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Dissolved oxygen and ecosystem metabolism in Auckland rivers: 2020–24

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Dissolved oxygen and ecosystem metabolism in Auckland rivers: 2021–24

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Prepared for Auckland Council

Glossary

Term	Definition
DO	Dissolved oxygen. Can be measured in units of mg/L or % saturation
EM	Ecosystem metabolism
ER	Ecosystem respiration
GPP	Gross primary production
NEMS	National Environmental Monitoring Standards
NPS-FM	National Policy Statement for Freshwater Management 2020 (MfE 2024)
SOE	State of the environment
STAG	Science and Technical Advisory Group that contributed to the content of the NPS-FM

Contents

Executive summary

There is a widespread understanding that water chemistry alone cannot fully capture river ecosystem health, highlighting the need for indicators such as dissolved oxygen (DO) and ecosystem metabolism (EM) – the combination of gross primary production (GPP) and ecosystem respiration (ER). As one of the key attributes in the National Policy Statement for Freshwater Management 2020 (NPS-FM), DO provides essential insights into river health. Auckland Council has continuous high-frequency DO monitoring at 27 rivers, with records extending up to 22 years for some sites.

This study represents the latest analysis of DO and EM data across the Auckland Region. Using R-based code, DO minima and EM rates were assessed across the full dataset, moving beyond prior limitations of short, snapshot assessments. The report also contextualises DO minima within NPS-FM standards and provides a comparable evaluation of EM, even though the indicator currently lacks a formal NPS-FM banding system. The temporal and spatial variability of these metrics is also explored.

The findings highlight substantial variability in DO minima across Auckland Region sites, with reference sites often maintaining higher DO minima levels (above 8 mg/L), and more intensively modified catchments such as urban and high-intensity rural sites experiencing near-anoxic conditions (0 mg/L). Reference sites, such as West Hoe Stream and Cascades (Waitākere) Stream, maintained high attribute bands over the 2020–24 period. In contrast, Rural – High, Urban and Rural – High catchments in the Pukekohe area mostly fell within C and D bands, signalling lower water quality in terms of DO and consequent risks to aquatic life.

Most sites showed relatively stable summer 5-year rolling medians for the 1-day minimum and 7-day mean minimum DO metrics, indicating consistent DO levels over time. There was no strong evidence for trends over time, but this would need to be confirmed with formal trend analyses.

A close examination of the DO data indicated that tidal patterns may impact DO variability in several sites near the coast, with substantial drops in DO coinciding with high tides. This may be a common phenomenon in the lower reaches of rivers throughout Aotearoa New Zealand. It may also represent a potential stress on aquatic organisms living in these tidal lowland river areas, as well as migratory fish that must pass through them as they swim to and from the ocean to complete their life cycle.

These results highlight stable long-term DO conditions for most sites and emphasise the importance of ongoing monitoring of DO to capture shifts in water quality and changes in ecosystem health.

This report also identified substantial spatial and temporal variability in GPP and ER across the monitoring sites. The reference site (West Hoe), achieved an A-band grade for both GPP and ER, as did Opanuku and Te Muri. Several Urban and Pukekohe sites (Lower Vaughan, Puhinui and Waitangi) were graded as being in the D band for EM.

Between the baseline period (2013–17) and the current period (2020–24), nearly all sites showed statistically significant changes in metabolism rates. However, these differences did not always translate to shifts in band classifications. For those sites that did shift bands, a mix of improvements and degradations was recorded.

Variability in GPP and ER across sites further indicates ecosystem health. Stable sites such as West Hoe and Rangitopuni indicate healthier conditions, while sites with high metabolic variability (e.g. Waitangi, Kaipara and Puhinui) were often associated with lower attribute bands.

In conclusion, this report highlights the substantial variability in ecosystem health across Auckland Region rivers, driven by differences in land use and specific environmental factors such as tidal patterns. DO minima, GPP and ER collectively reveal that reference sites are in good health. In contrast, urban and high-intensity rural sites frequently showed lower DO minima and higher variability in metabolic rates. Changes in metabolic rates between the baseline and current periods, while often statistically significant, did not always correspond to shifts in attribute bands, highlighting the need for nuanced long-term analysis to truly understand ecological trends. These findings reinforce the importance of tailored monitoring efforts, especially for vulnerable and degraded sites, to further understand changes in DO, EM and ecological health over time.

1. Introduction

River ecosystem metabolism (EM) and dissolved oxygen (DO) for all rivers are compulsory attributes of the ecosystem health value under the National Policy Statement for Freshwater Management 2020, updated in October 2024 (NPS-FM; MfE 2024). They are part of the National Objectives Framework (NOF) (MfE 2024, table 21 and table 17, respectively). The two attributes differ in their requirements under the NPS-FM, as NOF bands were defined for the DO attribute and target attribute setting is accordingly required. The EM attribute currently lacks defined NOF bands, which leaves some discretion on how to set target attribute states (narrative or numeric).

Auckland Council has one of the longest datasets in the country for these attributes and has recently expanded its monitoring network to cover more rivers. The river sites monitored by Auckland Council are not specifically associated with point-source discharge locations and therefore the DO analysis in this report focuses on the application of NOF table 17 of the NPS-FM in relation to all rivers. Specific analysis of DO in rivers below point sources (NOF table 7; MfE 2024) is not included in this report.

Auckland Council commissioned Cawthron Institute (Cawthron) to summarise minimum DO statistics for 27 sites over the 2020–24 period and rates of EM for 15 of those sites over the same period. This report builds on an earlier analysis of DO minima and EM by Casanovas et al. (2022). The outcomes of this work will update information required for the upcoming plan change to implement the NPS-FM, and in doing so will support Auckland Council's statutory environmental monitoring requirements.

Under the NPS-FM (MfE 2024), regional authorities are required to define the baseline attribute state (BAS) and current attribute state for all compulsory attributes. Auckland Council currently defines the BAS period for compulsory attributes as the state in September 2017 based on data from five hydrological years of monitoring (July 2013–June 2017). Both attributes reported here – DO minima for all rivers and EM – are action planning attributes that require no defined limit in the regional plan but do require planned actions to work towards improvement or maintenance of the BAS. The DO minima attribute in the NPS-FM (MfE 2024, table 17) defines a national bottom line for this attribute, which in this case is the C band. If state assessment identifies sites below this bottom line, the NPS-FM requires improvement to at least the bottom-line value. Authorities can decide to improve or maintain the attribute state further depending on aspirations of communities, stakeholders and iwi.

What is ecosystem metabolism?

Ecosystem metabolism (EM) refers to the metabolic processes that transform oxygen, carbon and energy. Broadly, it measures the way carbon is cycling through an ecosystem.

There are two components of EM: gross primary productivity (GPP) and ecosystem respiration (ER). GPP (or photosynthesis) involves the use of energy from sunlight to produce organic matter, using carbon dioxide and releasing oxygen in the process. ER involves the consumption of energy stored in organic matter, using oxygen and releasing carbon dioxide in the process. The balance between these two components provides an indication of the net flows of energy in an ecosystem. Ecosystems that produce more organic matter than is being consumed (i.e. $GPP > ER$) will either store or export organic matter, while ecosystems that consume more energy than is produced on-site (i.e. $GPP < ER$) require a source of organic matter from outside the system to maintain respiration rates.

The latter situation is common in river ecosystems, where inputs of organic matter from upstream or the surrounding catchment are required to fuel metabolic activity in the river channel.

EM in rivers responds to a wide variety of factors, including light intensity, shading by riparian vegetation, water temperature, nutrient concentrations, chemical contaminants, organic pollution and flow fluctuations (Young et al. 2008; Bernhardt et al. 2018; Ferreira et al. 2020). Since EM responds strongly to such a wide variety of human activities / effects, it is considered a powerful integrative indicator for environmental management (Bernhardt et al. 2018; Jankowski et al. 2021). EM may also allow effective monitoring of river health in areas where other approaches are more difficult or impossible, such as macroinvertebrate monitoring in large non-wadeable rivers (Collier et al. 2013a, 2013b).

Continuous dissolved oxygen (DO) monitoring data are used to calculate EM. DO itself is a critical water quality indicator used in environmental management and assessment globally, and is also included as an attribute in the NPS-FM (MfE 2024).

2. Monitoring sites

Dissolved oxygen is being measured at 27 sites throughout the Auckland Region (Figure 1). This includes continuous data throughout the whole year at 15 sites and just summer–autumn data at 12 sites. An estimate of mean reach depth is required to calculate EM, and this information is available for only 15 of the 27 sites (Table 1). Therefore, EM analyses are presented only for a sub-set of the total number of sites where DO data are available. Furthermore, sites also differ in the length of the DO time-series available for analysis, starting between 2003 and 2021 and varying from four to 20+ years in length (Table 3). Hence, we were only able to compare DO and metabolism rates during the current period (hydrological years 2020–24) with the baseline period (hydrological years 2013–17) for a sub-set of 13 rivers from those that Auckland Council monitors.

The dominant land cover categories in the catchments upstream of the river monitoring sites are shown in Table 1. The colours in this table are used throughout the report to represent the different upstream catchments' dominant land cover groups. Dominant land cover categories were assigned based on Auckland Council's internal process, as described in Chaffe (2021) and summarised in Table 2. River sites within the Pukekohe area are marked as 'Pukekohe'. This area is of importance for national vegetable production, which needed to be taken into consideration for the NPS-FM plan change implementation, although this requirement was quashed in the October 2024 version of the NPS-FM (MfE 2024). The dominant land-use category in catchments of Pukekohe sites is Rural – High.

