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Summer dissolved oxygen conditions in six streams in the Waihou catchment, 2009

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Executive Summary

In small streams that are heavily abstracted, reduced flows can result in slower velocities in the lower reaches and amplify the nocturnal sag in dissolved oxygen (DO) levels associated with the dense macrophytes commonly present. Currently, little is known about the extent of these water quality impacts on fish or whether fish migration and/or habitat in small streams is compromised.

Environment Waikato (EW) is currently in the process of reviewing the status of water resource availability and allocation in the Waihou River catchment. One of the key objectives of the water allocation process is to ensure the protection of instream values from the effects of water resource exploitation. To provide an initial evaluation of DO dynamics and identify the potential need for integrating water quality aspects into the instream flow assessment programme, DO loggers were deployed at six lowland stream sites in the Waihou catchment between February and April 2009.

DO minima below 3 mg l^{-1} occurred at four of the six sites monitored during summer low flow conditions. These concentrations are below the recommended acute limits for dissolved oxygen for fish and thus present a potential problem for both resident and migratory fish. The magnitude of this effect will, however, depend on the duration and timing of any low DO episode and the fish species and life stages affected. At one site, mean DO remained below 3 mg l^{-1} for the entire monitoring period and on one occasion was below 1 mg l^{-1} for over two days. This is likely to cause severe impairment to fish and other ecological communities in the stream.

It is recommended that further monitoring of DO is carried out in the Waihou catchment and that DO depletion is considered in decisions regarding flow allocation.

1. Introduction

Lowland streams are important habitat for lowland fish species, but also critical migratory pathways to and from upstream habitats. Maintenance of suitable conditions for fish passage, as well as habitat for resident species, is an important consideration in establishing environmental flow requirements. Traditionally, this process has focussed on the relationships between flow and physical habitat, but as pressures on lowland river reaches increase in response to both land use change and more intensive use of water resources, the potential for impacts on fish via water quality changes, especially in smaller streams, is increasing. In small streams that are heavily abstracted, the reduced flow can result in slower velocities in the lower reaches and amplify the nocturnal sag in dissolved oxygen (DO) levels associated with the dense macrophytes and/or algae commonly present. Currently, little is known about the extent of these water quality impacts on fish or whether fish habitat in small streams is compromised. Nor is it known whether a low DO environment may inhibit migrations of fish through these reaches. Evidence is, however, beginning to emerge suggesting that, for some lowland streams in New Zealand, the flows required to maintain a water quality environment suitable for fish may be higher than those recommended on the basis of physical habitat assessment alone. There is therefore a need to identify the key water quality parameters for fish that are influenced by water abstraction.

Environment Waikato (EW) is currently in the process of reviewing the status of water resource availability and allocation in the Waihou River catchment. One of the key objectives of this process is to ensure the protection of instream values from the effects of water resource exploitation. Jowett (2008) identified minimum flow requirements for fish habitat in the Waihou River and selected tributaries. Franklin and Booker (2009) also investigated the role of flow variability for instream ecology in the Waihou River catchment. The next stage of the assessment process is to evaluate the need for flows to maintain appropriate water quality standards within the catchment. Of primary concern is the impact of low flows on DO dynamics. In order to provide an initial evaluation of DO status, DO loggers were deployed at six lowland stream sites in the Waihou catchment between February and April 2009. This report summarises the results of this monitoring.

2. Monitoring sites

Dissolved oxygen loggers were deployed at seven locations within the Waihou catchment in February 2009 (Table 2.1; Figure 2.1). A range of sites including the main river and selected lowland tributaries were monitored. Particular focus was placed on the Mangawhero Stream as this was previously identified as possibly being susceptible to low dissolved oxygen conditions (Jowett 2008).

Table 2.1: Grid references of the dissolved oxygen monitoring sites

Site	Location	Easting	Northing
1	Waihou River (Leslie Road)	2759275	6347795
2	Mangawhero Stream (Totman Road)	2751105	6359870
3	Mangawhero Stream (SH29)	2753605	6364800
4	Mangawhero Stream (SH27)	2753685	6366545
5	Depression Stream (Manawaru Road)	2757273	6386560
6	Karengorengo Stream (Tower Road)	2758628	6384754
7	Waihou River (Te Aroha)	2749470	6402765

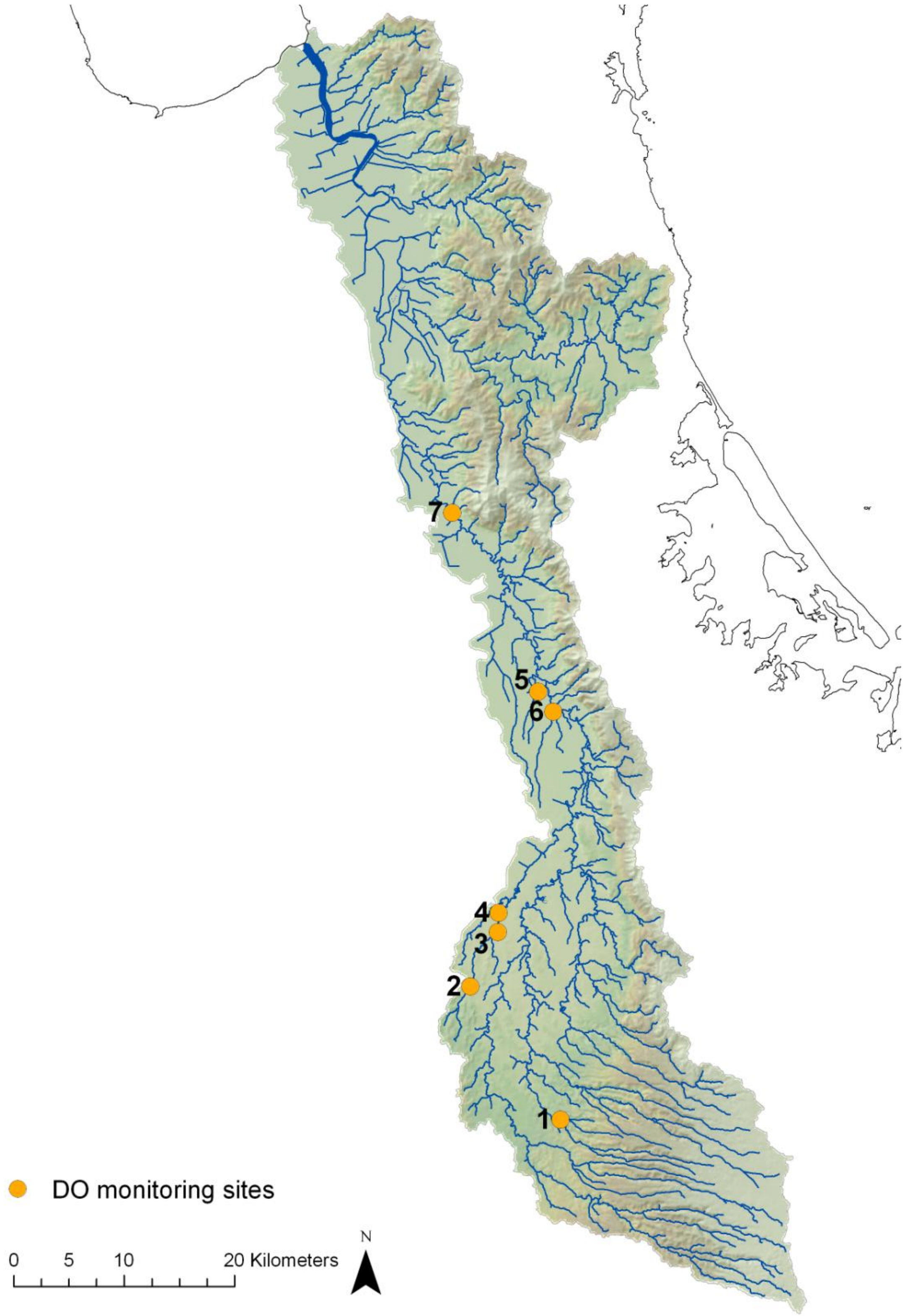

Figure 2.1: Location of dissolved oxygen monitoring sites in the Waihou catchment.

