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Temporal variation in ecosystem metabolism in relation to water quality in the Piako River

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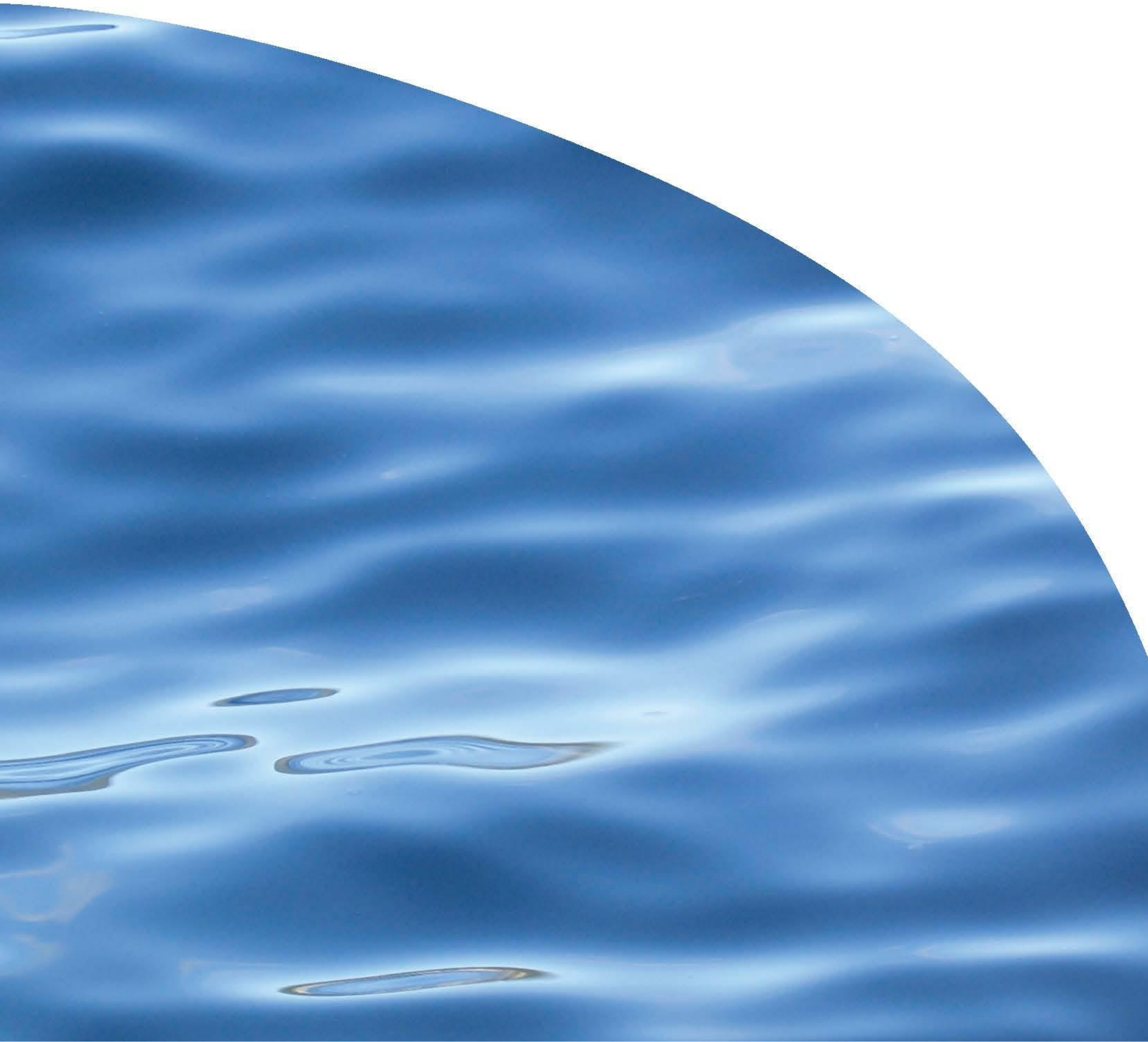

TEMPORAL VARIATION IN ECOSYSTEM METABOLISM IN RELATION TO WATER QUALITY IN THE PIAKO RIVER

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Prepared for Waikato Regional Council

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EXECUTIVE SUMMARY

Rates of ecosystem metabolism can be used to provide a functional assessment of stream health to accompany more traditional structural measures such as water quality and biological indicators. Ecosystem metabolism varies temporally driven by daily, seasonal and annual variation in the primary drivers of light, temperature, nutrients and stream discharge. As such, an increased understanding of the temporal trends in ecosystem metabolism can help determine the most appropriate temporal scale to assess stream health.

We explored the temporal and spatial variation in the ecosystem metabolism components of gross primary production (GPP) and ecosystem respiration (ER) in the Piako River (near Morrinsville, Waikato) in relation to measures of water quality. Ecosystem metabolism was estimated from continuous dissolved oxygen data collected from six sites on the Piako River. Monthly estimates from October 2012 to September 2013 were compared to monthly spot measures of water quality.

The Piako River was a net consumer of carbon throughout the year with productivity to respiration (P/R) ratios averaging 0.7. Rates of ecosystem metabolism reflected good to poor stream health longitudinally down the catchment and varying throughout the year. A small upland site with low land-use impacts, Piakonui, had consistently low levels of metabolism. In contrast, downstream sites subject to greater than 85% pasture catchments had increased metabolism, particularly during months of warmer temperatures and stable flow.

Higher rates of average annual metabolism occurred at larger stream sites with macrophyte beds and where there was higher water clarity, lower turbidity, higher conductivity and nutrient concentrations. Monthly metabolism estimates were most strongly related to water quality measured during the same calendar month, even when water quality measurements were made after metabolism estimates. On average water quality measurements were made four days before metabolism estimates. Fewer significant correlations were observed between metabolism estimates and water quality measured the month before (on average 33 days before), and between metabolism and the three-month rolling mean water quality value. A consistent positive relationship between ecosystem metabolism and conductivity regardless of time period suggests conductivity is an indicator of persistent and cumulative land-use impacts at each site; especially given that within each site there appeared to be a negative correlation over time. Similarly, the relationship between GPP and *E.coli* is more likely to be a correlative rather than causative, with both indicators showing poor stream health in the Piako River.

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1. INTRODUCTION

Ecosystem metabolism (the combination of primary production and ecosystem respiration) has been demonstrated as a good functional indicator of river health in the Waikato Region (Clapcott & Young 2008, 2009).

Ecosystem metabolism provides a measure of how much organic carbon is produced and consumed in river ecosystems. Organic carbon enters an ecosystem through photosynthesis (plant growth) and the sum of all plant growth is called gross primary production (GPP). Carbon leaves an ecosystem through respiration and the combined respiration of autotrophs (plants) and heterotrophs (other living organisms) is the ecosystem respiration rate (ER). Net ecosystem metabolism (NEM) is the net amount of carbon exchanged by an ecosystem at any given time. The ratio of production to respiration (P/R) provides a relative measure of ecosystem metabolism. In river ecosystems, a significant amount of carbon flux (in and out) can be attributed to terrestrial allochthonous carbon imports and exports to the downstream coastal zone (Naiman 1982).

The primary drivers of ecosystem metabolism in rivers are light, temperature, nutrients and physical habitat through the provision of energy and substrate and the physical limitation of metabolic processes. These primary drivers are all subject to natural temporal and spatial variability. However, what makes ecosystem metabolism a good indicator of river health is that it is affected by human impacts, especially through changes to these primary drivers. Increased knowledge of how ecosystem metabolism varies temporally, spatially, and in relation to drivers can help with the assessment of stream health.

Ecosystem metabolism provides a functional measure of steam health to complement more traditional structural measures, *e.g.* water quality or biological assessment. Holistic assessment of stream health should contain both structural and functional measures (Karr 1999, Bunn & Davies 2000). Recent studies have shown that structural and functional measures can respond differently to human impacts (Clapcott *et al.* 2012). The aim of this study is to examine the temporal variability in ecosystem metabolism in a study catchment, the Piako River, in relation to water quality. Specific questions of interest are:

1. What characterises temporal variability in ecosystem metabolism in the Piako River?
2. To what degree does ecosystem metabolism reflect the water quality of the Piako River?
3. At what temporal periods are ecosystem metabolism and water quality most closely related?

Results will aid in the interpretation of metabolism estimates and help determine whether metabolism and water quality provide comparable assessments of stream health.

2. METHODS

2.1. Study area

The Piako River flows north through the Hauraki Plains into the Firth of Thames. It is a 6th order river with a total catchment area of approximately 1,480 square kilometres. The Piako River has two major stems: the Waitoa River to the east which converges with Piako River main stem in the vicinity of the Kopuatai Peat Dome (Figure 1). The catchment consists of mostly flat to gently undulating topography, although some headwaters are strongly rolling to very steep. The predominant vegetation of the catchment is pasture used for intensive dairy farming.

Six sample sites were located within the study area — three sites on the Waitoa River, one site on the Piakonui Stream, which flows into the Piako River, and two sites on the Piako River main stem. The sites range in river size from 3rd to 6th order, between 2.5 m to 10 m wide and 0.3 m to 1.6 m deep (Table 1). During the study period (October 2012 to September 2013), the average daily flow ranged from an estimated 0.25 m^3/sec at the Piakonui Stream site, to 5.17 m^3/sec downstream at the Piako River at Paeroa-Tahuna Road (PT Rd) site.

The Piako River often fails to achieve 'satisfactory' physico-chemical water quality for ecological health and for human uses of water based on Waikato Regional Council (WRC) water quality guidelines and standards. This is because of high levels of total nitrogen and total phosphorus and low visual water clarity (Tulagi 2013). Although the 20-year trend (1993–2012) in water quality shows general improvements in turbidity, ammonia and total phosphorus, and deterioration in visual clarity across the catchment (Vant 2013). During the study period, the median value of total phosphorus exceeded water quality guidelines for all sites except Piakonui. Clarity was consistently less than the guideline value of 1.6 m at all sites except Piako River at Kiwitahi. These values have not been flow-adjusted however, and sampling may have occurred above base flow conditions.

During the study period, catchment hydrology reflected seasonal conditions with increased flows associated with rain events during the autumn / winter months, mainly May and June (Figure 2). Storm events resulting in increased flows were also observed over a short period in December and for longer duration in August through to October.

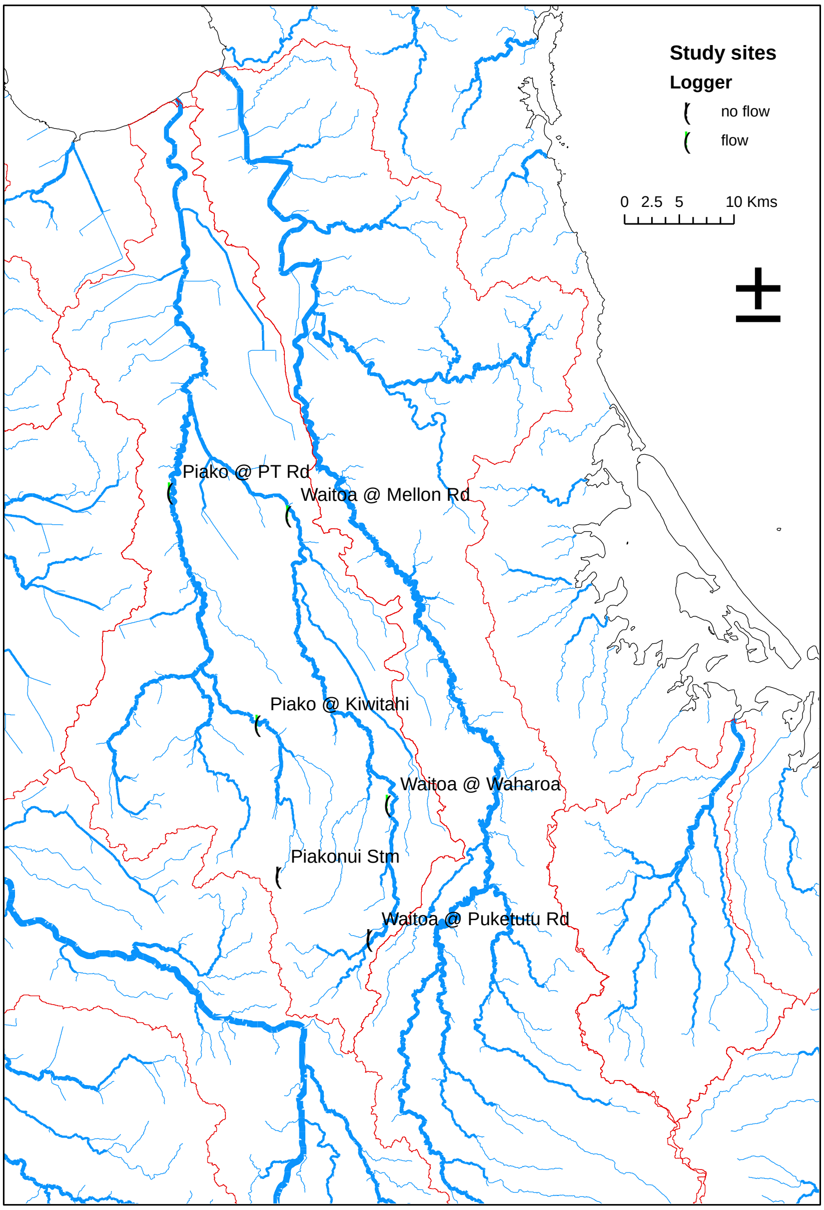

Figure 1. Map of the study area showing location of sample sites in the Piako River delineated by the presence or absence of a continuous flow recorder. Catchment boundaries are shown as red lines.

Table 1. Description of physical and catchment properties of the six study sites. Water quality parameters are median values for the study period of October 2012 to September 2013. Parameters that fail water quality guidelines and standards for ‘satisfactory’ water quality (after Tulagi 2013) are highlighted in red text. *Estimated from nearby flow recorder.

	Piakonui at Piakonui Rd	**Piako R at Kiwitahi**	**Piako R at Paeroa-Tahuna Rd**	**Waitoa River at Puketutu Rd**	**Waitoa R at Waharoa**	**Waitoa River at Mellon Rd**
Catchment area (km^2)	7.78	108.11	536.75	66.50	120.69	409.35
Native vegetation (%)	59	14	4	1	1	2
Pasture (%)	40	85	93	98	99	95
Order	3	5	6	5	5	5
Width (m)	2.5	10.2	13	4.3	8.3	10
Depth(m)	0.28	1	0.74	0.48	0.58	1.58
Mean daily flow^ (m^3/sec)	0.25*	1.01	5.17	0.75*	1.1	3.44
Black disk (m)	1.36	1.61	0.9	--	1.11	1.06
Turbidity (NTU)	4.25	4.05	9.3	4.5	5.3	6.35
Conductivity (mS/m@25°C)	7.4	14.95	21.4	12.95	15.95	29.1
pH	7.35	7.14	7.24	7.30	7.09	7.19
Dissolved reactive phosphorus (g/m^3)	0.011	0.038	0.118	0.029	0.022	0.073
Total phosphorus (g/m^3)	0.021	0.062	0.201	0.057	0.056	0.124
Ammoniacal nitrogen (g/m^3)	0.044	0.034	0.046	0.076	0.015	0.089
Total oxidised nitrogen (g/m^3)	0.211	1.000	1.400	0.690	1.510	2.200
Total Kjeldahl nitrogen (g/m^3)	0.145	0.345	0.520	0.385	0.370	0.500
E. coli (cfu/100 ml)	41	295	550	265	450	405

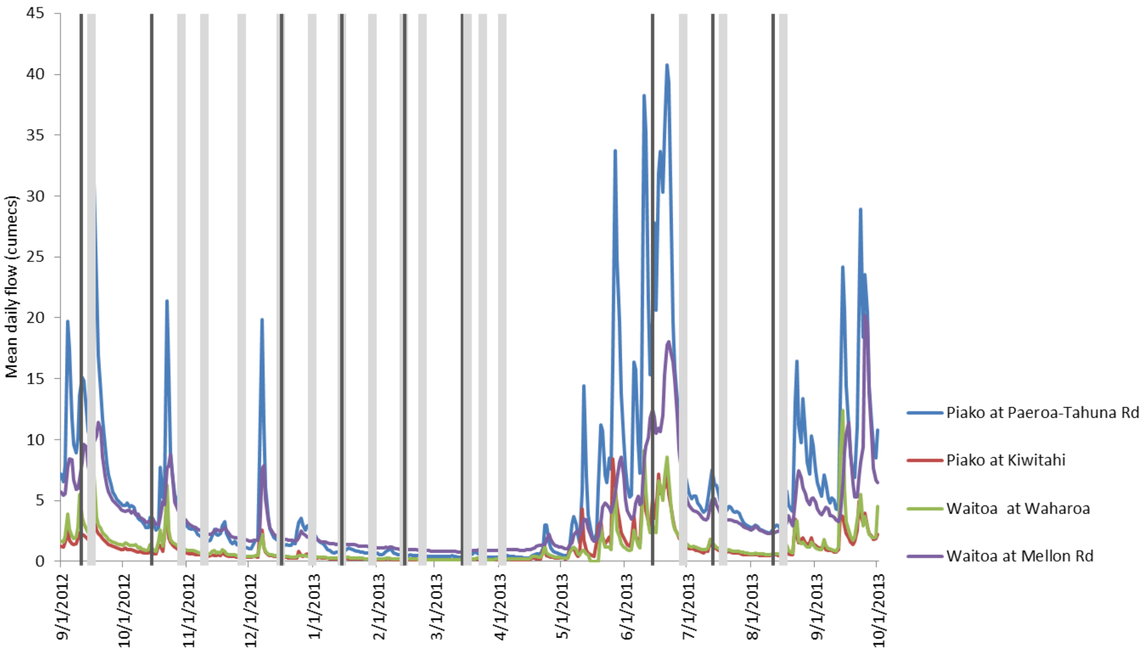

Figure 2. Mean daily flow measured at study sites from September 2012 to October 2013. Black vertical lines indicate water quality sampling times and grey vertical bands indicate ecosystem metabolism sampling times, for all sites.

