Environment Waikato Technical Report 2008/32

Spatial Variation of Function Indicators in Waikato River

www.ew.govt.nz
ISSN 1172-4005 (Print)
ISSN 1177-9284 (Online)

Environment Waikato
REGIONAL COUNCIL

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24 June 2008

Document #: 1333976

Peer reviewed by:
Dr. Kevin Collier Date July 2008

Approved for release by:
Dr. Vivienne Smith Date July 2008

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EXECUTIVE SUMMARY

The utility of different ecological monitoring approaches for assessing large river health has not been tested in New Zealand. This issue has particular relevance to the Waikato River where there is considerable interest in documenting current status and future trends brought about by management changes. Additionally, there is very limited information on the ecological function of large rivers, particularly with respect to sources of productivity. To address these issues the applicability of measuring functional indicators in large rivers as a measure of ecosystem health was tested in the Waikato River.

Ecosystem metabolism (the combination of primary production and ecosystem respiration) and rates of organic matter processing have been demonstrated as good functional indicators of ecosystem health. These indicators were measured at six sites within a 21 km reach of the Waikato River stretching from Hamilton Gardens downstream to Ngaruawahia. Site locations were chosen to represent an increasing gradient of catchment and reach pressures with the upper three sites close to urban river confluences and the lower three sites close to industrial discharges. Ecosystem metabolism was estimated using the single station open system method at nearshore and farshore locations at each site over two days. Similarly, organic matter processing was estimated at two locations at each site using a cotton strip assay which involved the deployment of cotton over seven days.

Both functional indicators showed a downstream response to disturbance. Gross primary productivity and respiration appeared to decrease downstream with consistent P/R ratios demonstrating the heterotrophic status of this reach of the Waikato River. Whilst there was no difference between nearshore and farshore locations, metabolic estimates were higher at sites closer to a point source impact. These results indicate that a single deployment per site is sufficient to characterise metabolism and suggest that, as long as it is not immediately downstream of a point source impact, a representative assessment of ecosystem health will be gained. Conversely, the effect of a point source impact may be readily assessed using this methodology. Organic matter processing increased downstream and concurrently was significantly higher at sites subject to industrial impacts compared to urban impacts. These results demonstrate the applicability of cotton strip assays to indicate potentially catchment, reach and local-scale disturbances.

In this survey, the functional assessment of the Waikato River was ‘healthy’ to ‘satisfactory’ based on reference values derived for smaller systems. However, these values need to be validated for larger systems. Temporal sampling would contribute to a better understanding of the functional dynamics of this reach of the Waikato and would lend greater confidence to ecosystem health assessments. The detectable response of functional indicators to small gradients in catchment change and larger gradients in point source impacts in the Waikato River suggest that these measures are likely to be good tools for assessing the ecosystem health of non-wadeable rivers.

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1. INTRODUCTION

There have been several recent studies that have demonstrated the relevance and applicability of functional measures in river health assessment (Fellows et al. 2006, Udy et al. 2006, Young et al. In press). Functional indicators measure the rates of ecological interactions (i.e. what is happening) and complement traditional measures of ecosystem structure (i.e. what lives there). Together, they allow for the assessment of a healthy river, which has been defined as "an ecosystem that is sustainable and resilient, maintaining its ecological structure and function over time while continuing to meet societal needs and expectations" (Meyer 1997). There have been several methods proposed as potential functional indicators from the relatively simple (e.g. biochemical oxygen demand, algal bioassays, organic matter processing, coarse particulate organic matter retention) to the relatively complex (e.g. ecosystem and/or benthic metabolism, denitrification, nutrient spiralling, bacterial activity, and stable isotope analysis of food web components).

Functional indicator development has occurred predominantly in small to medium sized streams, i.e. wadeable rivers. Therefore, there is a paucity of information on the functional health status of larger rivers, such as the Waikato River, and on the applicability of indicators in systems where there are issues with scale, ease of sampling, and habitat limitation using conventional biological monitoring techniques. Preliminary work carried out by Environment Waikato has highlighted that decomposition rates of wooden sticks can vary down the Waikato River in concert with increasing anthropogenic pressure, suggesting that functional indicators may be useful for monitoring the health of large rivers. The use of metabolism remains untested and information is required on how gross primary productivity and ecosystem respiration vary in relation to increased stress and spatially within a large river environment. Overseas work has highlighted the potential importance of dead zones in side arms, backwaters and embayments as areas of localised production that may contribute significantly to overall riverine productivity (Gawne et al. 2007, Preiner et al. 2008). This project is intended to investigate these issues on the lower Waikato River. The spatial scales of interest are variation within and between reaches representative of particular stressor types.

This report provides the results of measuring organic matter processing via a cotton strip assay and ecosystem metabolism during a one-off sampling event of Waikato River in April 2008. The objective of sampling was to test the effectiveness of ecological health indicators (cellulose decomposition, metabolism) at detecting differences between and within impact reaches of the Waikato River. Reach differences refer to (i) the presence of an increasing stressor gradient downstream and (ii) spatial differences between near-shore and far-shore environments at specific locations.