2.1 Site descriptions

Site 1 – Waihou River (Leslie Road)

Site 1 was in the upper Waihou River by the footbridge near Leslie Road. The river is predominately groundwater fed at this point and had a mean wetted width of 12 m. Substrate was mainly gravel with occasional patches of sand. Macrophytes were abundant and could be found as large patches instream and as floating mats in the margins. Land use was a mixture of rough pasture and bush (Figure 2.2).

Figure 2.2: Waihou River near Leslie Road.

Site 2 – Mangawhero Stream (Totman Road)

Site 2 was located in the Mangawhero Stream at the Totman Road bridge. Mean wetted width was about 2 m and mean depth around 0.4 m. Substrate was dominated by silt with occasional areas of gravel. Macrophytes were highly abundant and frequently covered the whole width of the stream. Land use was dominated by dairying.

Site 3 – Mangawhero Stream (SH29)

Site 3 was in the Mangawhero Stream by the SH29 road bridge. Mean wetted width was around 2 m and depth about 0.6 m. The substrate was primarily silt and the channel was completely filled with aquatic macrophytes (Figure 2.3). Land use was predominantly pasture.

Figure 2.3: Views of the Mangawhero Stream upstream and downstream of the SH29 bridge.

Site 4 – Mangawhero Stream (SH27)

Site 4 was in the Mangawhero Stream by the SH27 road bridge (Figure 2.4). Wetted width was approximately 3 m and mean depth about 0.7 m. Substrate was dominated by silt with occasional patches of sand. Habitat was primarily a combination of glides and pools. Aquatic macrophytes were again highly abundant within the stream, where they were not restricted by shading from riparian tree cover. Land use was primarily pasture for dairying.

Figure 2.4: View of the Mangawhero Stream upstream of the SH27 bridge.

Site 5 – Depression Stream (Manawaru Road)

Site 5 was in Depression Stream at the Manawaru Road bridge. Mean wetted width was approximately 2 m and mean depth about 0.4 m. Substrate was dominated by silt, with a high abundance of aquatic macrophytes. Land use was pasture and at the time of the survey the stream was not fenced off from livestock (Figure 2.5).

Figure 2.5: Views of Depression Stream downstream of the Manawaru Road bridge.

Site 6 – Karengorengo Stream (Tower Road)

Site 6 was located on the Karengorengo Stream at the Tower Road bridge. Mean wetted width was approximately 2.8 m and mean depth about 0.4 m. Substrate was dominated by sand, with some marginal aquatic macrophytes. Mesohabitat was dominated by runs interspersed with occasional pools. Land use was rough pasture and the stream was not fenced off from livestock (Figure 2.6).

Figure 2.6: Views of Karengorengo Stream upstream of the Tower Road bridge.

Site 7 – Waihou River (Te Aroha)

Site 7 was located by the footbridge over the Waihou River at Te Aroha. The median 7-day low flow at this site is 25.44 $m^3 s^{-1}$, and the river had a mean width of approximately 40 m. Landuse was a combination of urban and agricultural uses. Unfortunately, the logger located at this site disappeared in the final week before retrieval in mid-April and thus no data is available for this site.

2.2 Methodology

D-Opto loggers supplied and calibrated by Environment Waikato were used to collect temperature (°C) and dissolved oxygen (% saturation and mg l^{-1}) records throughout the study period. The loggers use a solid-state optical sensing system to measure dissolved oxygen and are considered highly stable over long periods of time. The loggers were deployed on either 12 or 13 February 2009 and set to record at 15 min intervals. All loggers, except for Site 1, were temporarily retrieved from the stream on 27 February due to the expectation of high rainfall and were redeployed on either 9 or 10 March. All loggers were then finally retrieved on 16 April and the data downloaded.

2.3 Data analysis

Following data checking, summary statistics were derived describing the DO dynamics at each site. A time series was plotted and diel variation graphed using boxplots of data at 15 min intervals for each site. Each box encloses 50% of the data, with the median value displayed as a line. The whiskers show the range of values, with outliers displayed as individual points. Percentage exceedence curves were also derived for DO concentration at each site. These indicate the percentage of the monitoring period for which a particular DO concentration was equalled or exceeded. Results were compared against recommended DO concentrations for adult fish as proposed by Dean and Richardson (1999) (Table 4.1).

3. Results

3.1 Flows

The DO monitoring was timed to coincide with the late summer low flow period when problems with low dissolved oxygen were considered most likely to occur. Flow data were not available for each of the individual survey sites, but to give an indication of flow dynamics over the monitoring period water levels recorded at the Shaftesbury gauging station located in the middle reaches of the Waihou River are shown in Figure 3.1. The period from 01 January to the beginning of the monitoring period (12 February) was typically characterised by stable, low flows. Following commencement of DO monitoring, three significant storm events occurred between 20 February and 10 March which resulted in elevated flows (Figure 3.1). At the request of EW, the DO loggers were removed from all but Site 1 during the two largest events, meaning that only limited data is available on the response of DO to changes in flow. The effects of the first storm event were however captured at all sites.

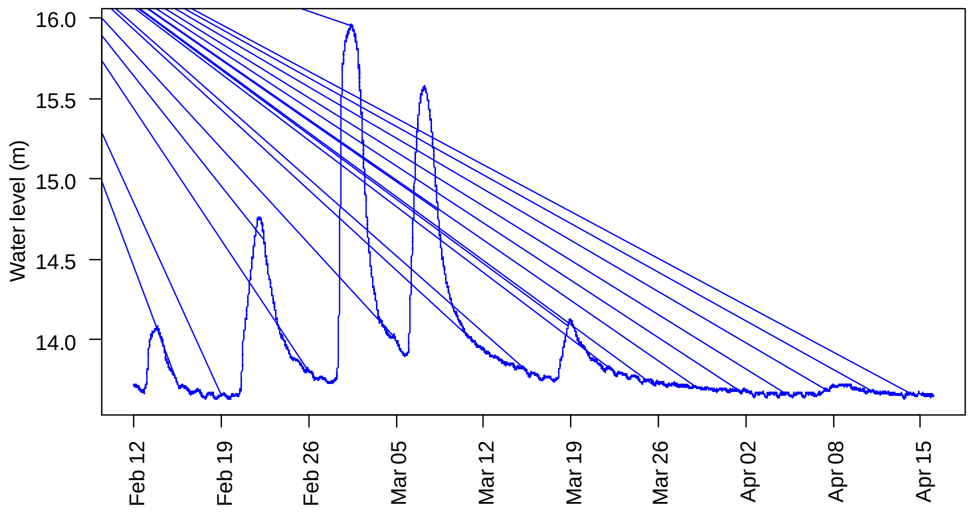

Figure 3.1: Water levels recorded at the Shaftesbury gauging station on the Waihou River over the DO monitoring period (Source: Data downloaded from EW website).

