Dissolved Oxygen and Ecosystem Metabolism in Auckland Rivers 2004-2020 State of the Environment Reporting

Paula Casanovas, Eric Goodwin, Jessica Schattschneider
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Paula Casanovas[1], Eric Goodwin[1], Jessica Schattschneider[1], Janine Kamke[2], Coral Grant[2]
Rhian Ingley[2], Stacey Fraser[2], Roger Young[1]
[1]Cawthron Institute; [2]Research and Evaluation Unit, Auckland Council

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Aerial photograph of weir at Manawhenau Stream at tributary of the Wairoa River, Mangawheau Stream Auckland. Photograph by Jonathan De Villiers.

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Puhinui Stream immediately upstream of the continuous dissolved oxygen monitoring site, Manukau Auckland, Photograph by Janine Kamke.

Executive summary

As part of its State of the Environment programme, Auckland Council has been monitoring dissolved oxygen (DO) continuously at 15 rivers for up to 17 years. This is the longest continuous DO dataset that we are aware of in New Zealand. DO is a critical water quality indicator and one of the action planning attributes in the National Policy Statement for Freshwater Management 2020 (NPS-FM 2020). There is now broad recognition that measuring water quality alone is not enough to assess river ecosystem health. A biophysical framework for river ecosystem health was included in the NPS-FM 2020 and incorporates five components — water quality, water quantity, habitat, aquatic life and ecological processes. Ecosystem metabolism (the combination of gross primary production (GPP) and ecosystem respiration (ER)) is an example of an ecological process indicator and was included as an attribute in the NPS-FM 2020. Continuous DO data are used to calculate ecosystem metabolism, so there are multiple benefits from measuring DO continuously.

This study is the latest analysis and reporting of DO data and ecosystem metabolism estimations for rivers in the Auckland region. Ecosystem metabolism was calculated using R code enabling the entire dataset to be examined, rather than just focusing on short representative ‘snapshot’ periods of the dataset which was the only feasible approach previously when metabolism calculation was a more manual process. We report DO minima values in relation to the NPS-FM attribute table and provide similar reporting for ecosystem metabolism, although a banding system for ecosystem metabolism has not yet been incorporated into the NPS-FM 2020. We also examine temporal and spatial variability in ecosystem metabolism and potential drivers of this variability.

DO minima, calculated only from the highest quality coded data, ranged from >7 mg/L at the reference site (West Hoe) down to almost anoxic conditions (i.e. 0 mg/L) at several sites draining rural, vegetable growing and urban catchments. In terms of NPS-FM 2020 attribute bands, the reference site was classified in the B-band for overall minimum DO status, suggesting that overall A-band status may be unachievable for Auckland streams. Ararimu, Kaukapakapa, Kumeu, Rangitopuni, Te Muri, Ngakoroa, Waitangi and all three urban sites (Kaipara, Lower Vaughan, Puhinui) had very low DO minima indicating overall D band status (below the national bottom line). Most sites had consistent overall band assessments between the proposed baseline (2013-2017) and current state (2016-2020) periods. The exceptions to this were Opanuku, Mahurangi, Ngakoroa, which all improved one band between the baseline and current state periods.

There is some ambiguity in the NPS-FM regarding whether DO minima should be determined for the whole year (i.e. NPS-FM table 17), or just the summer (November to April) period. In most cases the DO minima that were observed occurred within this summer period, but there were a few cases where annual DO minima occurred outside the summer period. Ideally, DO should be measured and analysed throughout the year, but if resources are limited a focus on the entire summer period will capture most DO minima events.

Ecosystem metabolism was calculated from the continuous DO data at all sites. Median rates of GPP over the whole data set ranged from 0.08 g O_2 m^{-2} day^{-1} at West Hoe (Reference site) through to 16.3 g O_2 m^{-2} day^{-1} at Puhinui (Urban). Median rates of ER over the whole data set ranged from -1.7 g O_2 m^{-2} day^{-1} at West Hoe (Reference) through to -24.6 g O_2 m^{-2} day^{-1} at Waitangi (Pukekohe SVGA). Based on the attribute state bands for ecosystem metabolism that were recommended by the Science and Technical Advisory Group for the NPS-FM (STAG, 2019), West Hoe (Reference site) would be classified in the A band for both GPP and ER. At the other end of the spectrum, Kumeu (Rural-High) and Waitangi (Pukekohe SVGA) were in the D band for both GPP and ER. Puhinui was in the D band for GPP, but C band for ER, while Lower Vaughan was in the D band for ER and C band for GPP. The other sites ranged from A band to C band with some differences in classification between GPP and ER bands. Metabolism results indicated possible declines in ecosystem health between the baseline and current state periods at the Wairoa and Kaipara sites, whereas there was evidence of potential improvements in band status for Te Muri and Ngakoroa between the same periods. Further investigations using other indicators of ecosystem health would be interesting to see if results from ecosystem metabolism are consistent with results from other indicators (e.g. macroinvertebrates, water clarity, nutrient concentrations, periphyton).

Median values of net ecosystem metabolism (i.e. the difference between GPP and ER; NEM) for most sites were negative indicating heterotrophic dominance where rates of ecosystem respiration are reliant on organic matter sources from upstream or the surrounding catchment. However, median NEM values were positive at Opanuku, Hoteo, Mahurangi and Puhinui indicating that more organic matter is being produced than respired at these sites and that these sites will tend to accumulate and / or export organic matter downstream.

NPS-FM band assessments from minimum DO and ecosystem metabolism were identical or relatively consistent for most sites. However, there were some inconsistencies. The overall minimum DO band at the reference site (West Hoe) indicated B-band status, while the overall ecosystem metabolism assessments indicated A-band status. This suggests that the A-band criteria for minimum DO are potentially unrealistic in Auckland, given the warm climate and so, naturally lower DO concentrations. At three sites (Kaukapakapa, Rangitopuni, Ngakoroa) there were considerable differences in band assessments between minimum DO and ecosystem metabolism. In all three cases, minimum DO indicate poor health (D-band or C-band), whereas ecosystem metabolism indicated better ecological condition (B-band, or A-band). It appears that while annual minimum DO concentrations experienced at these sites are very low, the daily fluctuations in DO resulting from ecosystem metabolism are not extreme.

In terms of differences among sites, small rivers tended to have lower absolute rates of GPP and ER, although this relationship was driven to some extent by the low rates of ecosystem metabolism at the reference site (West Hoe), which happens to be one of the smallest rivers in the monitoring programme. Many of these small rivers are also heavily shaded and tended to have lower absolute rates of GPP and ER, reflecting the importance of sunlight in driving photosynthesis (i.e. GPP). There was some evidence for correlations between nitrogen concentrations (in both dissolved and total forms) and rates of both GPP and ER. It is notable that there was no evidence for relationships between ecosystem metabolism metrics and either dissolved or total phosphorus concentrations, indicating that nitrogen appears to be more important in the Auckland region at regulating rates of periphyton and aquatic plant growth (and organic matter respiration) than phosphorus concentrations.

Macroinvertebrate index scores were negatively correlated with absolute rates of GPP and ER, reinforcing the view that sites with macroinvertebrates indicative of a healthy river tend to have low absolute rates of GPP and ER, while sites with high rates of ecosystem metabolism tend to support macroinvertebrates that are associated with impacted conditions.

Variability in ecosystem metabolism over time was low at the reference site and higher at more impacted sites, which is consistent with earlier analyses of data from these sites. Ecosystem metabolism estimates showed distinct seasonal patterns as well as shorter-term variation resulting from variation in light intensity and river flows. Long term changes could also be due to changes in climate or the condition of the surrounding environment that influence light availability, water temperature, flow regime, and nutrient and contaminant inputs.

Ecosystem metabolism is an integrative indicator of ecosystem health. It is affected by a wide range of potential stressors and our analysis of differences in metabolism among sites has shown correlations with shading, landcover, water temperature, and concentrations of nitrogen. However, it is difficult to pinpoint exactly which drivers are responsible for the differences as many of these drivers co-occur and have a cumulative effect on ecosystem metabolism. For example, rivers with little shading, draining catchments dominated by pasture grasses typically have warm temperatures and high concentrations of nutrients – and so respond with rates of ecosystem metabolism that are indicative of poor health. Similarly, management actions such as stock exclusion, revegetation of riparian zones, and associated control of contaminant runoff will result in rates of ecosystem metabolism more similar to reference conditions as well as improvements in various indicators of ecosystem health. We recommend the coordinated monitoring of pressures on freshwater ecosystems (e.g. land use change, shading, land cover, nutrient leaching) as well as ecological responses (e.g. DO minima, ecosystem metabolism, water quality, MCI scores) to better identify drivers and direct management actions.

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Glossary

Term	Description
D	oxygen deficit – the difference between observed oxygen concentration and the concentration expected at 100% saturation
DO	dissolved oxygen
EM	ecosystem metabolism
ER	ecosystem respiration
GPP	gross primary production
k	Reaeration coefficient – a measure of the ease at which gases cross the boundary between the river surface and the atmosphere. Deep slow rivers will have a low reaeration coefficient, while fast, shallow and turbulent rivers will have a higher reaeration coefficient.
LCDB	Land Cover Database https://lris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/
MfE	Ministry for the Environment
NEM	Net ecosystem metabolism (production + respiration)
NEMS	National Environmental Monitoring Standards

Term	Description
NPS-FM	National Policy Statement for Freshwater Management
R	A free software environment for statistical computing and graphics
R^2	A measure of relative reliability of the metabolism estimates
SOE	State of the Environment
STAG	Science and Technical Advisory Group for the NPS-FM
Stream order	A numbering system used to represent the level of branching in a river system. If two streams of the same order merge, the resulting stream is given a number that is one higher than the two tributaries.
SVGA	Specified Vegetable Growing Area as defined in the NPS-FM 2020

1 Introduction

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 and can be represented as the difference between GPP and ER (referred to as net ecosystem metabolism, NEM) or the ratio of GPP:ER. 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. 2013 a, b).

Throughout the world, assessment of river ecosystem condition has traditionally concentrated on just water quality and to a lesser extent the composition of macroinvertebrate communities. However, there is now broad recognition that measuring water quality alone is not enough to assess ecosystem health (Young et al. 2018; Freshwater Independent Advisory Panel 2020). Recent changes to environmental policy in New Zealand have recognised ecosystem health as a broader more holistic value to be maintained and improved in New Zealand's freshwater ecosystems. A biophysical framework for ecosystem health was included in the National Policy Statement for Freshwater Management 2020 (NPS-FM 2020) and incorporates five components—water quality, water quantity, habitat, aquatic life and ecological processes (Clapcott et al. 2020). EM is an example of an ecological process indicator and was included as an attribute in the NPS-FM 2020 (Freshwater Independent Advisory Panel 2020).

Continuous dissolved oxygen (DO) monitoring data are used to calculate ecosystem metabolism. 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 2020.

Auckland Council has been carrying out long term monitoring of DO at 15 rivers within their State of the Environment (SOE) programme (with rivers continuously monitored for between 7 and 17+ years). This is the longest DO dataset that we are aware of in New Zealand (Depree et al. 2016). Previous analysis of DO and metabolism data collected in Auckland Council's monitoring is reported in Young (2006) and Doehring & Young (2010). Clapcott et al. (2016) also reported on data from this monitoring programme.

The study presented here represents the latest update of river DO data and EM reporting for the Auckland Council SOE programme. It builds on improvements to automation of EM analysis developed for Northland Regional Council (Goodwin & Young 2022) and on-going updates to analysis methods. The specific aims of this study are to: 1) update the DO and EM reporting as part of the long-term SOE programme, 2) use time series data to examine the temporal and spatial variability in EM for 15 rivers (including consideration of natural variability), and 3) investigate possible drivers of spatial and temporal variability in EM.

Auckland Council will use the results presented in this report to improve their river ecosystem health monitoring programme and gain further benefit from existing monitoring. This knowledge can potentially help Auckland Council assess the management of catchment activities and instream water allocation to better understand their river health outcomes.

2 Monitoring sites and data compilation

Dissolved oxygen (DO) has been continuously monitored at 15 river sites within the Auckland region with long term datasets now available (starting between 2003 and 2013 and varying from 7 to 17+ years in length). The location of these sites is shown in Figure 1.

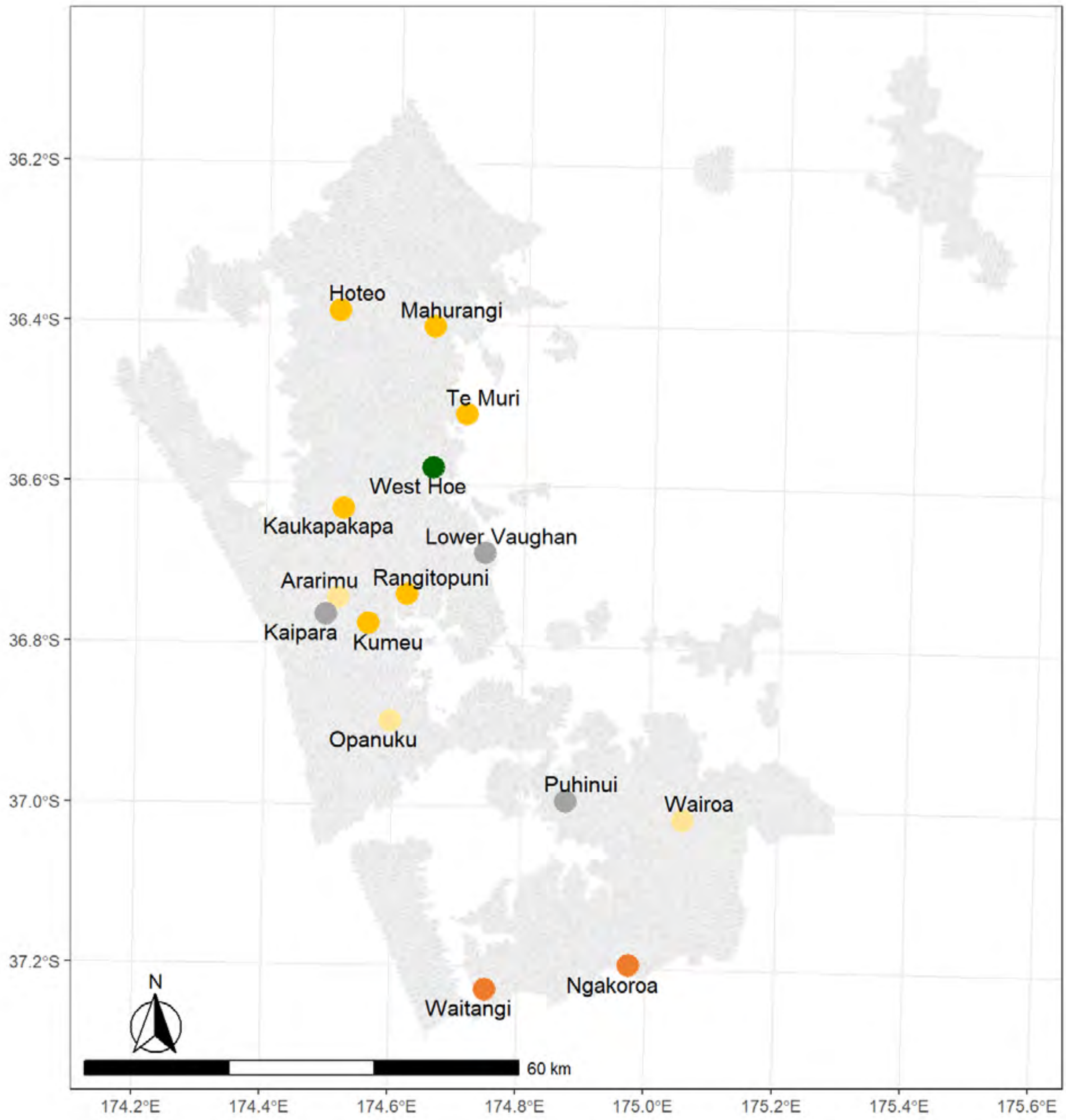

Figure 1. Site location of the dissolved oxygen sensors on the 15 rivers analysed in this study. Colours indicate the dominant land use category for each catchment (see Table 1 below).

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 Specified Vegetable Growing Area (SVGA) are marked as Pukekohe SVGA. Specific exemptions are provided for in this area in relation to meeting NPS-FM bottom line requirements for specific nutrient related attributes (as outlined in clause 3.33 and Part 2 Appendix 5 of the NPS-FM) regarding the importance of food production activities in the area.

Table 1. List of rivers, including broad upstream catchment land cover groups used throughout this report. Geology HS: hard sedimentary rocks; VA: volcanic acidic; SS: soft sedimentary. Climate WD: warm-dry; WW: warm-wet.

River name	Upstream catchment's dominant land cover group	Wadeable year round	Stream order	Geology	Climate
West Hoe	Reference	Wadeable	2	SS	WW
Wairoa	Rural - Low	Wadeable	5	HS	WW
Ararimu	Rural - Low	Non-wadeable	5	SS	WW
Opanuku	Rural - Low	Wadeable	3	SS	WW
Te Muri	Rural - High	Wadeable	1	SS	WD
Kaukapakapa	Rural - High	Non-wadeable	5	SS	WW
Rangitopuni	Rural - High	Non-wadeable	1	SS	WW
Hoteo	Rural - High	Non-wadeable	5	SS	WW
Kumeu	Rural - High	Wadeable	4	SS	WW
Mahurangi	Rural - High	Non-wadeable	4	SS	WW
Waitangi	Pukekohe SVGA	Wadeable	3	VA	WW
Ngakoroa	Pukekohe SVGA	Wadeable	3	VA	WW
Kaipara	Urban	Non-wadeable	5	SS	WW
Lower Vaughan	Urban	Wadeable	2	SS	WD
Puhinui	Urban	Non-wadeable	3	SS	WD

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

Dominant Land Cover Class	Definition
Urban	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.
Rural - High	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.
Rural - Low	
Exotic	More than 80% of the upstream/surrounding catchment within exotic forestry.
Native	These sites have more than 95% native forest or scrub remaining within the upstream/surrounding catchment. These are intended to represent reference quality conditions that have a very low level of land use pressure influence though they are not necessarily 'pristine'.

The following data were provided by Auckland Council from each of the 15 rivers included in this report:

- site information (name, location, relationships between river flow/level and mean reach depth upstream of the DO monitoring site, photos)
- dissolved oxygen (DO), temperature and flow timeseries data
- water quality data at or in proximity to the DO monitoring site
- macroinvertebrate community indices (MCI, EPT and taxa richness)
- land cover data
- canopy cover data (river shade via geospatial assessment).

Further detail on each of these data sets, other relevant data sets and the results of initial data compilation are discussed in the following sections. The data compilation process was conducted within the R environment.

2.1. Site information

River cross section data for each DO monitoring site (for calculating water depth), elevation, and notes on frequency of visits and type of sensors for DO sites were provided (Appendix 1). Information on which sites are wadable, based on experience from when the cross-section surveys were undertaken, along with a general impression for all years was included. Information from the

Auckland Council web feature service monitoring sites (WFS), and the REC2 database was added to the site information dataset: NZSegment, stream order, climate, source of flow, and geology classifications. Site photos were also supplied.

2.2. Dissolved Oxygen timeseries

The dissolved oxygen timeseries dataset from 16 sites located in the 15 rivers included: 1) date and time; 2) water level (in metres, representing the stage height for the sites); 3) discharge (in m^3/s - cubic meters per second); 4) water temperature (in °C); 5) per cent oxygen saturation; 6) dissolved oxygen concentration (in mg/L). The data were measured every 15 minutes at most sites, except for Te Muri and West Hoe (from 29-08-2014 until the end of the time series) which were measured every five minutes.

There were two separate datasets for West Hoe, Mahurangi River and Waitangi River. For this report we used only the dataset from West Hoe that had 15-minute data frequency. There are also two datasets for the Mahurangi River, because the location of the sensor site was changed in 2009 (see Appendix 1 for details). For this report, these two datasets were combined. The two datasets for Waitangi River were the same except for one record; for this report, the dataset with the most records was used (see Appendix 1).

The DO timeseries data for each river were compiled together, and the names of the variables and the river names were checked and changed if necessary for consistency. For each site, stage height / water level was converted to depth using the relevant river cross section data. The full time series per river are provided with this report as csv and rData files (all_rivers_raw_data.csv containing all data, individual csv and rData files for each site are also supplied). Plots of the full timeseries for each river are shown in Appendix 3: Results per river. Summary statistics for the timeseries variables are shown in Table 3.

Table 3. Summary statistics over the full period for variables from the dissolved oxygen (DO) dataset. Data specified as QC 42 and 43 were excluded from these summary statistics.

		Date		Depth (m)			Discharge (m^3/s)			Temp. (°C)			DO (%)			DO (mg/L)		
River name	**Number records**	Min	Max	Median	Min	Max	Median	Min	Max	Median	Min	Max	Median	Min	Max	Median	Min	Max
West Hoe	452703	2006/10/25	2020/12/11	0.18	0.12	2.02	0.18	0.0003	2.0258	13.2	6.3	20.0	90.4	74.6	109.1	9.5	7.1	12.8
Ararimu	541227	2004/01/15	2021/01/01	1.09	0.74	5.80	1.09	0.0267	90.6877	14.3	5.6	23.5	85.9	19.9	122.3	8.8	1.8	13.0
Opanuku	306141	2011/03/08	2020/12/01	0.46	0.33	3.78	0.46	0.008	62.7247	13.6	5.8	27.6	98.1	17.8	179.1	10.3	1.7	16.9
Wairoa	459127	2006/01/19	2021/01/01	0.94	0.73	5.70	0.94	0.2525	360.1926	14.3	4.7	24.3	95.1	34.6	252.3	9.7	3.7	24.2
Hoteo	521106	2005/06/15	2021/01/01	1.36	1.11	10.63	1.36	0.0901	306.5679	15.4	6.2	26.0	95.8	60.3	145.5	9.6	5.5	13.4
Kaukapakapa	529827	2004/05/11	2021/01/01	1.11	0.76	6.30	1.11	0.0031	116.3118	14.4	0.0	24.2	86.3	5.8	121.7	8.9	0.2	12.2
Kumeu	362451	2004/01/15	2015/04/08	1.17	0.78	4.59	1.17	0.0014	45.3638	14.8	6.3	23.4	83.4	0.0	131.8	8.6	0.0	14.3
Mahurangi	852074	2005/05/31	2021/01/01	1.26	0.46	4.34	1.26	0.0184	170.2100	15.2	6.6	25.0	99.3	4.4	197.9	10.0	0.4	20.0
Rangitopuni	413375	2007/07/26	2021/01/01	0.74	0.41	5.67	0.74	0.0017	126.2073	14.2	5.7	24.3	89.0	0.1	149.0	9.1	0.0	14.5
Te Muri	651839	2013/12/31	2021/01/01	0.35	0.31	1.57	0.35	< 0.0001	5.2274	16.1	5.8	24.9	78.8	7.3	206.5	7.7	0.7	18.5
Ngakoroa	534216	2003/08/06	2021/01/01	0.32	0.12	0.97	0.32	0.0017	4.7745	14.9	5.6	23.0	87.3	26.0	122.8	8.9	2.5	13.0
Waitangi	425871	2008/05/05	2021/01/01	1.14	0.92	3.12	1.14	0.022	29.5208	15.3	7.6	26.6	69.6	0.1	146.3	7.0	0.0	14.6
Kaipara	542222	2004/01/15	2021/01/01	1.14	0.41	5.98	1.14	0.0324	123.8779	14.7	6.6	25.2	86.7	23.8	125.6	8.8	2.1	12.8
Lower Vaughan	386282	2008/05/22	2021/01/01	0.39	0.26	2.66	0.39	< 0.0001	11.0309	14.6	4.9	26.3	67.1	0.7	276.0	6.9	0.1	24.1
Puhinui	439630	2005/03/16	2020/12/26	0.62	0.52	2.37	0.62	0.0076	29.3356	16.8	0.0	28.6	89.6	0.2	249.8	9.1	0.0	23.2

2.3. Land cover data and canopy cover data

Auckland Council provided the latest assessment of the upstream catchment land cover classes for each site (Table 1). Land cover data from the NZ Land Cover Data Base v5.0 (https://lris.scinfo.org.nz/) were available for 2008, 2012 and 2018.

Canopy cover data were also available as a one-time measurement at each site (2016/2018). Canopy cover was estimated based on a Canopy Height Model (CHM) derived from the 2016/18 regional LiDAR survey (Golubiewski et al. 2021). The CHM is a 1 m x 1 m raster surface model and represents vegetation canopy 3 m and greater. Canopy cover estimates are provided for each catchment and split by riparian buffer (buffer width varies depending on stream order, Order 1: 15 m buffer, in increments of 5 m up to Order 5: 35 m buffer), along with catchment area outside the riparian buffer and for the total catchment (see Lowe et al. 2016 for more information).

2.4. Water quality data

Monthly data collected from the Auckland Council's River Water Quality Monitoring Programme and data from relevant sites from NIWA's National River Water Quality Network were assessed. These are long-term datasets starting in the 1980s, but for this project the data analysed was from the period between 2003 and 2020. The Auckland Council programme includes information on up to 30 different water quality parameters over 12 of the 15 rivers included in this report. It is important to note that some water quality sites are not at the same paired location as the continuous DO monitoring sites, but in close proximity and still considered representative of the DO site (Table 4). NIWA water quality data were available for two rivers, Hoteo and Rangitopuni and included information on 15 different water quality parameters. We only used water quality data sourced from NIWA for these two rivers.

Data on macroinvertebrate indices were also available for nine rivers (Ararimu, Kumeu, Mahurangi, Ngakoroa, Puhinui, Lower Vaughan, Wairoa, Waitangi, West Hoe). See Table 4 for detail of the sites, including the site area number and site name for these data.

Table 4. River sites used in this study and availability of water quality data.

River flow/ continuous DO sites	Water quality sites	**Macroinvertebrates sites**
43807 Puhinui	43807 Puhinui (Paired)	1043826 Puhinui LTB (Paired)
43602 Waitangi	43601 Waitangi (approx. 1.2 km downstream of flow site)	43601 Waitangi Stream (approx. 1.2 km downstream of flow site)
43829 Ngakoroa	43829 Ngakoroa (Paired)	1043824 Ngakoroa LTB (Paired)
45315 Kumeu	45313 Kumeu (approx. 300 m downstream of flow site)	45369 Kumeu @ Weza (approx. 300 m downstream of flow site)

River flow/ continuous DO sites	Water quality sites	Macroinvertebrates sites
45415 Kaukapakapa	45415 Kaukapakapa (Paired)	No data
45311 Kaipara	No data	No data
7805 Rangitopuni	NIWA AK2 Rangitopuni (approx. 900 m downstream of flow site)	No data
8516 Wairoa	8516 Wairoa (Paired)	8553 Wairoa LTB (Paired)
45326 Ararimu	No data	45368 Ararimu @ Old North Road (Paired)
45703 Hoteo	NIWA AK1 Hoteo (Paired)	No data
6863/6806 Mahurangi	6804 Mahurangi (approx.. 750 m downstream of flow site)	6869 Mahurangi @ College (430 m upstream of flow site)
7506 Lower Vaughan	7506 Vaughan (Paired)	7527 Vaughan Lower (Paired)
7206 West Hoe	7206 West Hoe (Paired)	7213 West Hoe LTB (Paired)
7904 Opanuku	7904 Opanuku (Paired)	No data
6995 Te Muri	No data	No data

2.5. Climate data

Time series datasets of regional precipitation and air temperature were obtained from Statistics New Zealand (www.stats.govt.nz). These time series are for the Auckland Council Region, summarised as the average for the region per season and year. The average monthly values of the Southern Oscillation Index (SOI) were also obtained from Statistics New Zealand (original data from NOAA, https://www.ncdc.noaa.gov/teleconnections/enso/soi).

2.6. Quality coding (QC)

All variables from the DO timeseries and water quality dataset had associated quality coding (QC) metadata (see Table 5 for QC values and their meaning). Quality coding of DO data was completed to an Auckland Council internal standard which is different to the National Environmental Monitoring Standard (NEMS) quality coding system (NEMS Dissolved Oxygen Version 2.0 2016). For example, Auckland Council's standard for good quality (QC10) DO concentration data allows for 0.5mg/L deviation from the reference meter whereas the equivalent NEMS allow for a deviation of 0.3mg/L + 5% of the reference value for good quality (QC600) data. Auckland Council is currently implementing NEMS protocols and quality coding for ongoing monitoring of continuous DO data, but this process was not complete at the time of this report.

DO data sets were not adjusted for barometric pressure that will result from differences in elevation among sites, and fluctuations in air temperature and humidity. A gap filling regression based on dissolved oxygen concentration and water temperature was used to estimate per cent oxygen saturation where that data was not provided. These records were QC coded as 300: “synthetic” (following NEMS, see Appendix 2: Detailed and additional methods, for rationale and method description).

The percentage of temperature and DO records in each of the Auckland Council QC classes for each river is shown in Figure 2. Water quality data QC was also completed to an Auckland Council internal standard for data prior to 2020, and to NEMS River water quality Version 1.0.0 (2019) thereafter. Poor quality water quality data (coded as QC 42) and missing water quality data were not used in subsequent analyses.

Table 5. Dissolved Oxygen and temperature QC codes used in this study and their meaning.

QC	Meaning
10	Original Record to Q/A standards
20	Good Quality, edited data
30	Measured Data Unknown Quality[1]
40	Estimated/Extrapolated data
42	Poor Quality Data
43	Suspect data
44	Estimated data
140	Raw/undefined/Unknown quality
151	Missing Data
255	Data Gap/Missing data
300	Synthetic data[2]

[1] The Water Level data from Waitangi is QC30, as that data was derived from NIWA, not Auckland Council equipment. Auckland Council did not edit and QC NIWA data in their own data store, but the data and their QCs are available on NIWA hydro web portal.

[2] QC300 was used for data estimated for this work.

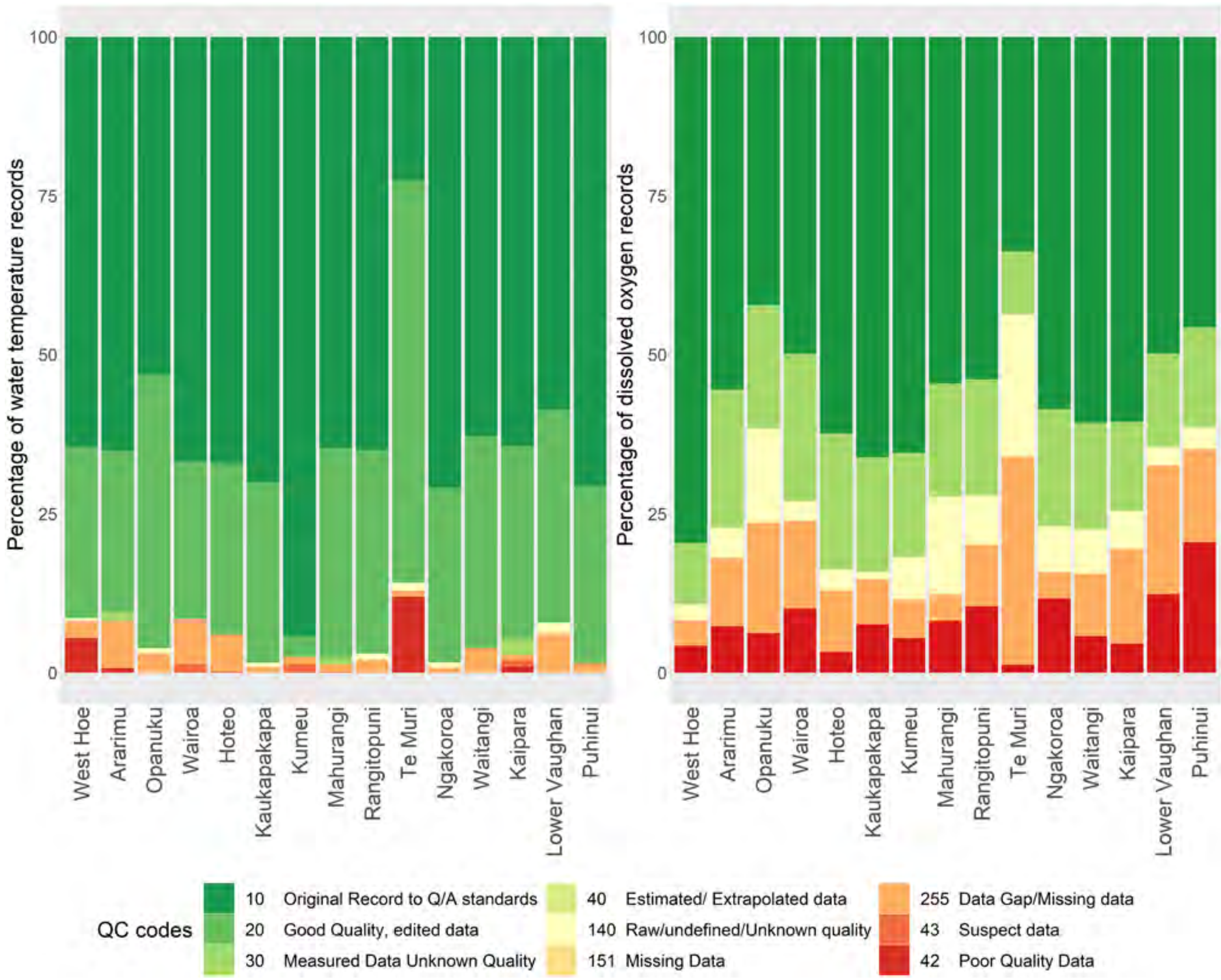

Figure 2. Percentage of raw records for water temperature (left) and dissolved oxygen saturation (right) in each QC code category for each river.

3 Dissolved oxygen minima

There are two compulsory river attributes related to dissolved oxygen identified in the NPS-FM 2020. The dissolved oxygen (DO) attribute in Table 7 of the NPS-FM (2020) is relevant for rivers below point source discharges of contaminants only. DO is also listed as an attribute in Table 17 of the NPS-FM (2020) 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), both metrics should be used to define the overall attribute band, although we note the discussion on bands in Dupree et al. (2016) outlining the value in determining statistics across multiple years. National bottom lines established for the 1-day dissolved oxygen minima aim to protect sensitive aquatic species from short duration exposure to low 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 dissolved oxygen events (Davies-Colley et al. 2013).

Table 17 of the NPS-FM specifies that the 1-day minimum should be calculated across ‘the whole summer period’ with no specified dates for calculation of the 7-day mean minimum. This currently creates opportunity for varying interpretation of how to calculate these Table 17 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 1st of November to the 30th of April).

3.1 Methods

In this report we have calculated both the 7-day mean minimum and 1-day minimum based on data over the whole summer (1st November to 30th April) period. 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. This assumption was checked by comparison to data for the entire hydrological year. Only high-quality data (QC10 and QC20) were used to calculate these minimum values.

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 data set ends. For example, the summer from 1st of November 2004 to the 30th of April 2005 is described as the summer of the hydrological year 2005.

The proposed baseline state for this attribute for Auckland Council was calculated using data over the 5-year period from 2013 to 2017 hydrological years, based on the definition of baseline state given in Section 1.4 of the NPS-FM (2020). A more recent current state was calculated using data over the 5-year period from the 2016 to 2020 hydrological years. The use of statistics calculated over a 5-year period is to help 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 baseline and current state.

Years with an incomplete summer dataset may not include the 'real' annual minima. Hydrological years with less than 90 days of data (i.e., 50% of the maximum possible days) were not included for calculating the 5-year median values for the baseline state and the current state of these attributes for each site (shown as "NA" in Table 5). Note that the current state does not include the 2021 hydrological year, as the timeseries provided ended in December 2020 (i.e., the summer of the hydrological year 2021 had less than 90 days of data).

From the minimum DO values for each hydrological year, a 5-year rolling median was calculated, for both the 7-day mean minimum and 1-day minimum values. For this calculation, the ends are smoothed by using symmetrical medians of subsequently smaller bandwidth. The 5-year rolling median approach aligns with Auckland Council's calculations of other NPS-FM attributes and helps to avoid regular changes in bands (state switching) 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. This is different from the baseline and current state assessment, because not including the years with less than 90 days of data would mean that the rolling median cannot be calculated for many years. Rolling median values calculated from years with less than 90 days of data should be treated with caution. These values are highlighted in the figures where appropriate.

3.2 Results

Differences among sites

The 7-Day mean minimum DO and 1-day minimum DO statistics and associated NPS-FM National Objectives Framework bands for DO (NPS-FM 2020 Attribute Table 17) for each site are shown in Table 6. These statistics were calculated as median values for the baseline state period (2013-2017 hydrological year) and a current state period (2016-2020 hydrological year) of years with more than 90 days of records during the summer for each site. An overall band is shown for each period, which is the worst band from the two attributes metrics.

Note that some of the mean values were calculated using less than three years of data (this is shown in Table 6 in between parenthesis), and these band assessments should be treated with caution as they are not representative of the whole period. As per previous national reporting of

DO NOF bands by Dupree et al. (2016), NOF 7-day mean minimum assessments tended to result in similar or lower bands than those derived from 1-day minimum assessments.

Table 6. NPS-FM bands (DO, Table 17) for the baseline state period (2013-2017 hydrological years) and, the current state period (2016-2020 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 between parentheses (only summers with more than 90 days of data were included). Band assessments based on <3 years of data are shaded and should be treated with caution. Overall bands were based on the worst band assessment for the 1-day or 7-day assessments.[3]

River name	1-day minimum baseline state (2013-2017)	7-day minimum baseline state (2013-2017)	Overall baseline state band (2013-2017)	1-day minimum current state (2016-2020)	7-day minimum current state (2016-2020)	Overall current state band (2016-2020)
West Hoe	B 7.46 (5)	B 7.6 (5)	B	A 7.77 (5)	B 7.99 (5)	B
Ararimu	D 2.41 (3)	D 3.22 (3)	D	D 4.08 (3)	D 4.08 (3)	D
Opanuku	B 6.64 (5)	B 7.01 (5)	B	A 7.59 (3)	B 7.96 (3)	B
Wairoa	B 6.06 (5)	C 6.61 (5)	C	C 6.33 (4)	C 6.33 (4)	C
Hoteo	B 6.43 (5)	C 6.86 (5)	C	C 6.57 (4)	C 6.57 (4)	C
Kaukapakapa	D 2.81 (4)	D 3.56 (4)	D	D 3.88 (5)	D 3.88 (5)	D
Kumeu	D 0.04 (2)	D 0.14 (2)	D	NA	NA	NA
Mahurangi	B 6.04 (5)	C 6.53 (5)	C	B 7.3 (2)	B 7.3 (2)	B
Rangitopuni	D 0.28 (1)	D 0.42 (1)	D	D 2.69 (2)	D 2.69 (2)	D
Te Muri	NA	NA	NA	D 2.13 (3)	D 2.13 (3)	D
Ngakoroa	D 3.63 (5)	D 4.53 (5)	D	C 5.42 (4)	C 5.42 (4)	C
Waitangi	D 0.38 (4)	D 0.5 (4)	D	D 0.55 (4)	D 0.55 (4)	D
Kaipara	D 2.93 (3)	D 3.86 (3)	D	D 4.08 (3)	D 4.08 (3)	D
Lower Vaughan	D 0.22 (5)	D 0.68 (5)	D	D 1.36 (4)	D 1.36 (4)	D
Puhinui	D 0.57 (2)	D 1.39 (2)	D	D 2.49 (2)	D 2.49 (2)	D

For the reference site (West Hoe), the 1-day minimum DO value places this site in the A band, while for the 7-day mean minimum evaluates it is at the top of the B band. There is no suggestion of a change between the proposed baseline state (as assessed with the 2013-2017 dataset) and the current state at this site (Table 6).

Of the Rural-Low sites, Opanuku and Wairoa are classified as B band or C band state for their overall state. In contrast, Ararimu had consistently low minimum DO levels below the overall band national bottom line during both time periods (Table 6). The overall band assessment for Opanuku indicates a move from C band baseline state to B band state currently (Table 5).

[3] There are no data for the last five years at Kumeu River and there are no data for the baseline period for Te Muri River.

Of the Rural-High sites, minimum DO levels in Hoteo and Mahurangi place these sites in the overall C band for the proposed baseline state (Table 6), with Mahurangi showing potential improvement in overall state (B band) for the current period. This result should be treated with caution because there were only two summers with more than 90 days of data over the current state period. The other Rural-High sites (Kaukapakapa, Kumeu, Rangitopuni and Te Muri) have very low DO minimum values, placing them in the overall D band below the national bottom line for both time periods where sufficient data is available to make an assessment. Minimum DO values at Kumeu and Rangitopuni were particularly low in the proposed baseline period, indicating likely anoxic conditions at times. However, these results are based on only two summers, and there are no records for Kumeu for the current period as this site was decommissioned in 2015[4] (see Figure 3 and Figure 4).

DO minima for the Pukekohe SVGA sites indicate overall D band status during the proposed baseline period, and over the current period at Waitangi (Table 6). Minimum DO concentrations at Waitangi were extremely low indicating likely anoxic conditions at times. There is an indication of improvement in minimum DO from baseline state at Ngakoroa from below the national bottom line (overall D band) to above the national bottom line (overall C band). It is important to note that the Pukekohe SVGA sites are predominantly groundwater fed. It is possible that inputs of low DO groundwater may contribute to the low DO values in these rivers, however groundwater interactions in this area are associated with excessive nutrient (nitrate) inputs to these streams that may contribute to excessive aquatic plant growth and the anoxic conditions observed (White et al. 2019; Foster and Johnson, 2021).

The urban sites (Kaipara, Lower Vaughan, Puhinui) also had very low DO minima placing them in the D band, well below the national bottom line, across both time periods. The extremely low DO values at these sites indicate that they are close to anoxic at times (see Figure 3 and Figure 4).

Looking just at overall band status (i.e. choosing the lowest of either the 1-day minima or 7-day mean minimum) 10 out of 15 sites had consistent bands between the proposed baseline and current state periods (Table 6). The exceptions to this were Opanuku, Mahurangi, Ngakoroa, which all improved one band between the baseline and current state periods, while Kumeu and Te Muri had insufficient data to be assessed in either one of the two periods (Table 6).

Variability in minimum DO over time

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. Annual summer values in hydrological years with less than 90 days of data during the summer period are also presented in Figure 3 and Figure 4 (black triangles) and included in the calculation of the 5-year rolling median, for completeness. Data from these years, and the mean values calculated with them, need to be treated with caution.

[4] The Kumeu site was decommissioned because it was not in a good location due to the wide flood plain and inability to rate the top end flows.

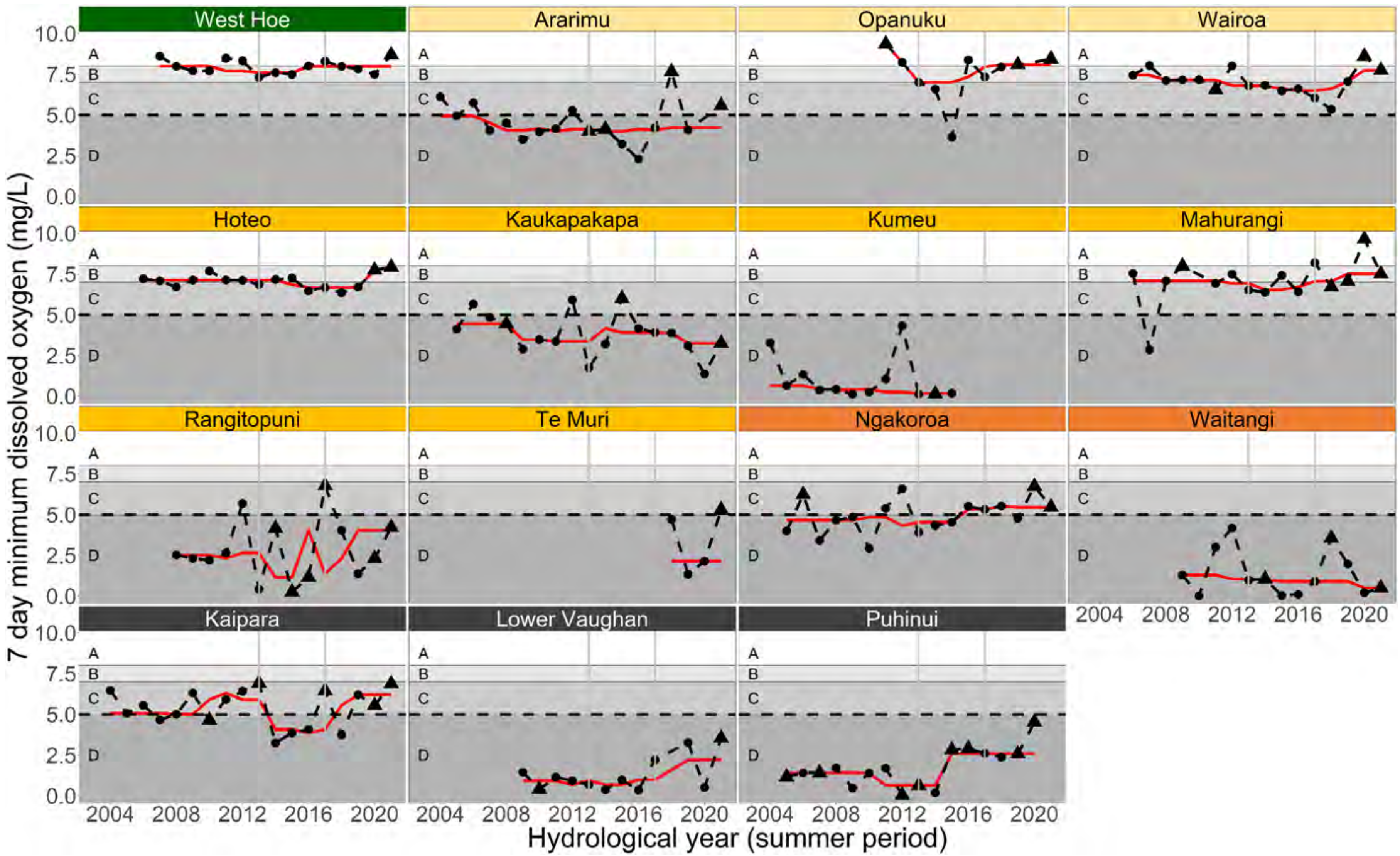

Figure 3. NPS-FM (DO, Table 17) band assessment for the 7-day mean minimum dissolved oxygen concentration. Five-year rolling median (full red colour lines) and actual annual values (dashed lines and dots/triangles) per hydrological year (summer) are shown for each river. Light grey vertical lines indicate the NPS-FM 2020 proposed baseline state period (2013 to 2017 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. Note that there were no data at Ararimu for the 2020 hydrological year.

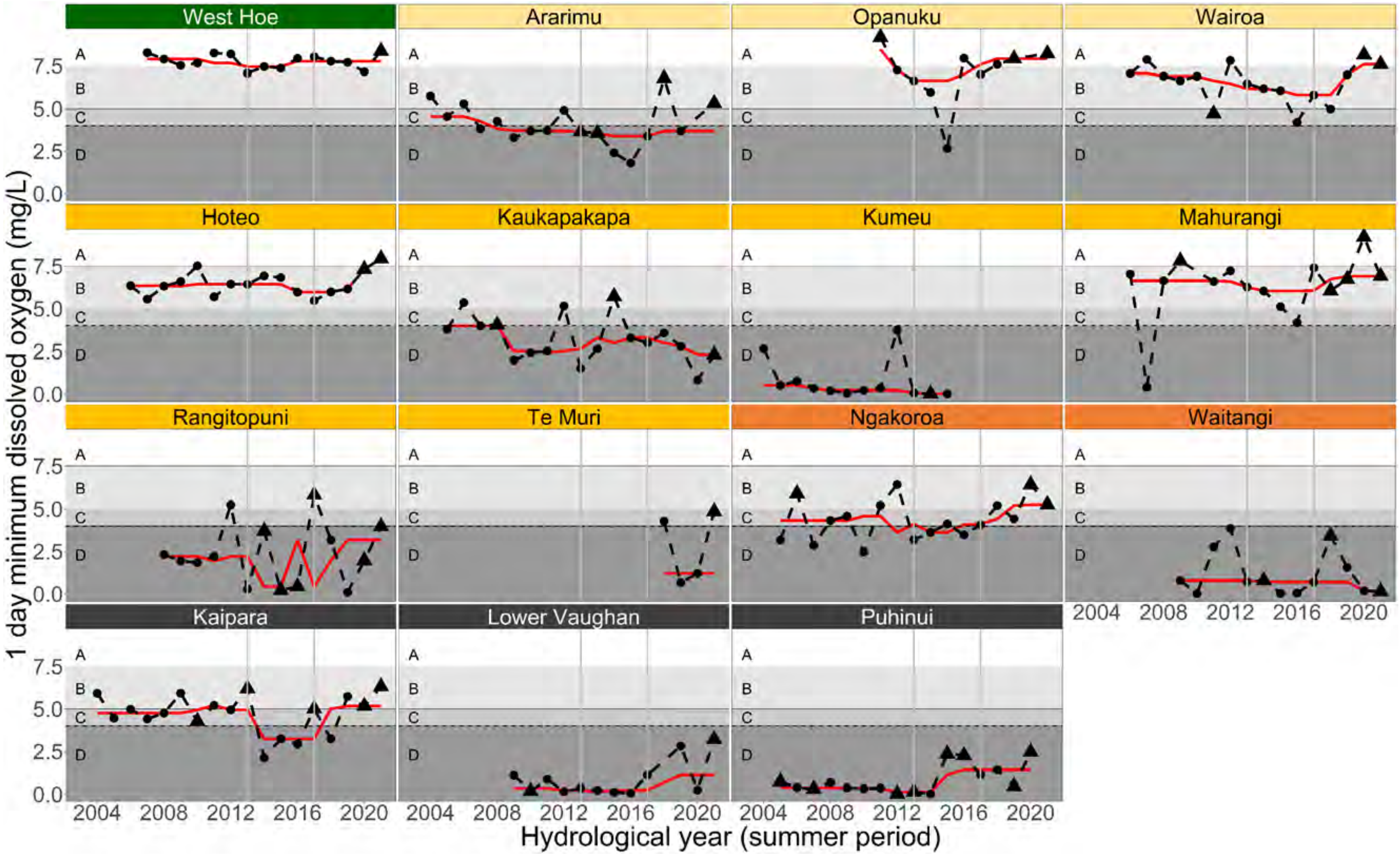

Figure 4. NPS-FM band assessments for the 1-day minimum dissolved oxygen concentration. Five-year rolling medians (full red colour lines) and actual annual values (dashed lines and dots/triangles) per hydrological year (summer) are shown for each river. Light grey vertical lines indicate the NPS-FM 2020 proposed baseline state period (2013 to 2017 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. Note that there were no data at Ararimu for the 2020 hydrological year.

Timing of DO minimum throughout the year

As mentioned above, the NPS-FM 2020 specifies that minimum DO values should be calculated in the summer period (November to April), although there is some ambiguity about whether this also applies for the 7-day mean minimum in Table 17 of the NPS-FM. Conceptually, it is important to identify any low DO issues that might occur at any time of the year (as noted by the original intent of the DO attribute tables, see Davies-Colley et al. 2013). Therefore, constraining assessment to just the summer period might miss important phenomena that could cause low DO at other times of the year (e.g. leaf fall in autumn/winter resulting in low DO caused by decomposing leaves). However, practically there can be logistical barriers to deploying continuous DO sensors for the entire year including risk of loss of equipment and resourcing constraints.

To assess the difference between examining the whole year and just the summer periods, the timeseries of daily minimum DO for three example rivers: West Hoe (Reference), Hoteo (Rural-high land cover) and Lower Vaughan (Urban land cover) are shown in Figure 5. For these sites, the daily minimum values for the whole summer period also represent the daily minimum value for the whole hydrological year. This also applies for the rolling median of 7 consecutive daily mean minimum DO values (not shown). The timeseries of daily minimum DO for all rivers are shown in Appendix 3 and summarised for all sites in Table 7.

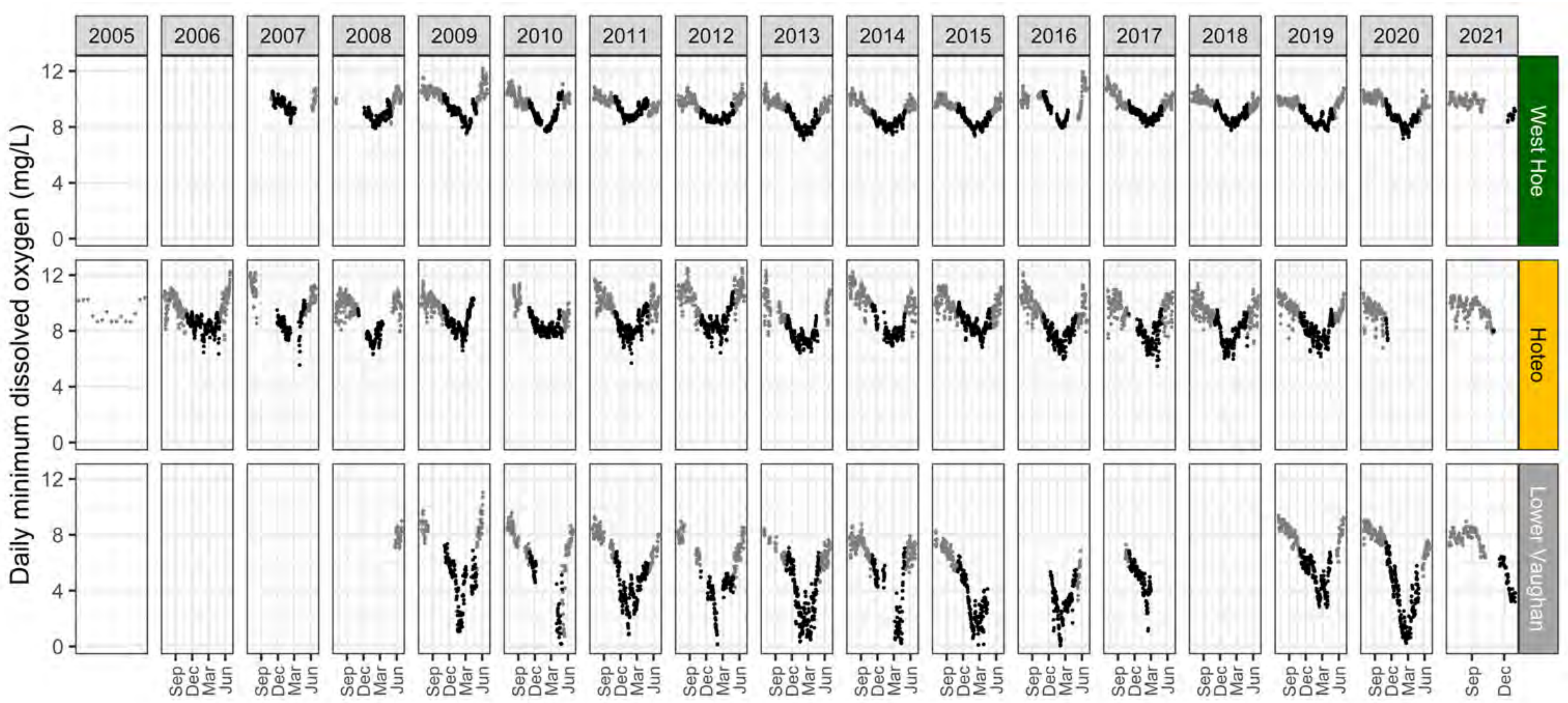

Figure 5. Timeseries of daily minimum dissolved oxygen for the three example rivers (grey points). The summer period is indicated by the black dots. Years are hydrological years (top facets).

Looking at all sites, the lowest DO value observed each year is typically in the November to April summer months (Table 7). However, as an exception, some rivers had daily minimum dissolved oxygen values in spring or autumn in some years. Specifically, October: Opanuku in 2018; Wairoa in 2013. Kaukapakapa had low minimum values of dissolved oxygen in May of 2021 and Mahurangi in May 2019 and June 2014. DO data were not available for the full summer at some sites (e.g. due to flow ceasing). To reduce the possibility that data gaps would influence the timing of annual minima we only specified the timing of DO minima in years with >90 days of data in the summer.

Table 7. Month of minimum dissolved oxygen values per hydrological year. Only years for which there were more than 90 days of data during the summer period are included (NAs indicates that this condition was not met for a hydrological year).

River name	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
West Hoe	NA	NA	NA	Feb	Feb	Mar	Feb	Dec	Feb	Feb	Feb	Feb	Apr	Feb	Feb	Jan	Feb
Ararimu	Jan	Mar	Dec	Mar	Feb	Feb	Feb	Jan	Feb	Feb	Feb	Mar	Feb	NA	NA	NA	NA
Opanuku	NA	NA	NA	NA	NA	NA	NA	NA	Nov	Nov	Feb	Feb	NA	**Oct**	Feb	Jan	NA
Wairoa	NA	NA	Mar	Sep	Jan	Feb	Feb	NA	**Oct**	Mar	Apr	Mar	Feb	Jan	Jan	Dec	NA
Hoteo	NA	NA	Apr	Mar	Jan	Feb	Apr	Jan	Feb	Mar	Feb	Apr	Feb	Jan	Feb	Feb	NA
Kaukapakapa	NA	Jan	Jan	Apr	NA	Feb	Feb	Jan	Feb	NA	Dec	Jan	Mar	Mar	Dec	Dec	**May**
Kumeu	Jan	Mar	Mar	Mar	Feb	Feb	Feb	Dec	Feb	Feb	NA	NA	NA	Feb	NA	NA	NA
Mahurangi	NA	NA	Mar	Feb	Mar	NA	NA	Jan	Nov	**Jun**	Nov	Dec	NA	Apr	**May**	NA	NA
Rangitopuni	NA	NA	NA	NA	Feb	Feb	Mar	Jan	Feb	NA	NA	NA	Feb	Mar	NA	Jan	NA
Te Muri	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Mar	NA	NA	Mar	Feb
Ngakoroa	NA	Mar	NA	Mar	Apr	Feb	Mar	Jan	Feb	Jan	Feb	Jan	Apr	Feb	Mar	Feb	NA
Waitangi	NA	NA	NA	NA	NA	Feb	Feb	Jan	Feb	Feb	Feb	Feb	Mar	Apr	NA	NA	Feb
Kaipara	Mar	Feb	Mar	Mar	Feb	Jan	NA	Jan	Jan	Mar	Feb	NA	Jan	NA	Feb	Jan	NA
Lower Vaughan	NA	NA	NA	NA	NA	Jan	NA	Jan	Feb	Feb	Feb	Feb	Mar	Jan	Apr	NA	Feb
Puhinui	NA	NA	Mar	NA	Jan	Jan	Apr	Jan	NA	NA	NA	Nov	NA	NA	Feb	Dec	NA

3.4 Discussion

DO minima calculated only from the highest quality coded data ranged from >7 mg/L at the reference site down to almost anoxic conditions (i.e. 0 mg/L) at several sites draining rural, vegetable growing and urban catchments.