2. METHODS

2.1. Study area

Six sites were selected as part of a greater study in April 2008 investigating the spatial variability in a range of biotic indices in Waikato River (Figure 1). The sites were selected to survey a potential range in human impacts and include three sites in each of two distinct reaches of the Waikato River of approximately equal length (c. 10 km). These reaches represent "urban" impacts between Hamilton Gardens and Pukete, and "organic enrichment" impacts between Pukete and Ngaruawahia. Sites were chosen to represent an increasing gradient of stress down river within each reach from the progressive or sequential input of potential contaminants (Table 1).

Table 1 Description of the six sampling sites. [*data from the Water bodies of National Importance dataset]

Site	**1**	**2**	**3**	**4**	**5**	**6**
Location	E2713635 N6374872	E2709848 N6379290	E2707631 N6382729	E2706493 N6384308	E2704328 N6387361	E2701954 N6389120
Distance from Site 1 (km)	0	7.04	11.91	13.93	17.94	21.07
Distance from major urban stream confluence (km)	0.6 *Mangaonua*	0.5 *Waitawhiriwhiri*	1.8 *Kirikirroa*			
Distance from a point source discharge (km)				1.5 *Pukete*	3.0 *Fonterra*	1.8 *AFFCO*
% Impervious cover*	3.0	3.4	3.5	3.5	3.5	3.6
% Native vegetation*	39.2	38.9	38.8	38.8	38.7	38.6
Mean depth (m)	3.5	3.6	2.1	3.4	2.4	2.4
Nearest WRMP# sampling location	d/s of 1131.101	d/s of 1131.64	d/s of 1131.121	u/s of 1131.69	d/s of 1131.69	u/s of 1131.102

#WRMP = Waikato River Monitoring Programme

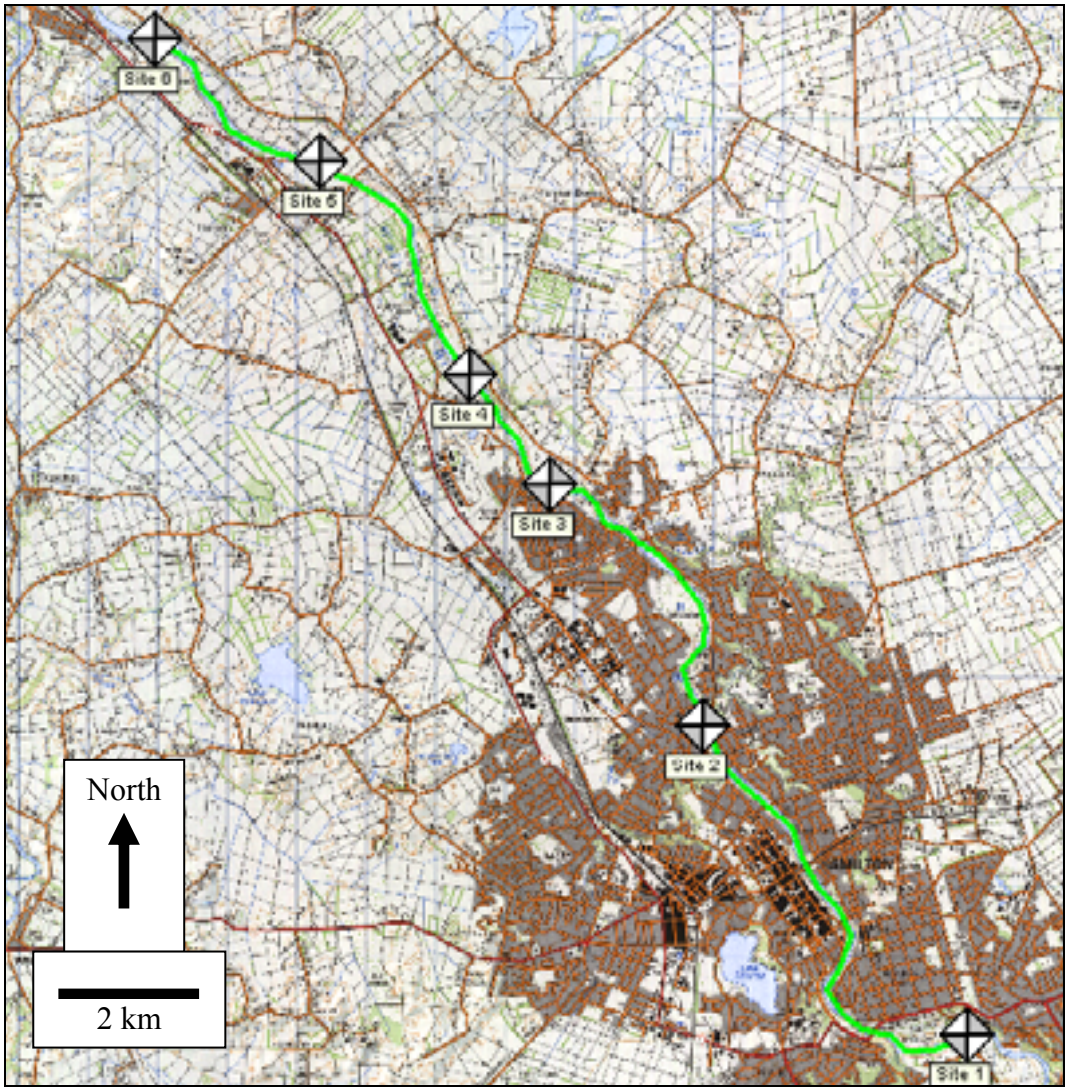

Figure 1 Map showing sampling sites located on the Waikato River.