3.2 Dissolved oxygen

Site 1 – Waihou River at Leslie Road

This site was selected as a control to evaluate the impact of abundant aquatic macrophytes on DO dynamics under more pristine river conditions. The DO dynamics of the reach over the monitoring period are shown in Figure 3.2 and are summarised in Table 3.1. DO saturation typically varies between 80% and 100% over the daily cycle, with a mean of 86.3%. EW state that water should be more than 80% saturated for aquatic plants and animals to thrive in it. DO fell below this threshold for only 5% of the time at this site. This was primarily associated with a storm event which occurred in late February, resulting in DO minima down to 77% saturation. The other storm events which followed later in the month and in early March appear to have had no significant impact on DO levels.

On average, the DO maxima occurred at around 14:00h, with a relatively stable minimum throughout the hours of darkness. The difference between mean daily maximum and minimum values was 1.5 mg l^{-1}, indicating a relatively stable dissolved oxygen environment within the stream.

Table 3.1: Summary of dissolved oxygen dynamics at Site 1.

Parameter	Value
Mean DO	9.1 mg l^{-1} (86.3%)
Maximum DO	11.1 mg l^{-1} (104.8%)
Minimum DO	7.9 mg l^{-1} (77.2%)
Mean daily maximum DO	10.1 mg l^{-1} (96.2%)
Mean daily minimum DO	8.6 mg l^{-1} (81.6%)
% of time DO <80% saturation	4.9%
% of time DO <3 mg l^{-1}	0%
Maximum duration of DO <3 mg l^{-1}	0 hours

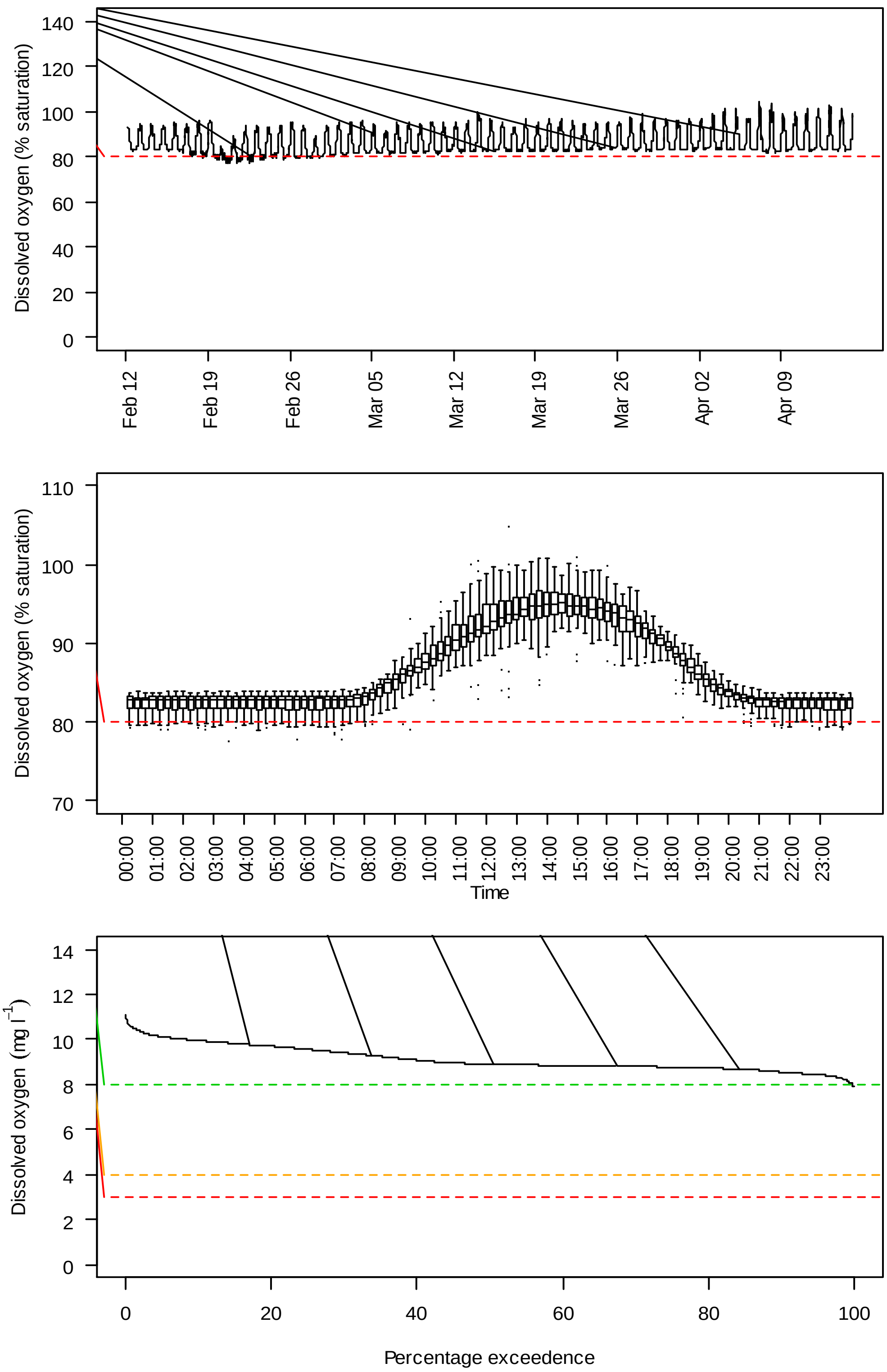

Figure 3.2: Dissolved oxygen time series (top), diel variability (middle) and duration curve (bottom) recorded in the Waihou River nr. Leslie Road between 12/02/09 and 15/04/09. Dashed red line at 80% saturation (top; middle) represents EW recommended level for aquatic plants and animals to thrive in. Dashed lines in the bottom figure show recommended DO concentrations for adult fish (Green (8mg l^{-1}) = no impairment; Orange (4 mg l^{-1}) = severe impairment; Red (3 mg l^{-1}) = acute limit).

Site 2 – Mangawhero Stream at Totman Road

The DO record for the monitoring period is summarised in Figure 3.3 and Table 3.2. The monitoring probe was removed from the stream for around a week at the beginning of March due to expected high flows. The battery then ran out at the end of March. Mean DO for the site over the sampling period was 7.0 mg l^{-1} (71.4% saturation), but ranged from 4.7 mg l^{-1} (54.6%) to 8.3 mg l^{-1} (84.2%). DO was below the 80% threshold recommended by EW for 97% of the time. However, the average daily minimum was 67.4% and at no stage did DO concentrations fall below 3 mg l^{-1}. This indicates that the degree of impairment is likely to have been relatively low. During the high flow event on 20 February, mean DO was lowered.