2.2. Physico-chemical data

2.2.1. Dissolved oxygen

Dissolved oxygen (DO) concentration and temperature were generally recorded every 15 minutes using data loggers (D-Opto, Zebra-Tech Ltd). These were deployed and maintained by WRC at six sites on the Piako River from October 2012 to September 2013. For October 2012, loggers recorded at 30-minute intervals. The loggers were deployed near the surface in a weir pool at four sites where permanent flow recorders were established (Piako at Kiwitahi, Piako at PT Rd[1], Waitoa at Waharoa, Waitoa at Mellon Rd) or in a natural pool at the two remaining sites (Piakonui at Piakonui Rd, Waitoa at Puketutu Rd). Loggers were downloaded monthly, except when high flow impeded site access in June 2012. Resulting DO data (parts per million and % concentration) and temperature data (degrees Celsius) was assigned a quality control code determined by confidence in the accuracy of the data. Generally the data were given a quality code relating to ‘original data’. However, when data was edited for some reason, it was given a lower quality code (*i.e.* one logger was 4°C out so this data [temperature and DO] was adjusted and therefore received the lower quality code of ‘use with caution’). The DO data were used to estimate ecosystem metabolism.

[1] No weir pool at this site; flow and DO loggers deployed in a natural pool.

2.2.2. Water quality

Water quality parameters were collected monthly at the six study sites[2] using standardised methods. Five of these six sites are existing long-term water quality monitoring sites (see Tulagi 2013). We chose to explore key water quality parameters with conceptual and empirical links to metabolism, including nutrients, clarity, pH, conductivity and *E.coli*. (Table 1).

2.3. Estimating ecosystem metabolism

Graphs of the full range of DO and flow data available at each site between October 2012 and September 2013 were inspected to identify suitable times to calculate metabolism, *i.e.* times of relatively stable flow and expected diurnal signals in DO and temperature data. Periods chosen for metabolic calculations were similar, but not the same, for each site each month. For each chosen period, ecosystem metabolism was calculated for five consecutive days; a minimum of three days where this was not possible.

Firstly, noise in the dissolved oxygen (DO) and temperature data was minimised using a moving average smooth function with an interval of five measurements. Then data were used to calculate ecosystem metabolism using the RiverMetabolismEstimator (v1.2) spreadsheet model developed by Young and Knight (2005). This model uses the night-time regression approach (Owens 1974). The rate of change of oxygen concentration over short intervals during the night was regressed against the oxygen deficit to yield:

$$dO/dt = ER + kD$$

where dO/dt is the rate of change of oxygen concentration (g O_2 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 (defined as Osat - O, where Osat is the saturation oxygen concentration, g O_2 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 are then used to determine gross photosynthetic rate over the sampling interval using:

$$GPPt = dO/dt + ER – kD$$

where GPPt 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 while the reaeration rate is assumed to increase by 2.41%

[2] For Waitoa at Waharoa, water quality data were collected approximately 200 m upstream at Waitoa at Landsdowne Road.

per degree (Kilpatrick *et al.* 1989). Daily gross primary production (GPP, g O_2 m^{-3} d^{-1}) is estimated as the integral of all temperature-corrected photosynthetic rates during daylight (Wiley *et al.* 1990).

This ‘single station’ approach assumes homogenous biological and physical structure for a distance of 3v/k upstream of the station (range 80 m–400 m river length in our study rivers), where v is reach-average flow velocity and k the reaeration coefficient per day (Chapra & Di Toro 1991). This assumption was not tested, but based on visual assessments, is likely to be marginal for Piakonui due to the presence of a tributary and boulder riffle immediately upstream of site (pers. obs. Mark Hamer, WRC).

An areal estimate of metabolism was obtained by multiplying the volume-based estimates by average reach depth (m) which was calculated from five depth measurements across the river at five transects upstream of each site in February 2012. Mean reach depth for each sample day was estimated by applying the differential site correction to stage height calculated from discharge rates reported by flow recorders closest to each site. Following depth adjustment, gross primary productivity and ecosystem respiration are expressed in units of g O_2 m^{-2} d^{-1}.

The balance between GPP and ER is a useful measure of the sources of energy driving a stream ecosystem and therefore the ratio (P/R) of GPP to ER was calculated. Similarly, net ecosystem metabolism (NEM) provides a measure of the net accumulation or consumption of organic carbon and so was calculated:

$$NEM = GPP - ER$$

Including estimates from ‘corrected’ data (see section below) we were able to calculate ecosystem metabolism for twelve months at all sites except Piakonui and Piako at PT Rd where high flows prohibited use of data in June.

2.3.1. Data ‘correction’

Problems associated with the raw DO data were evident at some sites on some occasions — Piako at PT Rd from July to September, Piakonui from February to May and September. 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 physically impossible for a site with high productivity, leading to greater than 100% DO saturation during the day, to not have equally high night time rates of respiration that 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 5%–15% were required. Estimates of metabolism on these occasions were calculated using this corrected data.

We conducted a sensitivity analysis to illustrate the potential effect this correction has on metabolism estimates. We applied a range of corrections (0%–15%) to three days of DO data from Piako at PT Rd and Piakonui sites. The increase in estimates of ER and decrease in estimates of GPP relative to the percentage of correction applied was site dependent (Figure 3). At Piako at PT Road, a 10% correction in DO and temperature data resulted in a 52% increase in estimated ER and a 10% decrease in GPP. At Piakonui, a 10% correction resulted in 152% increase in ER and a 15% decrease in GPP.

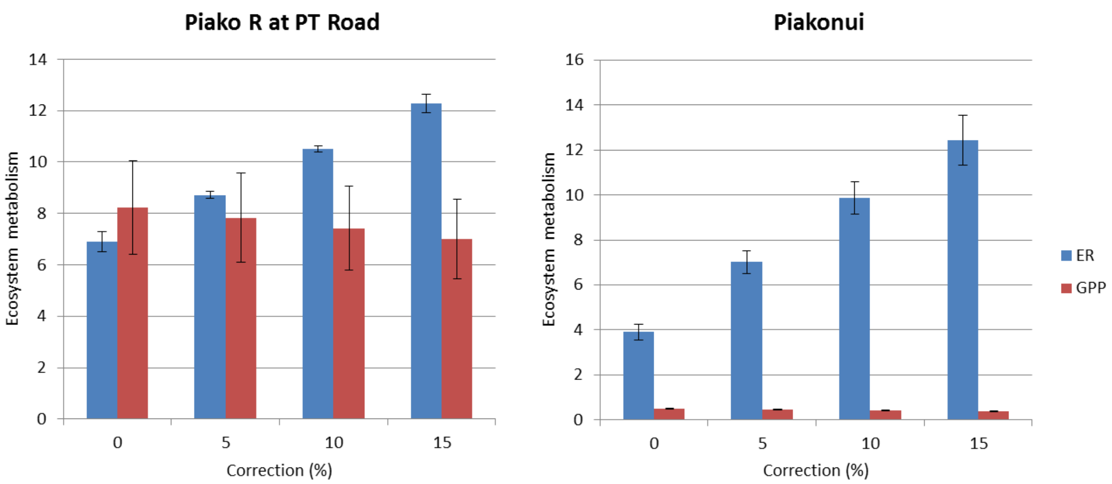

Figure 3. Estimates of ecosystem metabolism (g O_2 m^{-2} d^{-1}) at varying percentage corrections of dissolved oxygen and temperature data for two sites. Three-day mean ± standard deviation.

2.4. Data analysis

Gross primary productivity and ER data were square-root transformed to meet the assumptions of normality for statistical analysis. An analysis of variance (ANOVA) to test for similarity among sites and time was conducted in Systat Version 10.2. We chose to maximise the degrees of freedom in our ANOVA by including ‘month’ as the measure of time. However this required us to exclude all June estimates to maintain a balanced design, as there were no estimates for June 2012 at two sites. We repeated the ANOVAs by using ‘season’ as a measure of time and averaged monthly estimates into season as follows: summer (Dec–Feb), autumn (Mar–May), winter (June–Aug), spring (Sep–Nov).

We used pairwise correlations to test for relationship between the average monthly metabolism estimates and measures of water quality collected before and during the month of metabolic estimates. Most water quality parameters were transformed to meet the assumptions of normality for statistical analysis, including natural log transformation for total nitrogen, total phosphorus, dissolved reactive phosphorus, ammonia, turbidity and *E.coli*; and square-root transformation for total oxidised nitrogen.

3. RESULTS

3.1. Gross primary productivity

Daily rates of GPP ranged from 0.1 g O_2 m^{-2} d^{-1} (Piakonui in autumn) to 24.2 g O_2 m^{-2} d^{-1} (Piako at Kiwitahi in summer). The GPP was generally highest during the summer months (Figure 4) and indicative of unhealthy conditions at all sites except Piakonui according to the criteria suggested by Young *et al*. (2008). Rates of GPP generally indicated satisfactory to healthy conditions at all sites during the remainder of the year, except Piako at Kiwitahi where consistently high values were observed. The difference between minimum GPP and maximum GPP recorded during the 12-month study period averaged 11.0 g O_2 m^{-2} d^{-1} and ranged from 3.6 g O_2 m^{-2} d^{-1} at Piakonui to 17.4 g O_2 m^{-2} d^{-1} at Waitoa at Mellon Rd.

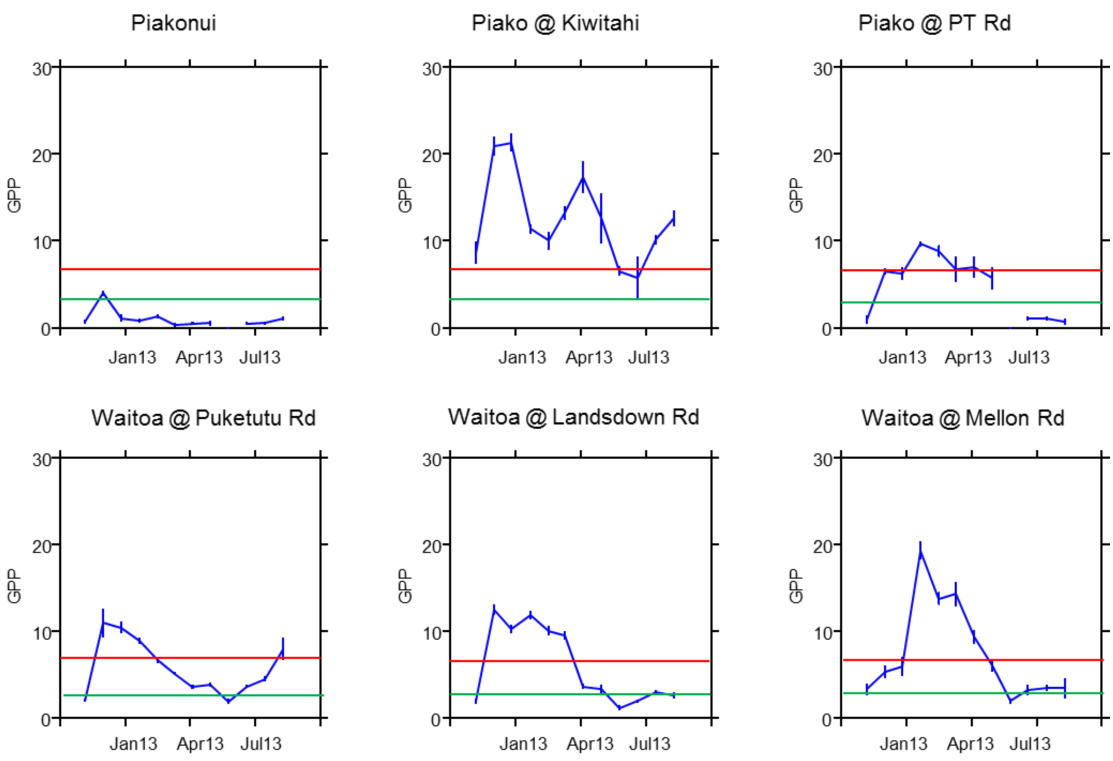

Figure 4. Rates of gross primary production (GPP; g O_2 m^{-2} d^{-1}) for six study sites in the Piako River catchment from October 2012 to September 2013 (± SE). Horizontal lines mark absolute values used to assess ecosystem health from Young *et al.* (2008): below the green line is 'healthy', above the green line is 'satisfactory' and above the red line is 'poor'.

An analysis of variance showed a significant difference in GPP among study sites ($F_{(5, 254)} = 543.1$, $p < 0.001$) and over time ($F_{(10, 254)} = 25.3$, $p < 0.001$). However, a significant interaction between the effects of site and month showed that the difference among sites varied with time ($F_{(50,254)} = 14.7$, $p < 0.001$); *i.e.* sites had different temporal trends. Repeated ANOVAs with season as the time factor indicated the same trends (results not shown), with a significant difference in GPP between sites, season, and different seasonal trends among sites.

Table 2. Average rates of ecosystem metabolism in the Piako River from October 2012 to September 2013. Values greater than the thresholds indicative of 'poor' ecosystem health according to Young *et al* (2008) are in red text.

	Gross primary production (g O_2 m^{-2} d^{-1})						
	Annual	**Spring**	**Summer**	**(January)**	**Autumn**	**Winter**	**(July)**
Piakonui	1.00	1.65	1.06	0.77	0.41	0.49	0.45
Piako at Kiwitahi	12.52	13.68	14.22	11.34	14.37	7.60	5.78
Piako at PT Rd	4.92	2.97	8.21	9.63	6.47	1.03	1.00
Waitoa at Puketutu Rd	5.80	7.00	8.67	8.91	4.19	3.35	3.66
Waitoa at Waharoa	5.98	5.68	10.71	11.85	5.50	2.04	1.95
Waitoa at Mellon Rd	7.46	4.02	13.51	19.33	9.88	3.06	3.27
	Ecosystem respiration (g O_2 m^{-2} d^{-1})						
	Annual	**Spring**	**Summer**	**(January)**	**Autumn**	**Winter**	**(July)**
Piakonui	2.70	3.61	0.95	1.01	2.79	3.45	2.84
Piako at Kiwitahi	21.05	15.71	20.70	18.36	28.94	18.83	14.61
Piako at PT Rd	6.28	4.88	8.51	7.64	7.81	2.15	1.47
Waitoa at Puketutu Rd	7.33	8.32	9.61	8.96	7.67	3.72	2.65
Waitoa at Waharoa	8.51	5.59	12.60	13.51	10.52	5.31	4.17
Waitoa at Mellon Rd	16.87	18.15	13.99	16.72	16.60	19.44	21.68

3.2. Ecosystem respiration

Rates of ER ranged from 0.14 g O_2 m^{-2} d^{-1} (Piakonui in summer) to 37.77 g O_2 m^{-2} d^{-1} (Piako at Kiwitahi in autumn). Ecosystem respiration was high throughout the study period at Piako at Kiwitahi and Waitoa at Mellon Rd sites and indicative of poor ecosystem health according to the criteria recommended by Young *et al.* (2008) (Figure 5). Rates of ER were generally highest during the summer months. The difference between minimum ER and maximum ER recorded over the 12-month study period averaged 10.6 g O_2 m^{-2} d^{-1} and ranged from 6.0 g O_2 m^{-2} d^{-1} at Piakonui to 20.2 g O_2 m^{-2} d^{-1} at Piako at Kiwitahi.

As with GPP, an analysis of variance showed that ER was statistically different among sites ($F_{(5, 254)} = 576.6$, $p < 0.001$) and over time ($F_{(10, 254)} = 143.3$, $p < 0.001$) and there was a significant interaction ($F_{(50,254)} = 20.5$, $p < 0.001$), suggesting the difference between sites varied monthly. Results were the same when ANOVA were repeated using season as the time factor.

