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# Dissolved oxygen monitoring and ecosystem metabolism

Dear Brennan,

This letter provides advice to Taranaki Regional Council (TRC) on continuous dissolved oxygen (DO) monitoring and how to apply the ecosystem metabolism attribute, as required in the National Policy Statement for Freshwater Management 2020 (NPS-FM 2020). I provide guidance on recommended sampling sites, placement of monitoring equipment, sampling frequency and duration, use of sensors with wipers, requirements for average reach depth measurement and calculation of ecosystem metabolism. I also summarise the advice I provided to Andrew Whiteford (Data analyst, TRC) on data processing and quality control procedures for DO data. Finally, I provide advice on interpretation of ecosystem metabolism results and potential attribute bands.

I understand that there are two main purposes for DO and ecosystem metabolism monitoring in the Taranaki Region: first, regional monitoring at key sites is used to determine baseline conditions applicable to each of the freshwater management units (FMUs) across the region; second, there is a need to consider developing a DO monitoring network for below point source discharges, which can be used to assess the effects of these discharges.

Ecosystem metabolism (the combination of gross primary production [GPP] and ecosystem respiration [ER]) is one of the attributes of the compulsory ecosystem health value in the NPS-FM 2020 and the only attribute representing the ecological processes component of ecosystem health. Continuous DO monitoring data are used to calculate ecosystem metabolism. DO itself is a critical water quality indicator and is also included as an attribute of the compulsory ecosystem health value in the NPS-FM 2020.

## Sampling site selection

### General considerations

The broader design of a DO / ecosystem metabolism monitoring programme involves many of the same requirements applicable to any other monitoring programme in terms of representativeness, health and safety requirements, and access. Additionally, there are some specific elements that need to be considered. For example, there are several pragmatic requirements in the placement of DO data loggers for the recording of DO over time. First, the logger should be placed in a position where the water is well mixed without any possibility of vertical or horizontal stratification or significant variations in DO concentration. This is to ensure that the recorded DO concentrations are representative of the full water column. The best place is typically as close as possible to the central flow (thalweg). Second, the logger should be placed in a position to ensure DO measurements can occur over a wide range of water levels and flows. As such, placing the logger in the vicinity of stage height instrumentation may be suitable as long as flow is not impeded. Third, consideration should be given to accessibility and risk of damage. Loggers need to be secure from potential flood damage and ideally located where vandalism is less likely. However, loggers also need to be accessible for regular data downloading, calibration and maintenance.

DO and metabolism at a site reflects conditions not just at that site, but also in a broad reach of river upstream of the monitoring site. There is generally limited small-scale variability in DO, assuming that measurements are taken within the main flow where the water is well mixed. The length of the reach influencing DO and metabolism will vary depending on the characteristics of the site, but it can be estimated from the following equation:

$$D = 3v/K,$$

where v is the mean water velocity and K is the reaeration rate. For example, in a river flowing at a mean velocity of 0.2 m/s and having a reaeration coefficient of 10 $day^{-1}$ (i.e. 0.000116 $s^{-1}$), DO and ecosystem metabolism measured at a particular site would be influenced by biological activity and conditions over a 5.2 km reach upstream of the DO recorder.

The model used for calculating metabolism assumes that the reach upstream of the logger is relatively homogenous, so it is wise to avoid areas with considerable amounts of upwelling groundwater, sharp transitions in land use / channel morphology, or significant tributary junctions. If these points are of interest, then I would recommend locating the logger at least 3v/K downstream of these features.

### Average reach depth measurement

In addition to continuous DO measurement, an estimate of mean depth in the river reach upstream of the DO sensor location is required to convert volumetric metabolism measurements to areal measurements and ensure metabolism estimates can be compared between sites. To estimate mean depth, I recommend taking 10–20 depth measurements at equal off-set distances across each of five transects upstream of the sensor location. The transects should be located upstream of the sensor location at intervals of about five times the stream width apart over a reach of about 20 times the stream width, thus capturing the variation in channel form at the site. If the channel morphology is very variable, then depth measurements across more transects should be taken.