2.2. Cellulose decomposition potential

Cotton strips were deployed at chosen sites on 4th April 2008 to measure cellulose decomposition potential. This assay was developed as an alternative to measuring leaf decomposition and provides a standardized assessment of the ability of a lotic system to process organic matter (Boulton and Quinn 2000, Young 2006). Five cotton strip replicates were attached at 3-4 m and 10 m intervals on a metal chain that was deployed along the benthos from the wetted edge at each site, thus providing 'nearshore' and 'farshore' locations for estimates of cellulose decomposition potential. Cotton was retrieved after 7 days and gently washed in-stream and frozen until analysis. After being thawed, cotton was gently rinsed in tap water and dried at 40°C for 24 h in a forced draft oven. Threads were frayed from the side of each strip until each strip was 100 threads (~3 cm) wide and then the tensile strength (in kg) was measured using a commercial tensometor (Sundoo Instruments).

Instead of simply reporting the percentage of cotton tensile strength lost relative to a control, which assumes decomposition is linear over time, the tensile strength of cotton strips was used to calculate exponential decay rates (-*k*) using the following formula (Petersen and Cummins 1974):

$$k = -\log_e\left(\frac{W(t_f)}{W(t_i)}\right)/(t_f - t_i) \quad (1)$$

where t_i refers to the initial tensile strength of cotton (calculated using procedural controls that were wetted in the laboratory and processed with samples) and t_f refers to the tensile strength after time (t). As such the cellulose decomposition potential of cotton strips reported for this study are exponential decay coefficients and thus refer to the proportion of cotton processed per day.

2.3. Ecosystem metabolism

Ecosystem metabolism was estimated using the single-station open-channel approach (Young and Huryn 1996). Dissolved oxygen (DO) concentration and temperature were recorded every 15 minutes using data loggers (D-Opto, Zebra-Tech Ltd) suspended from a buoy at approximately 1 m depth at nearshore and farshore locations at each site. Data loggers were deployed on 8th April 2008 and retrieved on the 11th April 2008 to ensure a minimum of 24 hours of data was obtained. Prior to deployment all 12 DO loggers were cross calibrated in the laboratory. Light loggers (Odyssey Ltd) were deployed at each site to obtain light data for metabolic data analysis.

Before analysis, random noise in the oxygen data was reduced using a moving average smooth function with an interval of 5-7 measurements. Metabolism values were then calculated using the RiverMetabolismEstimator (v1.2) spreadsheet model developed by Young and 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 nighttime regression method (Owens 1974), which uses only data collected in the dark (<2 µmol m^{-2} s^{-1}). The rate of change of oxygen concentration over short intervals during the night is regressed against the oxygen deficit to yield:

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

where dO/dt is the rate of change of oxygen concentration (gO_2 m^{-3} s^{-1}), ER is the ecosystem respiration rate (gO_2 m^{-3} s^{-1}), k is the reaeration coefficient (s^{-1}), and D is the oxygen deficit (gO_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:

$$GPPt = dO/dt + ER - kD \quad (3)$$

where GPPt is the gross photosynthetic rate ($gO_2\ m^{-3}\ s^{-1}$) over time interval (t). To compensate for daily temperature fluctuation, ER is assumed to double with a 10°C increase in temperature (Phinney and McIntire 1965) while the reaeration rate is assumed to increase by 2.41% per degree (Kilpatrick et al. 1989). Daily gross primary production (GPP, $gO_2\ m^{-3}\ d^{-1}$) is estimated as the integral of all temperature corrected photosynthetic rates during daylight (Wiley et al. 1990).

This analysis gives values of production and respiration per unit volume. An areal estimate is obtained by multiplying the volume based estimates by average reach depth (m) which allows comparison among stations with different depths. In this study, an estimate of average river depth was calculated from five depth measurements using a hand-held depth sounder (Speedtech Depthmate) across the river at five transects upstream of each site. Following depth adjustment, gross primary productivity and ecosystem respiration are expressed in units of $gO_2\ m^{-2}\ d^{-1}$. 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 for each location.

2.4. Environmental variables

Estimates of catchment impacts were calculated for each site using GIS software and the Water bodies of National Importance (WONI) pressures dataset (Table 1). A temperature logger (HOBO, Onset Solutions Ltd) was deployed alongside the cotton strips for 7 days at each location. From this data, daily minimum, maximum and range were ascertained and degrees days experienced at each site were calculated by multiplying average daily temperature by seven days.

On Day 1 the velocity ($m\ s^{-1}$) of river flow was recorded at each DO logger deployment location. Note that cotton deployment locations and DO logger location were not the same, but most were within approximately 100 m, although deployment locations were on opposite sides of the river at three sites. This was because it was observed that some cotton locations were in relatively still water compared to other locations. To obtain accurate estimates of metabolism DO loggers were deployed in flowing water of at least 0.5 $m\ s^{-1}$ flow.

2.5. Statistical analysis

Analysis of variance was used to examine differences between sites and locations. Downstream trends in variables were examined using simple linear regression, which was also used to investigate relationships between metabolic and environmental variables. Student t-test's were used to test for differences between upstream and downstream reaches. All diagnostics were checked according to Quinn and Keough (2002), and all analyses were carried out in SYSTAT version10 (SPSS 2000).

