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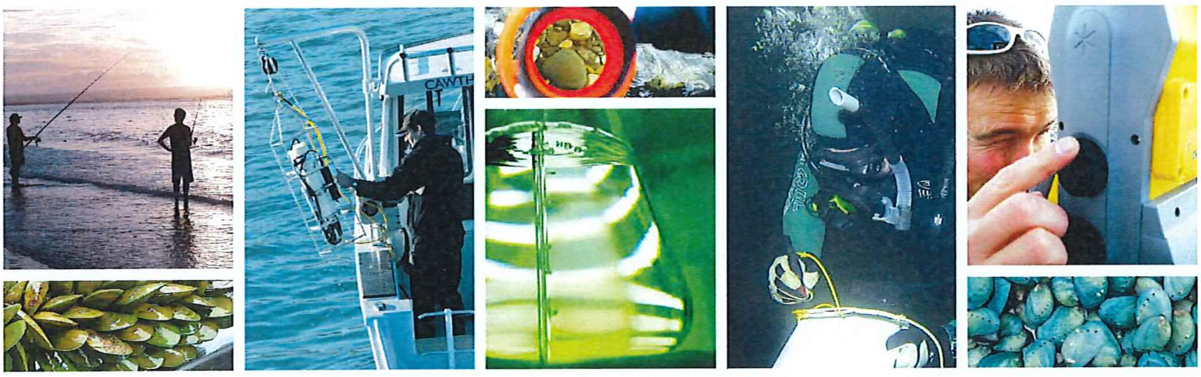
CAWTHRON

Temporal Variability in Ecosystem Metabolism of Rivers in the Manawatu–Whanganui Region – Updated



RESEARCH BASED SOLUTIONS

CAWTHRON

Temporal Variability in Ecosystem Metabolism of Rivers in the Manawatu–Whanganui Region

– Updated

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Prepared for

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EXECUTIVE SUMMARY

A one-off measurement of the daily change in dissolved oxygen in the lower Manawatu River in November 2007 indicated that this river has very high rates of ecosystem metabolism (primary production and ecosystem respiration) that are indicative of very poor ecosystem health. An assessment of the lower Rangitikei River on the same day suggested this site also had poor ecosystem health due to high rates of ecosystem respiration. Horizons Regional Council has been collecting continuous records of dissolved oxygen (DO) at five sites throughout the region since 2005, which can be used to calculate ecosystem metabolism. The aim of this study was to determine if the concerns raised about these rivers are consistent over time or among sites. This updated report replaces an earlier report (Clapcott & Young 2009) that was based on calculations from raw data which has subsequently been shown to have some measurement errors. These errors have now been addressed and metabolism rates for the five sites recalculated.

We calculated ecosystem metabolism using DO data from five sites over one year (2007). The sites were Manawatu at Hopelands, Manawatu at Teachers College, Mangatainoka at Pahiatua Town Bridge, Rangitikei at Mangaweka and Rangitikei at Onepuhi. The sites varied in their intensity of catchment land use ranging from 39% native vegetation in the catchment for the Rangitikei at Mangaweka to 10% native vegetation for the Manawatu at Hopelands. Dissolved oxygen data generally displayed characteristic daily patterns at most sites. However, we had concerns with the accuracy of the data, at some sites during some seasons where night-time DO values did not drop below 100% saturation prior to dawn. To address these concerns we corrected the data, but uncertainties involved with the correction mean that less confidence can be placed on metabolism values calculated from corrected data.

Rates of gross primary production (GPP) were low in the Rangitikei River at Onepuhi and Mangaweka and indicate good–satisfactory health throughout the year according to broad guidelines on interpretation of these measures. Rates of GPP and ecosystem respiration (ER) in the Manawatu River at Teachers College and Mangatainoka at Pahiatua suggested good–satisfactory health in autumn, winter and spring, but were indicative of poor ecosystem health in summer. In contrast, rates of GPP and ER were consistently high at Manawatu at Hopelands and indicated poor ecosystem health throughout the year. These differences in rates of metabolism among sites reflect differences in land cover with the highest values found at the most modified site (Manawatu at Hopelands) and the lowest values found at the sites with the largest proportion of the upstream catchment in native forest (Rangitikei River at Mangaweka and Onepuhi), although a point-source discharge upstream of Mangaweka appears to have had an effect on the measurements at that site.

The balance between GPP and ER indicated that all five sites were generally relying on some organic matter from upstream or the surrounding catchment to support the recorded rates of ER. However, the ratio of GPP:ER was greater than one at Manawatu at Hopelands during autumn and spring, and at Rangitikei at Onepuhi during spring suggesting that algae probably contribute significantly to the food chain in these rivers at times.

As expected there were distinct seasonal patterns in the ecosystem metabolism measurements with most sites displaying higher values in the warmer months. For example, rates of GPP and ER in the Manawatu River at Teachers College indicated satisfactory–good ecosystem health in autumn, winter and spring, but higher in summer and suggesting poor ecosystem health.

A weak positive relationship was observed between rates of GPP and water clarity reflecting the importance of light availability at the riverbed for algal photosynthesis. There was also an indication that GPP may be positively related with concentrations of dissolved reactive phosphorus, although neither of these relationships were statistically significant with the available sample size.

Continuous monitoring of DO concentration provides the opportunity to calculate rates of ecosystem metabolism that can be used to assess ecosystem health. The accuracy of the metabolism calculations is heavily dependent on the accuracy of the raw DO data. Therefore, we recommend regular checks and calibration of the DO monitoring equipment. As more data becomes available it would be useful to compare results from the Manawatu–Whanganui Region with measurements from similar large rivers to determine if the broad guidelines used in this study to interpret the metabolism measurements are appropriate for large rivers generally. Furthermore, it would be useful to conduct further comparisons of ecosystem metabolism to traditional water quality, biomonitoring or periphyton assessments to determine whether rates of ecosystem metabolism provide suitable surrogate measures of ecosystem health for large river systems where other measures can not be easily undertaken.

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1. INTRODUCTION

River health assessment has traditionally concentrated on structural measurements related to abundance and community composition of macroinvertebrates and other stream life. However, it is increasingly recognised that a complete assessment of river health requires information on both structural and functional components of the ecosystem (Young *et al.* 2008). Functional components refer to the rates of key ecosystem processes. Ecosystem metabolism – the combination of primary productivity (photosynthesis) and ecosystem respiration – is a measure of the main factors controlling dissolved oxygen dynamics in rivers and indicates how much organic carbon is produced and consumed in river systems. Recent research has shown that ecosystem metabolism is a useful indicator of river ecosystem health and can be measured by monitoring the daily changes in oxygen concentration at a site (Fellows *et al.* 2006; Young *et al.* 2008). Dissolved oxygen concentrations rise during the day-time when sunlight facilitates photosynthesis and then decline during the night when only respiration is occurring. The size of the daily fluctuations depends on the amount of photosynthesis and respiration occurring within the river and also the flux of oxygen through the river surface. Sites with very high rates of primary production will normally be characterised by a riverbed covered with a high biomass of periphyton (algae and other slimes growing on the substrate) or other aquatic plants that are not limited by shading, or a lack of nutrients. Sites with high rates of ecosystem respiration are normally characterised by large inputs of organic matter from point-source discharges of sewage/wastewater, or large diffuse inputs from sources such as agricultural runoff and deciduous tree leaves. High biomasses of algae and other aquatic plants are also often associated with high rates of ecosystem respiration.