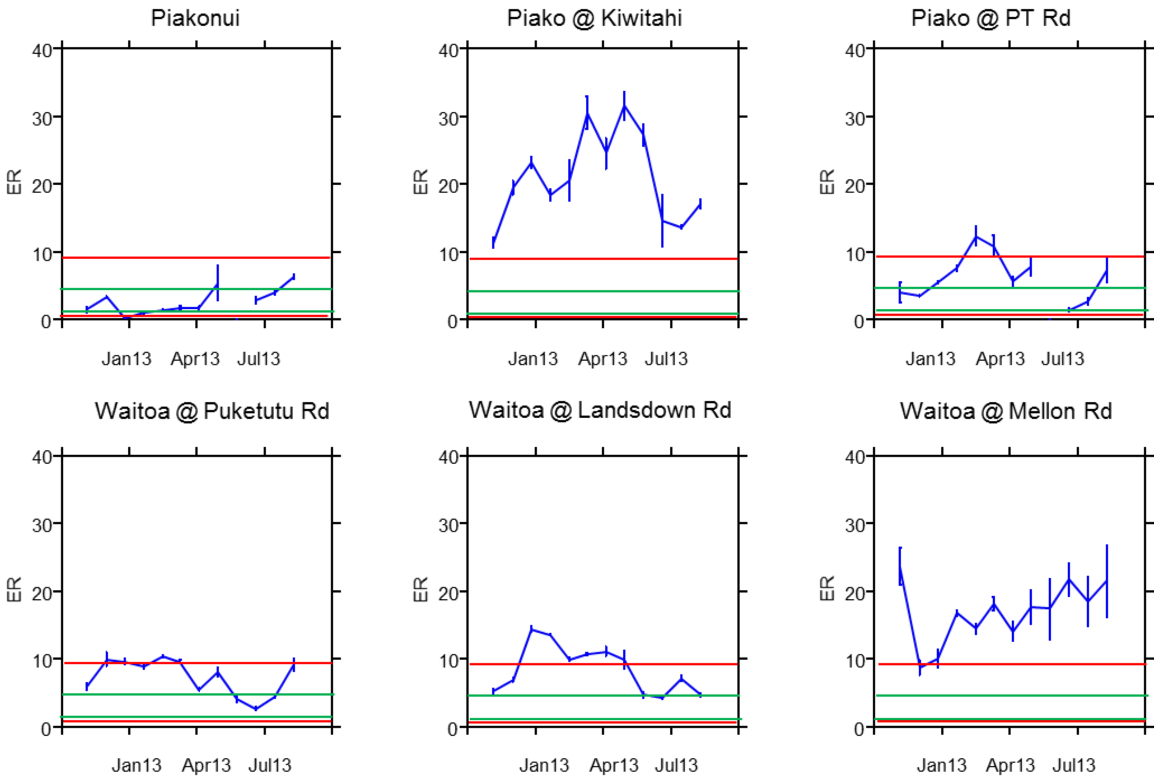

Figure 5. Rates of ecosystem respiration (ER; g O_2 m^{-2} d^{-1}) for six study sites in the Piako River catchment from October 2012 to September 2013 (± SE). Horizontal lines mark absolute values used to assess ecosystem health from Young *et al.* (2008): between the green lines is 'healthy', between adjacent green and red lines is 'satisfactory' and above and below the red lines is 'poor'.

3.3. Net ecosystem metabolism

Rates of NEM ranged from -28.8 g O_2 m^{-2} d^{-1} (Piako at Kiwitahi in autumn) to 6.8 g O_2 m^{-2} d^{-1} (Waitoa at Waharoa in spring) and showed that the study sites were net consumers of carbon throughout most of the study period (Figure 6). Only occasionally during summer months did production exceed respiration at all sites, otherwise there were few apparent trends in the data. Analysis of variance confirmed significant differences in NEM among sites ($F_{(5, 254)} = 101.9$, $p < 0.001$), times ($F_{(5, 254)} = 37.2$, $p < 0.001$) and site differences over time ($F_{(50, 254)} = 15.1$, $p < 0.001$).

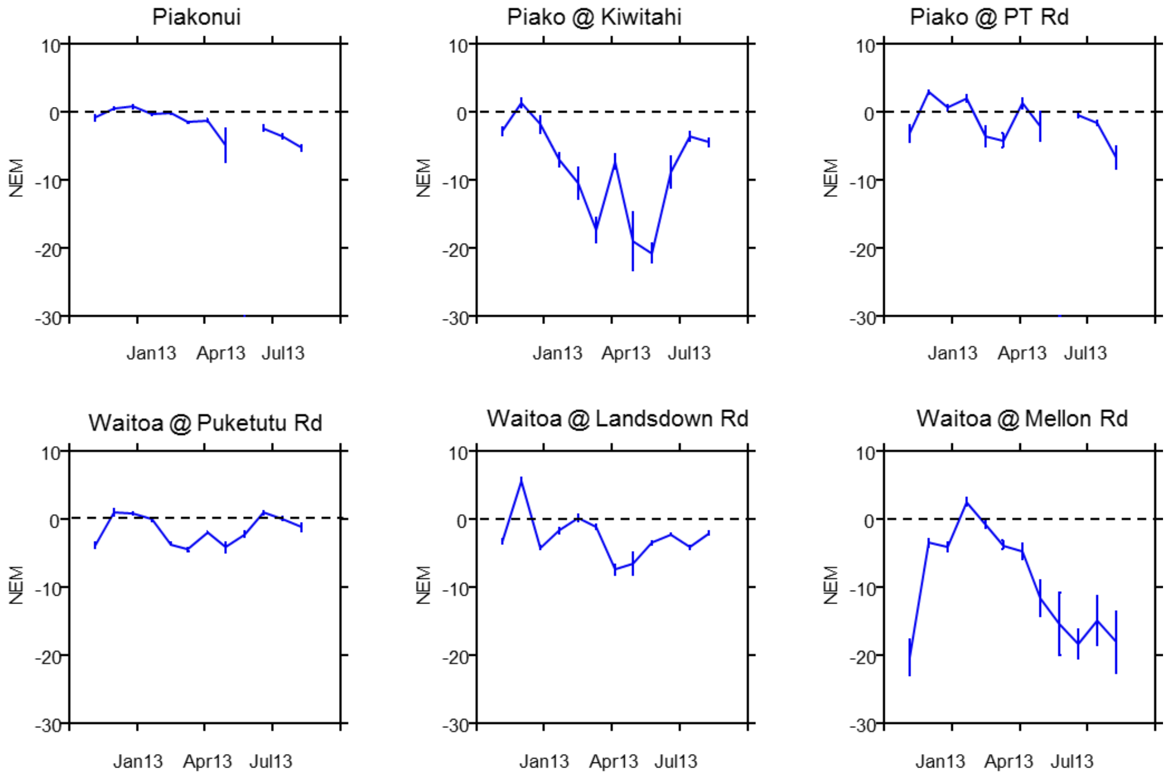

Figure 6. Rates of net ecosystem metabolism (NEM; g O_2 m^{-2} d^{-1}) for six study sites in the Piako River catchment from October 2012 to September 2013 (± SE). The dashed line at zero indicates a balance between production and respiration.

3.4. Production / Respiration ratio

The P/R ratios ranged from 0.03 (Waitoa at Waharoa in spring) to 7.1 (Piakonui in summer) and averaged 0.7, further illustrating the net consumption of carbon at all study sites during the 12-month study period (Figure 7). Analysis of variance confirmed significant differences in P/R ratios among sites ($F_{(5, 254)} = 9.0$, $p < 0.001$), times ($F_{(5, 254)} = 45.6$, $p < 0.001$) and site differences over time ($F_{(50, 254)} = 16.3$, $p < 0.001$).

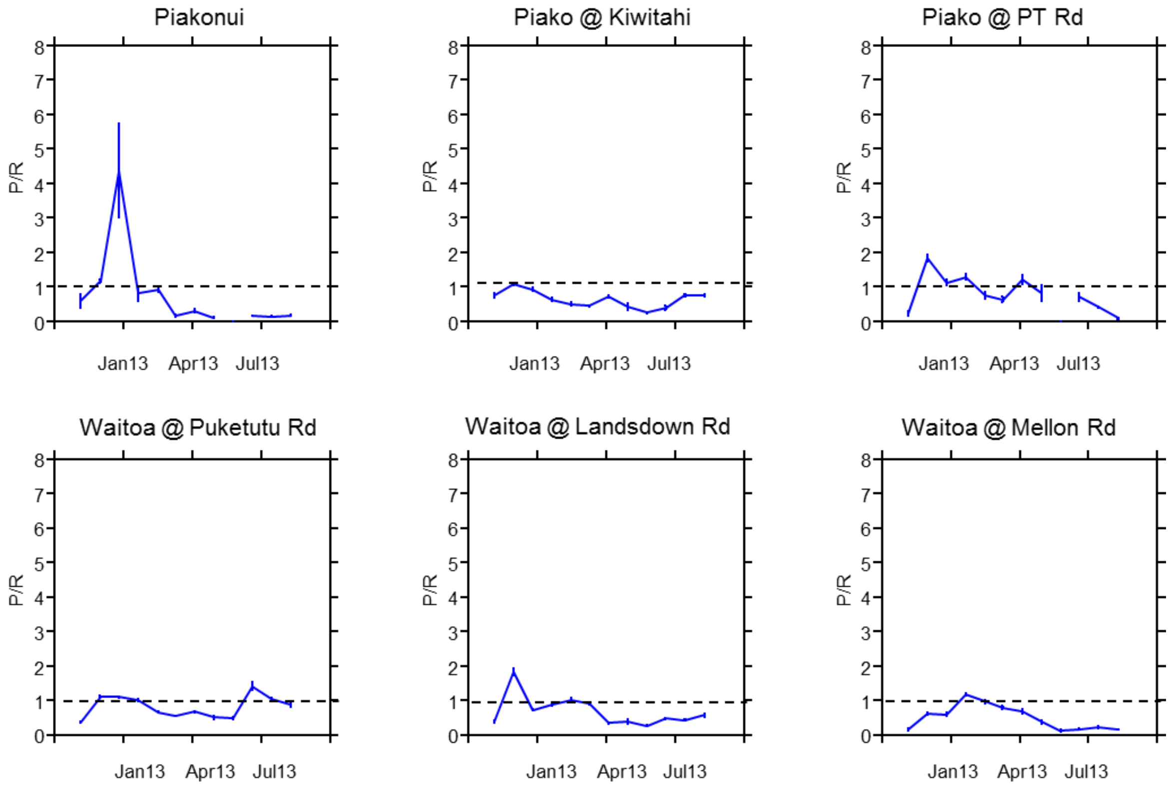

Figure 7. Production to respiration (P/R) ratios for six study sites in the Piako River catchment from October 2012 to September 2013 (± SE). The dashed line at one indicates a balance between production and respiration.

3.5. Relationships between stream metabolism metrics

Similarity in temporal trends between ER and GPP in the Piako River (Figure 4, Figure 5) suggested a strong production-respiration coupling at the sample sites and that GPP and ER are both seasonally driven by temperature. This was evident in the average correlation between GPP and ER at all sites (R = 0.620,Table 3). Further examination of this relationship by site showed that strong production-respiration coupling only occurs at sites with macrophyte beds, *e.g.* Waitoa at Waharoa, Waitoa at Mellon Rd, and Piako at Paroa-Tahuna Rd sites (Table 3). On average, NEM was more related to ER than GPP reflecting the dominant heterotrophic pathway of carbon cycling in the Piako River.

Table 3. Pearson correlation coefficient (R) for the relationship between stream metabolism metrics at sites on the Piako River. Significance is indicated by bold (P < 0.01) and italics (P < 0.05). Proportional macrophyte cover as estimated in February 2013 is shown for each site.

	All sites	**Piakonui at Piakonui Rd**	**Piako R at Kiwitahi**	**Piako R at Paeroa-Tahuna Rd**	**Waitoa R at Waharoa**	**Waitoa River at Mellon Rd**	**Waitoa River at Puketutu Rd**
N	338	52	60	52	60	60	54
GPP: ER	**0.620**	0.159	0.335	**0.589**	**0.729**	**0.686**	-0.116
GPP: NEM	0.086	0.258	**0.424**	**0.435**	**0.507**	0.553	**0.761**
ER: NEM	**-0.728**	**-0.875**	**-0.705**	**-0.451**	-0.202	-0.222	**-0.722**
GPP: PR	**0.261**	0.296	**0.726**	**0.705**	**0.535**	**0.812**	**0.938**
ER: PR	**-0.200**	**-0.530**	*-0.371*	-0.082	-0.157	0.183	*-0.409*
Macrophyte cover		0	1	0.95	0.45	0.35	0

3.6. Relationships between stream metabolism and physical habitat descriptors

Average site rates of GPP and ER displayed correlations with catchment land use and stream size (Table 4), although none of the correlations were significant based on Bonferroni corrected probabilities. For catchment land use, relationships appeared strongly driven by the Piakonui 'reference' site where low rates of GPP and ER were associated with high native vegetation cover and moderate pasture cover in the catchment. Generally, higher rates of GPP and ER occurred at wider and deeper sites despite depth adjustment and calculation by unit area. Strongest correlations between land use and rates of GPP and ER were evident in summer. In comparison, strongest correlations between stream size and GPP occurred in autumn, with no seasonal differentiation in the relationships between ER and stream size. Once again, none of the seasonal correlations were significant based on Bonferroni corrected probabilities.

Table 4. Pearson correlation coefficient (R) for the relationship between catchment land use and stream size and average annual and seasonal rates of gross primary production (GPP) and ecosystem respiration (ER). N = 6.

	Native veg. (%)	Pasture (%)	Stream width	Stream depth
Annual GPP	-0.685	0.688	0.598	0.641
Spring GPP	-0.406	0.428	0.212	0.291
Summer GPP	-0.872	0.872	0.685	0.699
Autumn GPP	-0.687	0.679	0.763	0.762
Winter GPP	-0.454	0.466	0.283	0.492
Annual ER	-0.531	0.527	0.544	0.813
Spring ER	-0.446	0.436	0.368	0.859
Summer ER	-0.782	0.787	0.638	0.646
Autumn ER	-0.500	0.501	0.581	0.707
Winter ER	-0.208	0.201	0.314	0.829

3.7. Relationships between metabolism and water quality measures

3.7.1. Annual

Average site rates of GPP and ER displayed few correlations with annual median water quality parameters (Table 5), and none of the correlations were significant based on Bonferroni corrected probabilities. Generally, metabolic rates were higher at sites with higher concentrations of nitrogen and lower values of pH.

Table 5. Pearson correlation coefficient (R) for the relationship between water quality parameters and average annual rates of gross primary production (GPP) and ecosystem respiration (ER).

	N	Annual GPP	Annual ER
Black disk (m)	5	0.482	0.458
Turbidity (NTU)	6	-0.037	-0.033
Conductivity (mS/m@25°C)	6	-0.398	0.506
pH	6	-0.652	-0.634
Dissolved reactive phosphorus (g/m^3)	6	0.035	-0.054
Total phosphorus (g/m^3)	6	0.116	0.044
Ammoniacal nitrogen (g/m^3)	6	0.193	0.406
Total oxidised nitrogen (g/m^3)	6	0.457	0.517
Total Kjeldahl nitrogen (g/m^3)	6	0.449	0.442
E. coli (cfu/100 ml)	6	0.324	0.287

3.7.2. Calendar month

From paired samples in the same calendar month, on average metabolism estimates were made within four days of water quality readings, or within a week. But there were occasions where metabolism estimates were up to 20 days before or 23 days after water quality readings. Monthly rates of ER and GPP showed significant correlations with some water quality parameters (Table 6). Both ER and GPP were higher at sites and times of increased conductivity (Figure 8) and water clarity (Figure 9). Higher rates of ER were related to higher concentrations of total nitrogen, and higher rates of GPP were related to higher levels of *E.coli* (Table 6).

Table 6. Pearson correlation coefficient (R) for the relationship between water quality parameters and average rates of gross primary production (GPP) and ecosystem respiration (ER) measured in the same calendar month. Significance is indicated by bold and ** ($P < 0.01$) and * ($P < 0.05$).