The diel variation in DO was lower at this site compared to Site 1, with a difference of 0.9 mg l^{-1} between the mean daily maximum and minimum DO concentrations. However, this is partially attributable to a higher degree of daily variation across the monitoring period. On average, peak concentrations occurred at around 15:00h, with the minimum occurring at around 08:00h (Figure 3.3).

Table 3.2: Summary of dissolved oxygen dynamics at Site 2.

Parameter	Value
Mean DO	7.0 mg l^{-1} (71.4%)
Maximum DO	8.3 mg l^{-1} (84.2%)
Minimum DO	4.7 mg l^{-1} (54.6%)
Mean daily maximum DO	7.4 mg l^{-1} (76.6%)
Mean daily minimum DO	6.5 mg l^{-1} (67.4%)
% of time DO <80% saturation	97.3%
% of time DO <3 mg l^{-1}	0%
Maximum duration of DO <3 mg l^{-1}	0 hours

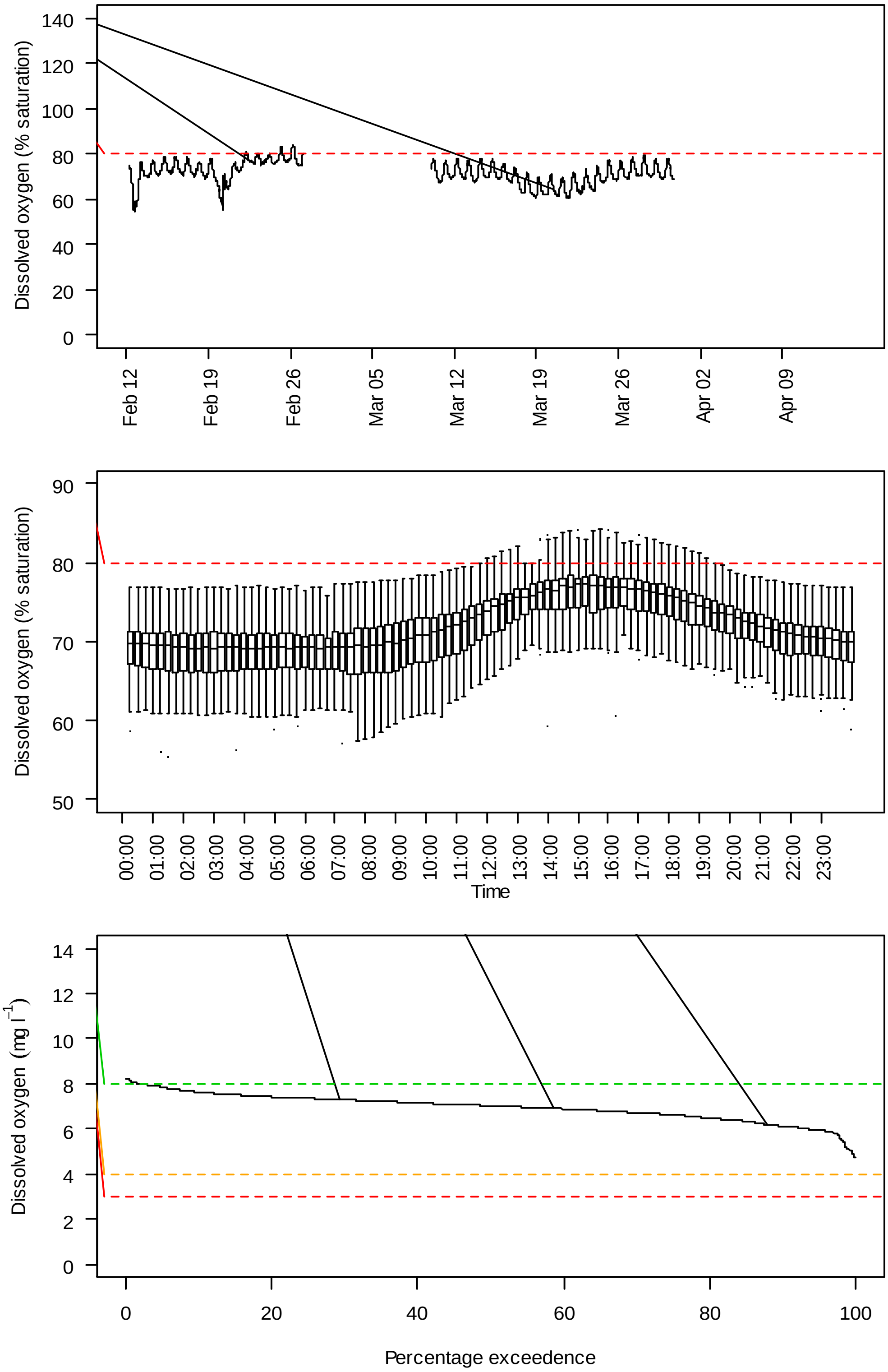

Figure 3.3: Dissolved oxygen time series (top), diel variability (middle) and duration curve (bottom) recorded at Site 2 in the Mangawhero Stream at Totman Road between 12/02/09 and 15/04/09. Dashed red line at 80% saturation (top; middle) represents EW recommended level for aquatic plants and animals to thrive in. Dashed lines in the bottom figure show recommended DO concentrations for adult fish (Green (8mg l^{-1}) = no impairment; Orange (4 mg l^{-1}) = severe impairment; Red (3 mg l^{-1}) = acute limit).

Site 3 – Mangawhero Stream at SH29

The DO record for the monitoring period is summarised in Figure 3.4 and Table 3.3. The monitoring probe was removed from the stream for around a week at the beginning of March due to expected high flows. Mean DO for the site over the sampling period was 1.2 mg l^{-1} (12.0% saturation), but ranged from 0.5 mg l^{-1} (5.5%) to 4.0 mg l^{-1} (38.0%). DO was below the 80% threshold recommended by EW for 100% of the time and below 3 mg l^{-1}, which is the recommended acute limit for adult fish, for 97.5% of the monitoring period (Figure 3.4; bottom). This indicates a significant problem with low DO in this reach and means that it is extremely likely that aquatic communities would be significantly impaired. Whilst the characteristics of this site make it susceptible to low DO episodes, the sustained nature of low DO concentrations at the site could indicate the presence of a point or diffuse discharge with high oxygen demand. This is supported by the increase in DO levels associated with elevated flows caused by the storm event on 20 February, which would have diluted the impact of any discharge.

During February, there was no strong pattern evident in the DO dynamics of the reach. Slight peaks in DO are recorded in association with elevated flows. Through March and into April a typical diel cycle in DO concentrations developed. The difference between mean daily maximum and minimum DO concentrations was relatively low at 0.8 mg l^{-1}, despite a high abundance of aquatic macrophytes being present. On average, peak concentration occurred at around 16:00, with the minimum occurring at around 08:00 (Figure 3.4).

Table 3.3: Summary of dissolved oxygen dynamics at Site 3.