In the past, limitations of dissolved oxygen (DO) probes and logging equipment, as well as knowledge of the temporal and spatial variability associated with river metabolism, have acted as barriers to the routine use of ecosystem metabolism as a form of ecosystem health assessment. However, recent development of optical DO probes have made it possible to deploy equipment for long periods. Prior to this development, oxygen loggers could only be deployed for 1–2 days before requiring sensor maintenance and recalibration. There is also a rapidly growing amount of literature reporting rates of ecosystem metabolism of streams, and to a lesser degree large rivers, in New Zealand and abroad (Uehlinger 2006; Gawne *et al.* 2007; Young *et al.* 2008; Collier *et al.* 2009; Young & Collier 2009). This has enabled a better understanding of natural variability in ecosystem metabolism. Horizons Regional Council has deployed dissolved oxygen loggers on a continuous basis in a selection of rivers since 2005. This dataset provides the opportunity to investigate spatial and temporal variability in ecosystem metabolism and to demonstrate the additional value that can be extracted from a continuous DO data. However, protocols for long-term deployment, sensor maintenance, data storage and quality control are still being refined based on experience with this relatively new technology, so this dataset also demonstrates the challenges of long-term deployments.

Ecosystem processes, such as ecosystem metabolism, are affected by upstream activities but can also be influenced by local impacts such as point-source discharges and riparian vegetation clearance (Gücker *et al.* 2006; Von Schiller *et al.* 2008). As such, different reaches in a large river can have different rates of metabolism. By comparing rates of metabolism among different reaches of a river system and also among rivers with differing land-use intensities, it is possible to comment on the pressures potentially influencing river metabolism at any one location.

Ecosystem metabolism varies seasonally in relation to temperature, river flow and light availability (Uehlinger 2006). Seasonal variation and flow must be accounted for when establishing and assessing ecosystem health in relation to reference conditions. Based on trends observed in smaller rivers, we would expect metabolic rates to be higher in the warmer months and lower immediately after high flows due to scouring and/or flushing of organic matter from the system. Ecosystem metabolism can also vary on a smaller temporal scale, *i.e.* on a weekly basis, due to weather conditions. For example, clouds reduce the intensity of light reaching the river which can result in lower gross primary productivity (Young & Huryn 1996).

In this updated report we investigate the temporal variability in ecosystem metabolism at five sites on large rivers in the Manawatu–Whanganui Region characterised by a range of land-use intensities. An earlier version of this report (Clapcott & Young 2009) was based on calculations from raw data which has subsequently been shown to have some errors. These errors have now been addressed and metabolism rates for the five sites recalculated. This information improves our understanding of temporal variability in metabolism rates that are likely to be encountered in the Manawatu and Rangitikei rivers and the potential effects of land use on this variability. We also compare the metabolism rates with existing guidelines on what represents good and poor ecosystem health.

2. METHODS

Environmental data was investigated for five sites located on rivers throughout the Manawatu-Whanganui Region. The sites were located on large rivers with catchments subject to a range of land-use intensities and varying geologies (Figure 1, Table 1).

Data supplied by Horizons Regional Council included average water depth, discharge, temperature and dissolved oxygen (DO) values. The latter was comprised of 15-minute measurements of DO concentration collected using optical DO loggers. Graphs of the full range of data available at each site between February 2006 and May 2008 were inspected to identify gaps in the datasets and to choose suitable times to calculate metabolism *i.e.* times of relatively stable flow. Periods chosen for metabolic calculations were 18-22 February 2007 (summer), 7-11 May 2007 (autumn), 21-25 August (winter) and 19-23 November 2007 (spring). For each date, metabolic estimates were calculated with DO data from midday to the following midday. Following the production of our initial report (Clapcott & Young 2009) we discovered a problem with the dissolved oxygen saturation readings being delivered from the Horizons database. This issue was resolved by recalculating dissolved oxygen saturation values from the recorded DO concentration and water temperature measurements. A further investigation of Horizons sensor maintenance records revealed that the dissolved oxygen sensor at the Manawatu at Hopelands site had been damaged by flooding during August 2007 making data from that period unsuitable for metabolism calculations.

Table 1. Catchment characteristics of the sites on five rivers in the Manawatu-Whanganui Region. Land-cover data was supplied by Horizons Regional Council.

Site	Northing	Easting	Stream order	% Native vegetation	% Urban area	% Pastoral land
Rangitikei at Mangaweka	2750300	6151300	7	39	0.1	45
Rangitikei at Onepuhi	2720100	6122200	7	35	0	53
Manawatu at Hopelands	2761500	6089800	6	10	0.4	85
Manawatu at Teachers College	2733100	6089200	7	20	0.5	75
Mangatainoka at Pahiatua	2750100	6080200	6	20	0.6	77

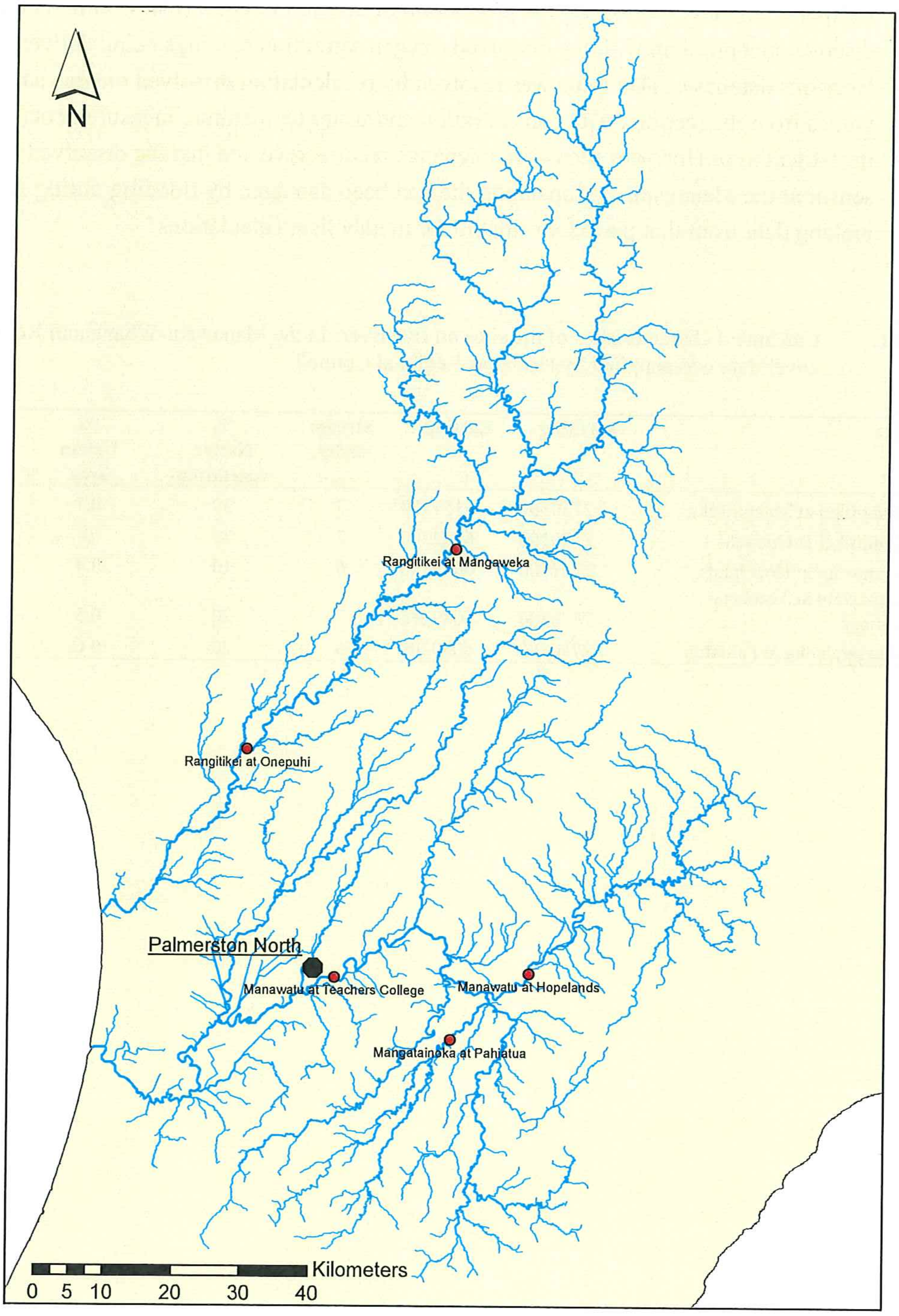

Figure 1. Map showing location of the five sampling sites.