	N	Monthly GPP	Monthly ER
Black disk (m)	54	***0.339**	***0.362**
Turbidity (NTU)	65	***-0.372**	-0.231
Conductivity (mS/m@25°C)	65	***0.394**	****0.465**
pH	65	0.173	-0.207
Dissolved reactive phosphorus (g/m³)	65	0.290	0.259
Total phosphorus (g/m³)	65	0.262	0.283
Ammoniacal nitrogen (g/m³)	65	-0.186	0.124
Total oxidised nitrogen (g/m³)	65	-0.003	0.241
Total Kjeldahl nitrogen (g/m³)	65	0.207	***0.365**
E. coli (cfu/100 ml)	45	***0.376**	0.261

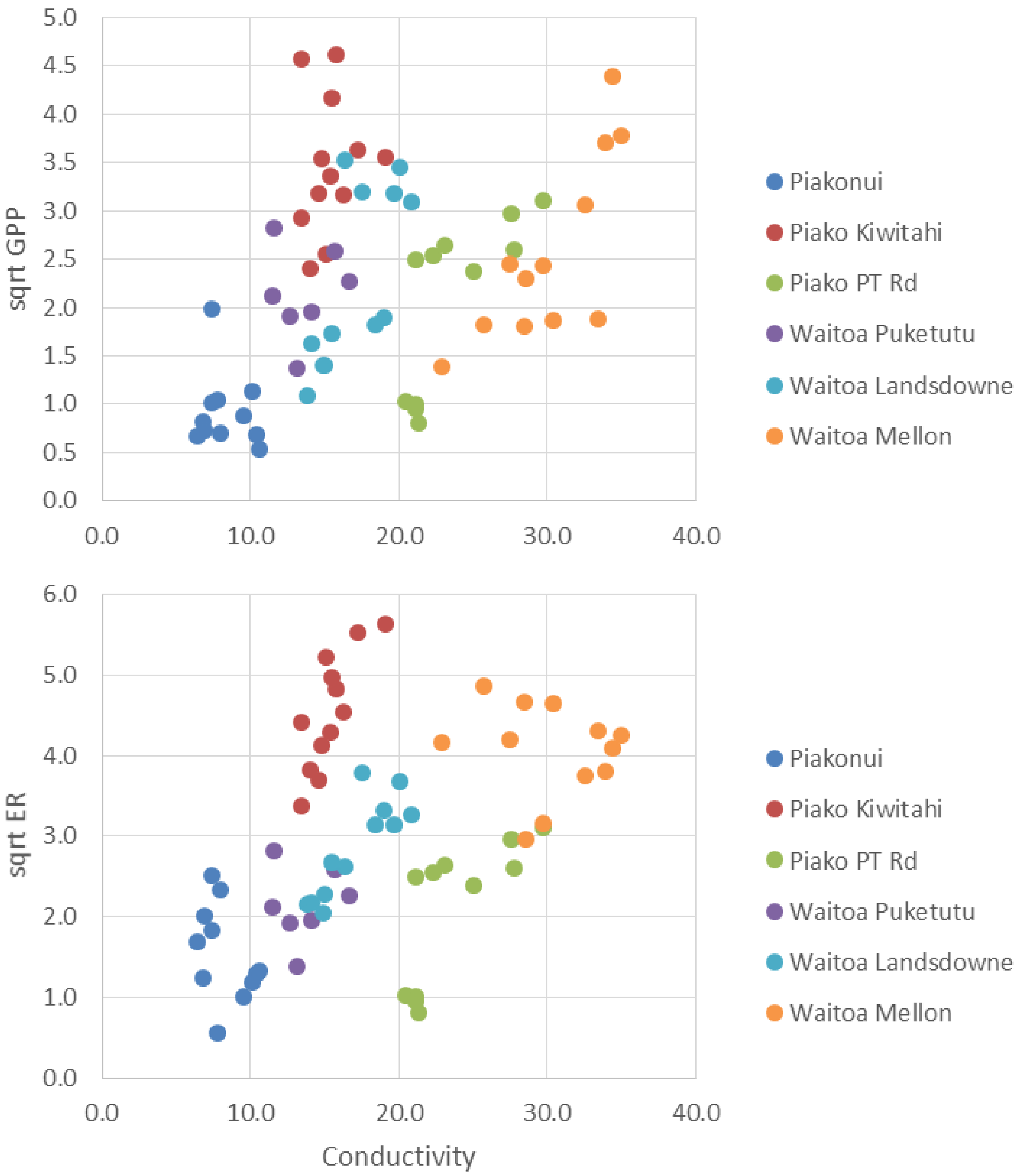

Figure 8. Relationships between gross primary production (GPP, g O_2 m^{-2} d^{-1}) and ecosystem respiration (ER, g O_2 m^{-2} d^{-1}) and conductivity (mS/m@25°C) at six sample sites on the Piako River during October 2012 to September 2013.

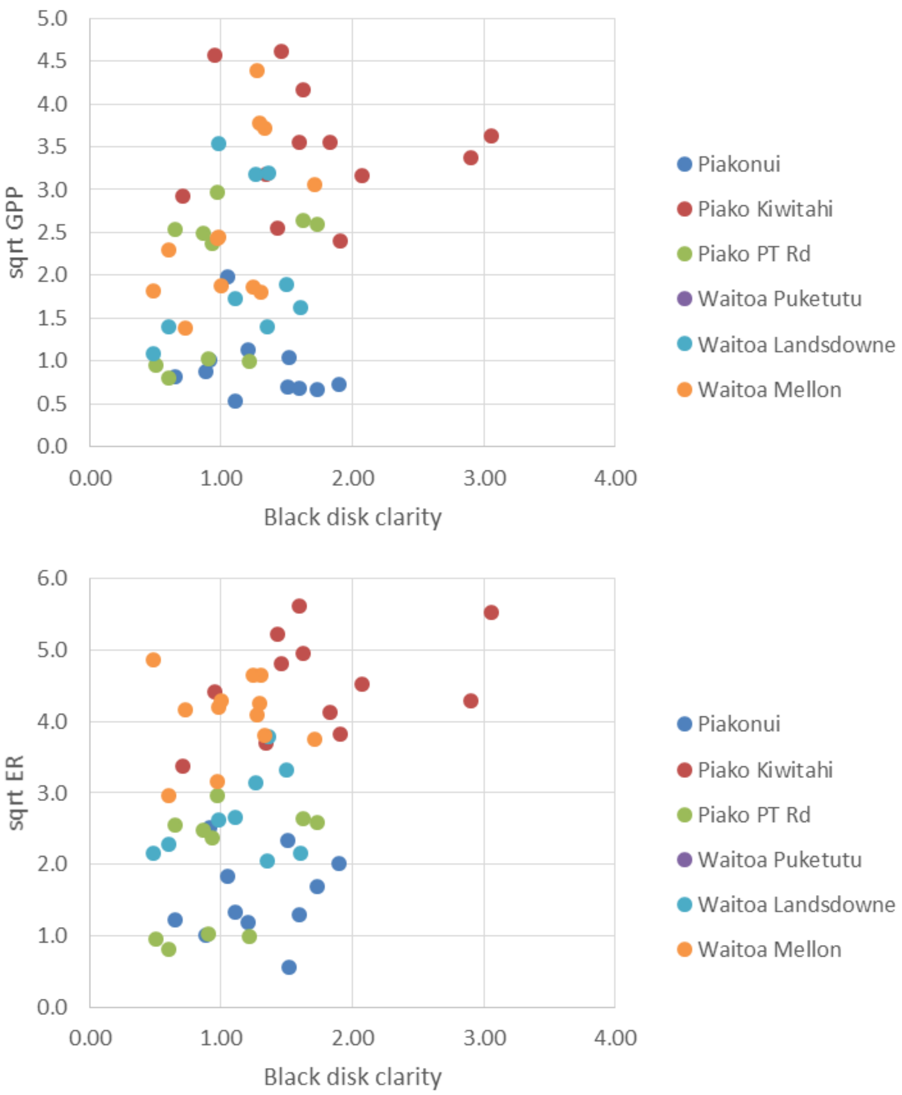

Figure 9. Relationship between gross primary production (GPP, g O_2 m^{-2} d^{-1}) and ecosystem respiration (ER, g O_2 m^{-2} d^{-1}) and black disk visual clarity (m) at six sample sites on the Piako River during October 2012 to September 2013. Note there was no clarity data for Waitoa at Puketutu site.

There were 39 paired samples where metabolism estimates occurred after water quality sampling in the same calendar month; on average 11 days after with a range from 0 to 20 days. Despite lower sample N, similar correlations were observed as previously between metabolism estimates and single water quality measures from the same calendar month, such as with total nitrogen (Figure 10). The exception being for measures of water clarity which were no longer significantly correlated to metabolic estimates (Table 7).

Table 7. Pearson correlation coefficient (R) for the relationship between average rates of gross primary production (GPP) and ecosystem respiration (ER) and water quality parameters measured in the same calendar month prior to metabolism estimates. Significance is indicated by bold and ** ($P < 0.01$) and * ($P < 0.05$).

	N	Monthly GPP	Monthly ER
Black disk (m)	37	0.272	0.368
Turbidity (NTU)	37	-0.330	0.305
Conductivity (mS/m@25°C)	39	***0.396**	****0.473**
pH	39	0.131	-0.186
Dissolved reactive phosphorus (g/m³)	39	0.330	0.262
Total phosphorus (g/m³)	39	0.310	0.314
Ammoniacal nitrogen (g/m³)	39	-0.245	0.051
Total oxidised nitrogen (g/m³)	39	0.006	0.116
Total Kjeldahl nitrogen (g/m³)	39	0.399	***0.454**
E. coli (cfu/100 ml)	21	***0.584**	0.389

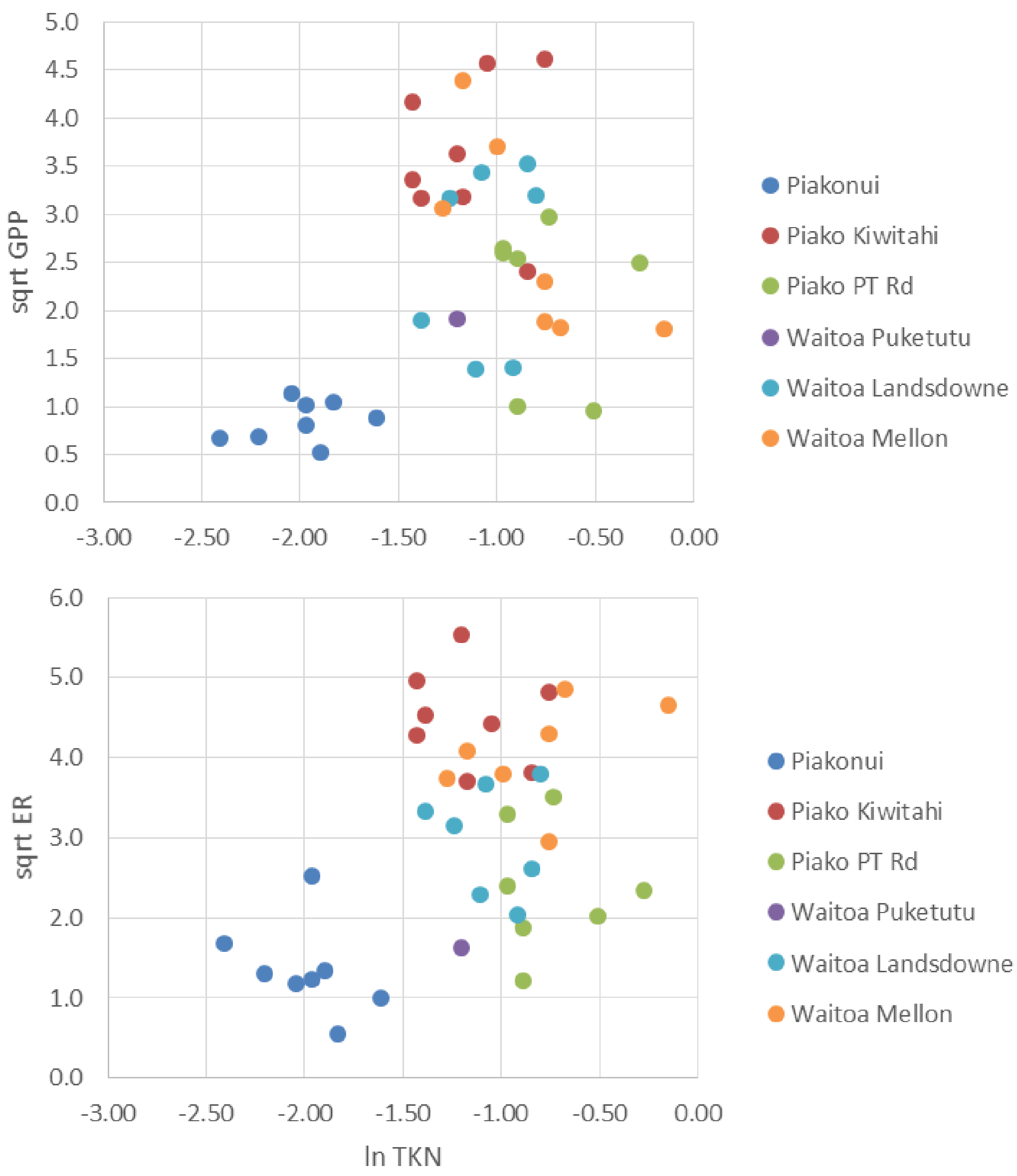

Figure 10. Relationships between gross primary production (GPP, g O_2 m^{-2} d^{-1}) and ecosystem respiration (ER, g O_2 m^{-2} d^{-1}) and total Kjeldahl nitrogen (TKN, g/m^3) at six sample sites on the Piako River during October 2012 to September 2013.

3.7.3. Month(s) before

Metabolism estimates were correlated to water quality readings conducted in the previous calendar month; on average metabolism estimates were made 33 days after water quality readings, and between 7 and 71 days after. The only significant relationships observed were high rates of both GPP and ER associated with high conductivity values (Table 8)

Table 8. Pearson correlation coefficient (R) for the relationship between average rates of gross primary production (GPP) and ecosystem respiration (ER) and water quality parameters measured in the previous calendar month. Significance is indicated by bold and ** ($P < 0.01$) and * ($P < 0.05$).

	N	Monthly GPP	Monthly ER
Black disk (m)	54	0.231	0.312
Turbidity (NTU)	64	-0.219	-0.220
Conductivity (mS/m@25°C)	64	***0.359**	****0.456**
pH	64	0.192	-0.040
Dissolved reactive phosphorus (g/m³)	64	0.325	0.298
Total phosphorus (g/m³)	64	0.296	0.274
Ammoniacal nitrogen (g/m³)	64	-0.082	0.071
Total oxidised nitrogen (g/m³)	64	-0.012	0.099
Total Kjeldahl nitrogen (g/m³)	64	0.243	0.273
E. coli (cfu/100 ml)	44	0.268	0.146

The pairing of metabolism estimates to the previous 3-month rolling average of water quality readings also showed significant correlations (Table 9). As with pairings from the same calendar month, higher conductivity was associated with higher rates of both GPP and ER, as were higher *E.coli* levels (Figure 11). Unobserved in previous correlations were higher values of GPP associated with higher phosphorus values.

Table 9. Pearson correlation coefficient (R) for the relationship between average rates of gross primary production (GPP) and ecosystem respiration (ER) and the 3-month rolling average for water quality parameters. Significance is indicated by bold and ** ($P < 0.01$) and * ($P < 0.05$).

	N	Monthly GPP	Monthly ER
Black disk (m) *	53	0.163	****0.431**
Turbidity (NTU)	58	-0.187	-0.290
Conductivity (mS/m@25°C)	58	***0.351**	****0.441**
pH	58	0.192	-0.127
Dissolved reactive phosphorus (g/m³)	58	***0.347**	0.278
Total phosphorus (g/m³)	58	***0.396**	0.325
Ammoniacal nitrogen (g/m³)	58	0.007	0.099
Total oxidised nitrogen (g/m³)	58	0.052	0.175
Total Kjeldahl nitrogen (g/m³)	58	0.330	0.321
E. coli (cfu/100 ml)	58	****0.496**	0.296

Figure 11. Relationship between gross primary production (GPP, g O_2 m^{-2} d^{-1}) and the three month rolling average of *E.coli* (cfu/100 ml) and total phosphorus (TP, g/m^3) at six sample sites on the Piako River during October 2012 to September 2013.

3.7.4. Seasonal trends

There were few strong relationships between average seasonal rates of GPP and ER and average seasonal measures of water quality (Table 10). Statistically significant correlations occurred between ER and conductivity and GPP and *E. coli* (Figure 12).

Table 10. Pearson correlation coefficient (R) for the relationships between average seasonal rates of gross primary production (GPP) and ecosystem respiration (ER) and water quality parameters measured at the six samples sites. Significance is indicated by bold and ** ($P < 0.01$) and * ($P < 0.05$).