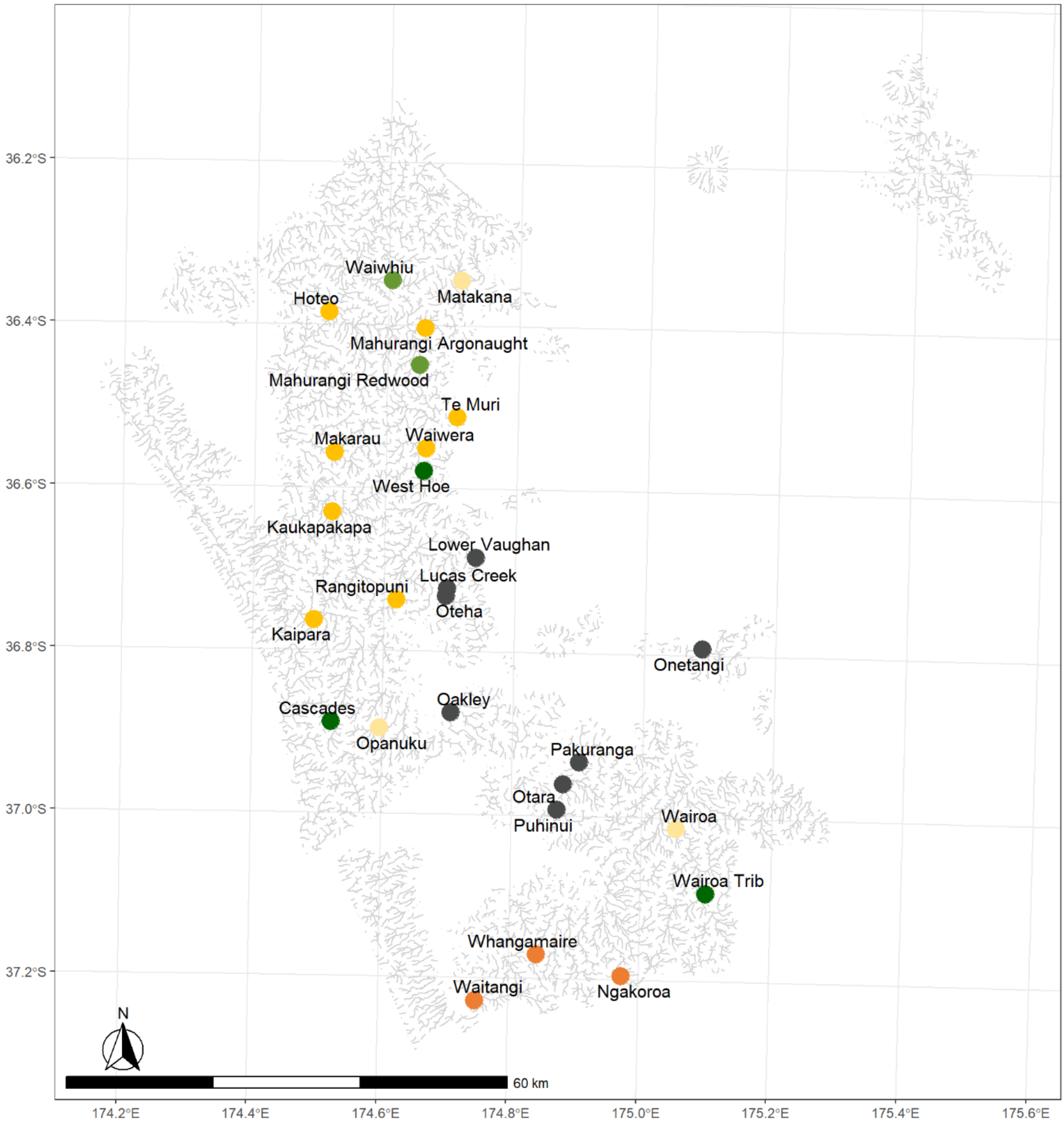

Figure 1. Site location of the dissolved oxygen sensors on the 27 sites analysed in this study. Colours indicate the dominant land-use category for each catchment (see Table 1). Map made using R.

Table 1. List of sites, including broad upstream catchment land cover groups used throughout this report. Geology:[1] HS = hard sedimentary rocks, VA = volcanic acidic, SS = soft sedimentary. Climate:[1] WD = warm-dry, WW = warm-wet. The column 'Metabolism analyses' denotes whether mean reach depth data were available for that site and therefore whether metabolism analyses were performed. Wadeability information is provided for sites included in ecosystem metabolism analysis only; all other sites are shown as not applicable (NA).

Site name	Upstream catchment's dominant land cover group	Wadeable year round	Stream order	Geology	Climate	Metabolism analyses
West Hoe	Native / Reference	Wadeable	2	SS	WW	Yes
Cascades	Native / Reference	NA	4	VA	WW	No
Wairoa Tributary	Native / Reference	NA	2	HS	WW	No
Waiwhiu	Exotic	NA	2	SS	WW	No
Mahurangi Redwood	Exotic	NA	2	SS	WW	No
Kaipara	Rural – High	Non-wadeable	5	SS	WW	Yes
Waiwera	Rural – High	NA	4	SS	WW	No
Hoteo	Rural – High	Non-wadeable	5	SS	WW	Yes
Kaukapakapa	Rural – High	Non-wadeable	5	SS	WW	Yes
Mahurangi Argonaught	Rural – High	Non-wadeable	4	SS	WW	Yes
Makarau	Rural – High	NA	5	SS	WW	No
Rangitopuni	Rural – High	Non-wadeable	1	SS	WW	Yes
Te Muri	Rural – High	Wadeable	1	SS	WD	Yes

1 Geology and climate classes for the sites are based on the River Environment Classification New Zealand (2010) (https://data.mfe.govt.nz/layer/51845-river-environment-classification-new-zealand-2010).

Site name	Upstream catchment's dominant land cover group	Wadeable year round	Stream order	Geology	Climate	Metabolism analyses
Opanuku	Rural – Low	Wadeable	3	SS	WW	Yes
Matakana	Rural – Low	NA	4	SS	WW	No
Wairoa	Rural – Low	Wadeable	5	HS	WW	Yes
Ngakoroa	Rural – High Pukekohe	Wadeable	3	VA	WW	Yes
Waitangi	Rural – High Pukekohe	Wadeable	3	VA	WW	Yes
Whangamaire	Rural – High Pukekohe	NA	2	VA	WW	No
Lower Vaughan	Urban	Wadeable	2	SS	WD	Yes
Puhinui	Urban	Non-wadeable	3	SS	WD	Yes
Lucas Creek	Urban	Non-wadeable	3	SS	WD	Yes
Oteha	Urban	Non-wadeable	3	SS	WD	Yes
Oakley	Urban	NA	3	SS	WW	No
Onetangi	Urban	NA	1	HS	WD	No
Otara	Urban	NA	3	SS	WD	No
Pakuranga	Urban	NA	2	VA	WD	No

Table 2. Broad land cover classes used to describe differences between sites based on the New Zealand Landcover Database version 5.0 (LCDB 5).

<table>
<tr><th>Dominant Land Cover Class</th><th>Definition</th></tr>
<tr><td>Urban</td><td>More than 7% urban land cover in the upstream / surrounding catchment.
This reflects the disproportionate influence of urban land use on water quality and ecological health. Some ‘urban’ waterways also have a high proportion of rural land use within the catchment.</td></tr>
<tr><td>Rural – High</td><td rowspan="2">The majority of Auckland remains within rural land cover. Two different classes are included to give a better resolution of this pressure gradient where possible. Rural – High has less than 50% exotic or native forestry cover remaining in the upstream catchment, while Rural – Low has more than 50% of the upstream / surrounding catchment that retains some forest or scrub.</td></tr>
<tr><td>Rural – Low</td></tr>
<tr><td>Exotic[2]</td><td>More than 80% of the upstream / surrounding catchment within exotic forestry.</td></tr>
<tr><td>Native</td><td>These sites have more than 95% native forest or scrub remaining within the upstream / surrounding catchment. These sites are intended to represent reference quality conditions that have a very low level of land-use pressure influence, although they are not necessarily ‘pristine’.</td></tr>
</table>

2 For the purposes of this report, the dominant land cover class for the catchment of the Waiwhiu Stream monitoring site was assigned as ‘exotic’. This assignment does not comply with the categories in this table but was considered best fit in the absence of other categories. Land cover in the Waiwhiu monitoring site catchment is 99.8% forest (51% exotic, 48.8% native).

3. Data preparation and analysis

The data provided for this report included dissolved oxygen (DO) and temperature time-series from 27 sites within the Auckland Region. For 12 of these sites, the time-series contained both raw measurements from deployed sensors and manual measurements for data calibration and validation. Cawthron performed quality control using these data according to the National Environmental Monitoring Standard (NEMS) protocols for continuous DO and temperature data (NEMS 2016, 2019, 2022). The data for these sites included date and time, water temperature (°C), DO saturation (%), barometric pressure (hPa), rainfall data and related site metadata. Measurements of all variables were recorded every 15 minutes at all sites. After quality control, the resulting datasets included an edited temperature time-series, a barometrically adjusted and edited DO saturation time-series, and an estimated barometrically adjusted DO concentration (mg/L) time-series. Since mean depth data were unavailable for these sites, only DO minima analyses were performed, and ecosystem metabolism (EM) analyses were not carried out (Table 1).

The time-series datasets from the remaining 15 sites had already been through quality control processes before being supplied to Cawthron. Data previous to 1 November 2021 were quality coded to an Auckland Council internal standard, which is different to the NEMS coding system. After 1 November 2021, all time-series were quality coded according to NEMS standards and barometrically adjusted. These data included date and time, water level (in metres, representing the stage height for the sites), discharge (in m^3/s – cubic metres per second), water temperature (in °C), per cent oxygen saturation and DO concentration (in mg/L). The data were measured every 15 minutes at most sites, except for Te Muri and West Hoe (from 29 August 2014 until the end of the time-series), which were measured every 5 minutes. For each site, stage height / water level was converted to average reach depth using the relevant river cross-section data. Summary statistics for the time-series variables are shown in Table 3.

All variables in the DO and temperature time-series had an associated quality code (QC), either following NEMS or Auckland Council's internal standards (see Table 4 for QC codes and their meanings). While these two frameworks differ, they share similarities in how they classify data (Table 4). We used both frameworks to filter the data before analysis. For the summary statistics (Table 3), we excluded any data points with missing QC or with a QC of 42, 43, 400 or 200. For DO minima and EM calculations, we used only high-quality data, specifically those with a QC of 10, 20, 300, 500 or 600. The percentage of temperature and DO records in each Auckland Council QC and NEMS category for each river is shown in Figure 2.

The flow and water-level data used in the analysis for the Hoteo River site may have been compromised by erosion at the water-level control structure, meaning that the flow data used in the analysis from 27 January 2023 onwards is likely underestimated at low flows. A new rating has been developed for this flow site, taking into account the erosion, but the updated discharge data were not incorporated into the analyses presented in this report. Therefore, all metabolism results for the Hoteo River from 27 January 2023 onwards should be treated with caution.

Note that the Pakuranga monitoring site has a known point-source influence that heavily affects water quality. This site was the only site that did not have 90 days of good-quality data to calculate a DO minimum (see Section 4), so the results should be treated with caution. Results for this site were excluded from the main report and are provided in Appendix 1.

Table 3. Summary statistics over the full period for variables from the dissolved oxygen (DO) dataset. Data specified as QC 42, 43, 200 and 400 were removed from the dataset prior to calculating these summary statistics. Note that the Mahurangi Argonaught site is referred to as Mahurangi River in some other Auckland Council monitoring reports.

		Date		Depth (m)			Discharge (m³/s)			Temp. (°C)			DO (%)			DO (mg/L)		
River name	No. records	Min	Max	Median	Min	Max	Median	Min	Max	Median	Min	Max	Median	Min	Max	Median	Min	Max
West Hoe	1,024,420	25/10/2006	01/06/2024	0.31	0.12	2.85	0.005	< 0.001	3.637	13.5	6.3	20.2	90.4	74.6	109.1	9.5	7.1	12.8
Cascades	52,055	03/11/2021	10/05/2024							16.9	8.5	23.7	98.8	78.9	144.6	9.6	7.5	13.6
Wairoa Tributary	55,516	12/11/2021	21/05/2024							14.7	5.9	20.5	99.3	93.6	112.5	10.1	8.6	12.5
Waiwhiu	38,339	04/11/2022	01/05/2024							16.0	11.7	20.7	97.2	81.1	117.8	9.6	8.1	11.5
Mahurangi Redwood	48,563	04/11/2021	01/05/2024							17.3	10.8	24.9	96.3	71.4	123.4	9.3	6.7	12.1
Kaipara	650,032	15/01/2004	27/05/2024	1.14	0.41	7.48	1.322	0.032	430.659	14.8	6.6	25.2	86.1	23.4	125.6	8.8	2.1	12.8
Waiwera	49,517	10/11/2021	08/04/2024							18.3	11.4	23.7	90.1	47.8	114.3	8.5	4.5	11.1
Hoteo	596,521	15/06/2005	14/05/2024	1.38	1.11	10.63	2.518	< 0.001	306.568	15.3	6.2	26.0	95.1	60.3	145.5	9.5	5.5	14.1
Kaukapakapa	638,526	03/02/2003	01/06/2024	1.08	0.44	6.74	0.489	0.003	216.426	14.5	0.0	24.2	85.9	3.2	132.2	8.8	0.2	14.0
Mahurangi Argonaught	824,779	31/05/2005	06/05/2024	1.25	0.46	4.97	0.416	0.018	246.498	15.3	6.6	25.0	98.9	4.4	197.9	9.9	0.4	20.0
Makarau	48,987	18/11/2021	06/05/2024							17.9	11.5	25.1	94.1	55.6	146.1	9.1	5.2	14.4
Rangitopuni	493,610	26/07/2007	27/06/2024	0.79	0.41	8.93	0.540	0.002	293.613	14.2	5.7	24.3	89.3	0.1	149.0	9.1	0.0	14.5
Te Muri	991,169	31/12/2013	02/05/2024	0.37	0.31	1.57	0.002	< 0.001	5.227	16.0	5.8	24.9	81.2	7.3	206.5	8.0	0.7	18.5