Before analysis, random noise in the dataset was removed/reduced by applying a moving average smooth that averaged across an interval of five measurements. Metabolism values were then calculated using the RiverMetabolismEstimator spreadsheet model (version 1.2) developed by Young & Knight (2005). This model uses the following approach to calculate metabolism values. Mean daily ecosystem respiration (ER) and the reaeration coefficient (k) were determined using the night-time regression method (Owens 1974), which uses only data collected in the dark (<2 μmol m^{-2} s^{-1}). Light data were not available for the sites, so the night-time period was determined by examining the oxygen data. Night-time typically is the period between the fastest recorded reduction in oxygen concentration (dusk) and the highest recorded oxygen deficit (difference between the oxygen concentration at saturation and the observed concentration in the water) which occurs at dawn. The rate of change of oxygen concentration over short intervals during the night was regressed against the oxygen deficit to yield:

$$dO/dt = ER + kD \quad (1)$$

where dO/dt is the rate of change of oxygen concentration (g m^{-3} s^{-1}), ER is the ecosystem respiration rate (g O_2 m^{-3} s^{-1}), k is the reaeration coefficient (s^{-1}), and D is the oxygen deficit (g m^{-3}). The slope of the regression line estimates k and the y-intercept estimates ER (Kosinski 1984).

The reaeration coefficient and ecosystem respiration rate obtained were then used to determine gross photosynthetic rate over the sampling interval using:

$$GPP_t = dO/dt + ER - kD \quad (2)$$

where GPP_t is the gross photosynthetic rate (g O_2 m^{-3} s^{-1}) over time interval (t). To compensate for daily temperature fluctuation, ER is assumed to double with a 10°C increase in temperature (Phinney & McIntire 1965) while the reaeration rate is assumed to increase by 2.41% per degree (Kilpatrick *et al.* 1989). Daily gross primary production (GPP, g O_2 m^{-3} s^{-1}) was estimated as the integral of all temperature corrected photosynthetic rates during daylight (Wiley *et al.* 1990).

This analysis gave values of production and respiration per unit volume. An areal estimate was obtained by multiplying the volume based estimates by average reach depth (m) which allowed comparison among stations with different depths.

Even after addressing the concerns with the DO saturation data initially delivered by the Horizons database, problems associated with the DO data were evident at some sites on some occasions. On these occasions DO values did not fall below 100% saturation at any time over the 24 hour sampling period. We consider that it is impossible for a site with high productivity, leading to greater than 100% DO saturation during the day, to not have equally high rates of respiration which would reduce the dissolved oxygen concentration to below 100% saturation at dawn. The DO probes appear to have been recording artificially high values either due to insufficient calibration or technical failure. In these situations we corrected the oxygen data by subtracting a sufficient proportion to ensure that concentrations were below 100% saturation at dawn. Corrections of between 3–20% were required at times. Estimates of metabolism on these occasions were calculated using this corrected data. It is possible that the DO measurements were still too high after correction, however we have no way of knowing how much more to correct the data. Inaccuracy in DO data will have a strong effect on rates of ER that are calculated, but a relatively small effect on rates of GPP (McCutchan *et al.* 1998).

GPP and ER data were log-transformed to meet the assumptions of normality for statistical analysis. An analysis of variance (ANOVA) to test for similarity among sites and over time was conducted in Statistica version 8.

3. RESULTS

3.1. Dissolved oxygen data

The largest daily fluctuations in DO were seen at the Manawatu at Hopelands site (Figure 2; Table 2). Supersaturation of dissolved oxygen (>100% DO) was evident at all sites, while DO minima were very low at times at the Manawatu at Hopelands and the Mangatainoka at Pahiatua sites. Minimum DO concentrations at both of these sites were well below the dissolved oxygen saturation standards that are in the Proposed One Plan at these sites (Manawatu at Hopelands = 70% Saturation; Mangatainoka at Pahiatua = 80% Saturation) and breached the standards on a relatively regular basis (Table 2). However, DO concentrations at the other sites were generally above the proposed standards during these periods.

Table 2. Range in temperature and dissolved oxygen data at the five study sites.

Site	Temp Min	Temp Max	% DO Min	% DO Max	Percentage of measurements breaching proposed DO standard (*>70% Saturation, #>80% Saturation)
Manawatu at Hopelands	7.0	25.6	34	158	19*
Manawatu at Teachers College	8.3	23.6	71	124	0*
Mangatainoka at Pahiatua	7.8	22.7	65	111	11#
Rangitikei at Mangaweka	5.8	22.7	87	110	0#
Rangitikei at Onepuhi	6.9	24.6	79	117	0.3#

