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Spatial and Temporal Variation of Functional Indicators in Waikato Rivers

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Prepared by:
Joanne Clapcott
Roger Young
(Cawthron Institute)

For:
Environment Waikato
PO Box 4010
HAMILTON EAST

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Spatial and Temporal Variation of Functional Indicators in Waikato Rivers

RESEARCH BASED SOLUTIONS

Spatial and Temporal Variation of Functional Indicators in Waikato Rivers

Joanne Clapcott

Roger Young

Prepared for

Environment Waikato

Cawthron Institute
98 Halifax Street East, Private Bag 2
Nelson, New Zealand
Ph. +64 3 548 2319
Fax. + 64 3 546 9464
www.cawthron.org.nz

Reviewed by: Joe Hay

Approved for release by: Rowan Strickland

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EXECUTIVE SUMMARY

There is considerable interest in documenting current status and future trends brought about by management changes in Waikato rivers. An increasing number of studies have shown that assessing the ecological function of large rivers can be achieved using functional indicators. The applicability of functional indicators in large rivers as a measure of ecosystem health was tested in the Waikato River and in other non-wadeable rivers throughout the Waikato region.

Ecosystem metabolism (the combination of primary production and ecosystem respiration) and rates of organic matter processing have been demonstrated as effective functional indicators of ecosystem health. Ecosystem metabolism was measured at six sites within a 21 km reach of the Waikato River stretching from Hamilton Gardens downstream to Ngaruawahia in October 2008. Ecosystem metabolism was estimated using the single station open-system method at each site over a 24-hr period. Rates of gross primary production and ecosystem respiration indicated the Waikato River had mostly healthy to satisfactory ecosystem health, based on the balance of processes affecting dissolved oxygen levels. A comparison to rates measured in April 2008 suggested temporal variation in ecosystem metabolism unrelated to expected seasonal trends.

An earlier study had identified a potential downstream response in functional indicators correlated with disturbance intensity. To test this hypothesis, ecosystem metabolism was measured above and at three sites at increasing distances below a thermal discharge at Huntly power station and a sewerage treatment point discharge at Pukete in April 2009. Results were inconclusive due to high ecosystem metabolism rates above Pukete sewerage treatment plant and suppressed rates above and below the Huntly power station. This suggests a one-off measure of metabolism is insufficient to assess the effects of these point-source discharges on river function. However, organic matter processing was estimated at each site using a cotton strip assay which involved the deployment of cotton over seven days. Cotton decay rates clearly showed accelerated organic matter processing below Pukete compared to above and suppressed organic matter processing below Huntly compared to above.

Spatial variation in the ecological function of large rivers throughout the Waikato region was examined in a survey of 10 randomly selected sites, including reaches of the Waipa, Puniu, Waitoa, Tongariro, Mokau and Waikato rivers in December 2008. There was a wide range in ecosystem metabolism values for the 10 river reaches, indicative of 'healthy' to 'poor' conditions based on reference values from national and international datasets. There was no apparent relationship between rates of ecosystem metabolism and catchment land-use. However, significantly greater cotton decay rates were observed in reaches with catchments containing less than 50% native vegetation cover, compared to lower rates at sites with more than 60% native vegetation cover.

The three surveys of ecosystem function in Waikato rivers, as well as an earlier survey in April 2008, show that ecosystem metabolism can be highly spatially and temporally diverse and more temporal sampling is probably necessary to consistently relate measures to impacts. By contrast, measures of organic matter processing consistently correlate to point-source and catchment-scale impacts and may provide a simple assessment of ecosystem function in non-wadeable streams.

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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 & Collier 2009). Functional indicators measure the rates of ecological processes (*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). Promising functional indicators include rates of organic matter decomposition and ecosystem metabolism.

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. This project is intended to widen our knowledge of the potential application of these methods in the Waikato River and other non-wadeable rivers around the region, and test their applicability for measuring the functional effects of point-source discharges.

Research carried out in collaboration with the University of Waikato and Environment Waikato has highlighted that metabolism and decomposition rates can vary down the Waikato River and other large rivers, suggesting that functional indicators may be useful for monitoring their ecological health (Young & Collier 2006; Clapcott & Young 2008; Collier *et al.* 2009). It was recommended that further assessment above, and at varying distances below, selected discharges in the Waikato River be carried out to test whether these indicators were discriminating the effects of point-source inputs (Clapcott & Young 2008). This work was carried out in 2009 and a wider range of non-wadeable sites was sampled in late 2008 to test the utility of cellulose breakdown and metabolism as regional indicators of river health.