If a water stage height recorder is at the site, the stage must be measured when the depths are measured; this will ensure that change in average depth with changing flow can be estimated. Ideally, a relationship between stage height and mean depth should be developed at each site (using multiple measures of mean reach depth at different flows / water levels) so that an estimate of mean depth on any day can be used to accurately convert the volumetric metabolism estimates to daily areal measures. In the absence of such a relationship, mean depth can be assumed to vary linearly with stage height (if stage height data are available). If no information is available on how mean depth will change with flow, then mean depth could be assumed to be constant despite changes in flow and water level; although, this is obviously a poor assumption. Depth measurements should be repeated after any substantial flood or change in bed profile to determine if there has been a change in the relationship between water stage height and mean depth. However, if little change is expected, then depth surveys will only need to be repeated occasionally (e.g. every 5–10 years).

### Regional monitoring

A key requirement of regional monitoring is appropriate representative coverage of the region. Ideally, all FMUs and river types should be represented within regional monitoring. I understand that only the Coastal Terraces, Pātea and Volcanic Ring Plain FMUs have representative continuous DO monitoring sites. Therefore, I recommend that installation of continuous DO monitoring sites within the Northern Hill Country, Waitara and Southern Hill Country FMUs is a high priority.

I understand that the two sites in the Coastal Terraces FMU are located downstream of two large industrial zones, which are not characteristic of the rest of the FMU. Therefore, I recommend that sites in the upper reaches of at least one waterway within the Coastal Terraces FMU are considered for inclusion in the DO / ecosystem metabolism monitoring programme.

I also understand that the sites in the Pātea FMU are positioned in upper and mid-catchment locations. There would be benefit in installing a site in the lower reaches of the Pātea River to represent the cumulative effect of land use and discharges in the upper and middle parts of this FMU.

I understand that the three sites in the Volcanic Ring Plain FMU are located at the bottom of their respective catchments. It would be valuable to have a site representing the upper parts of these catchments.

Ideally, some sites within the monitoring network should be chosen as being representative of reference condition. Sites in the upper reaches of waterways in the Volcanic Ring Plain FMU might be suitable reference sites. However, it may also be necessary to determine reference condition within each FMU and / or for a range of stream types.

There may also be a need to select DO monitoring sites where impacts are suspected or apparent using other indicators. For example, DO and ecosystem metabolism monitoring may help to diagnose the cause of low macroinvertebrate community index (MCI) scores and provide information to guide management actions.

Measurement of ecosystem metabolism in small, very turbulent streams can be difficult because of the large amount of reaeration of oxygen that occurs compared to the changes in DO concentration associated with biological activity (i.e. ecosystem metabolism) (Young et al. 2008). DO concentrations in these types of waterways are likely to be close to 100% saturation constantly, and therefore they are probably not a priority for DO monitoring.

### Monitoring of point source discharges

Assessment of the effects of a discharge on DO concentrations requires upstream and downstream monitoring of DO. The upstream monitoring location needs to be as close as possible to, but upstream of, the discharge point. However, the best downstream location for monitoring the full effects of the discharge on DO requires some consideration. There is a long history in the literature on DO sags that can occur downstream of discharges of organic waste and sewage. The Streeter–Phelps equation (Streeter 1925) represents this process and relates biological oxygen demand (BOD) and oxygen reaeration of the water with DO concentrations at different points downstream of a waste discharge. The distance downstream is directly related to the time component of the Streeter–Phelps equation and the velocity of the stream.

The lowest daily minimum DO concentrations (or DO sag) will not occur immediately downstream of the discharge, but rather some distance downstream (Xcrit) as the breakdown of the waste material reduces DO concentrations (Figure 1). Further downstream (beyond Xcrit), the minimum DO concentrations rise again as the rate of oxygen uptake caused by breakdown of the waste decreases, which is due to the decreasing BOD of the remaining material (Figure 1). The location of the lowest daily minimum DO concentration downstream of the discharge (Xcrit) will change with flow, as the water will travel more quickly, and thus further, during high flows.