3. RESULTS AND DISCUSSION

3.1. Cellulose decomposition potential

Cotton strips were retrieved from all sites and locations. Despite temperature data suggesting cotton strips at site 6a were out of the water (Figure 3), they were submerged when collected but it was noted that the water level had dropped. It was also noted that strips deployed at Site 2b were disturbed and possibly removed and replaced closer to the shore for an unknown period of time (up to 4 days).

Rates of cotton decay ranged from 0.016 day^{-1} to 0.122 day^{-1} (Figure 2) and correspond to loss in tensile strength of 10.5 % to 57.4 %. This loss represents 'healthy' conditions according to the criteria for streams and small rivers of Young et al. (2006). A significant site x location interaction ($F_{(5, 48)} = 14.576$, $p < 0.001$) suggests that even though there was a significant trend for higher cotton decay at far shore compared to near shore locations ($F_{(1, 48)} = 20.634$, $p < 0.001$) this trend was not observed at all sites. For example, Figure 2 illustrates how cotton decay appears much higher at far shore than near shore locations at Site 3 and Site 6 in particular. There was a linear trend for increasing cotton decay downstream from Site 1 to Site 6 ($r^2 = 0.40$; $F_{(1, 58)} = 10.416$, $p = 0.002$) and when grouped, significantly greater cotton decay in the downstream compared to the upstream reach ($t_{(1,58)} = -4.096$, $p < 0.001$).

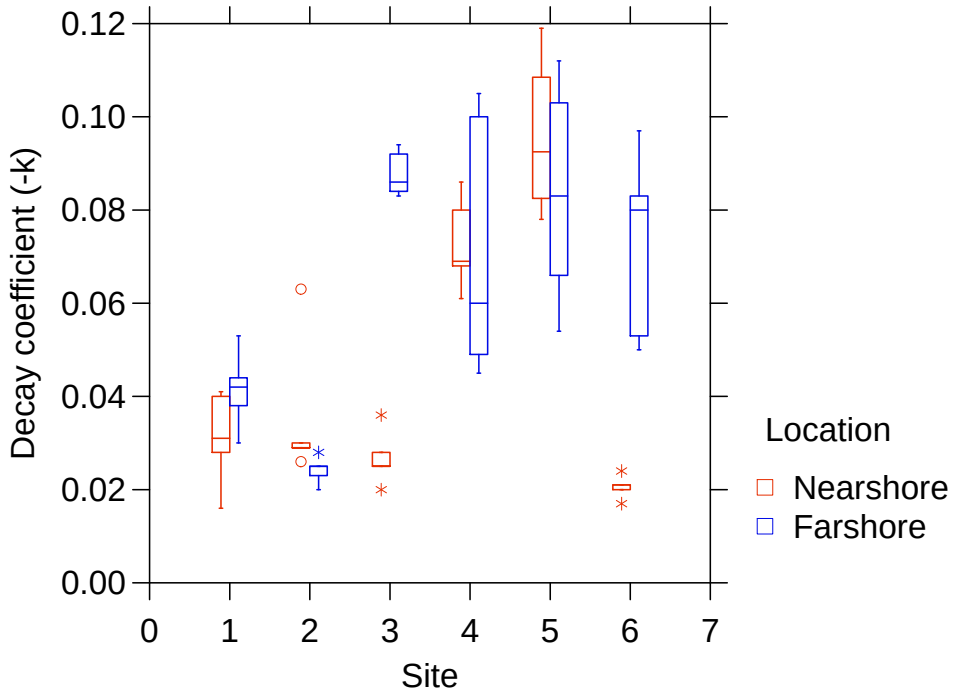

Figure 2 Box plot of the decay coefficient (-*k*) of cotton strips deployed at two locations at six sites in the Waikato River.