River name	No. records	Date		Depth (m)			Discharge (m^3/s)			Temp. (°C)			DO (%)			DO (mg/L)		
		Min	Max	Median	Min	Max	Median	Min	Max	Median	Min	Max	Median	Min	Max	Median	Min	Max
Opanuku	356,979	08/03/2011	01/06/2024	0.47	0.33	5.28	0.147	< 0.001	114.467	13.7	5.8	27.6	97.9	17.8	179.1	10.2	1.7	16.9
Matakana	53,523	04/11/2021	01/05/2024							18.0	11.1	24.2	91.8	60.6	123.5	8.8	5.4	11.0
Wairoa	572,463	19/01/2006	25/07/2024	0.91	0.52	5.70	1.316	0.252	475.098	14.5	4.7	25.7	94.8	34.6	252.3	9.6	3.7	24.2
Ngakoroa	633,863	06/08/2003	01/06/2024	0.34	0.12	1.10	0.059	0.002	6.319	15.0	5.6	23.0	87.0	26.0	122.8	8.8	2.5	13.0
Waitangi	521,552	05/05/2008	23/05/2024	1.10	0.63	3.12	0.149	0.017	35.502	15.3	7.6	26.6	68.4	0.0	154.0	6.8	0.0	14.6
Whangamaire	55,894	05/11/2021	10/05/2024							17.9	8.7	25.6	75.1	16.8	145.3	7.3	1.5	14.0
Lower Vaughan	482,774	22/05/2008	04/04/2024	0.42	0.26	3.93	0.008	< 0.001	17.599	15.0	4.9	26.3	66.8	0.0	276.0	6.8	0.0	24.1
Puhinui	489,085	16/03/2005	30/04/2024	0.63	0.52	3.34	0.088	0.008	64.793	17.0	0.0	28.6	88.8	0.2	249.8	8.9	0.0	23.2
Lucas Creek	67,500	29/11/2021	01/06/2024	0.65	0.60	3.89	0.046	0.007	42.141	17.1	9.3	24.0	87.6	54.0	123.0	8.5	5.0	10.7
Oteha	53,253	20/02/2022	28/05/2024	0.78	0.76	5.42	0.075	0.02	158.946	16.3	9.5	23.5	87.5	3.1	116.3	8.5	0.3	11.3
Oakley	42,099	11/11/2021	10/05/2024							18.6	11.6	24.7	93.0	43.2	127.9	8.8	3.9	11.0
Onetangi	47,796	29/10/2021	27/05/2024							16.3	9.5	19.9	80.0	14.5	105.4	7.9	1.4	10.3
Otara	44,364	05/11/2021	23/05/2024							19.6	10.7	26.9	75.1	0.0	152.6	7.0	0.0	13.2

Table 4. Dissolved oxygen and temperature quality codes (QCs) used in this study and their meaning.

QC	Meaning	Source
10	Original Record to Q/A standards	Auckland Council
20	Good Quality, edited data	Auckland Council
30	Measured Data Unknown Quality	Auckland Council
40	Estimated / Extrapolated data	Auckland Council
42	Poor Quality Data	Auckland Council
43	Suspect data	Auckland Council
44	Estimated data	Auckland Council
140	Raw / undefined / Unknown quality	Auckland Council
151	Missing Data	Auckland Council
255	Data Gap / Missing data	Auckland Council
100	Missing Data	NEMS
200	No quality or Non-Verified	NEMS
300	Synthetic data	NEMS
400	Poor Quality Data	NEMS
500	Fair Quality Data	NEMS
600	Good Quality Data	NEMS

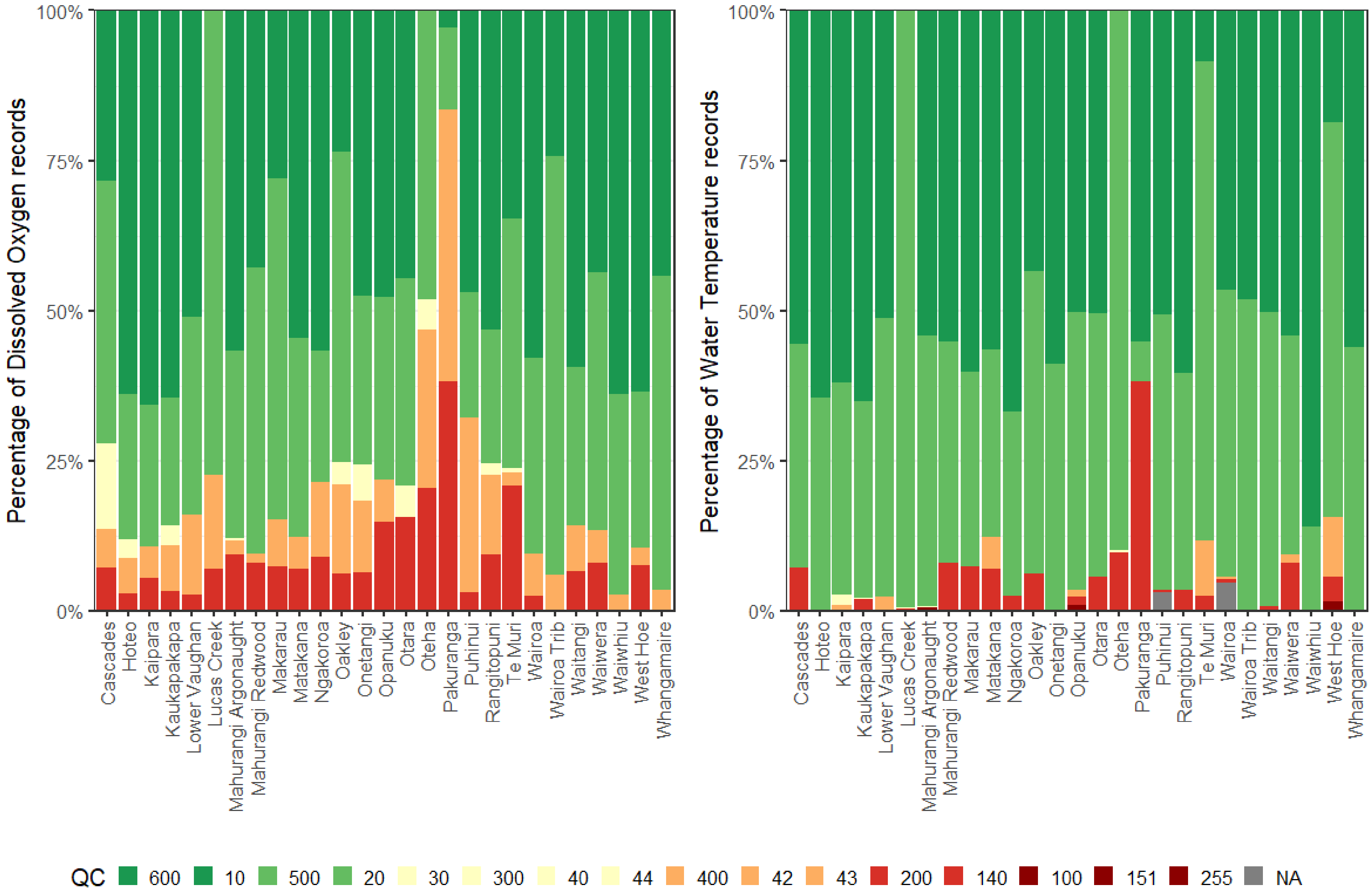

Figure 2. Percentage of records for dissolved oxygen saturation (left) and water temperature (right) in each QC code category for each river.

4. Dissolved oxygen minima

Two compulsory river attributes related to dissolved oxygen (DO) are identified in the NPS-FM (MfE 2024). The DO attribute in table 7 of the NPS-FM is relevant only for rivers below point-source discharges of contaminants. DO is also listed as an attribute in table 17 of the NPS-FM, and this attribute is relevant for all rivers, not just below point-source discharges. Table 7 of the NPS-FM is within 'Appendix 2A – Attributes requiring limits on resource use', while table 17 of the NPS-FM is within 'Appendix 2B – Attributes requiring action plans'. The river sites monitored by Auckland Council are not specifically associated with point-source discharge locations and therefore this analysis focuses on the application of table 17 in relation to all rivers. Table 17 of the NPS-FM includes two metrics, the 7-day mean minimum and 1-day minimum DO levels. As per the original technical advice for the development of this attribute (Davies-Colley et al. 2013), we used both metrics to define the overall attribute band.

National bottom lines established for the 1-day DO minima aim to protect sensitive aquatic species from short-duration exposure to low-DO concentrations that exceed their acute mortality thresholds. National bottom lines established for the 7-day mean minimum aim to protect aquatic species from chronic impacts caused by continuous or frequently occurring low-DO events (Davies-Colley et al. 2013). Table 17 of the NPS-FM (MfE 2024) specifies that the 1-day minimum DO should be calculated across 'the whole summer period' and gives no specified dates for calculation of the 7-day mean minimum DO. This currently creates opportunity for varying interpretation of how to calculate these metrics. However, table 7 of the NPS-FM specifies that the 7-day mean minimum and 1-day minimum should be calculated over the summer period (defined as 1 November to 30 April), so we focused our analyses on data from this period.

Why measure dissolved oxygen?

Dissolved oxygen (DO) is a fundamental element of the life-supporting capacity of aquatic systems. Fish, invertebrates and many other aquatic organisms rely on DO for respiration. Insufficient oxygen can lead to hypoxia (low oxygen levels) or anoxia (absence of oxygen), which can harm or kill aquatic life. Many aquatic organisms require relatively high concentrations of DO to survive. Others have specific morphological or behavioural adaptations that allow them to survive in water with low DO. For example, some fish gulp air at the water surface to access oxygen from the atmosphere. Hover fly larvae (also called rat-tailed maggots) have a long breathing tube that acts like a snorkel, enabling them to breathe underwater.

Concentrations of DO also affect some key biogeochemical processes in waterways. This includes the transformation of ammoniacal nitrogen to nitrate nitrogen, which can happen only if DO is available. A lack of DO at the bottom of rivers and lakes can unlock phosphorus that would otherwise be bound to sediments. This release of phosphorus makes it more available for uptake by algae and other aquatic plants, potentially stimulating algal blooms.

The amount of DO in water depends on several factors, including water temperature (warm water holds less oxygen), the amount of gas exchange with the atmosphere (shallow, turbulent streams have lots of oxygen exchange with the atmosphere), the release of DO into the water from photosynthesising aquatic plants, and the demand for DO within the water resulting from the decomposition of organic matter and associated respiration of microbes and aquatic life. DO varies on a diel cycle due to metabolic activities in the water. DO generally increases during the day, when aquatic plants are photosynthesising and releasing DO into the water, and declines at night due to uptake of DO associated with respiration. Highest daily concentrations of DO typically occur in mid-afternoon, while DO minima typically occur just before dawn.

DO is an important indicator for water quality and ecosystem health assessment. Measuring DO is essential for determining if concentrations comply with regulations developed to protect aquatic life. Single spot measurements of DO have limited value due to the daily variations in concentrations that occur. Continuous DO monitoring is ideally required to capture DO minima and the daily changes in DO.