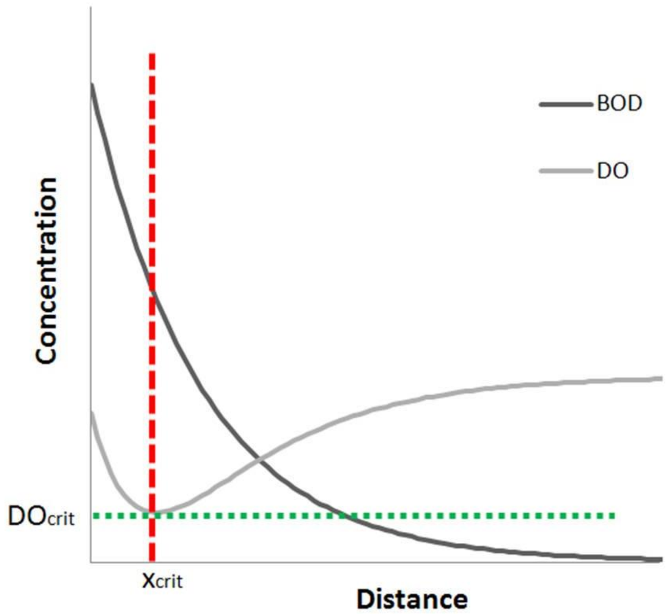


Figure 1. Changes in the concentration of dissolved oxygen (DO) and biological oxygen demand (BOD) predicted downstream of a waste discharge by the Streeter–Phelps equation (from Streeter–Phelps equation – Wikipedia).

The basic Streeter–Phelps equation makes a variety of assumptions, including in particular that the decomposition of waste material is the only mechanism causing DO reductions in the water, and that the reaeration of DO is the only mechanism of DO renewal to the water. These assumptions are relatively poor in most situations since uptake and release of DO by periphyton on the riverbed is another important mechanism affecting DO dynamics. Nevertheless, the equation provides some guidance on the distance downstream where minimum DO concentrations are likely to occur and emphasises that this location will change with flow. Predictions from the equation and observations of minimum DO concentrations indicate that minimum DO concentrations in large rivers like the Manawatu are expected to occur between 1–14 km downstream of a discharge, with a shorter distance during extreme low flows and a longer distance at higher flows (Young and Kelly 2023).

## Sampling frequency and duration

Dissolved oxygen can vary considerably within a daily period, so the measurement of DO is required on a relatively high frequency basis. I support the 15-minute sampling frequency that TRC has adopted at their current DO monitoring sites, which is also consistent with advice in the DO National Environmental Monitoring Standard (NEMS 2016).

Based on the requirements of the NPS-FM 2020, the absolute minimum period of continuous DO data required to enable calculation of the DO attribute assessment statistic is the whole summer period (1 November to 30 April), whereas the ecosystem metabolism attribute assessment statistic needs to be calculated over at least one period of 7 consecutive days over the same summer period. This specified 'summer' period is likely to represent worst case conditions due to intense sunlight, low flows, warm water temperatures and long sunlight hours, which contribute to peak annual rates of metabolism (and minimum DO values) (Casanovas et al. 2022). However, I recommend that continuous DO monitoring should be conducted throughout the whole year to ensure any instances of low DO or extreme ecosystem metabolism outside the summer period are detected. Monitoring throughout the whole year will also give a good indication of the frequency and duration of low DO / extreme ecosystem metabolism occurrences and enable the assessment of annual patterns in DO and ecosystem metabolism.

## Data processing and quality control approaches

Andrew Whiteford provided me with copies of a draft data processing process, a data processing procedure and, of most interest, a document on continuous DO data processing. We also met and discussed the data processing procedures and reviewed examples of raw and adjusted DO data. This helped identify common data processing issues and showed the effectiveness of quality control (QC) processes. Key items that were discussed include:

<u>Data processing philosophy for DO data.</u> Data processing procedures for flow records typically aim to avoid gaps in the flow record wherever possible. Synthetic flow data are often used to fill gaps when necessary. However, in my opinion, a different data processing philosophy is required for DO data. It is better to have gaps in the DO record, rather than including data with questionable accuracy.

<u>Sensor fouling.</u> Fouling of the DO sensor membrane can be an issue, resulting in inaccurate measurements of DO. This usually shows up in the DO data record as a gradual increase in the size of the daily DO fluctuations that are observed over time between sensor maintenance sessions. A sudden drop back to 'normal' daily fluctuations after sensor maintenance / cleaning confirms that fouling was an issue. Fouling appears to be significant at some sites and relatively minor at others – perhaps relating to the enrichment of the site promoting or restricting periphyton growth on the sensor lens. Issues

associated with fouling appeared to be more prevalent in the first few years of DO data collected at the earliest DO sites that were installed. I understand that regular sensor cleaning and recalibration now occurs at all current sites. Based on my experience from other regions, sensors should be cleaned at least monthly, and more regularly at sites where fouling is consistently a problem. I understand that the use of sensors with wipers at some sites in the Taranaki Region has helped address fouling issues, and this appears to be a good solution.