In terms of NPS-FM 2020 attribute bands, the reference site was classified in the B-band for overall minimum DO status, suggesting that A-band status may be unachievable for Auckland streams.

Ararimu, Kaukapakapa, Kumeu, Rangitopuni, Te Muri, Ngakoroa, Waitangi and all three urban sites (Kaipara, Lower Vaughan, Puhinui) had very low DO minima indicating D band status (below the national bottom line). Most sites had consistent overall band assessments between the proposed baseline and current state periods. The exceptions to this were Opanuku, Mahurangi, Ngakoroa, which all improved one band between the baseline and current state periods.

Variability in annual summer values for both the 7-day mean minimum and 1-day minimum was modest for some sites with variations typically within one or two neighbouring NPS-FM bands (i.e. < 2 mg/L difference). However, variations were substantial for several sites (e.g. Opanuku and Mahurangi) with fluctuations over the full range of bands from year to year (Figure 3 and Figure 4). Variability in minimum DO at the reference site (West Hoe) was small compared with the other rivers. Note that these small fluctuations are around the threshold between bands A and B, exemplifying a case of state switching from year to year that does not necessarily reflect a meaningful change in river health. Consistent changes in state over time in minimum DO levels were not apparent at most sites, with the possible exceptions of Ararimu and Kaukapakapa which tended to have declining DO minima over the data record (Figure 3 and Figure 4). As the dataset lengthens it will be possible to do formal trend analysis to determine if changes over time are meaningful.

There is some ambiguity in the NPS-FM regarding whether DO minima should be determined for the whole year (i.e., NPS-FM table 17), or just the summer (November to April) period. In most cases the DO minima that were observed occurred within this summer period, but there were a few cases where annual DO minima occurred outside the summer period. The results presented here showed that there are limited cases where constraining assessment to just the summer period might miss important phenomena that could cause low DO at other times of the year (e.g., leaf fall in autumn resulting in low DO caused by decomposing leaves). It is recommended to deploy DO sensors for the entire year. However, if there are logistical or resource barriers to deploying continuous DO sensors for the entire year, concentrating the efforts during the entire summer period defined in Attribute Table 7 of the NPS-FM 2020 (i.e. November to April) would capture, in most cases, the year-round minimum values for the two DO metrics.

4 Ecosystem metabolism calculations

4.1 Ecosystem metabolism estimates

River ecosystem metabolism parameters were calculated from the dissolved oxygen timeseries data following the single-station night-time regression method (Owens 1974; Jankowski et al. 2021) implemented in R as described in Goodwin & Young (2022). Key parameters are ecosystem respiration (ER), gross primary production (GPP), and net ecosystem metabolism (NEM). Metabolism in stream ecosystems comprises photosynthesis during daylight hours (represented by GPP), and respiration occurring during both night and day (represented by ER). Photosynthesis increases dissolved oxygen in the water and respiration depletes dissolved oxygen 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 dissolved oxygen 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 is represented in Equation 1.

$$dDO/dT = \mathrm{GP}P + \mathrm{E}R + kD \qquad \text{Equation 1}$$

In Equation 1 the term dDO/dT means the change in dissolved oxygen over time (units g m^{-3} day^{-1}). Oxygen levels in the water may rise or fall over time, giving respectively positive or negative values of dDO/dT. GPP represents the contribution to change in oxygen made by photosynthesis. Because photosynthesis generates oxygen, GPP should be a positive contribution. ER represents the contribution to change in oxygen made by respiration. Because respiration depletes oxygen, ER should be negative. The *kD* term represents the physical gas exchange with the atmosphere through the water surface. Depending on the degree of oxygen deficit (*D*, units g m^{-3}), *kD* may be positive (water undersaturated in oxygen) or negative (water supersaturated in oxygen). *k* is the reaeration coefficient (units day^{-1}), characteristic of the stream at a certain water level, positive and ideally constant over time at a given level of flow. Shallow turbulent streams have a high *k*, while deep, slow-flowing rivers will have a low *k*. The reaeration coefficient, *k*, can be estimated from the gradient (slope) obtained by regressing change in O_2 (dDO/dT) against O_2 deficit during the dark period of the day. The rate of respiration (ER) can be estimated by looking at the rate of change in O_2 at times when the deficit is zero. This is the intercept of the regression line between the change in O_2 over time (dDO/dT) against O_2 deficit. This night-time regression method and is one of the methods commonly used for estimating ecosystem metabolism globally (Jankowski et al. 2021).

From the original dissolved oxygen data, two new variables were derived for performing the above calculations: 1) **oxygen saturation concentration**, the dissolved oxygen concentration (in mg/L) at which water is fully (100%) saturated at the current water temperature, calculated from the relationship between dissolved oxygen (mg/L) and percentage of oxygen saturation; and **oxygen deficit**, the difference between oxygen saturation concentration and actual measured dissolved oxygen concentration.

Because the dataset provided does not contain light data to match with the dissolved oxygen and temperature data, the first step in the calculations is finding the dark period of the day, from the oxygen data. It is important to note that the estimations of the stream metabolism parameters depend in part on the accuracy of this first step.

Rates of GPP and ER are initially calculated on a volumetric basis in g O_2 m^{-3} day^{-1}. To better compare rates of metabolic activity between rivers of different scale, the volumetric estimates are 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. Rates of respiration, primary productivity and net metabolism are then expressed in grams of oxygen per square metre per day (g O_2 m^{-2} day^{-1}).

Details of the method including all the steps required to estimate these parameters are in "Appendix 2: Detailed and additional methods".

4.2 Reliability of metabolic estimates

Poor quality and suspicious data (QC 42 and 43) were removed before calculating metabolic estimates. After the calculation of the estimates, additional quality control filters needed to be applied, based on the results from the regression to calculate *k* and ER, and the resulting values of GPP and NEM.

While we use 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 are not strictly met by time-series datasets. While the point estimates of *k* and ER are 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. Nonetheless, these caveats apply to all data subsets equally, and thus the regression performance diagnostics are comparable with similar metabolic studies. The R^2 value from the regression should be considered as an indication of 'relative reliability', rather than a true R^2 value as would be calculated from independent datapoints. In the following analyses, metabolism estimates (GPP, ER and NEM) calculated with a relative reliability (R^2) below 0.25 were removed.

It is not possible to have positive values of ER or negative values of GPP. Therefore, any positive values of ER and any negative values of GPP are spurious. Because ER, GPP and NEM 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 removed from further analyses. These extremely high values were very rare and comprised 0.22% of the ER values and 0.03% of the GPP values.

The relative reliability of metabolic estimates can vary dramatically throughout a dataset (see Figure 6 for example rivers), with periods of poor reliability often being seen during periods of rainfall and high flows (when dissolved oxygen values are influenced by reaeration via precipitation rather than metabolic activity within the river).

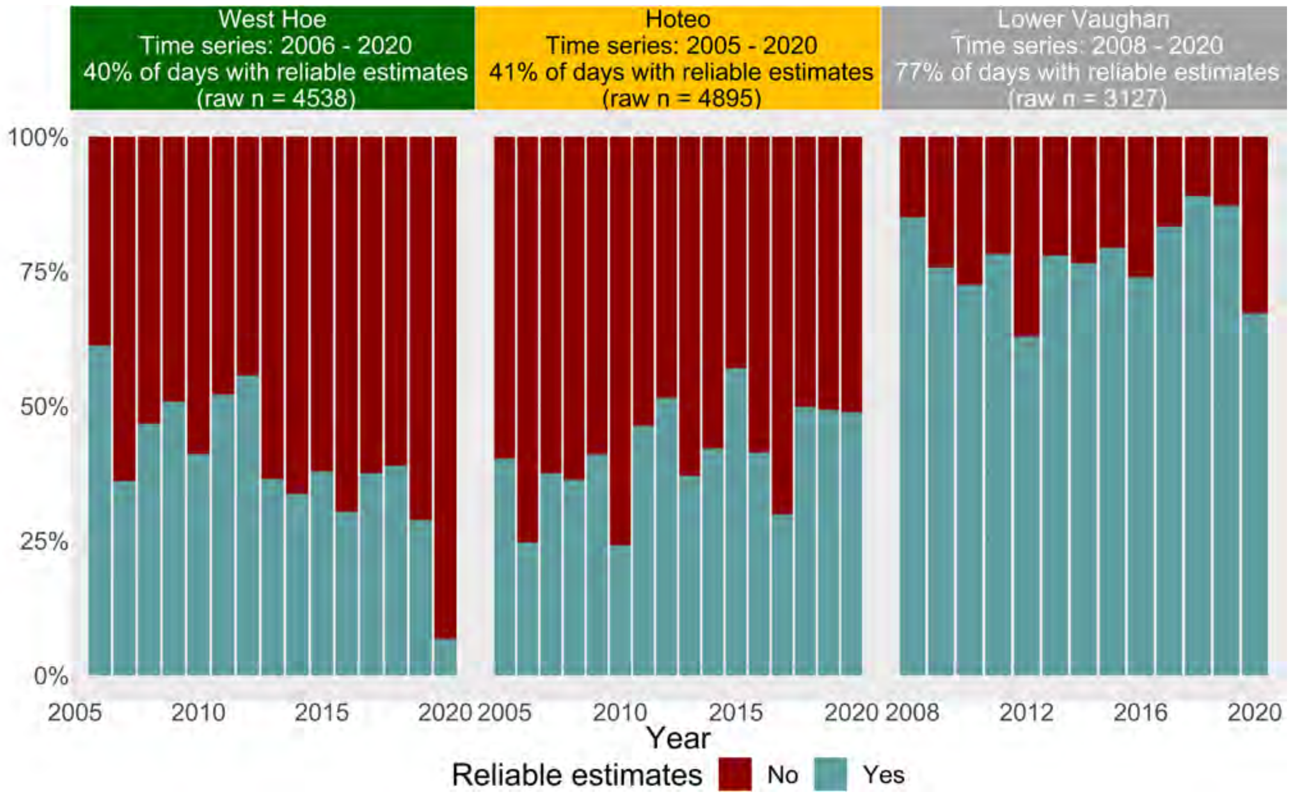

Figure 6. Percentage of days with reliable estimates of metabolism per year for each example river.

Poor reliability of metabolism estimates can also occur during extremely low flows if water in the river channel is no longer well mixed, and stratification occurs in the water column. Figure 7 shows how the proportion of days where estimates were excluded were more frequent when related to extreme water levels. This figure shows data for all rivers combined, but the depth percentile was calculated for each river separately.

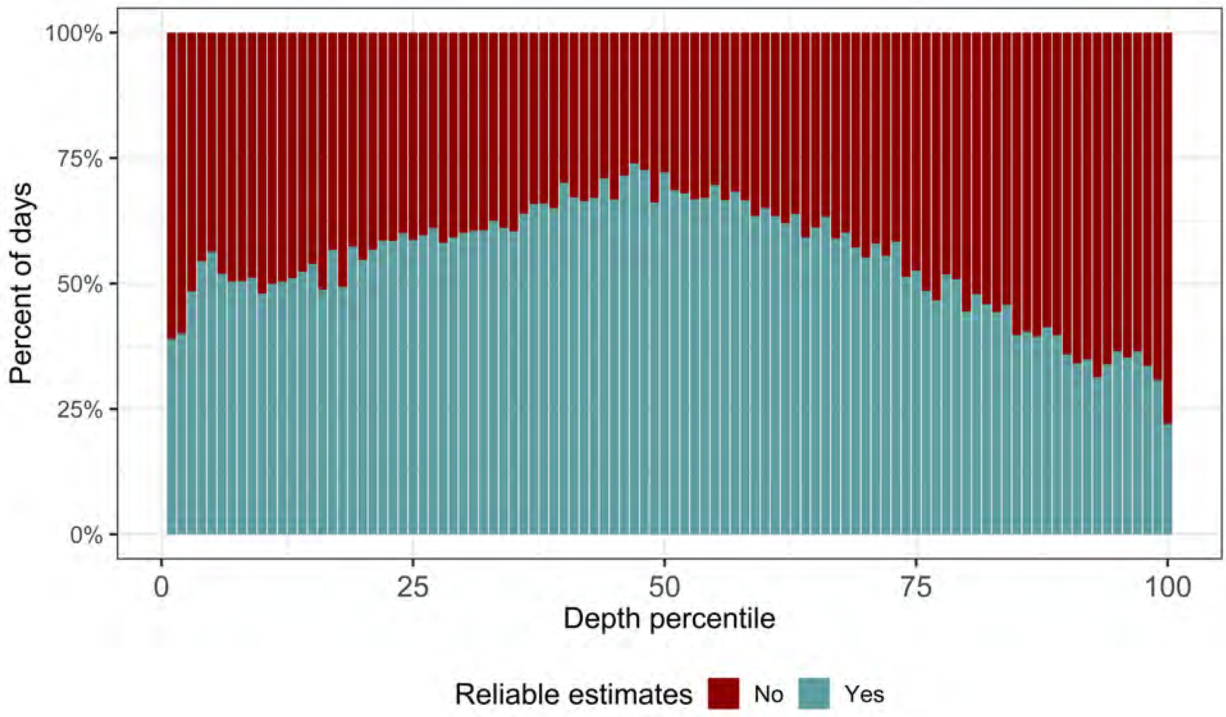

Figure 7. Total percentage of days with reliable estimates as a function of depth percentile (calculated for each river, but all rivers are combined for this figure). Note that days with non-reliable estimates are more prevalent in extreme water depths (i.e. lower and higher depth percentiles).

For rivers with very low GPP and ER, the rate of change in DO values is close to the level of precision and accuracy provided by the DO sensors. This means that the metabolic 'signal' is small relative to size of noise/error in the data and thus reliability (R^2) of the metabolic estimates in rivers with very low rates of metabolism are expected to be relatively low compared with sites with higher rates of metabolism.

It is important to note that low reliability of metabolism estimates does not necessarily mean that there is a problem with the accuracy of the DO measurements themselves, but rather that processes other than just photosynthesis, respiration and reaeration are influencing dissolved oxygen, or that the metabolic 'signal' was low relative to noise in the data. For example, the highest quality data (QC 10 and QC20) had similar (or lower) relative reliability to QC30, QC300, QC40, QC140 and QC151 (see Table 5 for a description of QC codes) (Figure 8). On the other hand, it is clear that data coded as QC44 (estimated data) and QC255 (Data gap/missing data) had a very low relative reliability if used for metabolism calculation (Figure 8).

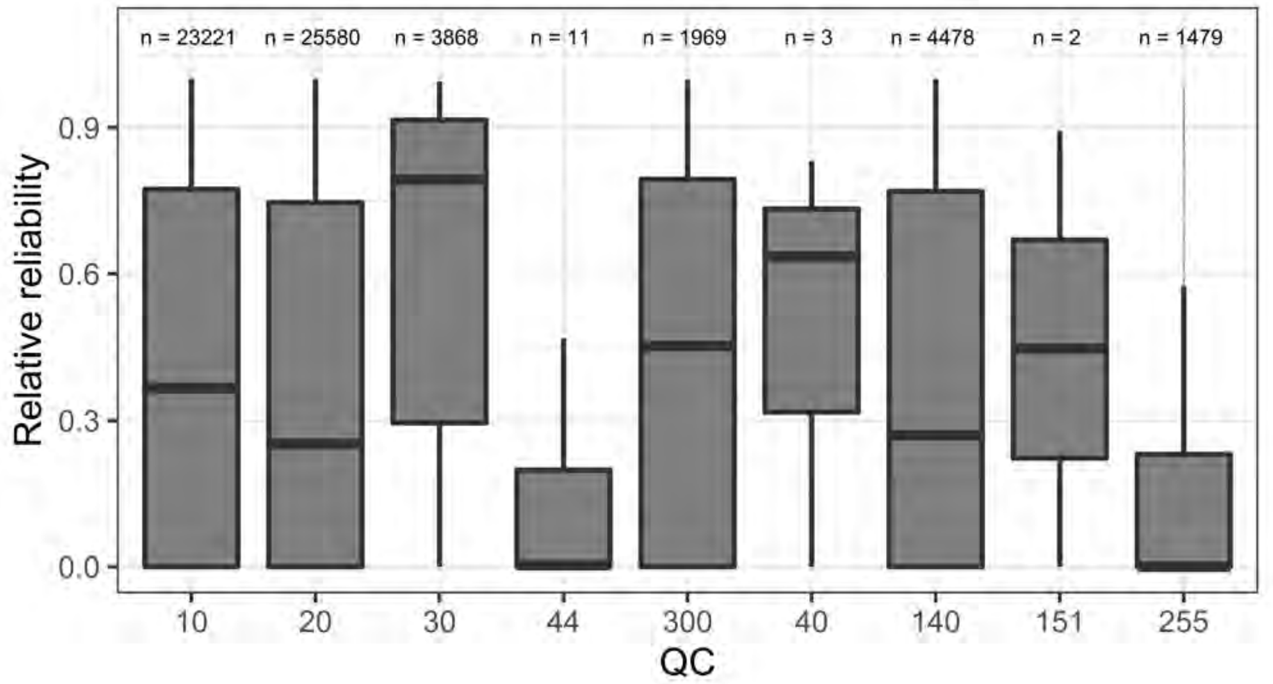

Figure 8. Comparison of relative reliability across original QC for the input data. For this comparison, the worst QC from the set of variables used in the calculation of metabolic estimates for a day was chosen. Note that original data with QC42 and QC43 were not included to calculate the metabolism estimates.

5 Ecosystem metabolism analyses

The analyses of ecosystem metabolism results included: 1) comparisons of ecosystem metabolism among sites (spatial variability), 2) exploration of the potential drivers of the differences among sites, 3) changes in ecosystem metabolism over time (temporal variability), and 4) what are the potential drivers of the changes over time. Throughout this section, we use the West Hoe River, the Hoteo River, and the Lower Vaughan River to exemplify the analyses. Results for other rivers are provided in Appendix 3. Because GPP (by aquatic plants) and ER (by both plants and animal life) may be influenced by separate factors, there is potential to see differences or changes in only one component of ecosystem metabolism, or in both. When changes occur in both, they might balance or compound so that there may or may not be apparent differences or changes in the combined NEM.

Nutrient enrichment affects the rate of both GPP (through stimulation of algal growth) and ER (via nutrient effects on all parts of the food web). However, river ecosystem metabolism is also influenced by other drivers unrelated to nutrient enrichment (e.g. light, temperature, flow regime), as is also the case for periphyton and macrophytes in rivers (MfE 2022).

5.1 Comparison of ecosystem metabolism among sites

5.1.1 Methods

While Auckland Council has a long history of monitoring DO and ecosystem metabolism to support understanding of river health in relation to catchment management, ecosystem metabolism is now an attribute included in the NPS-FM 2020 (Table 21 of the NPS-FM). The continuous timeseries data available from the Auckland SOE monitoring programme 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 timeseries record, Auckland Council's NPS-FM proposed baseline period (2013 -2017 hydrological years), and the current period (2016-2020 hydrological years) were also calculated. We did not include the hydrological year 2021 in the calculation above because there was only an incomplete record for that summer at the time of this reporting, and to align with the DO reporting. Otherwise, all available records were used for the calculation of the median values. The difference in medians between proposed baseline state and current state were tested with a Wilcoxon rank sum test with continuity correction.

Potential attribute state bands for ecosystem metabolism (Table 8) were recommended by the Freshwater Science and Technical Advisory Group (STAG) (2019) that helped inform the development of the NPS-FM (2020). Although these bands were not eventually incorporated into attribute Table 21 of the NPS-FM, they provide potentially useful assessment criteria, against which to evaluate the ecosystem metabolism dataset reported here. The proposed guidelines specify different criteria for wadeable and non wadeable rivers. The assessment criteria described in Young et al. (2008) could also be used although they use a three-tier ‘healthy’, ‘satisfactory’, ‘poor’ framework that is not aligned with the four-tier NPS-FM banding framework.

Table 8. Potential banding system for ecosystem metabolism as discussed by the Freshwater Science and Technical Advisory Group 2019 that helped inform the National Policy Statement for Freshwater Management (2020). 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.

5.1.2 Results

Median rates of GPP over the whole data set ranged from 0.08 g O_2 m^{-2} day^{-1} at West Hoe (Reference site) through to 16.3 g O_2 m^{-2} day^{-1} at Puhinui (Urban) (Table 9). Median rates of ER over the whole data set ranged from -1.7 g O_2 m^{-2} day^{-1} at West Hoe (Reference site) through to -24.6 g O_2 m^{-2} day^{-1} at Waitangi (Pukekohe SVGA) (Table 9).

Table 9. Ecosystem metabolism attribute bands for each site based on median values for the whole dataset and criteria recommended by STAG (2019). Colours represent the metabolism bands for wadeable and non-wadeable rivers discussed by the STAG but not eventually included in the NPS-FM (2020): A-band (blue), B-band (green), C-band (yellow) and D-band (red). The overall band is determined from the lowest grade of the GPP or ER contributing metrics.

Wadeable rivers

River name	GPP Band	ER Band	Overall Band
West Hoe	A 0.08	A -1.69	A
Opanuku	A 3.13	A -2.28	A
Wairoa	B 4.18	A -4.84	B
Kumeu	D 11.57	D -21.89	D
Te Muri	A 2.48	B -6.66	B
Ngakoroa	A 3.13	B -6.7	B
Waitangi	D 15.44	D -24.61	D
Lower Vaughan	B 4.97	D -12.84	D

Non-Wadeable rivers

River name	GPP Band	ER Band	Overall Band
Ararimu	B 4.86	C -10.58	C
Hoteo	C 7.14	B -5.54	C
Kaukapakapa	A 2.24	B -7.12	B
Mahurangi	B 4.86	A -2.82	B
Rangitopuni	A 1.21	B -4.17	B
Kaipara	B 3.5	C -10.23	C
Puhinui	D 16.29	C -12.57	D

Based on the attribute state bands for ecosystem metabolism that were recommended by STAG (2019), West Hoe (Reference) would be classified in the A band for both GPP and ER (Table 9). At the other end of the spectrum, Kumeu (Rural-High), Waitangi (Pukekohe SVGA) were in the D band for both GPP and ER (Table 9). Puhinui (Urban) was in the D band for GPP but C band for ER, while Lower Vaughan (Urban) was in the D band for ER and B band for GPP (Table 9). The other sites ranged from A band to C band with some differences in classification between GPP and ER bands (Table 9). When there are differences between the two classifications metrics GPP and ER, it is recommended to take the lower grade of the two for the general assessment of river metabolism status.

Median rates of GPP and ER between Auckland Council's proposed NPS-FM baseline period and the current state period were significantly different ($p < 0.05$) for many of the sites (Table 10, 11 of 15 sites for GPP and 12 of 15 sites for ER). However, these differences included a mix of increases and decreases in metabolism rates and none of the changes were large (Table 10). We note that the median GPP increased at Wairoa (from 4.2 to 5.3 g O_2 m^{-2} day^{-1}) resulting in a change from B-band to C-band, and median ER increased at Kaipara (from -12.58 to -15.84) resulting in a change from C-band to D-band. These changes potentially signal the need for further investigation at these sites. It is worth noting that median GPP at Kaipara decreased (from 5.9 to 5.0) resulting in a change from C-band to B-band (Table 10). We also note the improvements in band status for Te Muri and Ngakoroa, which may also be worthy of further investigations in relation to any mitigations and management actions underway in these catchments.

Table 10. Median values of GPP and ER for each river for the Auckland Council's NPS-FM defined baseline period (2013-2017), and the current state (2016 to 2020). Colours represent the metabolism bands for wadeable and non-wadeable rivers discussed by the STAG but not included in the NPS-FM (2020): 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.

Non-Wadeable rivers

	Baseline state (2013-2017)			Current state (2016-2020)			Wilcoxon Rank test Difference	
River name	GPP	ER	Overall	GPP	ER	Overall	GPP p-value	ER p-value
Ararimu	C 7.06	D -14.05	D	C 6.4	D -13.75	D	0.0002	0.5561
Hoteo	C 7.15	B -5.63	C	C 6.52	B -6.12	C	0.1288	0.0001
Kaukapakapa	A 1.98	B -7.52	B	A 1.82	B -6.07	B	0.1425	0.0003
Mahurangi	C 5.98	A -2.85	C	C 6.09	B -3.55	C	0.0474	0.0003
Rangitopuni	A 1.06	B -4.09	B	A 1.48	B -4.69	B	< 0.0001	0.0153
Kaipara	C 5.87	C -12.58	C	B 5	D -15.24	D	0.0443	0.002
Puhinui	D 17.03	D -13.93	D	D 14.38	C -11.59	D	< 0.0001	< 0.0001

Wadeable rivers

	Baseline state (2013-2017)			Current state (2016-2020)			Wilcoxon Rank test Difference	
River name	GPP	ER	Overall	GPP	ER	Overall	GPP p-value	ER p-value
West Hoe	A 0.08	A -1.84	A	A 0.08	A -1.6	A	0.1597	0.0006
Opanuku	A 3.2	A -2.59	A	A 2.6	A -2.19	A	< 0.0001	< 0.0001
Wairoa	B 4.03	A -5.16	B	C 5.75	B -5.9	C	< 0.0001	0.0001
Kumeu	D 12.21	D -23.46	D	NA	NA	NA	NA	NA
Te Muri	B 3.77	C -7.44	C	A 2.34	B -6.47	B	0.0081	0.0693
Ngakoroa	A 3.4	B -6.42	B	A 2.67	A -5.46	A	< 0.0001	< 0.0001
Waitangi	D 12.34	D -27.64	D	D 14.47	D -24.27	D	< 0.0001	< 0.0001
Lower Vaughan	C 5.08	D -13.53	D	C 5.95	D -11.54	D	0.0057	< 0.0001

Median rates of NEM over the whole data set ranged from 3.3 g O_2 m^{-2} day^{-1} at Puhinui (Urban) through to -8.9 g O_2 m^{-2} day^{-1} at Kumeu (Table 11). Sites that were heterotrophic (negative NEM) during the proposed baseline period remained the same during the current period, and the same situation applied for autotrophic sites that had consistently positive NEM during both the baseline and current state periods (Table 11).

Table 11. Median values of NEM for each river for the Auckland Council's NPS-FM defined baseline period (2013-2017), the current state (2016 to 2020), and the full dataset available. The Wilcoxon Rank test identifies whether differences between the baseline state and current state periods are statistically significant.

Wadeable rivers				
River name	NEM Baseline state (2013-2017)	NEM Current state (2016-2020)	NEM Full dataset	Wilcoxon Rank test p-value
West Hoe	-1.72	-1.48	-1.56	0.0002
Opanuku	0.52	0.48	0.70	0.5186
Wairoa	-1.00	-0.38	-0.58	0.0001
Kumeu	-8.72	NA	-8.93	NA
Te Muri	-4.09	-3.79	-3.85	0.8206
Ngakoroa	-2.79	-2.58	-3.33	0.0031
Waitangi	-13.63	-9.68	-8.74	< 0.0001
Lower Vaughan	-7.37	-5.11	-7.15	< 0.0001

Non-Wadeable rivers				
River name	NEM Baseline state (2013-2017)	NEM Current state (2016-2020)	NEM Full dataset	Wilcoxon Rank test p-value
Ararimu	-6.79	-7.34	-5.75	0.0667
Hoteo	1.19	0.25	1.32	0.0002
Kaukapakapa	-5.14	-4.20	-4.63	0.0061
Mahurangi	2.71	2.72	1.93	0.1767
Rangitopuni	-2.93	-2.86	-2.66	0.2032
Kaipara	-6.14	-10.15	-5.81	< 0.0001
Puhinui	3.17	2.61	3.34	0.086

A total focus on just median GPP and ER values is somewhat restrictive and there are potential benefits in looking at the distribution of GPP and ER values and determining the proportion of time that sites are in different bands. The statistical distribution of all reliable values of GPP and ER for each river, in relation to the recommended attribute bands, is shown in Figure 9 using the whole dataset (the whole timeseries available) from each site.

There was very little variability in rates of GPP and ER at West Hoe (Reference – native forest), while there was considerable variability in both GPP and ER rates at Kumeu, Waitangi, Ararimu, Kaipara and Puhinui (Figure 9). This is consistent with earlier findings based on the same sites and the suggestion by Clapcott et al. (2016) that measures of variability in metabolism, as well as the metabolism measurements themselves, may be useful indicators of river ecosystem health and resilience.

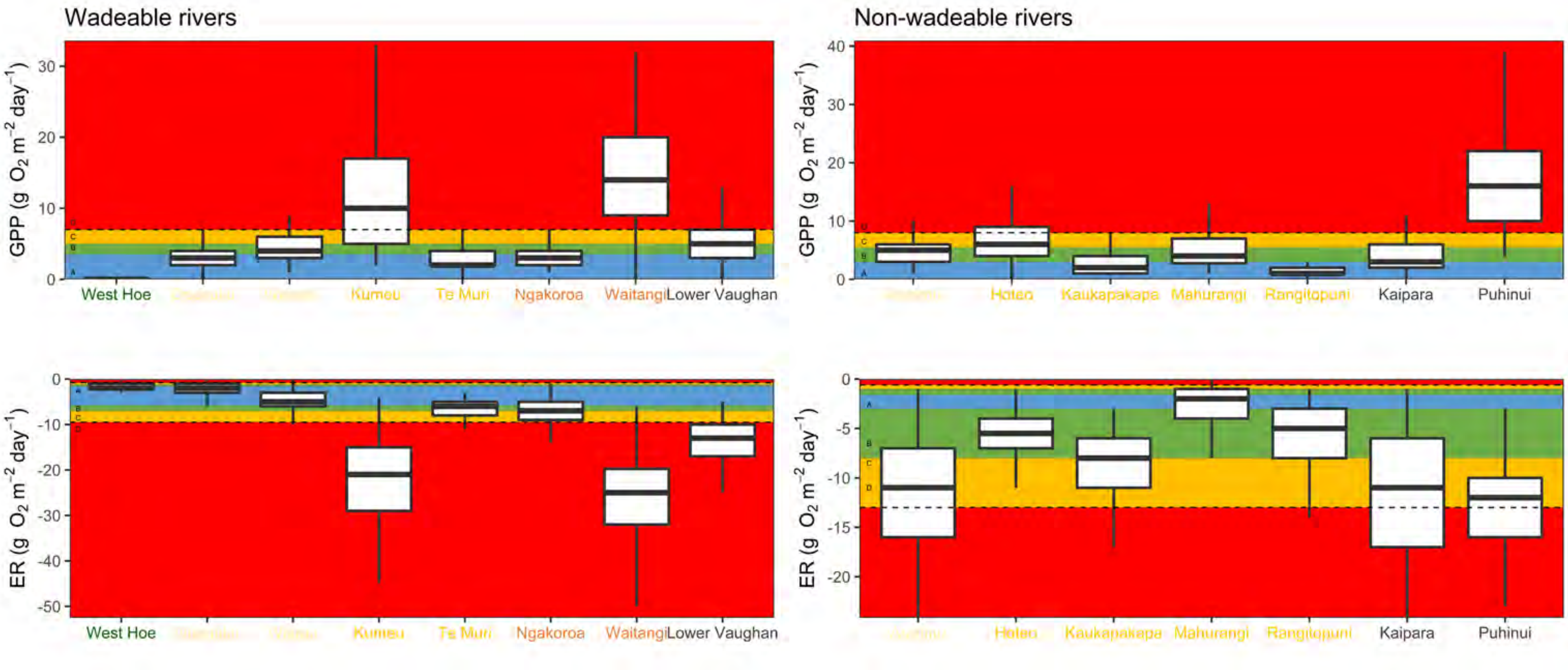

Figure 9. Distributions of daily GPP and ER for each river for the whole timeseries. The central tendencies of each distribution are shown, and extreme values (outliers) were excluded. The middle line inside the box represents the median of the distribution, and the lower and upper hinges correspond to the 25th and 75th percentiles. 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 a NPF-FM context would be described as national bottom lines.

5.1.3 Discussion

Based on instruction in the NPS-FM attribute Table 21, GPP and ER should be derived from at least seven days of continuous DO monitoring conducted at least once during summer (December to March inclusive). We note the inconsistency of this summer period for ecosystem metabolism assessment in the NPS-FM with the summer period defined in relation to DO (Table 7 in the NPS-FM, i.e. November to April). It is our understanding that the NPS-FM summer period defined by MfE for ecosystem metabolism sought to provide guidance on when ecosystem metabolism should be measured if council monitoring resources are limited, and year-round continuous DO monitoring is not feasible. There does not appear to be any reason why summer is defined differently in the NPS-FM for metabolism and DO. We consider that year-round DO monitoring, which enables year-round ecosystem metabolism assessment, is preferable to only focusing on the summer period. However, if resources are limited then a focus on the summer period is most important. As for minimum DO assessment, monitoring of metabolism over the whole summer period will likely capture 'worst case' conditions and provide a robust estimate of metabolism over the whole summer, whereas a focus on just a minimum 7-day period in summer is likely to miss 'worst case' conditions and not generate a robust estimate.

We envisage that median rates of GPP and ER would be the primary statistics for reporting in an NPS-FM context. It would make sense to calculate the median for each site over five years in the same way done for several other attributes to avoid state switching issues that might occur if annual medians were the focus of reporting (McBride 2016). However, as discussed in Clapcott et al. (2016), additional information on variability in ecosystem metabolism over time may also have value for ecosystem health reporting. Statistics such as the standard deviation of metabolism measurements at each site, or the proportion of time that each site occupies different assessment bands, as shown in Figure 9, deserve some attention alongside site medians.

The general patterns found in relation to ecosystem metabolism, with low rates of GPP and ER at West Hoe (indicative of good ecosystem health) and high rates of GPP and ER at Kumeu, Waitangi, Puhinui, Lower Vaughan (indicative of poor ecosystem health) are consistent with an earlier analysis of ecosystem metabolism at these sites using subsets of the data over the 2003-2009 period (Doehring & Young 2010). The two river sites in the Pukekohe SVGA showed contrasting results in terms of ecosystem metabolism with rates at one site Ngakoroa indicative of good ecosystem health (A-B band), while rates at the other site (Waitangi) were indicative of poor ecosystem health (D-band). These two sites are subject to groundwater influences (e.g., the baseflow of Ngakoroa is 85% groundwater derived, White et al. 2019), and this should be considered when discussing and interpreting the results shown in this report as significant inputs of low DO groundwater may influence the ecosystem metabolism calculations (Hall & Tank 2005).

Median rates of NEM for most sites were negative (Table 11) indicating a heterotrophic system where rates of ecosystem respiration are reliant on organic matter sources from upstream or the surrounding catchment. However, median NEM values were positive at Opanuku, Hoteo, Mahurangi and Puhinui (Table 11) indicating that more organic matter is being produced than respired at these sites and that these sites will tend to accumulate organic matter or export organic matter downstream.

Metabolism results indicated possible declines in ecosystem health between the proposed baseline and current state periods at the Wairoa and Kaipara sites, whereas there was evidence of potential improvements in band status for Te Muri and Ngakoroa between the same periods. Further investigations using other indicators of ecosystem health would be interesting to see if results from ecosystem metabolism are consistent with results from other indicators and to help identify potential drivers of change.

5.2 What are the drivers of the differences among rivers?

5.2.1 Methods

As discussed earlier, ecosystem metabolism is a useful integrative indicator of ecosystem health because it is potentially influenced by a wide range of drivers. In this section we relate rates of ecosystem metabolism with potential drivers in three separate analyses to determine the likely drivers of differences in ecosystem metabolism seen among Auckland rivers. Firstly, we visually compared ecosystem metabolism results among classes of river categorised based on four broad catchment/river characteristics: wadeability, stream order, geology and climate. Wadeability was assessed by Auckland Council staff, while data for stream order, geology and climate were sourced from the REC2 database. More robust statistical comparisons among the classes were not possible because of the lack of balance in number of sites among different classes, with some classes only represented by one site.

Secondly, we sought to identify any relationships between ecosystem metabolism and dominant land cover categories for the rivers as defined by Auckland Council. Visual comparisons among the dominant land cover categories were made, rather than statistical comparisons, again due to the lack of balance in number of sites among different categories, with some categories represented by only one site. Spearman rank correlations were fitted to understand the relationship between ecosystem metabolism and contributing catchment per cent of grassland, cropland, and urban area, as well as riparian cover. Only GPP, ER and NEM and land cover data from 2016 to 2018 was used for this analysis, to match the date of the data on riparian canopy cover. The data were summarized as the median of the values for each river.

Thirdly, we explored the relationship between rates of ecosystem metabolism and water quality parameters for 12 of the 15 rivers, performing Spearman rank correlations between metabolic parameters and the water quality variables. Thirteen water quality variables were selected for this analysis: Ammonia as N - total (mg/L) (NH_3+NH_4), Dissolved Inorganic Nitrogen (DIN mg/L), E.coli (CFU), Nitrate + Nitrite N total, pH field, Soluble Phosphorus as P (milligrams/litre), Total Phosphorus as P (milligrams/litre), Total Nitrogen - lab (total dissolved N by membrane filtration), Total Suspended Solids (mg/L), Turbidity NTU, Elec Conductivity @ 25C - Field (mS/cm), salinity (field, ppt) and water temperature ($^{\circ}$ C). The water quality, GPP, ER and NEM values were summarised using the median value per river. Different variables had different temporal data availability. Even though the data was summarised by river, we only used data for hydrological years where there was matching water quality and ecosystem metabolism data for each river. Median macroinvertebrate index values (taxa richness, MCI and per cent EPT) were also correlated in the same manner against median values of GPP, ER and NEM for each site.

5.2.2 Results

River characteristics

The distribution of metabolism estimates between wadeable and non-wadeable sites was very similar (Figure 10). In contrast, the distributions of metabolism estimates differed for different stream orders, with first order streams having the lowest GPP and smallest ER and third order streams having the fastest rates of GPP and ER (Figure 10). There was some evidence for differences in GPP and ER distributions relating to geology classes. However, with only one river representing the hard sedimentary (HS) category, and two rivers representing the volcanic acidic (VA) category, this result may highlight differences among rivers, not necessarily relating to their geology class (Figure 10). There were two climate classes represented among the rivers, and there was no evidence of differences in the distribution of the metabolic estimates between them (Figure 10).

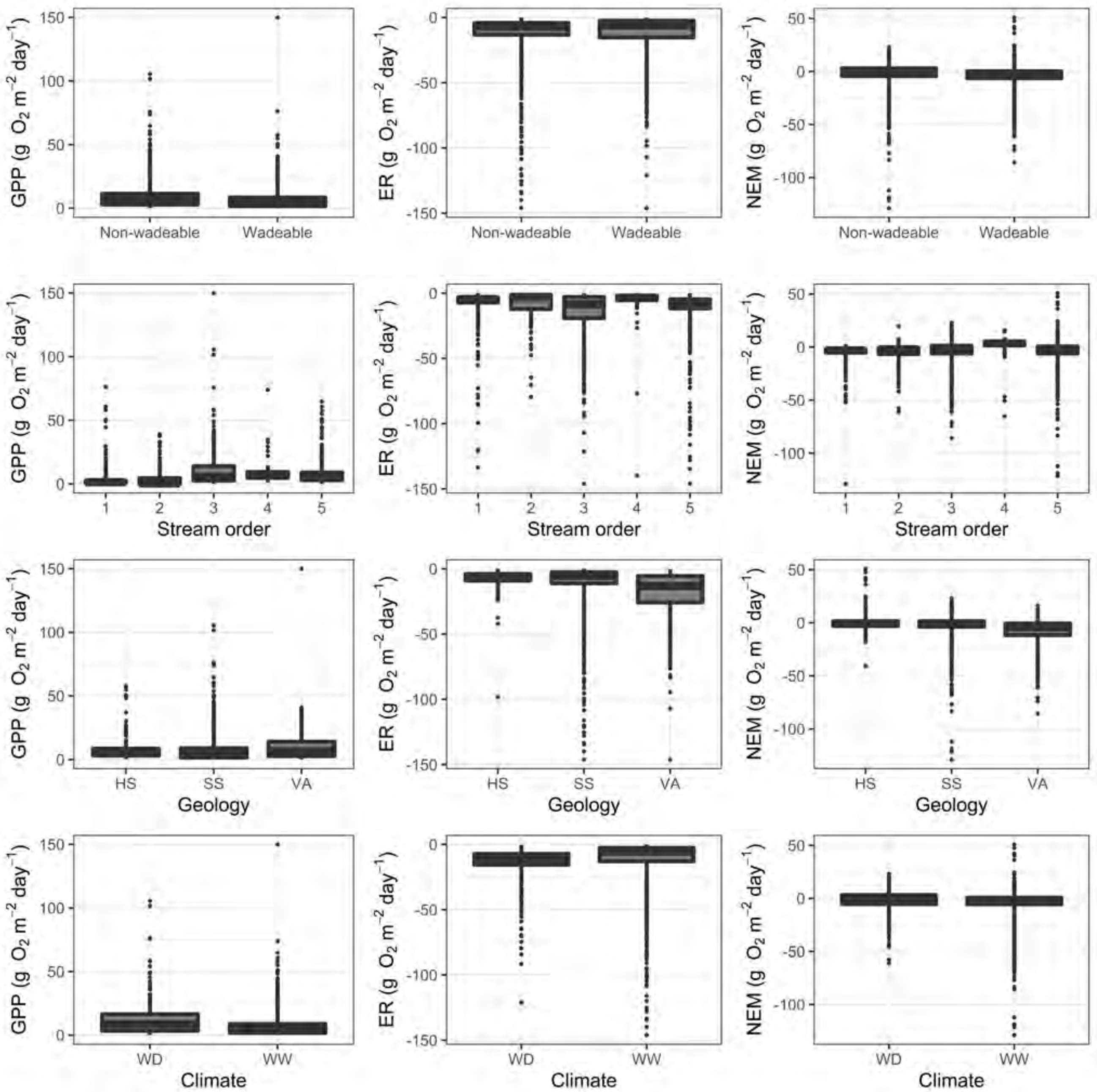

Figure 10. Distribution of daily GPP, ER and NEM data for sites with different river characteristics. The middle line inside the box represents the median of the distribution, and the lower and upper hinges correspond to the 25th and 75th percentiles. For Geology: HS: hard sedimentary rocks (Wairoa River); VA: volcanic acidic (Ngakoroa and Waitangi Rivers); SS: soft sedimentary (all other rivers). For Climate WD: warm-dry (Lower Vaughan, Puhinui and Te Muri); WW: warm-wet (all other rivers). The upper and lower whisker extends from the hinge to the data maximum and minimum value, respectively, no further than 1.5 times the distance between the first and third quartiles from the hinge.

Land cover and upstream canopy cover

A visual comparison among dominant land cover categories indicated that sites where the dominant land cover was urban had the highest median GPP, although the Pukekohe SVGA category sites had the highest overall maximum GPP values (Figure 11). The single reference river had the lowest values of GPP, although this result should be considered with caution, as there is only one river representing the reference category. The rates of GPP observed at the reference site are consistent with those observed in other rivers considered to be in reference or relatively unmodified state (Young et al. 2008). Rates of ER were highest (most negative) at the Pukekohe SVGA and urban sites and lowest (less negative) at the reference site (Figure 11). Inputs of low DO groundwater in the SVGA streams may be responsible for the high absolute rates of ER estimated at these sites. NEM was centred around zero for most land cover categories but tended to be more negative for the Pukekohe SVGA sites, reflecting their particularly large rates of ER (Figure 11).

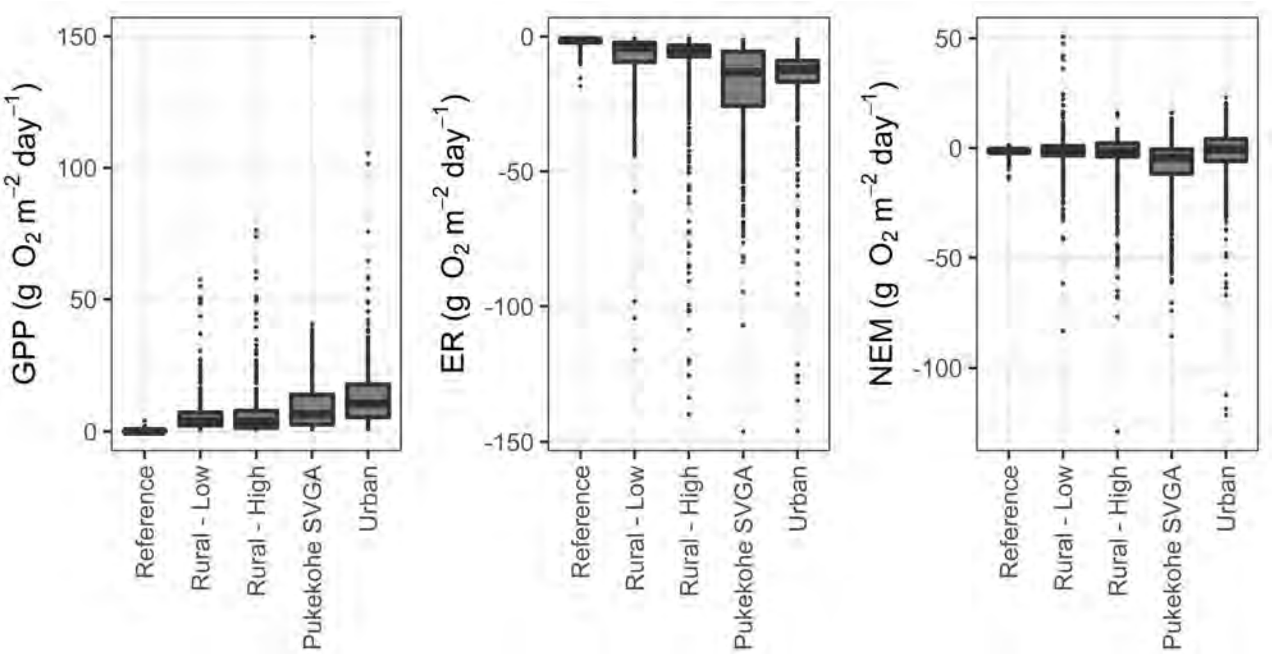

Figure 11. Distribution of daily GPP, ER and NEM for sites in the different dominant land cover categories. The middle line inside the box represents the median of the distribution, and the lower and upper hinges correspond to the 25th and 75th percentiles. The upper and lower whisker extends from the 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.

Correlations between the per cent of grassland, cropland and urban land cover in the catchment upstream versus rates of GPP and ER did not identify any statistically significant ($p<0.05$) relationships, although with only the 15 sites there is limited statistical power to detect correlations. NEM did show a statistically significant relationship with per cent grassland in the catchment upstream with NEM values becoming more negative at sites with higher per cent of grassland in the catchment upstream (Figure 12). This relationship between per cent pasture and NEM was largely driven by the tendency for sites with high per cent pasture to have strongly negative rates of ER, which although not statistically significant at $p < 0.05$, was still apparent in the results (Figure 12). There is an inverse relationship between per cent grassland in the catchment upstream and the per cent native forest in the catchment upstream. Therefore, it is fair to also say that sites with a low per cent of native forest in the catchment upstream tended to have strongly negative ER. Rates of GPP also showed some indication of a positive relationship with per cent urban land cover, but this relationship was strongly driven by high rates of GPP at the one highly urban site (Puhinui) (Figure 12).

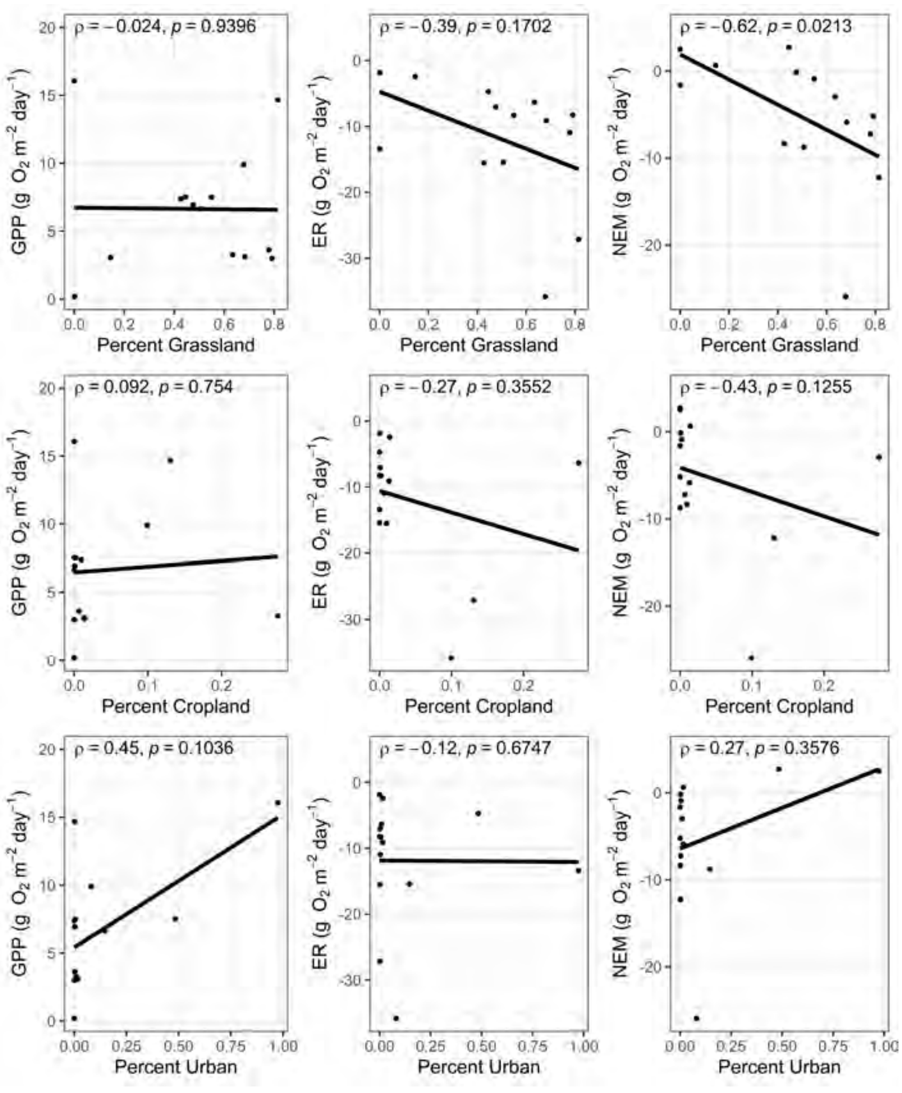

Figure 12. Correlations between per cent upstream land cover and mean site GPP, ER and NEM. ρ = Rho and p = probability value from the Spearman rank correlation.

Although not statistically significant, there was a tendency towards GPP and ER being smaller (less negative in the case of ER) at sites with a higher percentage of riparian canopy cover and shading in the catchment upstream (Figure 13). NEM did not show a significant relationship with riparian canopy cover (Figure 13).

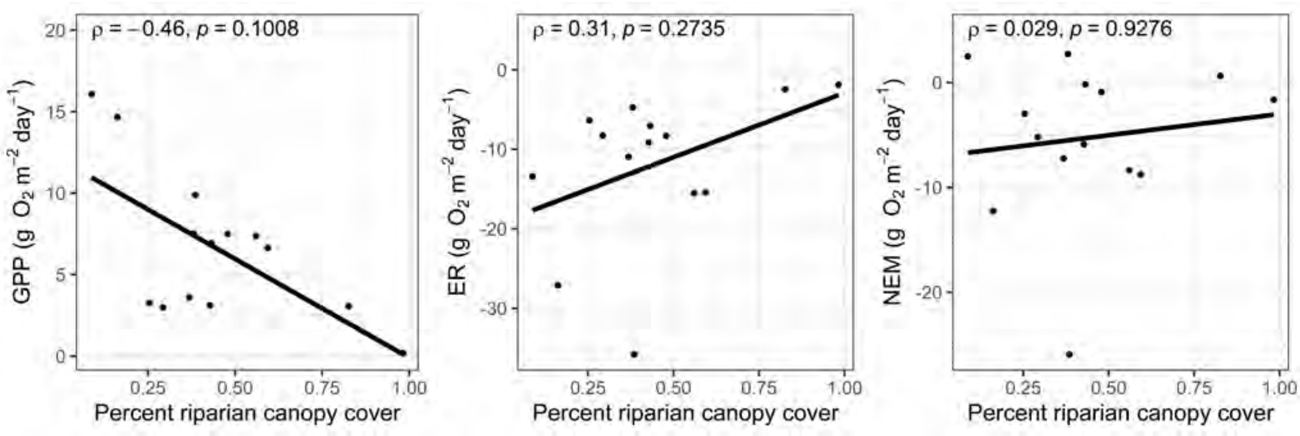

Figure 13. Relationship between mean site GPP, ER and NEM with per cent riparian cover. ρ = Rho and p = probability value from the Spearman rank correlation.

Water quality

Table 12 shows the number of hydrological years per river for which data were available, for each of the selected water quality parameters. All these water quality variables were included in the correlation analyses, as a preliminary study of the relationships between GPP, ER and NEM and these variables, regardless of the temporal autocorrelation that could exist at each site.

Table 12. Number of years of available data for select water quality variable at each river, that coincides with the available GPP, ER and NEM data availability.

analysis_method	West Hoe	Opanuku	Wairoa	Hoteo	Kaukapakapa	Kumeu	Mahurangi	Rangitopuni	Ngakoroa	Waitangi	Lower Vaughan	Puhinui
Ammonia as N - total (mg/L) (NH3+NH4)	15	10	15	16	12	12	15	14	18	12	13	16
DIN (calculated) (mg/L)	15	10	15	16	12	12	15	NA	18	12	13	16
E. coli CFU/100ml	15	10	15	16	12	10	15	14	15	12	13	15
Elec Conductivity @ 25C - Field (mS/cm)	15	10	15	16	12	12	15	14	17	12	13	16
Nitrate + nitrite as N - total (milligrams/litre)	15	10	15	16	12	12	15	14	18	12	13	16
pH (field)	12	10	12	NA	12	7	11	NA	12	12	12	12
Salinity (field; ppt)	15	10	15	NA	12	12	15	NA	18	12	13	16
Soluble Phosphorus as P (milligrams/litre)	15	10	15	16	12	12	15	14	18	12	13	16
Total Nitrogen - lab (total dissolved N by membr filtration)	12	10	12	16	12	7	11	14	12	12	12	12
Total Phosphorus as P (milligrams/litre)	15	10	15	16	12	12	15	14	18	12	13	16
Total Suspended Solids (mg/L)	15	10	15	NA	12	12	15	NA	18	12	13	16
Turbidity (NTU) - lab	15	10	15	16	12	12	15	14	18	12	13	16
Water Temperature (degC; field)	15	10	15	16	12	12	15	14	18	12	13	16

The Spearman rank correlations were performed using the median values of the water quality parameters and the median values of GPP, ER and NEM per river. Spearman rank correlations between water quality variables and ecosystem metabolism metrics for each site are shown in Table 13. Rates of GPP were strongly correlated with the site median of field temperature measurements, while rates of ER were negatively correlated with median concentrations of Total Nitrogen (Table 13). Rates of NEM were positively correlated with median pH (Table 13). Although not quite significant at $p < 0.05$, there was an indication of a correlation between rates of GPP and ER and concentrations of DIN (and nitrate and nitrite N) (Table 13). Although also not significant at $p < 0.05$, there were also indications of negative relationships between rates of ER and concentrations of *E. coli*, electrical conductivity and water temperature (Table 13).

Table 13. Spearman correlations between water quality parameters and GPP, ER and NEM. The strength of the correlations are reflected by the Rho statistics while the p-value represents the level of statistical significance. Correlations with p-values < 0.05 are unshaded.

	GPP		ER		NEM	
Water quality parameter	**Rho**	**p-value**	**Rho**	**p-value**	**Rho**	**p-value**
Ammonia as N - total (mg/L) (NH3+NH4)	0.270	0.40	-0.441	0.15	-0.056	0.86
DIN (calculated) (mg/L)	0.573	0.07	-0.564	0.08	-0.154	0.65
E. coli CFU/100ml	0.315	0.32	-0.476	0.12	-0.308	0.33
Elec Conductivity @ 25C - Field (mS/cm)	0.266	0.40	-0.503	0.10	-0.182	0.57
Nitrate + nitrite as N - total (milligrams/litre)	0.566	0.06	-0.566	0.06	-0.140	0.67
pH (field)	0.212	0.56	0.346	0.33	0.806	0.01
Salinity (field; ppt)	0.142	0.70	-0.332	0.35	-0.105	0.77
Soluble Phosphorus as P (milligrams/litre)	0.329	0.30	-0.294	0.35	0.238	0.46
Total Nitrogen - lab (total dissolved N by membr filtration)	0.336	0.29	-0.657	0.02	-0.336	0.29
Total Phosphorus as P (milligrams/litre)	0.210	0.51	-0.336	0.29	0.042	0.90
Total Suspended Solids (mg/L)	0.285	0.43	-0.285	0.43	0.079	0.84
Turbidity (NTU) - lab	-0.028	0.94	-0.077	0.82	-0.147	0.65
Water Temperature (degC; field)	0.790	0.00	-0.469	0.13	0.287	0.37

Median values of Macroinvertebrate Community Index (MCI) scores, per cent EPT and taxa richness were significantly correlated (p-values < 0.001) with both GPP (negative relationships) and ER (positive relationships) (Figure 14). MCI and per cent EPT had the highest Rho values for the Spearman rank correlation (Rho -0.87 and -0.76 for GPP and Rho 0.78 and 0.79 for ER). Macroinvertebrate taxa richness Rho values were lower for both GPP and ER (Rho -0.68 and 0.69 respectively). NEM was not related to any of the macroinvertebrate indices.