Parameter	Value
Mean DO	1.2 mg l^{-1} (12.0%)
Maximum DO	4.0 mg l^{-1} (38.0%)
Minimum DO	0.5 mg l^{-1} (5.5%)
Mean daily maximum DO	1.9 mg l^{-1} (19.3%)
Mean daily minimum DO	0.8 mg l^{-1} (8.1%)
% of time DO <80% saturation	100%
% of time DO <3 mg l^{-1}	97.5%
Maximum duration of DO <3 mg l^{-1}	161.5 hours

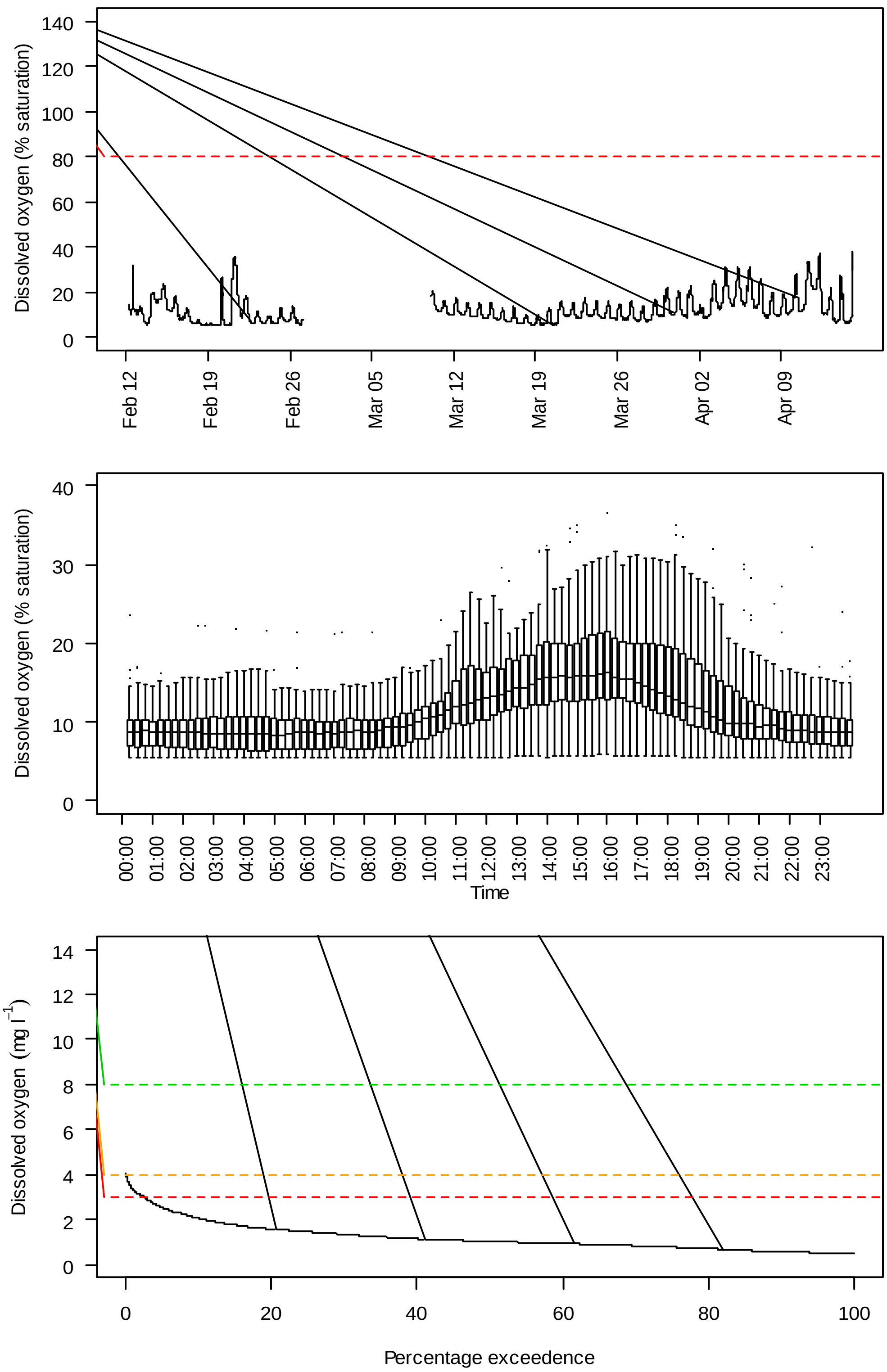

Figure 3.4: Dissolved oxygen time series (top), diel variability (middle) and duration curve (bottom) recorded at Site 3 in the Mangawhero Stream at SH29 between 12/02/09 and 15/04/09. Dashed red line at 80% saturation (top; middle) represents EW recommended level for aquatic plants and animals to thrive in. Dashed lines in the bottom figure show recommended DO concentrations for adult fish (Green (8mg l^{-1}) = no impairment; Orange (4 mg l^{-1}) = severe impairment; Red (3 mg l^{-1}) = acute limit).

Site 4 – Mangawhero Stream at SH27

The DO record for the monitoring period is summarised in Figure 3.5 and Table 3.4. The monitoring probe was removed from the stream for around a week at the beginning of March due to expected high flows and the battery ran low at the end of March. Mean DO for the site over the sampling period was 3.6 mg l^{-1} (37.3% saturation), but ranged from 2.1 mg l^{-1} (23.2%) to 5.6 mg l^{-1} (57.4%). DO was below the 80% threshold recommended by EW for 100% of the time and below 3 mg l^{-1}, which is the recommended acute limit for adult fish, for 20.7% of the monitoring period. This indicates a recovery in the DO levels from Site 3 upstream, but DO is likely to remain a problem within this reach and it is likely that aquatic communities would be impaired. The longest continuous duration over which DO remained below the acute limit of 3 mg l^{-1} was 15.5 hours. For approximately 70% of the time, DO levels were below 4 mg l^{-1} which is the threshold below which severe impairment of adult fish becomes likely.

A typical diel variation in DO concentrations was observed throughout the monitoring period (Figure 3.5). The difference between mean daily maximum and minimum DO concentrations was 1.4 mg l^{-1}, reflecting the influence of aquatic macrophytes on DO levels. On average, peak concentration occurred at around 15:00, with the minimum occurring at around 07:00 (Figure 3.5).

Table 3.4: Summary of dissolved oxygen dynamics at Site 4.