	N	Seasonal GPP	Seasonal ER
Black disk (m) *	25	0.455	0.451
Turbidity (NTU)	30	-0.420	-0.254
Conductivity (mS/m@25°C)	30	0.392	***0.487**
pH	30	0.134	0.073
Dissolved reactive phosphorus (g/m^3)	30	0.309	0.285
Total phosphorus (g/m^3)	30	0.311	0.318
Ammoniacal nitrogen (g/m^3)	30	-0.036	0.156
Total oxidised nitrogen (g/m^3)	30	0.040	0.256
Total Kjeldahl nitrogen (g/m^3)	30	0.371	0.397
E. coli (cfu/100 ml)	30	***0.499**	0.381

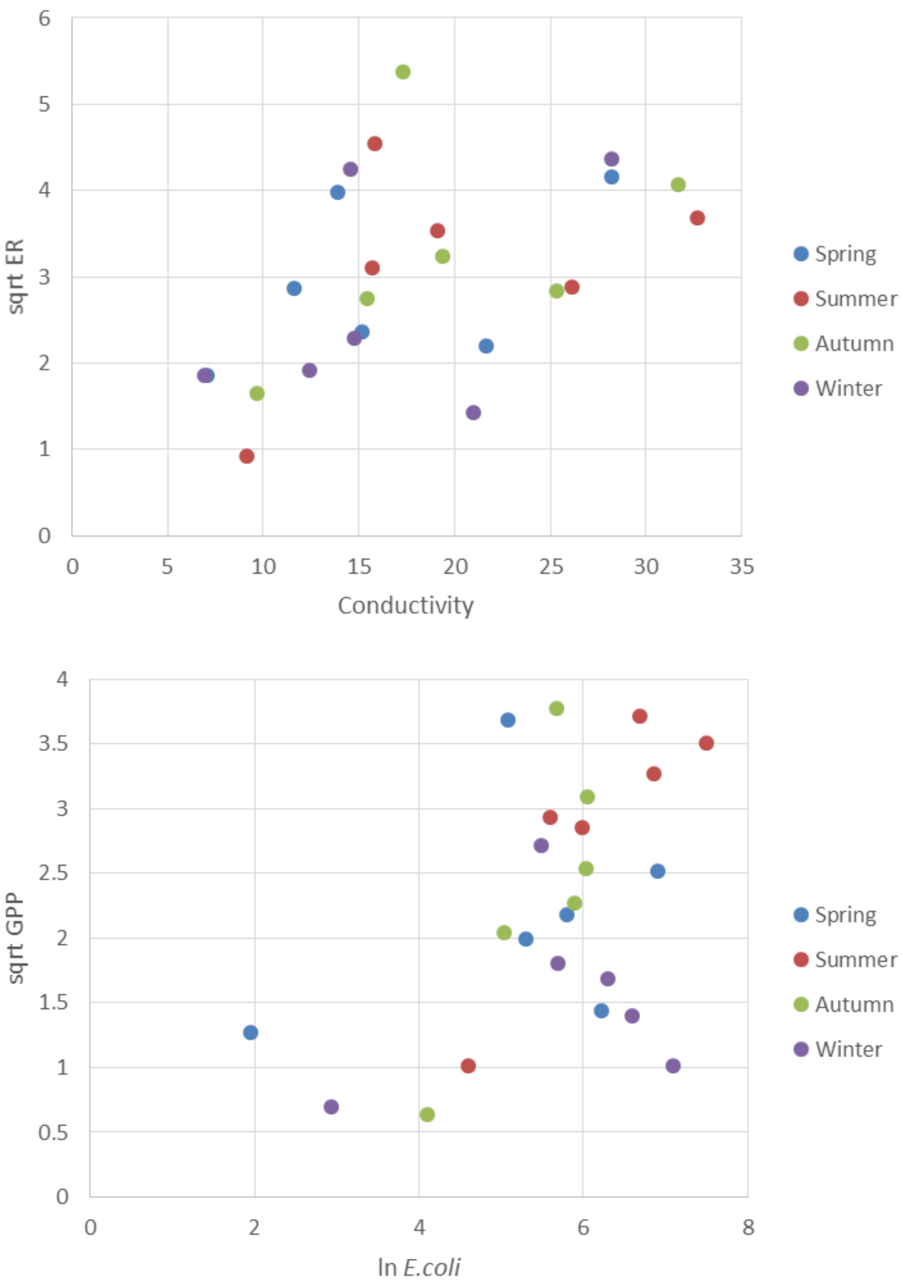

Figure 12. Relationships between seasonal averages for ecosystem respiration (ER, g O_2 m^{-2} d^{-1}) and conductivity (mS/m@25°C) and gross primary production (GPP, g O_2 m^{-2} d^{-1}) and *E. coli* (cfu/100 ml) at six sample sites on the Piako River during October 2012 to September 2013.

4. DISCUSSION

4.1. Temporal variability in ecosystem metabolism

Ecosystem metabolism in the Piako River varied spatially and temporally in a predictable manner. High rates of ER and GPP occurred at downstream sites associated with increased land-use impact and in the presence of macrophytes. Rates of GPP greater than 7.0 g O_2 m^{-2} d^{-1} indicate poor ecosystem health, according to the criteria of Young *et al*. (2008). This occurred at all sites during summer, except for at the Piakonui headwater site. Likewise, rates of ER greater than 9.5 g O_2 m^{-2} d^{-1}, which is also indicative of poor ecosystem health, occurred at all sites in summer, except for at the Piakonui headwater and Piako at PT Rd sites. At the Piako at Kiwitahi and Waitoa at Mellon Rd sites, levels of ecosystem metabolism exceeded thresholds indicative of poor ecosystem health throughout the majority of the 12-month study period. Note however, that Young *et al*. (2008) thresholds are not specifically calibrated for variation observed in macrophyte-dominated streams.

Results show that a one-week estimate of ecosystem metabolism in a summer month (*e.g*. January, Table 2) would indicate that the average state of stream health in the downstream reaches of the Piako River was poor. Seasonal estimates would indicate that some downstream sites on the river had consistently poor ecosystem health, whereas other sites vary from good to poor depending on season. Rates of GPP and ER at the Piakonui headwater site varied little throughout the year and consistently indicated good ecosystem health. Similarly, reference sites showed less temporal variation in ecosystem metabolism than sites subject to land-use impact in Manawatu (Young & Clapcott 2010) and Auckland (Doehring & Young 2010). The ratios of summer to winter rates or seasonal variation are promising metrics to assess the effects of land use on stream metabolism (Clapcott *et al.* in review). These previous analyses also showed that summer estimates of ecosystem metabolism provided the most informative assessment of stream health — at a time when the stream was most subject to stress due to low flows and warm temperatures. These factors along with more daylight hours probably facilitated the effect of increased nutrients on periphyton and possibly macrophyte proliferation in the Piako River in summer.

The Piakonui headwater site had consistently ‘good’ ecosystem health throughout the year despite corrections of DO and temperature data prior to metabolism calculations, which can significantly inflate estimates of ER (see Section 2.3.1). These results suggest this site is suitable as a reference site for the Piako River catchment. However, site observations (Mark Hamer, WRC) and patterns in DO data (even at times when probes were working correctly) indicate a heterogeneous flow environment upstream of the DO logger, which violates the assumptions of the open system method for estimating steam metabolism. The relocation of the DO logger is likely to alleviate this issue.

4.2. Relationships with water quality parameters

Ecosystem metabolism in the Piako River was moderately related to measures of water quality during the study period. Physico-chemical parameters correlated to stream metabolism included conductivity, total nitrogen, total phosphorus, turbidity and black disk measures of water clarity. The causal pathways through which these parameters influence stream metabolism are well documented (*e.g.* Phinney & McIntire 1965; Young & Huryn 1996; Tank *et al.* 2010). Nutrients stimulate autotrophic and heterotrophic processes and higher rates of both GP and ER were associated with higher concentrations of nitrogen and phosphorus. Dissolved substances in the water column reduce water clarity and limit the amount of light reaching primary producers hence limiting photosynthesis. In the Piako River lower rates of GPP were associated with low water clarity. Likewise, turbidity increases light attenuation, but mainly due to suspended solids such as clay and silt, and in the Piako River increased turbidity was associated with decreased GPP. Higher turbidity in pastoral streams in the Waikato can be attributed to livestock disturbance of clay-rich soils (Wilcock & Chapra 2005).

Consistently, higher rates of ecosystem metabolism were related to higher conductivity values. As a measure of inorganic dissolved solids, conductivity is likely to reflect the concentration of clay-adsorbing particles such as nitrate and phosphate ions. These ions stimulate autotrophic and heterotrophic processes and can cause algal blooms or 'eutrophication'. Conductivity also reflects salt content. Temporal patterns in conductivity and alkalinity at the Piako at Kiwitahi site have been shown to reflect the influence of macrophyte dominance and groundwater inputs (Wilcock & Chapra 2005). Not surprisingly, highest rates of GPP occurred at sites where macrophytes were present. There was also strong GPP-ER coupling at macrophyte-dominated sites.

The relationships between ecosystem metabolism and water quality were relatively weak – with all correlation coefficients less than 0.6. Previous studies suggest a combination of proximate variables (causal pathways through which land use influences metabolism) best predict stream metabolism, including light, temperature, nutrients, habitat (*e.g.* substrate / sediment composition) and flow (*e.g.* Rier & King 1996; Young & Huryn 1999; Roberts *et al.* 2007; Tank *et al.* 2010). To better interpret spatial patterns in metabolism in the Piako River and / or develop predictive models would require some additional information be collected, such as average reach shading. Also, continuous light and / or turbidity data collected at the same time as DO and temperature data would be useful to determine whether suspended solids affects temporal patterns in metabolism in the Piako River. Information on the temporal variability in macrophyte cover would also be beneficial in explaining temporal patterns in metabolism.

Meanwhile, the strongest correlations observed were between estimates of ecosystem metabolism and water quality measured during the same calendar month. However, the greatest number of significant correlations was observed between ecosystem metabolism and the three-month rolling average of water quality variables. A three-month average incorporates seasonal and flow effects. In the current analysis, some water quality sample times corresponded with high flow events which may have resulted in outliers in monthly measurements. A rolling average would even out such effects. Alternatively, water quality metrics could be flow-weighted prior to analysis; this is an avenue for future investigations.

4.3. Summary and recommendations

What characterises temporal variability in ecosystem metabolism in the Piako River?

- General seasonal trends in ecosystem metabolism in the Piako River were observed with highest rates in late summer and lowest rates in winter. The Piakonui headwater site has low rates of ecosystem metabolism with low seasonal variability compared to downstream sites and could be used as a benchmark for stream metabolism assessment (with suitable logger placement, see comment below). A more suitable benchmark site would have a similar network position (stream order ~ 5) preferably in a neighbouring catchment, if available.

To what degree does ecosystem metabolism reflect the water quality of the Piako River?

- Ecosystem metabolism estimates are correlated to measures of water quality as well as other indicators of stream health (*e.g. E.coli*) and as such provide a complementary assessment indicating generally poor health in the Piako River.
- A summer estimate of ecosystem metabolism, at the time when streams are subject to low flows, high temperature and longer day lengths indicated that overall the Piako River is in poor health. We recommend that five continuous days of DO data should be used to calculate 'summer' metabolism, which would provide a sensitive assessment of stream health.
- One week per season (*e.g.* four weeks per year) of metabolism estimates should be made if the aim was to characterise the seasonal variability in ecosystem metabolism, which would provide a balanced assessment of the health of the Piako River that takes into account the temporal variability in stream function.

At what temporal periods are ecosystem metabolism and water quality most closely related?

- Ecosystem metabolism estimates are most closely related to structural water quality parameters measured in the same calendar month showing a synchronicity between environmental drivers and the ecosystem level response.

- Summer measures of metabolism or potentially summer:winter ratios are likely to be the most useful temporal periods for assessing stream health as it encompasses the period of greatest potential metabolism.
- Consistent relationships between conductivity and stream metabolism at all time periods is unlikely to be causative, and instead is likely to be due to correlations between stream metabolism and land use and conductivity and land use respectively. However, overlapping gradients of groundwater inputs and macrophytes with land use is a complicating factor for interpreting conductivity correlations with metabolism in the Piako River.
- We calculated stream metabolism after periods of stable flow and as such assessments do not take into account the effects of high flows. As such, three-month rolling averages are probably the best temporal period to compare metabolism and water quality allowing for the incorporation of seasonal and flow effects. Alternatively, monthly water quality measures could be flow-weighted.

Other points of interest

- The single station method of calculating ecosystem metabolism appears valid for all sites, except possibly Piakonui where upstream heterogeneity in flow conditions is likely to be affecting calculations. The method could be validated with measures of stream velocity and habitat assessment upstream of logger deployments. Movement of the Piakonui logger may be necessary.
- The procedure used to correct DO data that failed to fall below 100% saturation has the potential to greatly affect metabolism estimates. Despite this, estimates of ecosystem metabolism made using corrected data provided similar ratings of stream health as uncorrected data in the same season. We recommend against using data correction in future metabolism estimates.

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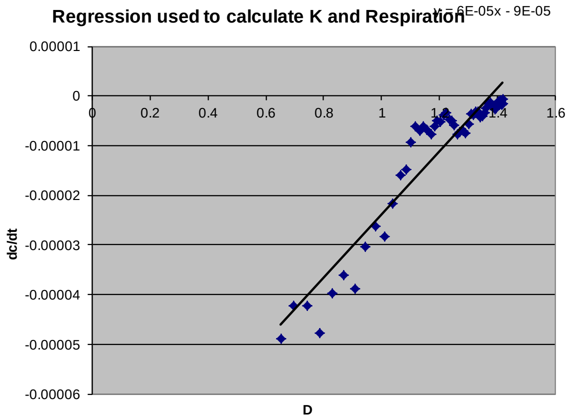
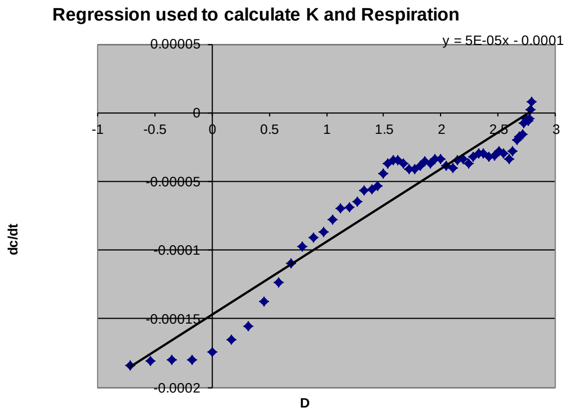
6. APPENDICES

Appendix 1. Scatterplots of night-time regression equations from metabolism calculations for six study sites.

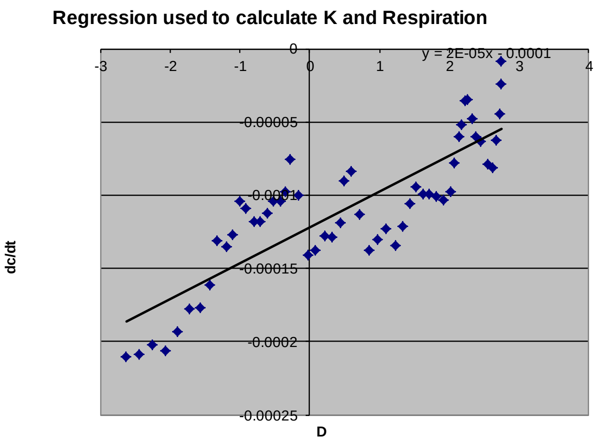
Waitoa River at Waharoa on 3 June 2013.
R^2 = 0.89.



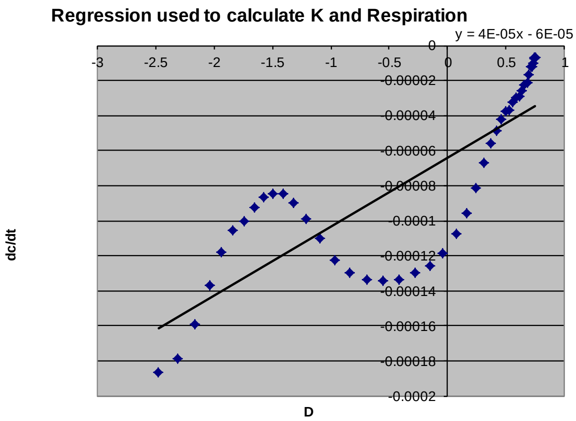
Waitoa River at Puketutu Road on 7 April 2013.
R^2 = 0.92



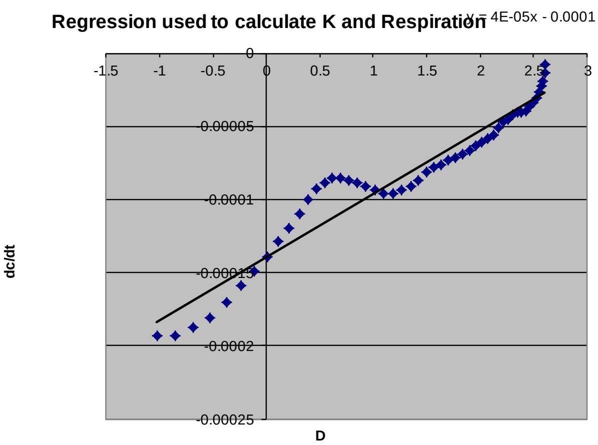
Waitoa River at Mellon Road on 27 Feb 2013.
R^2 = 0.71.



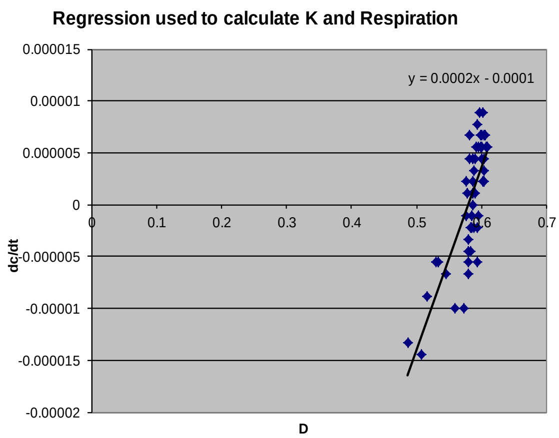
Piako River at PT Road on 28 Nov 2012.
R^2 = 0.66.



Piako at Kiwitahi on 10 Sept 2013.
R^2 = 0.93.



Piakonui on 5 Aug 2013.
R2 = 0.63



Appendix 2. Metabolism estimates for six study sites. Note the date format in these following tables is: MM/DD/YYYY.