4.1 Methods

In this report we have calculated both the 7-day mean minimum DO and 1-day minimum DO based on data over the whole summer period (1 November to 30 April).[3] This assumes that DO minima are most likely to occur in summer, when instream plant biomass and water temperature are high and flows are generally low. Only high-quality data (QC 10, 20, 300, 500 and 600) were used to calculate these minimum values. In contrast to the previous report (Casanovas et al. 2022), we modified the 7-day minima calculation by excluding 7-day periods that lacked consecutive DO records. That is, we calculated 7-day minima only for periods of time without gaps in the data over 7 consecutive days. This change caused small differences compared to the previous report, both in median values (Table 5) and in subsequent analysis of the 7-day minima time-series (Figure 3).

The baseline state for this attribute for Auckland Council was calculated using data over the 5-year period from the 2013–17 hydrological years for those sites with available data during this period. This baseline state is based on the definition given in the NPS-FM (MfE 2024, section 1.4). The current state was calculated using data over the 5-year period from the 2020–24 hydrological years. The use of statistics calculated over a 5-year period provides a robust snapshot of the state of the environment and helps avoid changes in bands (state switching) that might occur with annual statistics (McBride 2016; Depree et al. 2016). We calculated the median value for both the baseline and current state (Table 5). Hydrological years with fewer than 90 days of data (i.e. less than 50% of the maximum possible days) were excluded from the calculation of 5-year median values for the baseline and current state of these attributes for each site (Table 5). Median values based on less than 3 years of data should be treated with caution and are shaded grey in Table 5. Median values based on 3 and 4 years of data are considered to represent interim attribute state results, while median values based on 5 years of data are considered to represent final attribute states.

To help with the visualisation of long-term trends in minimum DO, a 5-year rolling median was calculated for both the 7-day mean minimum and the 1-day minimum values. To align with NPS-FM practices, the rolling median was calculated as a right-aligned 5-year median. This approach uses the median of the previous 4 years plus the current year for each value. Consequently, the rolling median could not be calculated for the first 4 years of the time-series because there was not 5 years of data to generate a median value. For sites with less than 5 years of data, no rolling median was calculated. As discussed above, the 5-year rolling median approach helps to avoid regular changes in bands (state switching), which is potentially seen if using annual summary statistics in isolation. This approach also considers the recommendation of Dupree et al. (2016) when characterising the DO state of streams to look at multi-year / seasonal DO records. Hydrological years with less than 90 days of data during the summer period were included in the calculation of the 5-year rolling median for completeness. Because this rolling median was calculated using hydrological years with less than 90 days of data, differences might arise

[3] The hydrological year is used to identify the year of a given summer, with the name of the hydrological year applying to the year in which the dataset ends. For example, the summer from 1 November 2004 to 30 April 2005 is described as the summer of the hydrological year 2005.

when comparing it to the median values in Table 5. Rolling median values calculated from years with less than 90 days of data are highlighted in Figure 3 and Figure 4 and should be treated with caution.

4.2 Results

The 7-day mean minimum DO and 1-day minimum DO statistics and associated NPS-FM bands for DO for each site are shown in Table 5. Some median values were calculated using less than 3 years of data (indicated in Table 5 in parentheses) and should be interpreted with caution as they do not represent the full period. Of the 12 sites with baseline period data, three lacked enough data during the current state period for accurate comparisons. The remaining nine sites stayed in the same overall band for the current state as they were during the baseline period, regardless of which dominant land cover group they belonged to (Table 5).

The reference sites were classified within the A band (Cascades, Wairoa Tributary) and B band (West Hoe) for their overall current state (2020–24) The two exotic forest sites – Mahurangi Redwood and Waiwhiu – fell in the C and A bands, respectively. Overall current state bands for Rural – Low sites ranged from B (Opanuku) to C (Matakana and Wairoa). Opanuku was notably affected by the revised method for calculating the 7-day mean minima, resulting in a shift of its baseline state from that presented in Casanovas et al. (2022), i.e. from B to C (Table 5). This site has also experienced changes in sensor locations, which mean the result should be interpreted with caution.[4] The gradings for the overall current state at Rural – High sites varied from B band at Makarau, to C band at Waiwera, Hoteo and Mahurangi Argonaught, and to D band at four sites (Kaipara, Kaukapakapa, Rangitopuni and Te Muri). Finally, all sites in the Pukekohe and Urban land cover groups were in the C (Lucas Creek and Onetangi) or D bands for both the 1-day minimum and 7-day mean minimum values. Within those sites, Waitangi had the lowest 1-day minima and 7-day mean minima of all sites (0.19 mg/L), indicating likely anoxic conditions at times (Table 5). Gradings based on 1-day minima and 7-day mean minima were consistent at about half the sites, but where there were differences, the gradings based on the 7-day mean minima were almost always lower than those based on the 1-day minima (Table 5).

The 5-year rolling median (red lines) and the individual annual summer values (dashed black line and circles) for the 7-day mean minimum DO and 1-day minimum DO metrics are shown in Figure 3 and Figure 4, respectively. Note that Figures 3 and 4 include values in hydrological years with less than 90 days of data during the summer period; these values are depicted as black triangles and should be treated with caution. Furthermore, results for sites with less than 5 years of data have insufficient data to calculate the 5-year rolling median used to determine final attribute states.

The 5-year rolling median provides a useful tool for visualising long-term changes in DO minima, but it differs from the 5-year median presented in Table 5, as it includes years with fewer than 90 days of data. As a result, discrepancies may appear when comparing Figures 3 and 4 with Table 5, particularly for sites

[4] The sensor location at Opanuku was affected by gravel build-up and weather events throughout the time-series, and results may be affected by site relocations, including: 4 June 2020 – moved from true right to true left bank due to gravel build-up; 30 August 2021 – site destroyed by flooding; 9 November 2022 – reinstalled at true right bank; 27 January 2023 – site destroyed by Auckland Anniversary floods; 23 June 2023 – site reinstalled on true left bank.

with several years of sparse data. In this report, the 5-year rolling median is used solely for visualisation purposes, and preference should be given to the calculations in Table 5. For most sites with sufficient data, the long-term values of both the 7-day mean minimum DO and 1-day minimum DO rolling median tend to stay within a consistent range, despite year-to-year fluctuations (Figures 3 and 4). Notable exceptions are Rangitopuni and Ngakoroa, where recent increases in the 5-year rolling median for both DO metrics suggest possible improvements (Figures 3 and 4). However, these findings should be interpreted cautiously as they were calculated using years with less than 90 days of data and therefore differ from results in Table 5. Ongoing monitoring at these sites will help determine if these trends indicate lasting changes.

Table 5. NPS-FM bands for the baseline state period (2013–17 hydrological years) and the current state period (2020–24 hydrological years) for the minimum dissolved oxygen attribute (1-day minimum and 7-day mean minimum). The bands were assigned using the median value for the period, which is shown after the attribute band. The number of years used to calculate the median are within parentheses (only summers with more than 90 days of data were included). Band assessments based on < 3 years of data are shaded grey and should be treated with caution. Overall bands were based on the worst band assessment for the 1-day or 7-day assessments.

River name	1-day minimum baseline state (2013-2017)	7-day mean minimum baseline state (2013-2017)	Overall baseline state band (2013-2017)	1-day minimum current state (2020-2024)	7-day mean minimum current state (2020-2024)	Overall current state band (2020-2024)
West Hoe	B 7.46 (5)	B 7.47 (5)	B	A 7.93 (3)	B 7.94 (3)	B
Cascades	NA	NA	NA	A 8.27 (3)	A 8.28 (3)	A
Wairoa Trib	NA	NA	NA	A 9.16 (3)	A 9.17 (3)	A
Waiwhiu	NA	NA	NA	A 8.19 (2)	A 8.23 (2)	A
Mahurangi Redwood	NA	NA	NA	B 6.78 (3)	C 6.8 (3)	C
Kaipara	D 2.93 (3)	D 3.03 (3)	D	D 3.66 (4)	D 3.72 (4)	D
Waiwera	NA	NA	NA	B 5.61 (3)	C 5.62 (3)	C
Hoteo	B 6.43 (5)	C 6.45 (5)	C	B 6.72 (1)	C 6.73 (1)	C
Kaukapakapa	D 2.81 (4)	D 3.22 (4)	D	D 1.72 (3)	D 1.88 (3)	D
Mahurangi Argonaught	B 6.04 (5)	C 6.06 (5)	C	B 6.05 (3)	C 6.2 (3)	C
Makarau	NA	NA	NA	B 7.39 (3)	B 7.39 (3)	B
Rangitopuni	D 0.28 (1)	D 0.29 (1)	D	D 3.39 (2)	D 3.6 (2)	D
Te Muri	NA	NA	NA	D 1.39 (5)	D 1.41 (5)	D
Opanuku	B 6.64 (5)	C 6.86 (5)	C	B 7.37 (2)	B 7.39 (2)	B
Matakana	NA	NA	NA	B 6.34 (3)	C 6.35 (3)	C
Wairoa	B 6.06 (5)	C 6.11 (5)	C	B 6.26 (3)	C 6.46 (3)	C
Ngakoroa	D 3.63 (5)	D 3.65 (5)	D	C 4 (3)	D 4.36 (3)	D
Waitangi	D 0.38 (4)	D 0.4 (4)	D	D 0.19 (3)	D 0.19 (3)	D
Whangamaire	NA	NA	NA	D 2.25 (3)	D 2.57 (3)	D
Lower Vaughan	D 0.22 (5)	D 0.27 (5)	D	D 0.24 (5)	D 0.4 (5)	D
Puhinui	D 0.57 (2)	D 0.78 (2)	D	D 2.41 (3)	D 2.54 (3)	D
Lucas Creek	NA	NA	NA	B 5.14 (2)	C 5.25 (2)	C
Oteha	NA	NA	NA	D 3.44 (1)	D 4.23 (1)	D
Oakley	NA	NA	NA	C 4.03 (3)	D 4.98 (3)	D
Onetangi	NA	NA	NA	B 6.2 (2)	C 6.47 (2)	C
Otara	NA	NA	NA	D 0.2 (3)	D 0.72 (3)	D

