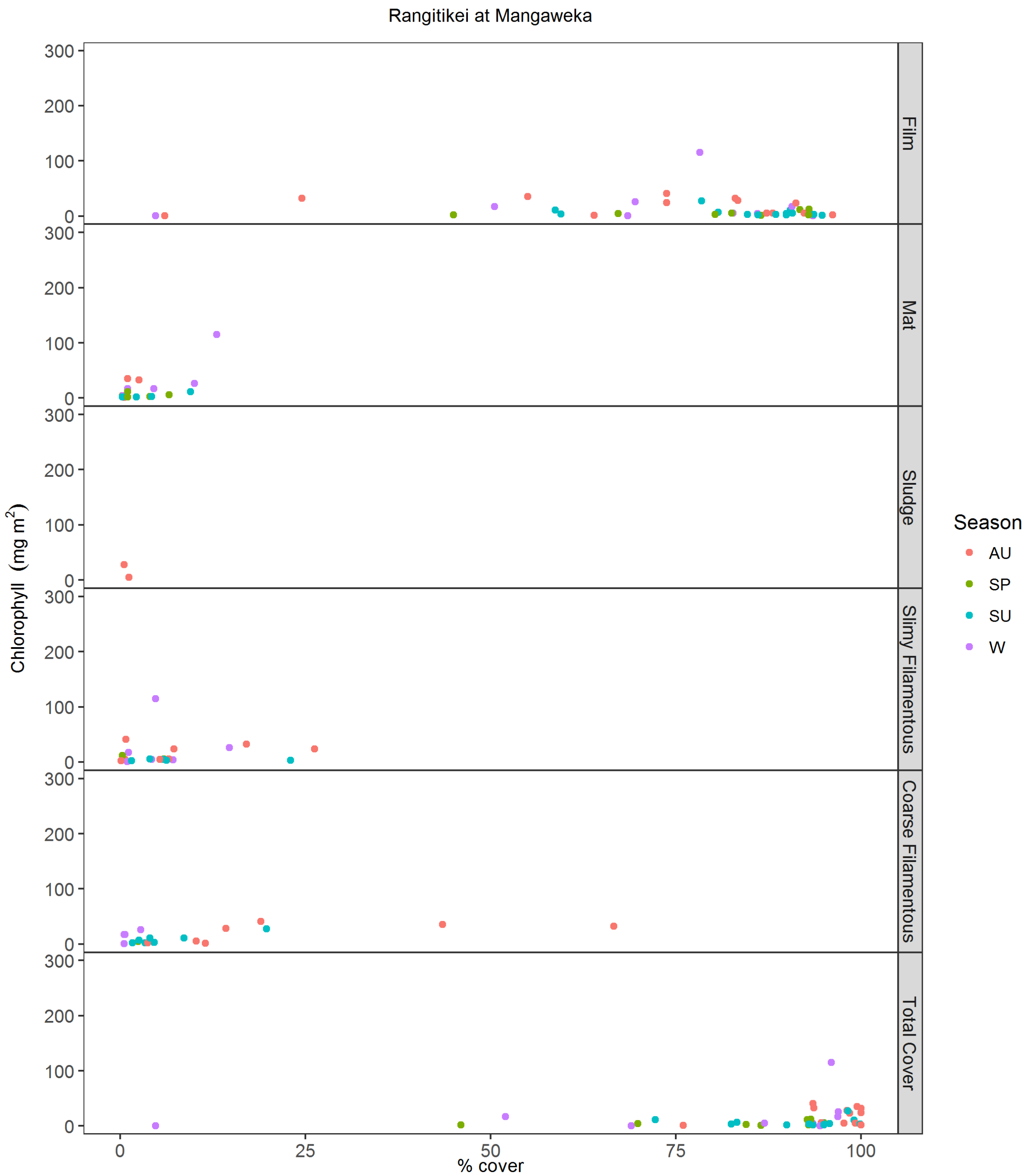


Manawatu at Teachers College
Chlorophyll (mg m^2)
300
200
100
0
Film
Mat
Sludge
Slimy Filamentous
Coarse Filamentous
Total Cover
0
25
50
75
100
% cover
Season
AU
SP
SU
W