<u>Data spikes.</u> Sudden short-term drops in DO are common in the unaudited DO data. Most of these data spikes coincide with sensor maintenance, presumably meaning that the sensor was out of the water at the time of the recording, and therefore they don't reflect a true reading of the site. Other data spikes may be caused by aquatic organisms passing over the sensor lens and interfering with the measurement. In both situations, the data spikes should be removed during data processing. TRC's current data processing procedures appear to address data spikes effectively.

<u>Data drift.</u> Data drift appeared to be relatively uncommon in the data that I reviewed. If present, it would be identified as a gradual increase or decrease over time in average daily DO – and a sudden step-change after sensor maintenance and calibration. I understand that ramp corrections are applied to data where adjustment for data drift is considered necessary. This is appropriate in my opinion, as long as any significant data adjustments are recorded via a lower QC code being applied to the data and / or relevant metadata.

<u>Variation to reference DO values</u>. Regular checks with a freshly calibrated reference DO sensor are an important part of the current DO monitoring procedure and should occur at least monthly alongside sensor maintenance. QC codes are applied to the data according to the tolerance levels, as recommended in NEMS (2016). Small differences within the NEMS tolerance range between reference values and sensor measurements generally will have minimal consequences for calculation and interpretation of DO and ecosystem metabolism metrics at most sites. However, if the variation in daily DO concentrations over a daily cycle is relatively small compared to the observed difference between the reference value and sensor measurements, then this could have implications for ecosystem metabolism results. In such situations, I recommend that data is adjusted if the difference between the reference value and sensor measurement is > 50% of the daily DO cycle, even if the difference is within the NEMS (2016) tolerance range.

<u>Downgrading QC coding for DO saturation values above 100%.</u> NEMS (2016) recommends that any DO data above 100% saturation should be downgraded to QC500 code or lower. I disagree that data above 100% saturation are necessarily lower quality. Most brands of DO sensors are calibrated at 100% saturation, or for sensors with two-point calibration, 100% saturation and 0% saturation. Either way, the accuracy of measurements close to 100% saturation will be high for values both above and below 100% saturation. I recognise that the accuracy of DO values considerably above 100% may be reduced, but values up to at least 120% saturation are likely to be accurate in my opinion. Based on my experience with DO datasets from across Aotearoa New Zealand, many sites have DO concentrations greater than 100% during some part of the day. Therefore, downgrading DO data to QC500 for most sites seems an extreme measure. This NEMS (2016) recommendation will also flow onto ecosystem metabolism measurement since any quality codes developed for ecosystem metabolism data would presumably incorporate the coding of the DO data used to calculate metabolism. For now, I recommend that TRC

continue to apply the current NEMS recommendations for QC coding of DO data, but TRC should have high confidence in QC500 DO data. Any future review of the DO NEMS should ideally reconsider this issue.

Daily minimum DO saturation > 100% is a red flag. Sites with DO concentrations > 100% saturation during the day will typically have DO concentrations well below 100% saturation at dawn (when minimum DO concentrations typically occur), due to the respiration of the periphyton and aquatic plant biomass during the night. I can't envisage any mechanism whereby a site would have a daily minimum DO concentration > 100% saturation. If this situation is observed, I consider this a cause for concern with the accuracy of the calibration of the DO sensors. Calibration concerns like this are often related to a lack of correction for site altitude (see further below).

Site altitude correction. The concentration of DO that is dissolved in water at 100% saturation is strongly related to air pressure, which in turn is strongly related to altitude. In other words, a high-altitude site will have a lower DO concentration than a low altitude site – even if DO is fully saturated at both sites. Calibration of DO sensors needs to consider the effects of site altitude. Sensors calibrated at sea level will not necessarily provide accurate data when used at higher altitude sites. Therefore, corrections to DO % saturation measurements need to be made, as outlined in the draft DO data processing document; although differences in altitude between sites where barometric pressure readings are available are more relevant than distances (in km) between sites. Due to the connections between DO concentration, DO % saturation and other parameters such as water temperature, barometric pressure and conductivity, I recommend that data processing for DO concentration and DO % saturation is conducted concurrently on a site-by-site basis, rather than processing all DO concentration data for all sites, independent of DO % saturation.