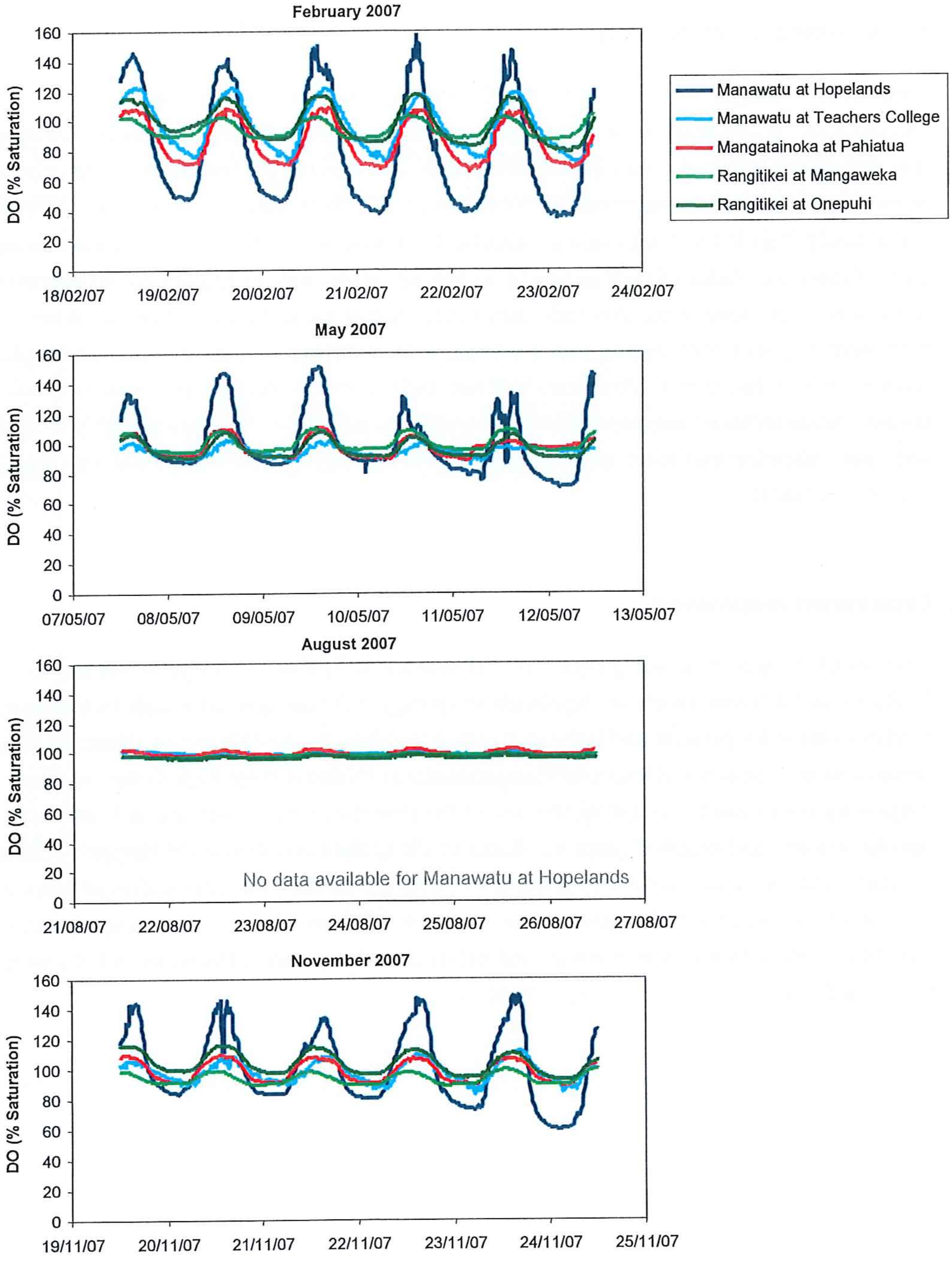

Figure 2. Graphs showing the five-daily range in dissolved oxygen data used in metabolic calculations for each of the five study sites for part of the study period.

3.2. Ecosystem metabolism

3.2.1. Gross primary productivity

Rates of GPP ranged from <0.1 g O_2 m^{-2} d^{-1} (Rangitikei at Onepuhi in winter) to 24.5 g O_2 m^{-2} d^{-1} (Manawatu at Hopelands in spring). Gross Primary Production was generally low throughout the study period in the Rangitikei at Onepuhi and indicated healthy conditions according to the criteria suggested by Young *et al.* (2008) (Figure 3). In contrast, GPP was consistently high in the Manawatu at Hopelands, indicating poor ecosystem health throughout 2007 (Figure 3). Rates of GPP generally indicated satisfactory to healthy conditions at the remaining three study sites, although rates in the Manawatu at Teachers College were indicative of poor health during summer (Figure 3). GPP was lowest in winter and highest in summer at all sites, except Manawatu at Hopelands where the highest values were observed in spring. An analysis of variance showed a significant interaction between the effects of site and time indicating that there were differences in GPP among sites that varied with time ($F_{11,74}$ = 17.8, p <0.001).

3.2.2. Ecosystem respiration

Rates of ER ranged from 0.1 g O_2 m^{-2} d^{-1} (Manawatu at Teachers College in winter) to 32.8 g O_2 m^{-2} d^{-1} (Manawatu at Hopelands in spring). ER was generally high throughout 2007 at Manawatu at Hopelands and indicated poor ecosystem health (Figure 4). Rates of ER at the Manawatu at Teachers College and Mangatainoka at Pahiatua were high in the summer, suggesting poor health, but during the rest of the year they were lower and indicative of satisfactory to good health (Figure 4). Rates of ER at the two sites on the Rangitikei River generally indicated satisfactory to good health throughout the year, although high rates were recorded in winter at the Mangaweka site. As with GPP, an analysis of variance found a significant interaction of site and time indicating that there were differences in ER among sites that varied with time ($F_{11,74}$ = 17.4, p <0.001).

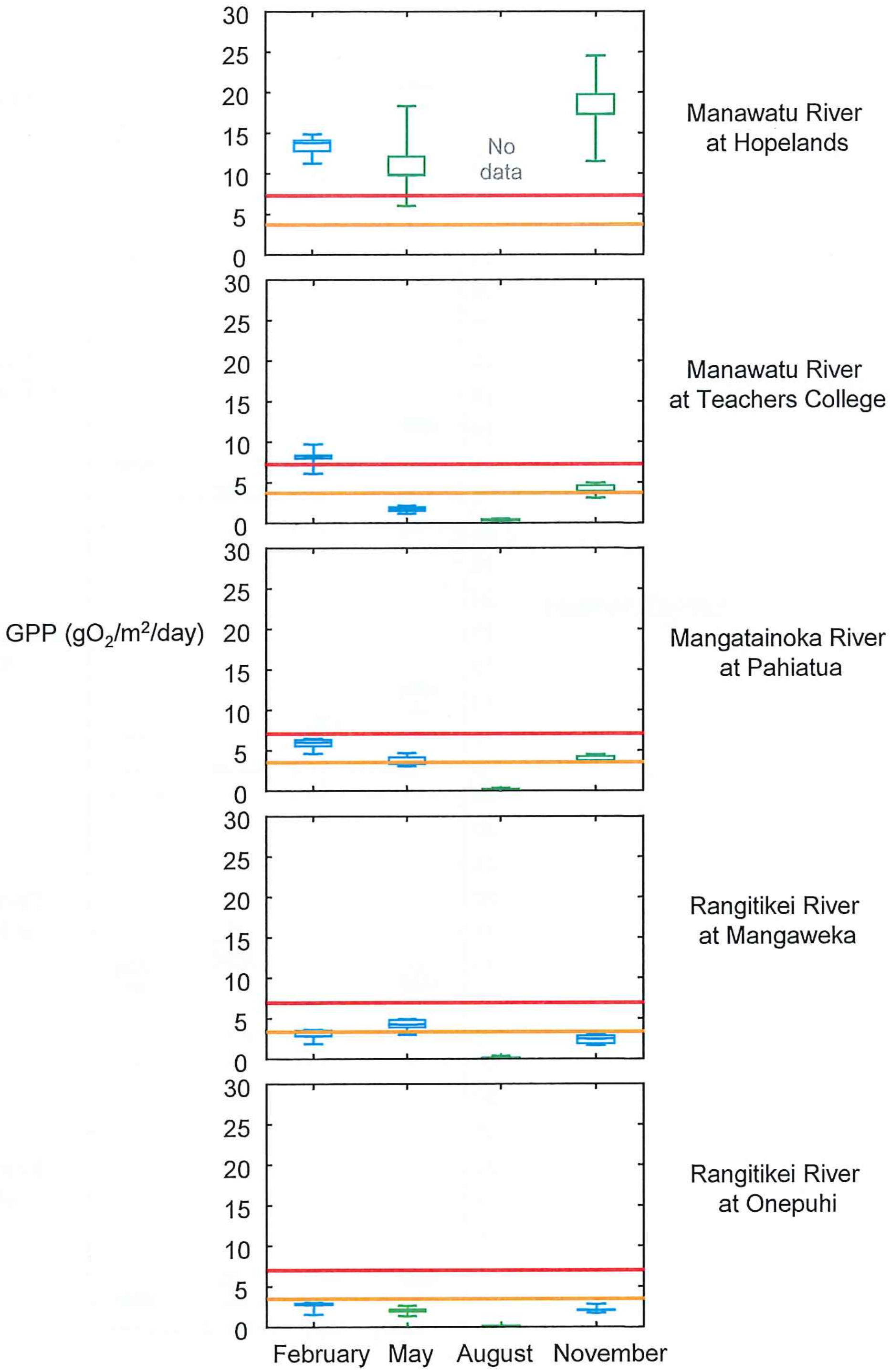

Figure 3. Rates of gross primary production (GPP) during 2007 for five study sites on rivers in the Manawatu–Whanganui Region. Box plots show the median, upper and lower quartiles and range of values. Green boxes indicate GPP calculated using corrected data. Horizontal lines mark absolute values used to assess ecosystem health from Young *et al.* (2008): below the orange line if 'healthy', between the orange and red lines is 'satisfactory' and above the red line is 'poor'. No data was available for the Manawatu at Hopelands site in August 2007.