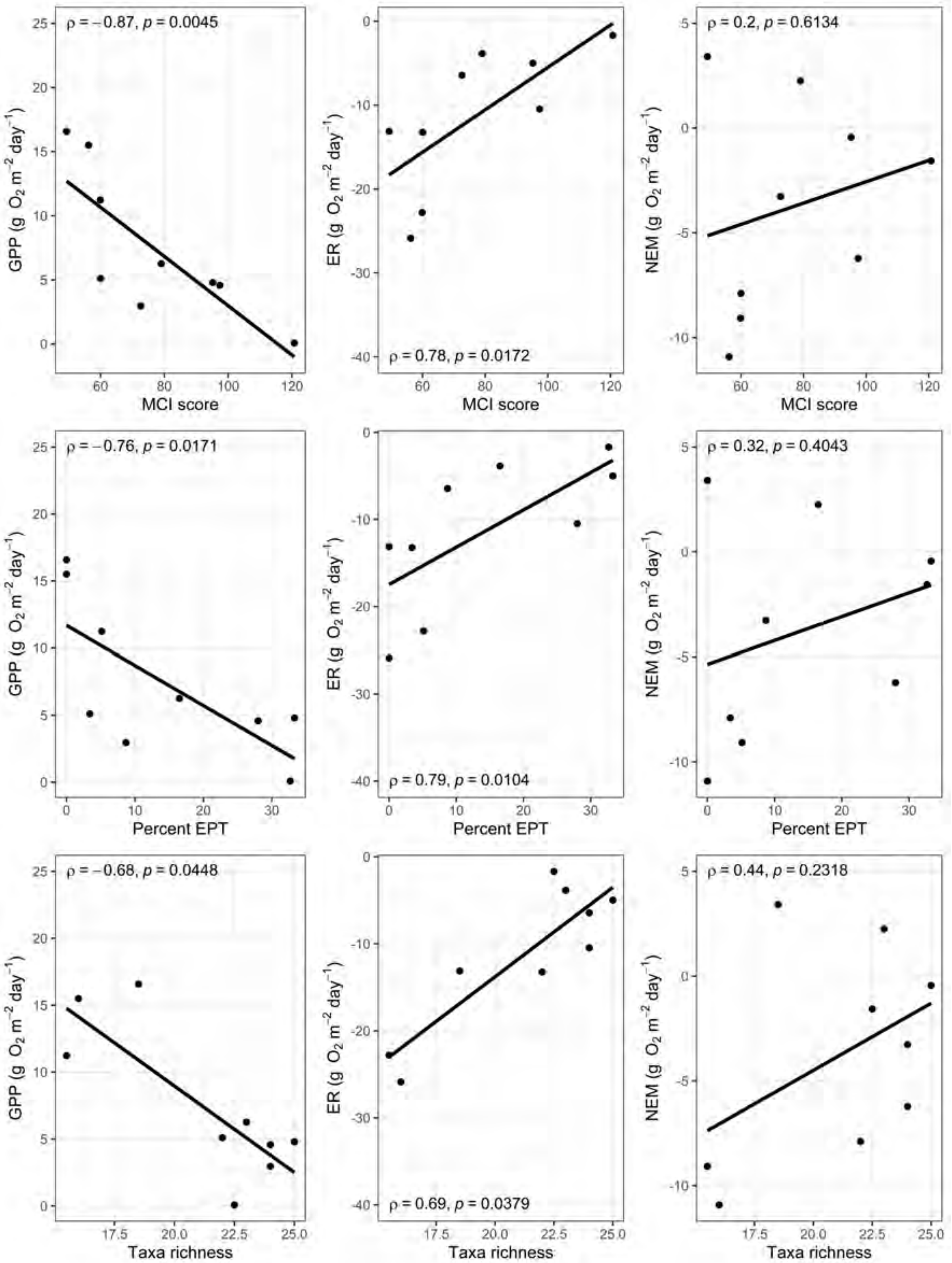

Figure 14. Correlations between MCI scores, per cent EPT, taxa richness and median values of GPP, ER and NEM for each river. ρ = Rho and p = probability value from the Spearman rank correlation.

5.2.3 Discussion

In terms of differences among sites, small rivers tended to have lower absolute rates of GPP and ER, although this relationship was driven to some extent by the low rates of ecosystem metabolism at the native forest reference site (West Hoe), which happens to be one of the smallest rivers and is heavily shaded. Rivers that were heavily shaded also tended to have lower absolute rates of GPP and ER, reflecting the importance of sunlight in driving photosynthesis (i.e., GPP). There was no difference between wadeable and non-wadeable rivers in GPP or ER.

Although not statistically significant ($p < 0.05$), ER values tended to be most negative with the per cent of grassland in the catchment upstream; i.e. higher rates of respiration with increased per cent of grassland area. For non-wadeable rivers of the Waikato region, Casanovas and Clapcott (2021) reported a similar relationship between ER and the percentage of upstream catchment area in 'high producing exotic grasslands'. The reason for this consistent relationship is not quite clear. Sites with a high proportion of upstream pasture are often unshaded, enabling high rates of GPP, and resulting in accumulation of aquatic plant biomass and thus associated high rates of ER. However, in these sites, there was no positive relationship between GPP and per cent grassland in the catchment, making the shading explanation unlikely. It is possible that organic and nutrient inputs to streams increase with the per cent of grassland in the catchment upstream, and these inputs fuel higher rates of ER.

The results from the water quality correlations showed that median site water temperature was significantly positively related to median rates of GPP (Table 13), a similar result to that reported by Clapcott et al. (2016). We expect that this correlation might be driven by a combination of cool, shaded rivers having lower rates of GPP, as well as temperature having a direct positive effect on rates of GPP. There was some evidence for relationships between dissolved nitrogen concentrations (DIN and nitrate/nitrite-N) and rates of GPP (Table 13), and between total and dissolved nitrogen concentrations and rates of ER (Table 13). In all cases, rates were highest (i.e. most negative for ER) at sites with high concentrations of nitrogen. These relationships are likely related to nitrogen stimulating rates of both GPP and ER. An analysis of non-wadeable rivers of the Waikato region showed that NEM was related to Total Kjeldahl Nitrogen, but not ER or GPP (Casanovas and Clapcott 2021). The indication of a correlation between ER and electrical conductivity and *E. coli* concentrations probably relates to intercorrelation between nitrogen concentrations and conductivity/*E. coli* and is unlikely to be indicative of a mechanistic relationship. It is notable that there was no evidence for relationships between ecosystem metabolism metrics and either dissolved or total phosphorus concentrations, indicating that nitrogen is more important in the Auckland region at regulating rates of periphyton and aquatic plant growth (and organic matter respiration) than phosphorus concentrations.

Macroinvertebrate index scores were negatively correlated with absolute rates of GPP and ER, reinforcing the view that sites with macroinvertebrates indicative of a healthy river tend to have low rates of GPP and ER, while sites with high rates of ecosystem metabolism tend to support macroinvertebrates that are associated with impacted conditions (Young & Collier 2009; Clapcott et al 2016).

5.3 Changes in ecosystem metabolism over time at each site

5.3.1 Methods

Ecosystem metabolism estimates vary over time, with distinct seasonal patterns as well as shorter-term variation resulting from changes in light intensity and river flows. Long term changes could also happen due to changes in climate or the condition of the surrounding environment that influence light availability, water temperature, flow regime, and nutrient and contaminant inputs. To investigate changes in ecosystem metabolism over time at each site, two approaches were used: 1) general visualisation of median metabolic estimates values over time, 2) a Kendall trend analysis of the monthly median values of the metabolism estimates. Four additional detailed timeseries analyses were performed as tools to evaluate each river in detail and identify further hypothesis that could be examined in the future: 1) timeseries decomposition analysis, 2) a Kendall trend analysis on the decomposed long-term trend 3) a point change analysis and 4) a more detailed examination of the metabolism timeseries looking at seasonal patterns. These four approaches are described in Appendix 2: Detailed and additional methods, and the results are shown per river in Appendix 3.

General visualisation of metabolic estimates over time

The metabolism timeseries were summarised using yearly medians to better understand the general temporal changes in relationship with the NPS-FM (2020) reporting.

Kendall trend analysis on monthly median values of metabolism estimates

Median values of metabolism estimates per month, per year and per river were used to test for linear trends over time, using a Kendall trend test (Kendall 1975). The Kendall trend test performed here is based on a rank correlation as implemented in the R EnvStats library (Millard 2013). The Kendall test accounts for seasonal differences where they are detected, if necessary, stratifying the comparison over time within season. The Kendall trend test estimates the slope of the trend as well as a “p value” of statistical significance.

5.3.2 Results

General visualisation of metabolic estimates over time

The time series of the annual median values of GPP and ER are shown in Figure 15 and Figure 16, respectively. The 5-year running median is shown in these figures, as well as the annual median values. Annual median GPP values were relatively consistent from year to year at most sites, although the sites with typically high GPP, such as Kumeu, Waitangi, and Puhinui also showed large variations from year to year (Figure 15). At Ararimu, variability in GPP increased over time in conjunction with an apparent increase in GPP (Figure 15). A similar pattern was evident for ER with relatively consistent values at many sites, but more year-to-year variations at the sites with the most negative ER (Figure 16).

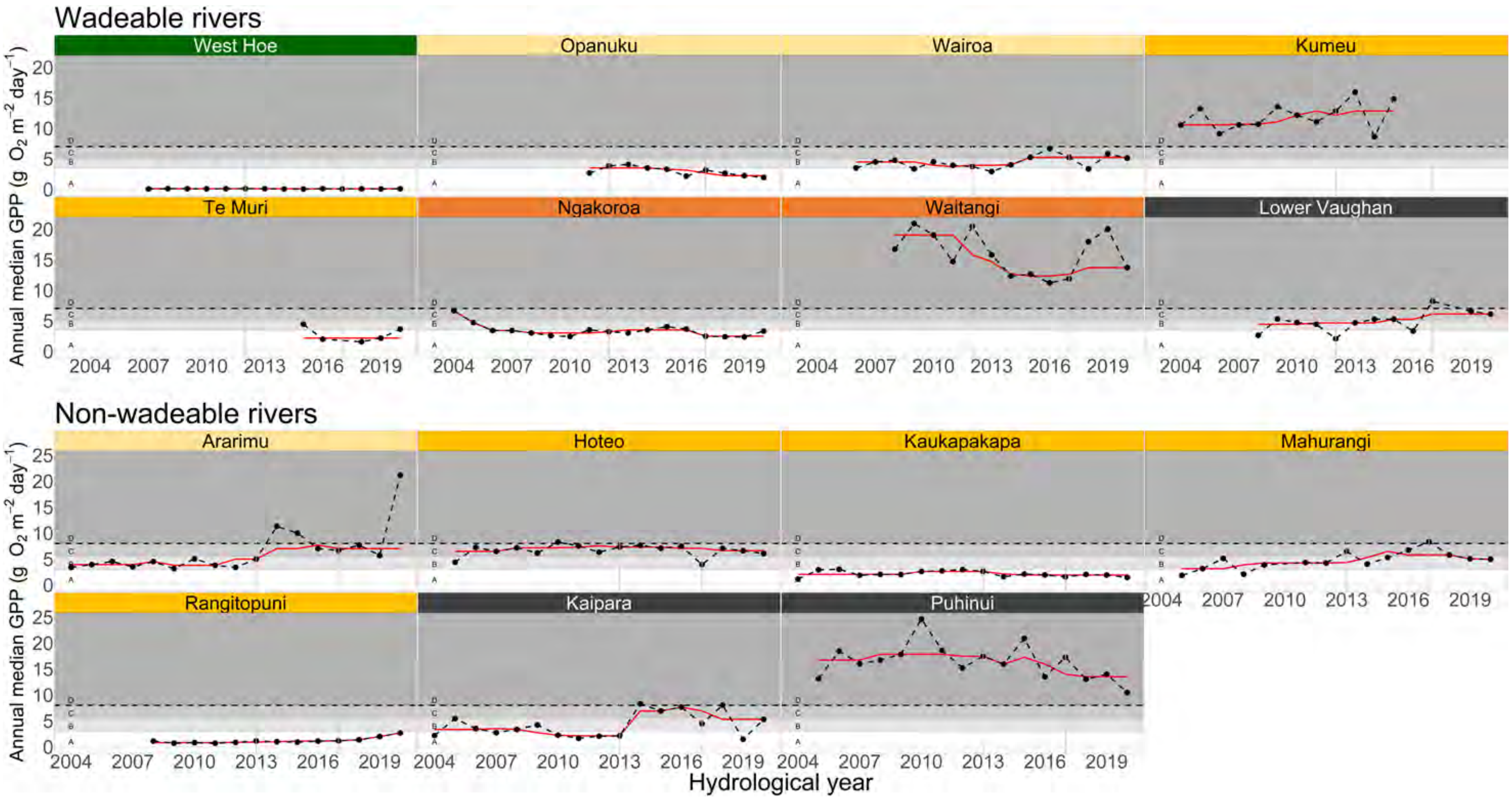

Figure 15. GPP annual median time series. The 5-year rolling median (full colour lines) and actual annual median values (dashed lines and dots) per hydrological year for each river. Light grey vertical lines indicate the NPS-FM 2020 baseline state period as identified by Auckland Council from 2013 to 2017 hydrological years. The horizontal dashed line shows the proposed national bottom-line.

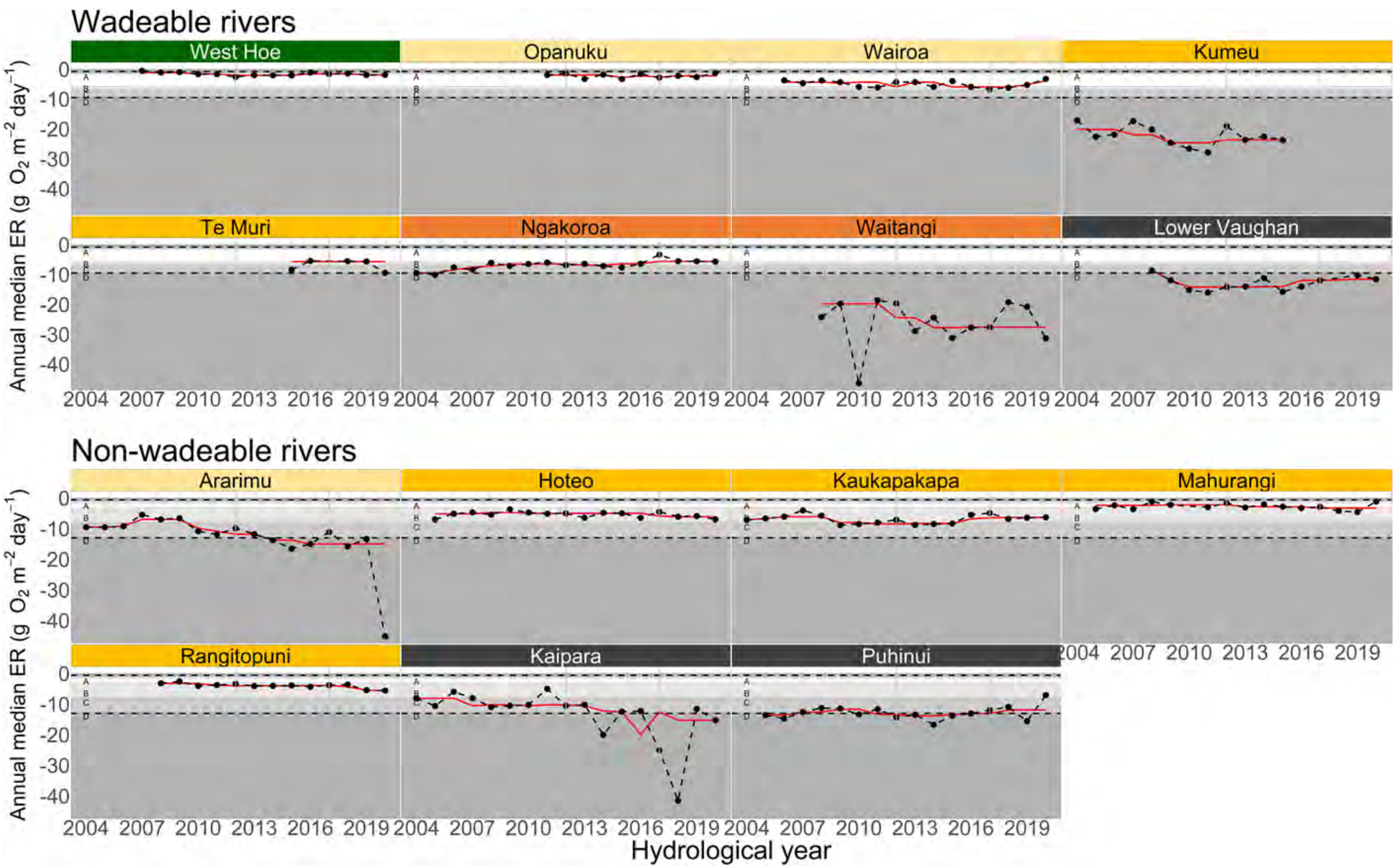

Figure 16. ER annual median time series. The 5-year rolling median (full colour lines) and actual annual median values (dashed lines and dots) per hydrological year for each river. Light grey vertical lines indicate the NPS-FM 2020 baseline state period as identified by Auckland Council from 2013 to 2017 hydrological years. The horizontal dashed line shows the proposed national bottom-line.

Kendall trend analysis on monthly median values of metabolism estimates

The results of the Kendall linear trend test on monthly median values of the time series data for all rivers is shown in Table 14. The trend slope is the slope of the 'line of best fit' through the set of points, while the p-value indicates whether the slope is statistically different from zero. A large slope value (positive or negative) would suggest a rapid rate of change, but if it is accompanied by a p value much greater than 0.05, it is unlikely that the suggested trend is credible. While a small slope value may be less dramatic, if it is accompanied by a p value smaller than 0.05, it is worth closer attention as a more reliable result. Most of the rivers showed significant long-term trends for all metabolism estimates, although with such a long sampling record over multiple years it is easy to identify possible linear changes that are not necessarily ecologically meaningful. Most slope values were relatively small (<0.001) and therefore unlikely to be ecologically meaningful (Table 14). Further analysis of changes over time at specific sites may be appropriate but was outside the scope of this report.

Table 14. Results from the Kendall trend analysis on median monthly values of the metabolism estimates. Gray cells indicate non-significant relationships.

	GPP		ER		NEM	
River name	slope	p-value	slope	p-value	slope	p-value
West Hoe	< 0.001	0.036	< 0.001	0.008	< 0.001	0.005
Ararimu	0.001	< 0.001	-0.001	< 0.001	< 0.001	0.03
Opanuku	< 0.001	0.04	< 0.001	0.786	< 0.001	0.318
Wairoa	< 0.001	0.095	< 0.001	0.028	< 0.001	0.753
Hoteo	< 0.001	0.543	< 0.001	0.234	< 0.001	0.513
Kaukapakapa	< 0.001	0.177	< 0.001	0.354	< 0.001	0.035
Kumeu	< 0.001	0.518	-0.001	0.405	< 0.001	0.796
Mahurangi	0.001	< 0.001	< 0.001	0.156	< 0.001	0.007
Rangitopuni	< 0.001	< 0.001	< 0.001	0.346	< 0.001	0.092
Te Muri	< 0.001	0.407	-0.001	0.301	< 0.001	0.381
Ngakoroa	< 0.001	0.001	< 0.001	< 0.001	< 0.001	0.053
Waitangi	-0.001	0.002	-0.001	0.105	-0.002	0.008
Kaipara	< 0.001	0.01	-0.001	< 0.001	-0.001	< 0.001
Lower Vaughan	< 0.001	0.048	0.001	0.005	0.001	0.001
Puhinui	-0.001	0.03	< 0.001	0.054	< 0.001	0.18

5.3.3 Discussion

Variability in ecosystem metabolism over time was low at the reference site and higher at more impacted sites, which is consistent with earlier analyses of data from these sites which suggested that measures of variability in metabolism could be useful indicators of ecosystem health and resilience in addition to the measurements of metabolism on their own (Clapcott et al. 2016).

Most of the rivers show significant trends for all metabolism estimates. However, most slopes were relatively small (<0.001) and close inspection of the timeseries alongside detailed information on changes over time at specific sites would be necessary to establish any ecological significance of these indicative trends.

Rates of GPP typically varied seasonally at most sites, with higher rates during summer and lower rates during winter (Appendix 3). This is consistent with other studies elsewhere and reflects the effect of longer days, more intense sunlight and warmer temperatures in the summer on photosynthesis (Young & Huryn 1999; Young & Clapcott 2010; Goodwin & Young 2022). Seasonal variation in GPP was limited at the forested reference site, which probably reflects the heavy shading of this site, reducing seasonal variations in light and temperature. Seasonal patterns in rates of ER were either absent or less obvious, which again is consistent with other studies, as ER is not influenced by light intensity or daylength to the same extent as GPP. The Hoteo site tended to be autotrophic (NEM >0) in summer and heterotrophic (NEM <0) in winter, whereas West Hoe and Lower Vaughan were heterotrophic throughout the year. This variability in trophic state over time might reflect an impairment of ecological health and resilience, requiring organisms living at this site to rely on different sources of energy at different times of the year (see also Clapcott et al. 2016).

5.4 What are the drivers of change over time?

5.4.1 Methods

Testing for the influence of a proposed driver of metabolic activity requires variation in both the proposed driver and in the metabolic response. In the context of river ecosystem metabolism, the potential drivers and response time series were at different temporal resolutions. Values of metabolic estimates are available at daily resolution, but measurements of potential drivers are available at much lower temporal resolution. Climate data (total regional rainfall and average regional temperature) were obtained at quarter-year resolution, and land cover was available at four-year intervals. Therefore, the metabolism timeseries were summarised using medians that better match the temporal resolution of potential explanatory variables such as climate and land cover data.

We sought to determine whether the rapidly fluctuating metabolic responses at each site shifted when the conditions affecting each site changed. Where changepoints or trends are identified in metabolic time series, they may align with climate changes, which could suggest a causative relationship. We acquired time series of regional precipitation, and air temperature from Statistics

New Zealand, as well as a series of Southern Oscillation Index (SOI) values, to represent potential climate drivers.

Any effects of climate change could take some time to appear in the metabolism time series, and the lag between climate change and metabolic response is unknown. As a preliminary investigation we temporally aligned potential drivers with metabolic responses. If changes in climate consistently aligned with changes in metabolic response, these relationships would then be tested statistically. GPP, R and NEM mean values were linearly regressed against regional mean air temperature, mean rainfall, and mean SOI. The data were summarized by season and year. We used log transformed values of ER and GPP to reduce the skewness of the data. Analysis of NEM used untransformed data.

Changes in the river metabolic estimates time series may also align with changes in land cover due to urban development, environmental restoration, or other human activities. As with the climate drivers, any effects of land cover change could take some time to appear in the metabolism time series, and the lag between land cover change and metabolic response is unknown. As a preliminary investigation we temporally aligned land cover changes with metabolic responses. Land cover data were available from 2001, 2008, 2012 and 2018 (LCDB 5).

5.4.2 Results

Climate analysis

The results from this analysis per river are shown in Table 15; only significant models are shown. Only a subset of the rivers had significant models between metabolism rates and climate variables (Table 15). It is noteworthy that there were no relationships between metabolism and climate drivers at the reference site (West Hoe). For those sites that did show significant models/relationships, temperature appeared to be the most common driver of changes over time (Table 15).

Table 15. Results from the linear regression analysis between metabolic estimates and potential climate drivers. Only rivers with significant models and drivers are shown.

River name	metabolism estimate	driver	estimate (driver)	p-value (driver)	p-value (model)	r squared (model)
Hoteo	GPP	temperature	-0.1226	< 0.001	< 0.001	0.4400
Hoteo	GPP	log(precipitation)	0.0624	0.7385	< 0.001	0.4400
Hoteo	GPP	soi	-0.1247	0.119	< 0.001	0.4400
Hoteo	NEM	temperature	-0.8753	< 0.001	< 0.001	0.3796
Hoteo	NEM	log(precipitation)	-1.2578	0.3213	< 0.001	0.3796
Hoteo	NEM	soi	-0.2589	0.6284	< 0.001	0.3796
Kaukapakapa	GPP	temperature	-0.1575	< 0.001	< 0.001	0.4935
Kaukapakapa	GPP	log(precipitation)	-0.3418	0.0403	< 0.001	0.4935
Kaukapakapa	GPP	soi	0.0582	0.4468	< 0.001	0.4935
Kumeu	GPP	temperature	-0.1926	< 0.001	< 0.001	0.7542
Kumeu	GPP	log(precipitation)	0.0967	0.5151	< 0.001	0.7542
Kumeu	GPP	soi	0.0736	0.2682	< 0.001	0.7542
Kumeu	ER	temperature	-0.1047	< 0.001	< 0.001	0.4614
Kumeu	ER	log(precipitation)	-0.1515	0.2622	< 0.001	0.4614
Kumeu	ER	soi	0.0246	0.6803	< 0.001	0.4614
Mahurangi	GPP	temperature	-0.1422	< 0.001	< 0.001	0.5711
Mahurangi	GPP	log(precipitation)	-0.1177	0.488	< 0.001	0.5711
Mahurangi	GPP	soi	-0.1746	0.0212	< 0.001	0.5711
Mahurangi	ER	temperature	-0.1868	< 0.001	< 0.001	0.4352
Mahurangi	ER	log(precipitation)	-0.3234	0.2518	< 0.001	0.4352
Mahurangi	ER	soi	-0.2469	0.0474	< 0.001	0.4352
Te Muri	GPP	temperature	-0.1330	0.0041	0.0004	0.7454
Te Muri	GPP	log(precipitation)	-0.1353	0.6601	0.0004	0.7454
Te Muri	GPP	soi	-0.5502	0.0091	0.0004	0.7454
Ngakoroa	GPP	temperature	-0.0733	< 0.001	< 0.001	0.3576
Ngakoroa	GPP	log(precipitation)	0.0743	0.5367	< 0.001	0.3576
Ngakoroa	GPP	soi	-0.0602	0.2723	< 0.001	0.3576
Puhinui	GPP	temperature	-0.1128	< 0.001	< 0.001	0.6162
Puhinui	GPP	log(precipitation)	0.1470	0.2336	< 0.001	0.6162
Puhinui	GPP	soi	0.0553	0.3045	< 0.001	0.6162
Puhinui	ER	temperature	-0.0668	< 0.001	< 0.001	0.3335
Puhinui	ER	log(precipitation)	0.0268	0.8208	< 0.001	0.3335
Puhinui	ER	soi	-0.0109	0.8331	< 0.001	0.3335

Land cover analysis

The dominant land cover class for each site did not change through the years, which meant there were no changes to compare with the changes in the metabolism estimates over time. Moreover, the proportion of different land cover classes did not change significantly at the study catchments (see Figure 17), except for Lower Vaughan which experienced a substantial increase in urban land cover between 2012 and 2018. There is no obvious change in rates of ecosystem metabolism over this period (see Figure 15 and Figure 16) that can be directly related back to this change in land cover.

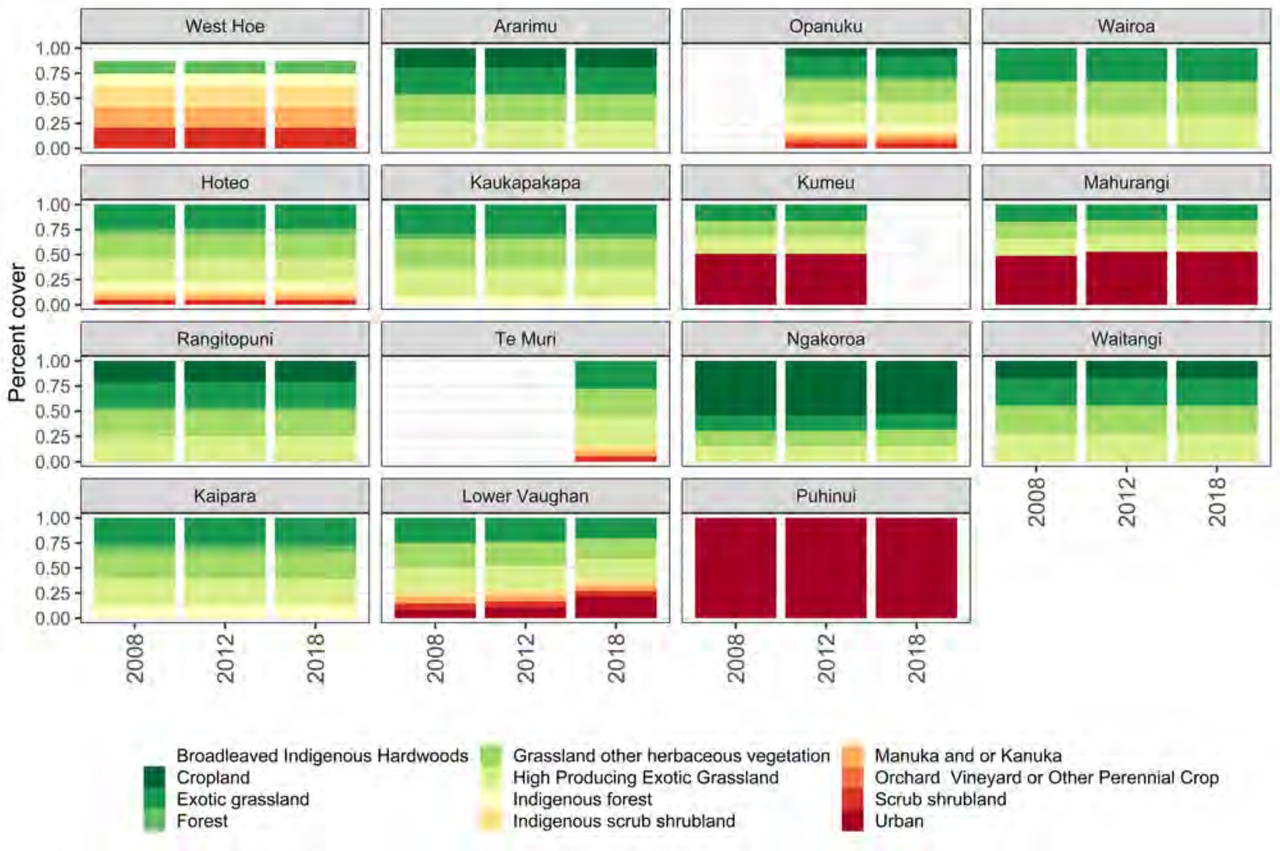

Figure 17. Changes in the per cent cover of different landcover types for each river between 2008 and 2018.

5.4.3 Discussion

The results from the climate analysis per river suggested that changes in temperature could be impacting changes in GPP, ER or NEM for seven of the 15 rivers studied. It is interesting to note that Lower Vaughan and Opanuku and West Hoe did not show any significant relationship with the climate variables analysed and have the highest per cent of riparian canopy cover (59%, 82% and 98%, respectively). High levels of riparian cover are likely to moderate/buffer any influences of climatic variability.

Land cover data is collected relatively infrequently, and the only clear change in the catchments upstream of the monitoring sites was at Lower Vaughan where there has been a considerable increase in urban development since 2012. These changes in land cover do not appear to have resulted in a noticeable change to rates of ecosystem metabolism at the Lower Vaughan site. There have been declining trends in ecological health at this site, as measured using macroinvertebrate community indices (Chaffe 2021). Urban development is on-going at this site but has also coincided with riparian planting and much of the development has followed water sensitive design principles (Rhian Ingley, pers. comm.).

6 General discussion

The NPS-FM has led to a step-change in thinking about how ecosystem health should be monitored in Aotearoa New Zealand rivers, encouraging the use of indicators beyond just the standard water quality and macroinvertebrate community indices that have typically dominated monitoring programmes globally in the past. The NPS-FM 2020 has also encouraged measurement and analysis of continuous data, shifting the previous reliance on monthly spot measurements of water quality or annual macroinvertebrate community samples. Dissolved oxygen (DO) varies widely within a single day making continuous data collection critical. Although the NPS-FM provides a framework upon which to interpret DO data, the collation, analysis and interpretation of this type of data is a relatively new field. Iterations and considerable learning are expected as people become more familiar with the opportunities and demands of continuous DO data analysis and reporting. Although building on previous analysis at many of the same sites, this report provides the most comprehensive analysis of Auckland Council's long-term continuous record of DO and ecosystem metabolism of rivers in the Auckland region, and the first analysis in relation to the NPS-FM attribute framework for these parameters in the Auckland region.

Our analysis of minimum DO and ecosystem metabolism data indicates a gradient of ecosystem health across the Auckland rivers that are included in the monitoring programme. The reference site (West Hoe) is characterised by relatively high minimum DO levels and low rates of ecosystem metabolism (i.e. 'good' health). In terms of NPS-FM 2020 attribute (or proposed draft) banding, the results would place this reference site in A band for ecosystem metabolism and B band for minimum DO. This reflects the relatively undisturbed catchment above this site that is dominated by native forest. The forest provides considerable shading for the stream and means there are limited inputs of sediment, nutrients and contaminants which can effect ecological processes. At the other end of the spectrum, DO minima for streams within the Pukekohe Specified Vegetable Growing Area (SVGA) (Ngakoroa and Waitangi), some rural sites (Kaukapakapa, Rangitopuni, Kumeu) and urban sites (Kaipara, Lower Vaughan, Puhinui) were very low placing them in the D band, below the national bottom line. DO minima at several of these sites (Waitangi, Lower Vaughan, Puhinui, Rangitopuni, Kumeu) were close to anoxic conditions at times, potentially severely restricting their life supporting capacity. Rates of ecosystem metabolism were elevated at Waitangi, Lower Vaughan, Kumeu, and Puhinui, representing D-band conditions, again indicative of poor ecosystem health.

For minimum DO, most sites had consistent overall band assessments between the proposed baseline and current state periods. The exceptions to this were Opanuku, Mahurangi, Ngakoroa, which all improved one band between the baseline and current state periods. Metabolism results indicated possible declines in ecosystem health between the baseline and current state periods at the Wairoa and Kaipara sites, whereas there was evidence of potential improvements in band status for Te Muri and Ngakoroa between the same periods. Chaffe (2021) reported declining trends in MCI and % EPT richness at the Wairoa site and improving trends in % EPT richness at

Ngakoroa over the 10-year period between 2010 and 2019, which are consistent with the metabolism results. There is little evidence in the literature of improvements in rates of ecosystem metabolism relating to specific restoration actions, perhaps due to lags in response time, or more likely due to restoration actions not occurring at sufficient scale to result in an ecological response (Gilling et al. 2013; Doehring et al. 2019).

It is interesting to compare the band assessments from minimum DO and ecosystem metabolism (i.e. comparing Table 6 and Table 10). For six sites, (Ararimu, Hoteo, Puhinui, Kumeu, Waitangi, Lower Vaughan) the band assessments were identical between overall minimum DO band and overall ecosystem metabolism band when data was available. At three sites (Mahurangi, Kaipara, Wairoa) the band assessments were also very similar, with a difference of only one band position occurring between minimum DO and ecosystem metabolism assessments. At West Hoe and Opanuku, the overall minimum DO bands were B, while the overall metabolism assessments indicated A-band status. Given that West Hoe is a reference site, perhaps the A-band criteria for minimum DO is unrealistic in Auckland, given the warm climate and thus naturally lower DO concentrations. To some extent this might be an artefact of the decision to use DO concentration (in mg/L), rather than DO % saturation, in the NPS-FM (Davies-Colley et al. 2013) since limits based on DO concentration do not account for differences in temperature among sites. For the remaining three sites where data was available for both minimum DO and ecosystem metabolism across both the baseline and current state periods (Kaukapakapa, Rangitopuni, Ngakoroa), there was considerable differences in band assessments between minimum DO and ecosystem metabolism. In all three cases, minimum DO indicated poor health (D-band or C-band), whereas ecosystem metabolism indicated better ecological condition (B-band, or A-band). It appears that while annual minimum DO concentrations experienced at these sites are very low (but not at anoxic levels), the daily fluctuations in DO resulting from ecosystem metabolism are not extreme.

The results of the analysis presented in this report are broadly consistent with earlier studies (Young 2006, Doehring & Young 2010, Clapcott et al. 2016) on the same or similar sites with a broad gradient of ecosystem health represented among the sites in the monitoring network. Issues with low DO minima seem to be relatively common among the sites in the Auckland monitoring network and perhaps more widely in the Auckland region (Depree et al. 2016). A recent analysis of similar data from six rivers in Northland also identified low DO minima as an important issue in some areas (Goodwin & Young 2022). Rates of ecosystem metabolism were also similarly elevated at some of the sites in Northland, although rates observed in Auckland and Northland are not as high as seen in some gravel-bed rivers in the Horizons and Hawkes Bay regions (Young & Clapcott 2010; Rutherford et al. 2020). Elevated rates of ecosystem respiration may be the cause of these low DO minima at some sites, while inputs of low DO groundwater may be a cause in streams dominated by groundwater inputs, such as those draining the Pukekohe SCGA zone. Further investigations are needed to determine the impact of groundwater at these sites.

There is considerable learning to be taken from how these types of data are analysed and interpreted. There is currently some ambiguity in the NPS-FM about the definition of summer and duration of assessment period (defined as November-April in relation to minimum DO, and

December-March in relation to ecosystem metabolism). We do not believe that this difference is intentional, but rather that summer was suggested as a period to examine if logistical or financial constraints mean that monitoring of DO throughout the whole year is not feasible. The summer period is when 'worst-case' conditions are expected to occur for both minimum DO and maximum rates of ecosystem metabolism. As shown in section 3 (see Table 7), this assumption generally holds true when assessing DO, but some sites in some years had DO minima outside the summer period. It is possible that data gaps during part of the critical summer periods may explain why DO minima occurred outside the summer period in some of these instances. If logistical or financial constraints limit sampling to just the summer period, ideally monitoring should occur over the whole summer period. Short burst of sampling over just seven days is likely to miss the worst-case conditions experienced at some stage in the summer. Ideally, monitoring of DO and ecosystem metabolism should be done for the whole year.

The NPS-FM stipulates that minimum DO calculations are done using 1-day absolute minimum and 7-day mean minimum statistics. A comparison of NPS-FM bands determined from both these statistics indicates that there is reasonable consistency between the two statistics (sites with low 1-day minima also have low 7-day minima), but the bands determined from the 7-day mean minima are often 1 band lower than the 1-day minima (Table 6). This was also observed in a recent similar analysis of DO in Northland (Goodwin & Young 2022). Ideally, both metrics are measured and considered together since the 1-day minimum, and 7-day mean minimum are reflective of acute and chronic effects of low DO, respectively (Davies-Colley et al. 2013), with an overall band assessment based on the lowest of the individual bands.

Annual summary statistics vary to some extent over time (Figure 3 and Figure 4, and Figure 15 and Figure 16 for minimum DO and ecosystem metabolism, respectively). This variation from year to year means that there is a risk of annual state band switching if values are close to the boundaries of NPS-FM bands or if annual variations are large. Consideration of rolling statistics calculated over five years, as required for other NPS-FM attributes, will help to avoid this state switching issue.

Analyses of differences among sites and potential drivers indicates the importance of riparian shading, landcover, water temperature and inputs of nitrogen as likely drivers of ecosystem metabolism in the Auckland region. It is notable that there was no evidence for relationships between ecosystem metabolism metrics and either dissolved or total phosphorus concentrations, indicating that nitrogen appears to be more important in the Auckland region at regulating rates of periphyton and aquatic plant growth (and organic matter respiration) than phosphorus concentrations.

There were strong correlations between rates of ecosystem metabolism and river health indicators based on macroinvertebrate community indices such as the MCI, suggesting that there is some consistency between these contrasting and complementary indicators. Complete alignment of results between EM and all macroinvertebrate attributes under the NPS-FM will require further investigation of potential relationships between EM parameters and the quantitative macroinvertebrate community index (QMCI) and the macroinvertebrate average score per metric (APSM). Like the MCI, ecosystem metabolism is an integrative indicator of ecosystem health and is affected by a wide range of potential stressors. However, it is difficult to pinpoint exactly which drivers are responsible for the differences as many of these drivers co-occur and have a cumulative effect on ecosystem metabolism and overall ecosystem health. For example, rivers with little shading, draining catchments dominated by pasture grasses typically have high concentrations of nutrients, faecal bacteria and contaminants – and thus respond with rates of ecosystem metabolism that are indicative of poor health. Similarly, management actions such as stock exclusion, revegetation of riparian zones, and associated control of contaminant runoff will result in rates of ecosystem metabolism more similar to reference conditions as well as improvements in various indicators of ecosystem health. To help address this complexity of multiple drivers affecting river ecosystem health, we recommend that coordinated monitoring of both pressures on our freshwater ecosystems (e.g. land use change, shading/light availability, land cover, nutrient leaching) as well as ecological responses (e.g. DO minima, ecosystem metabolism, water quality, MCI scores) should continue to be refined to get an improved picture of where there are issues with ecosystem health and to identify likely causes and resulting management actions to address the issues.

The long-term continuous DO dataset that has been analysed in this report is very valuable and further analyses may unveil more information on factors controlling the health of Auckland rivers. For example, site specific investigations linking groundwater inputs, groundwater DO concentrations and in-stream DO dynamics would be useful to identify potential causes of low minimum DO concentrations. Detailed site-specific investigations on changes in catchment condition may also provide information on how catchment activities will affect DO dynamics, ecosystem metabolism and the health of Auckland rivers.

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8 R scripts

The data compilation, metabolism calculations and all the analyses for this report were carried out in the R environment for statistical computing (R Core Team 2022). There are different scripts for different parts of this report, the table below describes the names of these scripts and the sections of the report that they cover:

Script file name	Report section
Report_code_functions.R	Several sections, this file has functions which are used in other R scripts.
raw_data_compilation.R	2 Monitoring sites and data compilation
oxygen_data_reporting.R	3 Dissolved Oxygen minima
ecosystem_metabolism_calculations.R	4 Ecosystem metabolism calculations
ecosystem_metabolism_analyses.R	5 Ecosystem metabolism analyses

To reproduce the results of this report, the scripts must be run in the order provided in the table above.

The code provided for this report is accurate and up-to-date currently, but it is likely that further improvements to the code will be incorporated in the future. We are providing the code in a zip file accompanying this report. However, a GitLab repository for this script exists and is kept up to date with version control, and it is shared by the authors of this report. Cawthron is not responsible for results generated with a modified version of this script by Auckland Council or any external parties, or the implementation of these steps using other datasets other than the ones used for this project.

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Appendix 1: Notes for dissolved oxygen sites

Continuous dissolved oxygen monitoring sites are serviced regularly according to NEMS requirements every 6-8 weeks (with a possible extension of up to 12 weeks under exceptional circumstances) for validation. With the exception of the Te Muri monitoring site, all sites are monitored using Zebratech D-Opto sensors with optical fluorescence technology and an internal thermometer. These are swapped as required based on data validation.

At the Te Muri monitoring site, DO is monitored using a YSI EXO dissolved oxygen sensor (optical luminesce) and temperature sensor. EXO sensor calibrations take place monthly for 100% DO calibration and annually for 0% calibration by swapping the sensor with a newly calibrated one. Additional 0% calibrations take place as required based on sensor performance. The sensor is validated monthly.

For both set ups, validations are undertaken using a YSI EXO sensor, calibrated with 100% water saturated air on the day of validation. Zero per cent calibration for the reference EXO sensor takes place at the same time as calibrations of the D-OPTO sensors, usually once a month but at least annually.

All deployed sensors were initially calibrated on site until mid-2014. From mid-2014 onwards calibrations took place in the AC workshop before swapping instruments. The following elevations apply to the different workshops (based on closest LINZ benchmark and converting from AVD to NZVD2016 using LINZ conversion grid):

- Franklin Rd 8.733 August 2019 to current
- Takapuna 19.428 End July 2017 to August 2019
- Albert Street - 26.394 (street level, but workshop is located in a basement 4 levels down) From start of Calibration record mid-late 2016 – to end July 2017
- Takapuna 19.428 Pre 2016

Sensor heights at the monitoring sites are close to zero staff gauge height, which is summarised in Table A1 below.

Table A1. Stage height and GIS coordinates for DO monitoring sites.

Site	NZVD2016 RL of zero stage height	NZTM (E)	NZTM (N)	
43807 Puhinui	14.614	1766420	5904316	
43602 Waitangi	27.417 (unknown datum)	1755195	5878315	
43829 Ngakoroa	141.268	1775153	5881619	
45315 Kumeu	18.436 (unknown datum)	1739254	5929059	
45415 Kaukapakapa	3.098	1735809	5945031	
45311 Kaipara	3.721	1733345	5930348	
7805 Rangitopuni	6.023	1744587	5933077	
8516 Wairoa	6.055	1782663	5901676	
45326 Ararimu	11.919	1734999	5932630	
45703 Hoteo	8.406	1735424	5972357	
6863 Mahurangi Argonaught (New Site)	6.555	1748589	5970087	
6806 Mahurangi College (Old Site)	8.618	1748387	5969849	
7506 Lower Vaughan	1.648	1755422	5938731	
7206 West Hoe	31.617	1748302	5950580	
7904 Opanuku @ Candia	20.065	1742162	5915566	
6995 Te Muri	19.389	1752915	5957910	

While at most sites water level is monitored by Auckland Council, water level data for 43602 Waitangi monitoring sites was from NIWA hydro portal :https://hydrowebportal.niwa.co.nz/Data/Location/Summary/Location/43602/Interval/Latest. This data was quality coded QC 30 – external data.

Cross sections at 7904 Opanuku at Candia were provided but may not be representative of conditions while DO was recorded as the cross sections were completed after the riverbed moved and the staff gauge was readjusted.

Two datasets were provided for Waitangi River. These originated from a trial to assess the influence of weir pond at the original site. No differences were found in this trial. This report therefore used the data from the original site with the most complete dataset.

Appendix 2: Detailed and additional methods

All data compilation and data analyses were carried out using the R environment for statistical computing R Core Team (2021). All peer reviewed R scripts used are included with this report. There is a different script for each section of this report. These scripts produce intermediate and final outputs for analyses. To reproduce the results for this report, the scripts need to be run in the order that follows the sections of this report, and the data must be kept as it was originally provided by Auckland Council. All original data needed for reproducing these results are also included with this report. The R scripts provided with this report are accurate and up-to-date currently. A GitLab repository for these scripts exists and is kept up to date with version control. Cawthron is not responsible for results generated with a modified version of these scripts by Auckland Council or any external parties.

Ecosystem metabolism estimates

Metabolism in stream ecosystems comprises photosynthesis during daylight hours, and respiration always occurring. Photosynthesis increases dissolved oxygen in the water and respiration depletes dissolved oxygen from the water. Alongside these biological processes, there is physical exchange of oxygen gas between stream water and atmospheric air. The gas transfer at the water surface is regulated by atmospheric pressure and temperature and acts to equilibrate dissolved oxygen with the atmospheric oxygen 'partial pressure'. That is, if the oxygen concentration in the water is below the 'saturation' concentration for the conditions (temperature, total pressure), oxygen will diffuse from the atmosphere into the water (reaeration). If oxygen concentration in water is higher than the saturation concentration for the conditions, oxygen will diffuse from water back to the atmosphere. The saturation concentration is the amount of oxygen water will hold at equilibrium, given the temperature and atmospheric oxygen partial pressure. As oxygen concentration rises and falls it may pass above and below the saturation concentration. Sometimes it will be in surplus, sometimes in deficit, relative to saturation concentration.

$$dDO/dT = P\mathrm{PG} + \mathrm{E}R + kD \qquad \text{Equation 1}$$

In Equation 1 the term dDO/dT means the change in dissolved oxygen over time (units g m^{-3} day^{-1}). Oxygen levels in the water may rise or fall over time, giving respectively positive or negative values of dDO/dT. GPP represents the contribution to change in oxygen made by photosynthesis. Because photosynthesis generates oxygen, GPP should be a positive contribution. ER represents the contribution to change in oxygen made by respiration. Because respiration depletes oxygen, ER is expected to be negative. The *k*D term represents the physical gas exchange with the atmosphere through the water surface. This component may be positive or negative, depending on the degree of oxygen deficit (D, units g m^{-3}), which may be positive (water undersaturated in oxygen) or negative (water supersaturated in oxygen). *k* is the reaeration coefficient (units day^{-1}), characteristic of the stream at a certain water level, positive and ideally constant over time at a given level of flow. Shallow turbulent streams have a high *k*, while deep, slow-flowing rivers will have a low *k*.

Identification of dark period of the day

To separate the three processes that alter dissolved oxygen concentration in stream water, it is important to note that no photosynthesis will occur in the absence of light, and that no diffusion will occur when water and air are at equilibrium with respect to oxygen levels. To exclude the influence of photosynthesis the dark period of the day needs to be identified. Intuitively this could be achieved by calculating the solar dawn and dusk times for the time of year and geographic location. However, meteorological (cloud), topographic (hill) or arboreal (tree) shading may extend the dark period beyond what would be predicted from sunrise and sunset times. It is more important at this stage of metabolic calculations to isolate a period of clean respiration, than it is to capture all the respiration period. The dark period is identified via a pair of simple characteristics of the dissolved oxygen curve observed over the course of each night. The start of the dark period is set at the time of greatest rate of decrease in dissolved oxygen, and the end of the dark period is set at the time of greatest oxygen deficit. These are fallible rules, and it is easy to find cases where they may underestimate or overestimate the dark period. We rely on the considerable number of days' data available and assume that any biases affect all sites equally. We also filter estimates and exclude any unlikely or low-reliability estimates that may be caused by poor dark-period estimation.

Estimation of respiration and the reaeration coefficient

Once the dark period of each day is identified, the oxygen concentration data from those periods is extracted, and linear regressions set up between oxygen deficit and rate of oxygen change.

Rate of respiration

The rate of respiration (reflected in oxygen depletion) is independent of light levels, but dependent on the active biomass, nutrient concentrations, oxygen availability and temperature at the site. Respiration is therefore steadier over time, and specifically it can be assumed to be occurring at the same rate during daytime as during the nights preceding and following. The respiration rate can be estimated from its effect on decreases in dissolved oxygen at night when it is confounded only by the effects of reaeration. Once the rate of reaeration is known, the rate of respiration can be determined.

Rate of reaeration

Positive reaeration occurs when water oxygen concentration is below its saturation concentration (that is, when it is less than 100% saturated), and the further it is below saturation, the higher the reaeration value will be. Negative reaeration occurs when water oxygen concentration is above its saturation concentration (>100% saturated). When water oxygen concentration is equal to its saturation concentration, no reaeration will occur. Any remaining oxygen concentration change must therefore be due to photosynthesis and respiration, and at night will be due to respiration alone.

Temperature correction

Rates of respiration and the reaeration coefficient are both affected by temperature. We have assumed that R doubles with a 10 °C increase in temperature (Phinney & McIntire 1965) and the reaeration rate increase by 2.41% per degree Celsius (Kilpatrick et al. 1989). Where water temperature was available, it was used to refine the nightly average values for k and R obtained from the night-time regression calculations into a time series with variation reflecting the fluctuations in temperature.

Estimation of gross primary production and net ecosystem metabolism

The rate of photosynthesis (reflected in oxygen generation) fluctuates over a 24-hour cycle. Its rate is determined by several factors including aquatic plant biomass, light levels, nutrient concentrations, carbon dioxide availability and temperature. Light fluctuates predictably over a daily cycle, while the other effects may be steadier over longer time periods, or less predictable. Daily fluctuation in the rate of photosynthesis follows the fluctuation in light levels. The rate of photosynthesis can be estimated from its effect on the increase in dissolved oxygen during the day. However, the rate of oxygen change during the day is also partly due to the constitutive effects of respiration and of reaeration, so it is only after these components have been estimated, that the contribution of photosynthesis can be resolved.

The regressions of change in oxygen concentration (in g m^{-3} day^{-1}) against oxygen deficit (in g m^{-3}) give respiration rate estimates in units of grams of oxygen per cubic metre per day (g m^{-3} day^{-1}), then gross primary production and net ecosystem metabolism are in the same units. To better compare rates of metabolic activity between rivers of different scale, the volumetric estimates are made relative 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. Rates of respiration, primary productivity and net metabolism are then expressed in grams of oxygen per square metre per day (g m^{-2} day^{-1}), giving an indication of the relative metabolic activity of the riverbed.

Gap filling regression for deriving oxygen saturation

At each site there are occasions when the per cent saturation data was not available for some time points, when the temperature and oxygen concentration, from which saturation is derived, were available. Because the metabolism estimation depends on the availability of oxygen saturation data, it is worthwhile deriving the missing saturation values where that is possible, to fill gaps where otherwise metabolism would not be estimated. Oxygen saturation can be determined according to a formula involving atmospheric pressure (largely due to site elevation), water salinity (assumed to be perfectly fresh in these river sites), water temperature and oxygen concentration. The equation is reasonably complex, and a simpler approach was adopted to fill gaps in this case. For any site, the elevation (and hence barometric pressure) will be fixed over time. Hence, the available complete dataset for each site can be used as a training set for a model that will fill in the gaps for that site. We investigated the performance of various linear regression models, to determine the complexity required to deliver adequate estimation precision using only water temperature and oxygen concentration to predict oxygen saturation (as salinity and pressure are constant).

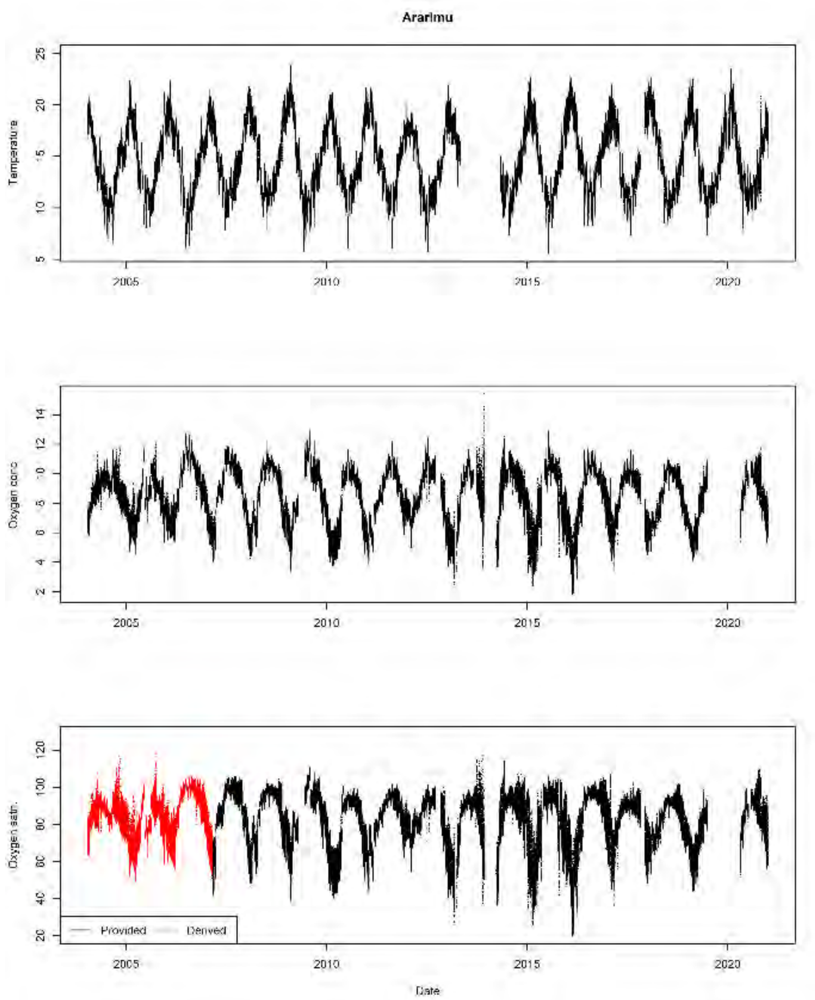


Figure A1. Derived oxygen saturation values (in red) using the gap filling approach for the Ararimu site.

We found that quadratic terms in the predictors were unnecessary but included an interaction term between water temperature and oxygen concentration, to achieve consistently excellent explanatory performance. The number of time points at which oxygen saturation values were missing, yet temperature and oxygen concentration data were available, varied from site to site, between 1 single time point and over 100000. The nearly 200000 additional points overall that can now contribute to metabolic estimates were QC tagged as ‘synthetic’ (NEMS code 300) to indicate their regression provenance.

Additional time series analyses

Timeseries decomposition analysis

Methods to detect differences and changes over long periods of time must account appropriately for seasonal, cyclic fluctuations that occur in all stream metabolism time series. To investigate underlying temporal changes, which might be obscured by the considerable seasonal fluctuation of the metabolic estimates, a time series decomposition analyses was performed. The overall time series can be described as comprising a repeated seasonal cycle ("seasonal component" of the time series), a deseasonalised moving average ("long-term trend") and short-term deviations from the general trend ('anomalies'). Each of these components can be isolated, and their combination reflects the original time series dataset.

First, the median value of GPP, ER and NEM were calculated per year and season, and then decomposed to long-term trend, seasonal and anomaly components. For extracting the time series components, a Generalised Additive Model (GAM) was built for each metabolic estimate time series, using a time index based on the combination of season and year for the smooth term that captured long term trend. We used log transformed values of ER and GPP to reduce the skewness of the data. Because all values of ER are negative, we log transformed the absolute values of ER before analysis. Untransformed data were used for analysis of NEM.