Data smoothing. Some DO sensors, even within the same brand / model, can potentially record more 'noisy' data. These random small variations in DO measurements have little effect on the calculation of minimum DO statistics but can make calculation of ecosystem metabolism more difficult, as the calculations rely on accurate measurements of DO change over time. I do not recommend that any data smoothing procedures are applied to the DO data as part of the data processing procedures. However, at sites where daily changes in DO concentration are relatively small, there may be benefits to smoothing the DO data before using it to calculate ecosystem metabolism. I recommend a moving average smooth using a 5-point moving window to reduce the effects of random sensor noise on the DO measurements.

Check other parameters that might be associated with step changes. In many cases, issues with DO data are relatively obvious, but sometimes unusual step changes in the DO data may accurately reflect conditions. TRC have adopted a good process of checking other data (e.g. flow) to see if there are changes in other parameters that could be responsible for unusual DO records. I support this approach.

## Calculation of ecosystem metabolism results

As requested, R code for calculation of ecosystem metabolism from DO data, along with example datasets, were provided to TRC (Joseph Pinion) on 19 March 2024. This code will help enable TRC to calculate ecosystem metabolism using the DO data that have been collected.

## Interpretation of ecosystem metabolism results

Young et al. (2008) used a compilation of ecosystem metabolism data from throughout Aotearoa New Zealand and globally to develop proposed criteria for interpreting how ecosystem metabolism measurements can be related to river ecosystem health. The proposed criteria were based on the quantiles of data from sites that were considered to be in reference condition based on the high proportion of native vegetation in their catchment upstream. This approach assumes that most measurements from reference sites are indicative of healthy conditions, but extreme values are indicative of impaired conditions (Figure 2).

For GPP, the 75th percentile defined the upper bound of 'healthy', while values between the 75th and 95th percentile of reference sites were considered 'satisfactory'. Values above the 95th percentile of the reference sites were considered to represent 'poor' condition (Figure 2).

For ER, 'healthy' state was defined as the values between the 25th and 75th percentile. Values between the 5th and 25th or the 75th and 95th percentiles were 'satisfactory', and the values in the most extreme 5% of either end were considered to represent 'poor' condition (Figure 2).

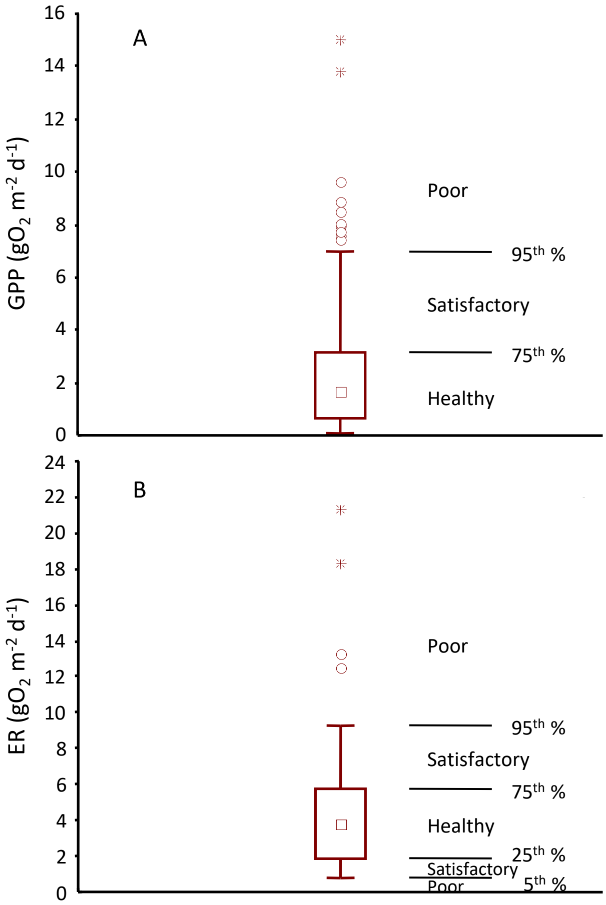


Figure 2. Data from reference sites used to define criteria for interpretation of ecosystem metabolism measurements. Source: Young et al. (2008).

The data used by Young et al. (2008) and some additional Aotearoa New Zealand data were used to inform the attribute table recommended by the STAG (Science and Technical Advisory Group 2019; Table 1), which follows the typical 4-attribute band NPS-FM 2020 framework. The STAG designated slightly different criteria for wadeable and non-wadeable rivers on the basis that non-wadeable rivers often exhibit higher GPP and a decreased ER range in comparison to rates observed in wadeable rivers and streams (Clapcott 2015). This distinction between wadeable and non-wadeable rivers was based on a relatively small dataset of non-wadeable rivers (n = 24) that were considered to be in reference condition.