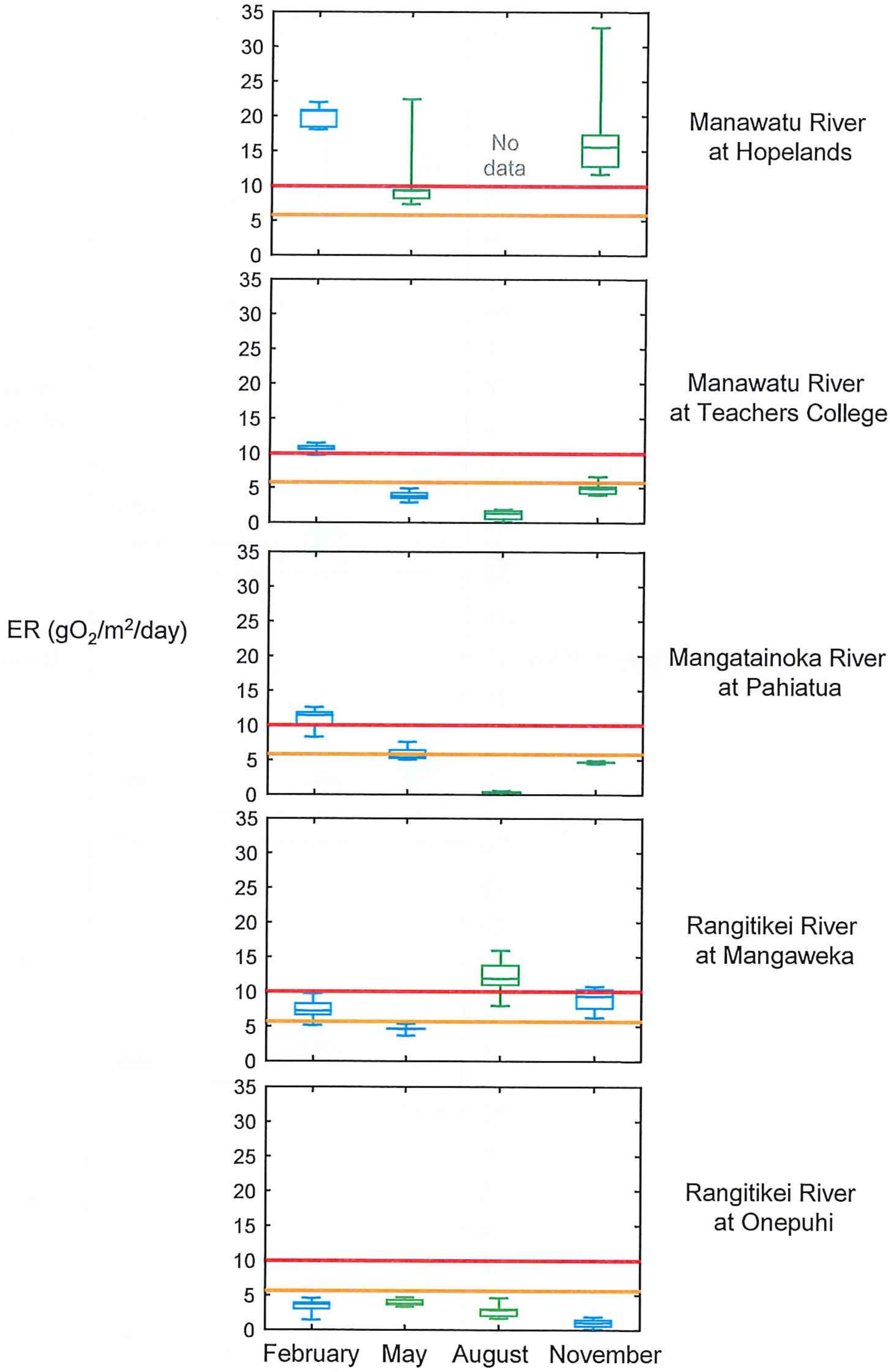

Figure 4. Rates of ecosystem respiration (ER) during 2007 for five study sites on rivers in the Manawatu–Whanganui Region. Box plots show the median, upper and lower quartiles and range of values. Green boxes indicate ER calculated using corrected data. Horizontal lines mark absolute values used to assess ecosystem health from Young *et al.* (2008): below the orange line if 'healthy', between the orange and red lines is 'satisfactory' and above the red line is 'poor'. No data was available for the Manawatu at Hopelands site in August 2007.

3.2.3. P/R ratio

The balance between GPP and ER has been considered a useful measure of the sources of energy driving a stream ecosystem (Odum 1956). If GPP equals or exceeds ER then organic matter produced within the system (*e.g.* periphyton biomass) is probably supporting the food chain, whereas if ER greatly exceeds GPP then organic matter from upstream or the surrounding catchment is being used to maintain the ecosystem (*e.g.* allochthonous inputs). The majority (84%) of P/R ratios were less than one indicating that these sites generally were relying on some organic matter from upstream or the surrounding catchment to support the food chain, although average ratios were greater than one at Manawatu at Hopelands during autumn and spring and at Rangitikei at Onepuhi during spring suggesting that algae contribute significantly to the food chain of these rivers at times.

The P/R ratio appears to be a relatively insensitive indicator of river ecosystem health compared to the raw GPP and ER values, although it is useful for determining the effects of canopy cover (Young *et al.* 2008). One of the main issues with the ratio is that the same P/R value can apply to vastly different systems. For example, a P/R ratio of 0.5 could be calculated from a GPP value of 10 $gO_2/m^2/day$ and an ER value of 20 $gO_2/m^2/day$ (both indicating poor health), and also a GPP value of 0.5 $gO_2/m^2/day$ and an ER value of 1 $gO_2/m^2/day$ (both indicating good health). This means that the P/R ratio needs to be interpreted with caution and should always be integrated with the actual values of GPP and ER.

3.2.4. Assessing ecosystem health

Preferably, local sites representing best attainable condition should be used to determine reference condition for assessing ecosystem health, rather than the broad guidelines used above (Young *et al.* 2006). None of the study sites appear ideal to represent reference condition based on land-use pressures (*e.g.* percent native vegetation). For example, a recent survey identified 60% native vegetation cover as a potential threshold for change in the response in ecosystem metabolism in New Zealand streams (Clapcott *et al.* in press). However, there was some evidence of a relationship between catchment land use and ecosystem metabolism in Manawatu rivers. For example, the Rangitikei at Onepuhi had consistently lower GPP and ER compared to other sites, associated with relatively low pressure values (*i.e.* relatively high native vegetation cover). In contrast, Manawatu at Hopelands had relatively high GPP and ER, associated with relatively high pressure values. The Rangitikei at Onepuhi could potentially be used to represent 'best attainable' condition for large rivers of the Manawatu region, based on consistently low ecosystem metabolism measures during the study period. However, it should be noted that more than half of the catchment upstream of this site is in pastoral land cover and therefore still potentially impacted.