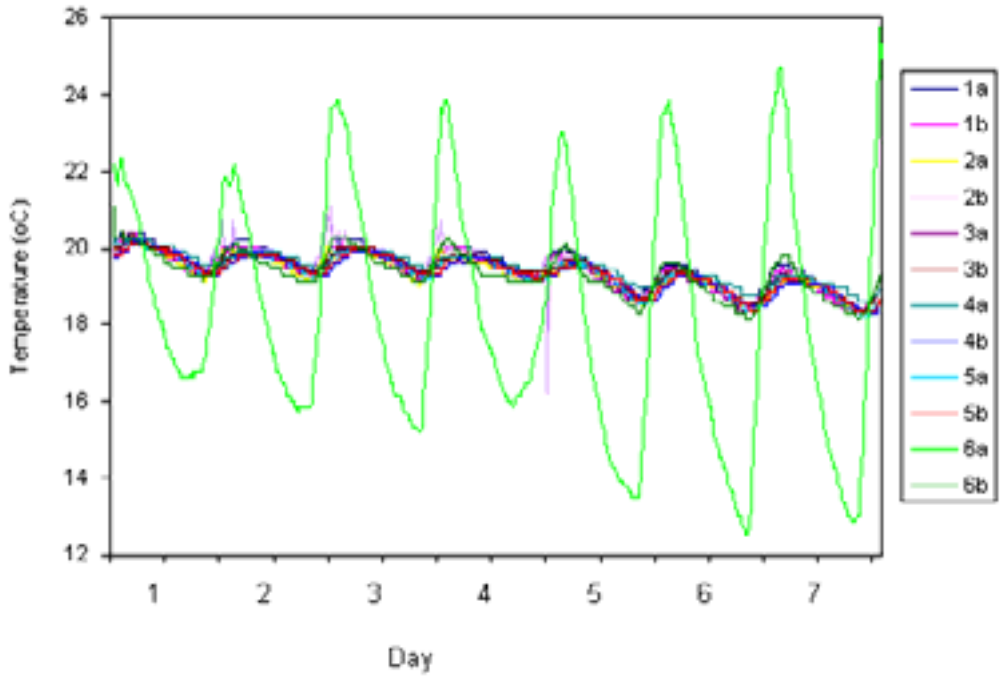

Figure 3 Diel changes in temperature at each of the sites in the Waikato River during the seven-day cotton deployment. 'a' and 'b' denotes nearshore and farshore respectively.

The relationship between cotton decay rates and temperature was examined to see if this could help explain some of the variability observed, as temperature is well known to be a primary limiting factor in microbial activity and organic matter breakdown (Young and Huryn 1999, Acuna et al. 2004, Clapcott and Barmuta In review). Locations 6a and 2b had unusual temperature records, namely higher diel variation indicative of removal from the water column (Figure 3). This may go someway to explaining the pattern observed, but given that Site 3 has quite disparate nearshore and farshore decomposition values it is clear that temperature variation is not the only driving variable in cellulose decomposition potential. This was supported by a weak linear regression between the decay coefficient and natural log (LogN) of temperature range ($r^2 = 0.54$; $F_{(1, 10)} = 4.043$, $p = 0.074$) or degree days ($r^2 = 0.30$; $F_{(1, 10)} = 1.003$, $p = 0.340$).

Other environmental factors that have been shown to contribute to cellulose decomposition potential and organic matter processing in general include flow, nutrients, and microbial and macroinvertebrate community structure (Webster et al. 1999, Gessner and Chauvet 2002, Acuna et al. 2004, Tiegs et al. 2007). These were not measured in this study (at these specific locations), but are known to be affected by disturbance (Allan et al. 1997, Houser et al. 2005, Fellows et al. 2006) and are likely to have contributed to the downstream patterns observed in decay coefficients. Data from the Waikato River Monitoring Program (Beard 2007) show a significant increase in a range of nutrient values from sites immediately above to downstream of the 21 km reach of this study (e.g. total organic carbon: 1.88-2.74 g C m^{-3}, nitrite/nitrate: 0.245-0.438 g N m^{-3}).

3.2. Dissolved oxygen curves

Dissolved oxygen readings were retrieved from all sites and locations for at least 24 hours and up to 48 hours except Site 2b where the logger failed to record data. Dissolved oxygen concentrations ranged from 90-108 % saturation with average daily minima just before dawn and daily maxima in the late afternoon (Figure 4).

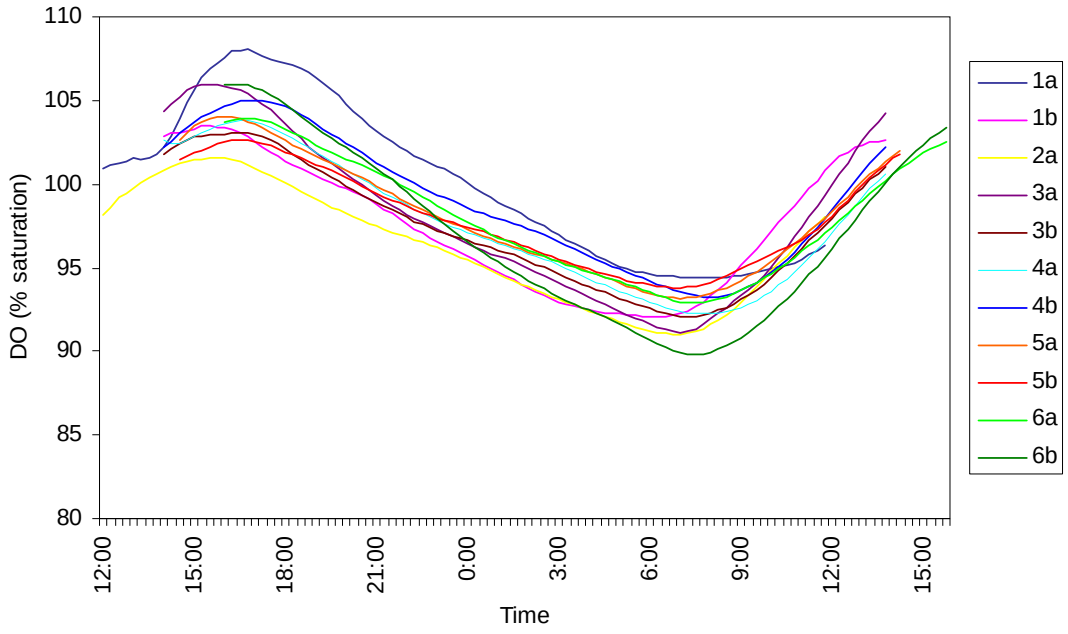

Figure 4 Diel changes in dissolved oxygen for Day 1 at each of the sites in the Waikato River. 'a' and 'b' denotes nearshore and farshore, respectively.