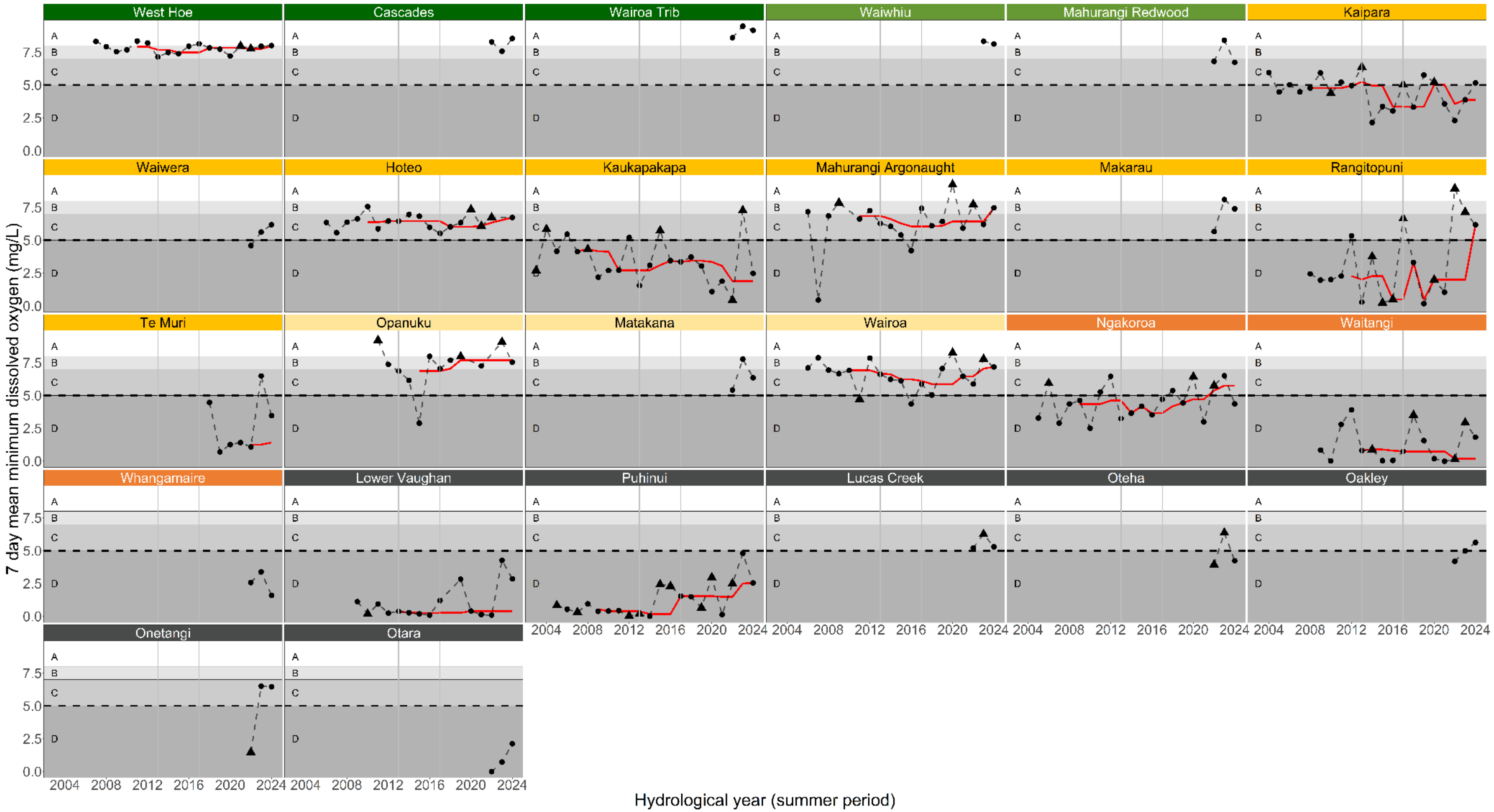

Figure 3. NPS-FM band assessment for the 7-day mean minimum dissolved oxygen concentration. The 5-year rolling median (red lines) and actual annual values (dashed black lines and black dots / triangles) per hydrological year (summer) are shown for each river. Light grey vertical lines indicate the NPS-FM baseline state period (2013–17 hydrological years). The horizontal dashed line shows the DO national bottom line. Triangles show annual values that were calculated with less than 90 days of data and should be treated with caution.

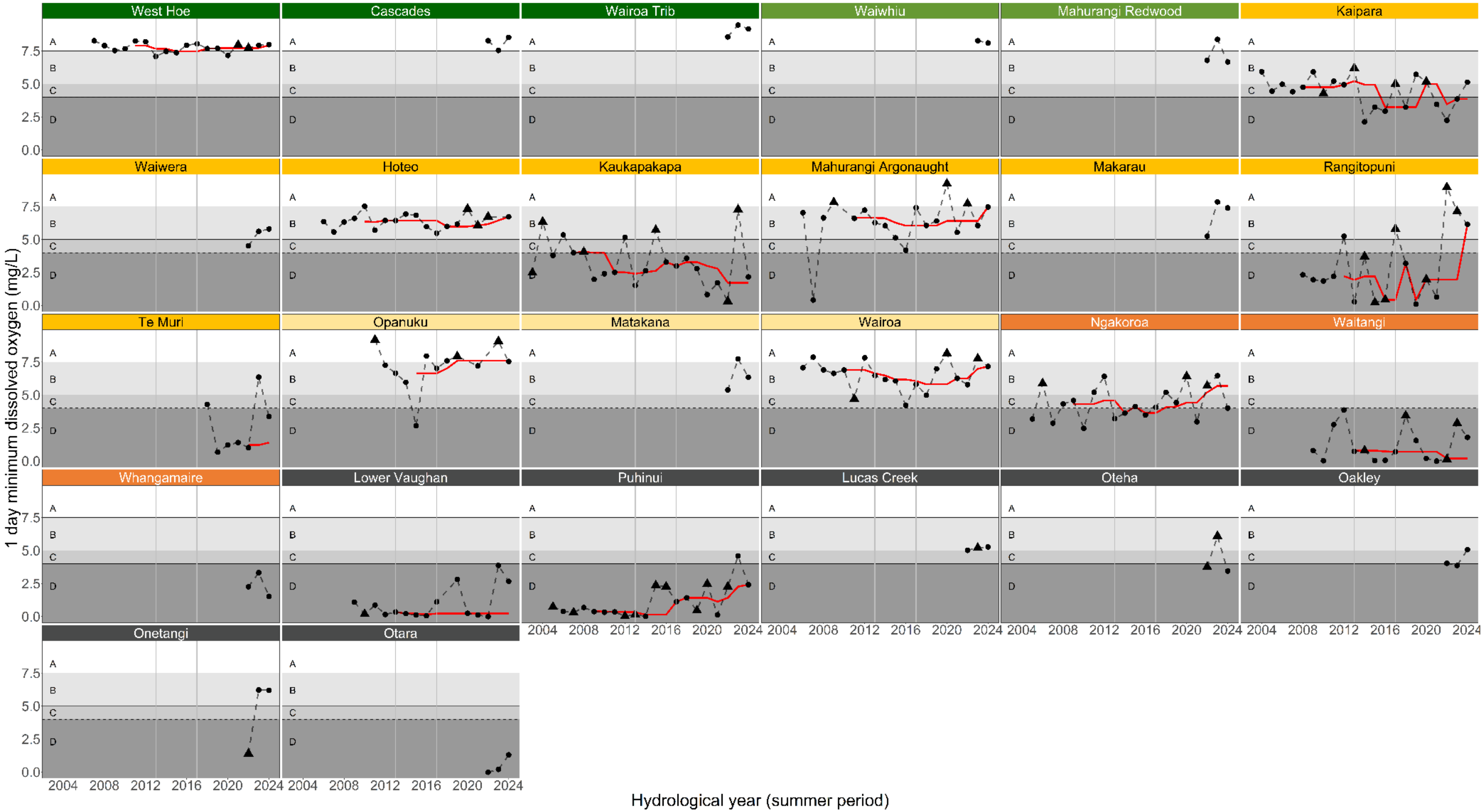

Figure 4. NPS-FM band assessments for the 1-day minimum dissolved oxygen concentration. The 5-year rolling medians (red lines) and actual annual values (dashed black lines and black dots / triangles) per hydrological year (summer) are shown for each river. Light grey vertical lines indicate the NPS-FM baseline state period (2013–17 hydrological years). The horizontal dashed line shows the DO national bottom line. Triangles show annual values that were calculated with less than 90 days of data and should be treated with caution.

Tidal effects on minimum DO

Apparent tidal effects on DO minima were detected during quality control checks on the DO data at two sites near the coast (Otara and Oakley). These appeared as sudden drops in DO twice per day, followed by recovery (Figure 5). The drops in DO occurred about an hour later on subsequent days, reflecting changes in the timing of the tides, and were more pronounced during some periods (spring tides) than at other periods (neap tides and during higher river flow) (Figure 5). The reductions in DO at these sites are aligned with fresh water backing up as a result of high tides (Figure 5). The reductions in DO that occurred during high-tide periods at night were more pronounced than those during daytime high-tide periods (Figure 5). Presumably this is because the oxygen uptake at night during high tide is not counteracted by oxygen release during photosynthesis, as it is to some extent during a daytime high-tide period. This finding highlights potential concerns with low DO in the lower reaches of rivers across the Auckland Region (and elsewhere). Further investigation is ideally required to determine the frequency and scale of this issue.

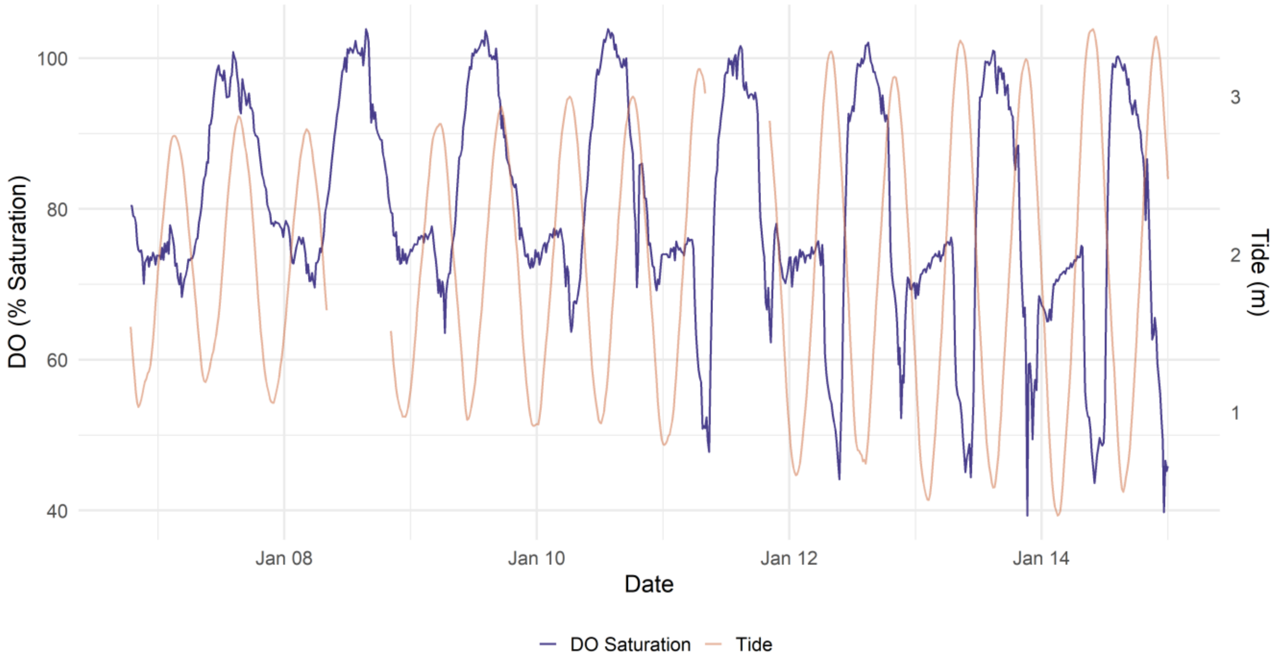

Figure 5. Time-series of dissolved oxygen (DO) saturation at Otara during January 2024 showing the effects of the tidal cycle on dissolved oxygen levels.

4.3 Discussion

Dissolved oxygen minima varied significantly, ranging from more than 8 mg/L at the Cascades site to nearly anoxic conditions (0 mg/L) at several sites draining Rural, Pukekohe and Urban catchments (Table 5). These results underscore the inherent variability across the Auckland Region and highlight the importance of monitoring a diversity of sites to capture the full range of DO levels within the region.

Minimum DO over the 2020–24 period was relatively high in the reference sites (West Hoe, Wairoa Tributary and Cascades), which were graded as being in the B band (West Hoe) and A band (Wairoa Tributary and Cascades) (Table 5). Based on information from West Hoe, Casanovas et al. (2022) suggested that it may not be feasible to achieve the A band for minimum DO in the Auckland Region, even for reference streams. However, data from the new Cascades and Wairoa Tributary reference sites prove that A-band status is possible in Auckland streams.