Metabolism estimates for Waitoa River at Waharoa

Date	Depth (m)	Temp. avg. night (°C)	ER (g O_2 m^{-2} d^{-1})	GPP (g O_2 m^{-2} d^{-1})	P/R	k (per day)	R^2	QC code	Correction
10/8/2012	0.734	13.99	5.97	1.95	0.33	5.43	0.67	1	
10/9/2012	0.737	14.51	4.48	1.82	0.41	3.91	0.69	1	
10/10/2012	0.729	14.59	5.41	2.22	0.41	4.94	0.73	1	
10/11/2012	0.719	14.47	4.73	2.09	0.44	4.46	0.76	1	
10/12/2012	0.713	15.44	5.45	1.66	0.30	4.66	0.65	1	
11/25/2012	0.657	17.30	6.60	13.42	2.03	9.33	0.77	1	
11/26/2012	0.654	17.01	6.42	13.07	2.04	8.91	0.78	1	
11/27/2012	0.650	18.16	7.05	11.81	1.68	6.50	0.71	1	
11/28/2012	0.646	18.08	7.89	13.07	1.66	7.42	0.77	1	
11/29/2012	0.642	17.31	6.39	10.97	1.72	6.34	0.75	1	
12/25/2012	0.657	21.69	13.74	9.42	0.69	6.63	0.67	1	
12/26/2012	0.657	22.14	14.98	10.66	0.71	7.37	0.76	1	
12/27/2012	0.656	21.78	14.83	10.06	0.68	7.47	0.76	1	
12/28/2012	0.646	20.81	13.10	9.74	0.74	6.59	0.75	1	
12/29/2012	0.641	22.06	15.28	11.24	0.74	7.74	0.79	1	
1/26/2013	0.580	18.69	13.40	12.80	0.96	5.14	0.96	1	
1/27/2013	0.579	19.36	13.70	12.39	0.90	5.39	0.97	1	
1/28/2013	0.582	19.64	13.46	11.74	0.87	5.20	0.97	1	
1/29/2013	0.576	19.87	13.67	11.68	0.86	5.04	0.97	1	
1/30/2013	0.570	19.97	13.33	10.64	0.80	4.77	0.97	1	
2/23/2013	0.535	19.80	10.52	10.44	0.99	4.63	0.93	1	
2/24/2013	0.535	19.53	9.61	11.01	1.15	4.19	0.92	1	
2/25/2013	0.533	19.25	9.95	10.08	1.01	4.83	0.92	1	
2/26/2013	0.530	19.19	9.70	8.60	0.89	4.39	0.94	1	
2/27/2013	0.529	19.22	9.78	10.21	1.04	4.47	0.93	1	
3/4/2013	0.535	19.30	10.69	8.46	0.79	4.94	0.91	1	
3/5/2013	0.531	18.02	10.22	9.43	0.92	4.73	0.96	1	
3/6/2013	0.528	18.06	10.75	10.18	0.95	5.80	0.96	1	
3/7/2013	0.528	18.40	10.87	9.80	0.90	5.83	0.92	1	
3/8/2013	0.528	19.06	10.71	9.94	0.93	6.05	0.97	1	
4/25/2013	0.666	16.07	13.00	3.34	0.26	7.35	0.92	1	
4/26/2013	0.656	15.54	11.41	3.59	0.31	6.40	0.92	1	
4/27/2013	0.642	15.53	9.16	3.15	0.34	5.26	0.91	1	
4/28/2013	0.630	15.40	11.41	4.10	0.36	6.82	0.93	1	
4/29/2013	0.626	15.55	10.26	3.89	0.38	5.93	0.93	1	
5/1/2013	0.603	15.02	8.56	3.43	0.40	4.70	0.95	1	
5/2/2013	0.592	15.02	8.86	4.06	0.46	4.99	0.96	1	
5/3/2013	0.592	15.15	8.88	3.69	0.42	5.07	0.94	1	

Date	Depth (m)	Temp. avg. night (°C)	ER (g O_2 m^{-2} d^{-1})	GPP (g O_2 m^{-2} d^{-1})	P/R	k (per day)	R^2	QC code	Correction
5/4/2013	0.601	15.66	8.55	3.26	0.38	4.12	0.75	1	
5/5/2013	0.679	15.23	14.53	2.17	0.15	7.61	0.97	1	
6/1/2013	0.732	11.28	4.52	1.33	0.29	4.79	0.85	1	
6/2/2013	0.720	11.57	5.34	1.52	0.28	5.41	0.93	1	
6/3/2013	0.711	11.09	5.42	1.13	0.21	5.50	0.89	1	
6/7/2013	0.752	10.79	4.57	1.26	0.28	5.42	0.91	1	
6/8/2013	0.733	10.96	3.50	0.73	0.21	3.58	0.66	1	
7/26/2013	0.702	11.11	4.25	1.77	0.42	6.51	0.95	1	
7/27/2013	0.696	10.86	4.28	1.98	0.46	6.81	0.91	1	
7/28/2013	0.691	10.15	3.84	1.91	0.50	6.53	0.87	1	
7/29/2013	0.685	9.86	4.41	2.09	0.48	7.20	0.92	1	
7/30/2013	0.681	10.08	4.07	2.02	0.50	6.57	0.88	1	
8/4/2013	0.675	12.35	6.95	2.61	0.38	7.64	0.94	1	
8/5/2013	0.671	12.47	7.42	3.06	0.41	8.23	0.96	1	
8/6/2013	0.670	12.38	7.46	2.99	0.40	8.68	0.93	1	
8/7/2013	0.670	12.73	5.94	2.70	0.46	6.34	0.93	1	
8/8/2013	0.668	12.83	7.72	3.49	0.45	8.58	0.95	1	
9/6/2013	0.751	11.32	3.98	2.53	0.63	5.12	0.91	1	
9/7/2013	0.727	12.58	4.60	2.59	0.56	5.24	0.94	1	
9/8/2013	0.723	13.44	4.88	2.96	0.61	5.48	0.96	1	
9/9/2013	0.719	12.92	4.94	3.07	0.62	6.29	0.94	1	
9/10/2013	0.714	13.38	5.03	2.03	0.40	5.47	0.92	1	
10/6/2013	0.770	17.29	8.03	3.84	0.48	7.70	0.91	1	
10/7/2013	0.761	16.12	6.44	3.13	0.49	5.82	0.92	1	
10/8/2013	0.755	16.02	6.81	2.42	0.36	6.32	0.87	1	
10/9/2013	0.760	14.59	5.40	3.35	0.62	5.73	0.96	1	
10/10/2013	0.759	14.96	5.96	1.94	0.33	4.81	0.95	1	

Metabolism estimates for Waitoa River at Puketutu Road

Date	Depth (m)	Temp. avg. night (°C)	ER ($g\ O_2\ m^{-2}\ d^{-1}$)	GPP ($g\ O_2\ m^{-2}\ d^{-1}$)	P/R	k (per day)	R^2	QC code	Correction
10/3/2012	0.664	14.64	7.02	2.05	0.29	5.76	0.99	1	
10/4/2012	0.652	14.06	6.29	2.17	0.35	5.53	0.94	1	
10/5/2012	0.652	14.10	6.15	2.28	0.37	4.79	0.99	1	
10/6/2012	0.652	14.09	4.65	1.90	0.41	3.88	0.90	1	
10/7/2012	0.659	13.67	5.32	1.84	0.35	3.91	0.96	1	
11/8/2012	0.578	17.11	8.86	9.87	1.11	7.69	0.86	1	
11/9/2012	0.575	17.35	8.63	9.99	1.16	7.87	0.70	1	
11/10/2012	0.573	17.89	13.56	16.20	1.19	11.88	0.71	1	
11/11/2012	0.572	16.25	10.05	10.24	1.02	8.57	0.95	1	
11/12/2012	0.572	16.36	8.60	8.65	1.01	6.21	0.92	1	
12/25/2012	0.557	22.26	10.41	11.19	1.07	5.65	0.99	1	
12/26/2012	0.557	22.50	10.54	11.44	1.09	4.96	0.98	1	
12/27/2012	0.556	22.82	9.52	11.03	1.16	4.91	0.99	1	
12/28/2012	0.546	21.59	9.11	9.61	1.06	4.90	0.98	1	
12/29/2012	0.541	22.38	8.32	8.89	1.07	4.21	0.95	1	
1/26/2013	0.480	19.72	8.73	9.57	1.10	5.89	0.98	1	
1/27/2013	0.479	19.98	7.87	8.07	1.03	5.04	0.94	1	
1/28/2013	0.482	20.47	9.55	9.08	0.95	5.40	0.98	1	
1/29/2013	0.476	20.63	9.15	8.81	0.96	5.46	0.97	1	
1/30/2013	0.470	20.71	9.50	9.02	0.95	4.99	0.99	1	
2/23/2013	0.435	19.82	10.14	6.36	0.63	4.96	0.98	1	
2/24/2013	0.435	19.49	10.79	7.01	0.65	5.47	0.98	1	
2/25/2013	0.433	19.16	10.32	6.40	0.62	5.48	0.99	1	
2/26/2013	0.430	19.14	10.17	6.99	0.69	5.12	0.98	1	
2/27/2013	0.429	19.24	10.06	6.50	0.65	5.10	0.98	1	
3/5/2013	0.431	18.25	9.65	5.35	0.55	4.56	0.97	1	
3/6/2013	0.428	17.79	10.34	5.28	0.51	5.17	0.95	1	
3/7/2013	0.428	17.93	9.35	5.02	0.54	4.97	0.97	1	
3/8/2013	0.428	18.74	9.06	4.96	0.55	4.66	0.98	1	
3/9/2013	0.427	18.37	9.42	4.98	0.53	5.00	0.98	1	
4/7/2013	0.472	14.44	6.12	3.87	0.63	4.59	0.92	1	
4/8/2013	0.464	13.45	5.04	3.30	0.65	3.69	0.90	1	
4/9/2013	0.462	13.37	5.75	3.59	0.62	4.54	0.96	1	
4/11/2013	0.451	12.82	5.14	3.63	0.71	4.28	0.94	1	
4/12/2013	0.449	13.30	5.25	3.65	0.70	4.58	0.92	1	
5/1/2013	0.503	14.56	7.53	3.93	0.52	4.22	0.95	1	
5/2/2013	0.492	14.19	7.40	4.19	0.57	4.37	0.97	1	
5/3/2013	0.492	14.30	6.70	3.75	0.56	3.94	0.98	1	
5/4/2013	0.501	14.69	8.44	3.55	0.42	3.92	0.94	1	
5/8/2013	0.615	12.57	9.90	3.85	0.39	5.99	0.94	1	

Date	Depth (m)	Temp. avg. night (°C)	ER (g O_2 m^{-2} d^{-1})	GPP (g O_2 m^{-2} d^{-1})	P/R	k (per day)	R^2	QC code	Correction
5/30/2013	0.664	8.18	2.77	1.46	0.53	4.01	0.83	1	
5/31/2013	0.641	9.72	3.82	1.98	0.52	4.40	0.79	1	
6/1/2013	0.632	10.85	5.02	2.13	0.42	5.51	0.85	1	
6/2/2013	0.620	11.16	5.33	2.30	0.43	5.72	0.87	1	
6/7/2013	0.652	9.87	3.59	1.65	0.46	4.84	0.74	1	
7/26/2013	0.602	10.21	3.23	3.43	1.06	5.96	0.97	1	
7/27/2013	0.596	9.76	3.03	3.84	1.27	6.75	0.98	1	
7/28/2013	0.591	9.00	2.36	3.63	1.54	6.06	0.97	1	
7/29/2013	0.585	8.79	2.29	3.58	1.56	5.90	0.97	1	
7/30/2013	0.581	8.67	2.34	3.84	1.64	6.11	0.98	1	
8/5/2013	0.571	11.34	4.43	3.91	0.88	5.22	0.91	1	
8/6/2013	0.570	11.33	4.78	4.62	0.97	6.42	0.95	1	
8/7/2013	0.570	11.51	4.22	4.29	1.02	5.88	0.90	1	
8/8/2013	0.568	11.62	4.18	4.63	1.11	5.83	0.99	1	
8/9/2013	0.565	11.19	4.35	4.97	1.14	6.25	0.98	1	
9/6/2013	0.651	10.41	9.34	9.89	1.06	10.81	0.91	1	
9/7/2013	0.627	11.66	6.79	5.89	0.87	6.90	0.72	1	
9/8/2013	0.623	13.04	10.10	7.98	0.79	8.51	0.91	1	
9/9/2013	0.619	12.62	11.32	10.63	0.94	11.06	0.90	1	
9/10/2013	0.614	12.82	8.17	5.48	0.67	7.54	0.90	1	
10/6/2013	0.670	17.23	11.24	8.34	0.74	6.24	0.62	1	
10/7/2013	0.661	15.95	10.49	8.49	0.81	7.42	0.76	1	
10/8/2013	0.655	15.54	8.74	3.17	0.36	6.01	0.67	1	
10/9/2013	0.660	13.94	9.49	7.38	0.78	7.15	0.84	1	
10/10/2013	0.659	14.68	9.84	3.20	0.32	6.80	0.75	1	

Metabolism estimates for Waitoa River at Mellon Road

Date	Depth (m)	Temp. avg. night (°C)	ER ($g\ O_2\ m^{-2}\ d^{-1}$)	GPP ($g\ O_2\ m^{-2}\ d^{-1}$)	P/R	k (per day)	R^2	QC code	Correction
10/8/2012	1.82	14.40	23.41	2.34	0.10	6.68	0.93	1	
10/11/2012	1.79	15.19	26.31	4.58	0.17	8.09	0.97	1	
10/12/2012	1.77	15.99	21.97	4.51	0.21	5.99	0.90	1	
10/13/2012	1.77	15.14	30.41	2.84	0.09	7.44	0.89	1	
10/15/2012	1.80	14.99	16.06	2.26	0.14	4.47	0.96	1	
11/24/2012	1.67	18.02	8.59	5.31	0.62	3.68	0.80	1	
11/25/2012	1.66	18.01	8.59	5.52	0.64	3.81	0.74	1	
11/26/2012	1.66	18.67	6.51	3.97	0.61	2.19	0.72	1	
11/27/2012	1.65	19.44	11.24	6.42	0.57	4.37	0.92	1	
12/1/2012	1.64	18.22	11.16	6.82	0.61	4.65	0.72	1	
12/3/2012	1.65	19.15	8.34	5.79	0.69	2.51	0.56	1	
12/4/2012	1.64	18.98	12.62	7.44	0.59	4.91	0.80	1	
12/5/2012	1.65	19.06	7.82	3.63	0.46	2.30	0.50	1	
1/24/2013	1.60	22.70	18.11	21.99	1.21	2.05	0.75	1	
1/25/2013	1.59	22.00	16.95	20.21	1.19	1.94	0.79	1	
1/26/2013	1.59	20.63	15.57	18.33	1.18	1.85	0.76	1	
1/27/2013	1.59	20.83	16.53	18.61	1.13	1.69	0.64	1	
1/28/2013	1.59	21.15	16.43	17.51	1.07	1.47	0.52	1	
2/23/2013	1.54	20.89	14.55	12.62	0.87	1.94	0.58	1	
2/24/2013	1.53	20.70	12.63	13.27	1.05	1.64	0.55	1	
2/25/2013	1.53	20.16	15.70	16.10	1.03	2.60	0.78	1	
2/26/2013	1.53	20.19	13.45	13.01	0.97	1.42	0.46	1	
2/27/2013	1.53	20.51	15.99	13.86	0.87	2.12	0.71	1	
3/1/2013	1.52	20.61	17.04	14.77	0.87	2.42	0.62	1	
3/2/2013	1.53	21.08	20.93	17.84	0.85	3.41	0.85	1	
3/3/2013	1.53	21.15	19.05	14.60	0.77	2.51	0.69	1	
3/4/2013	1.52	20.07	17.07	13.41	0.79	2.69	0.74	1	
3/5/2013	1.52	18.84	16.36	10.75	0.66	3.15	0.46	1	
4/12/2013	1.52	14.89	12.48	9.67	0.77	3.29	0.77	1	
4/13/2013	1.52	15.36	13.64	9.67	0.71	3.32	0.83	1	
4/14/2013	1.52	15.65	13.87	10.38	0.75	3.15	0.91	1	
4/15/2013	1.52	15.94	11.63	7.10	0.61	2.11	0.76	1	
4/16/2013	1.53	18.09	18.69	9.95	0.53	3.27	0.81	1	
5/1/2013	1.56	15.62	17.49	7.35	0.42	4.22	0.78	1	
5/2/2013	1.55	15.46	12.89	6.27	0.49	2.96	0.86	1	
5/4/2013	1.54	16.12	14.49	5.82	0.40	2.61	0.80	1	
5/5/2013	1.58	15.17	25.68	5.96	0.23	5.53	0.82	1	
5/6/2013	1.61	14.48	17.71	4.66	0.26	4.46	0.72	1	
6/2/2013	1.84	11.39	11.93	2.05	0.17	3.11	0.75	1	
6/3/2013	1.80	11.18	16.64	2.05	0.12	4.77	0.82	1	