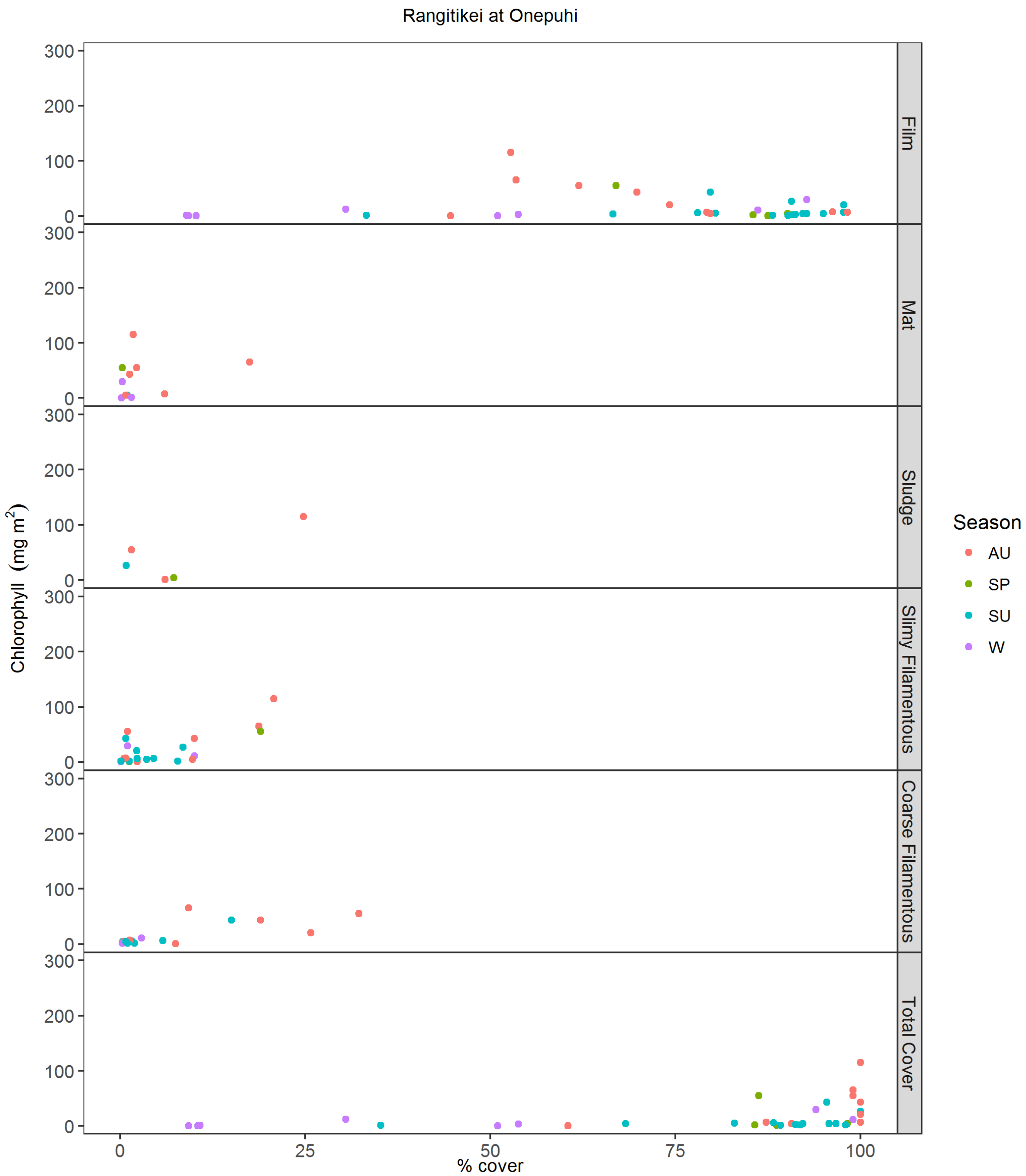

Manawatu at Weber Road
Chlorophyll (mg m^{2})
% cover
Film
Mat
Sludge
Slimy Filamentous
Coarse Filamentous
Total Cover
Season
AU
SP
SU
W
0
100
200
300
0
25
50
75
100

Mangatainoka at Pahiatua Town Bridge





Rangitikei at Mangaweka
Chlorophyll (mg m^2)
300
200
100
0
Film
Mat
Sludge
Slimy Filamentous
Coarse Filamentous
Total Cover
0
25
50
75
100
% cover
Season
AU
SP
SU
W



Rangitikei at Onepuhi
Chlorophyll (mg m^2)
% cover
300
200
100
0
0
25
50
75
100
Film
Mat
Sludge
Slimy Filamentous
Coarse Filamentous
Total Cover
Season
AU
SP
SU
W

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