Parameter	Value
Mean DO	3.6 mg l^{-1} (37.3%)
Maximum DO	5.6 mg l^{-1} (57.4%)
Minimum DO	2.1 mg l^{-1} (23.2%)
Mean daily maximum DO	4.4 mg l^{-1} (46.0%)
Mean daily minimum DO	3.0 mg l^{-1} (31.0%)
% of time DO <80% saturation	100%
% of time DO <3 mg l^{-1}	20.7%
Maximum duration of DO <3 mg l^{-1}	15.5 hours

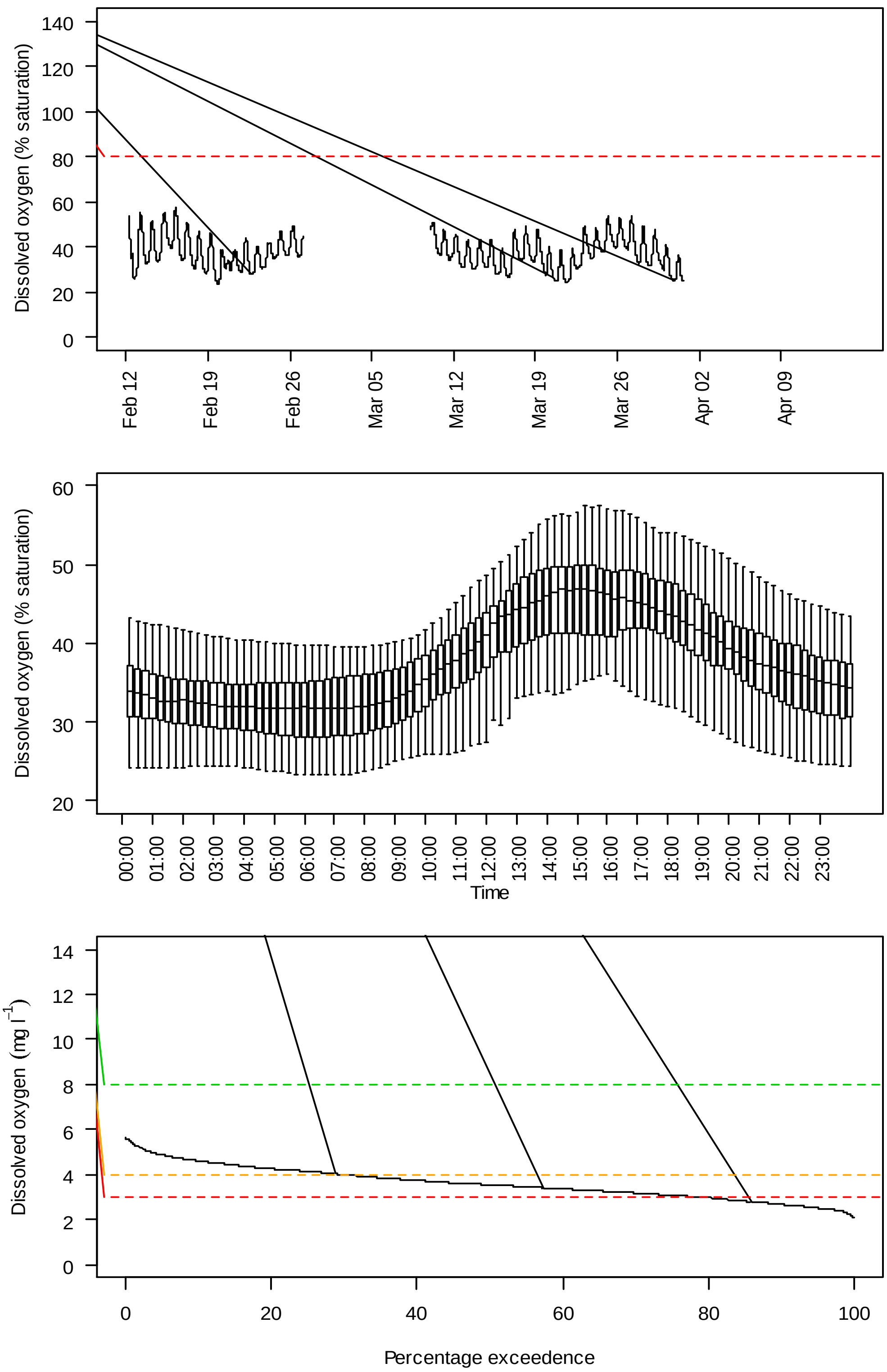

Figure 3.5: Dissolved oxygen time series (top), diel variability (middle) and duration curve (bottom) recorded at Site 4 in the Mangawhero Stream at SH27 between 12/02/09 and 15/04/09. Dashed red line at 80% saturation (top; middle) represents EW recommended level for aquatic plants and animals to thrive in. Dashed lines in the bottom figure show recommended DO concentrations for adult fish (Green (8mg l^{-1}) = no impairment; Orange (4 mg l^{-1}) = severe impairment; Red (3 mg l^{-1}) = acute limit).

Site 5 – Depression Stream at Manawaru Road

The DO record for the monitoring period is summarised in Figure 3.6 and Table 3.5. The monitoring probe was removed from the stream for around a week at the beginning of March due to expected high flows and the battery ran out towards the end of March. Mean DO for the site over the sampling period was 5.6 mg l^{-1} (58.1% saturation), but ranged from 1.2 mg l^{-1} (13.6%) to 13.2 mg l^{-1} (140.4%). It is notable that at this site there was an increasing trend in mean DO with time. DO was also lower during the elevated flows which occurred during late February. DO was below the 80% threshold recommended by EW for 80.8% of the time and below the threshold of 3 mg l^{-1} for 15.7% of the monitoring period. The longest continuous duration over which DO remained below the acute limit of 3 mg l^{-1} was 24 hours. For approximately 30% of the time, DO levels were below 4 mg l^{-1} which is the threshold below which severe impairment of adult fish becomes likely.

A strong diel variation in DO concentrations was observed throughout the monitoring period and it appears that the magnitude of the variation becomes greater with time as the daily maxima increases (Figure 3.6). The difference between mean daily maximum and minimum DO concentrations was high (3.9 mg l^{-1}), reflecting the significant influence of aquatic macrophytes on DO levels at this site. On average, peak concentration occurred at around 15:00, with the minimum occurring at around 03:00 (Figure 3.6).

Table 3.5: Summary of dissolved oxygen dynamics at Site 5.

Parameter	Value
Mean DO	5.6 mg l^{-1} (58.1%)
Maximum DO	13.2 mg l^{-1} (140.4%)
Minimum DO	1.2 mg l^{-1} (13.6%)
Mean daily maximum DO	7.9 mg l^{-1} (85.7%)
Mean daily minimum DO	4.0 mg l^{-1} (41.2%)
% of time DO <80% saturation	80.8%
% of time DO <3 mg l^{-1}	15.7%
Maximum duration of DO <3 mg l^{-1}	24 hours