To extract the long-term trend component, a GAM model was constructed with the season variable set to a constant value. To extract the seasonal component, the predicted values were estimated from the GAM model for a constant time index value and subtracted the mean of the metabolic series from the predicted values. To extract the residual anomaly, the difference between observed values and the sum of the trend and seasonal components values was calculated.

The decomposition analysis results for West Hoe, Hoteo and Lower Vaughan are shown in Figure 17, as examples to illustrate how to interpret these results for all sites (as provided in the Appendix 3). The long-term trend (red lines) helps identify any elements of ecosystem metabolism that have changed over time. GPP, ER and NEM will respond in different ways to different drivers, so they can potentially have similar or different trends (or lack of trend) at the same site. The seasonal component (black lines) shows the natural cycles through the seasons, which are similar for all rivers. The seasonal component is expressed as a deviation from the long-term trend, centred around zero. The peaks in magnitude of the production and respiration components are synchronised. The greatest positive GPP aligns with the greatest negative ER, in summer. Negative GPP and positive ER contributions in winter return the overall rates toward zero in this season. The magnitude of the fluctuations varies across rivers. The final component shows the remaining anomaly, unexplained by cyclic seasonal or long-term trend effects. These short-term discrete anomalies are likely to be caused by acute influences such as weather events and flow anomalies. Comparing the magnitudes of the three component contributions helps understand the weight of each component determining the overall variability of a given river. Time series decomposition results for all sites are shown in Appendix 3.

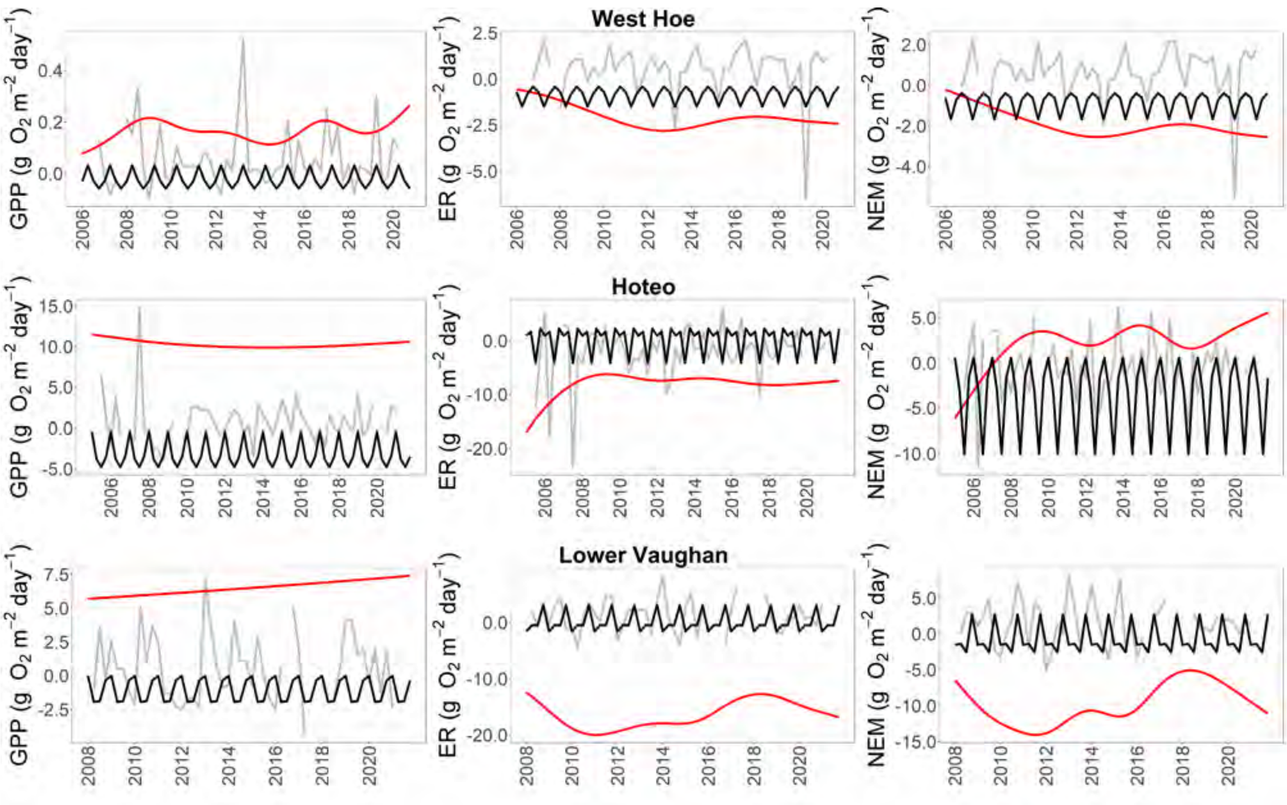


Figure A2. Time series decomposition of West Hoe, Hoteo and Lower Vaughan rivers. Red lines show the long-term trend, black lines show the seasonal component of the time series, and grey lines show the anomaly. Note that the anomaly line shows the gaps in data.

Kendall trend analysis on the decomposed long-term trend

The isolated long-term trend of the time series decomposition analysis above was used to test for a linear trend over time, using a Kendall trend test (Kendall 1975). The Kendall trend test performed here is based on a rank correlation as implemented in the R EnvStats library (Millard 2013). The Kendall test accounts for seasonal differences where they are detected, if necessary, stratifying the comparison over time within season. This is important in cases where the above decomposition fails to separate the seasonal pattern properly. The Kendall trend test estimates the slope of the trend as well as a "p value" of statistical significance.

The results of the Kendall linear trend test on the isolated long-term trend of the time series decomposition analysis above for all rivers is shown in Table A2. The trend slope is the slope of the 'line of best fit' through the set of points, while the p-value indicates whether the slope is statistically different from zero. A large slope value (positive or negative) would suggest a rapid rate of change, but if it is accompanied by a p value much greater than 0.05, it is unlikely that the suggested trend is credible. While a small slope value may be less dramatic, if it is accompanied by a p value smaller than 0.05, it is worth closer attention as a more reliable result. Most of the rivers show significant long-term trends for all metabolism estimates, although with daily data over multiple years it is easy to identify possible linear changes that are not ecologically meaningful. Most slope values are relatively small and therefore unlikely to be ecologically meaningful (Table A2). Further analysis of changes at specific sites may be appropriate but was outside the scope of this report.

Table A2. Results from the Kendall trend analysis on isolated long-term trend of entire time series.

	GPP		ER		NEM	
River name	slope	p-value	slope	p-value	slope	p-value
West Hoe	0.001	0.079	-0.023	< 0.001	-0.029	< 0.001
Ararimu	0.088	< 0.001	-0.216	< 0.001	-0.096	< 0.001
Opanuku	-0.031	< 0.001	-0.027	< 0.001	-0.042	< 0.001
Wairoa	0.022	< 0.001	-0.001	0.977	0.077	0.005
Hoteo	-0.009	0.005	-0.009	0.302	0.062	< 0.001
Kaukapakapa	0.000	< 0.001	-0.060	< 0.001	-0.055	< 0.001
Kumeu	0.125	< 0.001	-0.163	< 0.001	-0.050	< 0.001
Mahurangi	0.071	< 0.001	-0.052	0.001	-0.003	< 0.001
Rangitopuni	0.007	< 0.001	0.064	< 0.001	0.043	0.079
Te Muri	0.334	0.004	-0.405	0.003	-0.201	< 0.001
Ngakoroa	-0.013	0.004	0.029	< 0.001	0.003	0.093
Waitangi	-0.237	< 0.001	-0.374	< 0.001	-0.485	< 0.001
Kaipara	0.067	< 0.001	-0.256	< 0.001	-0.145	< 0.001
Lower Vaughan	0.031	< 0.001	0.086	< 0.001	0.099	< 0.001
Puhinui	-0.221	< 0.001	0.092	< 0.001	-0.068	< 0.001

Change point analysis

Aside from predictable seasonal fluctuations and gradual trend changes, long term change can manifest as discrete step changes. The approach to detecting the presence of step changes is exploratory and could be characterised as data mining as opposed to robust statistical testing of an *a priori* hypothesis, as it is not specified in advance where the step change or step changes might occur. Step changes were identified using an optimal detection of changepoints with a linear computational cost (Killick et al 2012) implemented with the R package “changepoint” (Killick and Eckley 2014). This function proposes various sets of changepoints for any time series, from few to many depending on the setting of a ‘penalty’ value for the introduction of an additional changepoint. We selected the simplest set of changepoints proposed for each time series for further inspection.

The results of the change point analysis for the three example rivers are shown in Figure 18. The grey line represents the long-term trend component from the time series decomposition, which is used as input in the change point analysis. The red vertical lines show the proposed change points, although these are not necessarily ecologically meaningful. Time series decomposition results for all sites are shown in Appendix 3.

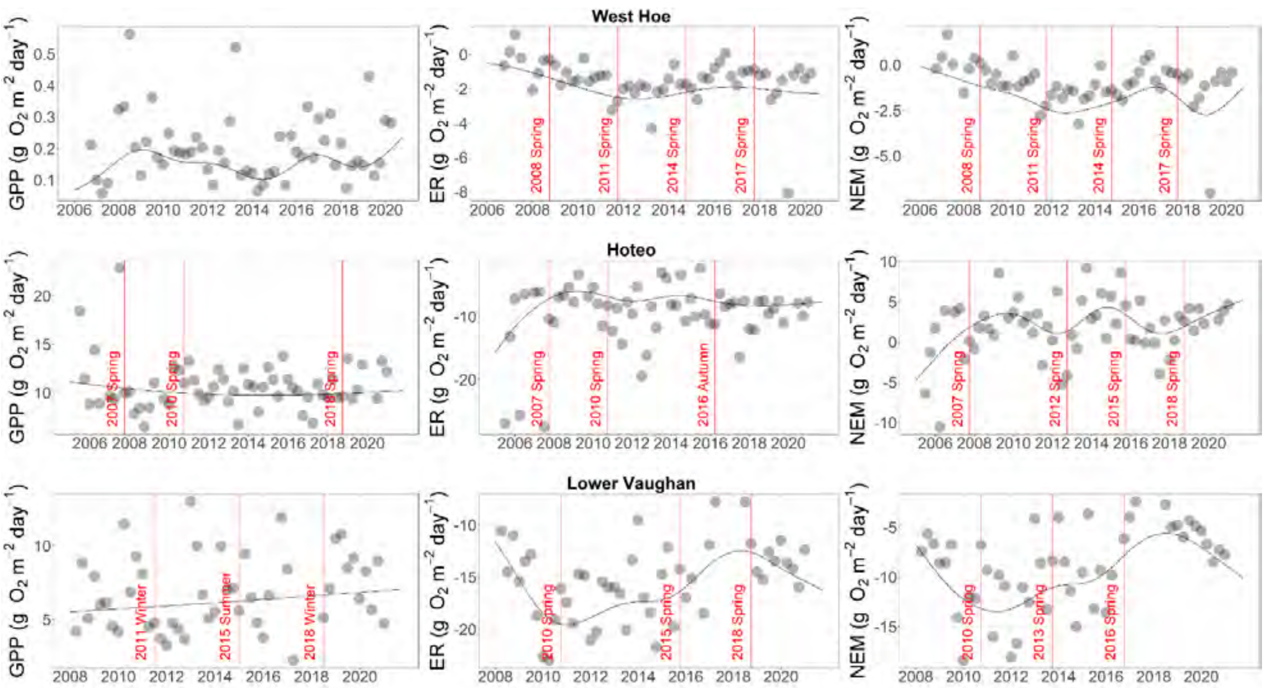


Figure A3. Change point analysis for GPP, ER and NEM for West Hoe, Hoteo and Lower Vaughan. The black lines are long-term trend components from the time-series decomposition analysis, vertical red lines are possibly change points and grey dots are seasonal median values.

Seasonal patterns in metabolism

Observed time series of GPP, ER and NEM were plotted for all rivers (see Appendix 3), to allow for a visual inspection of the data. GPP, ER and NEM values versus day of the year were also plotted for all rivers, to show the seasonality of these values.

Detailed plots showing seasonal patterns for all rivers are shown in Appendix 3. The three example rivers (West Hoe, Hoteo and Lower Vaughan) are again discussed here to illustrate the differences in patterns and guide the interpretation of the results from all the sites presented in Appendix 3. Daily metabolic estimates from the whole data record from West Hoe, Hoteo and Lower Vaughan, together with annual average and monthly average values are shown in Figure A4. Mean GPP at West Hoe was generally less than 1.0 g m^{-2} day^{-1}, while mean GPP at Hoteo and Lower Vaughan was typically between 5-10 g m^{-2} day^{-1} (Figure A4). ER was also lower (less negative) at West Hoe, with annual mean values generally around -1.5 g m^{-2} day^{-1}, whereas ER was up to -25 g m^{-2} day^{-1} at times at Hoteo and Lower Vaughan (Figure A4).

Seasonal patterns in GPP were evident at Hoteo with peaks in the summer and lower GPP at other times of the year (Figure A4). However, evidence for typical seasonal cycles were not obvious for ER at Hoteo or GPP or ER at West Hoe or Lower Vaughan (Figure A4). To investigate seasonal patterns further we plotted daily rates of ecosystem metabolism for all years against day of the year (i.e., 1st January = Day 1 of the year) (Figure A5). There was little annual variation in GPP at West Hoe (Figure A5). In contrast, GPP at Hoteo and Lower Vaughan was highest in the summer and lowest during the winter (Figure A5). ER rates at West Hoe appeared to be slightly greater during the winter period, but perhaps lower during winter at Hoteo and Lower Vaughan although this pattern is not obvious (Figure A5). At West Hoe and Lower Vaughan, NEM values seemed to be influenced by the ER patterns, and at both rivers the values were negative throughout the year (Figure A5). For the Hoteo river, NEM seemed to follow the GPP pattern, with negative values during the winter, and positive values during the summer period (Figure A5).

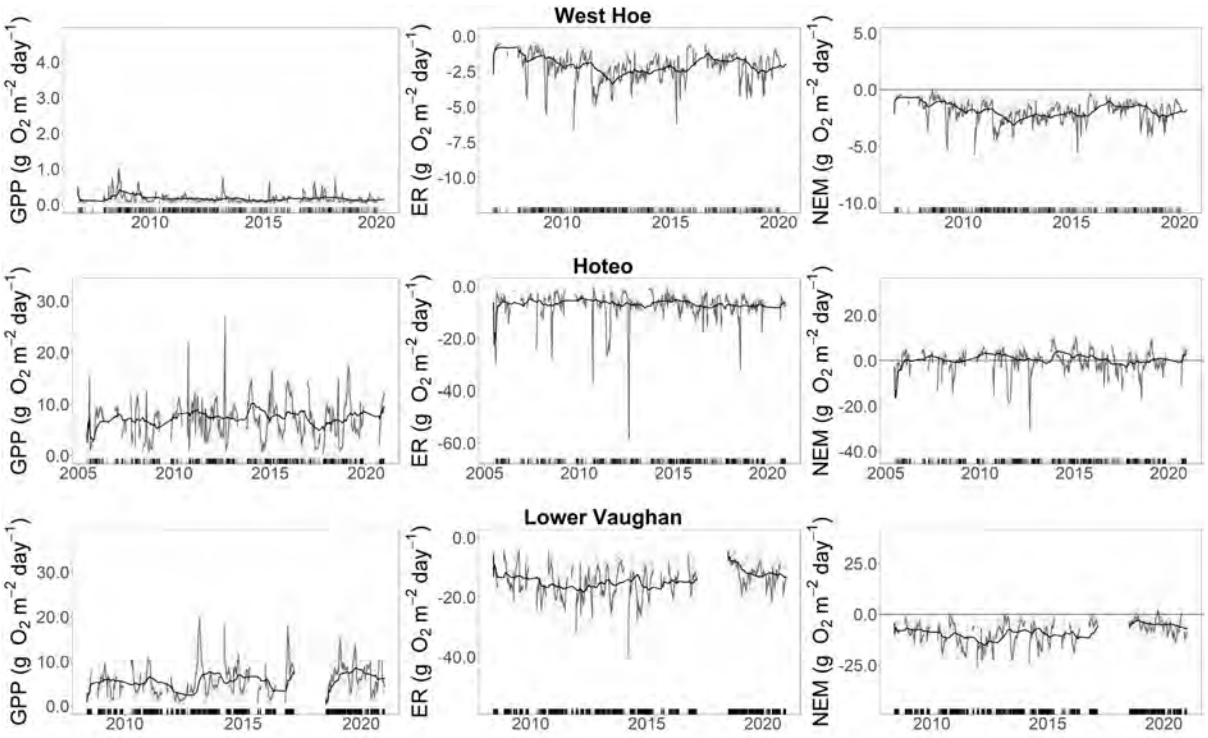


Figure A4. West Hoe, Hoteo and Lower Vaughan GPP, ER and NEM time series. The darker line shows a 12-month rolling mean and the grey line shows a 1-month rolling mean. The points are the daily ecosystem metabolism values between the 1st and 99th percentile. Years are hydrological years.

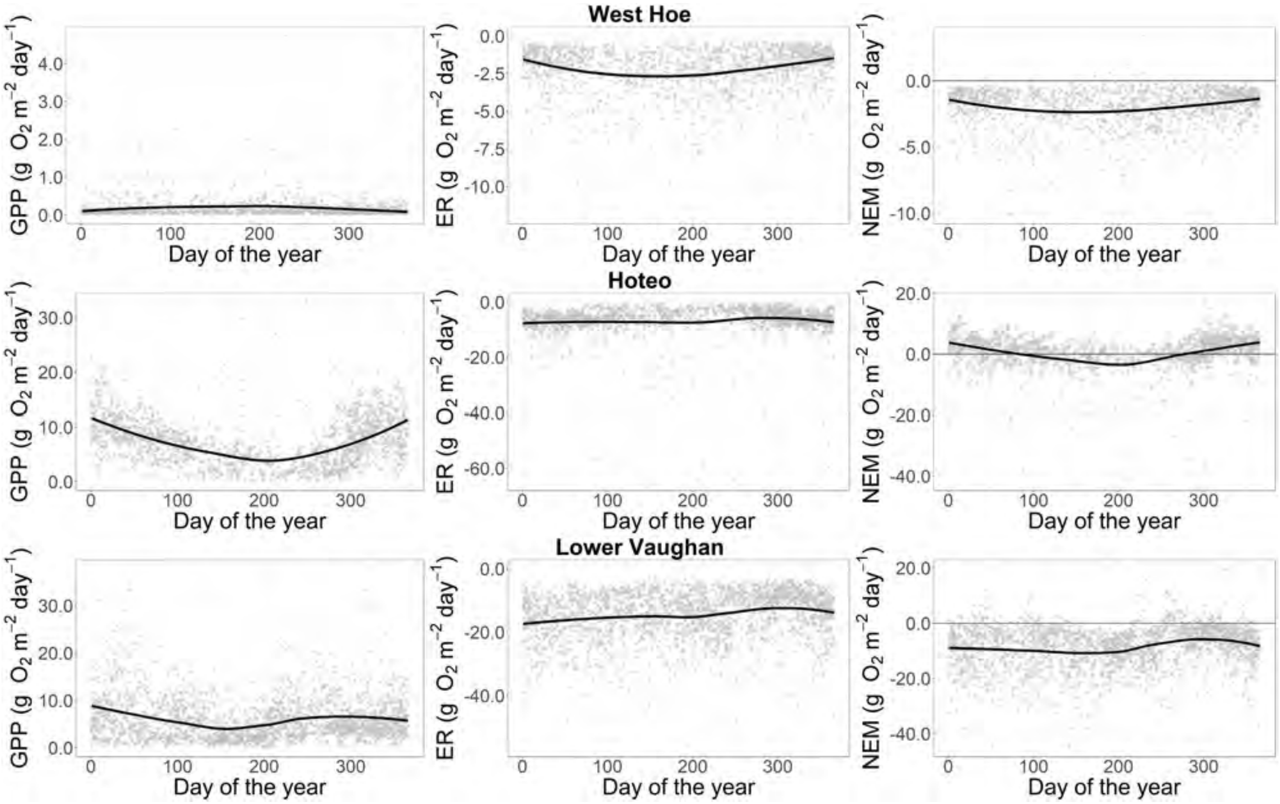


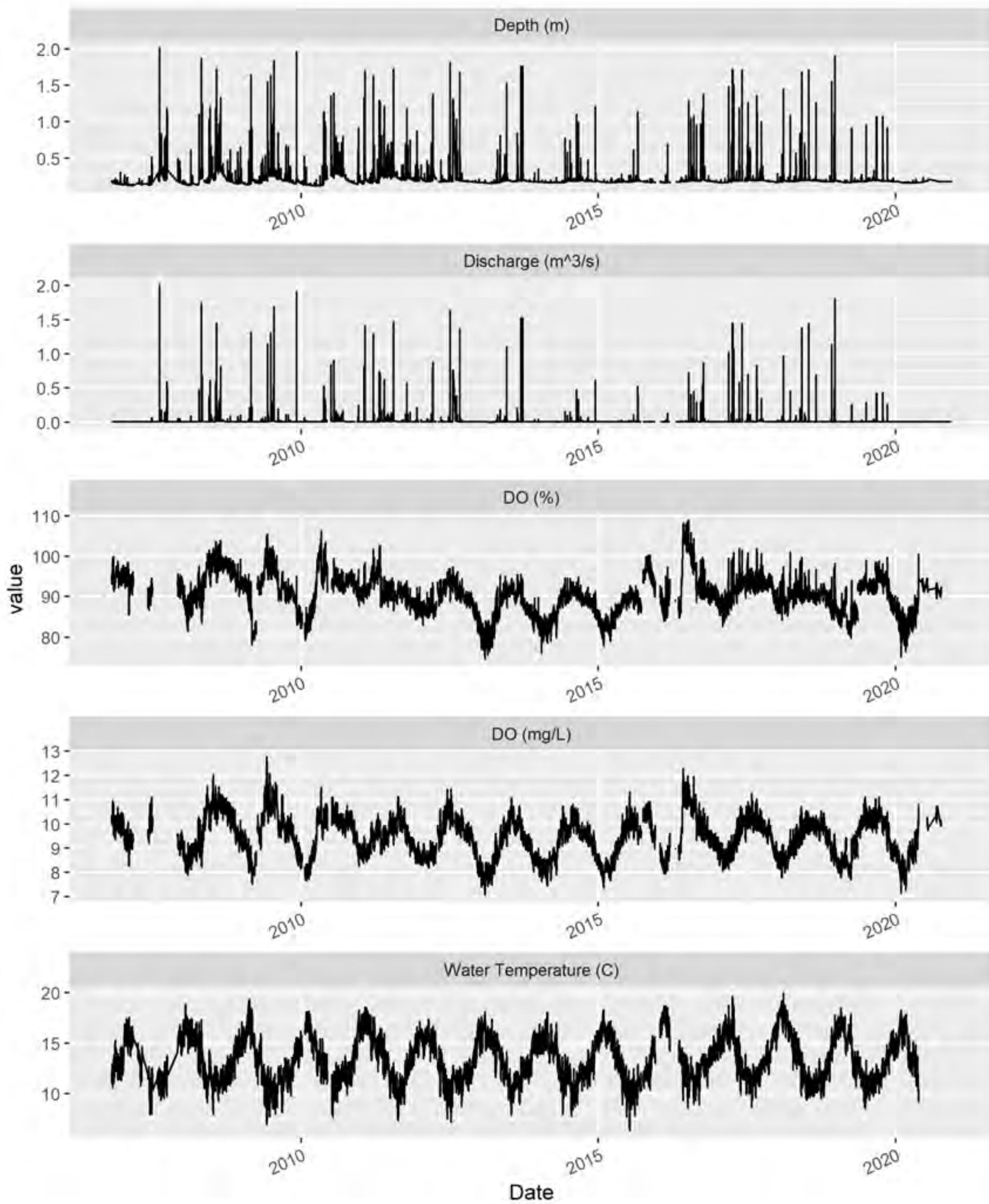
Figure A5. Annual patterns in daily metabolic estimates. The solid black line shows a LOESS smooth of the data.

Appendix 3: Results for each river

West Hoe

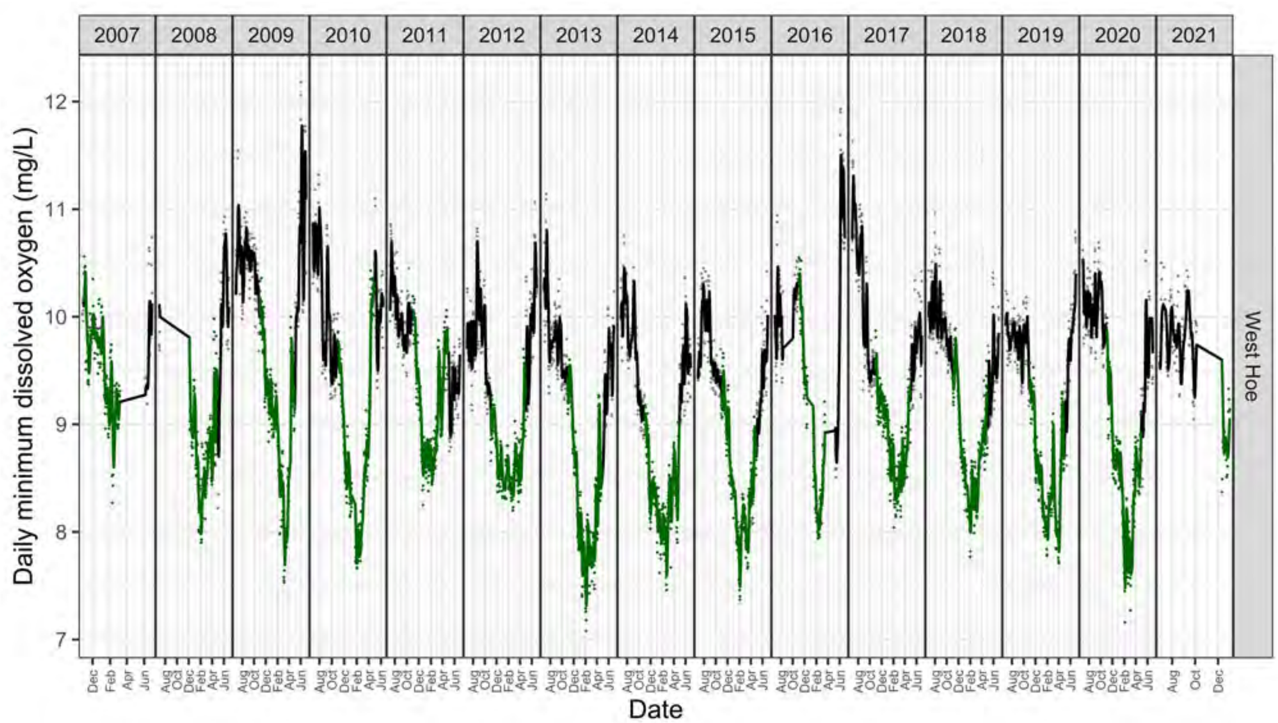
Raw data compilation

Original data Timeseries. Data with QC codes 42 and 43 have been removed.



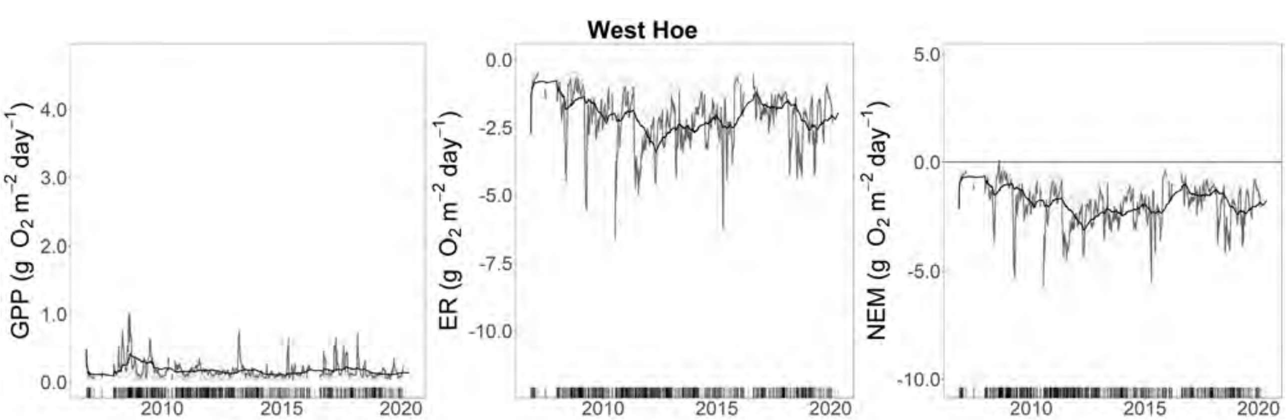
Oxygen data reporting

Timeseries of minimum dissolved oxygen. Points show the daily minimum values, and lines show the 7-day mean value. The summer period is indicated by the colour dots and lines (green), which also correspond with the catchment groupings by land cover (Table 1). Years are hydrological years.

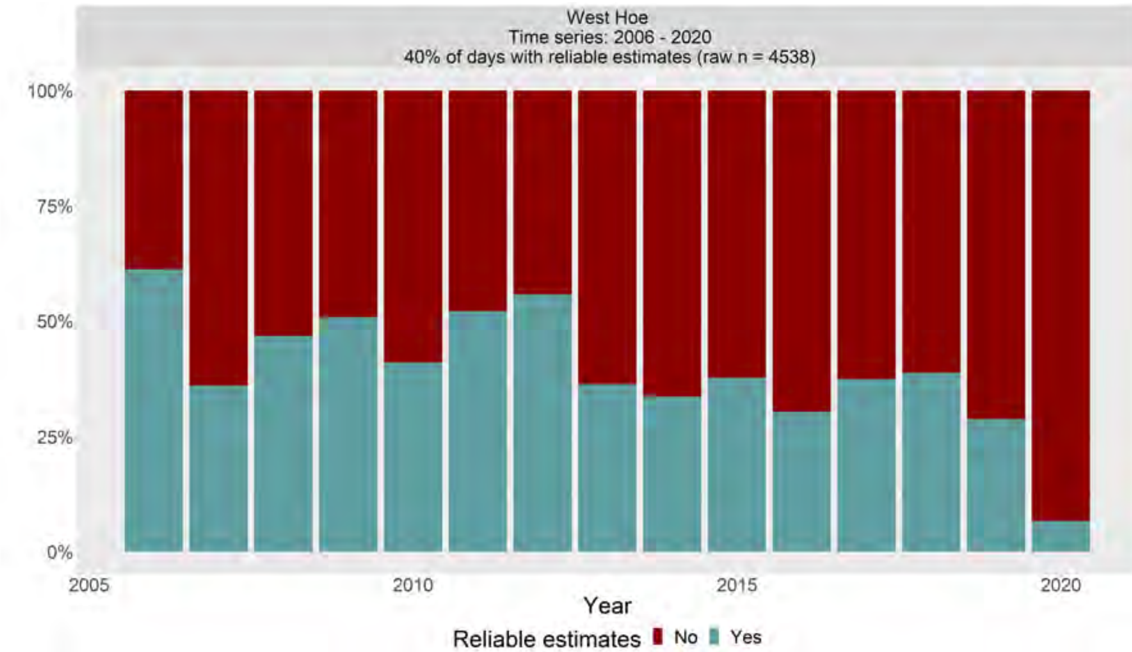


Metabolic estimate calculation

Time series of metabolic estimates (reliable data only)

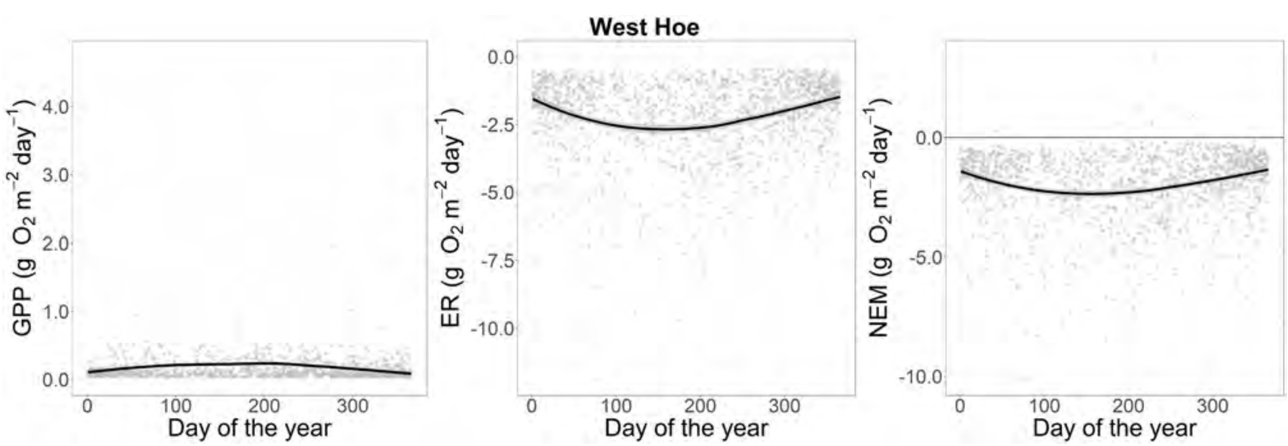


Per cent of days with reliable data based on the results of the metabolic estimates calculations.

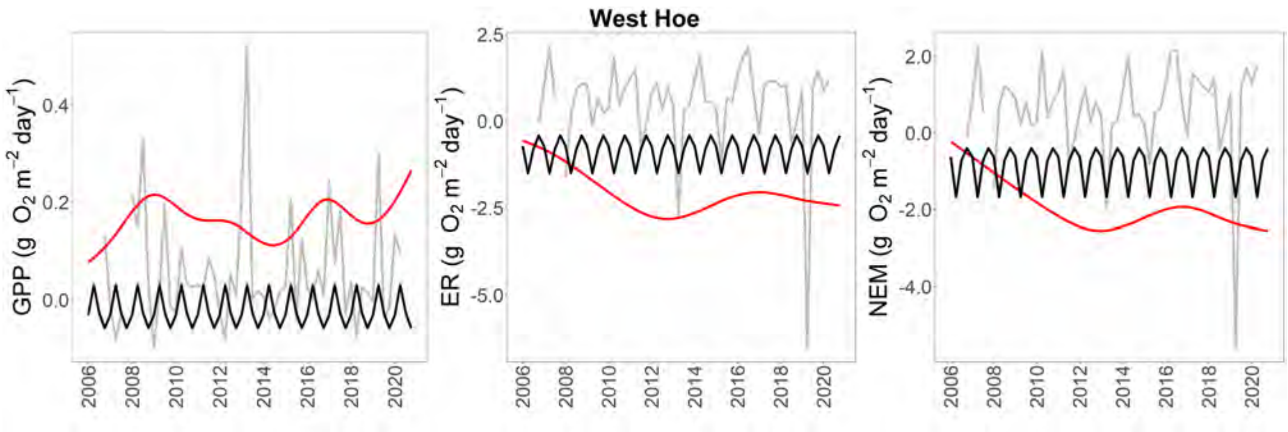


Analysis of metabolic results

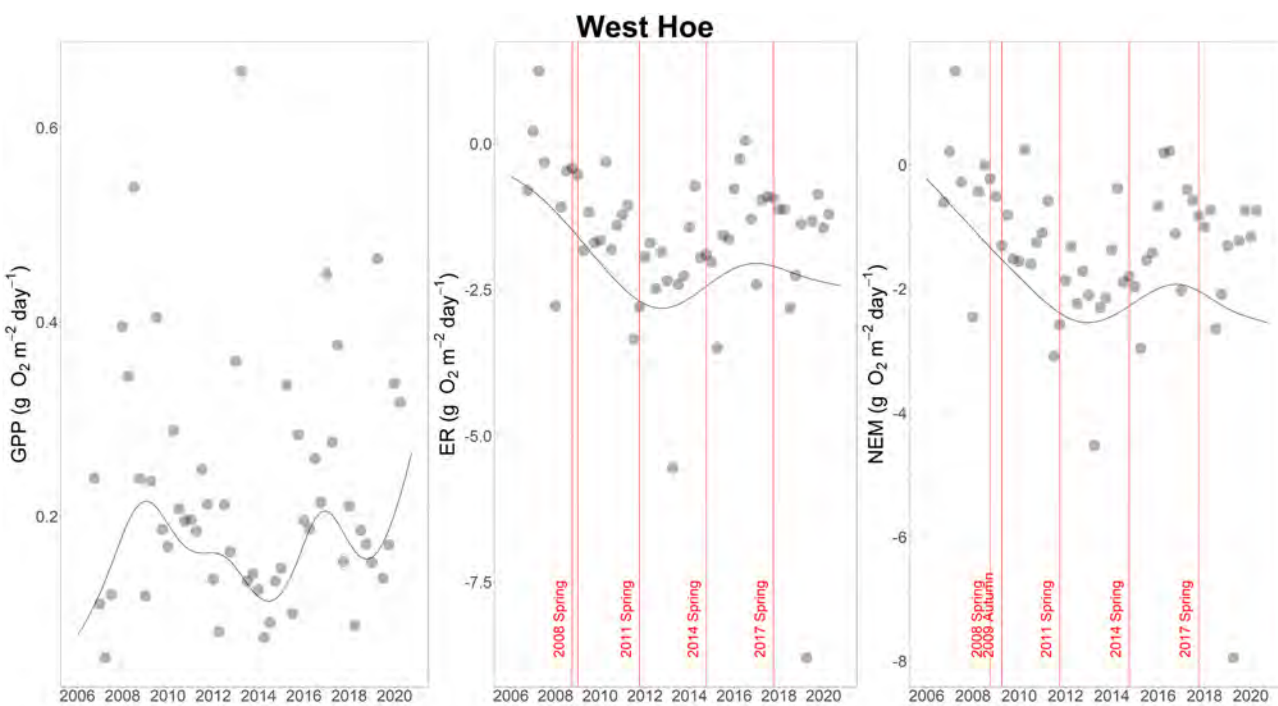
Seasonal distribution of metabolic estimates. One at the starts of the x-axis represents the 1st of January.



Time series decomposition analysis. The red line shows the long-term trend, the black line shows the seasonal component of the trend, and the grey line shows the anomaly.



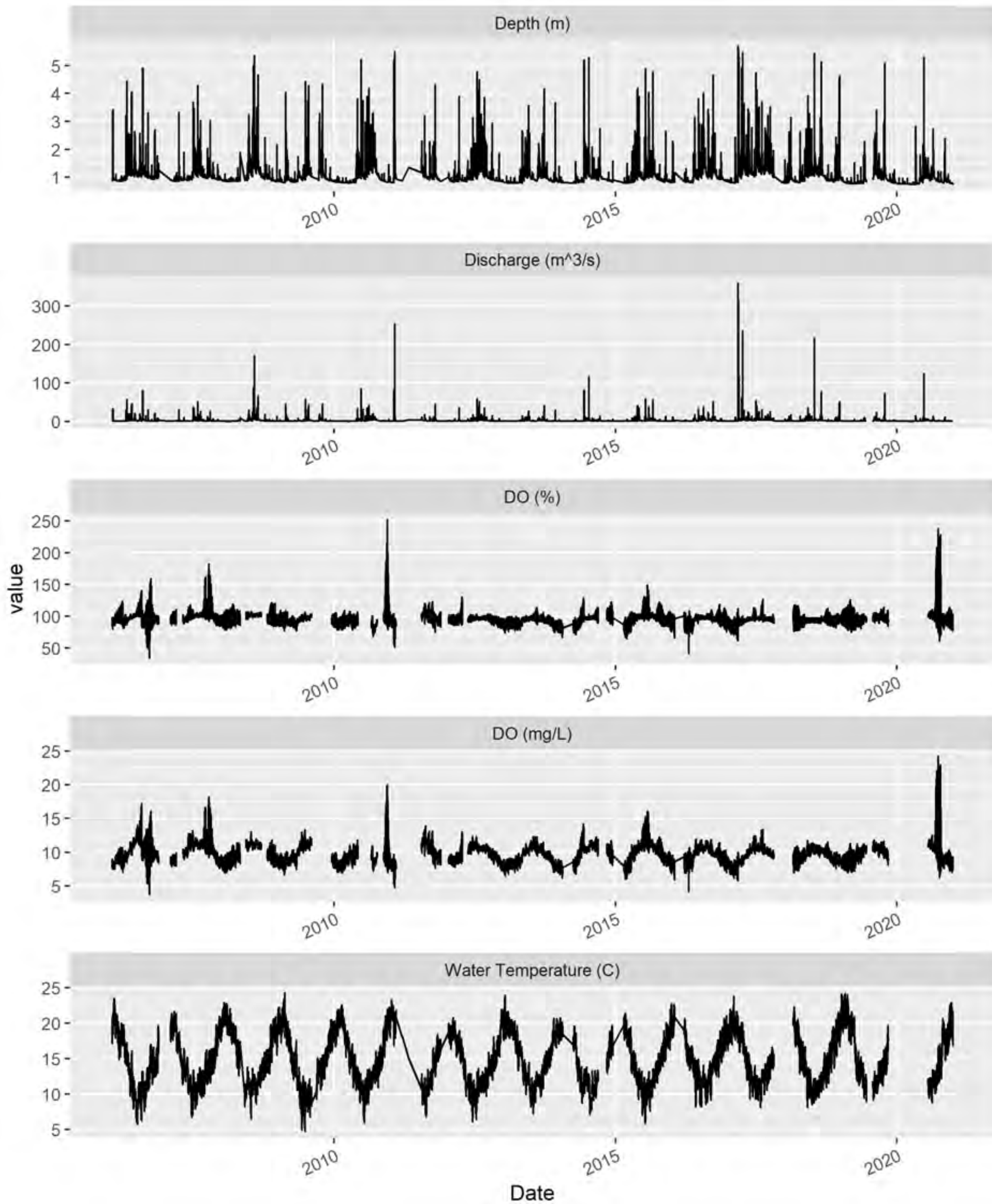
Point change analysis of the long-term trend (shown in black). The red vertical lines show suggested changes on the mean value of the metabolic estimates. The points show the anomaly for each summary data point (data was summarised by season and year).



Wairoa

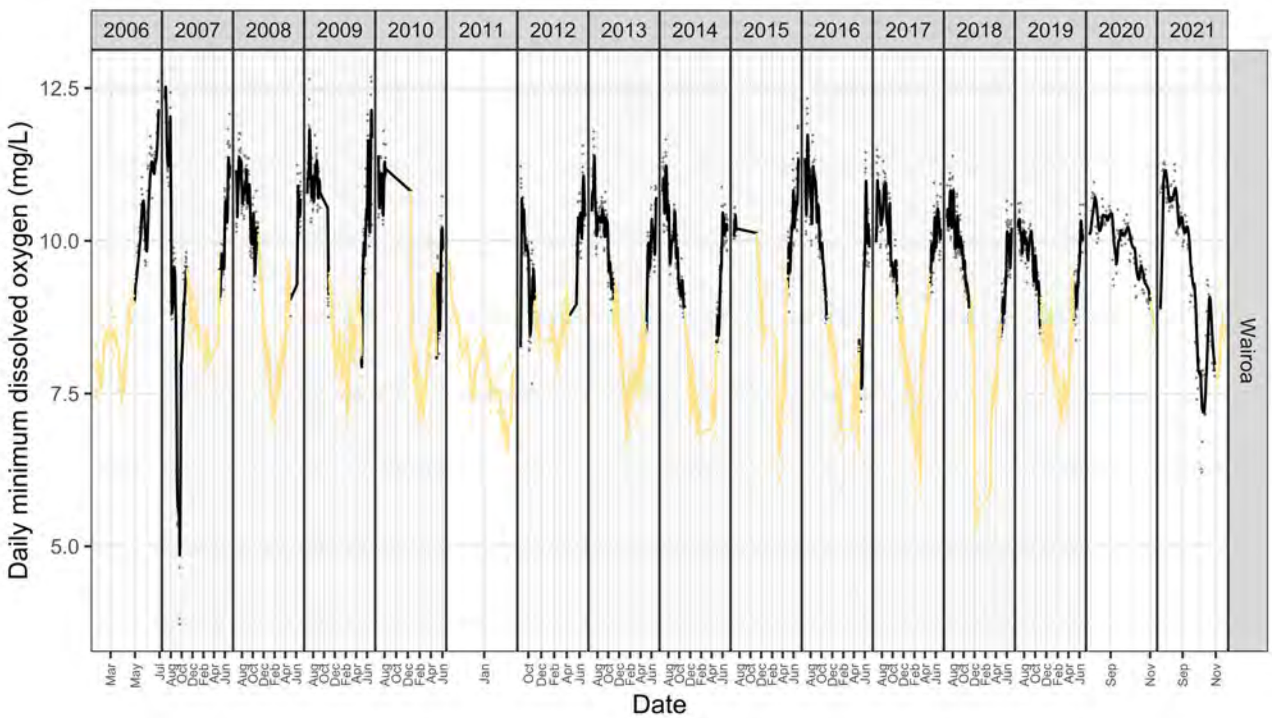
Raw data compilation

Original data Timeseries. Data with QC codes 42 and 43 have been removed.



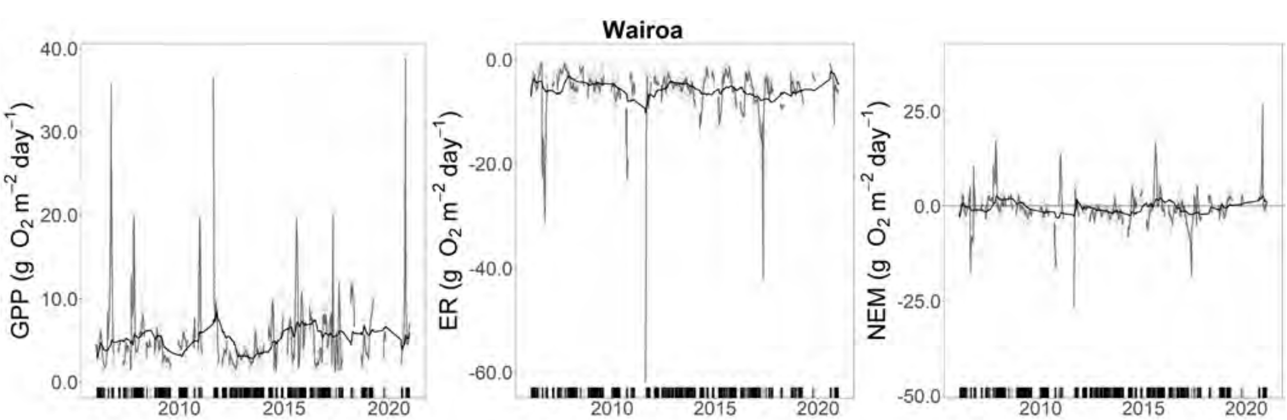
Oxygen data reporting

Timeseries of minimum dissolved oxygen. Points show the daily minimum values, and lines show the 7-day mean value. The summer period is indicated by the colour dots and lines (light yellow), which also correspond with the catchment groupings by land cover (Table 1). Years are hydrological years.

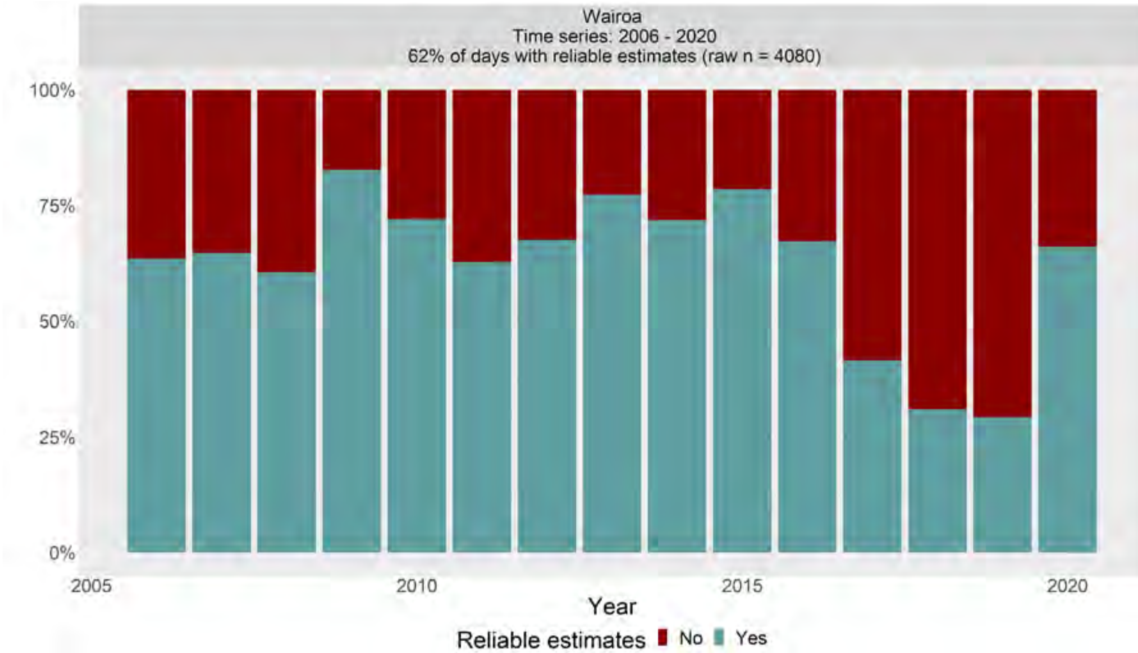


Metabolic estimate calculation

Time series of metabolic estimates (reliable data only)

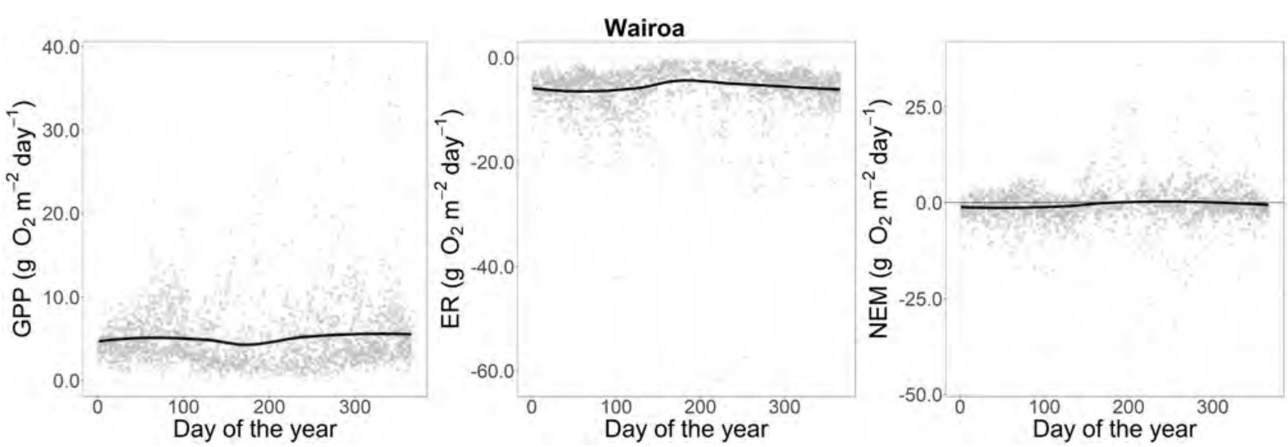


Per cent of days with reliable data based on the results of the metabolic estimates calculations.

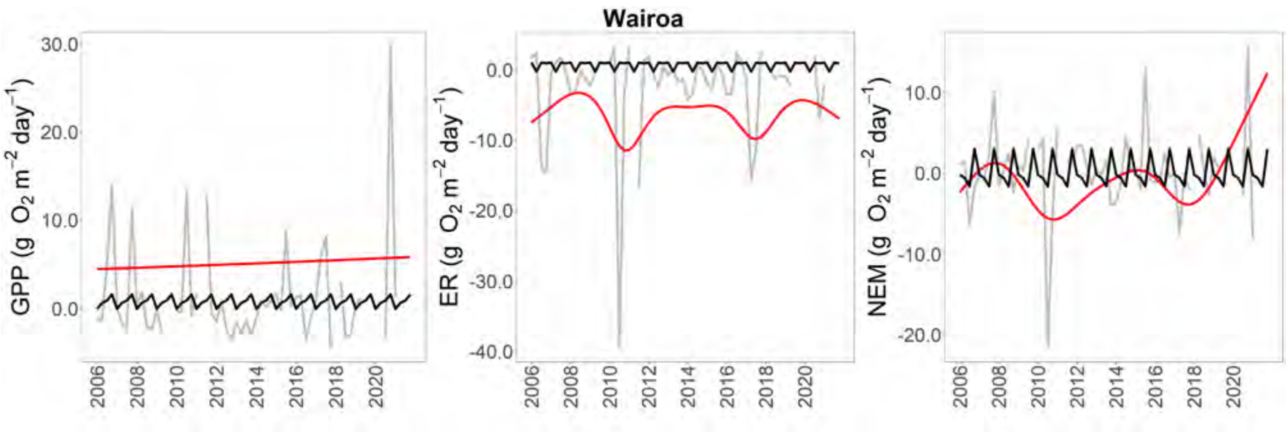


Analysis of metabolic results

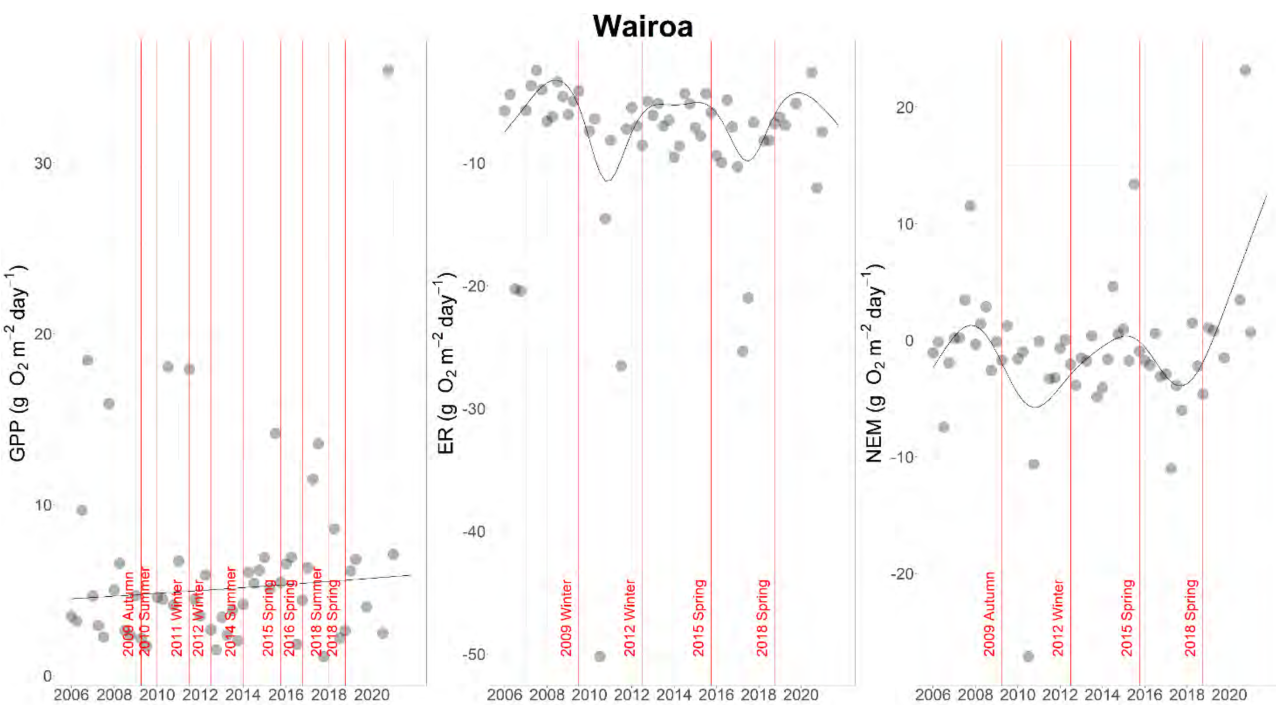
Seasonal distribution of metabolic estimates. One at the starts of the x-axis represents the 1st of January.



Time series decomposition analysis. The red line shows the long-term trend, the black line shows the seasonal component of the trend, and the grey line shows the anomaly.