Date	Depth (m)	Temp. avg. night (°C)	ER ($g\ O_2\ m^{-2}\ d^{-1}$)	GPP ($g\ O_2\ m^{-2}\ d^{-1}$)	P/R	k (per day)	R^2	QC code	Correction
6/4/2013	1.78	11.60	23.49	1.71	0.07	5.58	0.74	1	
7/23/2013	1.77	11.93	23.68	2.84	0.12	4.75	0.45	1	
7/24/2013	1.77	12.14	13.55	1.92	0.14	2.39	0.64	1	
7/25/2013	1.77	12.06	25.78	3.04	0.12	5.07	0.68	1	
7/26/2013	1.76	11.78	22.40	4.38	0.20	3.99	0.60	1	
7/27/2013	1.75	11.66	22.99	4.17	0.18	4.41	0.57	1	
8/7/2013	1.70	13.13	25.40	4.26	0.17	5.51	0.81	1	
8/8/2013	1.70	13.32	17.00	3.07	0.18	3.85	0.82	1	
8/9/2013	1.69	13.07	13.50	3.83	0.28	2.51	0.68	1	
8/16/2013	1.69	12.76	9.90	3.21	0.32	1.60	0.63	1	
8/17/2013	1.72	13.04	26.47	3.23	0.12	5.31	0.57	1	
9/1/2013	1.88	11.46	13.45	2.39	0.18	1.88	0.42	1	
9/3/2013	1.82	12.26	24.82	2.93	0.12	3.90	0.74	1	
9/4/2013	1.81	12.02	26.40	5.14	0.19	3.24	0.46	1	
10/6/2013	1.86	17.10	18.89	3.46	0.18	2.57	0.83	1	
10/7/2013	1.83	16.48	20.81	3.35	0.16	2.90	0.77	1	
10/10/2013	1.80	15.51	13.35	2.05	0.15	1.92	0.49	1	
10/17/2013	1.81	15.89	14.05	2.41	0.17	2.48	0.88	1	
10/18/2013	1.79	16.16	15.09	2.79	0.19	2.62	0.80	1	

Metabolism estimates for Piako River at PT Road

Date	Depth (m)	Temp. avg. night (°C)	ER (g O_2 m^{-2} d^{-1})	GPP (g O_2 m^{-2} d^{-1})	P/R	k (per day)	R^2	QC code	Correction
10/11/2012	0.88	14.19	7.84	1.81	0.23	8.00	0.85	1	
10/12/2012	0.85	15.35	2.12	0.34	0.16	1.90	0.54	1	
10/13/2012	0.86	14.82	3.03	0.35	0.11	2.50	0.73	1	
10/15/2012	0.91	14.32	3.33	1.17	0.35	2.48	0.72	1	
11/25/2012	0.75	17.60	3.55	6.10	1.72	4.39	0.76	1	
11/26/2012	0.74	17.78	3.65	6.59	1.80	4.75	0.64	1	
11/27/2012	0.74	18.59	3.03	5.88	1.94	3.92	0.84	1	
11/28/2012	0.74	18.20	4.15	6.72	1.62	3.40	0.66	1	
11/29/2012	0.74	17.71	3.35	7.03	2.10	3.35	0.70	1	
12/19/2012	0.78	22.19	6.18	6.80	1.10	3.13	0.60	1	
12/20/2012	0.78	22.24	5.50	6.15	1.12	3.46	0.72	1	
12/21/2012	0.78	22.15	5.55	6.48	1.17	3.14	0.55	1	
12/22/2012	0.80	22.06	5.57	7.27	1.30	3.22	0.70	1	
12/23/2012	0.79	22.02	4.86	4.24	0.87	2.70	0.43	1	
1/7/2013	0.80	21.06	7.24	9.73	1.34	3.26	0.83	1	
1/8/2013	0.78	20.30	6.39	9.67	1.51	3.20	0.75	1	
1/9/2013	0.77	21.61	7.78	9.56	1.23	1.76	0.50	1	
1/10/2013	0.75	23.35	8.55	10.12	1.18	1.51	0.49	1	
1/11/2013	0.75	22.66	8.23	9.09	1.10	2.02	0.60	1	
2/18/2013	0.66	20.47	8.78	8.97	1.02	1.92	0.57	1	
2/19/2013	0.66	21.46	12.69	9.99	0.79	3.26	0.66	1	
2/20/2013	0.65	20.95	14.71	9.97	0.68	3.46	0.51	1	
2/21/2013	0.64	20.93	10.35	7.18	0.69	2.13	0.48	1	
2/22/2013	0.63	20.71	15.25	7.88	0.52	3.68	0.59	1	
3/11/2013	0.57	19.64	13.76	10.19	0.74	3.32	0.56	1	
3/13/2013	0.56	19.88	10.30	5.24	0.51	3.32	0.72	1	
3/14/2013	0.56	19.90	11.92	5.94	0.50	3.25	0.73	1	
3/15/2013	0.56	20.13	7.59	5.56	0.73	2.29	0.47	1	
4/16/2013	0.55	17.46	5.82	8.86	1.52	5.49	0.89	1	
4/17/2013	0.58	17.71	4.43	4.28	0.96	2.42	0.48	1	
4/18/2013	0.60	16.84	3.42	3.98	1.17	2.23	0.51	1	
4/19/2013	0.61	16.13	6.46	10.26	1.59	8.02	0.97	1	
4/20/2013	0.61	16.48	7.18	7.72	1.07	6.59	0.88	1	
4/21/2013	0.61	16.98	7.07	6.74	0.95	6.93	0.71	1	
5/1/2013	0.59	14.97	6.82	6.01	0.88	7.63	0.92	1	
5/3/2013	0.58	14.65	5.03	6.86	1.36	6.15	0.81	1	
5/4/2013	0.58	14.85	8.47	8.73	1.03	9.83	0.94	1	
5/5/2013	0.66	14.14	6.93	3.69	0.53	4.79	0.83	1	
5/6/2013	0.85	14.11	11.88	3.02	0.25	7.82	0.53	1	
7/27/2013	0.83	9.64	1.96	0.90	0.46	5.37	0.70	2	10%

Date	Depth (m)	Temp. avg. night (°C)	ER ($g\ O_2\ m^{-2}\ d^{-1}$)	GPP ($g\ O_2\ m^{-2}\ d^{-1}$)	P/R	k (per day)	R^2	QC code	Correction
7/28/2013	0.80	9.30	1.23	0.74	0.61	4.24	0.61	2	10%
7/30/2013	0.78	8.38	1.42	1.17	0.82	4.97	0.50	2	10%
7/31/2013	0.77	8.54	1.29	1.18	0.91	6.84	0.47	2	10%
8/3/2013	0.78	10.42	3.15	1.23	0.39	4.95	0.50	2	10%
8/4/2013	0.77	10.65	2.02	0.79	0.39	3.42	0.46	2	10%
8/5/2013	0.75	10.47	4.06	1.51	0.37	7.40	0.59	2	10%
8/6/2013	0.75	10.27	2.24	0.96	0.43	4.26	0.53	2	10%
8/7/2013	0.74	10.40	2.01	0.84	0.41	3.78	0.49	2	10%
9/1/2013	1.10	9.84	9.03	0.86	0.10	5.48	0.40	2	10%
9/4/2013	0.97	10.21	5.04	0.64	0.13	2.44	0.48	2	10%
9/6/2013	1.04	9.89	10.73	0.95	0.09	6.34	0.77	2	10%
9/7/2013	0.95	11.07	4.51	0.15	0.03	2.92	0.94	2	10%
10/19/2013	0.95	14.57	5.82	1.91	0.33	2.65	0.60	2	10%
10/20/2013	0.95	14.29	9.62	3.30	0.34	4.31	0.65	2	10%
10/22/2013	0.95	14.93	4.65	1.18	0.25	1.97	0.49	2	10%
10/23/2013	0.95	15.23	5.59	2.26	0.40	2.46	0.53	2	10%
10/24/2013	0.95	16.08	7.20	0.94	0.13	3.86	0.67	2	10%

Metabolism estimates for Piako River at Kiwitahi

Date	Depth (m)	Temp. avg. night (°C)	ER ($g\ O_2\ m^{-2}\ d^{-1}$)	GPP ($g\ O_2\ m^{-2}\ d^{-1}$)	P/R	k (per day)	R^2	QC code	Correction
10/6/2012	1.28	14.51	11.70	7.83	0.67	3.80	0.87	1	
10/7/2012	1.26	13.77	9.67	5.06	0.52	3.26	0.82	1	
10/8/2012	1.23	13.83	9.15	6.88	0.75	3.00	0.43	1	
10/9/2012	1.26	14.83	12.35	8.96	0.73	3.73	0.95	1	
10/10/2012	1.22	14.74	12.06	10.61	0.88	4.20	0.83	1	
10/11/2012	1.20	15.32	13.38	12.16	0.91	5.11	0.85	1	
11/23/2012	1.14	18.92	21.71	23.95	1.10	4.47	0.96	1	
11/25/2012	1.14	18.01	17.62	20.56	1.17	2.61	0.67	1	
11/26/2012	1.13	18.72	17.03	18.56	1.09	2.23	0.67	1	
11/27/2012	1.13	19.46	20.21	19.91	0.99	2.91	0.71	1	
11/28/2012	1.14	19.10	21.11	21.48	1.02	2.70	0.67	1	
12/8/2012	1.63	18.41	24.58	19.62	0.80	3.93	0.98	1	
12/9/2012	1.45	19.18	24.39	20.85	0.86	4.09	0.95	1	
12/11/2012	1.30	19.52	22.74	22.01	0.97	4.03	0.85	1	
12/14/2012	1.24	20.74	23.50	24.17	1.03	3.56	0.77	1	
12/15/2012	1.22	21.49	20.85	20.01	0.96	2.56	0.72	1	
1/23/2013	1.04	22.00	15.53	11.90	0.77	1.00	0.74	1	
1/24/2013	1.03	22.70	19.70	11.97	0.61	2.12	0.41	1	
1/25/2013	1.03	21.75	18.77	11.66	0.62	2.04	0.41	1	
1/27/2013	1.01	20.93	19.07	10.23	0.54	2.90	0.51	1	
1/29/2013	1.00	21.76	18.73	10.93	0.58	2.32	0.53	1	
2/8/2013	1.01	20.58	18.59	11.32	0.61	2.15	0.57	1	
2/9/2013	1.00	20.88	13.91	7.27	0.52	1.28	0.43	1	
2/10/2013	1.00	21.06	27.14	11.84	0.44	3.77	0.76	1	
2/12/2013	1.00	21.15	25.96	10.42	0.40	3.35	0.46	1	
2/13/2013	0.99	20.08	17.12	9.16	0.54	2.11	0.44	1	
3/25/2013	0.97	18.07	35.30	14.37	0.41	5.76	0.56	1	
3/26/2013	0.97	18.53	32.39	13.27	0.41	5.21	0.58	1	
3/27/2013	0.97	19.38	27.84	13.50	0.48	4.27	0.54	1	
3/28/2013	0.97	19.49	33.29	13.83	0.42	5.15	0.58	1	
3/29/2013	0.97	19.10	24.05	10.89	0.45	2.76	0.59	1	
4/10/2013	1.00	14.10	19.72	15.02	0.76	5.27	0.52	1	
4/11/2013	0.99	14.67	31.41	23.08	0.73	9.73	0.69	1	
4/12/2013	0.99	15.05	23.36	17.23	0.74	6.06	0.77	1	
4/13/2013	1.00	15.57	22.08	15.24	0.69	5.19	0.60	1	
4/14/2013	0.99	15.79	26.50	16.08	0.61	6.28	0.64	1	
5/1/2013	1.03	15.45	31.81	15.67	0.49	6.31	0.92	1	
5/2/2013	1.02	14.97	29.95	17.41	0.58	5.62	0.92	1	
5/3/2013	1.02	15.46	26.84	16.17	0.60	5.77	0.93	1	
5/5/2013	1.49	15.23	31.77	4.79	0.15	6.05	0.86	1	

Date	Depth (m)	Temp. avg. night (°C)	ER (g O_2 m^{-2} d^{-1})	GPP (g O_2 m^{-2} d^{-1})	P/R	k (per day)	R^2	QC code	Correction
5/6/2013	1.55	14.16	37.77	8.96	0.24	7.98	0.97	1	
6/1/2013	1.78	12.20	26.70	6.44	0.24	7.14	0.98	1	
6/2/2013	1.69	12.09	25.37	6.76	0.27	6.84	0.99	1	
6/3/2013	1.62	11.47	23.63	5.45	0.23	6.34	0.99	1	
6/6/2013	1.93	11.72	31.25	6.35	0.20	7.20	0.97	1	
6/7/2013	1.80	11.38	29.55	7.61	0.26	8.09	0.99	1	
7/26/2013	1.33	11.23	7.85	3.33	0.42	1.78	0.66	1	
7/27/2013	1.28	11.14	18.89	5.04	0.27	5.88	0.59	1	
7/28/2013	1.26	10.49	20.89	11.24	0.54	3.43	0.55	1	
7/30/2013	1.24	9.51	10.82	3.51	0.32	3.54	0.66	1	
8/10/2013	1.17	12.60	14.43	8.98	0.62	4.76	0.86	1	
8/11/2013	1.21	12.89	14.16	9.96	0.70	4.26	0.94	1	
8/12/2013	1.25	12.31	12.72	9.95	0.78	3.56	0.93	1	
8/13/2013	1.23	12.61	13.71	10.72	0.78	3.88	0.81	1	
8/14/2013	1.21	12.22	13.57	11.11	0.82	4.21	0.93	1	
9/6/2013	1.51	11.34	16.47	12.46	0.76	3.93	0.94	1	
9/7/2013	1.45	12.60	15.38	11.74	0.76	3.15	0.91	1	
9/8/2013	1.45	13.56	19.05	14.75	0.77	4.15	0.96	1	
9/9/2013	1.46	13.32	17.59	13.41	0.76	3.92	0.97	1	
9/10/2013	1.39	13.05	16.82	10.55	0.63	3.74	0.93	1	
10/2/2013	1.68	15.01	25.00	20.60	0.82	5.18	0.96	1	
10/3/2013	1.61	15.41	24.45	19.29	0.79	4.95	0.99	1	
10/4/2013	1.56	14.97	21.23	15.88	0.75	4.09	0.97	1	
10/5/2013	1.53	16.46	19.22	12.42	0.65	3.25	0.95	1	
10/6/2013	1.49	17.39	25.64	20.61	0.80	4.41	0.97	1	

Metabolism estimates for Piakonui

Date	Depth (m)	Temp. avg. night (°C)	ER (g O_2 m^{-2} d^{-1})	GPP (g O_2 m^{-2} d^{-1})	P/R	k (per day)	R^2	QC code	Correction
10/2/2012	0.60	11.22	0.59	0.61	1.03	9.60	0.79	1	
10/3/2012	0.54	11.54	1.15	0.39	0.34	10.76	0.78	1	
10/5/2012	0.53	11.13	2.06	0.66	0.32	13.74	0.76	1	
10/8/2012	0.43	11.19	2.97	1.25	0.42	20.70	0.68	1	
10/11/2012	0.40	11.50	0.57	0.70	1.23	5.24	0.59	1	
10/12/2012	0.37	11.34	1.76	0.35	0.20	10.83	0.77	1	
11/9/2012	0.36	11.36	3.20	3.92	1.22	17.99	0.67	1	
11/10/2012	0.35	11.91	3.29	3.54	1.08	16.09	0.54	1	
11/11/2012	0.35	12.00	3.63	4.17	1.15	15.62	0.64	1	
11/12/2012	0.36	12.06	3.32	4.03	1.22	11.10	0.63	1	
12/18/2012	0.39	15.53	0.61	1.68	2.75	17.81	0.67	1	
12/19/2012	0.39	15.64	0.17	1.19	7.12	14.10	0.72	1	
12/20/2012	0.37	15.21	0.14	0.74	5.31	10.35	0.58	1	
12/21/2012	0.35	15.41	0.34	0.77	2.26	9.62	0.59	1	
1/18/2013	0.30	13.75	1.23	0.70	0.57	13.12	0.73	1	
1/19/2013	0.29	13.65	1.05	0.49	0.47	9.51	0.76	1	
1/20/2013	0.27	14.48	0.94	0.88	0.94	11.18	0.61	1	
1/21/2013	0.26	14.71	0.82	0.99	1.21	12.23	0.57	1	
2/22/2013	0.17	13.83	1.34	1.14	0.85	6.19	0.63	2	15%
2/23/2013	0.17	13.67	1.27	1.15	0.90	10.54	0.61	2	15%
2/24/2013	0.16	13.19	1.02	1.17	1.14	8.32	0.60	2	15%
2/25/2013	0.15	13.07	1.68	1.56	0.93	13.26	0.77	2	15%
2/26/2013	0.15	12.62	1.74	1.37	0.79	11.13	0.70	2	15%
3/12/2013	0.12	12.38	2.06	0.44	0.21	14.30	0.90	2	15%
3/13/2013	0.12	12.60	1.44	0.16	0.11	9.32	0.74	2	15%
3/14/2013	0.12	13.02	2.27	0.40	0.18	14.01	0.80	2	15%
3/15/2013	0.13	13.11	1.79	0.29	0.16	10.83	0.72	2	15%
3/16/2013	0.13	13.25	1.36	0.10	0.08	7.36	0.46	2	15%
4/13/2013	0.20	11.57	1.22	0.47	0.38	16.99	0.75	2	5%
4/14/2013	0.19	12.06	1.29	0.53	0.41	14.85	0.77	2	5%
4/15/2013	0.19	12.52	1.25	0.28	0.22	10.80	0.42	2	5%
4/16/2013	0.27	13.74	2.39	0.44	0.19	14.93	0.65	2	5%
4/18/2013	0.34	13.73	2.30	0.65	0.28	16.70	0.72	2	5%
5/2/2013	0.22	10.94	1.88	0.26	0.14	6.21	0.67	2	15%
5/3/2013	0.22	11.13	1.53	0.20	0.13	4.56	0.51	2	15%
5/7/2013	0.79	10.50	9.99	0.71	0.07	11.40	0.54	2	15%
5/8/2013	0.55	9.86	8.35	0.79	0.09	12.75	0.52	2	15%
7/25/2013	0.56	9.97	4.48	0.65	0.14	14.86	0.53	1	
7/28/2013	0.46	8.94	2.44	0.39	0.16	14.40	0.55	1	
7/29/2013	0.45	8.46	2.87	0.46	0.16	18.62	0.47	1	