The two exotic forest sites, Mahurangi Redwood and Waiwhiu, were graded in the C and A bands, respectively. The overall grade at Mahurangi Redwood is from a relatively short record of data and based on the 7-day mean minimum, while the 1-day minimum was in the B band. If there is good shading of the stream channel by mature trees, exotic forest sites would be expected to have healthy DO concentrations.

Sites classified in the Rural – Low land cover group graded as B band (Opanuku) or C band (Wairoa, Matakana) (Table 5), reflecting fair DO minima. In contrast, DO minima were very low at most sites in the Rural – High (including Pukekohe sites) and Urban land cover groups, and graded in the C or D bands. The only exception to this was Makarau, which had a higher DO minimum and was classified in the B band (Table 5). The Makarau upstream catchment is predominantly Rural – High land cover, but it includes 34% forest cover, potentially resulting in reduced pressures. Further investigation is needed to understand DO dynamics at this site compared to other Rural – High sites in the monitoring network.

All sites with sufficient data for a robust comparison of the baseline and current periods showed no change in band. Only 2 years of data were available for analysis during the current period at Opanuku, but these data indicate an improvement in DO minima, with this site graded in the C band during the baseline period and the B band during the current period (Table 5). However, it should be noted that the DO sensor location was changed for this site part way through the data record and the improvement could be a result of the sensor being located closer to the main flow.

The DO minima at each site vary to some extent over time. Some sites are very consistent (e.g. West Hoe), while others varied more widely with potential changes in band grading from year to year (Figures 3 and 4). No sign of increasing or decreasing trends over time is apparent at any of the sites, as the 5-year rolling median tends to stay within the same attribute bands. However, formal trend analysis of the data would be required to identify any trends in DO minima time-series.

The results reported here are largely consistent with those reported in Casanovas et al. (2022), with relatively high DO minima in reference sites and very low values at some sites in Rural – High (including Pukekohe sites) and Urban land cover groups.

5. River ecosystem metabolism

Metabolism in stream ecosystems comprises photosynthesis during daylight hours, and respiration during both night and day. Photosynthesis increases dissolved oxygen (DO) in the water and respiration depletes DO from the water. Alongside these biological processes, there is physical exchange of oxygen gas between stream water and the atmosphere. The gas transfer at the water surface is regulated by atmospheric pressure and temperature, and acts to equilibrate DO with the atmospheric oxygen partial pressure. The saturation concentration is the amount of oxygen that water will hold at equilibrium, given the temperature and atmospheric oxygen partial pressure. The relationship between these biological and physical processes can be expressed as:

$$dDO/dT = GPP + ER + kD \qquad \text{Equation 1}$$

Where the term dDO/dT represents the change in DO over time ($g \cdot m^{-3} \cdot day^{-1}$). The term *GPP* represents the contribution to change in oxygen made by photosynthesis, which is always positive. In contrast, the term *ER* represents the rate of the depletion of oxygen made by respiration and is always negative. Finally, the term *kD* represents the physical gas exchange with the atmosphere through the water surface. Depending on the degree of oxygen deficit (*D*; g/m^3), *kD* may be positive (water undersaturated in oxygen) or negative (water supersaturated in oxygen).

Within the *kD* parameter, *k* corresponds to the reaeration coefficient (per day), which is characteristic of the stream at a certain water level, positive and ideally constant over time at a given level of flow. The value of the reaeration coefficient will depend on the flow of the stream. Shallow, turbulent streams have a high *k*, while deep, slow-flowing rivers will have a low *k*. The reaeration coefficient can be estimated from the slope obtained by the regression of dDO/dT against the oxygen deficit (*D*) that occurs during the dark period of the day. *ER* can be estimated as the intercept of this regression. This night-time regression is one of the methods commonly used for estimating ecosystem metabolism (EM) globally (Jankowski et al. 2021).

5.1 Methods

From the original DO time-series, two new variables were derived for performing the required calculations to estimate EM:

- oxygen saturation concentration – the DO concentration (in mg/L) at which water is fully (100%) saturated at the current water temperature, calculated from the relationship between DO (mg/L) and percentage of oxygen saturation
- oxygen deficit – the difference between oxygen saturation concentration and actual measured DO concentration.

The first step in our calculations was determining the dark period of the day from the DO time-series. This was estimated for each day in the time-series using the DO dataset itself – dusk corresponds with the most negative value of dDO/dT over the 24-hour, period while dawn corresponds with the highest value of the oxygen deficit (*D*) (Appendix 2; Casanovas et al. 2022). The dark period was then defined as the time between dusk and dawn. It is important to note that the estimation of the stream metabolism parameters depends in part on the accuracy of this method to identify the dark period.

Estimates of *GPP* and *ER* were initially calculated on a volumetric basis in grams of oxygen per cubic metre per day (g $O_2 \cdot m^{-3} \cdot day^{-1}$) by using the regression of dDO/dT against the oxygen deficit (*D*) and Equation 1. To better compare rates of metabolic activity between rivers of different size, the volumetric estimates were converted to unit riverbed area by multiplying by the mean water depth upstream of the oxygen monitoring location. In most rivers, the bulk of metabolic activity occurs on and within the riverbed rather than within the water column itself. The rates of ER and GPP are then expressed in grams of oxygen per square metre per day (g $O_2 \cdot m^{-2} \cdot day^{-1}$). Details of the method used to calculate these parameters can be found in Casanovas et al. (2022).

While we used a linear regression model to estimate the gradient and intercept that represent *k* and *ER*, it should be noted that the assumption of independence of the data for a regression is not strictly met by time-series datasets. While the point estimates of *k* and *ER* are likely robust to these violations of regression assumptions, any reported intervals around these estimates would be smaller than expected under independence, and the model performance (i.e. R^2, the measure of fit) will be exaggerated. The R^2 value from a regression in this context should be considered as an indication of 'relative reliability' rather than a true R^2 value, as would be calculated from independent data points. In the following analyses, metabolism parameter estimates (GPP and ER) calculated with a relative reliability (R^2) below 0.25 were removed. As noted in Casanovas et al. (2022), there are many factors that can result in poor relative reliability of metabolism parameter estimates, including a low metabolic 'signal' relative to noise in the data, or heavy rainfall causing altered DO dynamics of a substantial part of the river flow.

We further cleaned the metabolism parameter estimates by excluding any positive values of ER and any negative values of GPP. Because ER and GPP are linked, if one of the estimates was spurious, all estimates for that day were removed. In addition, any absolute values of ER and GPP greater than 150 were considered unlikely to be real given the known ranges of metabolism calculated globally, and thus were removed from further analyses. These extremely high values were very rare across all sites.

Finally, we compared EM estimates among sites to explore spatial variability within the Auckland Region. The continuous time-series data available allowed for the calculation of GPP and ER for the whole year. Therefore, for reporting purposes, we used median values calculated from data for the whole year. Median values for the time-series record, Auckland Council's NPS-FM baseline period (2013–17 hydrological years) and the current period (2020–24 hydrological years) were also calculated. The difference in medians between the baseline state and current state periods were tested with a Wilcoxon rank sum test with continuity correction.

Following Casanovas et al. (2022), we used the proposed attribute state bands for EM recommended by the Freshwater Science and Technical Advisory Group (STAG 2019; Table 6). The proposed guidelines specify different criteria for wadeable and non-wadeable rivers. While these attribute bands are not currently part of the NPS-FM, they provide useful assessment criteria. Therefore, we use the proposed attribute state bands to evaluate and compare EM parameters across sites both for the overall band (Tables 7 and 8), and for the baseline and current state bands (Tables 9 and 10). The assessment of whether a site is wadeable or non-wadeable is somewhat subjective and dependent on flows at the time. The wadeability assessment relates to the specific site, rather than the river as a whole (e.g. upstream reaches may be relatively shallow and easily waded, whereas the lowland reaches of the same river may be deep and unwadeable).

Table 6. Potential banding system for ecosystem metabolism as discussed by the Freshwater Science and Technical Advisory Group (STAG 2019) that helped inform the National Policy Statement for Freshwater Management (MfE 2024). The values for the metrics in this table are absolute numbers (ER values are reported as negative numbers in this report).

Value	Ecosystem health				
Freshwater Body Type	Rivers				
Attribute	Ecosystem metabolism				
Attribute Unit	g O_2 m^{-2} d^{-1} (grams of dissolved oxygen per square metre per day)				
Attribute State	Numeric Attribute State[1]				Narrative Attribute State
	Gross primary production		Ecosystem respiration		
	Non-wadeable	Wadeable	Non-wadeable	Wadeable	
A	≤3.0	≤3.5	1.6-3.0	1.6-5.8	No evidence of an impact on ecosystem metabolism.
B	>3.0 and <5.5	>3.5 and <5.0	>1.0 and <1.6 Or >3.0 and >8	>1.2 and <1.6 Or >5.8 and <7	Mild effect on ecosystem metabolism.
C	≥5.5 and ≤8.0	≥5.0 and ≤7.0	≥0.6 and ≤1.0 Or ≥8.0 and ≤13.0	≥0.8 and ≤1.2 Or ≥7.0 and ≤9.5	Moderate effect on ecosystem metabolism.
D	>8.0	>7.0	<0.6 or >13.0	<0.8 or >9.5	Severely impaired ecosystem metabolism.

1. Derived from 7 consecutive days of continuous dissolved oxygen monitoring. Objective applies year-round.

5.2 Results

Median GPP values in wadeable rivers across the dataset ranged from 0.09 g $O_2 \cdot m^{-2} \cdot day^{-1}$ at West Hoe (reference site) to 13.24 g $O_2 \cdot m^{-2} \cdot day^{-1}$ at Puhinui (Urban) (Tables 7 and 8). For ER, median values ranged from -0.94 g $O_2 \cdot m^{-2} \cdot day^{-1}$ at Lucas Creek (Urban) to -22.5 g $O_2 \cdot m^{-2} \cdot day^{-1}$ at Waitangi (Pukekohe) (Tables 7 and 8). The reference site (West Hoe) was graded in the A band using the attribute state bands recommended by STAG (2019), while grades for other sites ranged from A band to D band. Sites that fell into the D band included Waitangi (Pukekohe), Lower Vaughan (Urban) and Puhinui (Urban) (Tables 7 and 8).

Table 7. Ecosystem metabolism attribute bands for each site based on median values for the whole dataset and criteria recommended by the Freshwater Science and Technical Advisory Group (STAG 2019). Colours represent the metabolism bands for wadeable rivers discussed by the STAG but not eventually included in the NPS-FM (MfE 2024): A band (blue), B band (green), C band (yellow) and D band (red). The overall band is determined from the lowest grade of the gross primary production (GPP) or ecosystem respiration (ER) contributing metrics.

Wadeable rivers			
River name	GPP Band	ER Band	Overall Band
West Hoe	A 0.09	A -1.8	A
Te Muri	A 1.71	A -5.12	A
Opanuku	A 2.5	A -1.87	A
Wairoa	B 4.02	A -4.67	B
Ngakoroa	A 2.84	B -6.39	B
Waitangi	D 13.11	D -22.5	D
Lower Vaughan	B 3.78	D -10.48	D

Table 8. Ecosystem metabolism attribute bands for each site based on median values for the whole dataset and criteria recommended by the Freshwater Science and Technical Advisory Group (STAG 2019). Colours represent the metabolism bands for non-wadeable rivers discussed by the STAG but not eventually included in the NPS-FM (MfE 2024): A band (blue), B band (green), C band (yellow) and D band (red). The overall band is determined from the lowest grade of the gross primary production (GPP) or ecosystem respiration (ER) contributing metrics.