In comparison to average annual values for Rangitikei at Onepuhi, rates of GPP suggest that Manawatu at Hopelands has poor ecosystem health (>5 times higher than the reference site) using the framework presented in Young *et al.* (2008) and the remaining three sites have satisfactory ecosystem health (2.5–5 times higher than the reference site) for most of the year (Figure 5). Similarly, in comparison to average annual rates of ER for the Rangitikei at Onepuhi, the Manawatu River at Hopelands and Teachers College has poor health (>2.7 times reference, Young *et al.* 2008), while the Mangatainoka River at Pahiatua and Rangitikei River at Mangaweka are indicative of satisfactory to poor health (Figure 5).

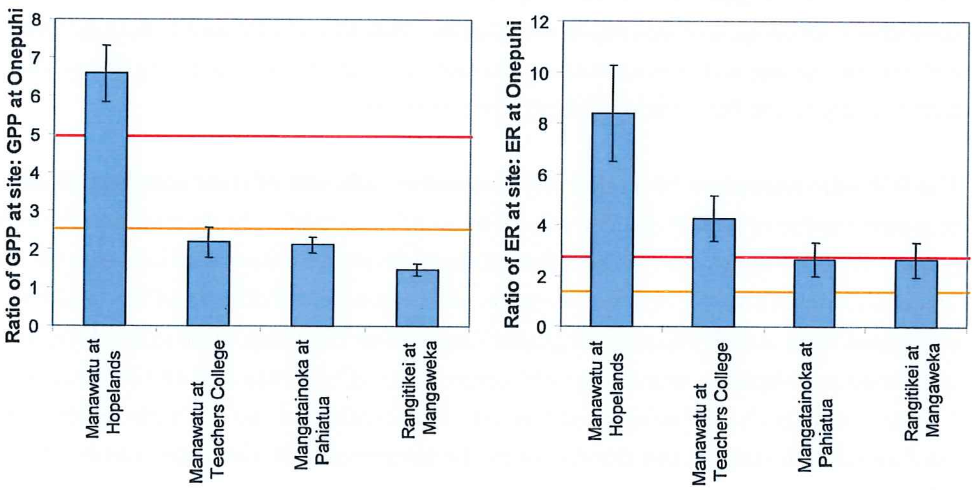

Figure 5. Comparison of rates of GPP and ER (g O_2 m^{-2} d^{-1}) for four sites on rivers in the Manawatu–Whanganui Region with a potential best attainable condition site (Rangitikei at Onepuhi). Bars show annual means and standard errors. Horizontal lines mark values used to assess ecosystem health from Young *et al.* (2008): below the orange line is 'healthy', between the orange and red lines is 'satisfactory' and above the red line is 'poor'

3.3. Comparison with independent data

In late November 2007, metabolism was measured in the lower reaches of the Manawatu River at Opiki and the lower reaches of the Rangitikei River at Bulls as part of a national study of large river ecology (Collier *et al.* 2009). The metabolism measurements at these sites were generally higher than those measured in this report (Figure 6). In fact, the high rates of GPP and ER observed in the Manawatu River at Opiki by Collier *et al.* (2009) are among the highest ever reported internationally (*cf.* Young *et al.* 2008) and indicating very poor ecosystem health.

The Opiki site on the Manawatu River is 21 km downstream of the Teachers College site and has the same percentages of pasture (75%) and native forest (20%) in the catchment upstream as the Teachers College site. However, urban land cover in the catchment upstream is higher than at Teachers College and there are some substantial discharges to the river downstream of Palmerston North (McArthur & Clark 2007). Similarly, the Bulls site on the Rangitikei River is 19 km downstream from the Onepuhi site and potentially affected by discharges of wastewater from Marton and Hunterville.

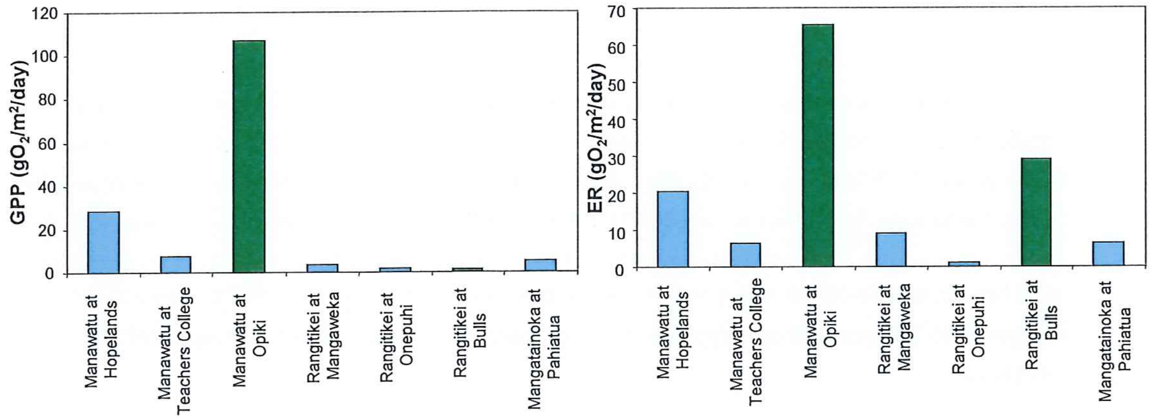

Figure 6. Rates of GPP and ER for seven sites on rivers in the Manawatu-Whanganui Region on 27 November 2007. Green bars indicate sites measured as part of another study (Collier *et al.* 2009).

3.4. Comparison with water quality data

A comparison of metabolic rates with water quality data collected from the study sites showed no statistically significant relationships between average metabolic rates for a particular month and any of the water quality parameters measured on the same month (Table 3). However, there was some indication that rates of GPP and ER were positively related with water clarity (and negatively related with turbidity) reflecting the importance of light availability to the riverbed for algal photosynthesis. There was also a weak indication that GPP may be positively related with concentrations of dissolved reactive phosphorus (Table 3).

Table 3. Pearson's correlation coefficients for metabolic variables and water quality metrics for data from five sites on rivers in the Manawatu–Whanganui Region during the study period. Values in bold highlight possible relationships ($P < 0.15$), although none were significant at $P < 0.05$.

	N	ER	GPP
Black disk clarity	17	0.235	**0.370**
Conductivity	19	-0.016	-0.036
Dissolved reactive phosphorus (DRP)	19	0.214	**0.366**
E. coli	19	-0.213	-0.118
Ammoniacal nitrogen (NH_4-N)	19	-0.300	-0.180
Dissolved Inorganic Nitrogen (DIN)	19	-0.060	0.096
pH	19	-0.096	-0.058
Total nitrogen (TN)	19	-0.106	0.068
Total phosphorus (TP)	19	-0.264	-0.146
Turbidity	19	**-0.405**	**-0.361**

4. DISCUSSION

The metabolism measurements indicate that the five sites examined in this study cover a gradient of river health. During the study period, Manawatu at Hopelands had consistently high rates of GPP and ER. While they were not as high as rates observed in the lower reaches of the Manawatu by Collier *et al.* (2009), rates of GPP and ER consistently indicated that the health of this stretch of the river was poor. This 'poor' classification was based on comparison with broad guidelines for interpreting metabolism results (Young *et al.* 2008) as well as when compared to an approximate regional 'best attainable condition' site (*i.e.* Rangitikei at Onepuhi).