Date	Depth (m)	Temp. avg. night (°C)	ER (g O_2 m^{-2} d^{-1})	GPP (g O_2 m^{-2} d^{-1})	P/R	k (per day)	R^2	QC code	Correction
7/30/2013	0.44	8.23	2.46	0.41	0.17	16.01	0.54	1	
7/31/2013	0.42	8.70	1.92	0.33	0.17	10.13	0.55	1	
8/2/2013	0.44	10.32	4.30	0.49	0.11	15.18	0.75	1	
8/3/2013	0.44	10.21	3.83	0.47	0.12	13.16	0.50	1	
8/4/2013	0.41	10.38	5.30	0.77	0.15	20.42	0.57	1	
8/5/2013	0.41	10.31	3.61	0.51	0.14	15.18	0.61	1	
8/6/2013	0.40	10.28	3.29	0.42	0.13	15.70	0.51	1	
9/7/2013	0.65	9.04	6.85	1.11	0.16	16.22	0.49	2	10%
9/8/2013	0.65	9.61	6.99	1.20	0.17	15.86	0.60	2	10%
9/9/2013	0.66	9.37	5.44	1.06	0.20	14.16	0.41	2	10%
9/10/2013	0.59	9.18	5.61	1.10	0.20	14.94	0.64	2	10%
9/11/2013	0.57	10.25	6.77	0.70	0.10	19.63	0.57	2	10%
10/26/2013	0.65	11.03	3.19	0.20	0.06	6.85	0.57	2	
10/27/2013	0.65	10.86	6.07	0.65	0.11	11.50	0.65	2	
10/28/2013	0.65	10.71	3.49	0.40	0.12	7.09	0.55	2	
10/29/2013	0.65	10.11	6.76	0.90	0.13	13.23	0.76	2	
10/30/2013	0.65	10.26	6.18	0.74	0.12	11.16	0.64	2	

Appendix 3. Response to reviewer comments.

Review comments from Michael Pingram, Mark Hamer, Jeff Smith (Waikato Regional Council), Kevin Collier (University of Waikato), John Nagels and Graham McBride (NIWA) were received in the form of an email dated 30 September 2014. The table below summarises the comments and the author's response. (Note that minor editorial comments are omitted).

Comments from Mike Pingram			**Response from author**	
No.	**Reference**	**Comment**	**Comment**	**Action**
1	S 1	Should this be in the introduction?	We suggest the inclusion is appropriate here as it provides a description of the study site. The water quality data used in our analysis is subsequent to that reported in Tulagi 2013.	Leave as is
2	Figure 1	Figure should have a North arrow, and the purple lines are a bit hard to see, could try making them thicker or using a colour like red?		Amended Figure to include North Arrow and adjusted catchment lines to red
3	S 2.2.2	Is there a citation for this?	The citation provided is relevant for the whole sentence	Leave as is
	S 4.1	Larger catchment? Or larger waterway? Or both?		Deleted 'larger' as causing confusion.
	S 4.1	It isn't necessarily clear in the Methods how the one-week estimate was calculated (*i.e.* over how many days)		Added sentence to section 2.3 "For each chosen period, ecosystem metabolism was calculated for five consecutive days; a minimum of three days and a maximum of six days."
	S 4.1	And also "subject to" certain stressors?		Replaced 'sensitive to' with 'subject to'
	S 4.1	Was there any relationship with mean daily or monthly water temperatures?		

Comments from Mike Pingram			Response from author	
No.	**Reference**	**Comment**	**Comment**	**Action**
	S 4.2	A couple of general citations would be nice		Added References
	S 4.3	It would be good to have the answers to questions 1–3 from the introduction laid out more explicitly here. Suggestion from Mark - “Temporal variability in ecosystem metabolism in the Piako River is characterised by...” OR Suggestion from Jeff - have subheadings for each question	Good idea	Reordered section 4.3
	S 4.3	Sentence is hard to follow, we think we know what you saying but aren’t quite sure. Also, I think it would be more correct to use a word other than “reflect” in this case.		Reworded “Consistent relationships between conductivity and stream metabolism at all time periods is unlikely to be causative, and instead is likely to be due to correlations between stream metabolism and land use and conductivity and land use respectively.”

Comments from Mark Hamer			Response from author	
No.	**Reference**	**Comment**	**Comment**	**Action**
	Figure 2	Mark on the hydrograph when WQ samples and DO data were collected		Added lines to Figure 2 delineating sample times and amended figure header
	S 2.2.1	Piako at PT Rd doesn't have a weir pool, so the loggers were in a natural pool / run.		Added a footnote
	S 2.2.1	Landsdowne Rd site should be "Waitoa at Waharoa". The Landsdowne Rd WQ site is a couple of hundred metres upstream of the flow / DO recorder site.	We weren't aware of this.	Changed site name throughout and clarified in this section with a footnote.
	S 2.2.1	Provided additional text to explain quality control coding	Thank you	Added text
	Figure 11	Correlation between *E.coli* and GPP appears to be driven by the site at Piakonui (same for in TKN and conductivity in Figs 8 and 10). If this is the case then it would be worth covering in the discussion.		
	S 3.7.4	Some form of analysis of water levels (flow) when water quality samples were collected would be good. For example this would be to ascertain whether low E. coli and good water clarity values are all from low flow periods and high nutrients and conductivity from high flow periods. These WQ parameters could have stronger correlations to flow than to GPP. Low flows are generally between Jan to May and higher flows June to December. Mark suggests taking the impacts of flow on WQ into account in your analysis somehow. You are comparing GPP and ER determined during stable flows to WQ samples collected across a range of flows (some stable, some high) which might confuse things with a seasonal bias.	Agree an analysis of both water quality variables and metabolism in relation to the antecedent flow could be informative. Would entail a significant reanalysis of data and is outside the scope of current project. Also, by adding sample times to Figure 2 we can see that WQ was collected at base flow on all but two occasions.	Added discussion relating to potential flow effects and recommendations for future study.

Comments from Jeff Smith			**Response from author**	
No.	**Reference**	**Comment**	**Comment**	**Action**
	Table 1	Change header points to footnotes	Cawthron report style prefers to retain these in the Table header	Leave as is
	S 2.3	Include scatterplots of regression equations in an Appendix	There are 369 regressions; one for each time daily metabolism is calculated.	We have included an example for each site in Appendix1.
Comments from John Nagels			**Response from author**	
No.	**Reference**	**Comment**	**Comment**	**Action**
	S 1	Can carbon leave the ecosystem as CH_4, C_2H_6?		
1	Table 1	Table 1: Include upstream catchment area for the six sites		Added row to Table with Catchment area (km^2)
	S 2.3	Add Wiley et al reference to citation list		Done
	Table 2	Insert units in Table		Done

Comments from Graham McBride			Response from author	
No.	**Reference**	**Comment**	**Comment**	**Action**
	Overall	Nice report, well-written. Sound conclusions. A couple of typos need fixing, especially in the Executive Summary. I would need extra information about the correction procedure used in sec. 2.3, para 6, before accepting it. That required information is given in my comment on that section. The metabolism estimation procedure used in the report (the "night-time regression approach", NTRA) is valid, and seems to deliver similar "P/R" estimates to an approach that we have successfully used for the Mangapiko Stream -- the ADM (Approximate Delta Method), McBride & Nagels (2014). Individual estimates of P and R can differ somewhat between the NTRA and ADM, but their ratio seems stable between the methods, and their ratio is an important metabolism metric. So that's good. One attractive feature of the ADM is that the validity of the overall DO model and its estimated parameters can be checked by running the model with those parameters (k, P and R) and comparing the results with the raw DO data [see Figure 4 in McBride & Nagels 2014]. I suggest that figure gives readers some comfort that the model is OK. I don't think such a comparison can be made with the NTRA, because it doesn't use analytical solutions of the governing equation, whereas ADM is built on an elegant analytical solution. It would be nice if it could. Having said that, I know only one formal comparison between the NTRA and ADM (Wilcock *et al.*, 2011). I can't help wondering if there should be a bit more effort put in to such a	More information about the correction procedure is given. Agree it would be interesting to compare the NTRA and ADM and am happy to conduct a future study.	Add section 2.3.1 and acknowledged in discussion No change

Comments from Graham McBride			Response from author	
No.	**Reference**	**Comment**	**Comment**	**Action**
		comparison—a (small) future research project. (References omitted)		
	Exec Summary	0.7 surely, as stated in sec. 3.4		Corrected to 0.7
	S 2.1	Needs a reference; which guidelines? Are they stated in terms of sample medians?	This is addressed in the cited report. Amended sentence to further clarify.	Changed sentence “The Piako River often fails to achieve ‘satisfactory’ physico-chemical water quality for ecological health and for human uses of water, based on Waikato Regional Council water quality guidelines and standards, because of high levels of total nitrogen and total phosphorus and low visual water clarity (Tulagi 2013).”
	S 2.3	This "single-station" equation is only valid if the effects of upstream longitudinal DO gradients can be ignored. Can they? Note that Chapra & Di Toro [1991, J. Env. Eng. 117(5) 640-655] reckon there needs to be a homogeneous distribution of aquatic plants for a distance of 3k/U km upstream of the station, where U is reach-average velocity (m/s) and k is the reaeration coefficient (per day). Is this condition met? It was, marginally so, in a recent report on the Mangapiko [McBride, G.B., Nagels, J.W. (2014). Mangapiko Stream: Oxygen Kinetics and Mixing. NIWA Client Report No: HAM2014-037, Prepared for Waipa District Council, Project WPD14202, 35 p. May].		Added assumptions to the methods and discussed in relation to potential limitation of Piakonui data in particular
	S 2.3 Equation 1	Must be preceded by a minus sign. Respiration removes oxygen from water. So rewrite the right-hand-side of this equation as "kD - ER".	Agree that ER removes O_2 from water. But sum of kd and ER shows change in O_2 concentration. We have chosen to report rates as positive values. Regardless of whether O_2 is added or taken away, the rate of change cannot be negative. This equation has been published numerous times in its current form,	No change

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			e.g. Young RG, Huryn AD 1996. Interannual variation in discharge controls ecosystem metabolism along a grassland river continuum. Canadian Journal of Fisheries and Aquatic Sciences 53: 2199–2211.	
	S 2.3	It would be of great interest to me (and to others) to be told the estimated values of the reaeration coefficient (*i.e.*, k), and also to see how well those estimates compare with empirical equations for k, based on stream depth and cross-section-average-velocity, *e.g.* as done by Wilcock *et al.* (1995). Water quality in a polluted lowland stream with chronically depressed dissolved oxygen: causes and effects. New Zealand Journal of Marine and Freshwater Research 29: 277–288.	We can add the *k* estimates as an Appendix to aid future studies.	Added Appendix
	S 2.3	Suggest adding (just after the left parenthesis and before "gO2"): "defined as Osat - O, where Osat is the saturation oxygen concentration, "		Added text as suggested
	S 2.3	Suggest define this term (is it GPP - ER?)		Changed sentence to equation to clarify NEM = GPP - ER
	S 2.3	It seems inevitable to get such problems for DO probes over long periods. While the approach may be reasonable, I would first want to be satisfied that the unusual results are not the result of longitudinal gradients that should not have been ignored (as in my earlier comment on sec. 2.3). Also, to see the effect of these corrections it would be helpful to plot the raw and corrected data (so that readers can check that the corrected profiles really do look plausible).		Added section showing expected change due to corrections.
	Figure 3	Add units		Done. Also for Figures 4 and 5.

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	S 3.4	Want to add a footnote stating that statistical significance doesn't necessarily imply environmental significance? I think you're using p-values in a relative sense for similar sample sizes, and I agree that is instructive. But it might be helpful to address the point.	I feel this is not necessary and may confuse the reader. Visual inspection of the graphs shows a clear difference among sites, especially when considering the guidelines values, which further highlight environmental differences among sites.	No change
	Table 5	Did you look at results using Spearman's rank correlation coefficient? They might give stronger results.	We chose to investigate pairwise Pearson correlation coefficients because data met the assumptions of normality (following transformation)	No change

Comments from Kevin Collier with key points underlined by Mike Pingram including additional notes by Mike added in red			Response from author	
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1		The questions addressed by the report are pertinent given the lack of reliable indicators for monitoring non-wadeable river health and the need to understand the key drivers of spatial and temporal variability of candidate indicators such as metabolism. Do some caveats need to be applied to the aerial estimates given that depths were measured only during summer low flow and presumably were higher in winter - unless there is some evidence to infer constant base flow throughout the year?	The areal estimates are calculated from daily depths not a single depth. During metabolism estimates, average depth variation ranged from 0.20 to 0.96 m representing 40□100% increase in stream depth (excluding Piakonui which ranged from 0.12–0.87 m in depth). However, the depth was calibrated against stage height using a single measurement and ideally a stage-depth relationship would be developed from more than one measurement and this is a limitation of the current study.	Clarified text in methods
		The need to adjust the raw DO data to account for apparent erroneous data seems to be a fact of life with metabolism estimates - the fact that it occurred on 2 different dates and 2 different and distant sites suggests it may be a logger issue (would be interesting to know if it was the same logger number). The 5–15% adjustments required do not seem overly extreme but it would be useful to know to what degree these adjustments affected metabolism estimates, and whether despite this the same temporal patterns were evident as at other sites.		Added section 2.3.1 and associated discussion.
		It may be interesting to consider sub-catchment as a variable (Waitoa, Piako) given they are two similar-sized and parallel sub-catchments but with potentially different stressor intensities (upstream native forest - some in Piako, none in Waitoa)—perhaps even a paired comparison of similar sized sites would be useful to test whether this affected metabolism accounting for stream size. I wasn't sure about this, but I wondered whether you might have tried this already, particularly with regard to using the sub-catchment as a variable?	I have had a preliminary look at whether there are any sub-catchment differences and I think the sample size is insufficient to analyse sub-catchment differences robustly.	No change

Comments from Kevin Collier with key points underlined by Mike Pingram including additional notes by Mike added in red			Response from author	
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		Interesting that Piako @ Kiwitahi consistently rates as "poor" even though it is above the PT site where cumulative stressors might be expected to be greatest—is the PT sites shaded or incised (cf the open Kiwitahi site) and if so could shade account for some of this difference. The Kiwitahi site has extensive macrophyte cover but there was no significant correlation between ER & GPP—does this suggest something else is going on here?	Shade was not recorded and could definitely account for differences among sites with similar catchment land uses. Kiwitahi is an interesting site because despite a seasonal dominance in macrophyte cover NEM was more related to ER than GPP. Results suggest something additional is at play, fuelling dominant respiration. I don't have the data to infer what.	Added point about shade to discussion and need for data on the temporal variability in macrophyte cover.
		Given the sample size and the clear effects of one outlier I don't think the correlations with land use *etc* are worth including (Table 4, Fig. 7). I can see Kevin's point, however I expect it's one of those things that if you hadn't put it in then you probably would have been asked to add it by someone. Maybe it's worth keeping but in a scaled back version by dropping the table?.	Agree.	Deleted Figure and retained Table.
		Do the results infer that: (i) metabolism estimates best reflect the preceding 3 months (most number of sig. correlations) or 1 month (strongest correlations) of water quality (3 months indicated in Summary but confusing messages in Discussion)? (ii) it is best carried out is summer-autumn to detect the most stressful time and (iii) is 1-week deployment sufficient to characterise metabolism - some clear guidance on these would be helpful (ii is covered - although it is also stated that seasonal estimates are best - does this mean loggers should be deployed for 1 week 4 x per year?). These last two are likely to be pretty important from the councils point of view		Reordered section 4.3 to address these points. (i) Three-month rolling average best (ii) Summer best, unless annual characterisation desired (iii) 1-week for summer estimates, 4 weeks for seasonal variability.

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		Also is it worth considering the ratio of summer:winter ER or GPP as a measure of stress or impact/reference (assuming comparable reference sites are available which is unlikely in lower catchments)? Would you identify this as an avenue for further work?	Interestingly, work we have done in Auckland streams has shown much greater seasonal variability at impacted sites compared to control sites. So yes that would be of interest. Also it is always preferable to compare to a reference rather than a condition band. I do not think the Piakonui data was robust enough to warrant comparison in this instance.	Added point to discussion.
		Can you provide some guidance on what variables need to be measured to support interpretation of metabolism data (shade, depth of upstream reach, width *etc*?) I think something like this would be quite useful, particularly if we were to start doing this at a greater range of sites.		Added to discussion on what variables would be needed to better interpret spatial and seasonal trends in metabolism