3.3. Ecosystem metabolism

Whilst there was a trend for increased GPP on Day 1 of sampling, there was no significant difference between rates of GPP on Day 1 and Day 2 ($F_{(1, 18)} = 0.830$, $p = 0.374$) and therefore an average rate was used in further calculations. Similarly, for other metabolic variables (ER, P/R) there were no differences between Day 1 and Day 2 values and therefore averages were used in further analyses.

Rates of gross primary productivity (GPP) ranged from 2.9 g O_2 m^{-2} day^{-1} to 7.8 g O_2 m^{-2} day^{-1} (Figure 5), with the highest values recorded at Site 1 contributing to a general trend of decreasing GPP downstream ($r^2 = 0.60$; $F_{(1, 9)} = 5.058$, $p = 0.051$). Rates of GPP at all sites reflect 'healthy' to 'satisfactory' conditions according to the criteria of Young et al. (2006) and are within the range of values observed in large rivers overseas (Uehlinger 2006, Gawne et al. 2007).

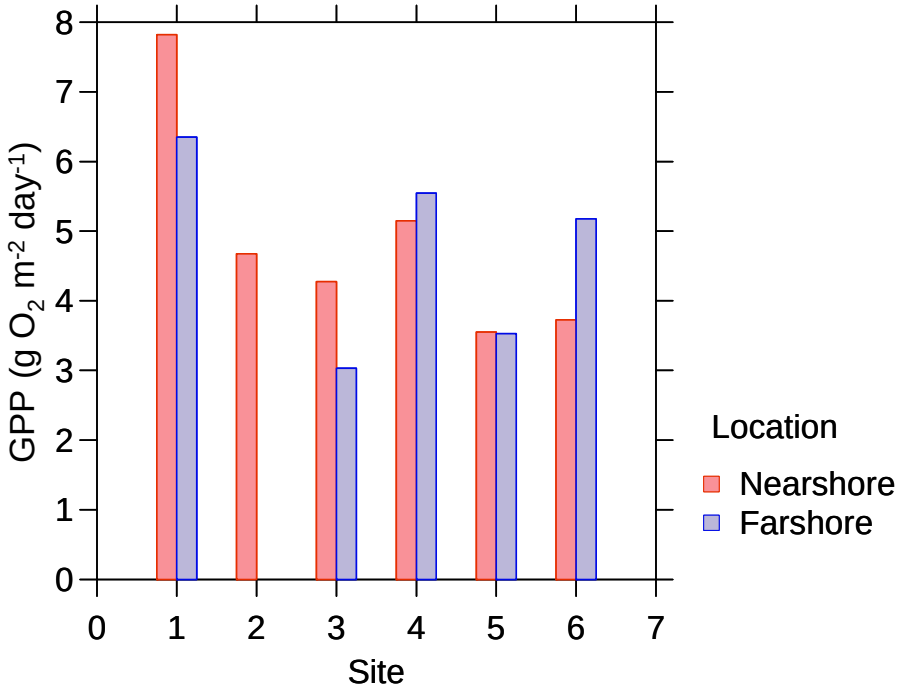

Figure 5 Average rates of gross primary productivity (GPP) measured over two days at six sites on the Waikato River.

On average, there was no difference between GPP of nearshore and farshore locations ($F_{(1, 9)} = 0.139$, $p = 0.718$), with some sites having greater GPP nearshore (Sites 1, 3) where as other sites had greater GPP farshore (Sites 4, 6) (Figure 5). As such there was no relationship between GPP and river velocity, which was significantly greater at farshore (mean = 0.552 m s^{-1}) compared to nearshore locations (mean = 0.082 m s^{-1}) ($t_{(1, 5)} = -7.626$, $p = 0.001$).This suggests that the water is laterally well-mixed and placement of DO loggers close to or far from shore is unlikely to significantly affect metabolic estimates at a short temporal scale as long as equipment is deployed in at least 0.5 m s^{-1} flow.

A student's *t*-test indicated no difference in rates of GPP between upstream (Sites 1-3) and downstream (Sites 4-6) reaches ($t_{(1,9)} = 0.959$, $p = 0.363$). This suggests that the sequential input of urban and point source impacts do not affect primary productivity within the 21 km of river studied. However, there was a significant linear relationship between GPP and the distance from an urban river confluence or point-source nutrient input ($r^2 = 0.74$; $F_{(1, 9)} = 10.560$, $p = 0.01$), with greater GPP closer to impacts (Figure 6). This further suggests that reach-scale impacts are likely to be better predictors of metabolic response to disturbance than catchment-scale impacts, although the range of the catchment-scale impacts (% impervious cover, % native forest, Table 1) was very narrow in this study.