Sites with very high rates of ecosystem metabolism are likely to have a lower life-supporting capacity than sites that are within the normal range. Sites with high rates of GPP are likely to experience algal and/or cyanobacterial blooms that can degrade aesthetic and recreational values, and have potential health implications for humans and animals. High algal densities associated with high rates of GPP can also cause large pH fluctuations, smother habitat for invertebrates, cause taste and odour problems for water supplies, and cause problems with low DO (such as fish kills) when the periphyton mats mature and decompose. The highest rates of production will occur in situations where there is plenty of light and nutrients available to support plant growth (Bunn *et al.* 1999). Sites with high rates of ER are normally characterised by large inputs of organic matter from point-source discharges of sewage/wastewater, or large diffuse inputs from sources such as agricultural run-off (Young & Huryn 1999; Gücker *et al.* 2006). High biomasses of algae and other aquatic plants are also often associated with high rates of ecosystem respiration. Sites with high rates of ER will be prone to low minimum dissolved oxygen concentrations which have the potential to kill fish and other aquatic life.

Dissolved oxygen data analysed in this study shows that the dissolved oxygen standards in the Proposed One Plan are being breached on a relatively regular basis at the Manawatu at Hopelands and Mangatainoka at Pahiatua sites (Table 2). The minimum DO saturation observed at the Manawatu at Hopelands site (34% Saturation) corresponded with a DO concentration of 3 mg/L. Sensitive fish would not be expected to live long under these conditions (Dean & Richardson 1999). Although also breaching the proposed DO standards, the minimum DO saturation observed in the Mangatainoka River at Pahiatua (65% Saturation) corresponded to a DO concentration of 6.3 mg/L. Immediate fish mortality would not be expected at this higher concentration and any effects at this site would be more likely related to fish health, growth, reproduction and long-term survival (BCME 1997).

Manawatu at Hopelands had the highest land-use pressure in terms of % pastoral land (Table 1) and would be expected to be the least healthy of the study sites. In contrast, Rangitikei at Onepuhi had relatively low land-use pressure with approximately 35% native vegetation cover in the catchment (Table 1). It had consistently low rates of GPP and ER and was classified as healthy in terms of both GPP and ER when compared to guideline values based on other reference sites. However, the majority of the land cover upstream of this site is still pasture plus other land-use impacts, such as point-source discharges, reduce its suitability as a long-term reference site. Ideally, reference sites would have at least 60% native vegetation cover, low-intensity land development in the remaining catchment, and no or limited point-source discharges. Reference sites should also cover the range of climate and geology expected in the region.

The Rangitikei at Mangaweka had the least land-use pressure (39% native vegetation) and as such we would expect this site to be the healthiest of the five sites. However, our metabolism data were often indicative of satisfactory health, rather than good health. Local environmental variables, such as naturally high levels of dissolved reactive phosphorus in the upper catchment, and/or human impacts, such as the Taihape sewerage treatment discharge to the Hautapu River (a tributary of the Rangitikei upstream of Mangaweka), are likely to be contributing to the relatively high rates of metabolism observed in the Rangitikei at Mangaweka.

As expected, most sites had higher metabolic rates in the warmer months. Seasonal variability influenced the assessment of ecosystem health when compared to the broad guideline values. For example, rates of GPP in the Manawatu River at Teachers College indicated good health in autumn and winter, satisfactory health in spring, and poor health in summer. This matched our expectation for the most marked divergence from healthy conditions to occur during summer when low flows, warm temperatures, plentiful sunlight and the accumulation of algal biomass combine to produce high rates of metabolism, although changes in flow which influence accumulation of algal biomass are not necessarily associated with particular seasons.

In conclusion, our assessment of ecosystem metabolism indicated a range in ecosystem health was evident for the five sites during 2007. Metabolism appeared to be linked with land use in the catchment upstream and possibly with some water quality parameters. Changes in flow, light availability and water temperature result in predictable seasonal changes in metabolism. Additional pressures and/or disturbances, such as point-source discharges, that were not examined in this study can also influence rates of river metabolism.

5. RECOMMENDATIONS

1. Calculate metabolism for ongoing DO data to establish inter-annual and seasonal trends and provide more robust data for analysis of relationships between metabolism and environmental data.
2. Compare metabolism estimates with similar large rivers from a national dataset as it becomes available.
3. Establish regional reference sites that cover the regional range in geology and climate.
4. Establish a data quality assurance methodology that includes regular calibration of equipment and data checking. Consider deploying two DO loggers at a site for a short time to cross-validate data. Single spot measurements are not sufficient for calibration.

5. Consider establishing several extra DO logging sites. A priority is the lower reaches of the Manawatu River near Opiki to determine the frequency of the extremely high metabolism rates that were observed by Collier *et al.* (2009).

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Appendix 1. Daily metabolism estimates from sites on five rivers in the Manawatu-Whanganui Region. Calculations with low R^2 values (<0.4) are in bolded and should be treated with caution. Corrected refers to whether DO data needed to be corrected before metabolism calculation – see methods section.

Season	Date	Depth	ER	GPP	PR	*k*	*R2*	Corrected
Manawatu River at Hopelands								
Summer	18/02/2007	0.57	18.1	13.9	0.8	5.3	0.95	No
Summer	19/02/2007	0.57	21.0	14.9	0.7	6.7	0.84	No
Summer	20/02/2007	0.57	20.8	12.7	0.6	5.9	0.89	No
Summer	21/02/2007	0.56	18.3	11.3	0.6	5.4	0.66	No
Summer	22/02/2007	0.56	22.0	14.2	0.7	5.8	0.97	No
Autumn	7/05/2007	0.61	7.4	9.8	1.3	9.9	0.98	Yes
Autumn	8/05/2007	0.60	8.1	12.2	1.5	11.0	0.97	Yes
Autumn	9/05/2007	0.60	9.3	9.8	1.2	10.4	0.99	Yes
Autumn	10/05/2007	0.60	9.5	6.1	0.6	7.3	0.86	Yes
Autumn	11/05/2007	0.60	22.5	18.3	0.8	13.2	0.89	Yes
Winter	21/08/2007	1.03						
Winter	22/08/2007	0.97						
Winter	23/08/2007	0.92						
Winter	24/08/2007	0.88						
Winter	25/08/2007	0.85						
Spring	19/11/2007	0.66	12.7	19.9	1.6	15.9	0.96	Yes
Spring	20/11/2007	0.64	11.7	11.5	1.0	12.5	0.99	Yes
Spring	21/11/2007	0.63	15.6	17.2	1.1	14.2	1.00	Yes
Spring	22/11/2007	0.62	17.5	17.4	1.0	11.9	0.92	Yes
Spring	23/11/2007	0.61	32.8	24.5	0.7	14.8	0.98	Yes