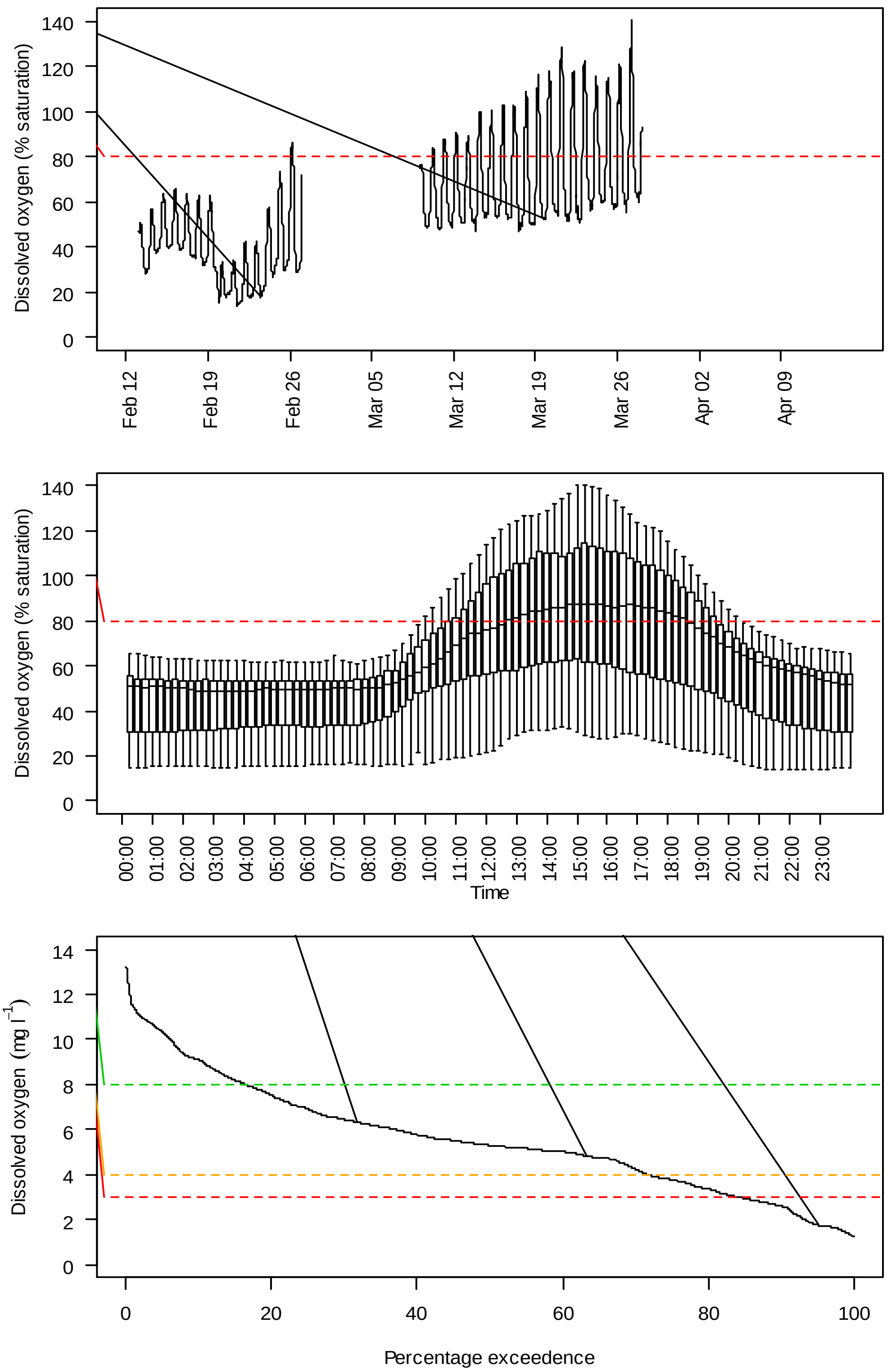

Figure 3.6: Dissolved oxygen time series (top), diel variability (middle) and duration curve (bottom) recorded at Site 5 in the Depression Stream at Manawaru Road between 12/02/09 and 15/04/09. Dashed red line at 80% saturation (top; middle) represents EW recommended level for aquatic plants and animals to thrive in. Dashed lines in the bottom figure show recommended DO concentrations for adult fish (Green (8mg l^{-1}) = no impairment; Orange (4 mg l^{-1}) = severe impairment; Red (3 mg l^{-1}) = acute limit).

Site 6 – Karengorengo Stream at Tower Road

The DO record for the monitoring period is summarised in Figure 3.7 and Table 3.6. The monitoring probe was removed from the stream for around a week at the beginning of March due to expected high flows. Mean DO for the site over the sampling period was 8.0 mg l^{-1} (80.8% saturation), but ranged from 2.6 mg l^{-1} (28.0%) to 11.0 mg l^{-1} (109.6%). DO was below the 80% threshold recommended by EW for 37.6% of the time, but below the threshold of 3 mg l^{-1} for only 1.0% of the monitoring period. The longest continuous duration over which DO remained below the acute limit of 3 mg l^{-1} was 12.5 hours, which was associated with elevated flows in late February. This could have been related to an increase in oxygen demand caused by mobilisation of sediments or organic material with a high biochemical oxygen demand (BOD) or flushing of a pollutant into the stream.

Diel variability in DO concentrations became less pronounced with time (Figure 3.6). There was also lower variation in the DO maxima compared to DO minima. The difference between mean daily maximum and minimum DO concentrations was relatively high at 2.6 mg l^{-1}, again reflecting the influence of aquatic macrophytes on DO levels in the reach. On average, peak concentration occurred at around 13:00, with the minimum occurring at around 03:00 (Figure 3.6).

Table 3.6: Summary of dissolved oxygen dynamics at Site 6.

Parameter	Value
Mean DO	8.0 mg l^{-1} (80.8%)
Maximum DO	11.0 mg l^{-1} (109.6%)
Minimum DO	2.6 mg l^{-1} (28.0%)
Mean daily maximum DO	9.5 mg l^{-1} (96.0%)
Mean daily minimum DO	6.9 mg l^{-1} (71.1%)
% of time DO <80% saturation	37.6%
% of time DO <3 mg l^{-1}	1.0%
Maximum duration of DO <3 mg l^{-1}	12.5 hours