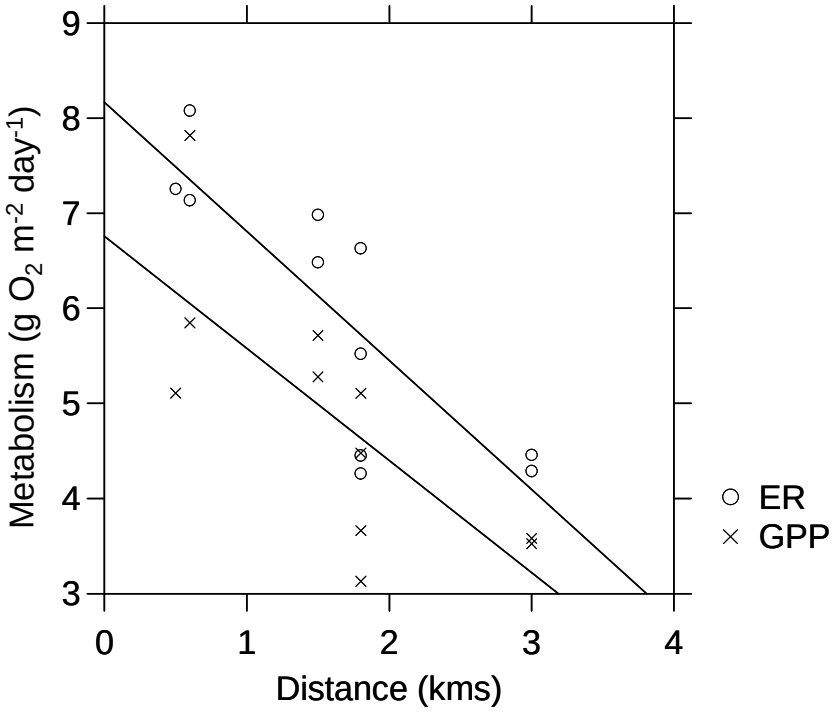

Figure 6 The relationship between metabolic variables and the distance from an urban river confluence or a point source impact on the Waikato River.

Rates of ecosystem respiration (ER) ranged from 3.8 g O_2 m^{-2} day^{-1} to 8.1 g O_2 m^{-2} day^{-1} (Figure 7). As with GPP, ER was greatest at Site 1, there was a trend of decreasing ER downstream ($r^2 = 0.60$; $F_{(1, 9)} = 5.056$, $p = 0.051$), and there was no significant difference between upstream and downstream reaches or between nearshore and farshore locations (Figure 7). There was, however, the same relationship of higher ER close to point source discharges ($r^2 = 0.83$; $F_{(1,9)} = 19.332$, $p = 0.002$), as was observed with GPP (Figure 6).

The ratio of gross primary productivity to ecosystem respiration (P/R) ranged from 0.68 to 1.05 (Figure 8). On average, all sites displayed net heterotrophy (i.e. P/R < 1) suggesting that metabolism is driven by the external input of carbon from upstream and the surrounding catchments. There was no downstream trend in P/R values and whilst there was no difference between nearshore and farshore locations, four out of six sites had higher P/R nearshore.

Where there were high levels of GPP there were also high levels of ER and this suggests that ecosystem metabolism in the Waikato River is contributed to by a balanced range of autochthonous and allochthonous processes. It would be erroneous to conclude that this represents the normal state of metabolic processes in Waikato River because this study was limited to a single weekend of data and other studies have demonstrated high temporal variability in lotic metabolism (Young and Huryn 1996, Chester and Norris 2006, Uehlinger 2006, Clapcott and Barmuta In review).

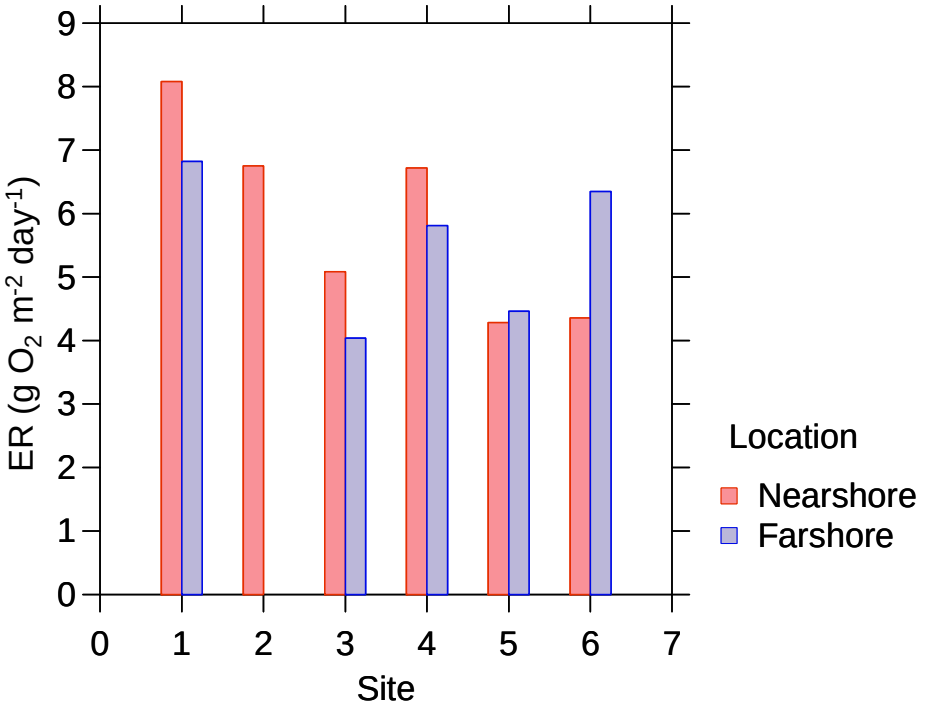

Figure 7 Average rates of ecosystem respiration (ER) measured over two days at six sites on the Waikato River.