Season	Date	Depth	ER	GPP	PR	*k*	*R2*	Corrected
Manawatu River at Teachers College								
Summer	18/02/2007	1.02	11.1	9.8	0.9	4.6	0.71	No
Summer	19/02/2007	1.01	9.8	8.3	0.9	3.3	0.54	No
Summer	20/02/2007	1.01	10.4	7.9	0.8	3.6	0.58	No
Summer	21/02/2007	1.00	11.5	8.5	0.7	4.7	0.63	No
Summer	22/02/2007	1.00	10.6	6.1	0.6	3.7	0.62	No
Autumn	7/05/2007	1.14	3.8	1.2	0.3	3.8	**0.31**	No
Autumn	8/05/2007	1.13	2.9	1.6	0.6	2.5	**0.13**	No
Autumn	9/05/2007	1.10	4.9	1.9	0.4	4.6	0.40	No
Autumn	10/05/2007	1.11	3.9	2.2	0.6	2.5	**0.12**	No
Winter	21/08/2007	1.15	0.1	0.3	3.0	6.2	0.73	Yes
Winter	22/08/2007	1.17	0.4	0.2	0.4	6.4	0.60	Yes
Winter	23/08/2007	1.19	1.4	0.5	0.3	8.4	0.52	Yes
Winter	24/08/2007	1.22	1.9	0.6	0.3	9.3	0.65	Yes
Winter	25/08/2007	1.24	1.8	0.3	0.2	5.7	**0.26**	Yes
Spring	19/11/2007	1.30	4.1	3.1	0.7	3.7	**0.44**	Yes
Spring	20/11/2007	1.26	4.9	3.6	0.7	4.2	**0.23**	Yes
Spring	21/11/2007	1.23	5.3	4.7	0.9	3.3	**0.33**	Yes
Spring	22/11/2007	1.20	4.0	3.9	1.0	1.1	**0.08**	Yes
Spring	23/11/2007	1.18	6.6	5.0	0.7	4.5	0.48	Yes

Season	Date	Depth	ER	GPP	PR	*k*	*R2*	Corrected
Mangatainoka River at Pahiatua								
Summer	18/02/2007	0.36	11.5	6.4	0.6	11.8	0.91	No
Summer	19/02/2007	0.35	10.0	5.5	0.5	10.0	0.95	No
Summer	20/02/2007	0.34	12.0	6.5	0.5	11.8	0.83	No
Summer	21/02/2007	0.34	8.4	4.6	0.6	7.6	0.65	No
Summer	22/02/2007	0.33	12.6	6.0	0.5	13.3	0.93	No
Autumn	7/05/2007	0.56	5.5	3.8	0.7	13.6	0.95	No
Autumn	8/05/2007	0.52	5.1	3.5	0.7	11.4	0.92	No
Autumn	9/05/2007	0.49	5.3	3.1	0.6	10.7	0.90	No
Autumn	10/05/2007	0.62	7.7	4.7	0.6	10.9	0.70	No
Winter	21/08/2007	0.89	0.6	0.4	0.7	9.9	0.91	Yes
Winter	22/08/2007	0.84	0.2	0.3	1.3	9.0	0.91	Yes
Winter	23/08/2007	0.80	0.5	0.1	0.3	6.1	0.76	Yes
Winter	24/08/2007	0.76	0.3	0.2	0.6	6.6	0.51	Yes
Winter	25/08/2007	0.73	0.4	0.1	0.3	5.9	0.86	Yes
Spring	19/11/2007	0.61	4.5	4.4	1.0	11.3	0.99	Yes
Spring	20/11/2007	0.58	4.9	4.5	0.9	12.1	0.98	Yes
Spring	21/11/2007	0.55	4.7	3.7	0.8	11.4	0.98	Yes
Spring	22/11/2007	0.53	4.7	3.7	0.8	10.2	0.89	Yes
Spring	23/11/2007	0.51	5.0	3.6	0.7	10.5	0.91	Yes

Season	Date	Depth	ER	GPP	PR	*k*	*R2*	Corrected
Rangitikei River at Mangaweka								
Summer	18/02/2007	0.66	5.2	1.9	0.4	9.8	0.87	No
Summer	19/02/2007	0.65	7.3	2.8	0.4	12.4	0.95	No
Summer	20/02/2007	0.65	6.6	2.8	0.4	9.9	0.83	No
Summer	21/02/2007	0.65	8.4	3.6	0.4	13.3	0.97	No
Summer	22/02/2007	0.65	9.8	3.6	0.4	14.4	0.95	No
Autumn	7/05/2007	0.72	5.4	4.3	0.8	13.8	0.97	No
Autumn	8/05/2007	0.70	4.7	4.9	1.0	13.3	0.93	No
Autumn	9/05/2007	0.69	4.7	5.0	1.1	17.1	0.99	No
Autumn	10/05/2007	0.68	3.7	3.0	0.8	12.1	0.98	No
Autumn	11/05/2007	0.69	4.6	3.8	0.8	12.6	0.98	No
Winter	21/08/2007	1.15	16.0	0.0	0.0	17.0	0.88	**Yes**
Winter	22/08/2007	1.10	13.9	0.3	0.0	15.9	0.76	**Yes**
Winter	23/08/2007	1.06	11.9	0.0	0.0	15.1	0.66	**Yes**
Winter	24/08/2007	1.03	10.9	0.0	0.0	14.2	0.91	**Yes**
Winter	25/08/2007	1.00	8.0	0.0	0.0	10.1	0.75	**Yes**
Spring	19/11/2007	0.79	6.3	1.7	0.3	10.5	0.85	No
Spring	20/11/2007	0.78	7.5	1.8	0.2	12.3	0.80	No
Spring	21/11/2007	0.76	9.4	2.5	0.3	14.0	0.71	No
Spring	22/11/2007	0.75	10.5	3.2	0.3	15.3	0.93	No
Spring	23/11/2007	0.74	10.8	3.0	0.3	16.8	0.93	No

Season	Date	Depth	ER	GPP	PR	*k*	*R2*	Corrected
Rangitikei River at Onepuhi								
Summer	18/02/2007	0.38	1.4	1.5	1.1	5.2	0.90	No
Summer	19/02/2007	0.37	2.9	2.8	1.0	7.7	0.96	No
Summer	20/02/2007	0.36	3.7	3.0	0.8	8.5	0.98	No
Summer	21/02/2007	0.36	4.1	2.9	0.7	8.0	0.97	No
Summer	22/02/2007	0.35	4.6	2.8	0.6	7.1	0.99	No
Autumn	7/05/2007	0.49	4.7	2.6	0.6	10.7	0.99	Yes
Autumn	8/05/2007	0.46	3.8	2.3	0.6	9.9	0.96	Yes
Autumn	9/05/2007	0.44	3.6	1.8	0.5	9.0	0.98	Yes
Autumn	10/05/2007	0.43	3.4	1.4	0.4	8.1	0.97	Yes
Autumn	11/05/2007	0.42	4.5	2.1	0.5	10.2	0.98	Yes
Winter	21/08/2007	1.16	1.9	0.0	0.0	5.1	0.68	**Yes**
Winter	22/08/2007	1.08	2.9	0.0	0.0	7.7	0.59	**Yes**
Winter	23/08/2007	1.01	3.1	0.0	0.0	11.5	0.82	**Yes**
Winter	24/08/2007	0.66	1.7	0.0	0.0	8.0	0.70	**Yes**
Winter	25/08/2007	0.91	4.7	0.0	0.0	14.7	0.88	**Yes**
Spring	19/11/2007	0.47	0.1	2.2	19.6	7.7	0.96	No
Spring	20/11/2007	0.43	0.5	2.1	4.7	8.0	0.97	No
Spring	21/11/2007	0.41	1.1	2.8	2.6	12.1	0.98	No
Spring	22/11/2007	0.39	1.6	1.9	1.2	8.0	0.96	No
Spring	23/11/2007	0.37	1.9	1.8	0.9	8.5	0.95	No