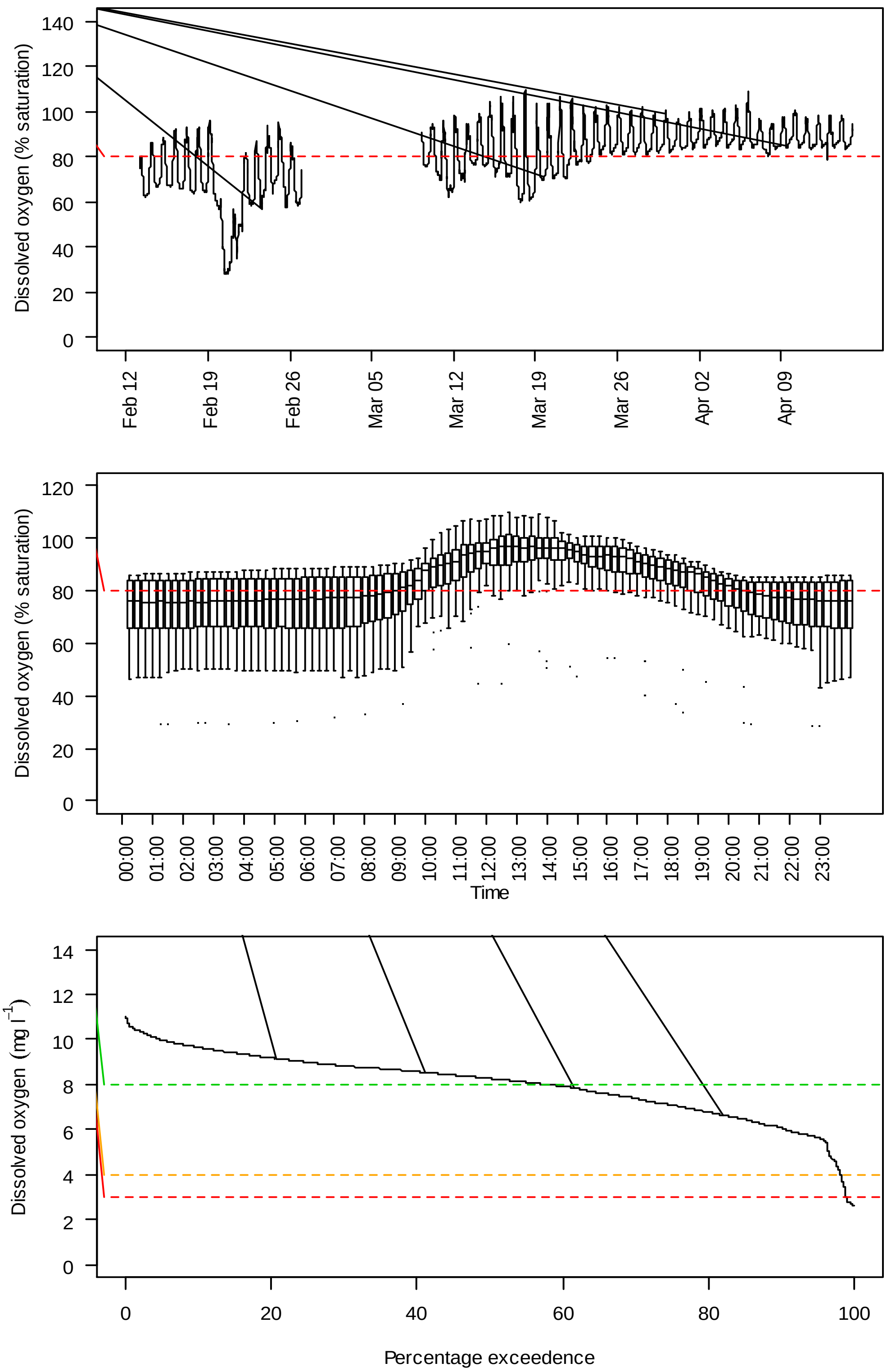

Figure 3.7: Dissolved oxygen time series (top), diel variability (middle) and duration curve (bottom) recorded at Site 6 in the Karengorengo Stream at Tower Road between 12/02/09 and 15/04/09. Dashed red line at 80% saturation (top; middle) represents EW recommended level for aquatic plants and animals to thrive in. Dashed lines in the bottom figure show recommended DO concentrations for adult fish (Green (8mg l^{-1}) = no impairment; Orange (4 mg l^{-1}) = severe impairment; Red (3 mg l^{-1}) = acute limit).

4. Discussion

The ability of New Zealand's native fish to survive in low oxygen environments depends on the duration of exposure, the level and constancy of DO, the species, life stage and health status of the fish, as well as on other environmental conditions e.g., temperature (Dean & Richardson 1999). A reduction in DO levels in the water column can result in low oxygen availability to body tissues, which may prompt physiological and behavioural modifications to compensate. These mechanisms can be adequate to compensate for short-term exposure to depressed DO levels, but as the severity and duration of low DO conditions increases, the costs in terms of energy expenditure and vulnerability to predation also increase.

Dean and Richardson (1999) determined the tolerances of seven New Zealand freshwater fish species to low levels of dissolved oxygen. Common smelt (*Retropinna retropinna*) at both the juvenile and adult life stages, juvenile common bullies (*Gobiomorphus cotidianus*) and juvenile rainbow trout (*Oncorhynchus mykiss*) were found to be most sensitive to low DO, with 50% mortality at DO levels of 1 mg l^{-1} occurring after 0.6-0.7 h, 0.6 h and 1 h respectively, and 100% mortality for all species within four hours. Juvenile banded kokopu (*Galaxias fasciatus*) were also relatively sensitive with 50% mortality at DO levels of 1 mg l^{-1} occurring in less than eight hours and 100% mortality by twelve hours. At a DO level of 3 mg l^{-1}, only juvenile trout appeared to be affected with 5% mortality after 48 h. The other species tested, including eels, showed little or no response. Dean and Richardson (1999) made recommendations for dissolved oxygen concentrations to confer differing levels of protection for fish (Table 4.1). In a separate study, Richardson et al. (2001) examined avoidance behaviour of common smelt, common bully and inanga (*Galaxias maculatus*) to low dissolved oxygen (c. 2 mg l^{-1}). Only common smelt illustrated an active avoidance, with no significant negative response displayed by the other species.

Table 4.1: Dissolved oxygen concentrations (mg l^{-1}) recommended to confer differing levels of protection for freshwater fish in New Zealand (after Dean & Richardson 1999).

Degree of impairment	Early life stages	Other life stages
None	11.0	8.0
Slight	9.0	6.0
Moderate	8.0	5.0
Severe	7.0	4.0
Acute limit	6.0	3.0

In the Waihou catchment, DO minima below 3 mg l^{-1} were recorded at four of the six sites monitored during summer low flow conditions. These concentrations are below the recommended acute limits for dissolved oxygen and thus present a potential impairment to both resident and migratory fish. The magnitude of the effect will, however, depend on the duration and timing of any low DO episode and the species and life stages affected.

In the case of Site 3, DO was on average below 3.0 mg l^{-1} for the entire monitoring period. At Site 4 the mean daily minima was 3.0 mg l^{-1} and was typically maintained for about six hours between midnight and 06:00. Dean and Richardson (1999) observed minimal effects on the native species, such as common smelt, common bully and banded kokopu, at DO concentrations of 3 mg l^{-1}. However, DO levels below 2 mg l^{-1} elicited active avoidance behaviour by smelt in laboratory tests and were recorded at two of the six sites. At Site 3, DO concentrations of less than 1.0 mg l^{-1} persisted for up to two days at a time. Effects would therefore be expected on fish and other benthic fauna, especially in summer when water temperatures increase fish metabolism demands. If DO was sustained at this level for this length of time there is a high potential for significant mortalities of sensitive species. The existence of such conditions raises the question of how this may impact upon decisions for allocating ecological flows.

The process of defining ecological flow requirements for a river relies on the ability to robustly delineate and define key flow-ecology linkages. In New Zealand, this has traditionally been focussed on the relationship between physical habitat for fish (defined in terms of water velocity, depth and substrate) and variations in discharge. The physical habitat approach is well established and is still often regarded as the most appropriate, scientific and legally defensible method for quantifying the amount of suitable habitat for a species under a given flow regime. However, use of this approach is based on the assumption that the availability of physical habitat is the limiting factor to fish populations. In the Waihou catchment, it is suggested that for some reaches, particularly in lowland areas, this may not be the case and that instead water quality may act as a control on fish populations.

5. Conclusion

Current understanding of the linkages between flow, DO (and other stressors) and ecological responses is not as robust as the understanding of the links between physical habitat and flows. There is therefore a need to enhance characterisation of these relationships in small streams in order to adequately integrate a robust and defensible approach for considering these emerging issues in the decision making process for defining ecological flows. This requires integrated monitoring of DO, flow and ecological responses in both impacted and un-impacted systems. There is also a need to consider the cumulative impacts with distance downstream. It is recommended that further monitoring of DO and flow be carried out in the Waihou catchment to better identify the effects of flow reductions on DO and the environmental consequences of low DO episodes during summer.

6. References

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