Ecosystem metabolism data can also be used to understand the balance of organic matter production and demand / respiration, using the ratio of GPP:ER or the difference between GPP and ER. However, in my opinion, interpretation of ecosystem health is best based on the GPP and ER measurements themselves.

Table 1. Attribute table recommended by the STAG for ecosystem metabolism (from Science and Technical Advisory Group 2019).The STAG recommended that data should be derived from 7 consecutive days of continuous dissolved oxygen monitoring and that the objective applies year-round.

| **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** | | | | **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<br>Or<br>> 3.0 and < 8.0 | > 1.2 and < 1.6<br>Or<br>> 5.8 and < 7.0 | Mild effect on ecosystem metabolism |
| **C** | ≥ 5.5 and ≤ 8.0 | ≥ 5.0 and ≤ 7.0 | ≥ 0.6 and ≤ 1.0<br>Or<br>≥ 8.0 and ≤ 13.0 | ≥ 0.8 and ≤ 1.2<br>Or<br>≥ 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 |

A comparison of the Young et al. (2008) bands and the wadeable river STAG bands are shown in Figures 3 and 4 for GPP and ER, respectively. The thresholds for A–B and C–D bands for the STAG framework are very similar to the thresholds between 'healthy' and 'satisfactory', and the threshold for 'satisfactory' and 'poor', respectively, for the Young et al. (2008) framework. The STAG threshold between B band and C band is in the middle of the 'satisfactory' range proposed by Young et al. (2008).

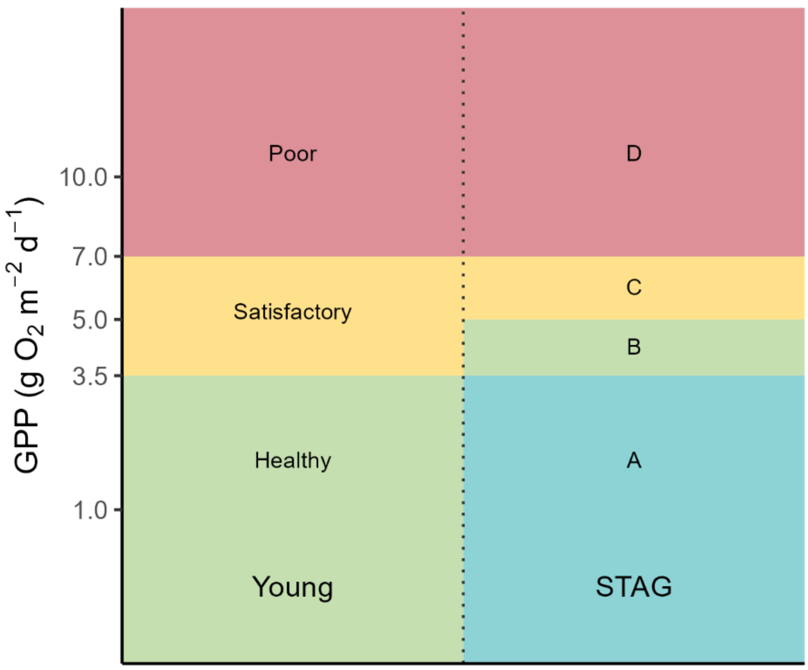


Figure 3. Gross primary production (GPP) attribute band ranges defined by Young et al. (2008) on the left and the STAG on the right. Blue is A band, green is healthy (Young) or B band (STAG), yellow is satisfactory (Young) or C band (STAG) and pink is poor or D band.