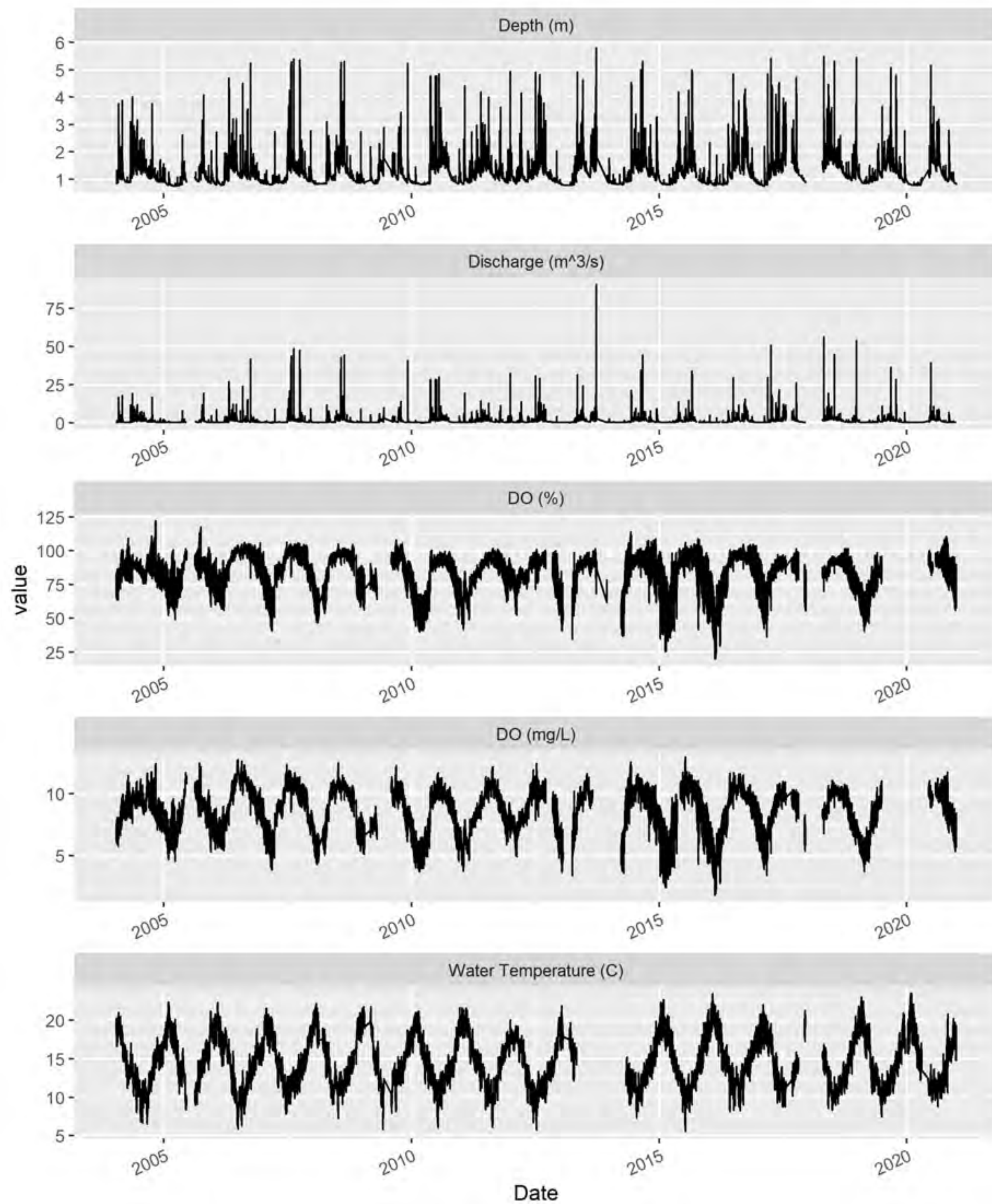
Point change analysis of the long-term trend (shown in black). The red vertical lines show suggested changes on the mean value of the metabolic estimates. The points show the anomaly for each summary data point (data was summarised by season and year).



Ararimu

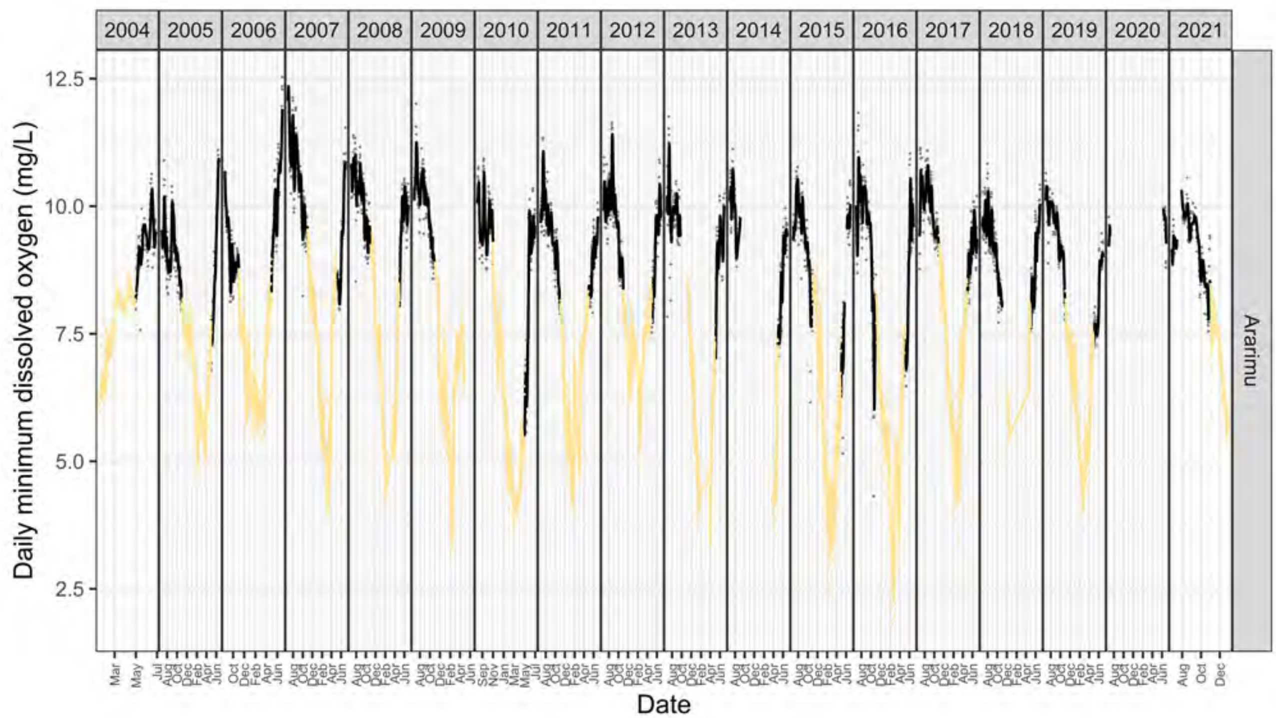
Raw data compilation

Original data Timeseries. Data with QC codes 42 and 43 have been removed.



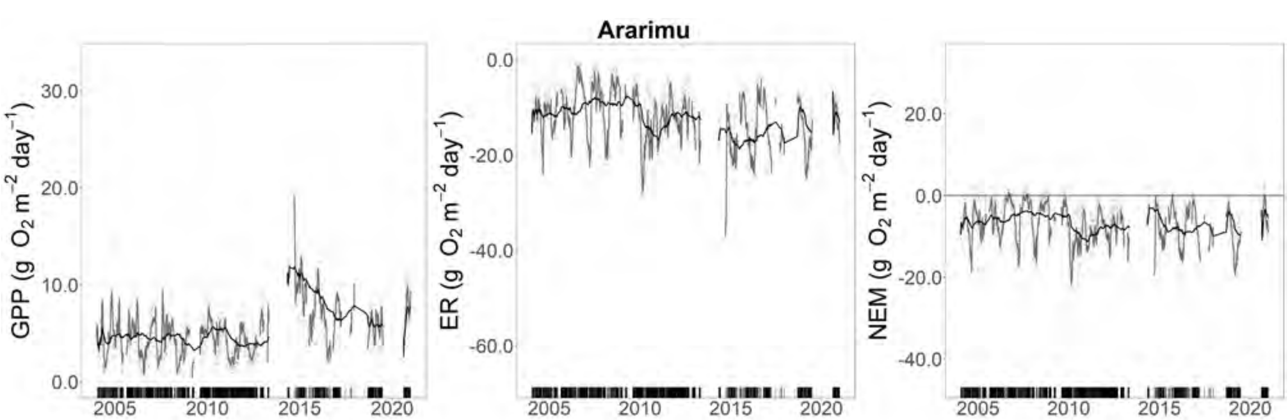
Oxygen data reporting

Timeseries of minimum dissolved oxygen. Points show the daily minimum values, and lines show the 7-day mean value. The summer period is indicated by the colour dots and lines (light yellow), which also correspond with the catchment groupings by land cover (Table 1). Years are hydrological years.

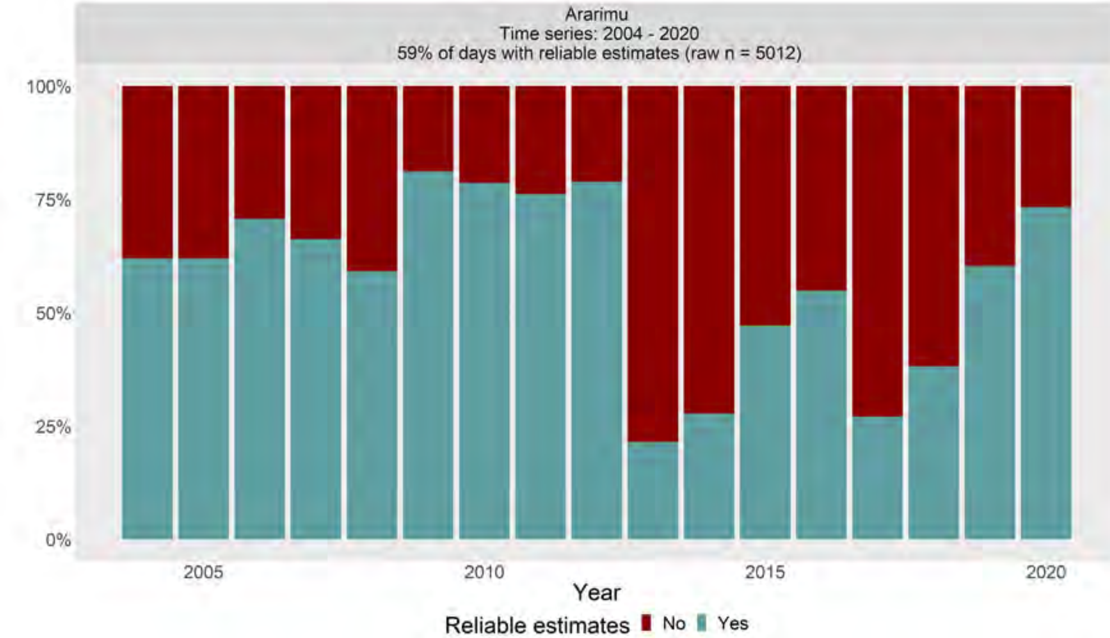


Metabolic estimate calculation

Time series of metabolic estimates (reliable data only)

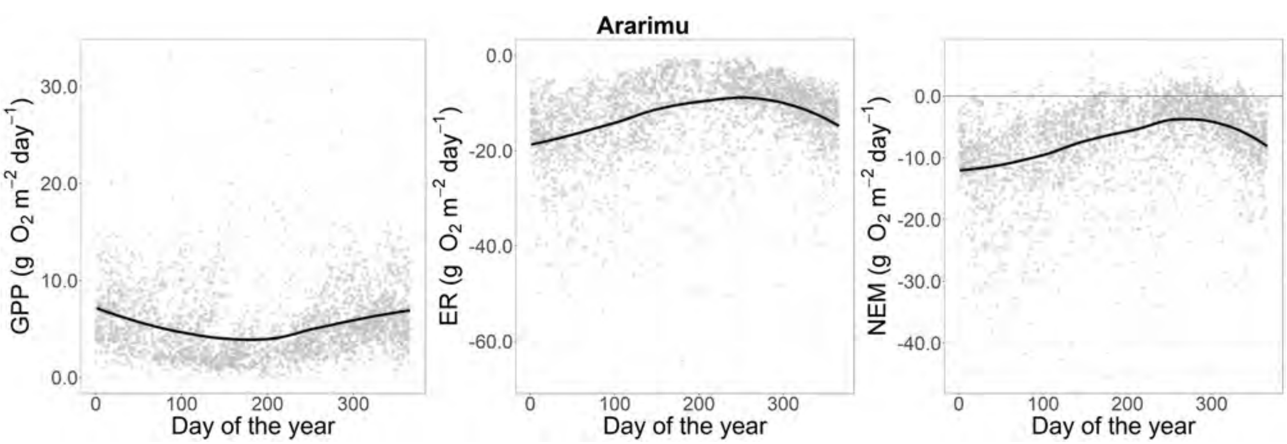


Per cent of days with reliable data based on the results of the metabolic estimates calculations.

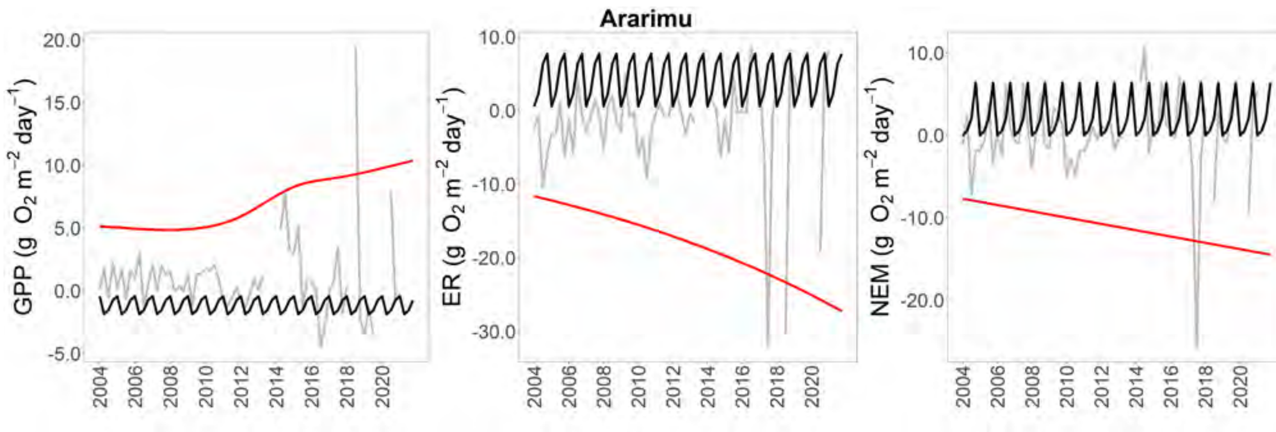


Analysis of metabolic results

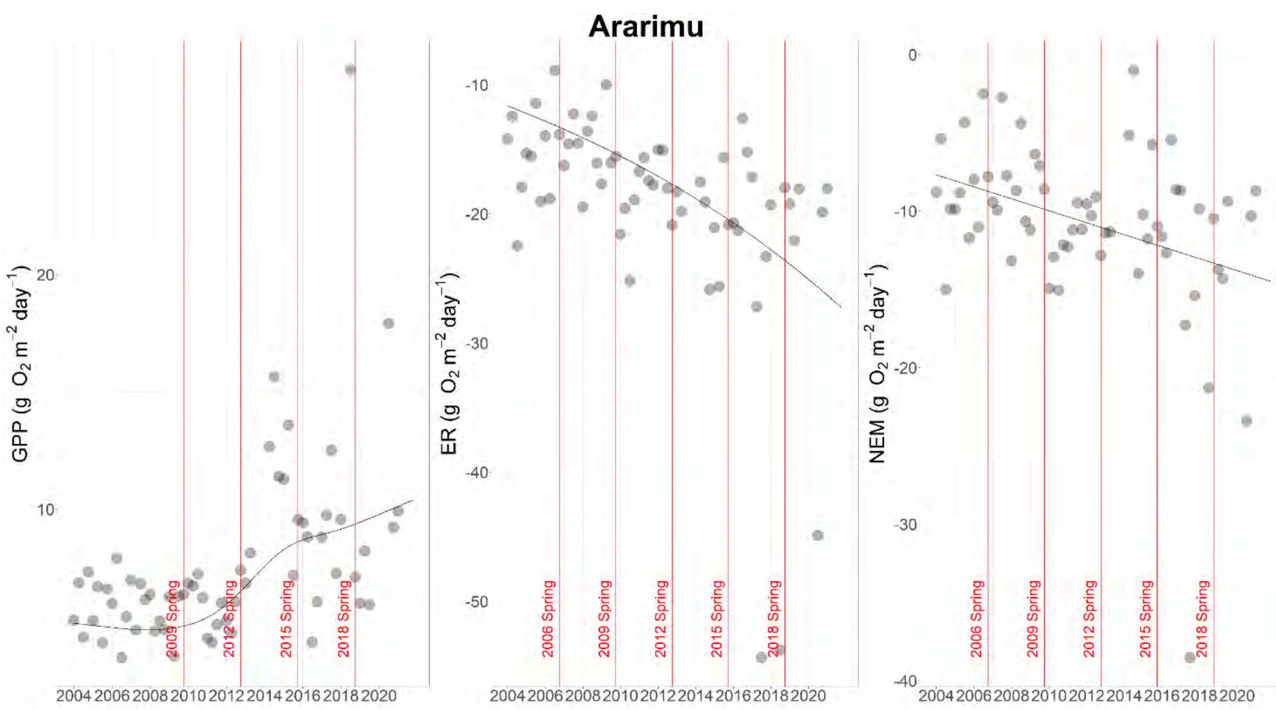
Seasonal distribution of metabolic estimates. One at the starts of the x-axis represents the 1st of January.



Time series decomposition analysis. The red line shows the long-term trend, the black line shows the seasonal component of the trend, and the grey line shows the anomaly.



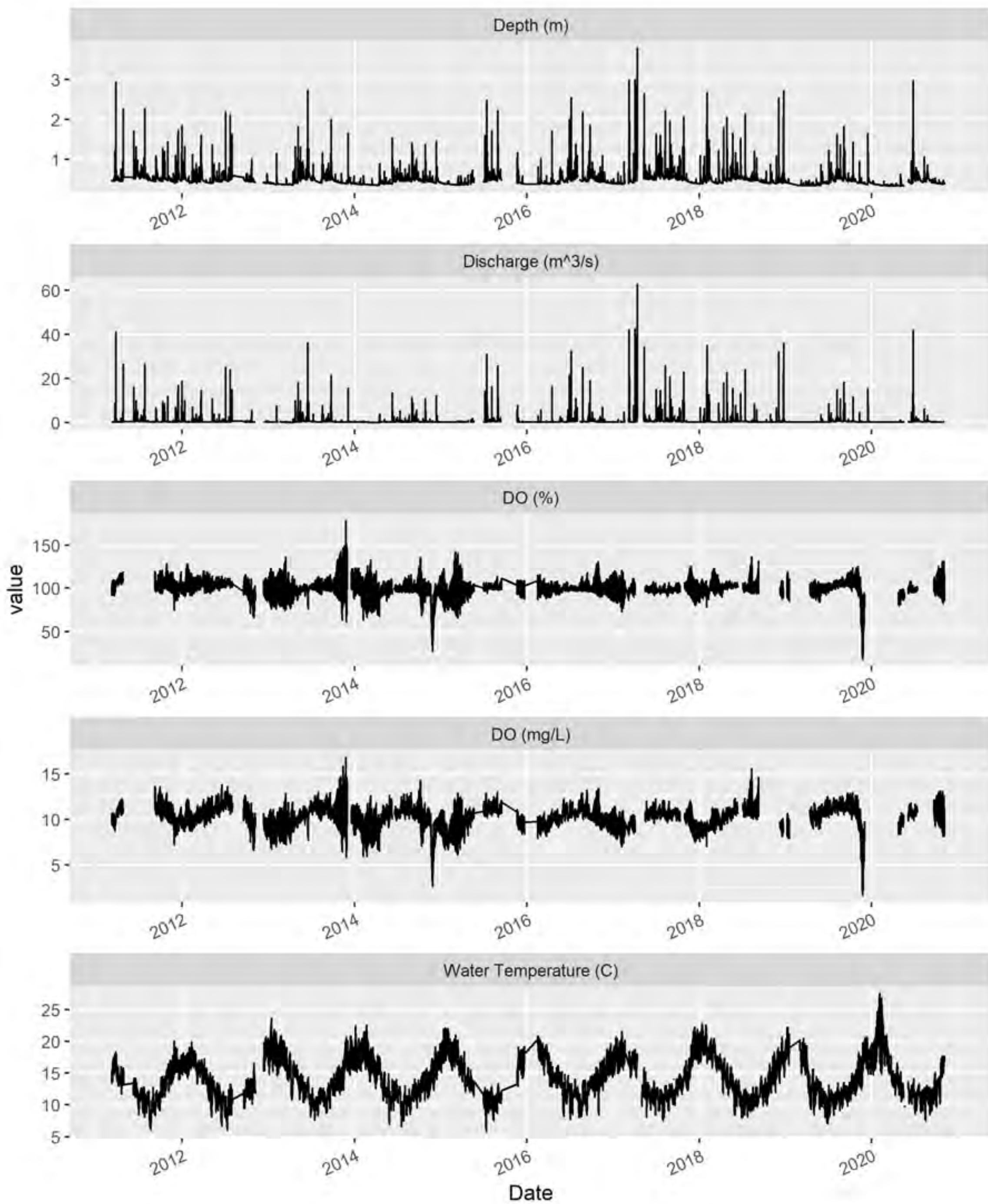
Point change analysis of the long-term trend (shown in black). The red vertical lines show suggested changes on the mean value of the metabolic estimates. The points show the anomaly for each summary data point (data was summarised by season and year).



Opanuku

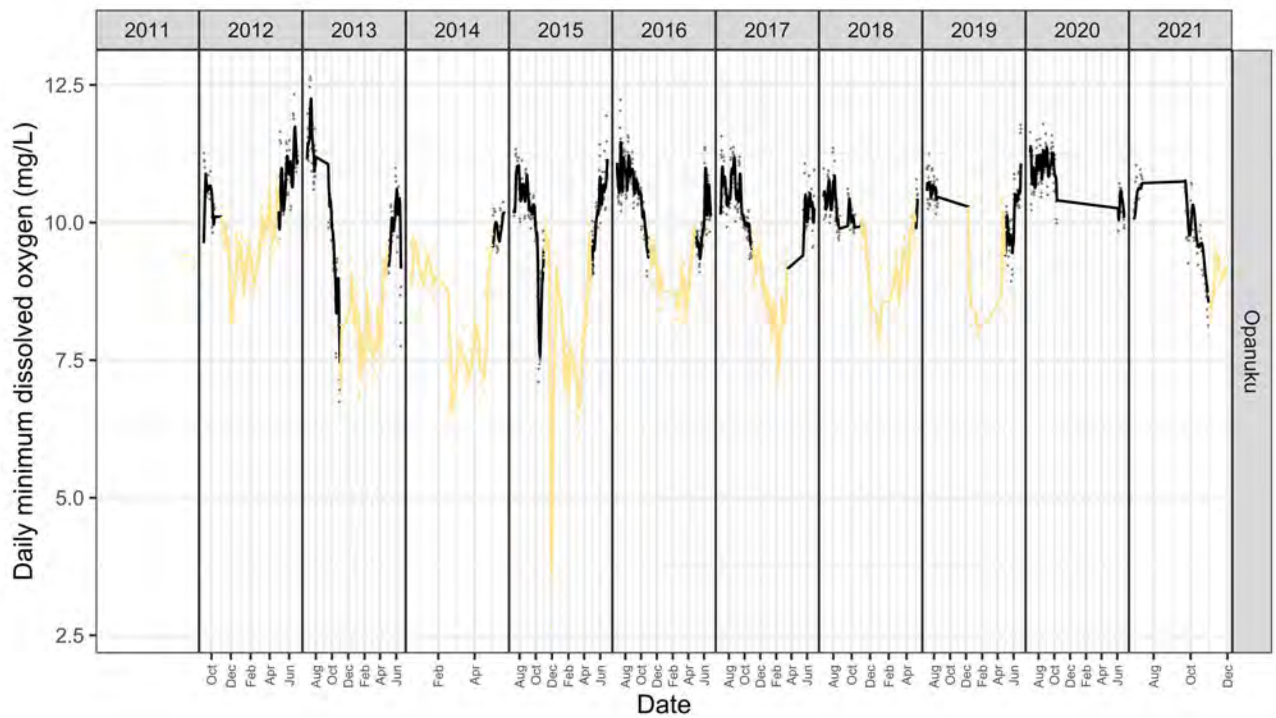
Raw data compilation

Original data Timeseries. Data with QC codes 42 and 43 have been removed.



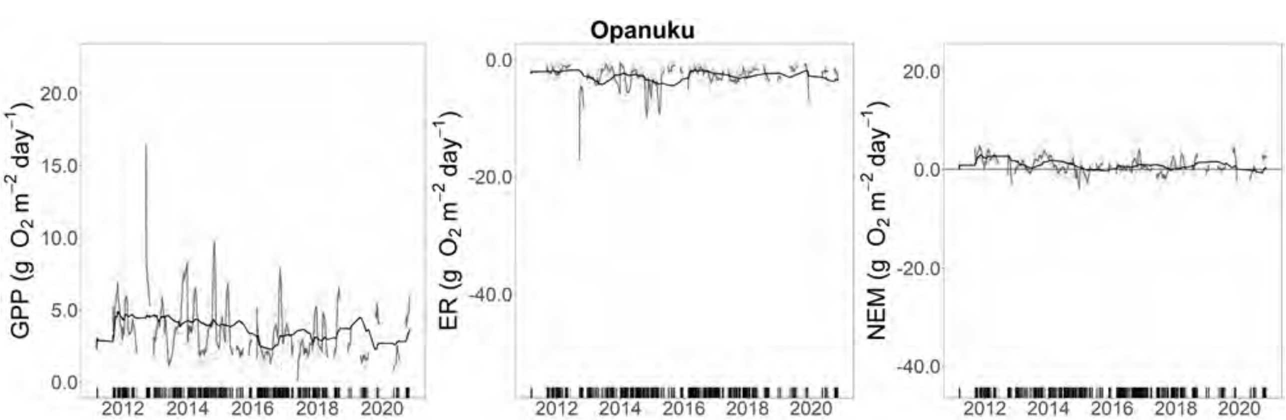
Oxygen data reporting

Timeseries of minimum dissolved oxygen. Points show the daily minimum values, and lines show the 7-day mean value. The summer period is indicated by the colour dots and lines (light yellow), which also correspond with the catchment groupings by land cover (Table 1). Years are hydrological years.

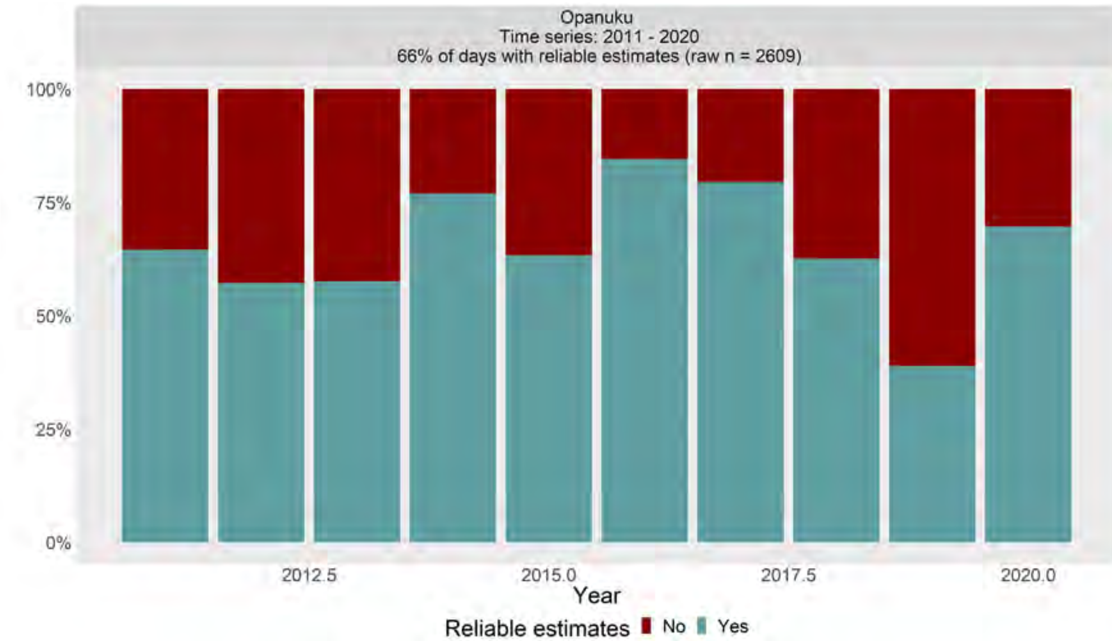


Metabolic estimate calculation

Time series of metabolic estimates (reliable data only)

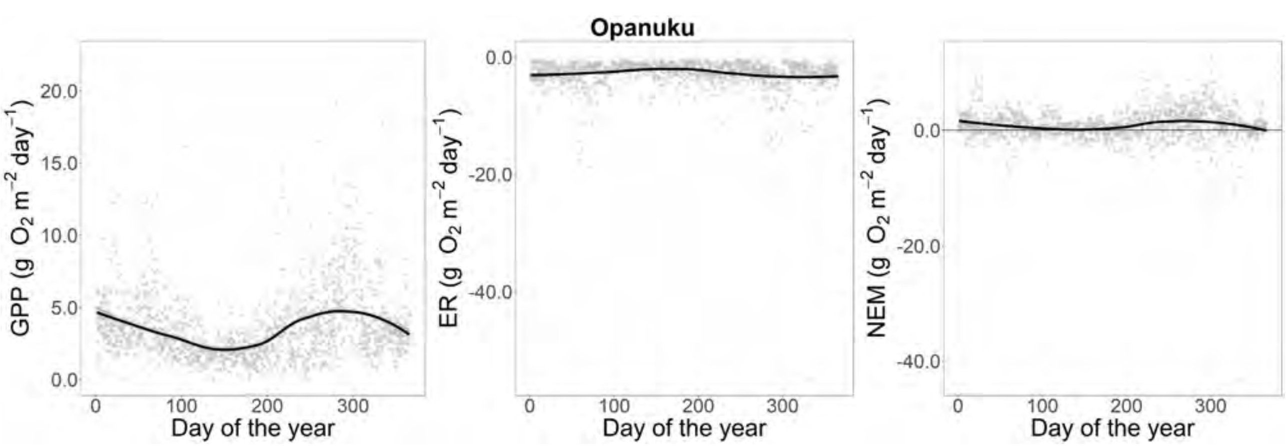


Per cent of days with reliable data based on the results of the metabolic estimates calculations.

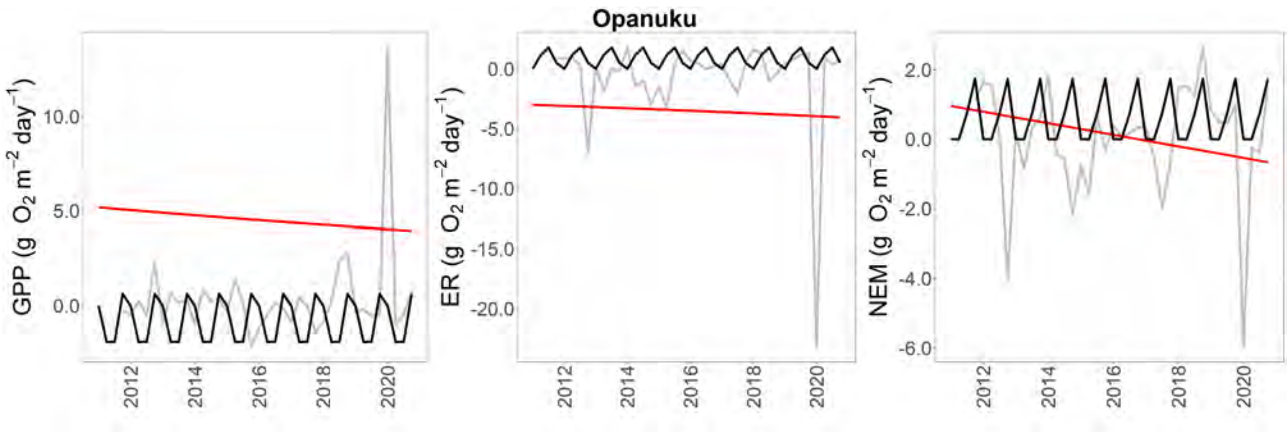


Analysis of metabolic results

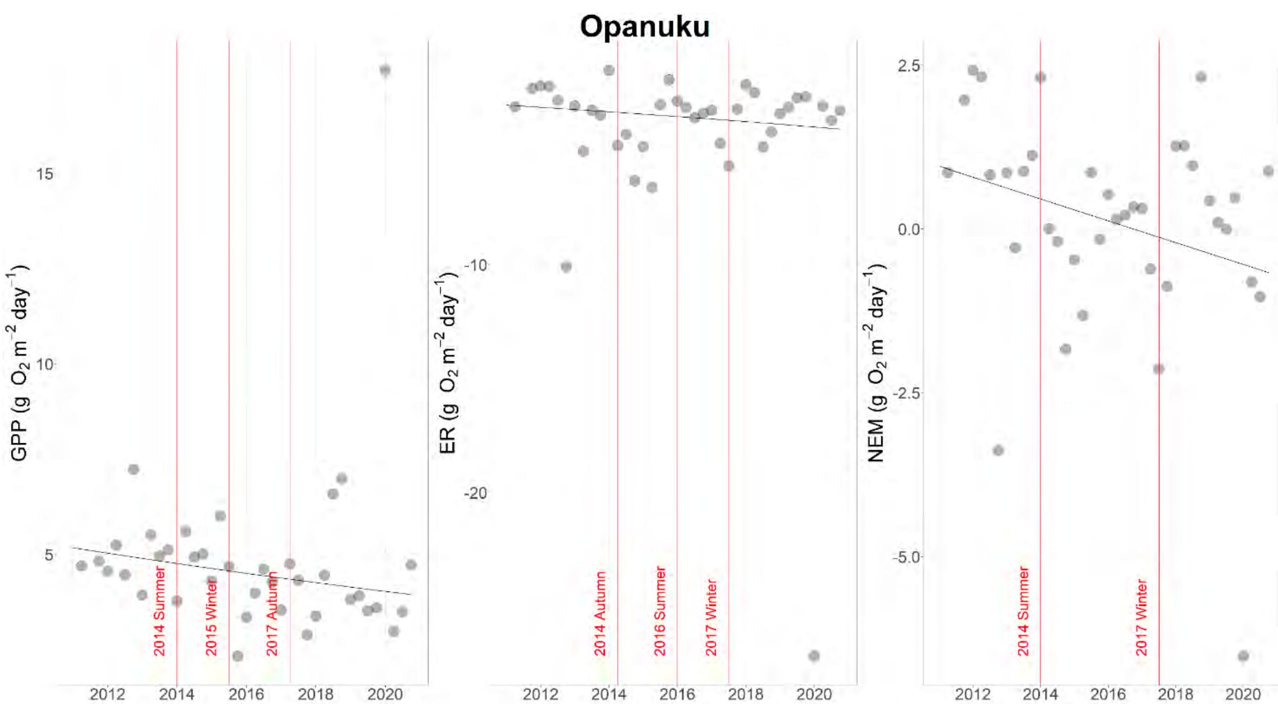
Seasonal distribution of metabolic estimates. One at the starts of the x-axis represents the 1st of January.



Time series decomposition analysis. The red line shows the long term trend, the black line shows the seasonal component of the trend, and the grey line shows the anomaly.



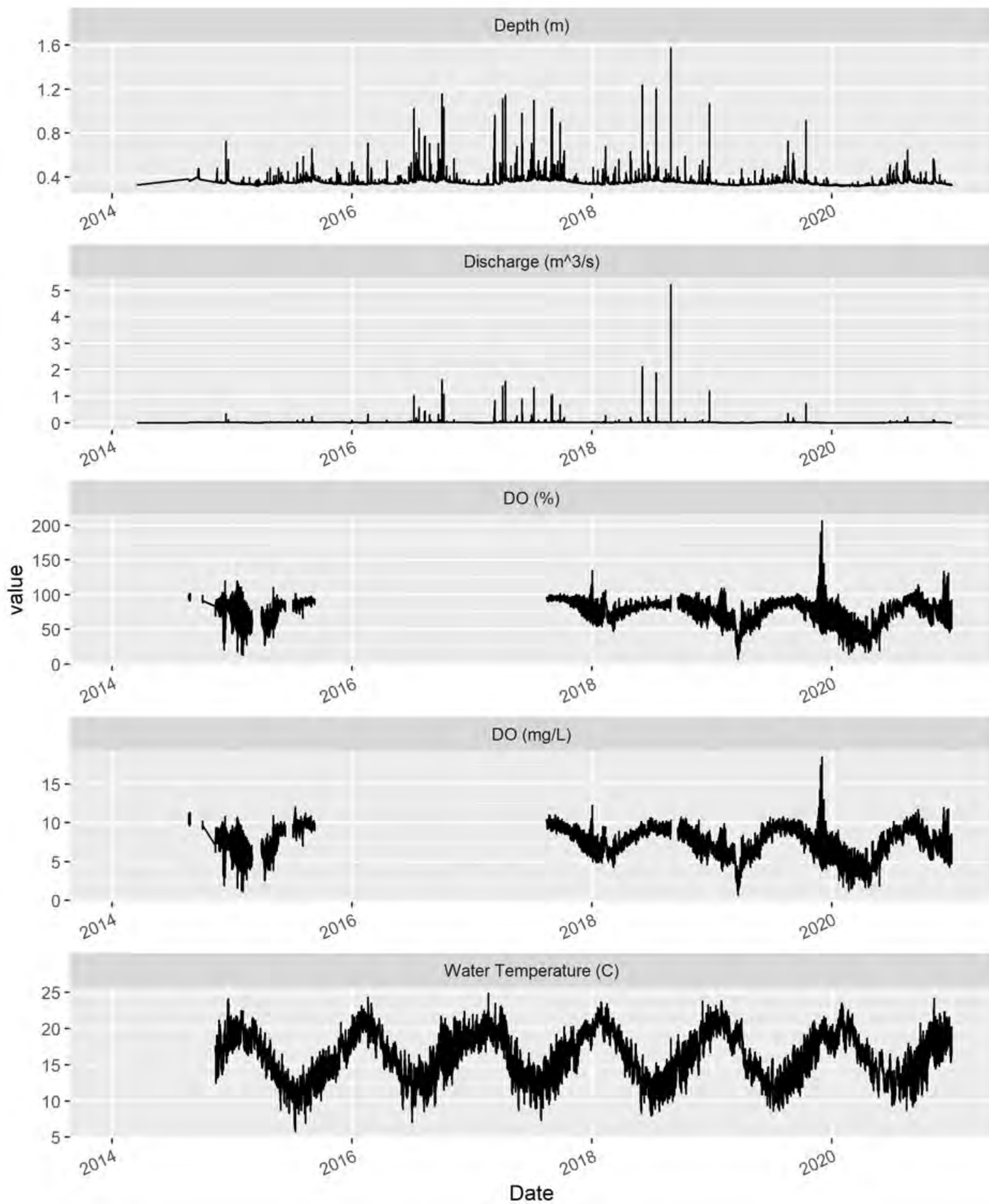
Point change analysis of the long-term trend (shown in black). The red vertical lines show suggested changes on the mean value of the metabolic estimates. The points show the anomaly for each summary data point (data was summarised by season and year).



Te Muri

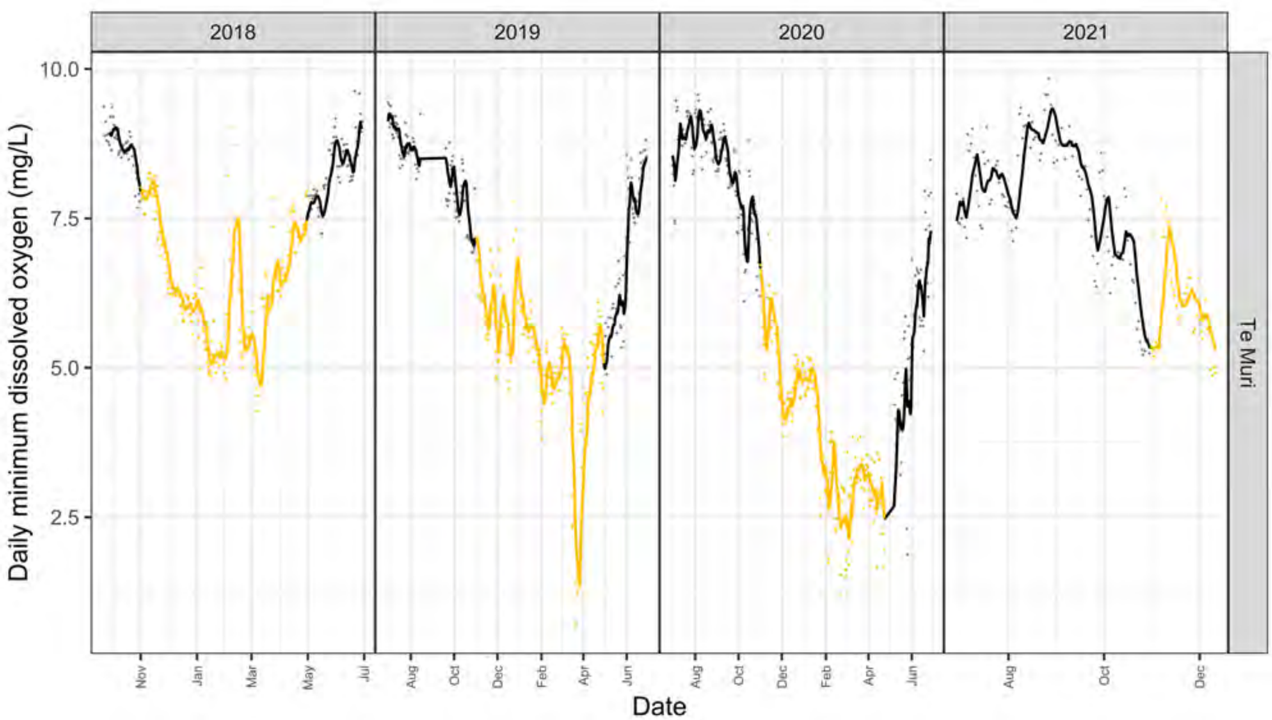
Raw data compilation

Original data Timeseries. Data with QC codes 42 and 43 have been removed.



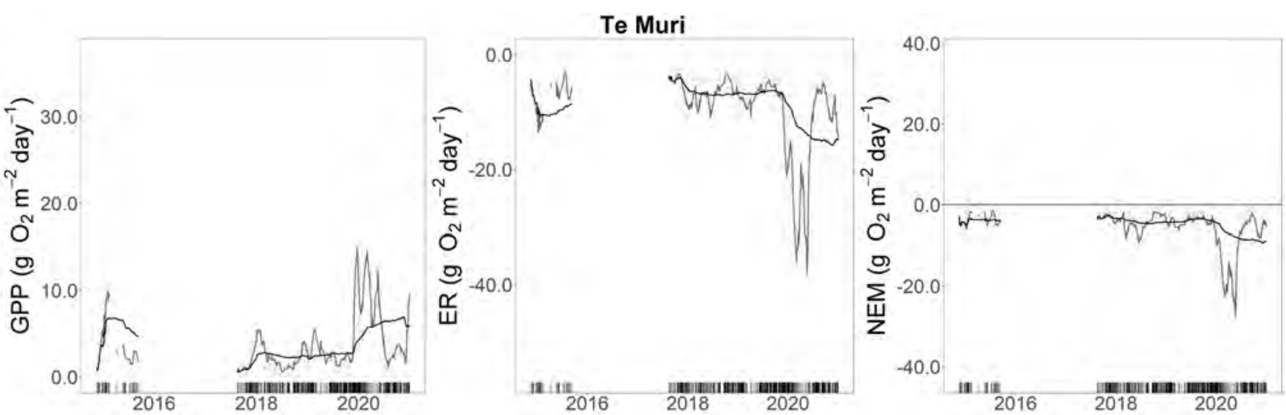
Oxygen data reporting

Timeseries of minimum dissolved oxygen. Points show the daily minimum values, and lines show the 7-day mean value. The summer period is indicated by the colour dots and lines (yellow), which also correspond with the catchment groupings by land cover (Table 1). Years are hydrological years.

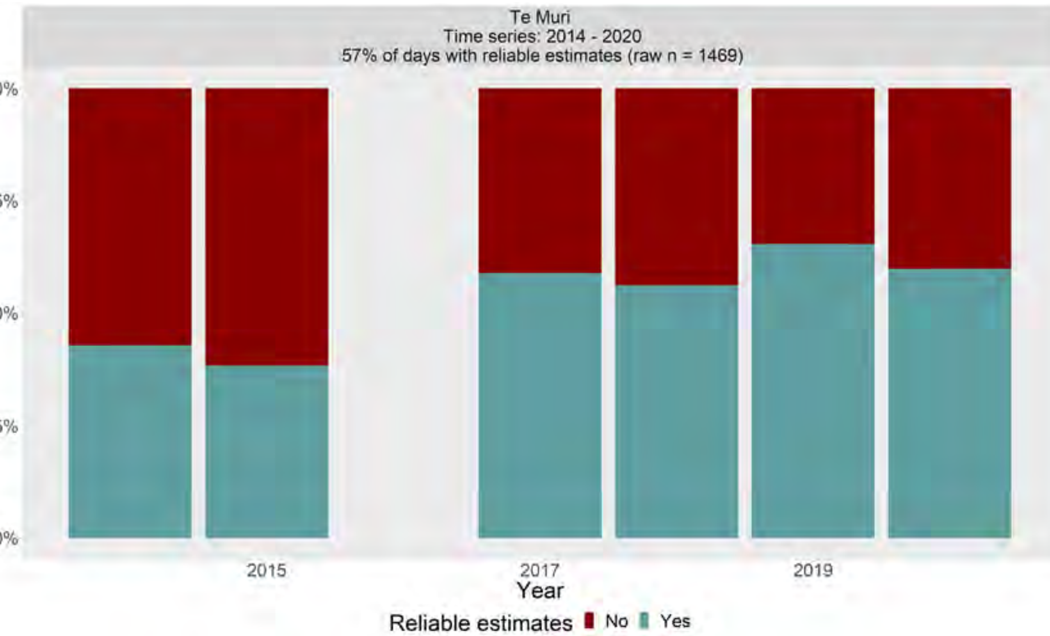


Metabolic estimate calculation

Time series of metabolic estimates (reliable data only)

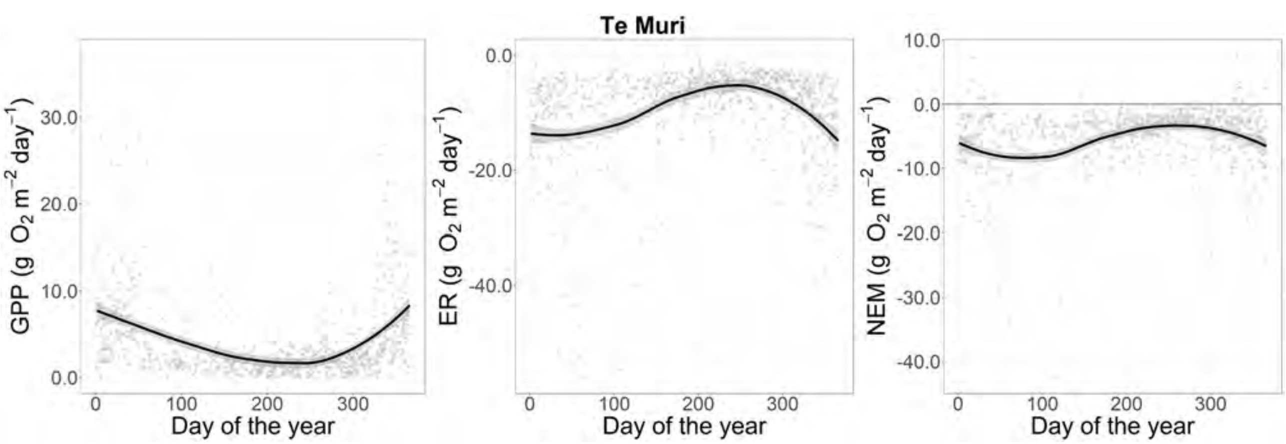


Per cent of days with reliable data based on the results of the metabolic estimates calculations.

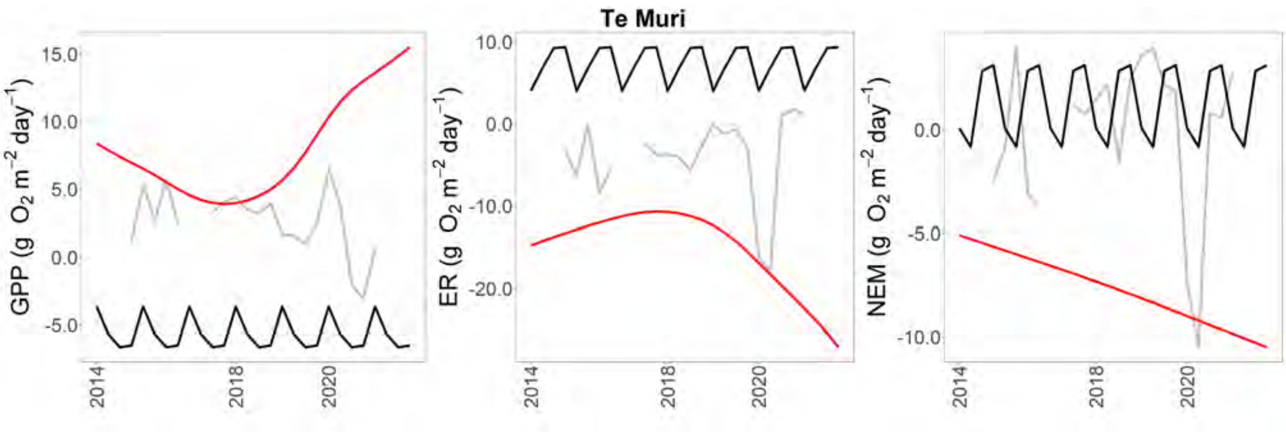


Analysis of metabolic results

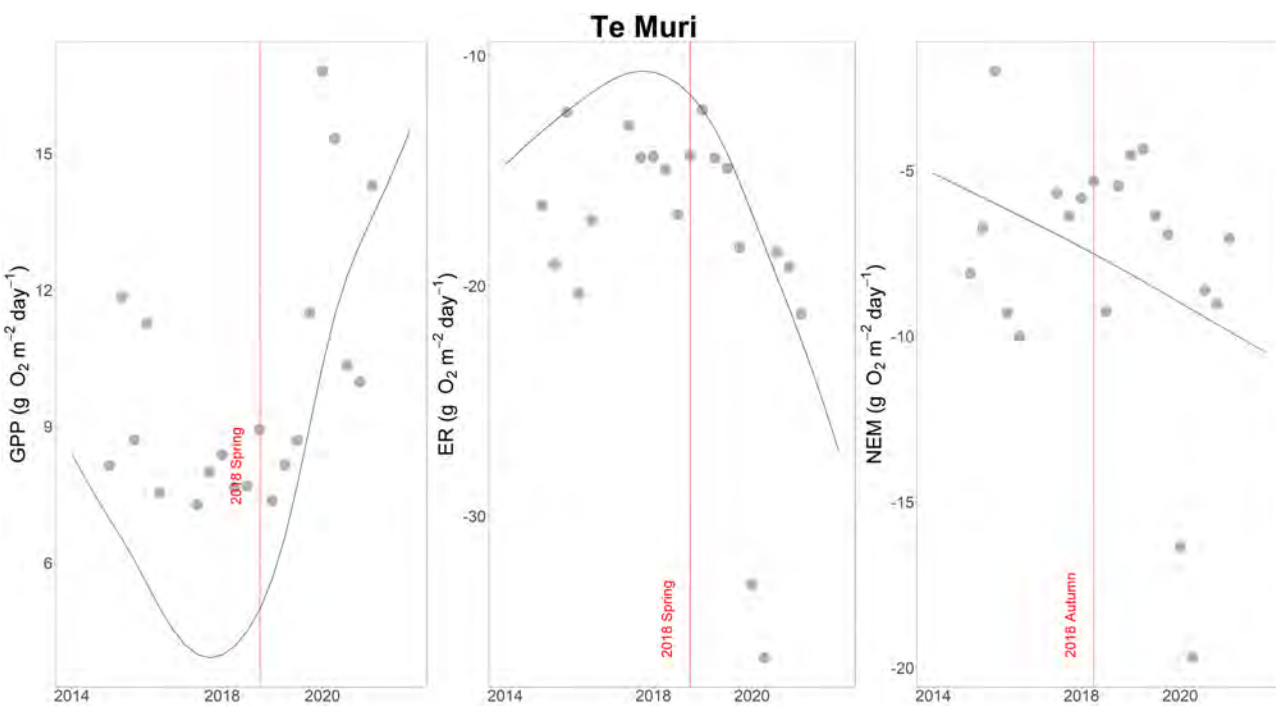
Seasonal distribution of metabolic estimates. One at the starts of the x-axis represents the 1st of January.



Time series decomposition analysis. The red line shows the long-term trend, the black line shows the seasonal component of the trend, and the grey line shows the anomaly.



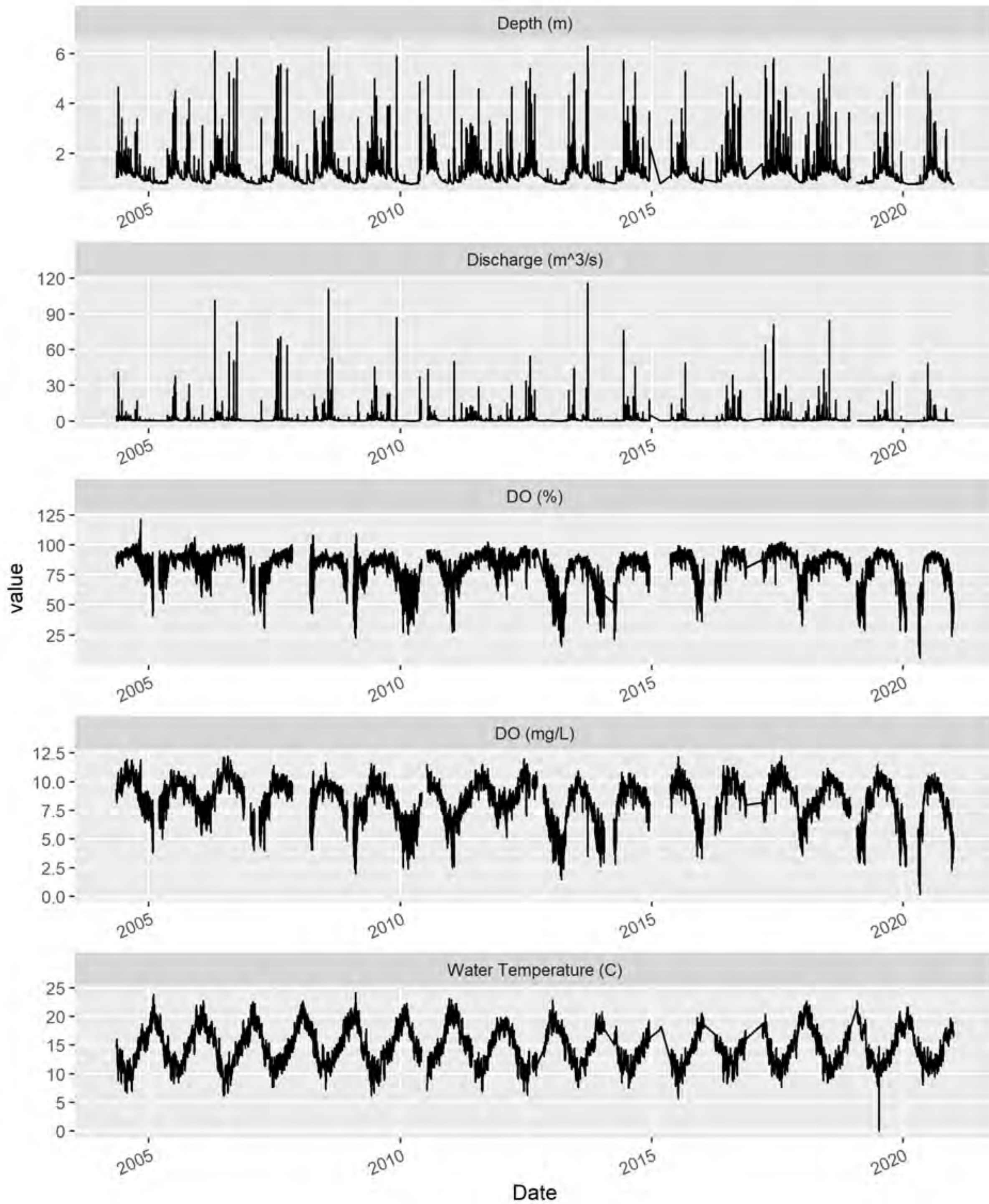
Point change analysis of the long-term trend (shown in black). The red vertical lines show suggested changes on the mean value of the metabolic estimates. The points show the anomaly for each summary data point (data was summarised by season and year).



Kaukapakapa

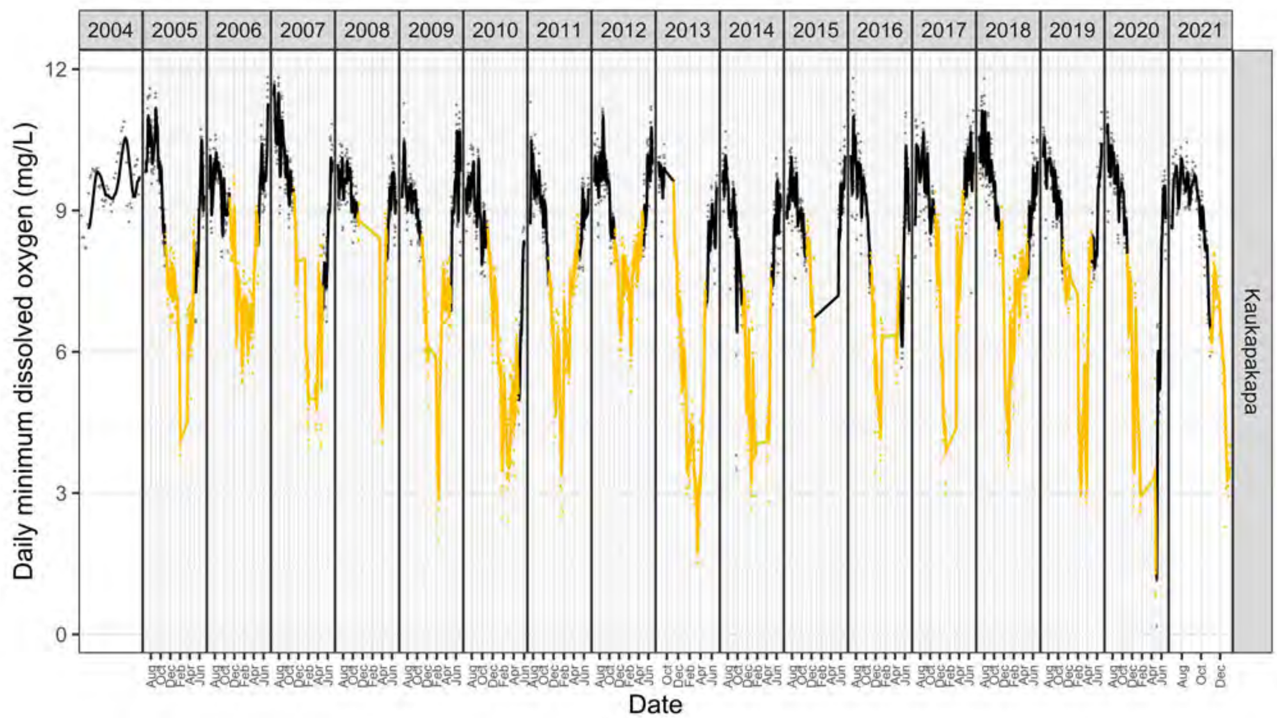
Raw data compilation

Original data Timeseries. Data with QC codes 42 and 43 have been removed.