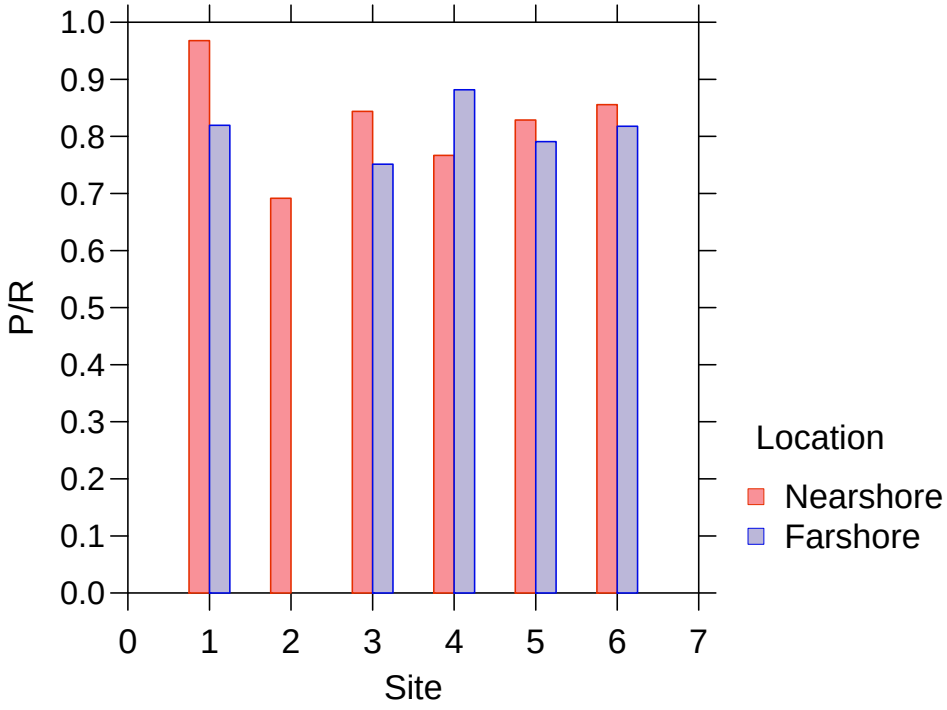

Figure 8 The ratio (P/R) of gross primary productivity to ecosystem metabolism measured over two days at six sites on the Waikato River.

4. SUMMARY

Estimates of ecosystem metabolism were relatively consistent throughout the 21 km of the Waikato River surveyed in April 2008. There was no predictable difference between nearshore and farshore estimates of metabolism, suggesting that the placement of DO loggers close to or far from shore is unlikely to significantly affect metabolic estimates at a short temporal scale as long as sufficient flow passes over loggers (i.e., not recommended to deploy them in backwaters or areas of low or no flow). There was a weak downstream trend of decreasing productivity and respiration suggesting that the small relative change in catchment-scale impacts is insufficient to elicit a significant response in river metabolism within a short river reach, especially given the high velocities experienced in-stream (e.g. at the lowest velocity measured at farshore locations river water would travel 21 km within 16 hours). There was a significant difference between metabolic response and distance from a point source impact, suggesting that if the aim is to assess overall ecosystem health, metabolism should not be measured immediately downstream of point source discharges. Conversely, this response suggests that the methodology may be sensitive to detecting effects from point source impacts, although further work is required to verify this. In April 2008, metabolic estimates in the Waikato River resulted in a 'healthy' or 'satisfactory' assessment based on reference values from smaller rivers. However, it is not clear how these reference measures relate to large rivers, and as such these require validation. To test spatial variability in ecosystem health, it is probably best to obtain multiple temporal samples, thus allowing for strengthened statistical analyses.

The processing of organic matter, assessed via a cotton strip assay, varied between sites and varied significantly between upstream and downstream reaches of the Waikato River, with higher cellulose decomposition potential at sites subject to point source nutrient impacts. The positive response to catchment-scale and reach-scale gradients in disturbance suggests that this measure may be valuable for assessing the ecological integrity of large rivers although, further assessment of spatial (both small-scale and large-scale) and temporal variability is required. In April 2008, rates of organic matter processing in the Waikato River resulted in a 'healthy' ecosystem health assessment, but as with metabolic assessments this requires validation within a large rivers context. Cotton strip assays have the advantage of incorporating a longer temporal response to disturbance than one-off measures.

5. RECOMMENDATIONS FOR FUTURE WORK

1. Establish at least one site within a minimally-impacted river section so that other sites can be compared with a realistic measure of reference condition for the Waikato River. If possible, sample other rivers in the region to compare the health of the Waikato River with regional measures of ecosystem health. Additionally, assess functional indicator trends in relation to data from other large rivers in New Zealand, as it becomes available.
2. Assess temporal variability in functional indicators by repetition in at least two seasons, e.g. April and September. This will allow for increased statistical confidence in spatial

patterns as well as investigating potential seasonal influences such as variability in temperature and flow. Incorporate site-specific measures of environmental variables, such as nutrients, to better quantify the relationship between functional indicators and environmental influences on ecosystem health in the Waikato River.

3. Assess the downstream extent of the effects of point source impacts by more intense sampling at a minimum of two impact sites.
4. Assess the effect of other point source impacts by adding new sites where applicable.

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