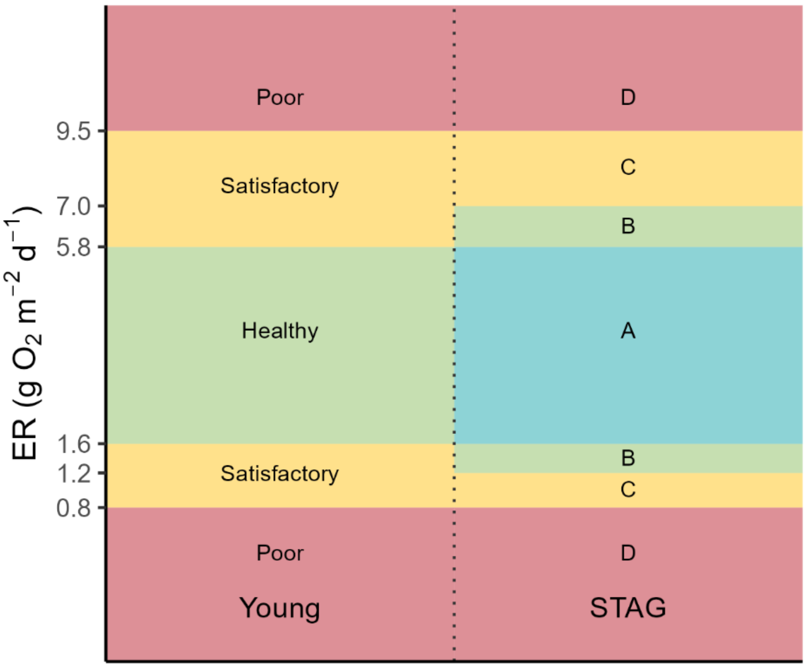


Figure 4. Ecosystem respiration (ER) attribute band ranges defined by Young et al. (2008) on the left and the STAG on the right. Blue is A band, green is healthy (Young) or B band (STAG), yellow is satisfactory (Young) or C band (STAG) and pink is poor or D band.

It should be noted that both of the above assessment frameworks for ecosystem metabolism were limited by the data available during their development. The attribute bands were derived from a combination of metabolism data from some sites on individual days, and site means or medians over multiple individual days at other sites. Ecosystem metabolism data from reference sites where medians of near continuous data over many years could be used for criteria development are currently limited. As more long-term data become available, attribute band definitions should be revisited using median values. Ecosystem metabolism is known to vary among natural stream ecosystems depending on the climate, geology, stream order, depth, water chemistry and canopy cover. Therefore, as more reference site data become available, variability in these driving variables could also be used to understand natural variability in ecosystem metabolism and potentially inform an appropriate stream classification for the development and application of attribute bands.

In the interim, the bands recommended by the STAG have recently been used to interpret ecosystem metabolism results from rivers and streams in the Northland Region (Goodwin and Young 2021) and Auckland (Casanovas et al. 2022). This banding system worked effectively in these regions with site classifications ranging from A band for reference sites to D band for heavily impacted sites.

I hope this advice is useful for the ongoing implementation of DO and ecosystem metabolism monitoring in the Taranaki Region.

Yours sincerely

Scientist

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Peer reviewed by Dr Joanne Clapcott
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## References

Casanovas PG, Goodwin E, Schattschneider J, Grant C, Ingley R, Fraser S, Young R. 2022. Dissolved oxygen and ecosystem metabolism in Auckland rivers (2004 to 2020). Auckland: Auckland Council. Auckland Council Technical Report 2022/18.

Clapcott J. 2015. Development of management bands for ecosystem metabolism in non-wadeable rivers. Nelson: Cawthron Institute. Cawthron Report No. 2770. Prepared for Environment Waikato.

Goodwin E, Young R. 2021. Dissolved oxygen and ecosystem metabolism measurement in Northland rivers. Nelson: Cawthron Institute. Cawthron Report No. 3684. Prepared for Northland Regional Council.

Ministry for the Environment. 2020. National Policy Statement for Freshwater Management 2020 (as amended in 2023). https://environment.govt.nz/publications/national-policy-statement-for-freshwater-management-2020-amended-february-2023/

[NEMS] National Environmental Monitoring Standard. 2016. Dissolved oxygen. Measuring, processing and archiving of dissolved oxygen data. Version: 2.0. https://www.nems.org.nz/documents/dissolved-oxygen/

Science and Technical Advisory Group. 2019. Freshwater Science and Technical Advisory Group – Report to the Minister for the Environment. https://environment.govt.nz/publications/freshwater-science-and-technical-advisory-group-report-to-the-minister-for-the-environment/

Streeter H. 1925. Studies of the pollution and natural purification of the Ohio River, Part III, Factors concerned in the phenomena of oxidation and reaeration. Public Health Bulletin. 146.

Young RG, Kelly L. 2023. Approaches for measurement, analysis and reporting of dissolved oxygen and ecosystem metabolism in rivers in the Horizons region. Nelson: Cawthron Institute. Cawthron Report 3905. Prepared for Horizons Regional Council.

Young RG, Matthaei CD, Townsend CR. 2008. Organic matter breakdown and ecosystem metabolism: functional indicators for assessing river ecosystem health. Journal of the North American Benthological Society. 27(3):605–625.