Non-Wadeable rivers			
River name	GPP Band	ER Band	Overall Band
Kaipara	B 4.34	C -12.35	C
Hoteo	C 6.6	B -5.41	C
Kaukapakapa	A 2.31	B -7.32	B
Mahurangi Argonaught	B 4.57	A -2.98	B
Rangitopuni	A 1.33	B -4.12	B
Puhinui	D 13.24	C -10.78	D
Lucas Creek	A 0.53	C -0.94	C
Oteha	B 3.87	B -6.68	B

Comparisons of median GPP and ER values between the baseline period (2013–17) and the current period (2020–24) showed statistically significant differences at many sites according to the Wilcoxon rank test (Tables 9 and 10). However, despite statistically significant differences at some of these sites, West Hoe, Wairoa, Waitangi, Kaukapakapa and Rangitopuni did not change bands between the baseline and current periods (Tables 9 and 10). The other sites experienced changes in metabolism rates that did result in band shifts between the baseline and current periods. Some sites improved their band grading (Te Muri, Ngakoroa, Lower Vaughan, Mahurangi Argonaught, Puhinui), while other sites received a lower band grading for the current time period (Opanuku,[5] Kaipara).

[5] See footnote 4.

Table 9. Median values of gross primary production (GPP) and ecosystem respiration (ER) for each river for the Auckland Council's NPS-FM defined baseline period (2013–17) and the current state (2020–24). Colours represent the metabolism bands for wadeable rivers discussed by the Freshwater Science and Technical Advisory Group (STAG 2019) but not included in the NPS-FM (MfE 2024): A band (blue), B band (green), C band (yellow) and D band (red). The Wilcoxon rank test identifies whether differences between the baseline state and current state periods are statistically significant.

Wadeable rivers

	Baseline state (2013-2017)			**Current state (2020-2024)**			**Wilcoxon Rank test Difference**	
River name	GPP	ER	Overall	GPP	ER	Overall	GPP p-value	ER p-value
West Hoe	A 0.08	A -1.83	A	A 0.1	A -3.12	A	0.0001	< 0.0001
Te Muri	B 3.81	C -7.61	C	A 1.32	A -4.58	A	< 0.0001	< 0.0001
Opanuku	A 3.2	A -2.59	A	A 1	C -0.97	C	< 0.0001	< 0.0001
Wairoa	B 4.03	A -5.16	B	B 3.88	A -4.4	B	0.0002	< 0.0001
Ngakoroa	A 3.4	B -6.42	B	A 1.66	A -5.03	A	< 0.0001	< 0.0001
Waitangi	D 12.32	D -27.64	D	D 7.68	D -15.39	D	< 0.0001	< 0.0001
Lower Vaughan	C 5.03	D -13.54	D	A 0.5	A -1.6	A	< 0.0001	< 0.0001

Table 10. Median values of gross primary production (GPP) and ecosystem respiration (ER) for each river for the Auckland Council's NPS-FM defined baseline period (2013–17), and the current state (2016–20). Colours represent the metabolism bands for non-wadeable rivers discussed by the Freshwater Science and Technical Advisory Group (STAG 2019) but not included in the NPS-FM (MfE 2024): A band (blue), B band (green), C band (yellow) and D band (red). The Wilcoxon rank test identifies whether differences between the baseline state and current state periods are statistically significant. Sites with NA do not have data for the baseline period.

Non-Wadeable rivers

	Baseline state (2013-2017)			**Current state (2020-2024)**			**Wilcoxon Rank test Difference**	
River name	GPP	ER	Overall	GPP	ER	Overall	GPP p-value	ER p-value
Kaipara	C 5.84	C -12.7	C	D 13.22	D -33.2	D	< 0.0001	< 0.0001
Hoteo	C 7.15	B -5.67	C	B 4.22	B -5.15	B	< 0.0001	0.0311
Kaukapakapa	A 1.98	B -7.52	B	A 2.11	B -7.52	B	0.2623	0.5724
Mahurangi Argonaught	C 5.98	A -2.85	C	B 4.13	B -3.55	B	< 0.0001	< 0.0001
Rangitopuni	A 1.05	B -4.11	B	A 2.12	B -4.28	B	< 0.0001	0.1523
Puhinui	D 17.04	D -13.94	D	B 3.58	A -2.93	B	< 0.0001	< 0.0001
Lucas Creek	NA	NA	NA	A 0.53	C -0.94	C	NA	NA
Oteha	NA	NA	NA	B 3.87	B -6.68	B	NA	NA

In terms of variability in the distribution of GPP and ER values, the sites that had least variability were West Hoe for wadeable rivers and Lucas Creek for non-wadeable rivers (Figure 6). In contrast, Waitangi (wadeable), and Kaipara and Puhinui (non-wadeable), showed large variability both in GPP and ER values, often extending across attribute state bands (Figure 6). Note that the sites with the greatest variability also had GPP and ER attribute bands that mostly denoted degraded states (Tables 9 and 10). This is consistent with findings from Casanovas et al. (2022) for the same sites. Variability in metabolism rates has been suggested as an indicator of river ecosystem health and resilience alongside the metabolism estimates themselves (Clapcott et al. 2016).

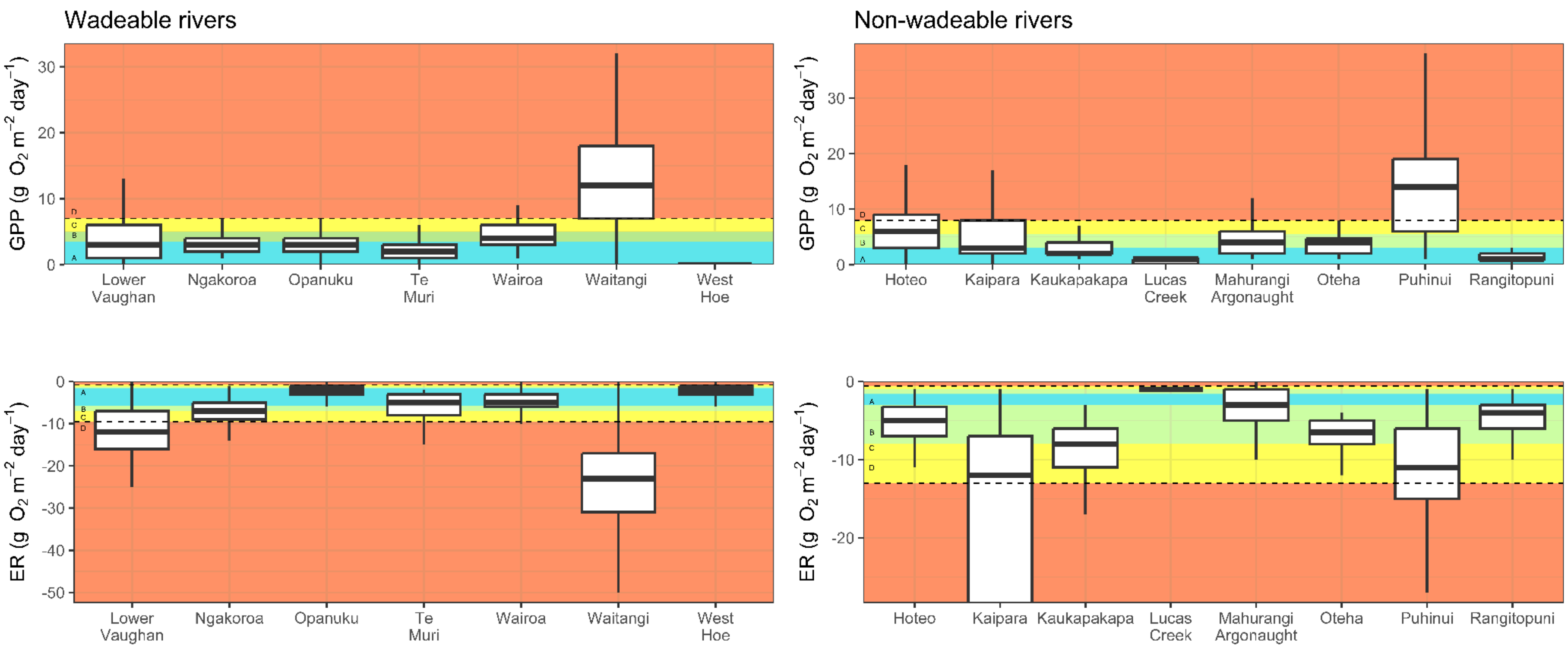

Figure 6. Distributions of daily gross primary production (GPP) and ecosystem respiration (ER) for each river for the whole time-series. The central tendencies of each distribution are shown, and extreme values (outliers) were excluded. The middle line inside the box represents the median of the distribution, and the lower and upper hinges correspond to the 25th and 75th percentiles, respectively. The upper and lower whisker extends from the hinge to the largest and smallest value, respectively, no further than 1.5 times the distance between the first and third quartiles from the hinge. The dashed lines represent the transition points between C band and D band, and if in an NPF-FM context would be described as national bottom lines.

5.3 Discussion

The results highlight significant spatial and temporal variations in gross primary production (GPP) and ecosystem respiration (ER) across the monitored sites.

The median values for each site across the whole sampling record (Tables 7 and 8) were assessed to give a broad picture of the grading over the whole sampling record at each site. A comparison between the baseline period (2013–17) and the current period (2020–24) revealed statistically significant differences in metabolism rates in nearly all sites, regardless of their catchment group. However, statistically significant differences do not necessarily translate to different grades or ecological differences.

The variability in GPP and ER values within sites over time is also a potentially important indicator of ecosystem health and resilience. Sites such as West Hoe and Rangitopuni, which exhibited low variability, tend to reflect more stable and healthier conditions. In contrast, sites with high variability, such as Waitangi, Kaipara and Puhinui, are indicative of more stressed ecosystems with widely fluctuating metabolism rates. This aligns with findings from Clapcott et al. (2016), which suggest that variability in metabolism could be a useful metric for assessing resilience and ecosystem health alongside the mean rates of GPP and ER.

The variability in rates of metabolism and changes in band between the baseline and current periods suggest that caution should be applied when grading sites using EM data collected over relatively short time-series. EM is known to vary considerably from year to year in response to climatic and river flow patterns (Young and Huryn 1996). Therefore, as more data become available there would be value in reconsidering the banding criteria proposed by the STAG (2019) to determine their utility alongside other metrics such as variability in metabolism.

6. General discussion

This report highlights substantial variability in dissolved oxygen (DO) minima across Auckland Region sites, with reference sites often maintaining high DO minima levels (above 8 mg/L), and more intensively modified catchments – such as urban and high-intensity rural sites – experiencing near-anoxic conditions (0 mg/L). Similarly, this report identifies substantial spatial and temporal variability in gross primary productivity (GPP) and ecosystem respiration (ER) across the monitoring sites, with rates of metabolism indicative of excellent health (A band) at reference sites, and of poor health (D band) at several Urban and Pukekohe sites.

DO minima and rates of ecosystem metabolism (EM) are related, with both being calculated from continuous time-series of DO measurements. Therefore, it makes sense that ecosystem health gradings for some sites are consistent based on DO minima and EM. However, the two attributes indicate quite different things, and so it is not surprising that gradings for some sites differ between DO minima and EM. For example, a low DO minima at a site might be caused by significant inputs of low-DO groundwater and not related to metabolic activities within the river itself. On the other hand, a site with a high load of organic pollution and high rates of ER indicative of poor health may not have a very low DO minima if its physical characteristics enable high exchange of DO with the atmosphere (i.e. the river is shallow and turbulent). Therefore, measurements of DO minima and EM should be considered as complementary assessments of ecosystem health, not a duplication.