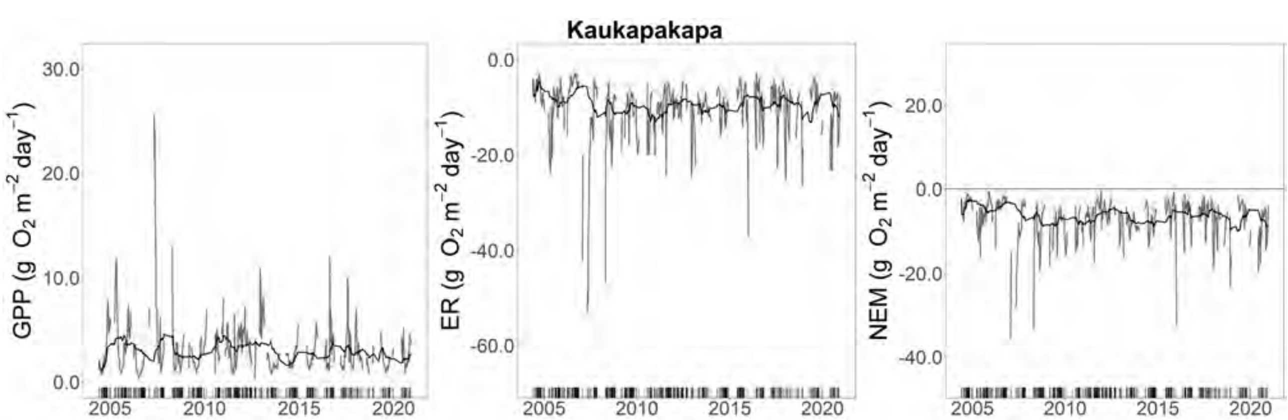
Oxygen data reporting

Timeseries of minimum dissolved oxygen. Points show the daily minimum values, and lines show the 7-day mean value. The summer period is indicated by the colour dots and lines (yellow), which also correspond with the catchment groupings by land cover (Table 1). Years are hydrological years.

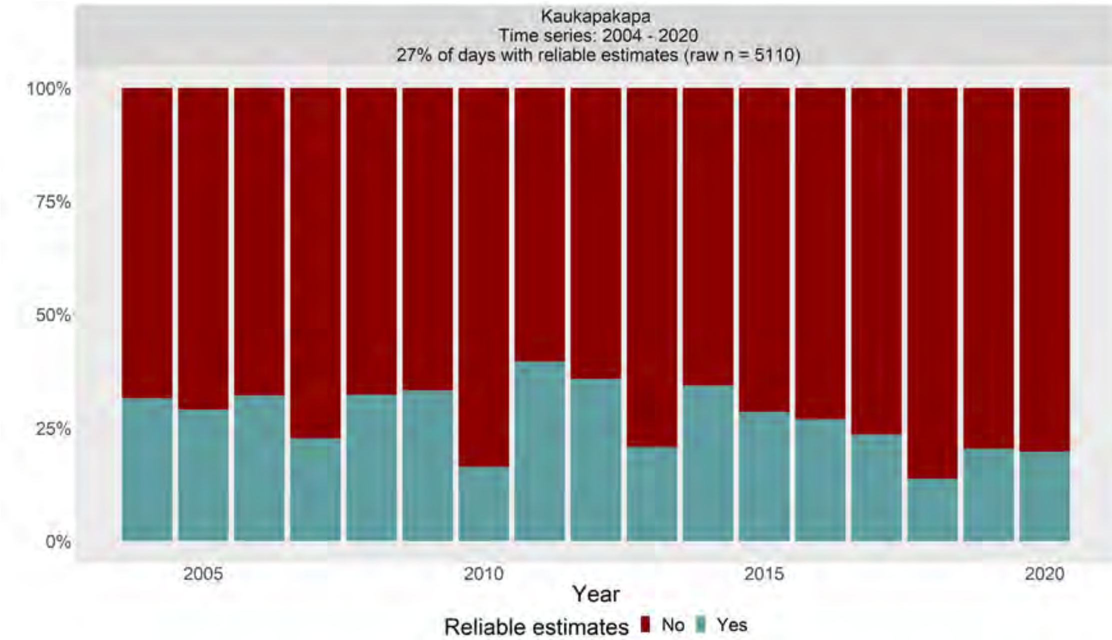


Metabolic estimate calculation

Time series of metabolic estimates (reliable data only)

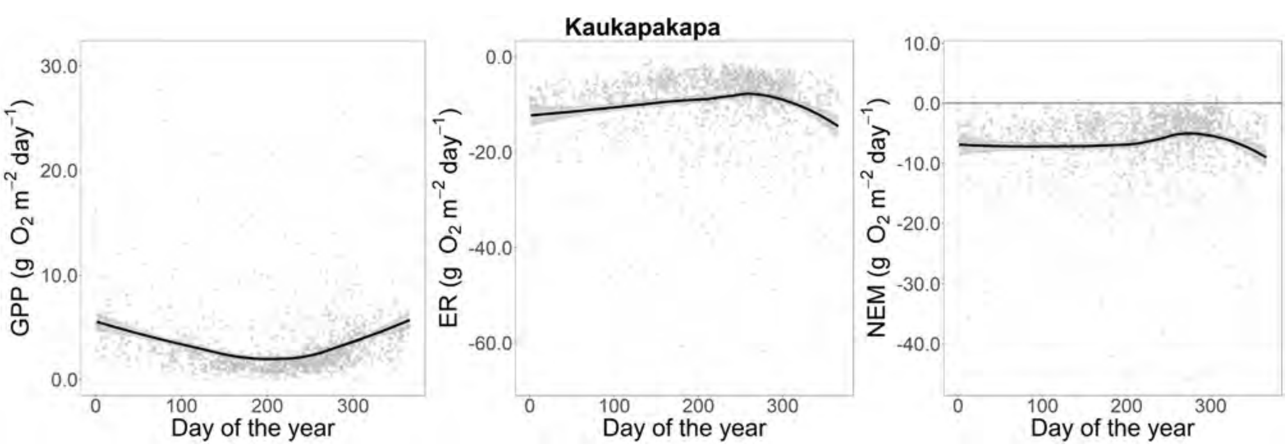


Per cent of days with reliable data based on the results of the metabolic estimates calculations.

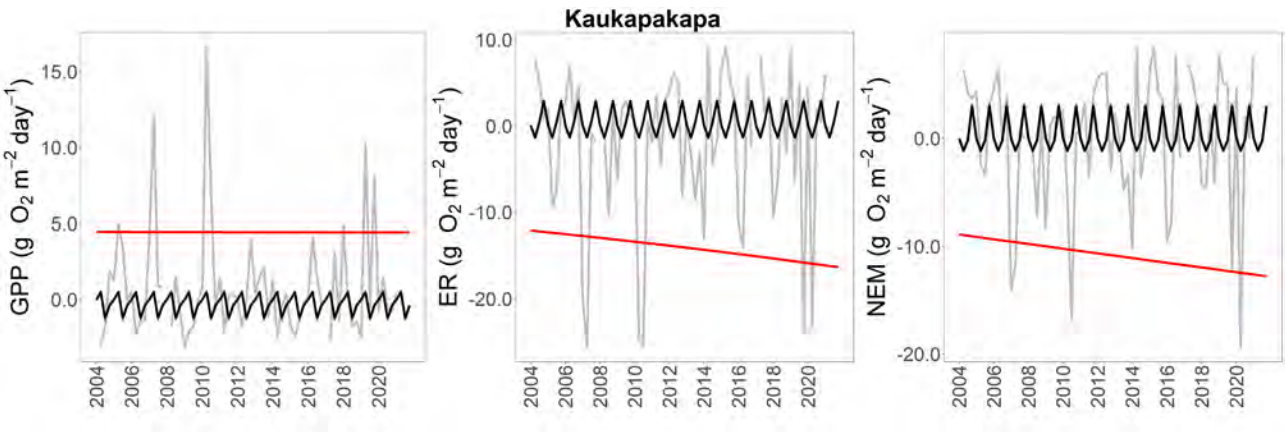


Analysis of metabolic results

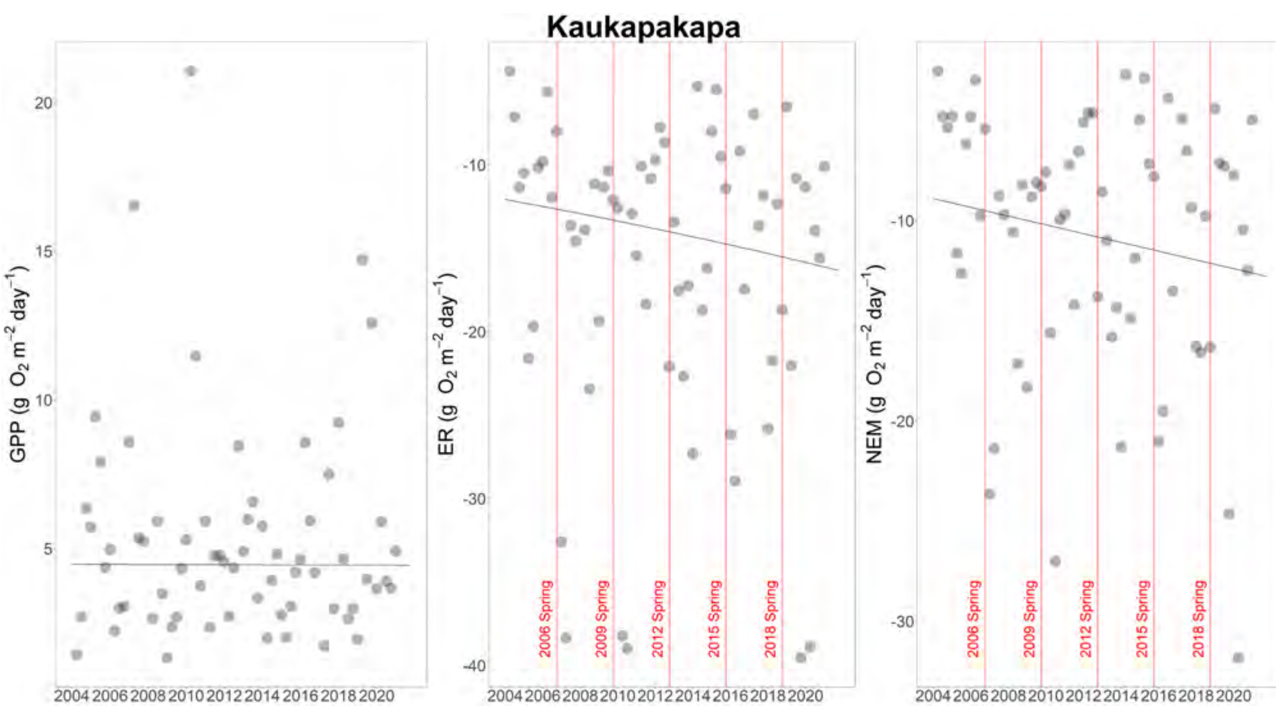
Seasonal distribution of metabolic estimates. One at the starts of the x-axis represents the 1st of January.



Time series decomposition analysis. The red line shows the long term trend, the black line shows the seasonal component of the trend, and the grey line shows the anomaly.



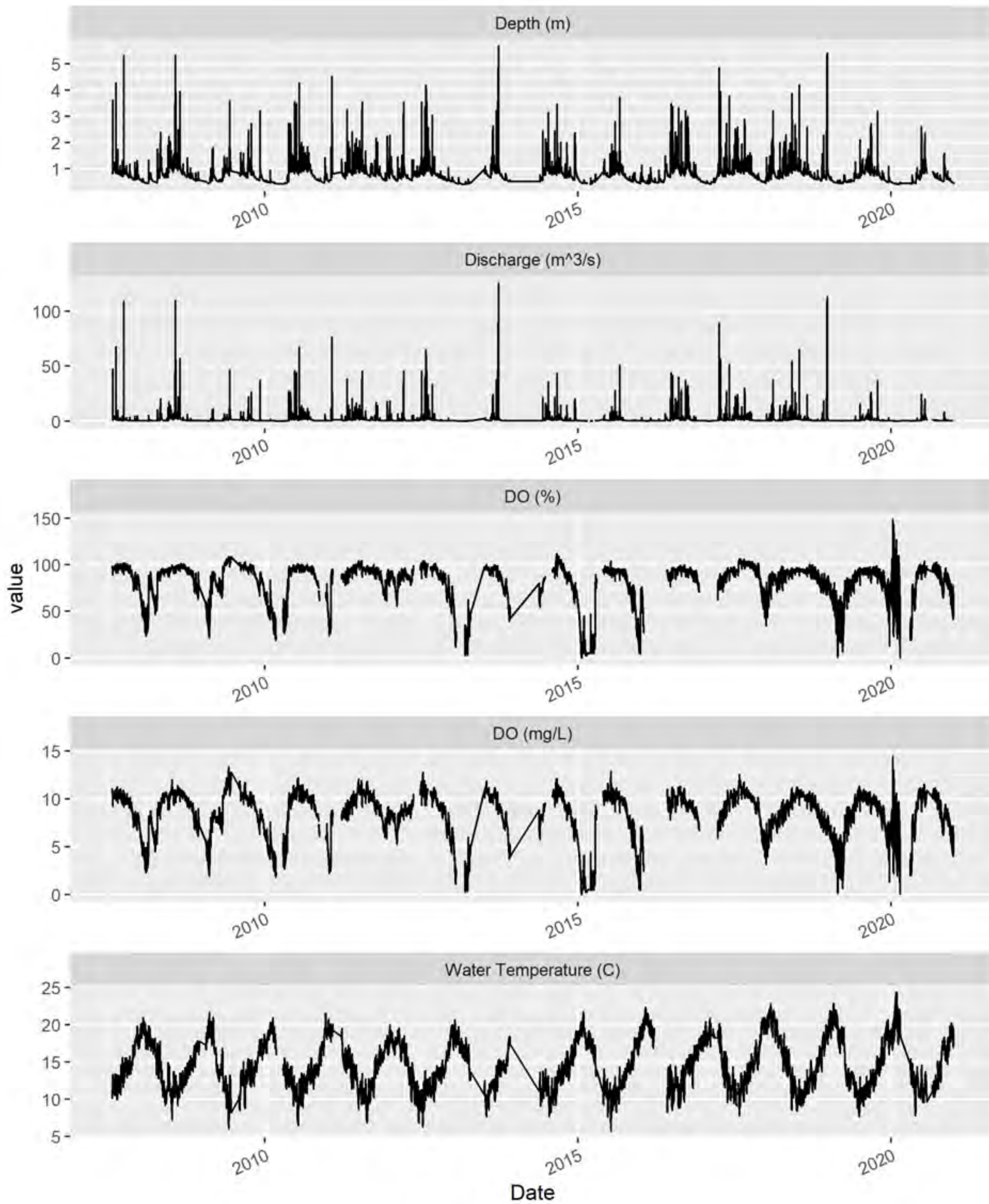
Point change analysis of the long-term trend (shown in black). The red vertical lines show suggested changes on the mean value of the metabolic estimates. The points show the anomaly for each summary data point (data was summarised by season and year).



Rangitopuni

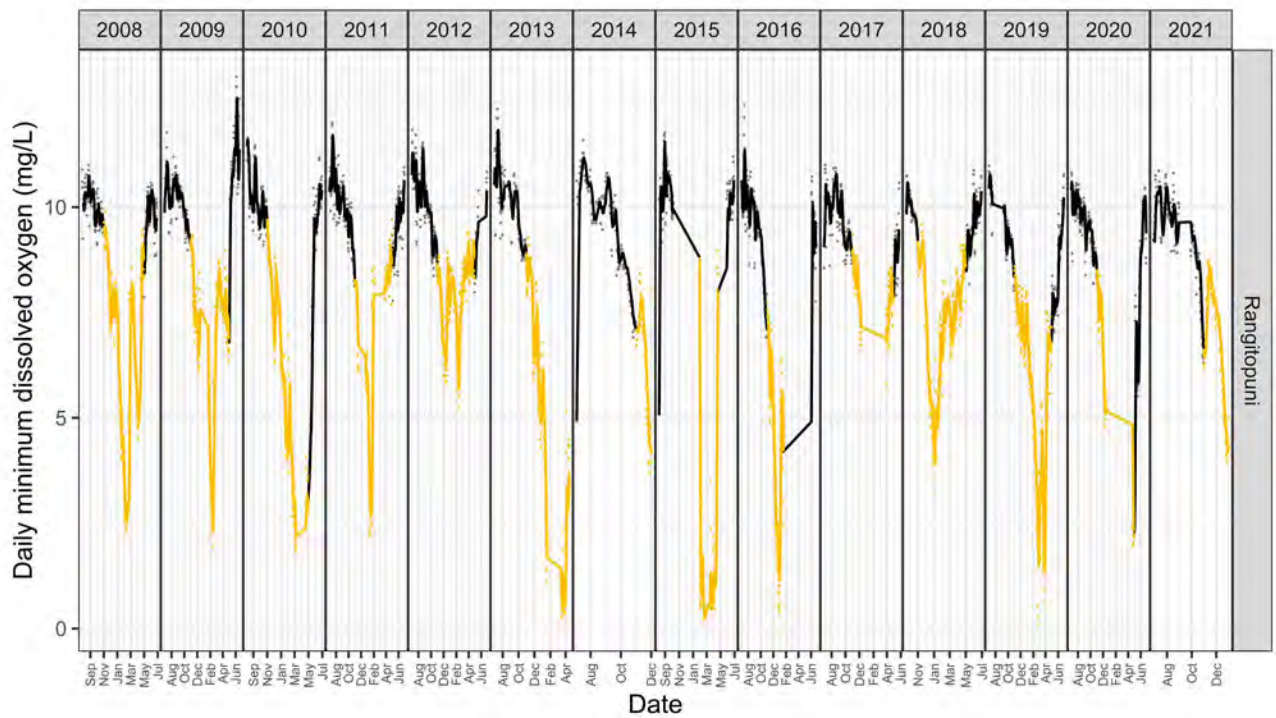
Raw data compilation

Original data Timeseries. Data with QC codes 42 and 43 have been removed.



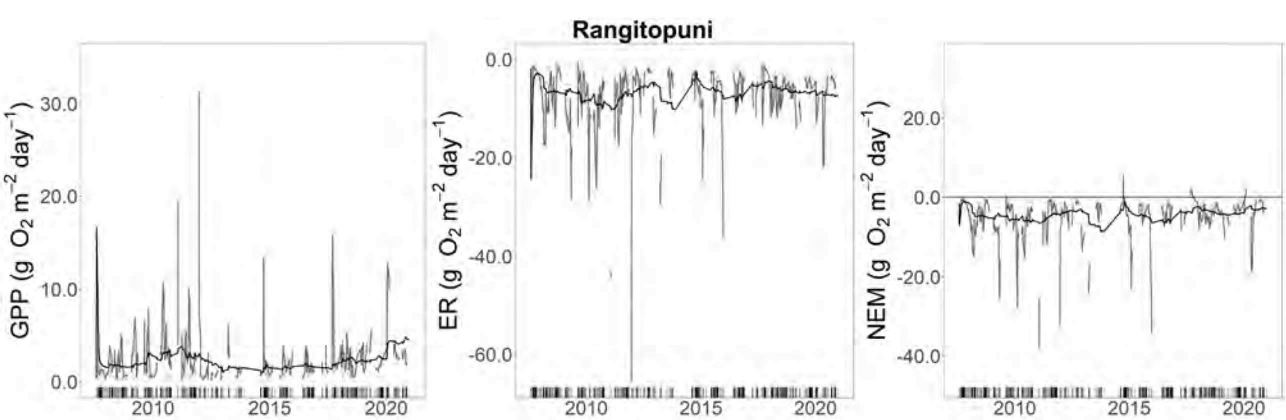
Oxygen data reporting

Timeseries of minimum dissolved oxygen. Points show the daily minimum values, and lines show the 7-day mean value. The summer period is indicated by the colour dots and lines (yellow), which also correspond with the catchment groupings by land cover (Table 1). Years are hydrological years.

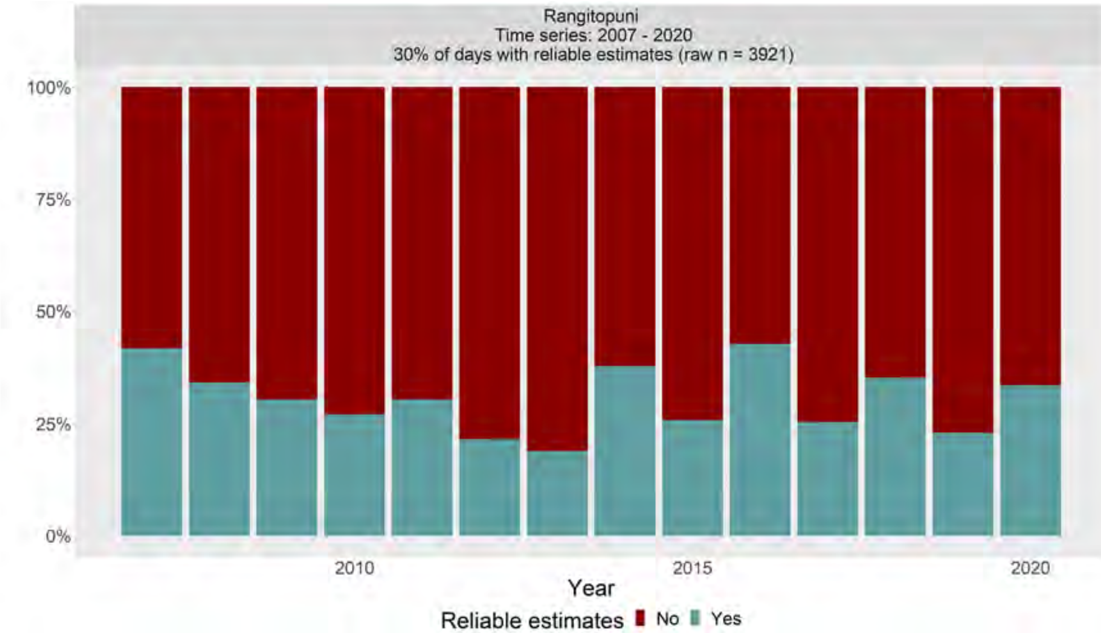


Metabolic estimate calculation

Time series of metabolic estimates (reliable data only)

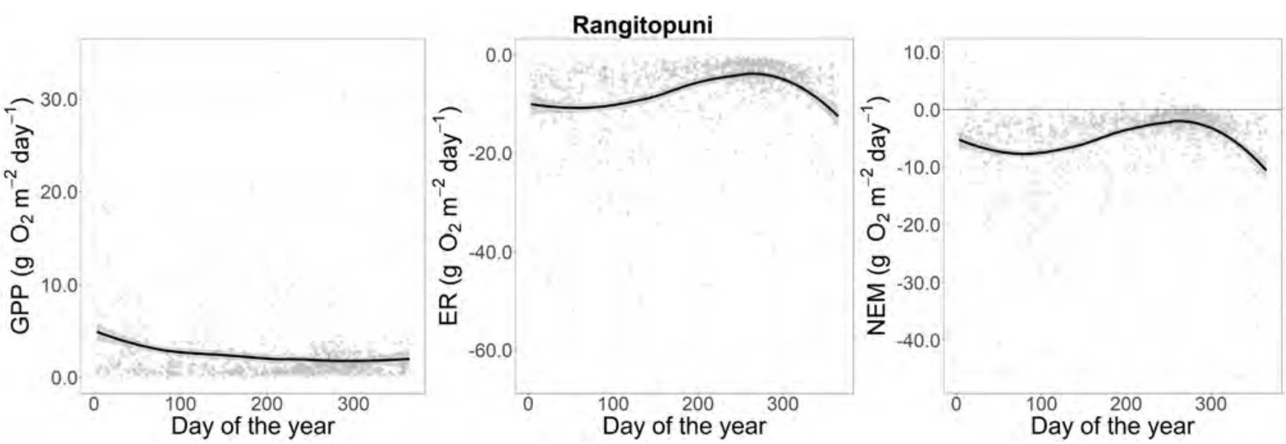


Per cent of days with reliable data based on the results of the metabolic estimates calculations.

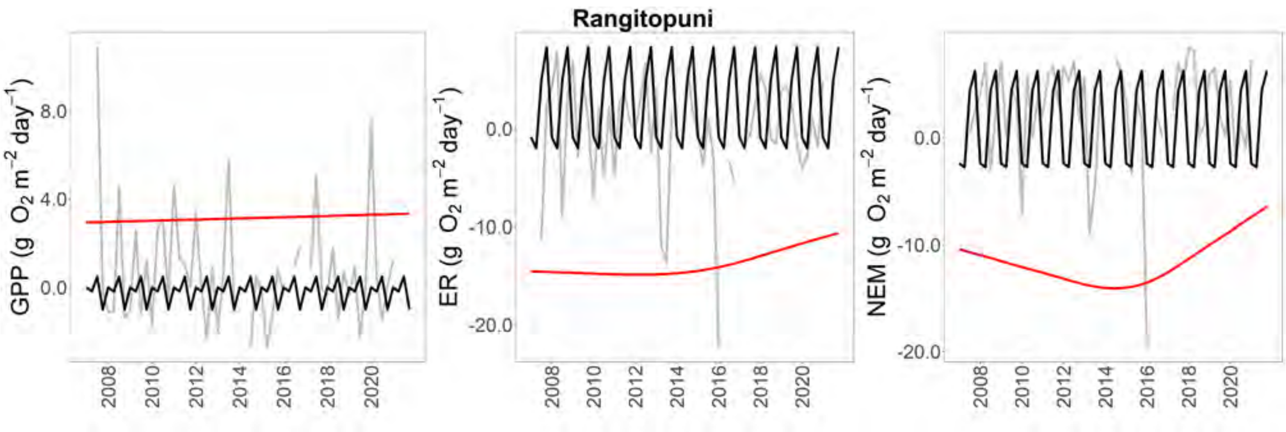


Analysis of metabolic results

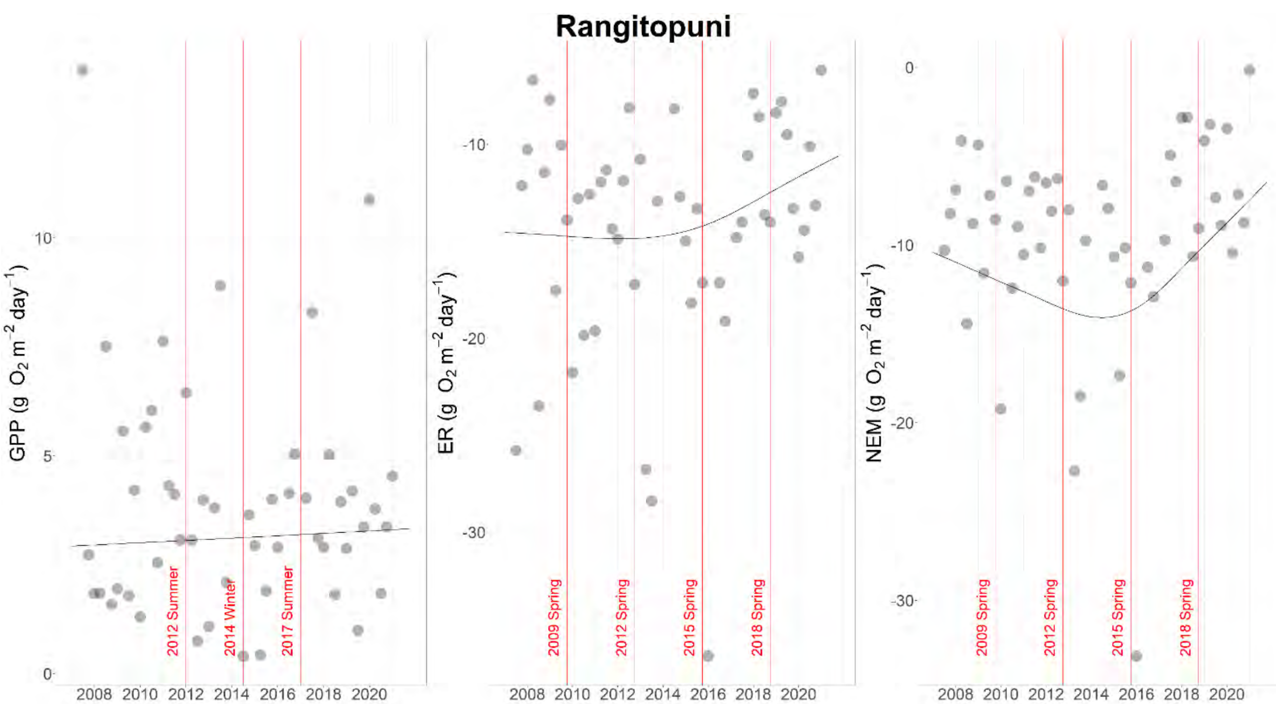
Seasonal distribution of metabolic estimates. One at the starts of the x-axis represents the 1st of January.



Time series decomposition analysis. The red line shows the long term trend, the black line shows the seasonal component of the trend, and the grey line shows the anomaly.



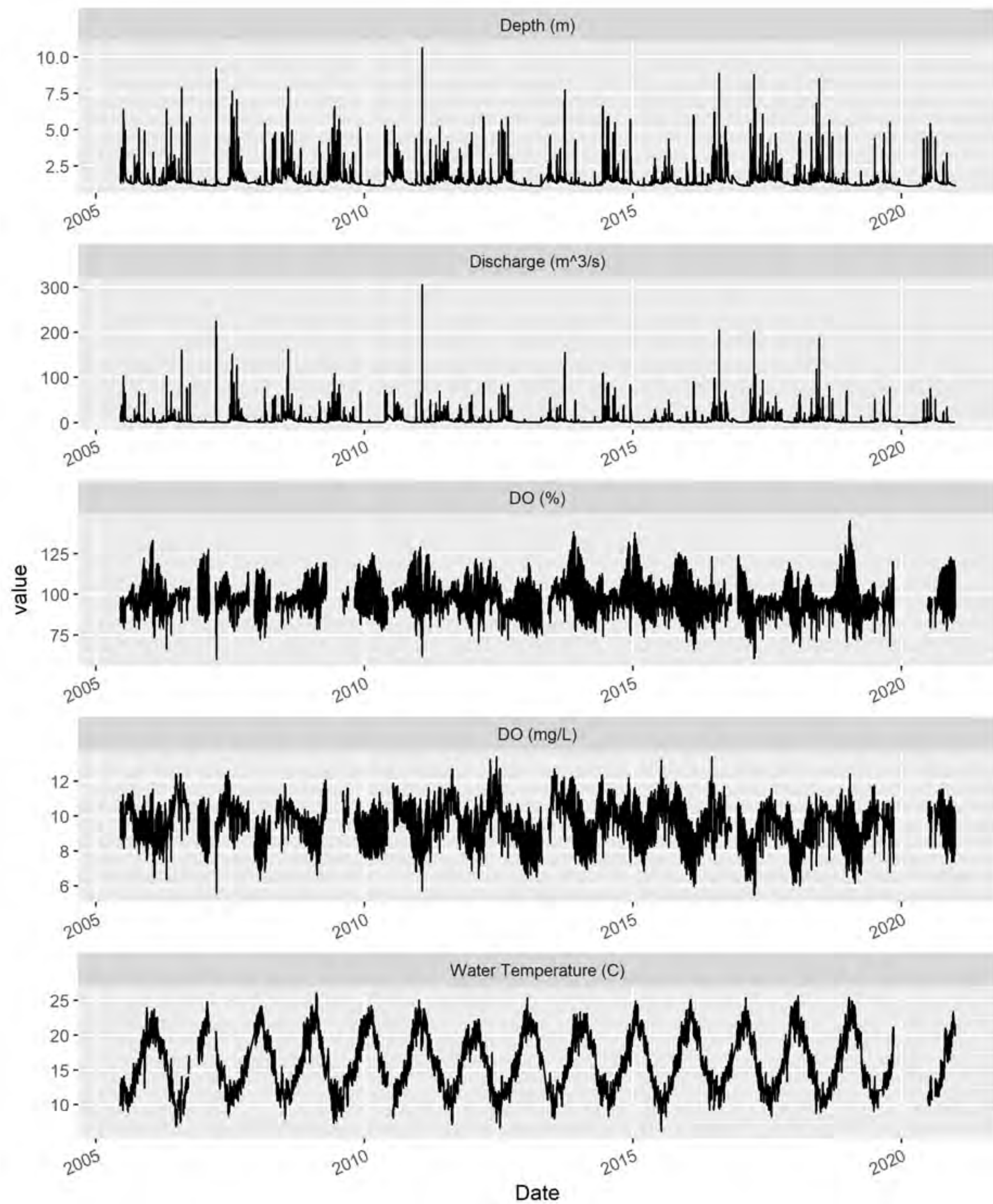
Point change analysis of the long-term trend (shown in black). The red vertical lines show suggested changes on the mean value of the metabolic estimates. The points show the anomaly for each summary data point (data was summarised by season and year).



Hoteo

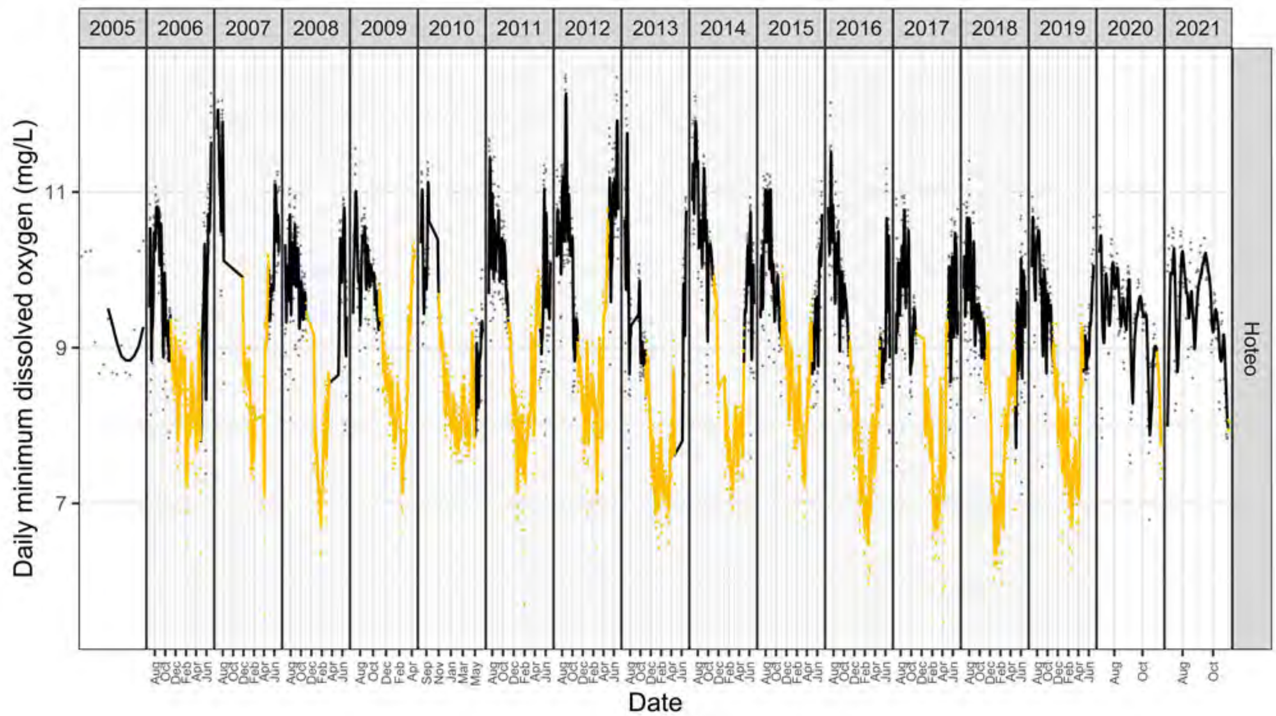
Raw data compilation

Original data Timeseries. Data with QC codes 42 and 43 have been removed.



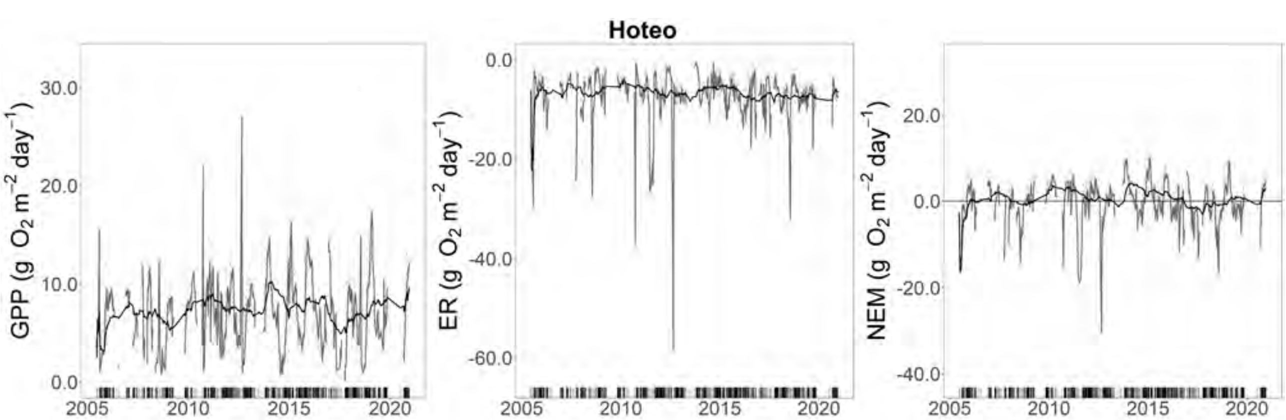
Oxygen data reporting

Timeseries of minimum dissolved oxygen. Points show the daily minimum values, and lines show the 7-day mean value. The summer period is indicated by the colour dots and lines (yellow), which also correspond with the catchment groupings by land cover (Table 1). Years are hydrological years.

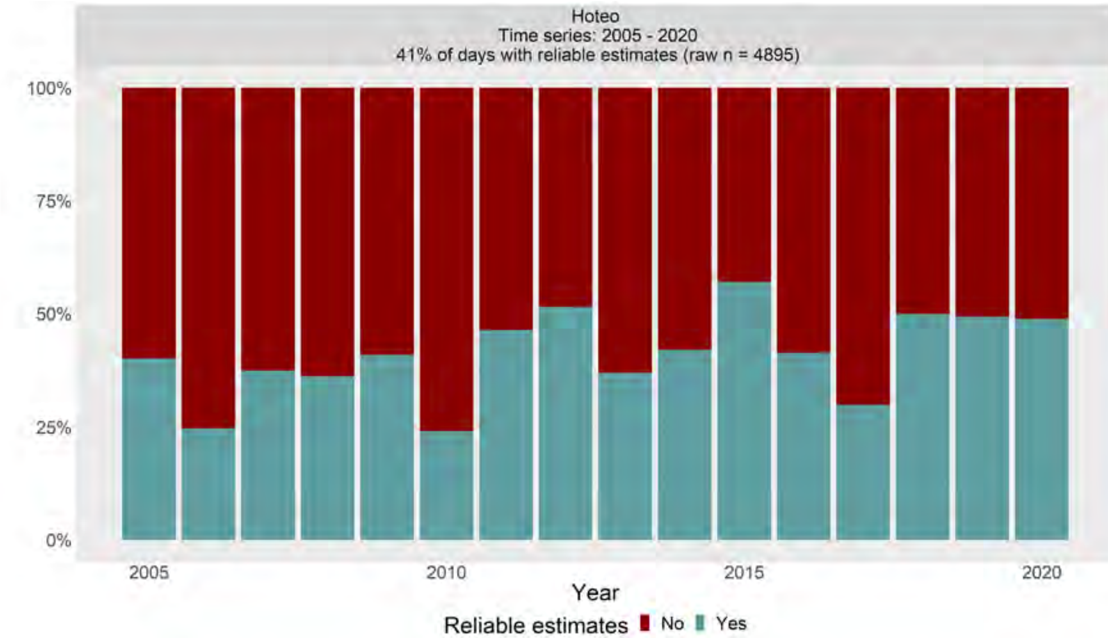


Metabolic estimate calculation

Time series of metabolic estimates (reliable data only)

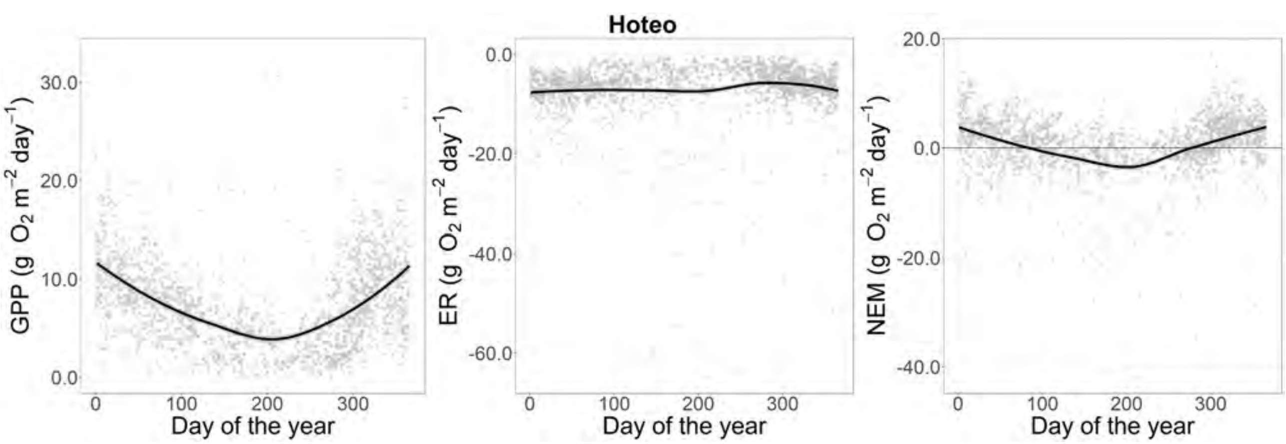


Per cent of days with reliable data based on the results of the metabolic estimates calculations.

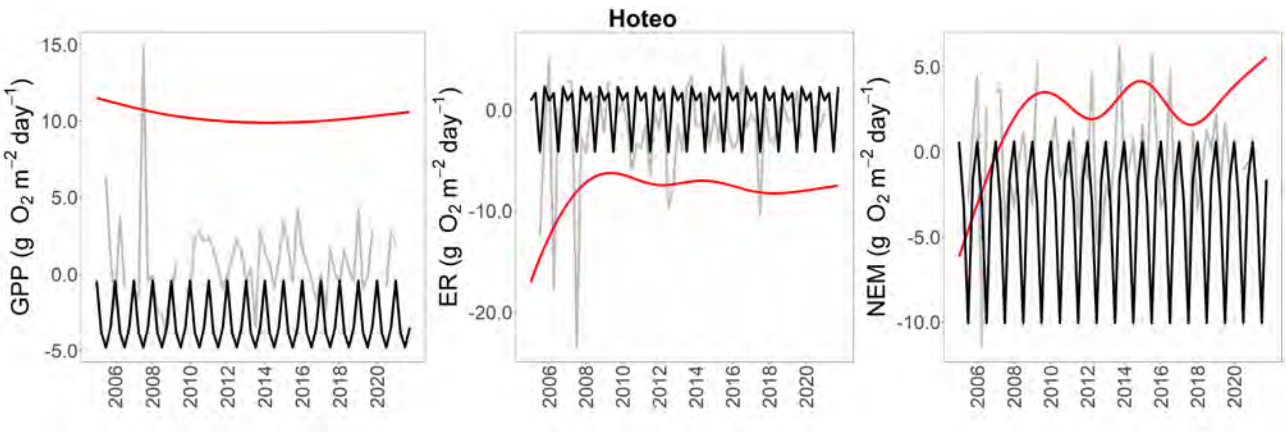


Analysis of metabolic results

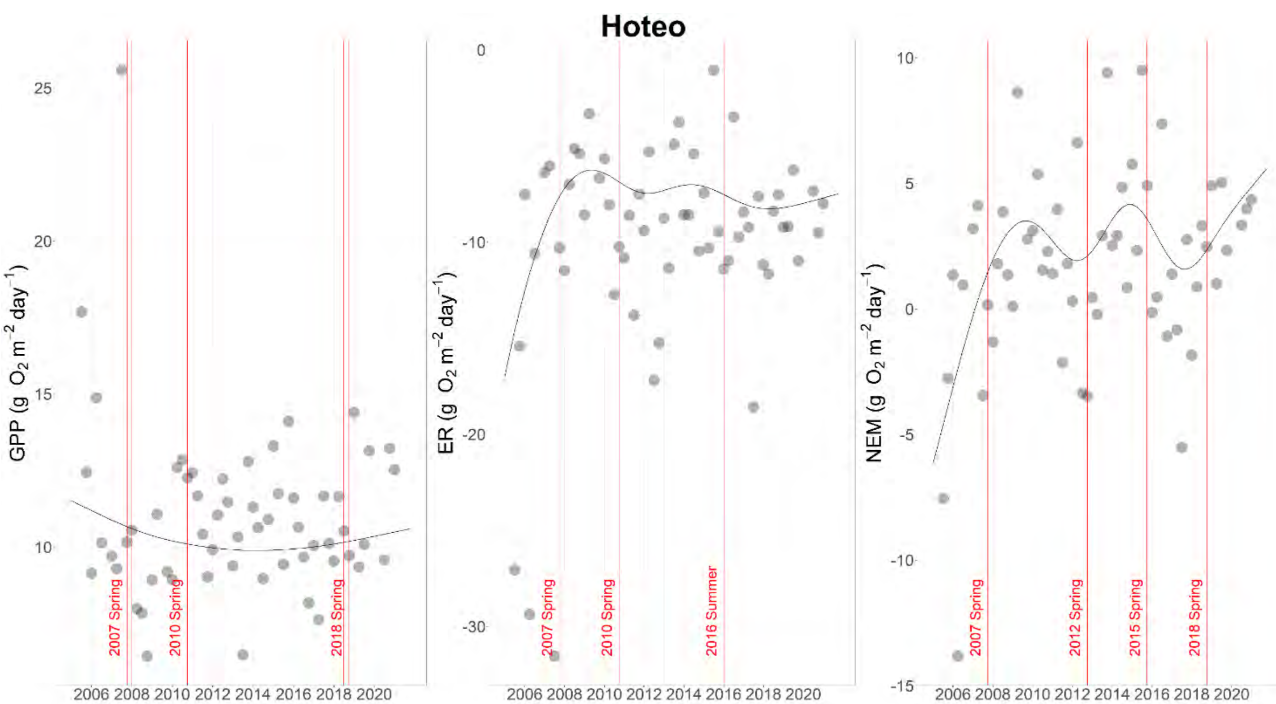
Seasonal distribution of metabolic estimates. One at the starts of the x-axis represents the 1st of January.



Time series decomposition analysis. The red line shows the long-term trend, the black line shows the seasonal component of the trend, and the grey line shows the anomaly.



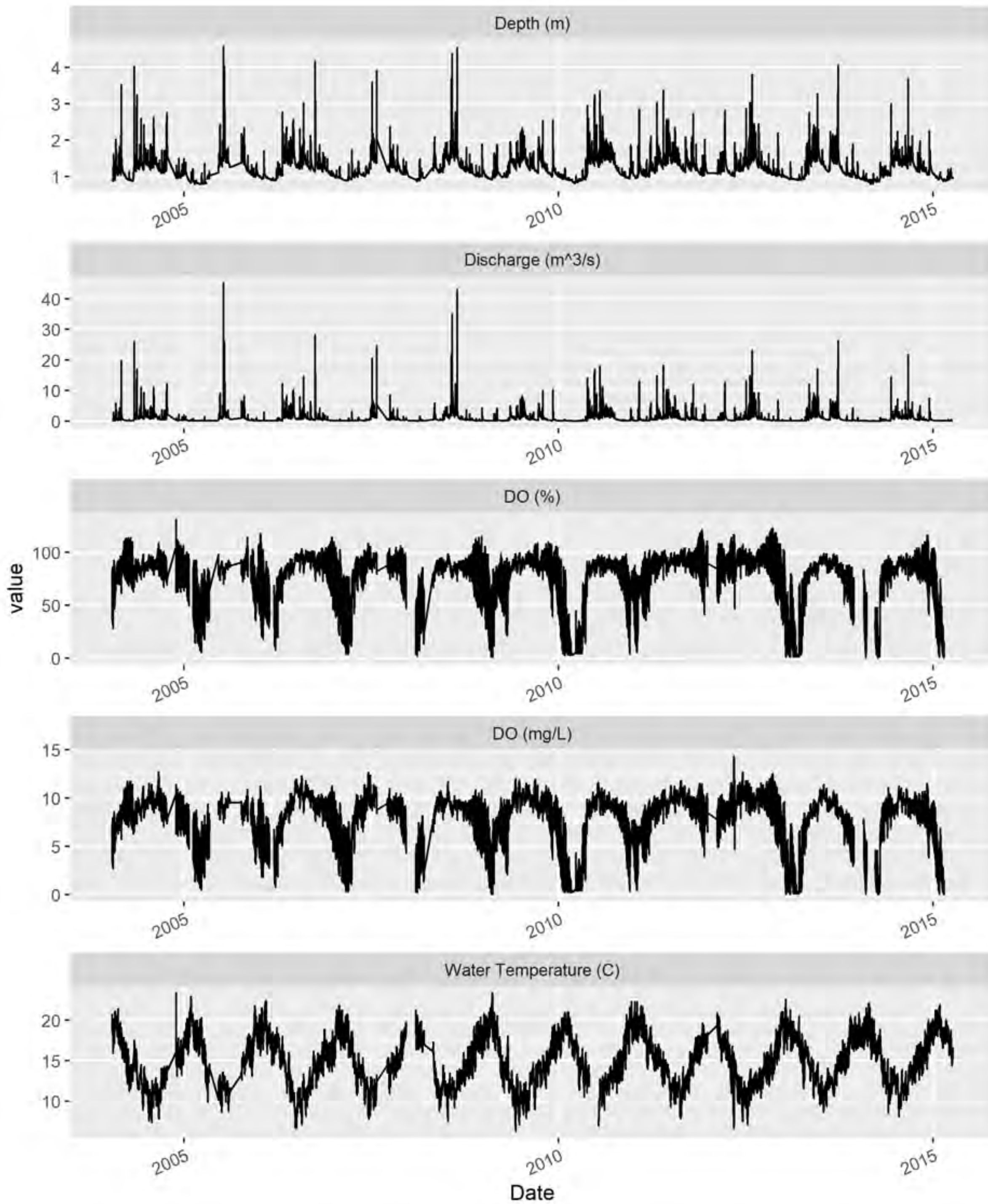
Point change analysis of the long-term trend (shown in black). The red vertical lines show suggested changes on the mean value of the metabolic estimates. The points show the anomaly for each summary data point (data was summarised by season and year).



Kumeu

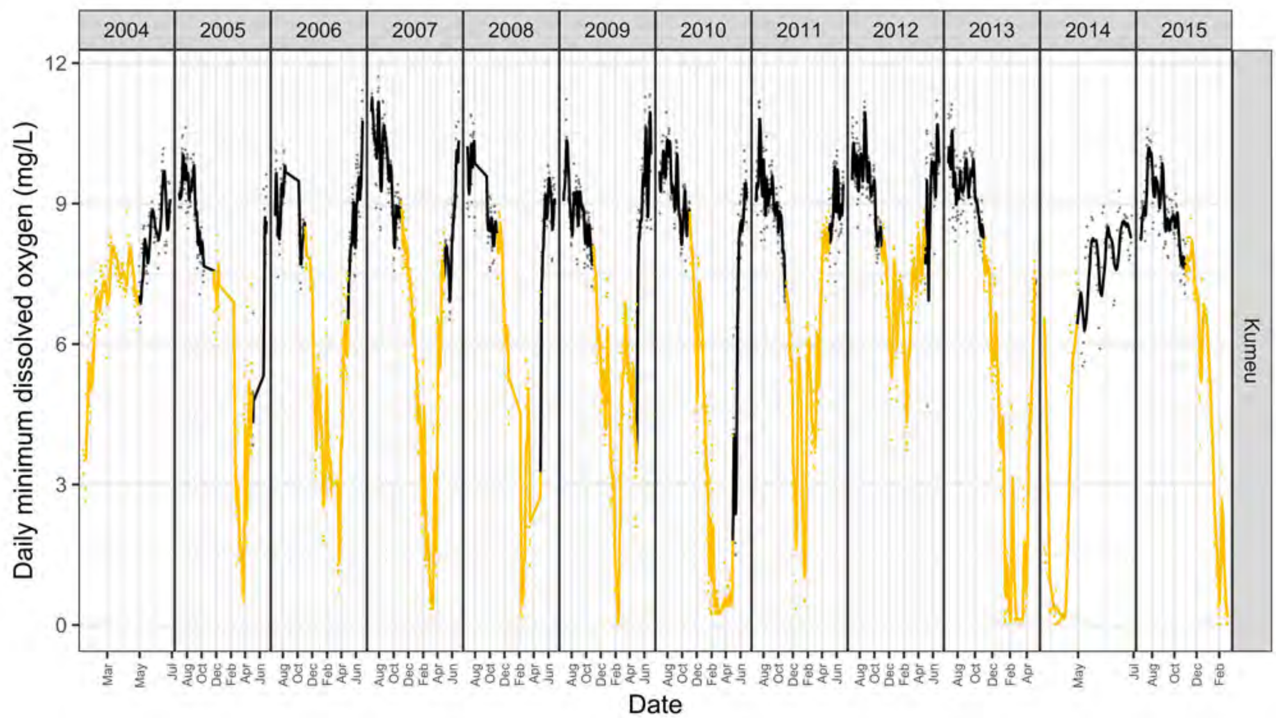
Raw data compilation

Original data Timeseries. Data with QC codes 42 and 43 have been removed.



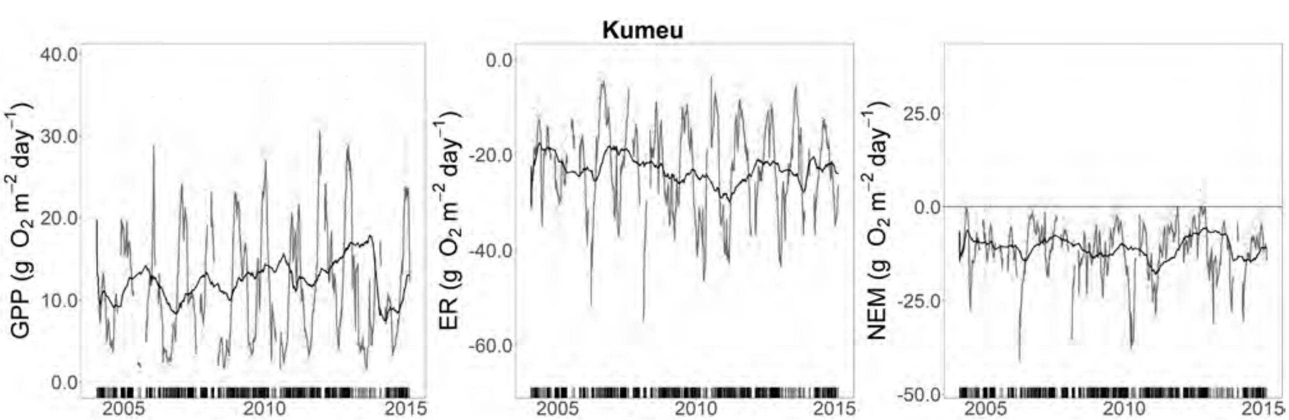
Oxygen data reporting

Timeseries of minimum dissolved oxygen. Points show the daily minimum values, and lines show the 7-day mean value. The summer period is indicated by the colour dots and lines (yellow), which also correspond with the catchment groupings by land cover (Table 1). Years are hydrological years.