The identification of substantial declines in DO associated with high tides at several lowland sites near the coast is very interesting and potentially important. Monitoring of river ecosystems typically avoids the lowland reaches affected by changes in tidal level. Similarly, estuarine monitoring typically focuses on estuarine areas influenced by a mix of fresh and saline water associated with tidal changes and does not extend upstream to areas that are predominantly fresh water. Therefore, the lowland tidal sections of rivers are often overlooked, and this finding is quite novel.

Many of our native fish species migrate to and from the ocean to complete their life cycle, so potential for these low-DO tidal sections of rivers to act as temporary barriers to migration deserves further investigation. Discussions with regional council staff in other parts of Aotearoa New Zealand suggest that this phenomenon has been seen elsewhere (e.g. Northland, Waikato, Southland), but it is not clear how widespread it is. Organic material transported downstream by rivers may often be deposited in tidal areas when tides cause the water to slow down and back up. Decomposition and uptake of DO associated with this accumulation of deposited organic material from upstream might be related to the low levels of DO observed during high-tide periods, or perhaps the low DO values are related to poor ecosystem health and low DO in the estuarine areas further downstream. Further monitoring of DO dynamics in the tidal reaches of rivers in the Auckland Region and elsewhere would be useful to determine the scale and severity of this issue.

The current government is undertaking various reforms to resource management policy and has signalled that it intends to modify the NPS-FM. National objectives relating to minimum DO for all rivers (not just rivers downstream of wastewater discharges) and EM are included in the current version of the NPS-FM (MfE 2024). The analyses of monitoring data for DO minima and EM in this report clearly demonstrate the value of these attributes for assessing key components of river ecosystem health. Minimum DO and EM are complementary measures that can be calculated from the same time-series of DO data. We recommend that continuous DO monitoring remains ongoing in the Auckland Region as a key component of river health monitoring and assessment efforts.

7. Appendices

Appendix 1. Dissolved oxygen metric data for the Pakuranga site

A relatively high proportion of the dissolved oxygen (DO) data from the Pakuranga site was considered to be of low quality and 90 days of good-quality data were not available to calculate a DO minimum for this site. Given this, the results should be treated with caution and were not presented in the main body of the report.

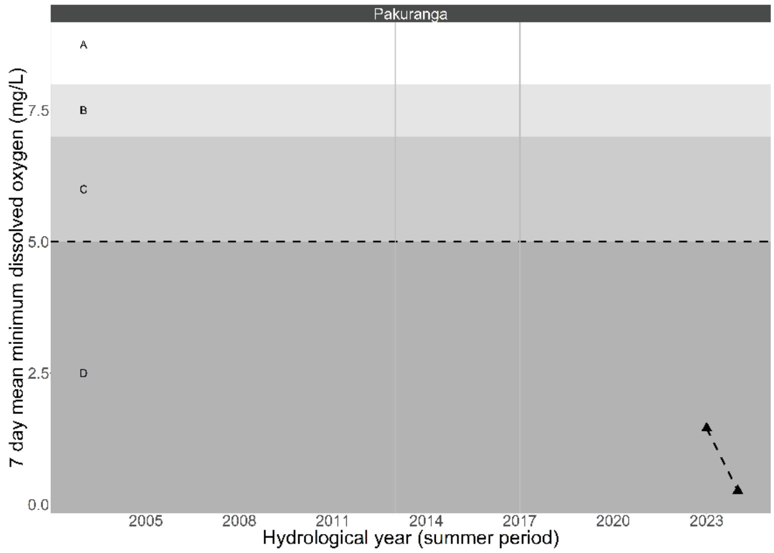

Figure A1.1. NPS-FM band assessment for the 7-day mean minimum dissolved oxygen (DO) concentration for the Pakuranga site. Light grey vertical lines indicate the NPS-FM baseline state period (2013–17 hydrological years). The horizontal dashed line shows the DO national bottom line. Triangles show annual values that were calculated with less than 90 days of data and should be treated with caution. This site was not included in the main body of the report due to the high proportion of low-quality data.

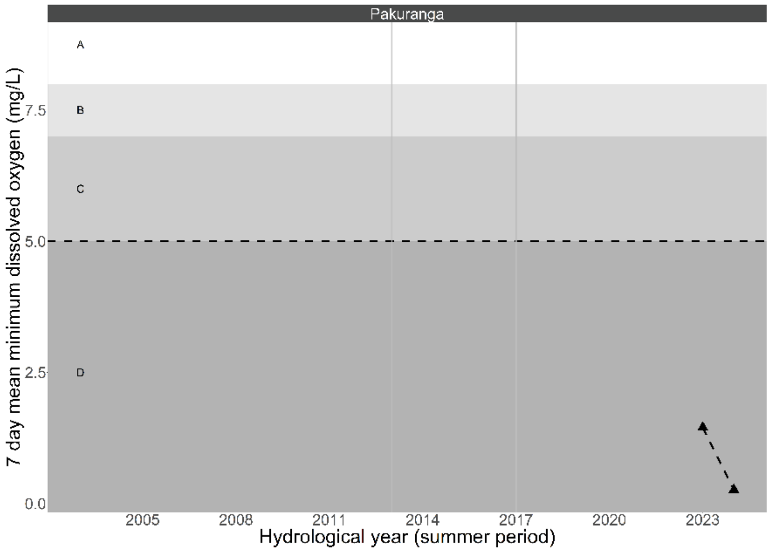

Figure A1.2. NPS-FM band assessment for the 1-day minimum dissolved oxygen (DO) concentration for the Pakuranga site. Light grey vertical lines indicate the NPS-FM baseline state period (2013–17 hydrological years). The horizontal dashed line shows the DO national bottom line. Triangles show annual values that were calculated with less than 90 days of data and should be treated with caution. This site was not included in the main body of the report due to the high proportion of low-quality data.

Appendix 2. An example of dusk and dawn identification from a dissolved oxygen data time-series

As discussed in Section 5.1, the first step in our calculations of ecosystem metabolism (EM) consisted of determining the dark period of the day from the dissolved oxygen (DO) time-series. This was estimated using the DO dataset itself. Dusk corresponds with the most negative value of dDO/dT over the 24-hour period, while dawn corresponds with the highest value of the oxygen deficit (*D*). The dark period was then defined as the time between dusk and dawn.

Figure A2.1 shows an example of DO data collected over a 24-hour period and the associated relationship between D and the rate of change in DO concentration (dDO/dT). In this example, the most negative value of dDO/dT occurred at 7.05 pm (Figure A2.1). The fastest rate of DO decline during a 24-hour period occurs at dusk because it is too dark for gross primary productivity (GPP) to occur and there is a strong DO partial pressure gradient between the water and the atmosphere, resulting in high flux of DO to the atmosphere via reaeration. The rate of DO decrease declines over the course of the night as oxygen moves from the water to the atmosphere and the DO partial pressure gradient between the water and the atmosphere reduces.

In this example (Figure A2.1), the highest value of D occurs at 6.45am. This maximum occurs at dawn because DO is reducing throughout the night as a result of respiration and gas exchange with the atmosphere, but DO input from photosynthesis has not yet begun. After dawn, the concentration of DO begins to rise, reducing the oxygen deficit.

Photosynthesis does not occur during night-time, so changes in DO over the night-time period are related only to reaeration and respiration, as represented in Equation 2:

$$dDO/dT = ER + kD \qquad \text{Equation 2}$$

Using only the night-time data, the relationship between the oxygen deficit (*D*) and the rate of change of oxygen concentration (dDO/dT) can be used to calculate the reaeration coefficient (*k*; i.e. the slope of the regression line) and the rate of ecosystem respiration (*ER*; the y-intercept). This equation is the basis of the night-time regression method that is used in this report to calculate EM.

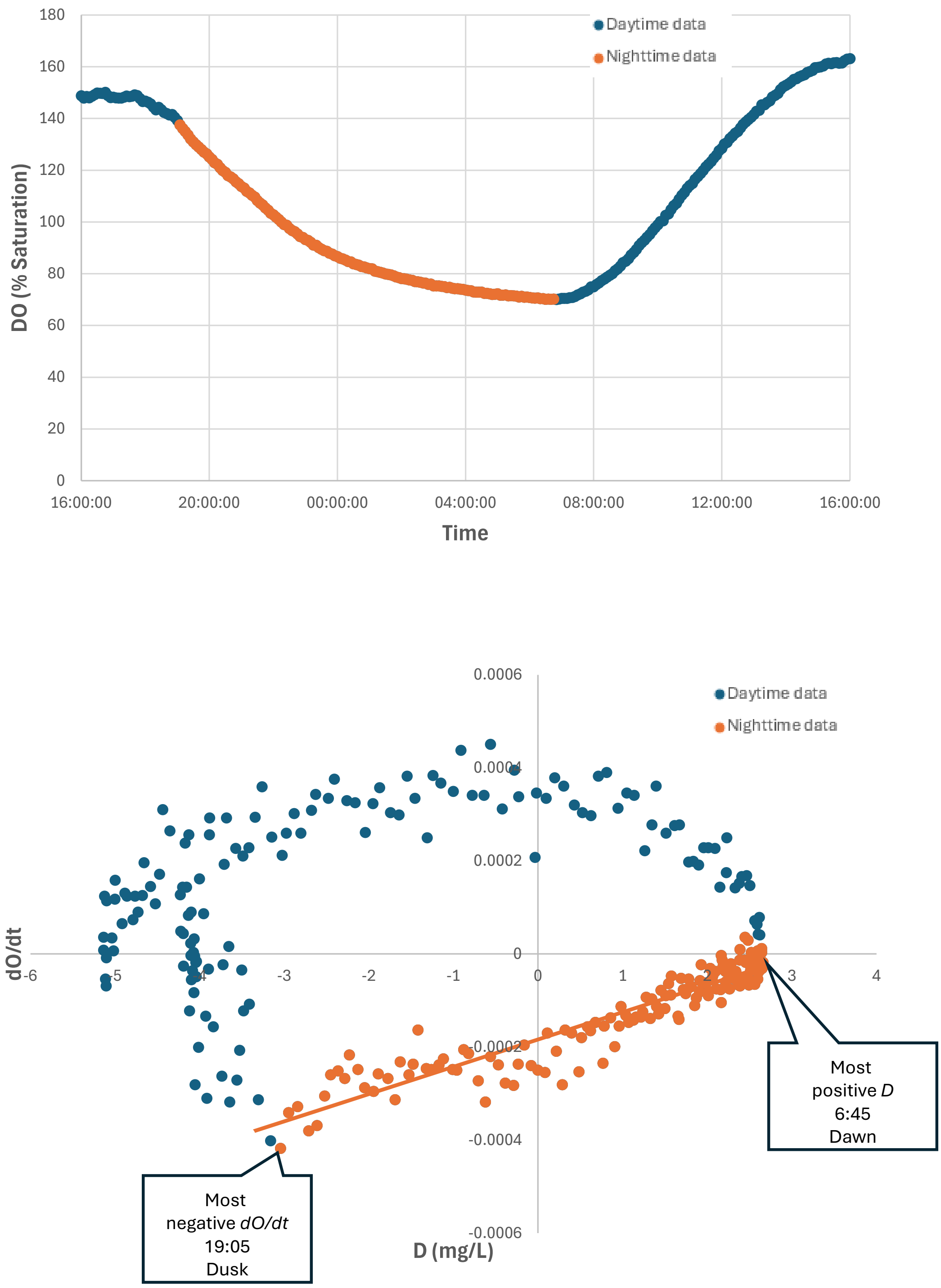

Figure A2.1. An example dissolved oxygen (DO) dataset over 24 hours, showing how dusk and dawn are identified from a plot of the oxygen deficit (*D*) versus the rate of change of DO (*dO/dt*). Using the night-time regression method, the night-time data between dusk and dawn are used to estimate the reaeration coefficient and rate of ecosystem respiration, and hence ecosystem metabolism.

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