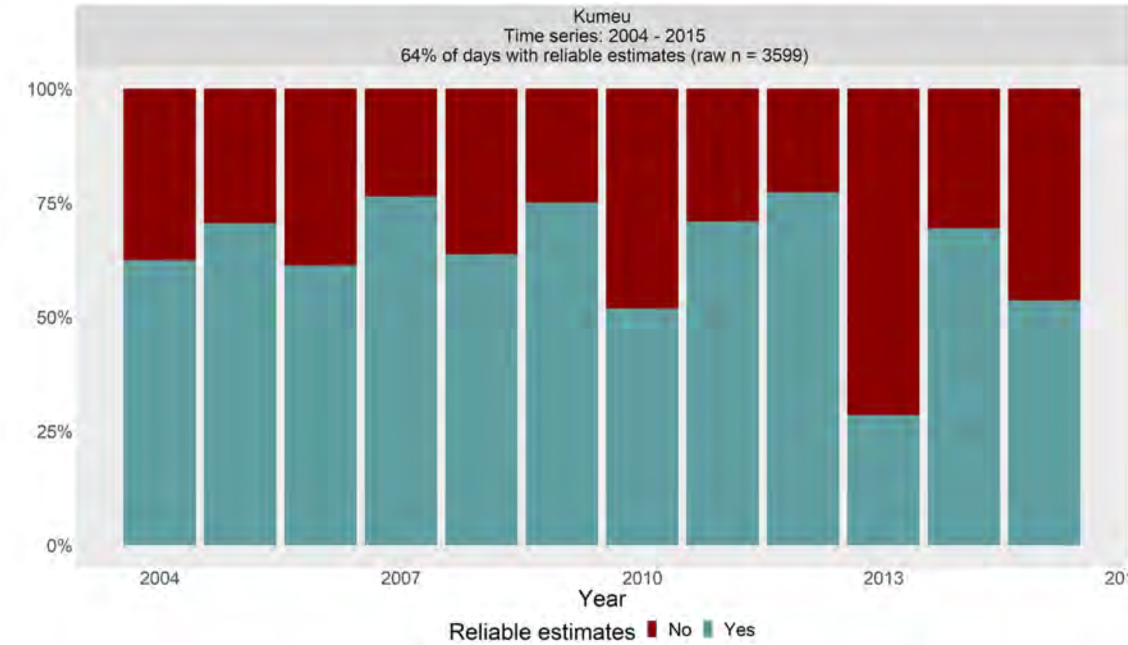


Metabolic estimate calculation

Time series of metabolic estimates (reliable data only)

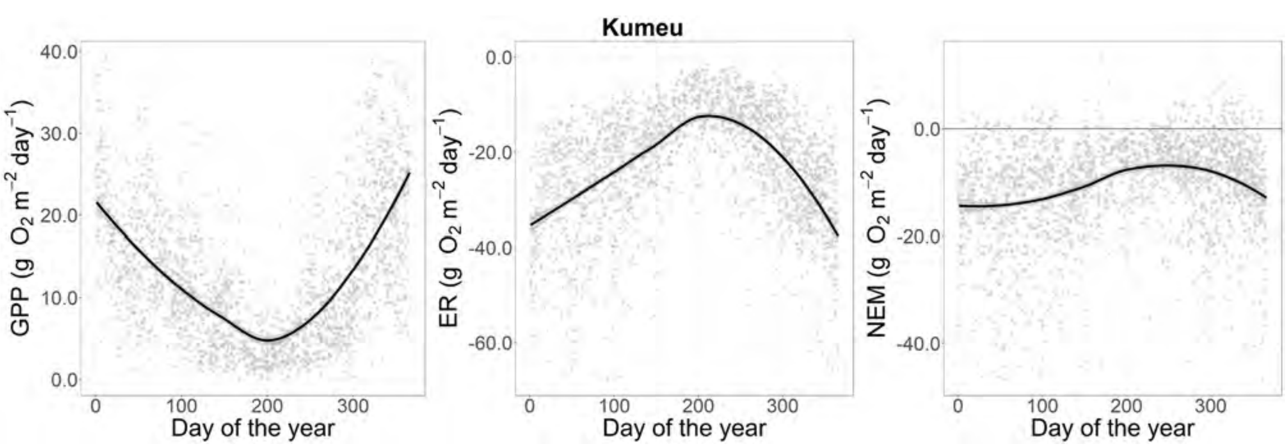


Per cent of days with reliable data based on the results of the metabolic estimates calculations.

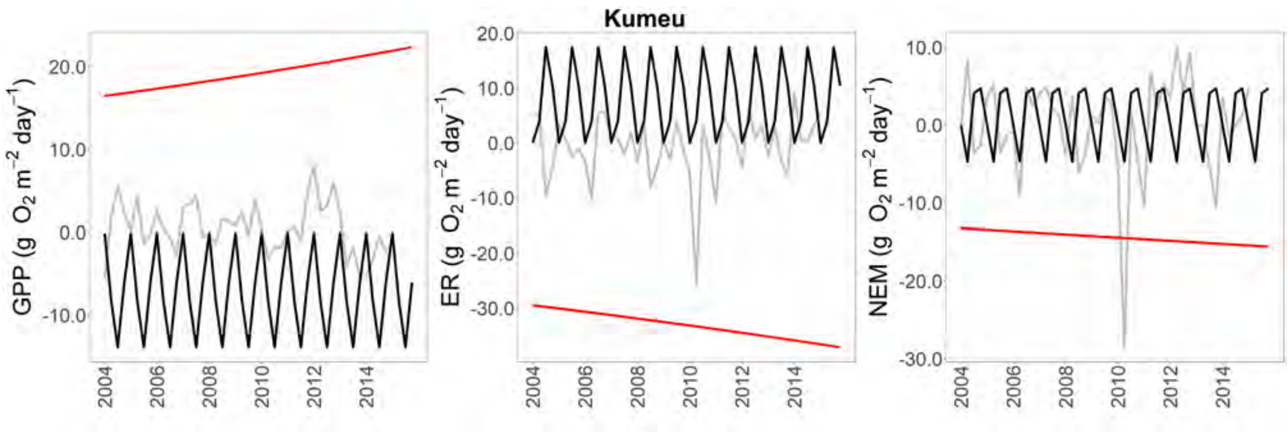


Analysis of metabolic results

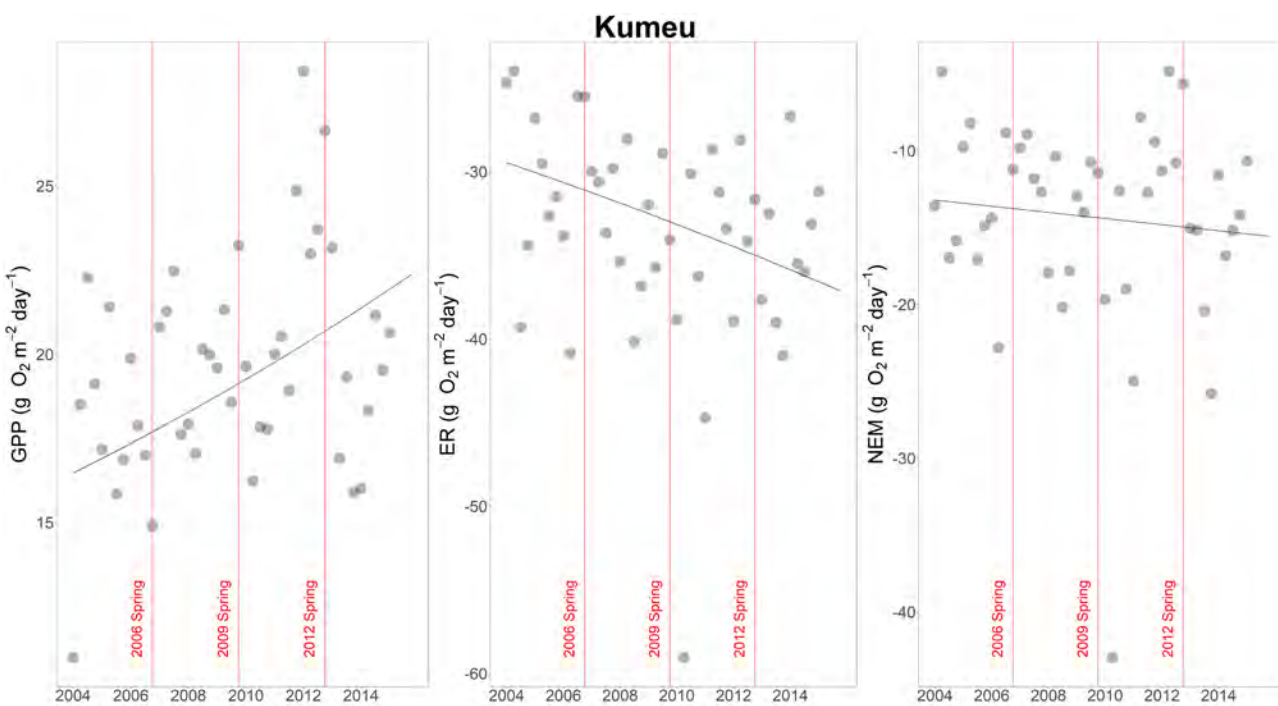
Seasonal distribution of metabolic estimates. One at the starts of the x-axis represents the 1st of January.



Time series decomposition analysis. The red line shows the long term trend, the black line shows the seasonal component of the trend, and the grey line shows the anomaly.



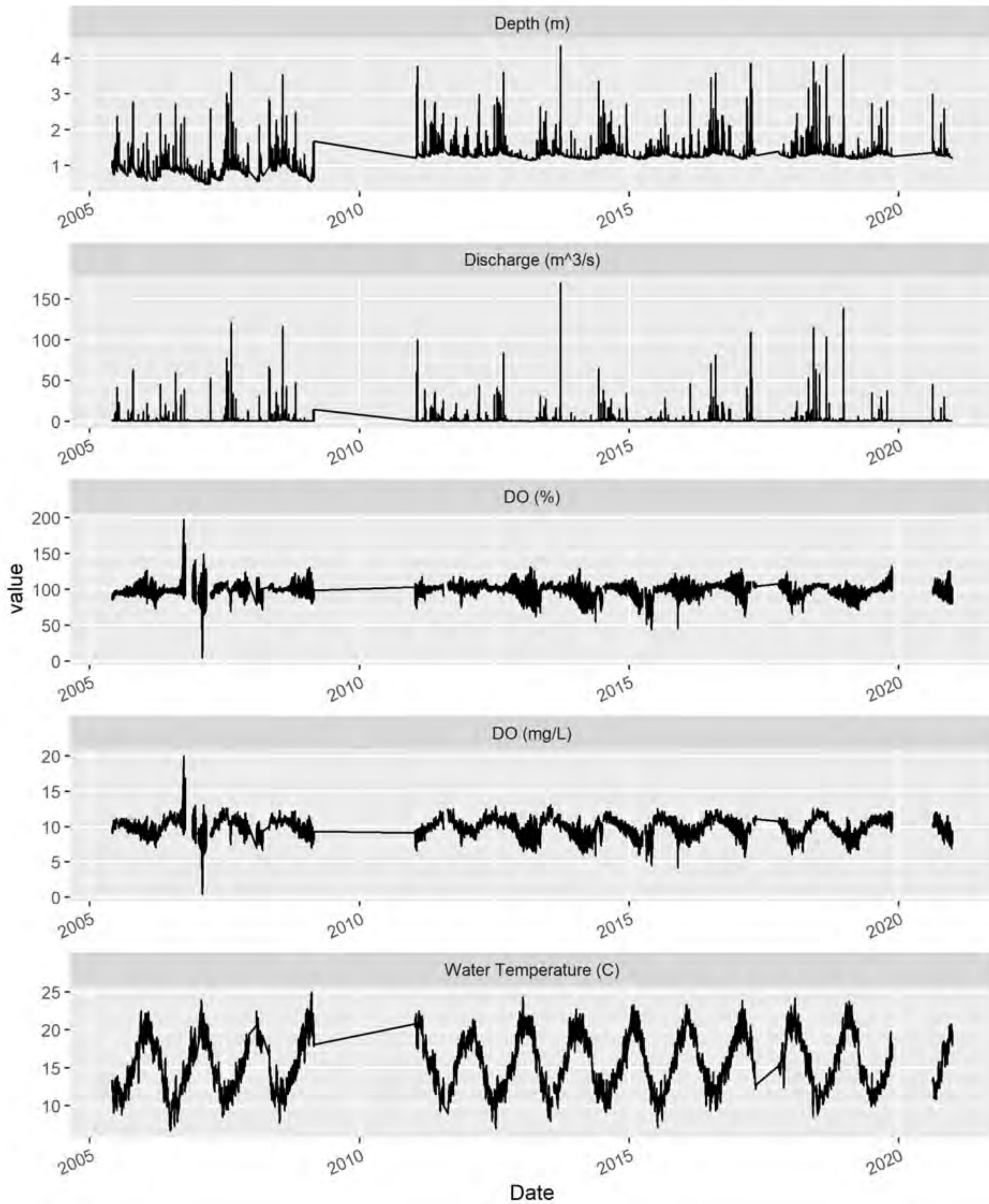
Point change analysis of the long-term trend (shown in black). The red vertical lines show suggested changes on the mean value of the metabolic estimates. The points show the anomaly for each summary data point (data was summarised by season and year).



Mahurangi

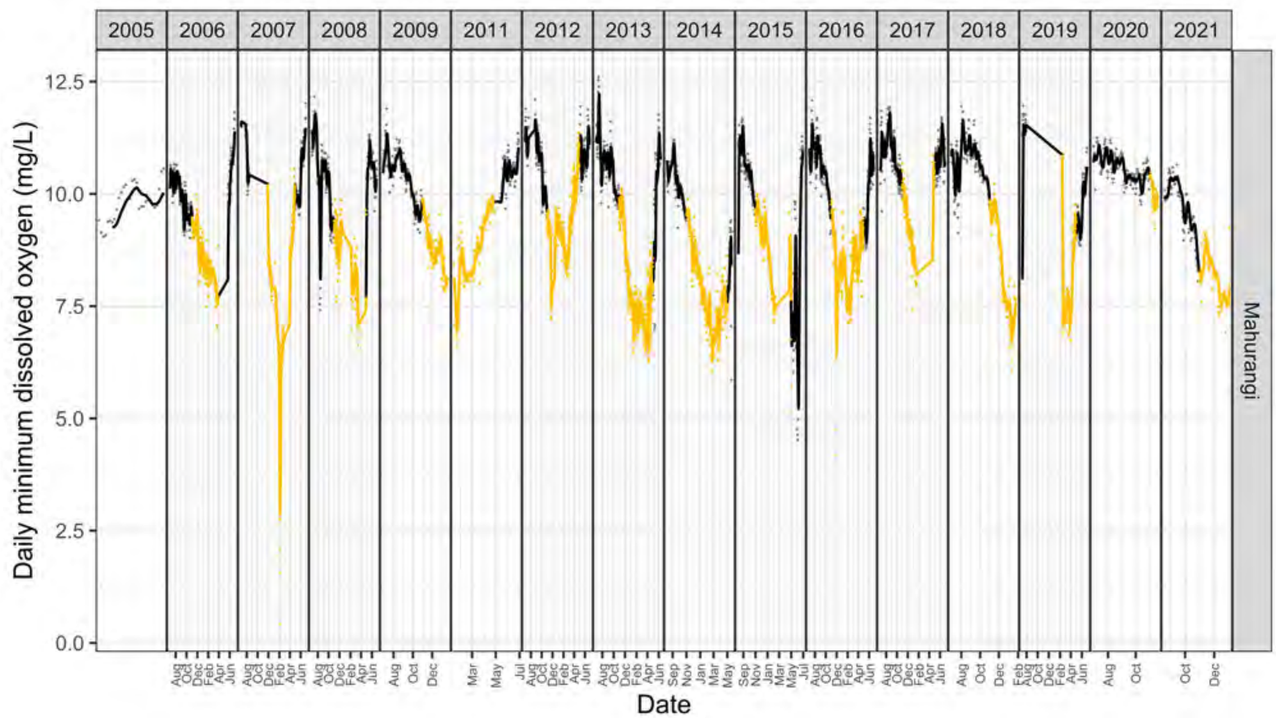
Raw data compilation

Original data Timeseries. Data with QC codes 42 and 43 have been removed.



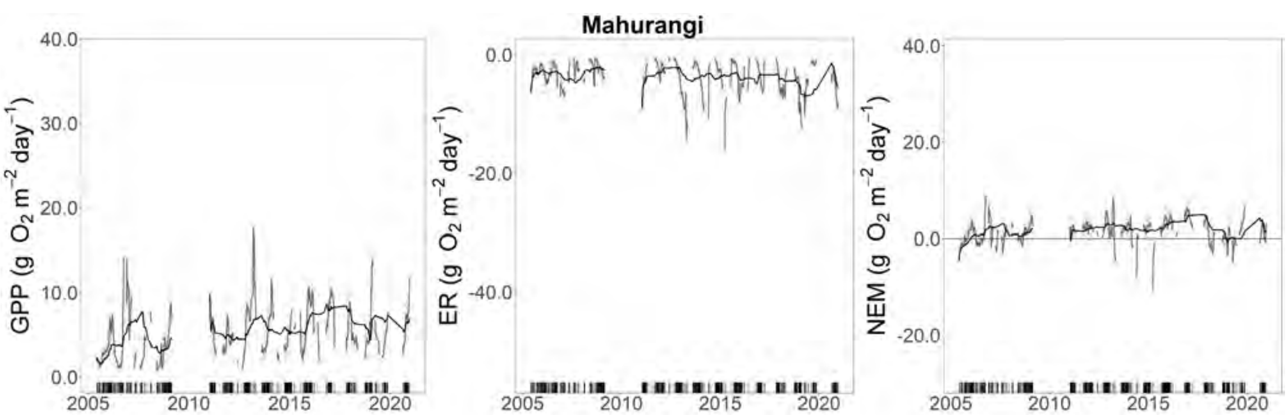
Oxygen data reporting

Timeseries of minimum dissolved oxygen. Points show the daily minimum values, and lines show the 7-day mean value. The summer period is indicated by the colour dots and lines (yellow), which also correspond with the catchment groupings by land cover (Table 1). Years are hydrological years.

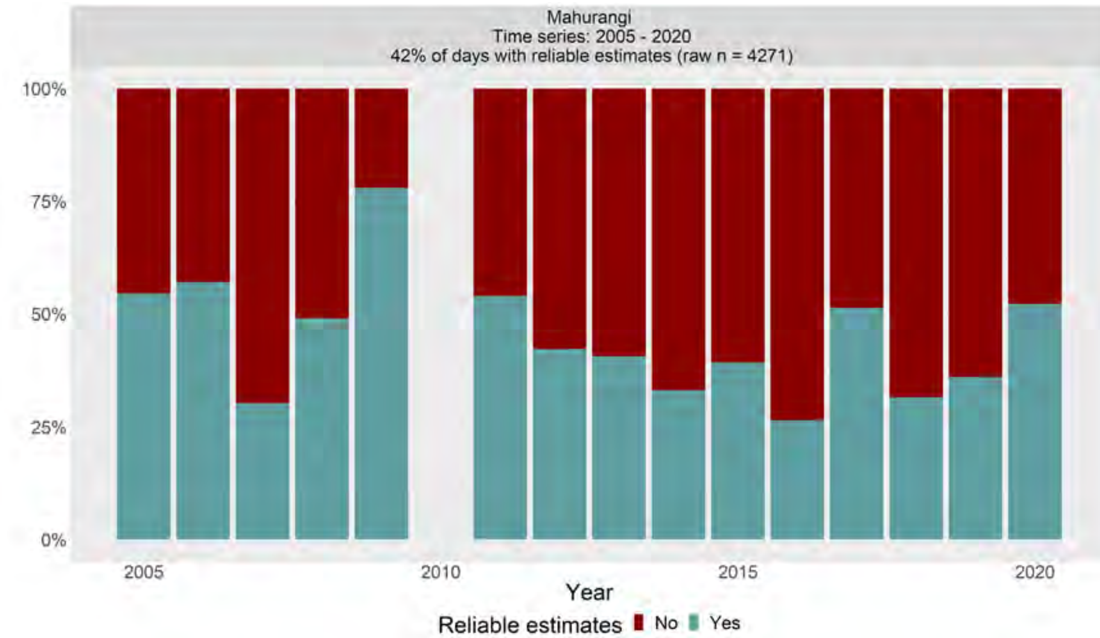


Metabolic estimate calculation

Time series of metabolic estimates (reliable data only)

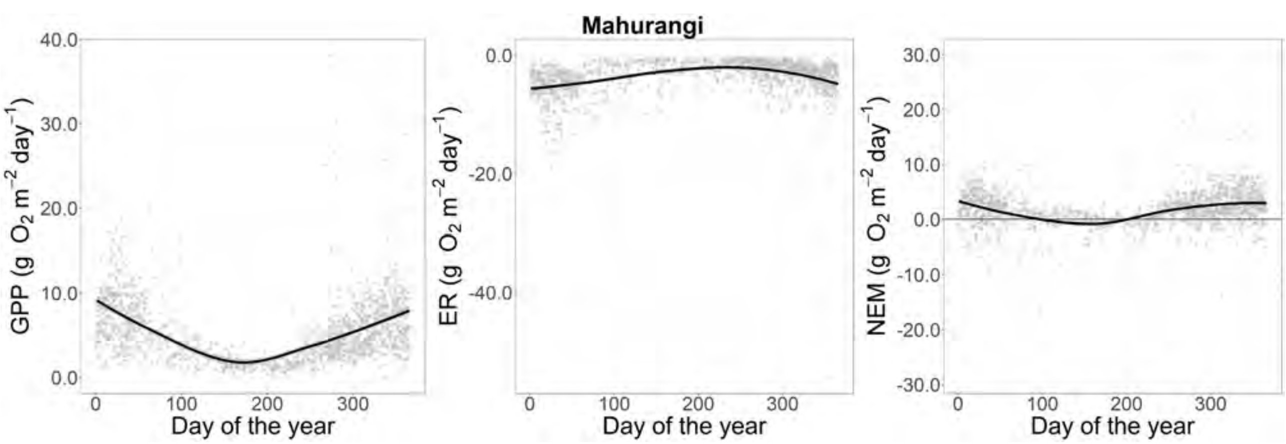


Per cent of days with reliable data based on the results of the metabolic estimates calculations.

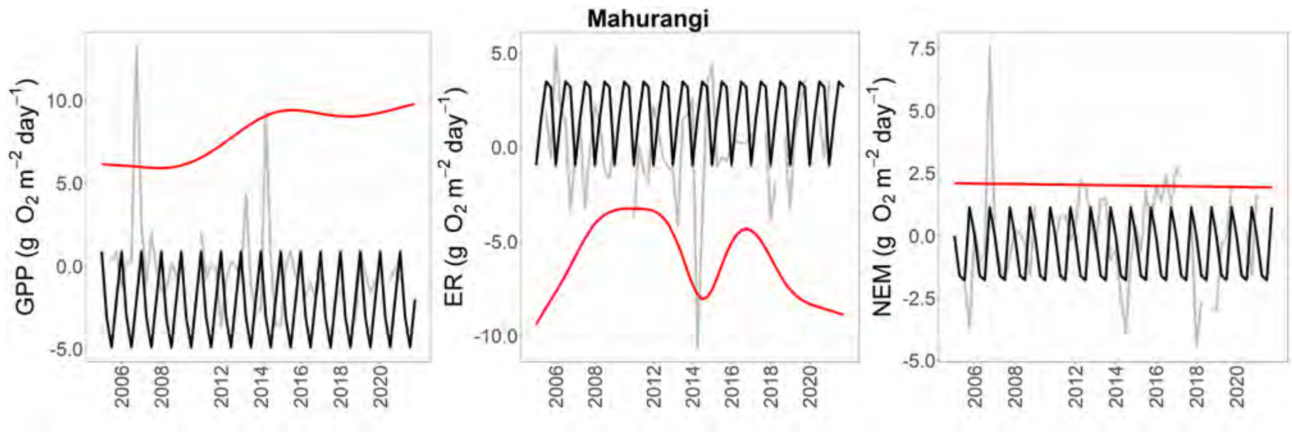


Analysis of metabolic results

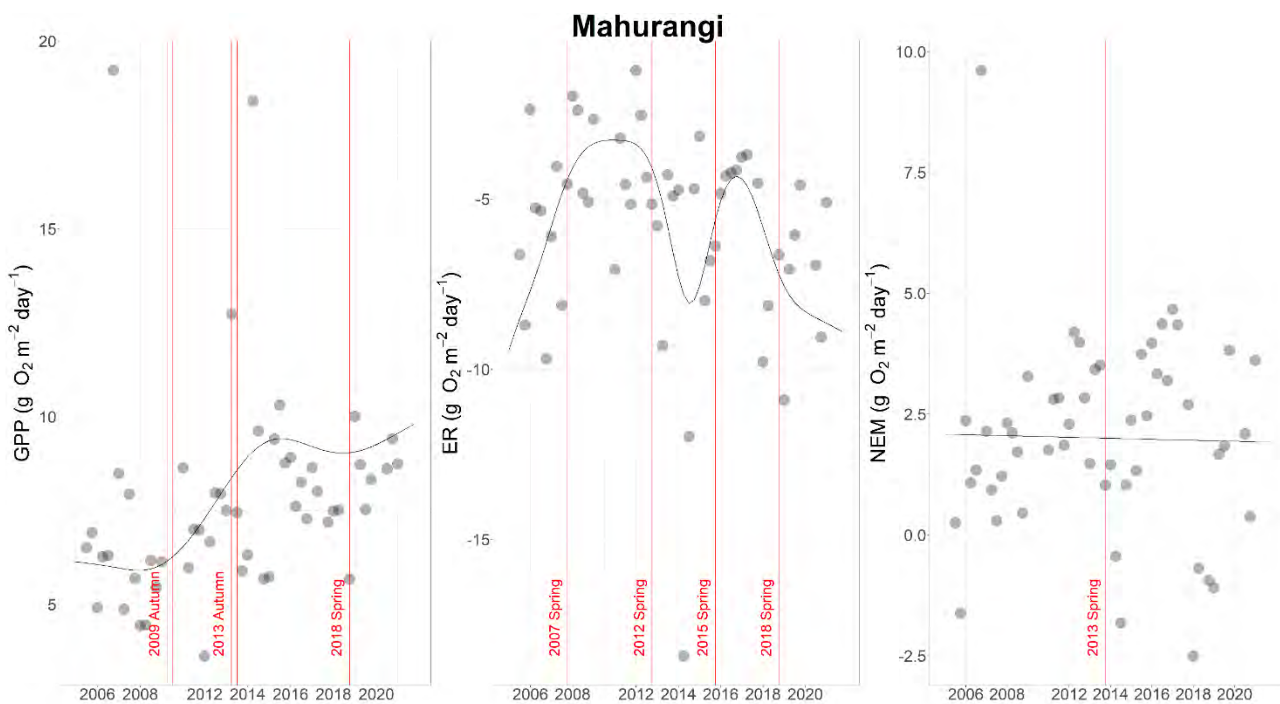
Seasonal distribution of metabolic estimates. One at the starts of the x-axis represents the 1st of January.



Time series decomposition analysis. The red line shows the long term trend, the black line shows the seasonal component of the trend, and the grey line shows the anomaly.



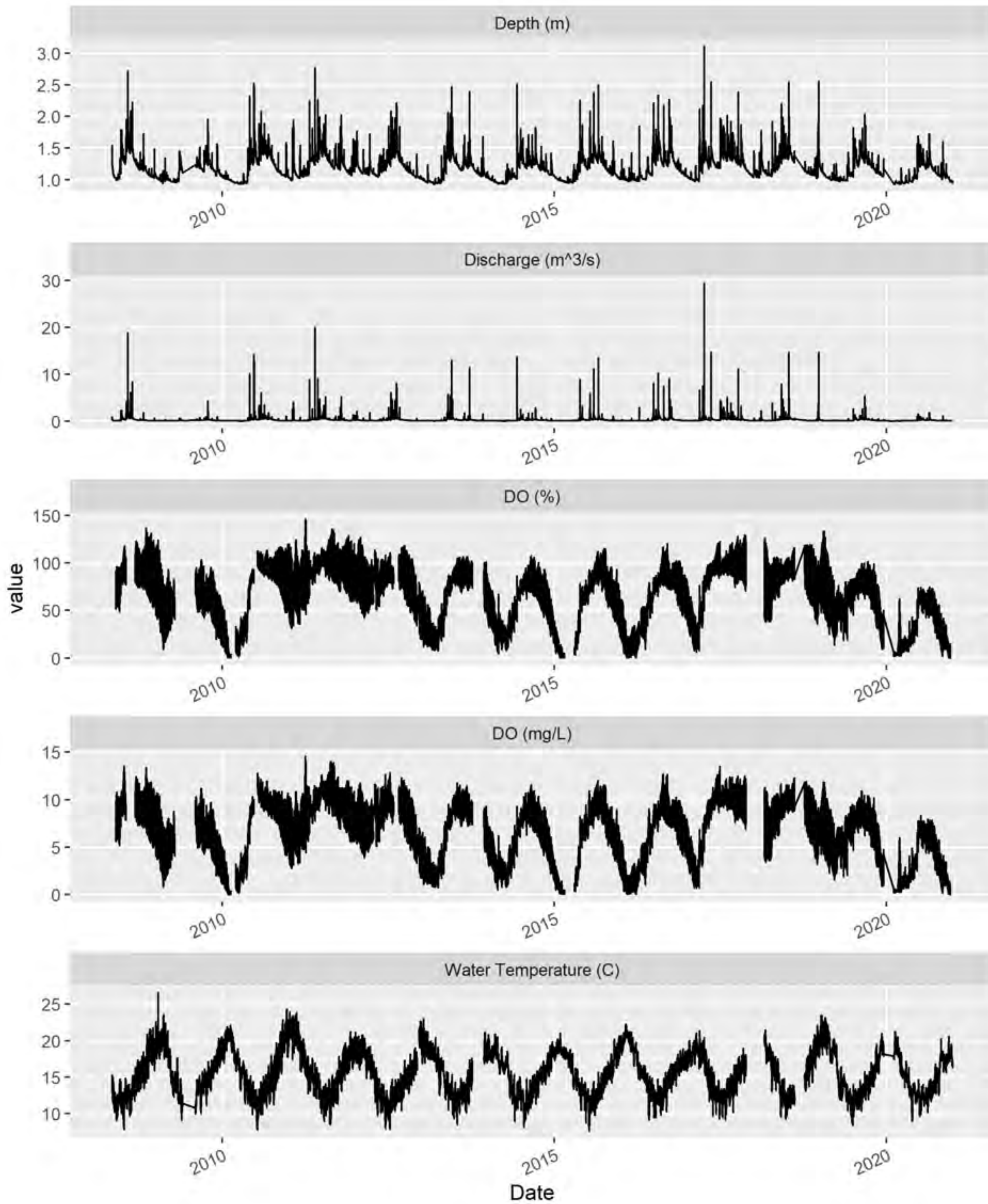
Point change analysis of the long-term trend (shown in black). The red vertical lines show suggested changes on the mean value of the metabolic estimates. The points show the anomaly for each summary data point (data was summarised by season and year).



Waitangi

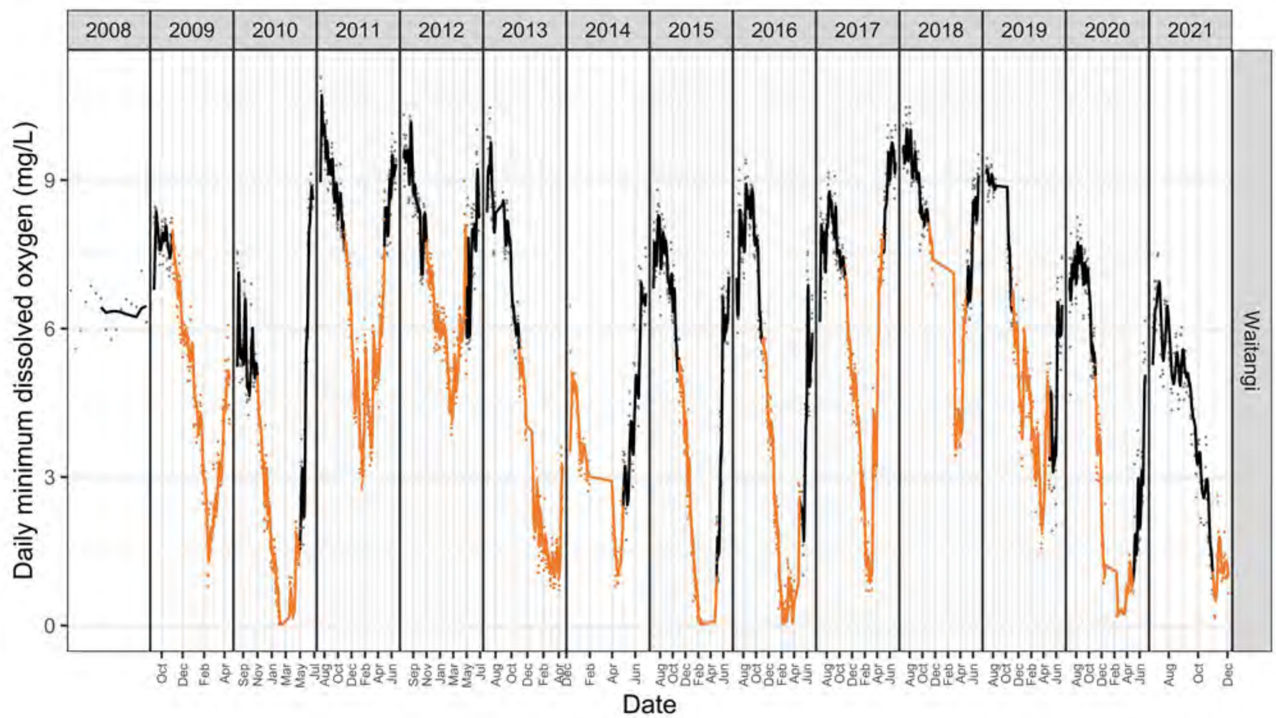
Raw data compilation

Original data Timeseries. Data with QC codes 42 and 43 have been removed.



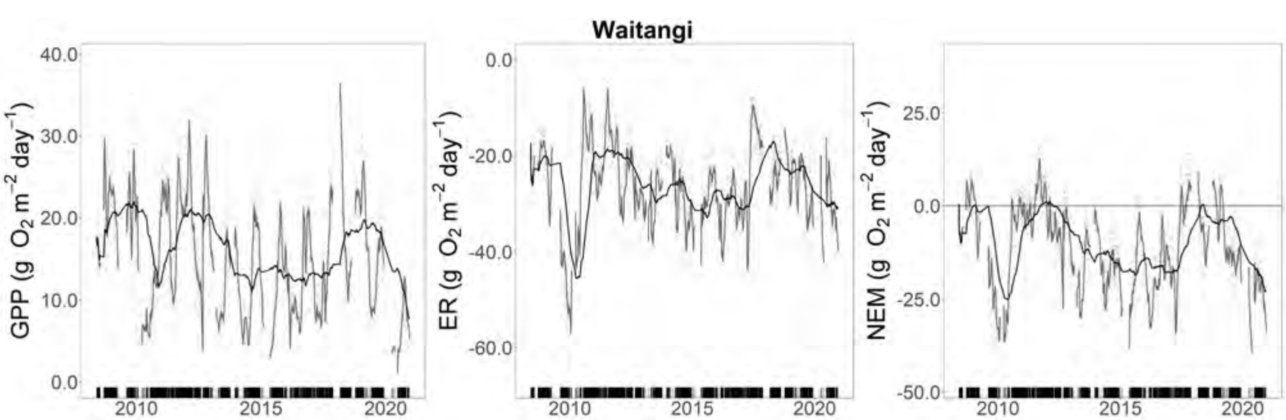
Oxygen data reporting

Timeseries of minimum dissolved oxygen. Points show the daily minimum values, and lines show the 7-day mean value. The summer period is indicated by the colour dots and lines (orange), which also correspond with the catchment groupings by land cover (Table 1). Years are hydrological years.

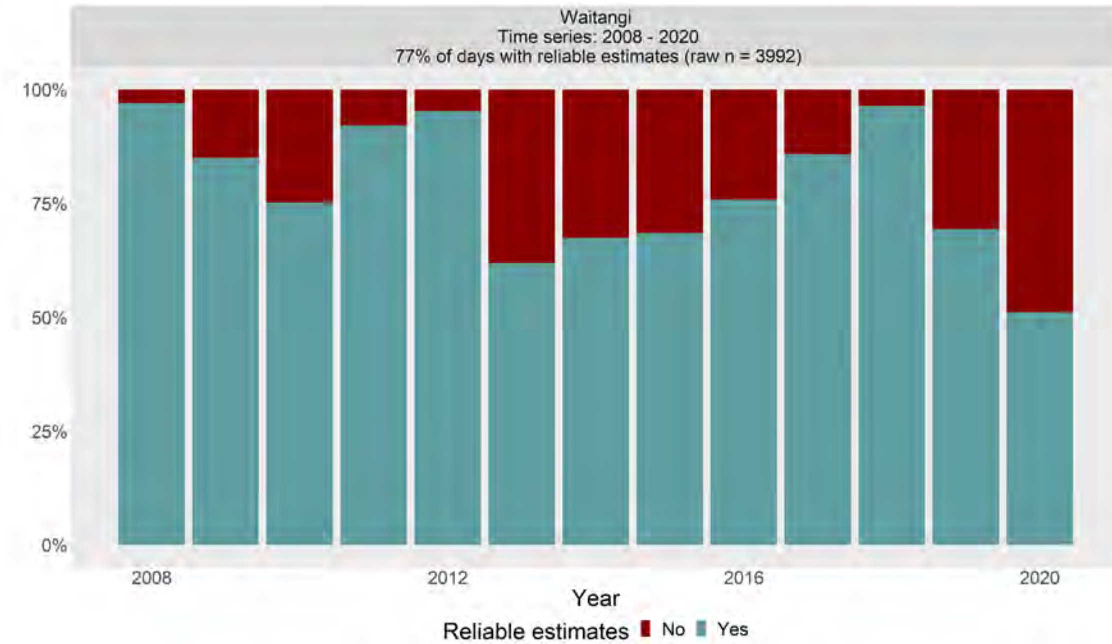


Metabolic estimate calculation

Time series of metabolic estimates (reliable data only)

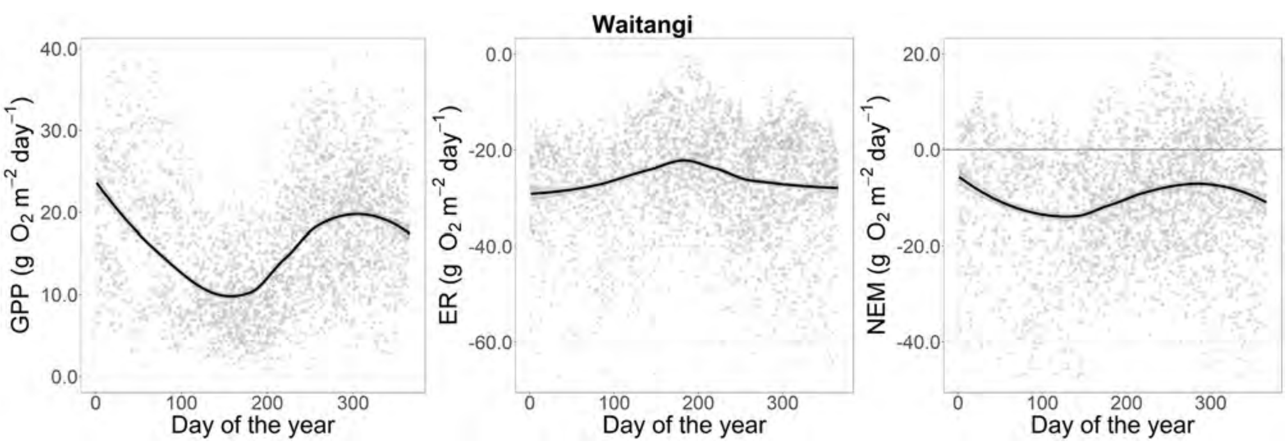


Per cent of days with reliable data based on the results of the metabolic estimates calculations.

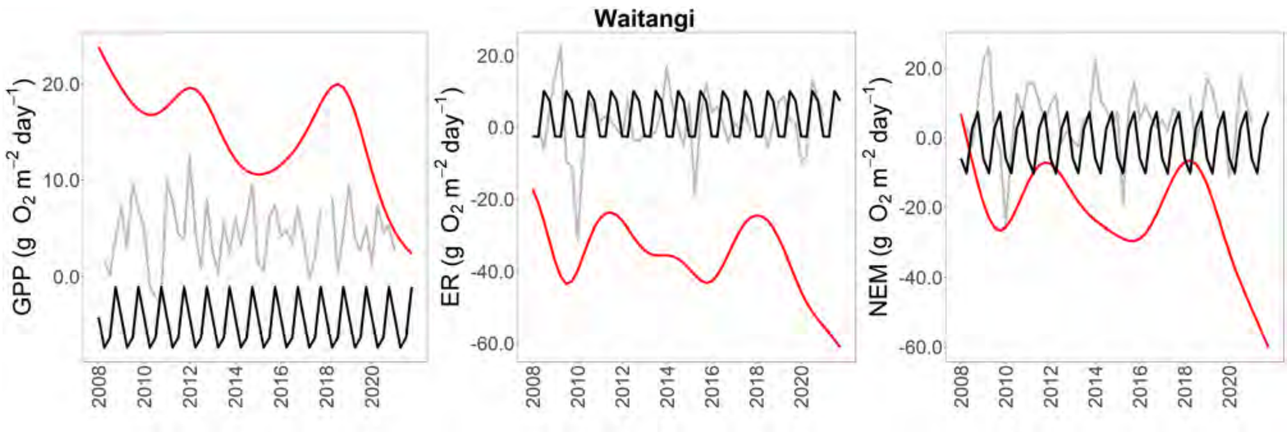


Analysis of metabolic results

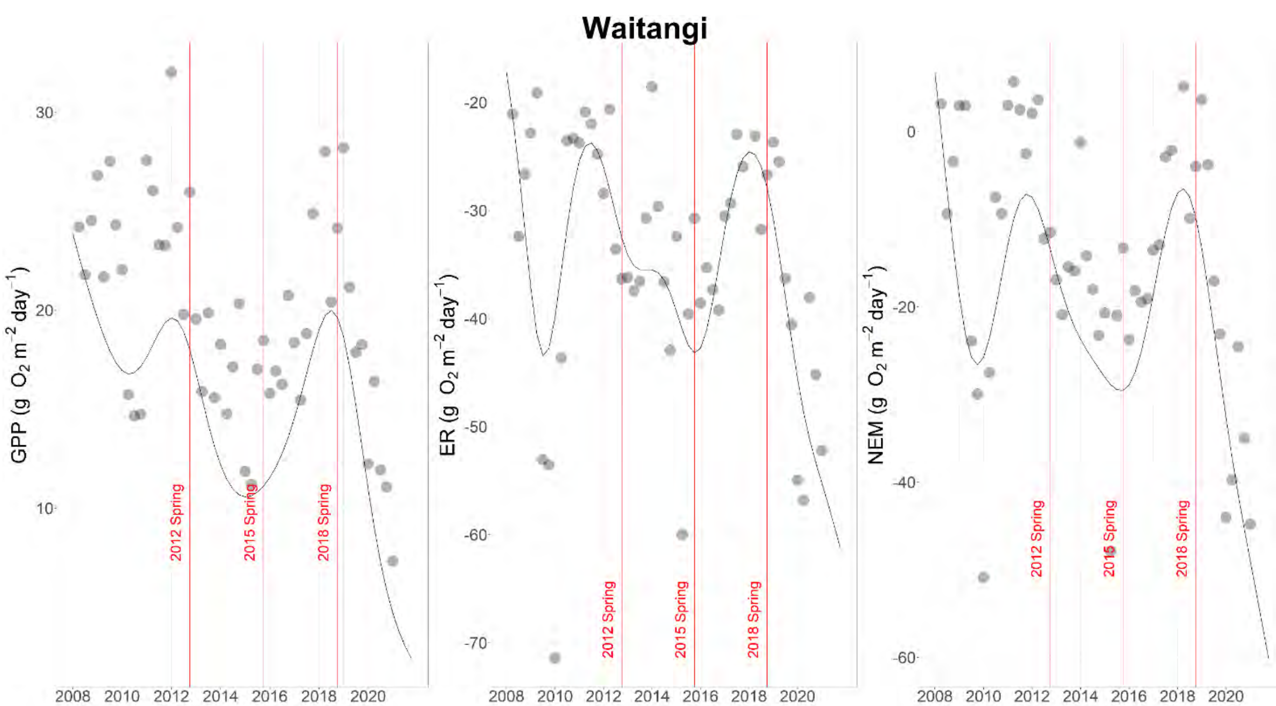
Seasonal distribution of metabolic estimates. One at the starts of the x-axis represents the 1st of January.



Time series decomposition analysis. The red line shows the long-term trend, the black line shows the seasonal component of the trend, and the grey line shows the anomaly.



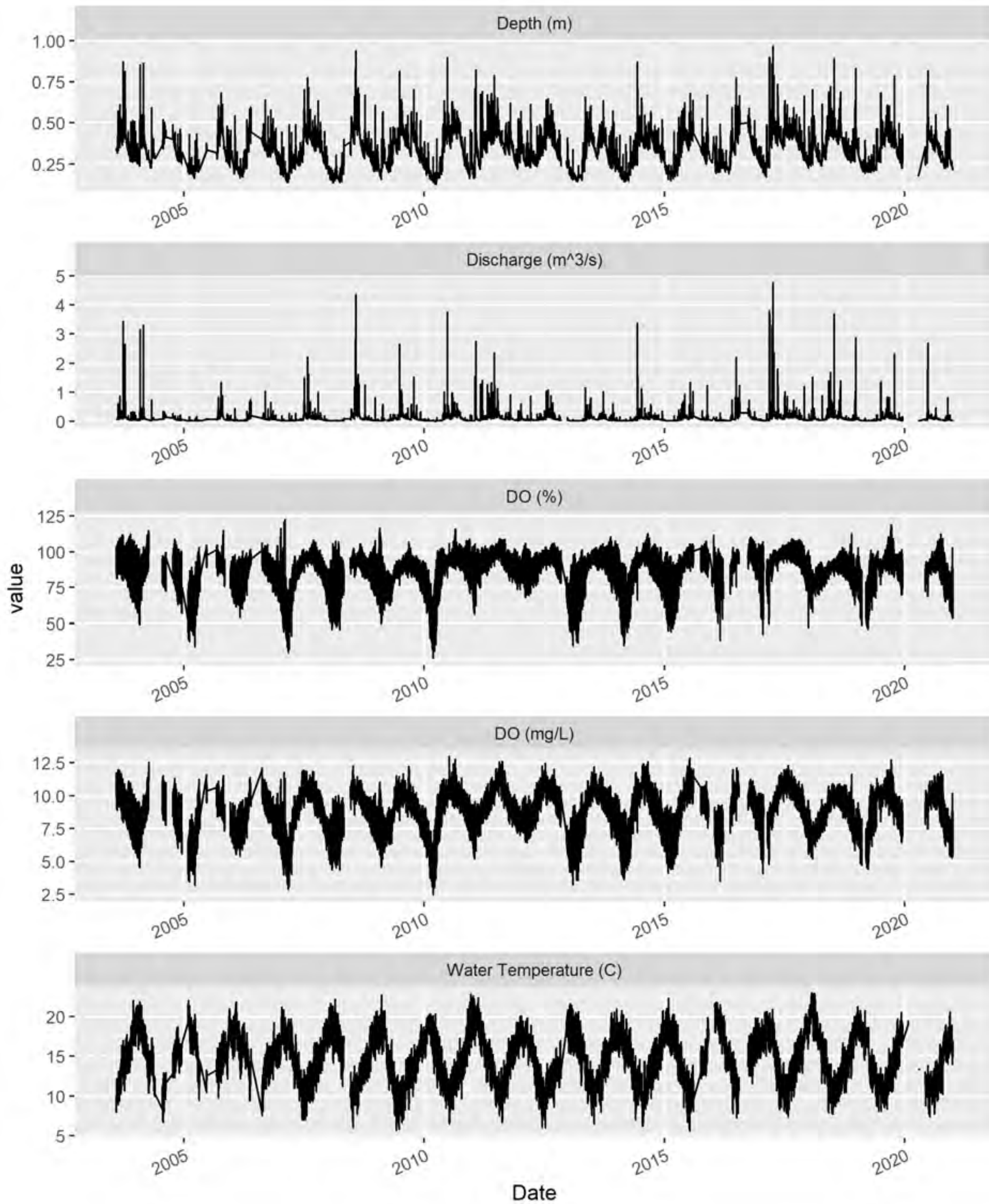
Point change analysis of the long-term trend (shown in black). The red vertical lines show suggested changes on the mean value of the metabolic estimates. The points show the anomaly for each summary data point (data was summarised by season and year).



Ngakoroa

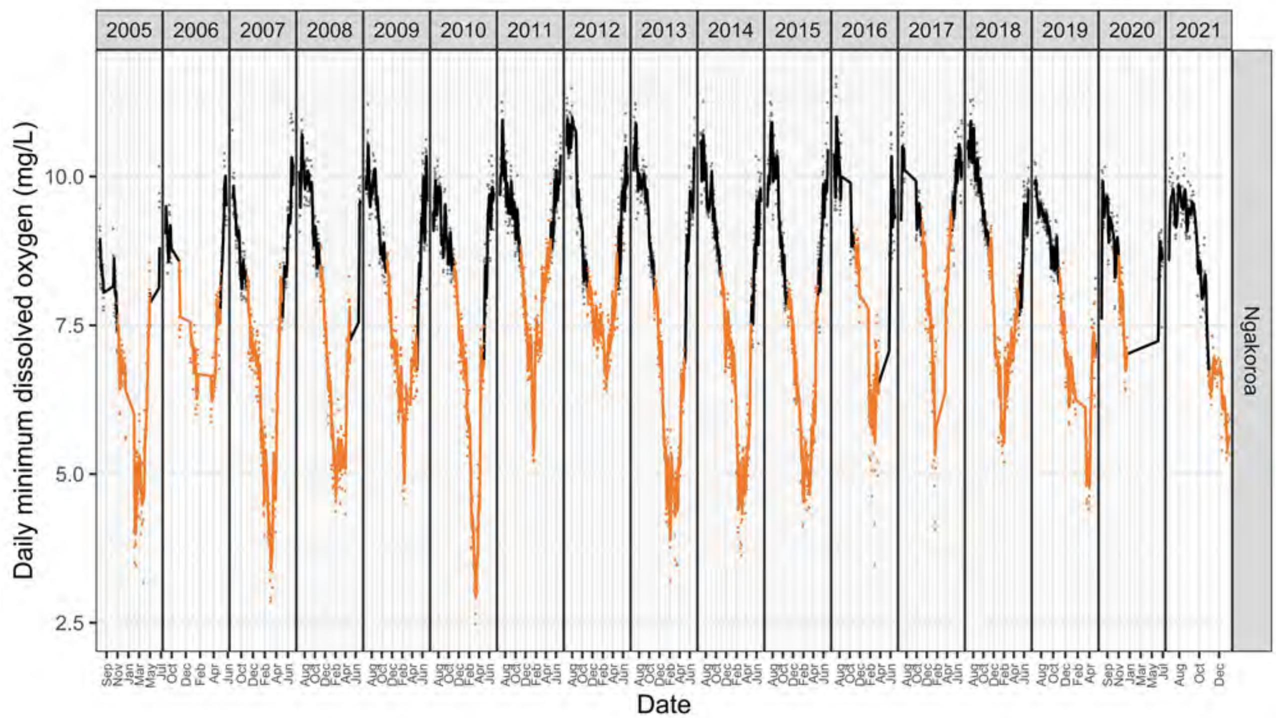
Raw data compilation

Original data Timeseries. Data with QC codes 42 and 43 have been removed.



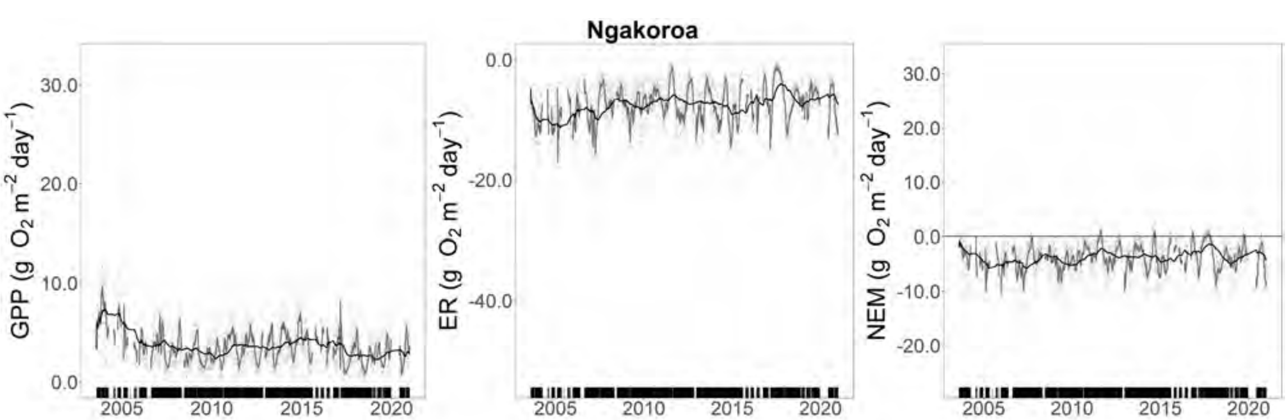
Oxygen data reporting

Timeseries of minimum dissolved oxygen. Points show the daily minimum values, and lines show the 7-day mean value. The summer period is indicated by the colour dots and lines (orange), which also correspond with the catchment groupings by land cover (Table 1). Years are hydrological years.

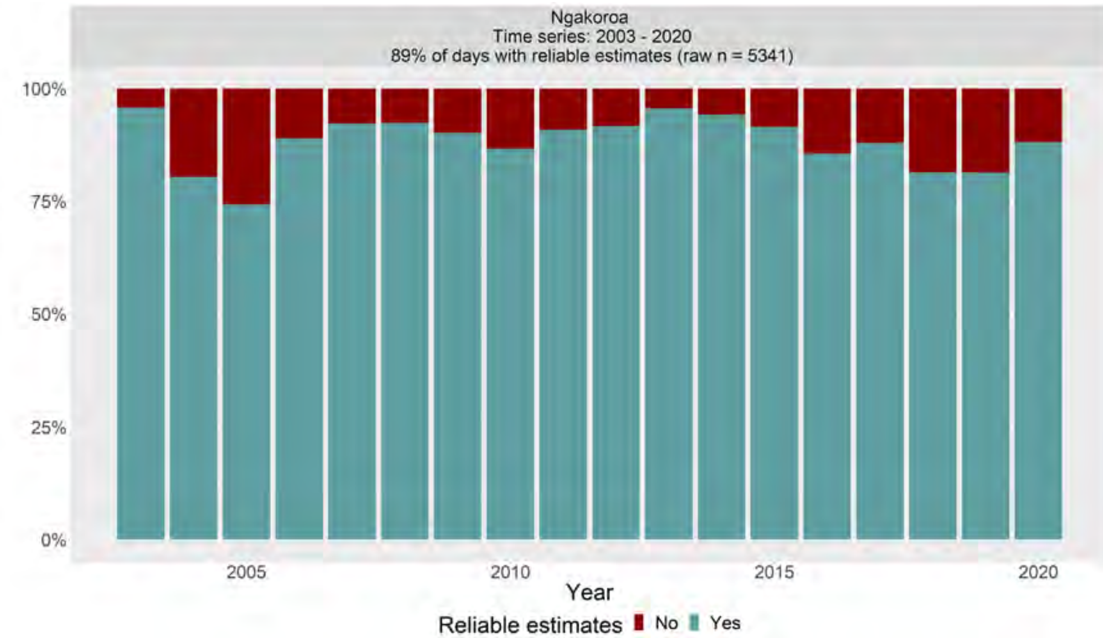


Metabolic estimate calculation

Time series of metabolic estimates (reliable data only)

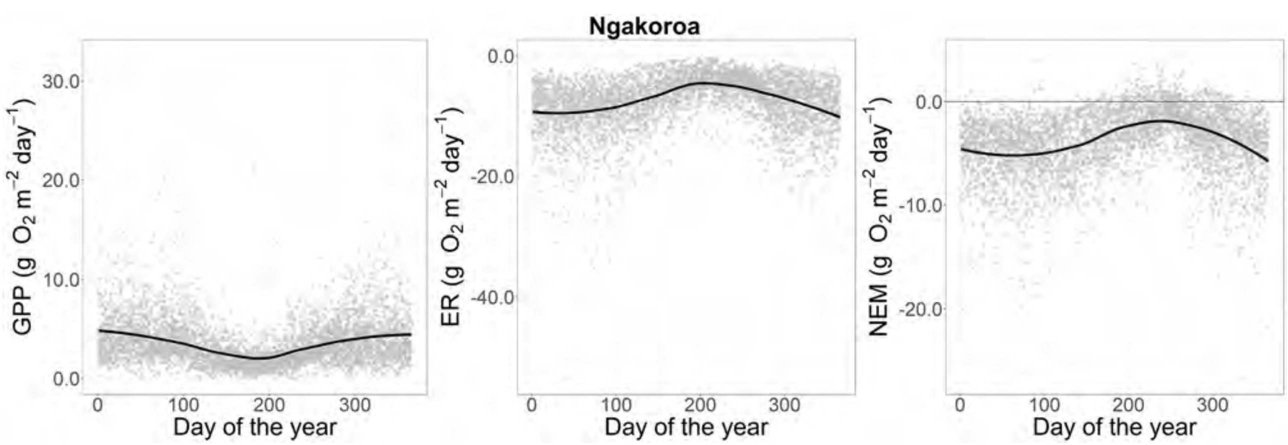


Per cent of days with reliable data based on the results of the metabolic estimates calculations.

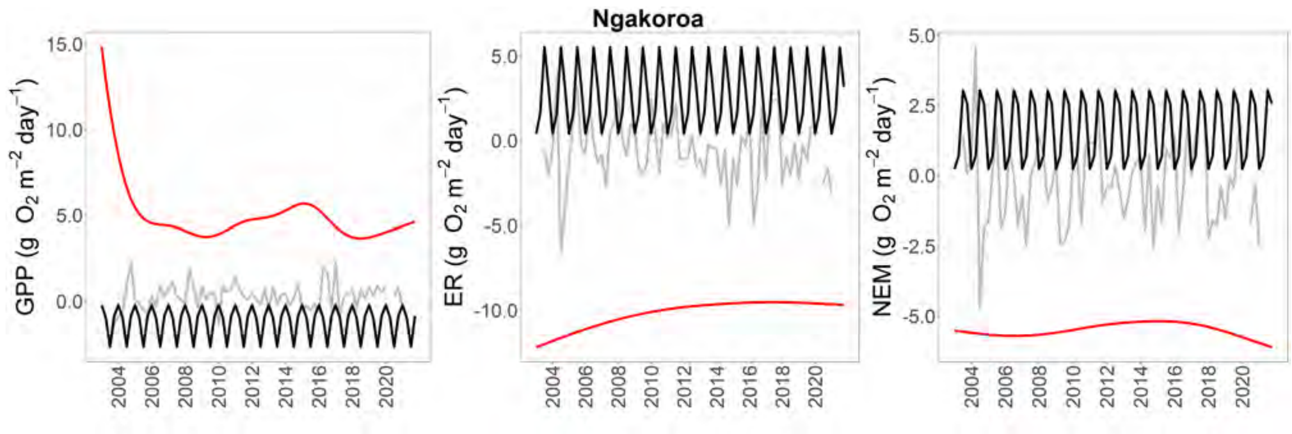


Analysis of metabolic results

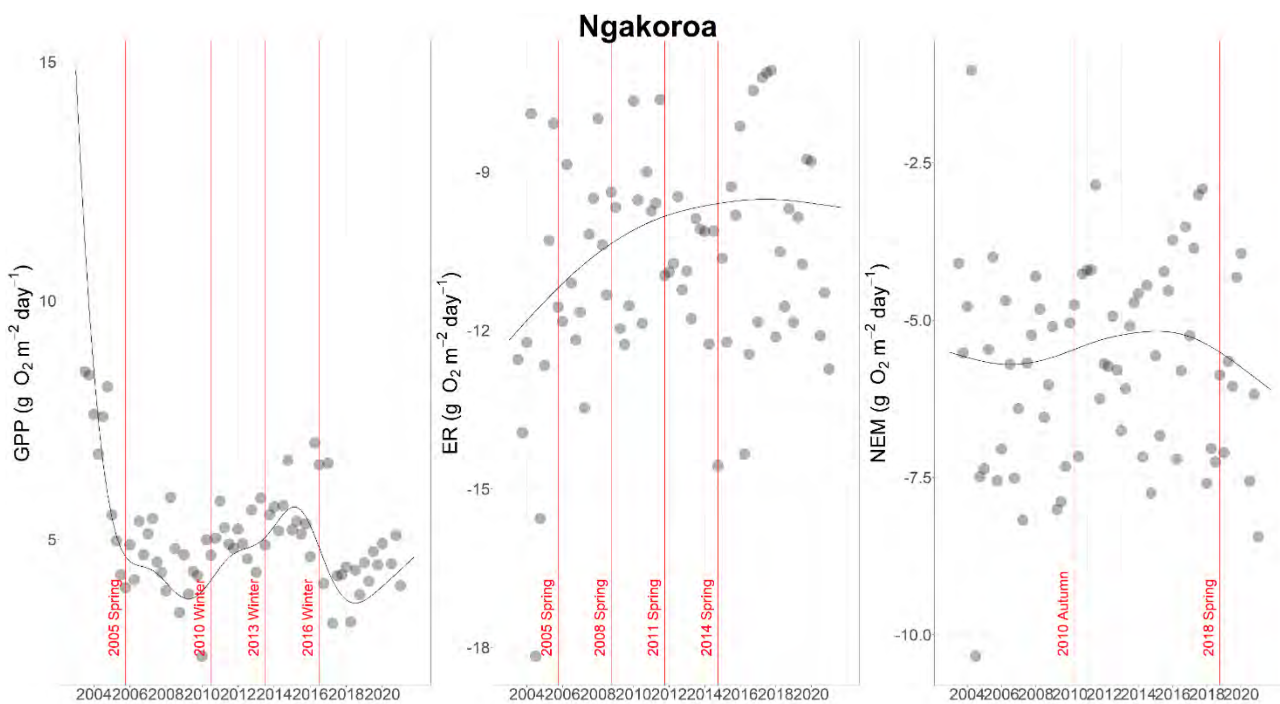
Seasonal distribution of metabolic estimates. One at the starts of the x-axis represents the 1st of January.



Time series decomposition analysis. The red line shows the long term trend, the black line shows the seasonal component of the trend, and the grey line shows the anomaly.



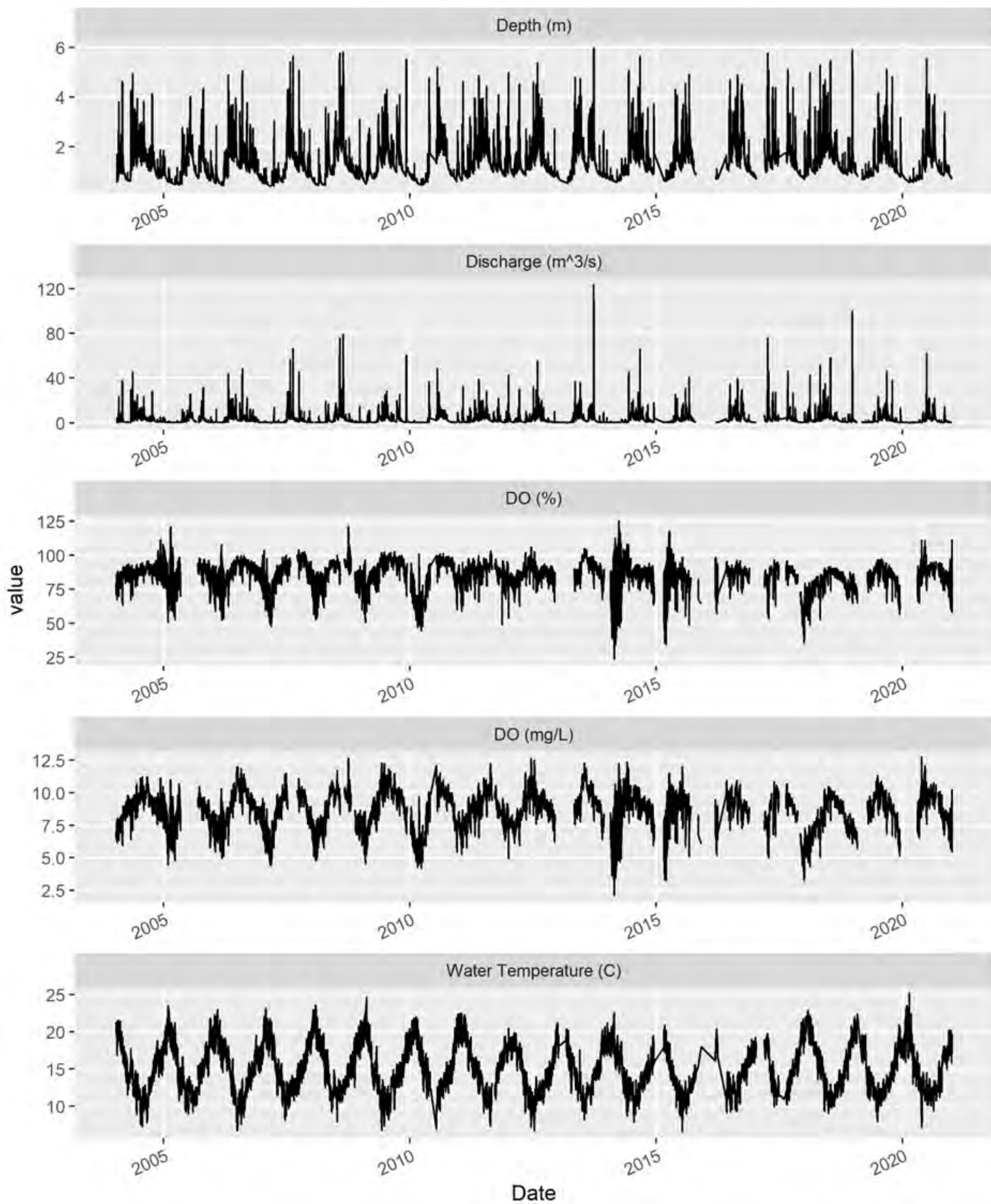
Point change analysis of the long-term trend (shown in black). The red vertical lines show suggested changes on the mean value of the metabolic estimates. The points show the anomaly for each summary data point (data was summarised by season and year).



Kaipara

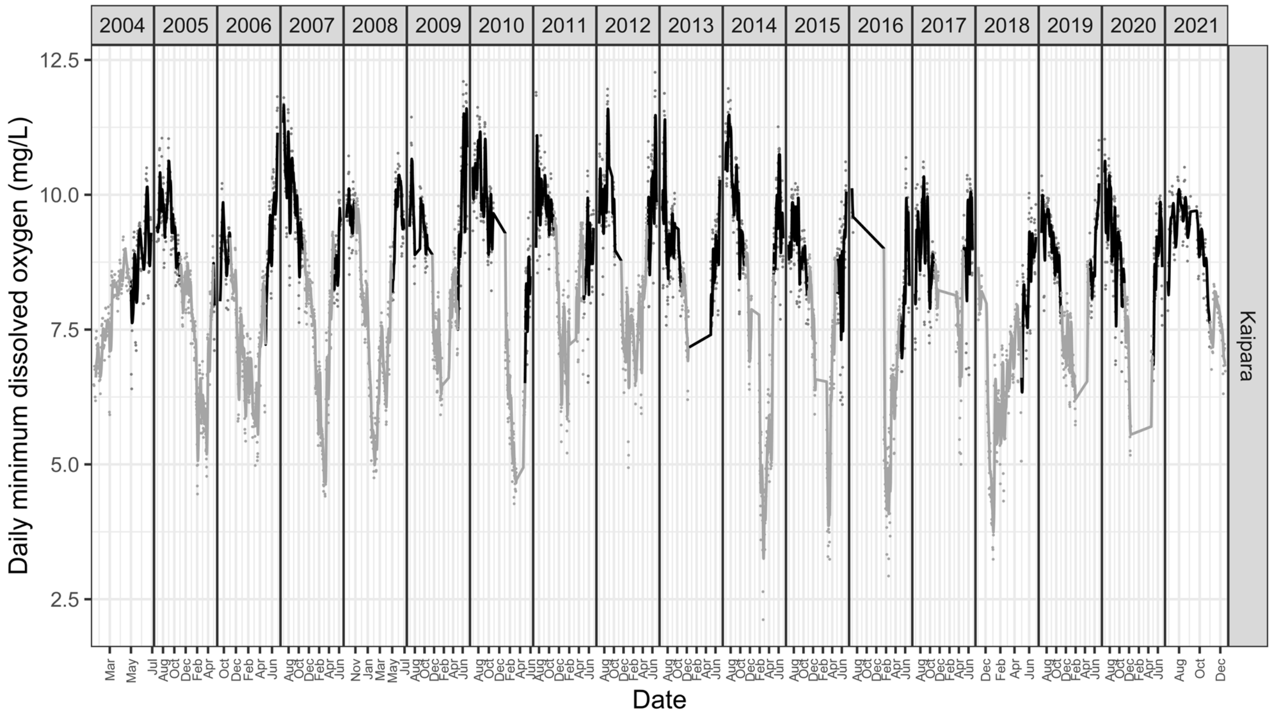
Raw data compilation

Original data Timeseries. Data with QC codes 42 and 43 have been removed.



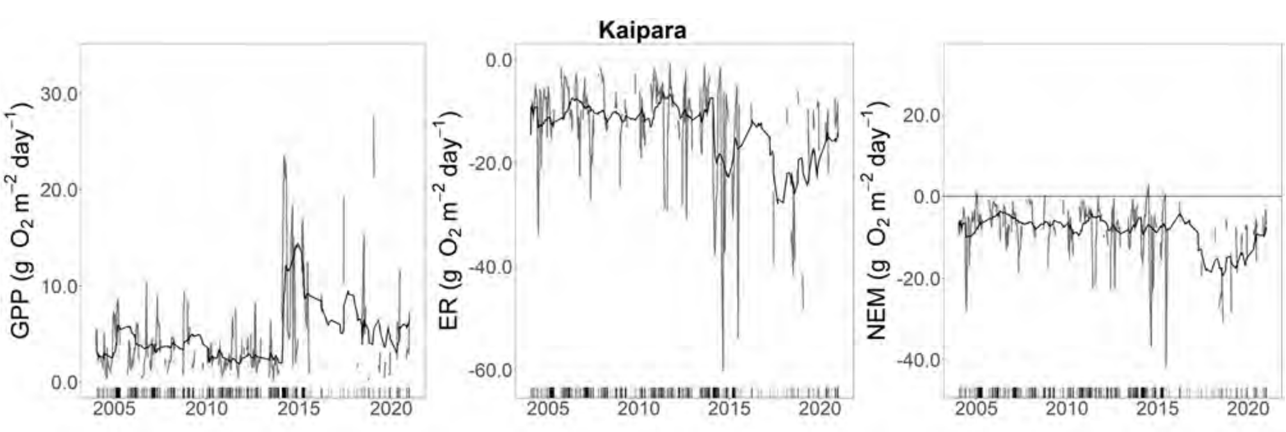
Oxygen data reporting

Timeseries of minimum dissolved oxygen. Points show the daily minimum values, and lines show the 7-day mean value. The summer period is indicated by the colour dots and lines (grey), which also correspond with the catchment groupings by land cover (Table 1). Years are hydrological years.

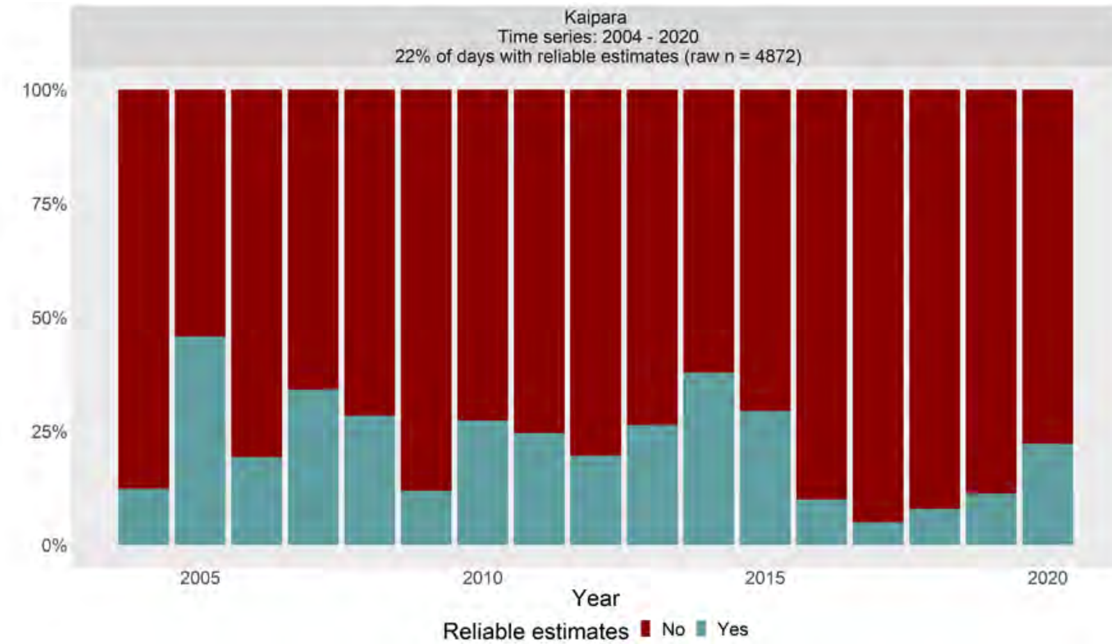


Metabolic estimate calculation

Time series of metabolic estimates (reliable data only)

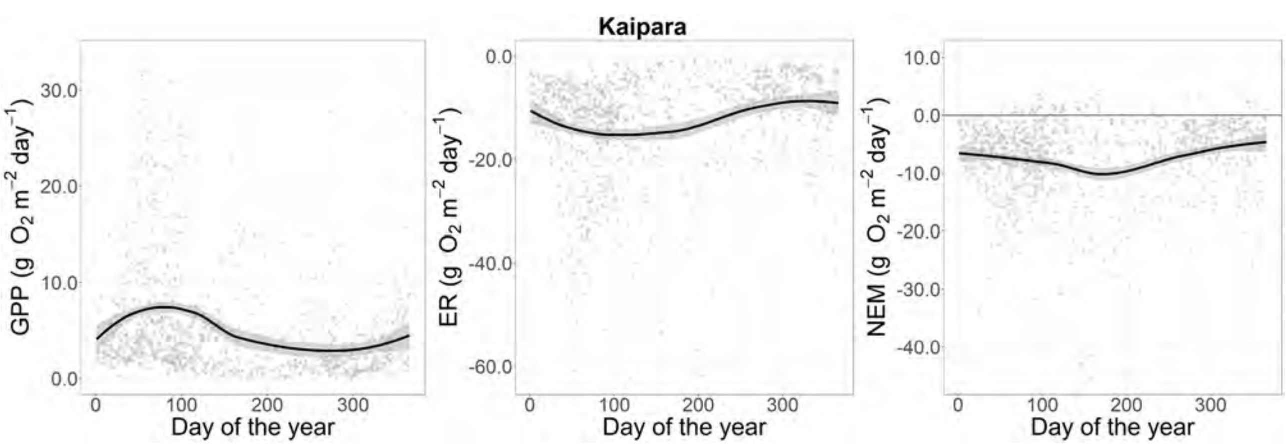


Per cent of days with reliable data based on the results of the metabolic estimates calculations.

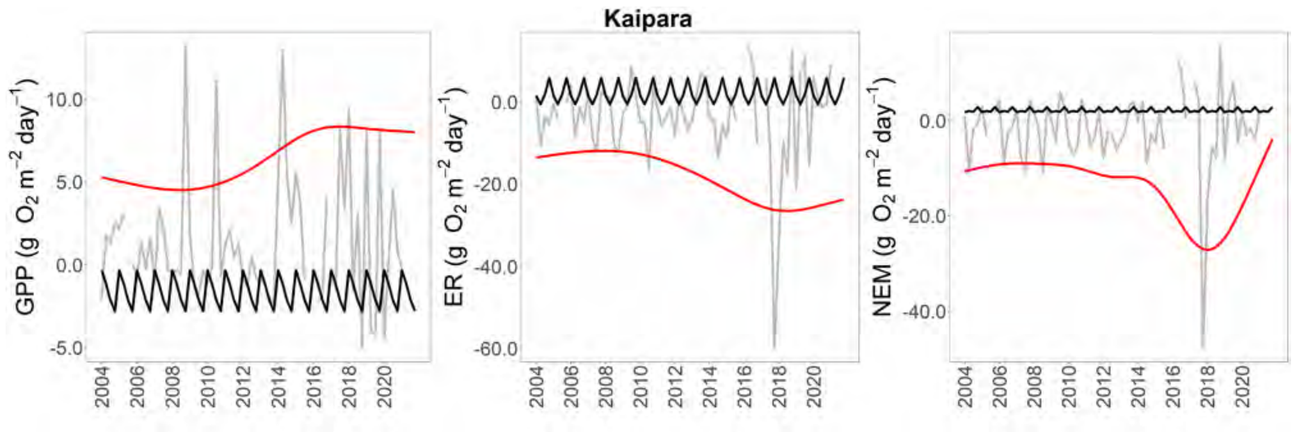


Analysis of metabolic results

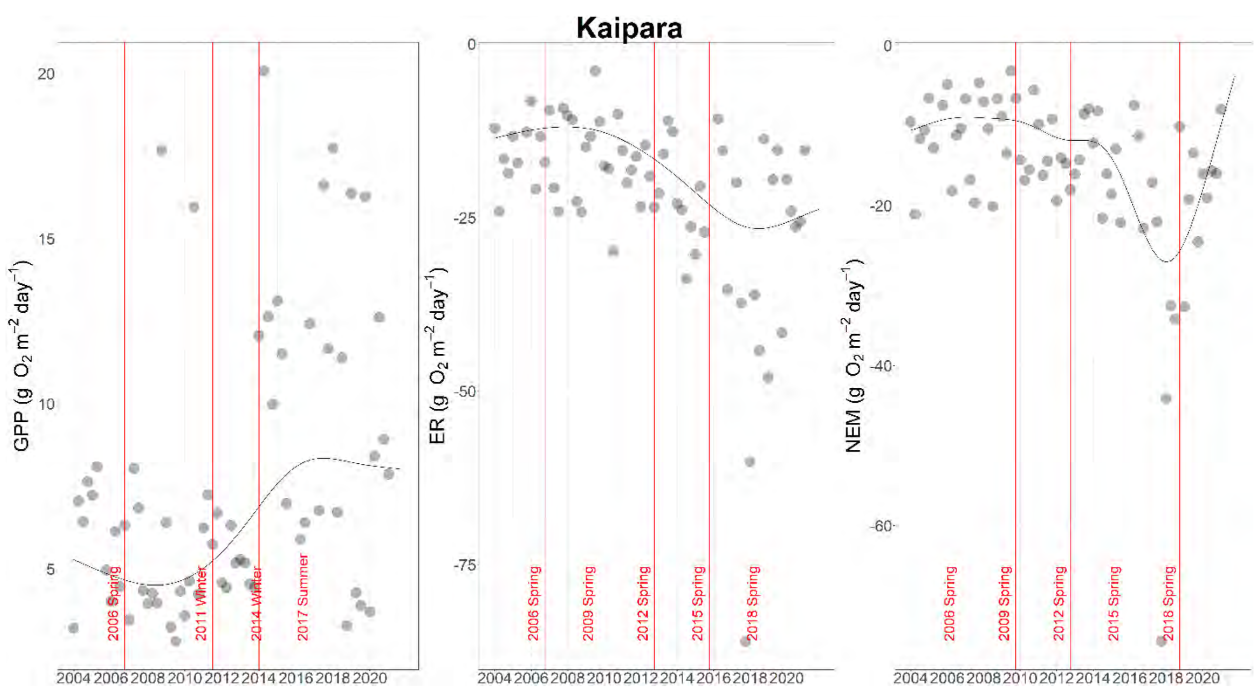
Seasonal distribution of metabolic estimates. One at the starts of the x-axis represents the 1st of January.



Time series decomposition analysis. The red line shows the long-term trend, the black line shows the seasonal component of the trend, and the grey line shows the anomaly.



Point change analysis of the long-term trend (shown in black). The red vertical lines show suggested changes on the mean value of the metabolic estimates. The points show the anomaly for each summary data point (data was summarised by season and year).

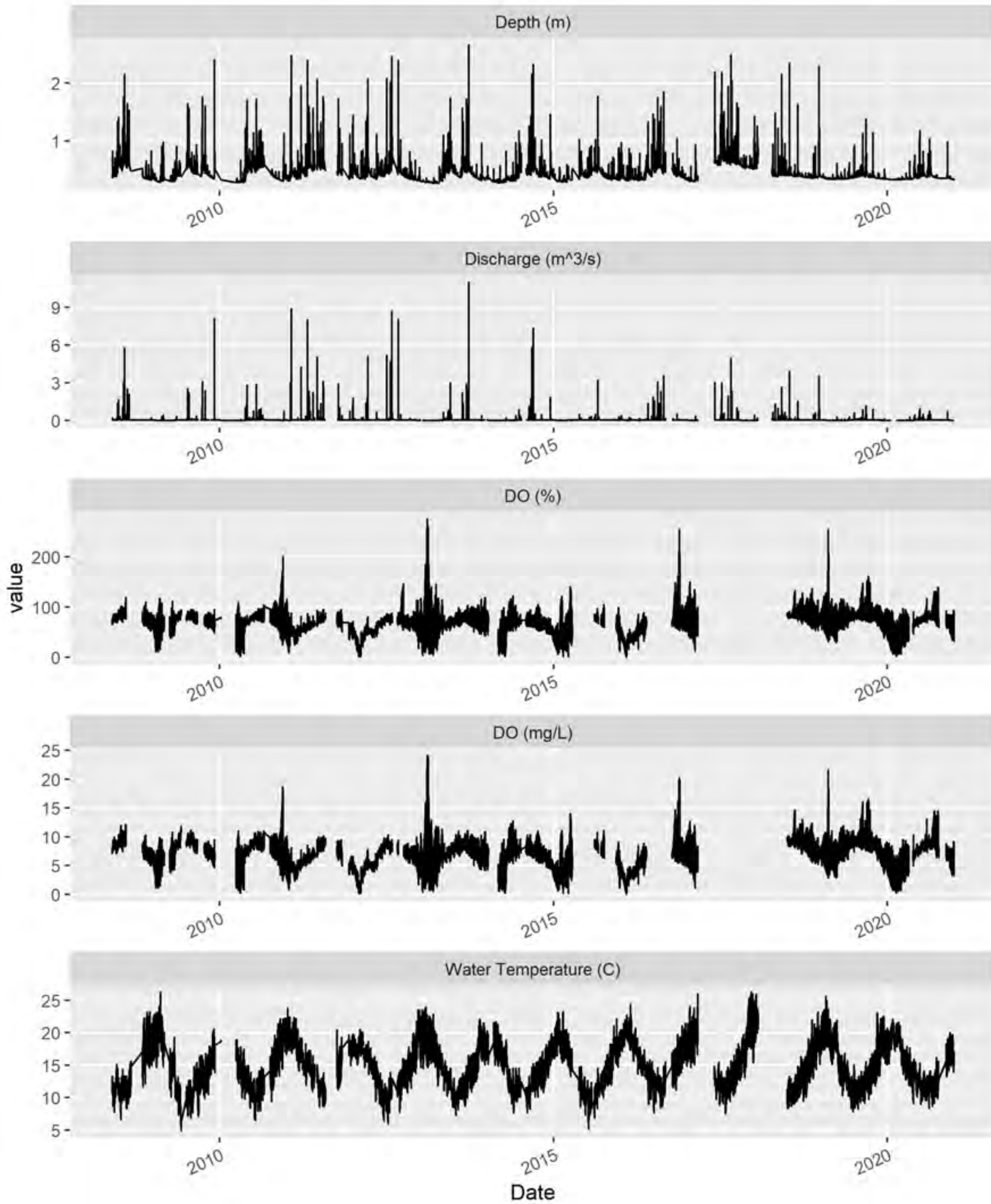


Lower Vaughan

Lower Vaughan is occasionally influenced by tidal fluctuations. The extent of this effect and whether it has any influence on DO concentrations would be worthy of further investigation.

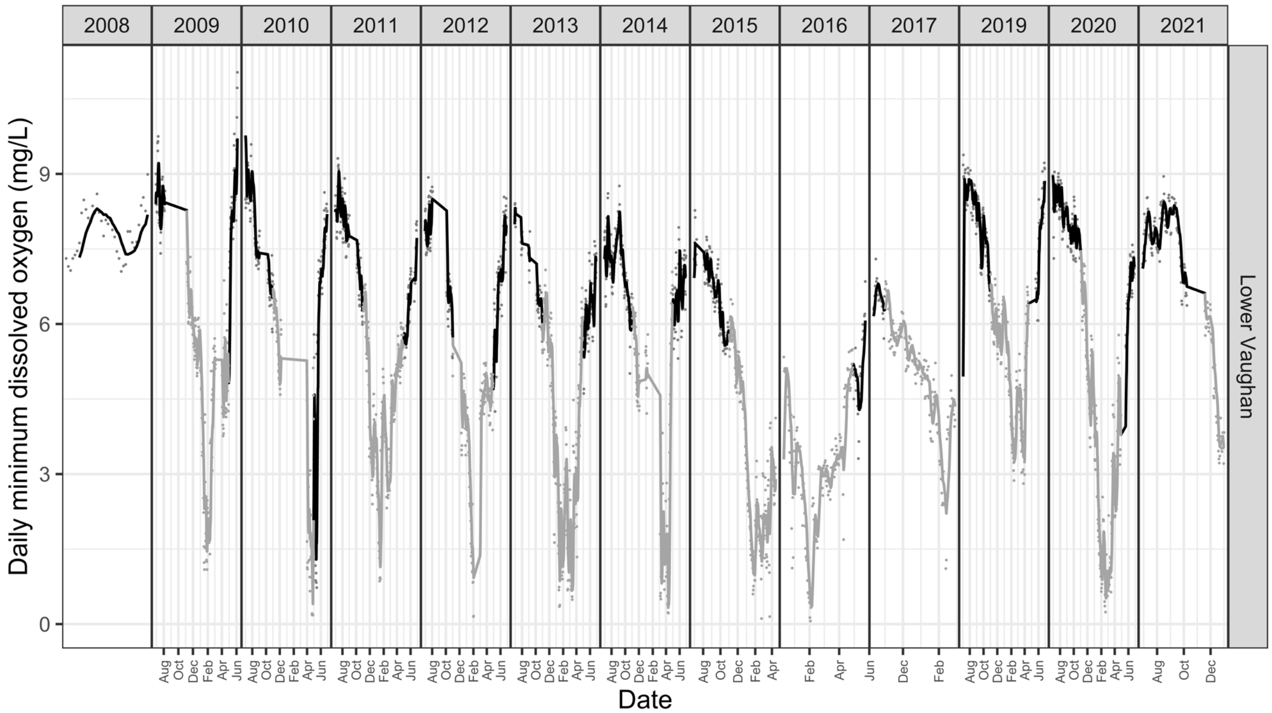
Raw data compilation

Original data Timeseries. Data with QC codes 42 and 43 have been removed.



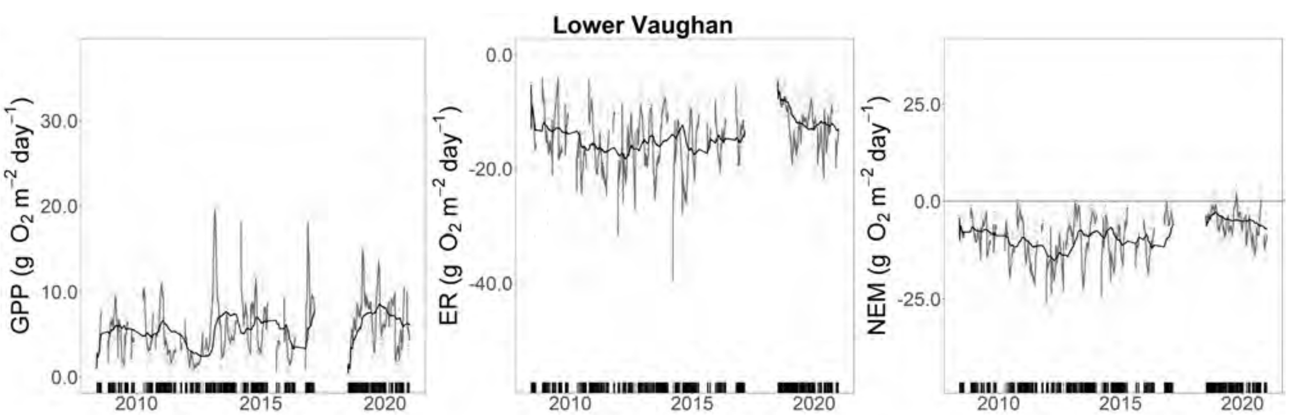
Oxygen data reporting

Timeseries of minimum dissolved oxygen. Points show the daily minimum values, and lines show the 7-day mean value. The summer period is indicated by the colour dots and lines (grey), which also correspond with the catchment groupings by land cover (Table 1). Years are hydrological years.

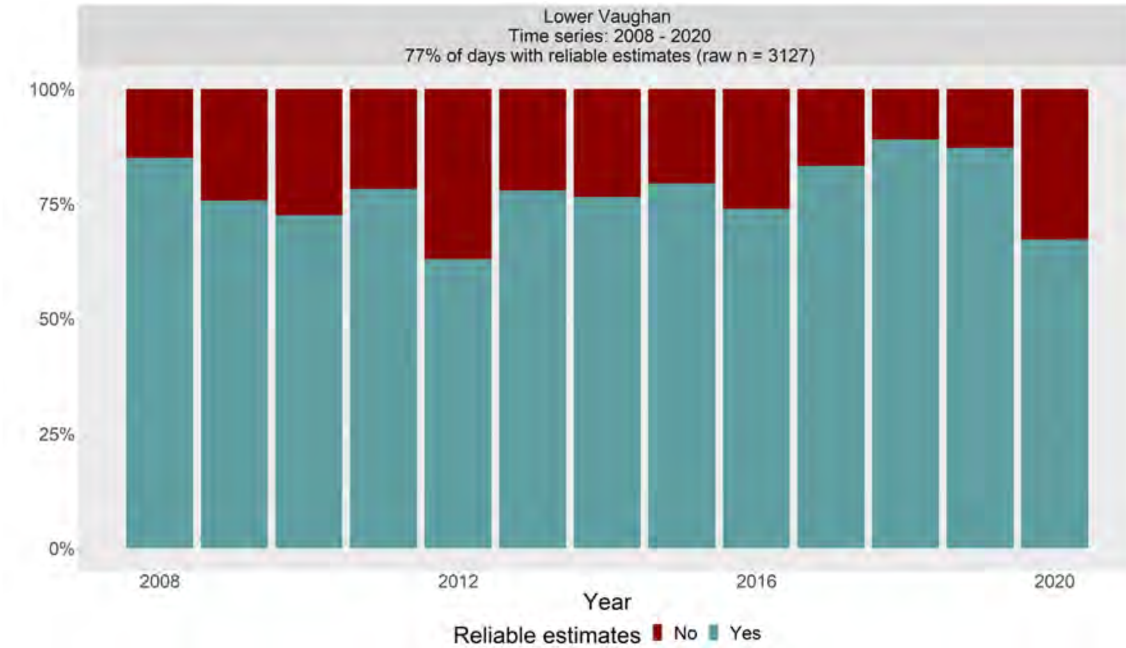


Metabolic estimate calculation

Time series of metabolic estimates (reliable data only)

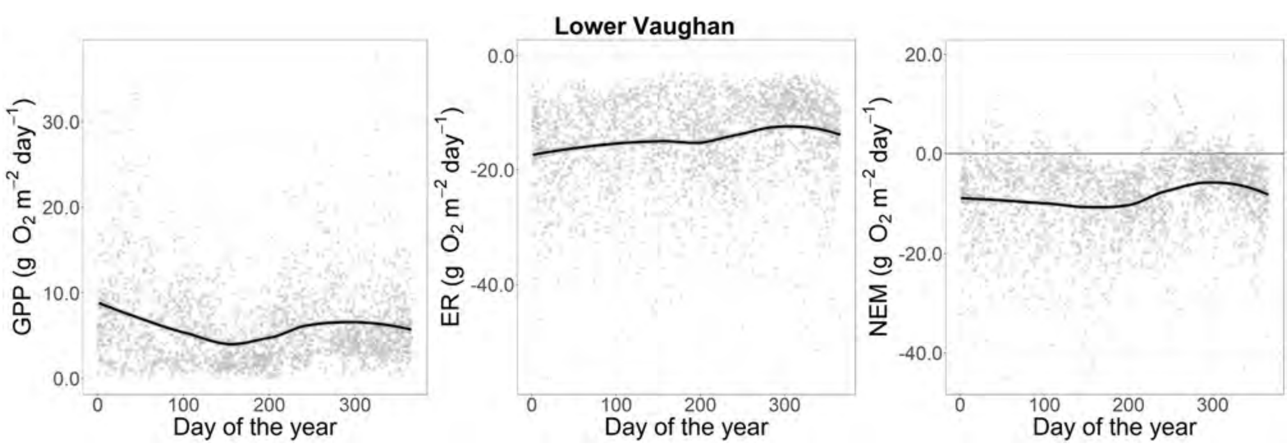


Per cent of days with reliable data based on the results of the metabolic estimates calculations.

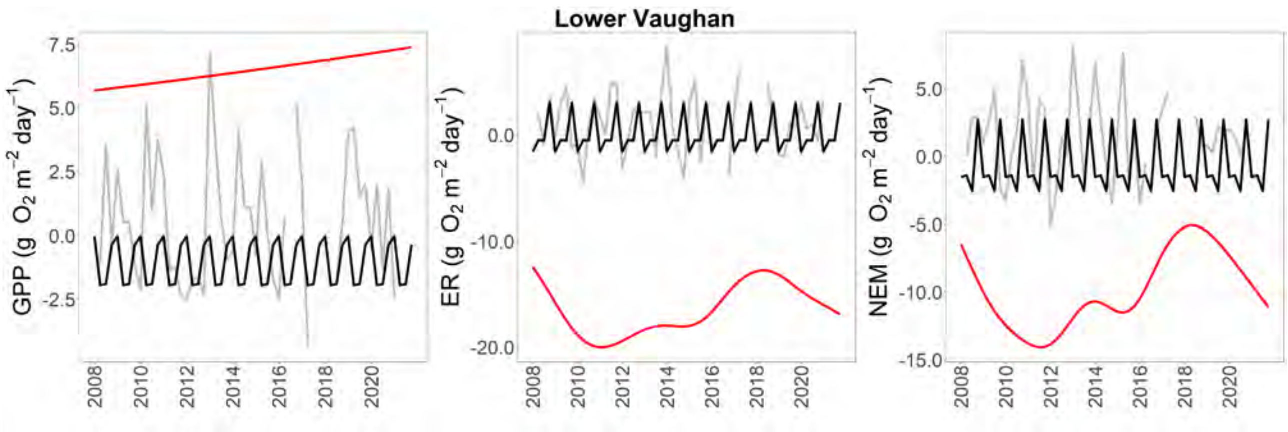


Analysis of metabolic results

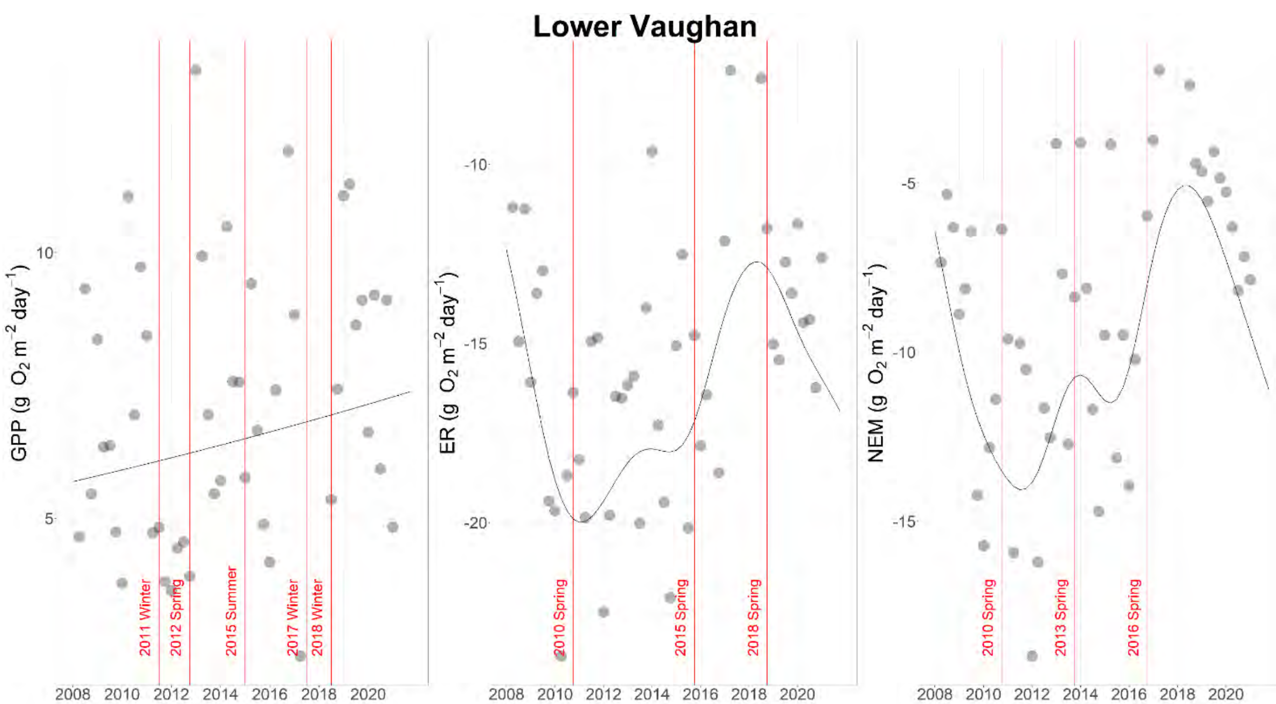
Seasonal distribution of metabolic estimates. One at the starts of the x-axis represents the 1st of January.



Time series decomposition analysis. The red line shows the long term trend, the black line shows the seasonal component of the trend, and the grey line shows the anomaly.



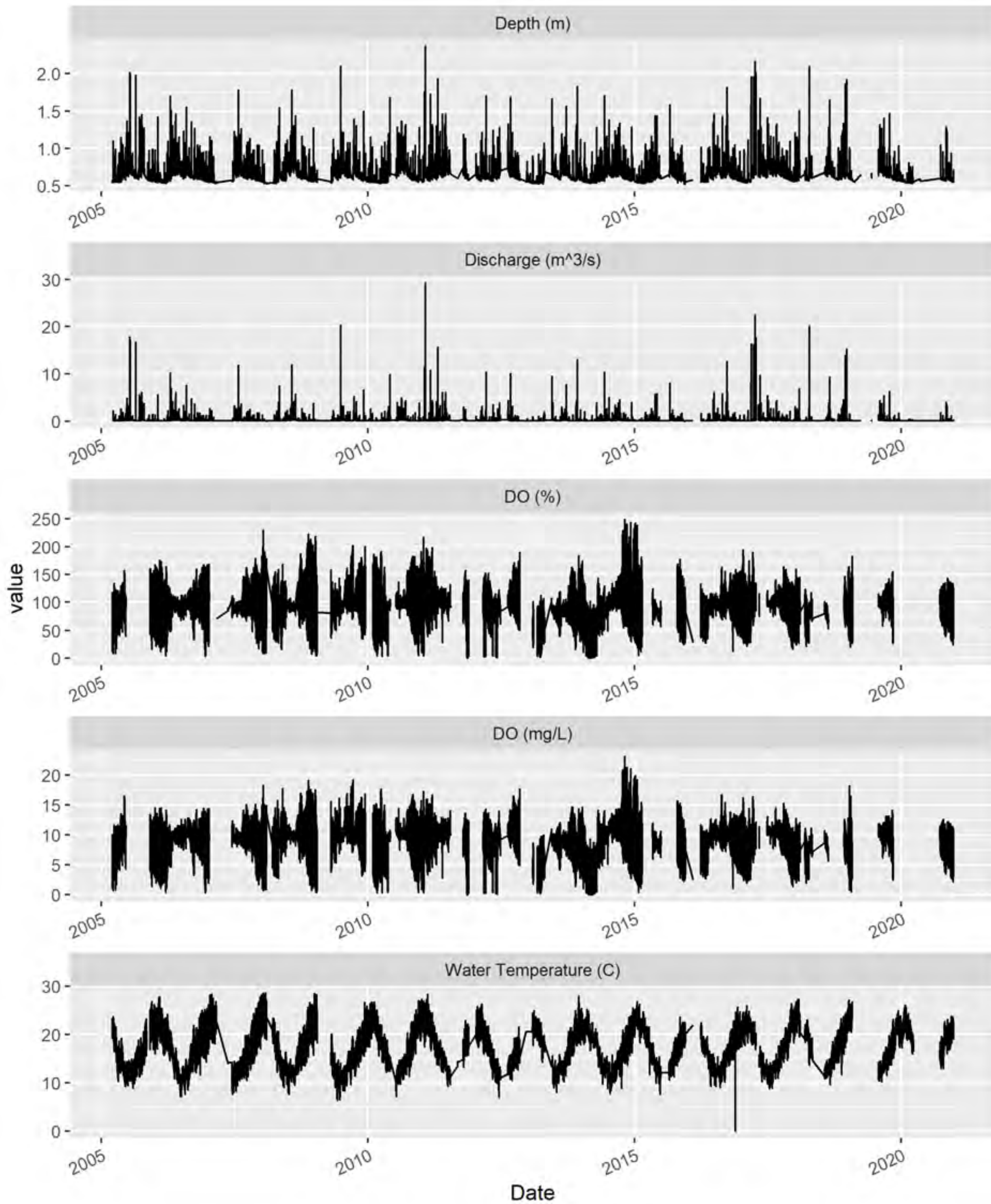
Point change analysis of the long-term trend (shown in black). The red vertical lines show suggested changes on the mean value of the metabolic estimates. The points show the anomaly for each summary data point (data was summarised by season and year).



Puhinui

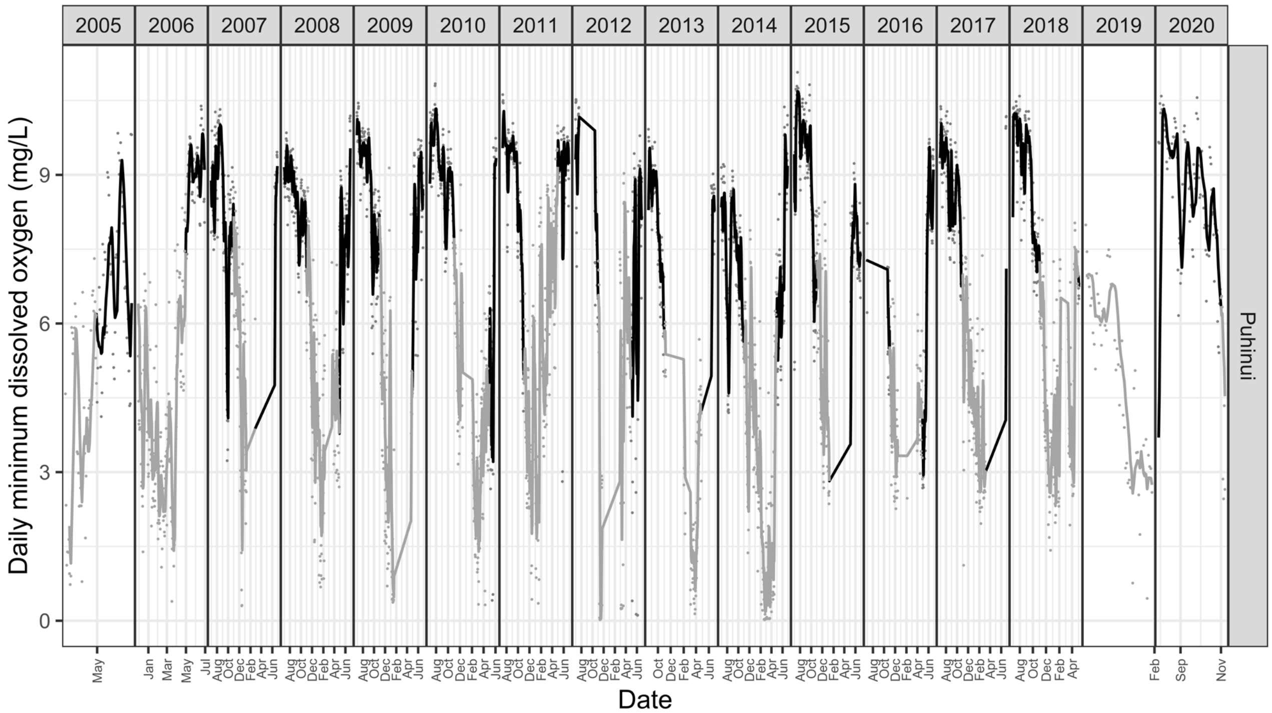
Raw data compilation

Original data Timeseries. Data with QC codes 42 and 43 have been removed.



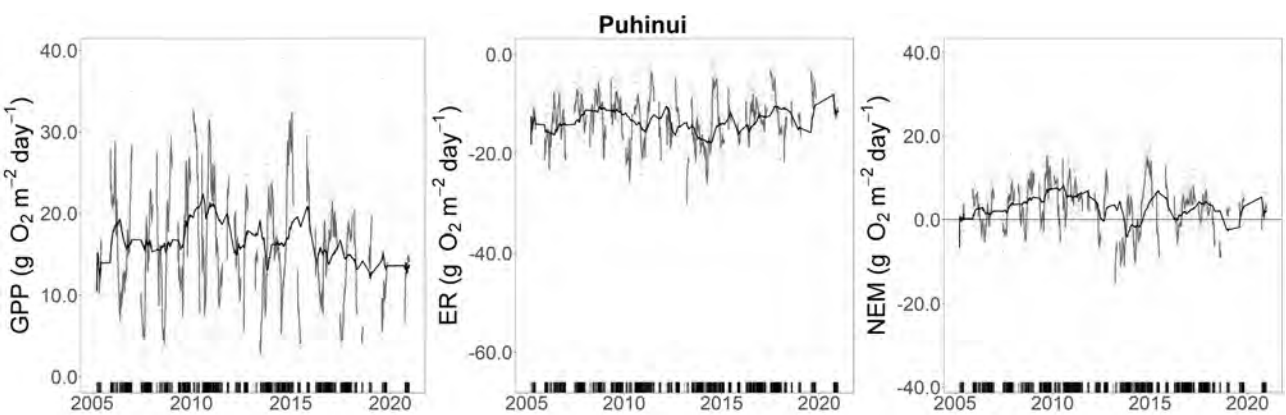
Oxygen data reporting

Timeseries of minimum dissolved oxygen. Points show the daily minimum values, and lines show the 7-day mean value. The summer period is indicated by the colour dots and lines (grey), which also correspond with the catchment groupings by land cover (Table 1). Years are hydrological years.

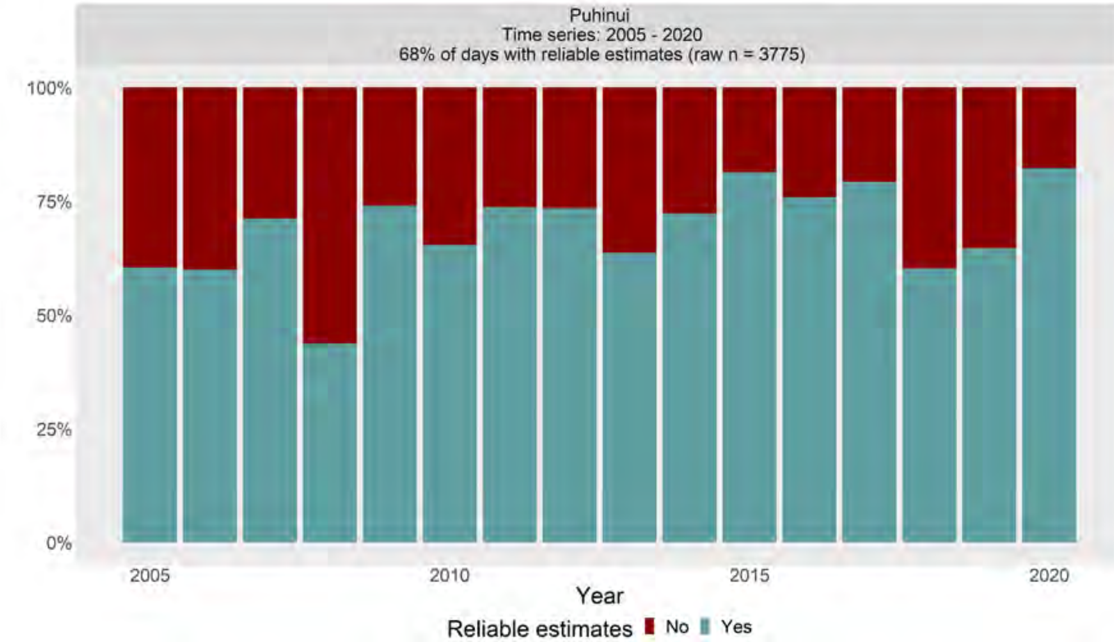


Metabolic estimate calculation

Time series of metabolic estimates (reliable data only)

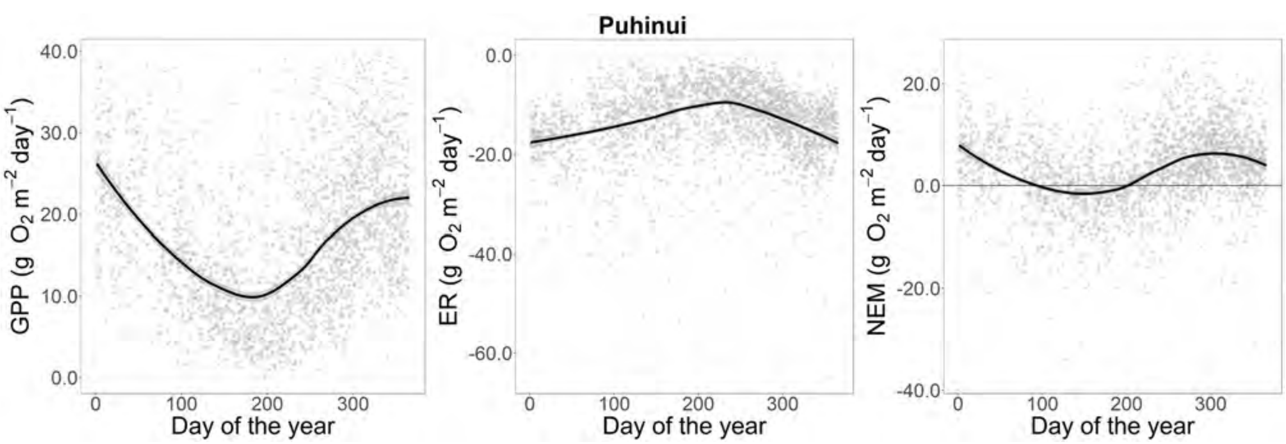


Per cent of days with reliable data based on the results of the metabolic estimates calculations.

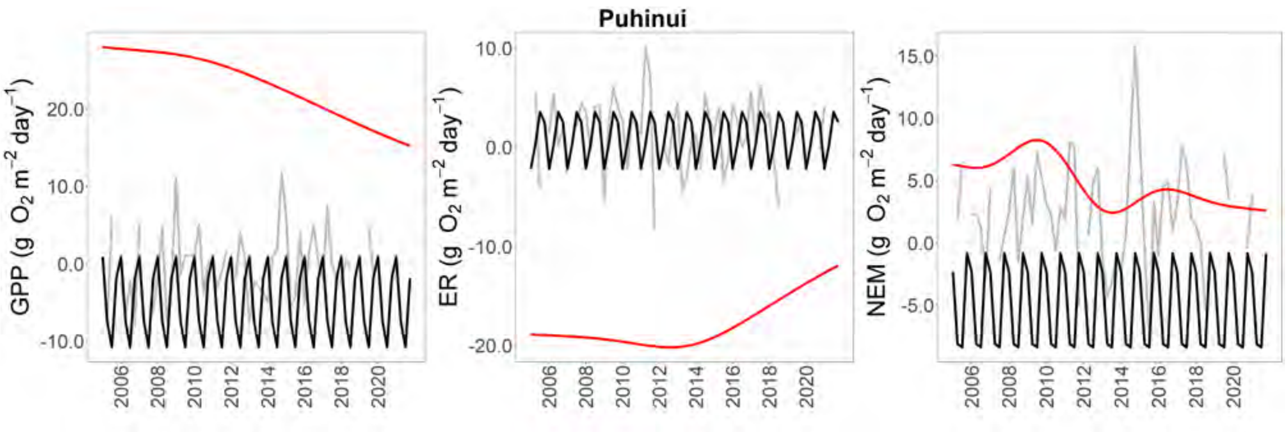


Analysis of metabolic results

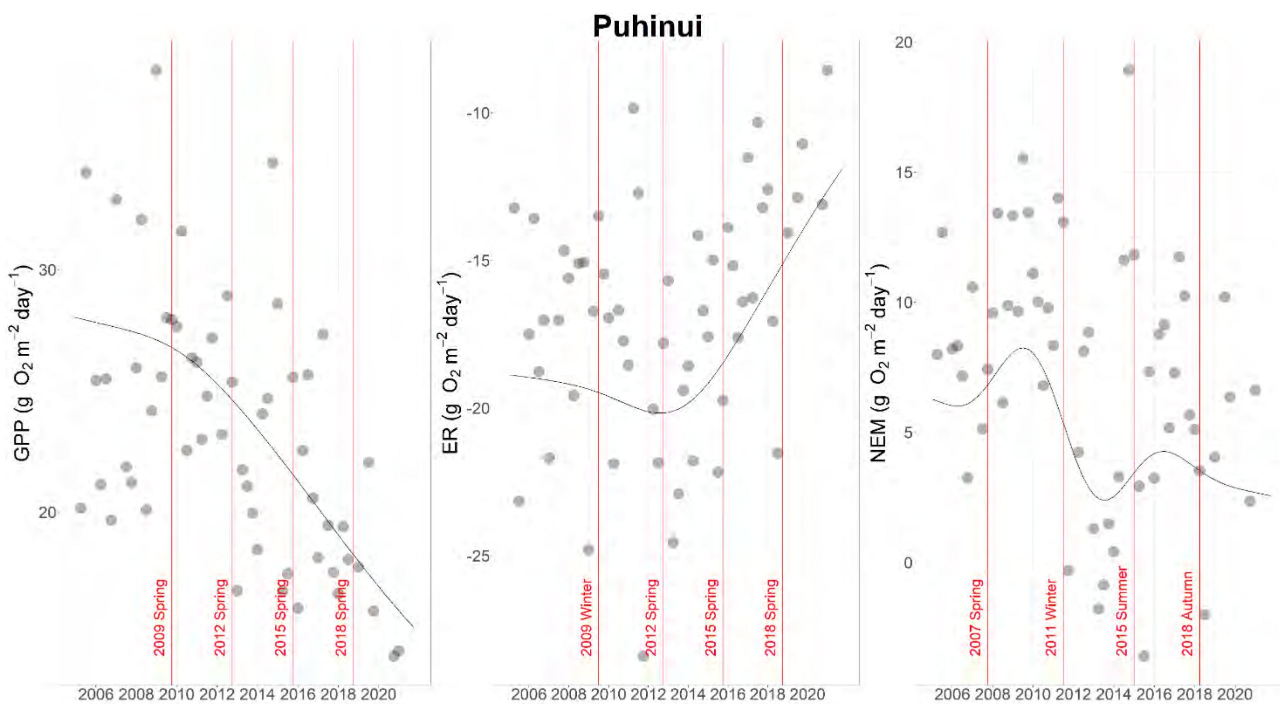
Seasonal distribution of metabolic estimates. One at the starts of the x-axis represents the 1st of January.



Time series decomposition analysis. The red line shows the long-term trend, the black line shows the seasonal component of the trend, and the grey line shows the anomaly.



Point change analysis of the long-term trend (shown in black). The red vertical lines show suggested changes on the mean value of the metabolic estimates. The points show the anomaly for each summary data point (data was summarised by season and year).



Find out more: rimu@aucklandcouncil.govt.nz
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