This report provides the results of measuring organic matter processing via a cotton strip assay and ecosystem metabolism during three sampling events of Waikato River in October 2008 and April 2009, and rivers of the Waikato region in December 2008. The objectives of sampling were to (i) test the effectiveness of ecological health indicators (cellulose decomposition, metabolism) at detecting differences between and within impacted reaches of the Waikato River, and (ii) examine broad-scale spatial variability in functional indicators within a representative selection of the region's non-wadeable rivers.

2. METHODS

2.1. Study area

Six sites were selected as part of a larger study in April 2008 investigating the spatial variability in a range of biotic indices in Waikato River (Figure 1). These sites were revisited in October 2008 to investigate temporal variability between the two sample times. Sites were originally chosen to represent an increasing gradient of stress down river, within each reach, from the progressive or sequential input of potential contaminants (Table 1).

Results from the April 2008 study suggested distinct downstream trends in ecosystem function related to reach-scale impacts (Clapcott & Young 2008) and so an additional eight sites were sampled in December 2008 to investigate the influence of point-source impacts. One site above and three sites at varying distances below the Huntly power station were sampled, and one site above and three sites below the Pukete sewerage treatment plant were sampled (Table 2). Furthermore, in April 2009 10 additional randomly selected sites on non-wadeable rivers throughout the Waikato region were sampled, to investigate broad-scale spatial variability in the ecosystem function of Waikato rivers (Figure 1; Table 3). The random site selection process resulted in three sites in close proximity on the upper Waikato River (Figure 1: Sites 1a, 16, 17).

Table 1. Description of the six sites on the Waikato River sampled in April and October 2008.

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
% 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 in April (m)	3.5	3.6	2.1	3.4	2.4	2.4
Mean depth in October (m)	5.7	5.0	4.2	5.5	4.0	4.3

[*data from the Water bodies of National Importance dataset; catchment area above the site]

Table 2. Description of study sites above and below point-source impacts on the Waikato River sampled in April 2009.

Site	Thermal above	T Below 1	T Below 2	T Below 3
Location	E2700642 N6404028	E2700608 N6404747	E2700965 N6406614	E2700636 N6409207
Distance below (km)	0	0.75	2.75	5.4
% Impervious cover*	8.0	8.0	3.5	3.5
% Native vegetation*	20.3	20.3	32.2	32.2
Mean depth (m)	1.58	1.46	2.30	1.70
Site	**Sewerage above**	**S Below 1**	**S Below 2**	**S Below 3**
Location	E2707328 N6382979	E2707091 N6383396	E2706839 N6383821	E2706002 N6384969
Distance below (km)	0	0.5	1.0	2.5
% Impervious cover*	3.5	3.5	3.5	3.5
% Native vegetation*	38.8	38.8	38.8	38.8
Mean depth (m)	2.89	2.94	4.92	4.21

[*data from the Water bodies of National Importance dataset; catchment area above the site]

Table 3. Description of additional 10 study sites through out the Waikato region sampled in December 2008.

Site	Waitoa10	Waikato1a	Waikato17	Waikato16	Waikato12
Location	E2743734 N6400397	E2795036 N6283842	E2797278 N6289187	E2798746 N6292458	E2691134 N6434402
% Impervious cover*	4.1	2.1	2.1	2.1	3.4
% Native vegetation*	3.5	65.7	64.4	64.1	30.2
Mean depth (m)	0.55	3.97	3.44	3.64	3.72
Site	**Waipa14**	**Waipa15**	**Puniu11**	**Mokau13**	**Tongariro5**
Location	E2699162 N6376824	E2705113 N6331800	E2716807 N6345463	E2676478 N6287591	E2752515 N6244934
% Impervious cover*	3.0	1.7	2.1	2.4	1.2
% Native vegetation*	18.9	41.4	18.5	16.9	84.8
Mean depth (m)	3.70	0.90	1.64	1.12	2.59

[*data from the Water bodies of National Importance dataset; catchment area above the site]

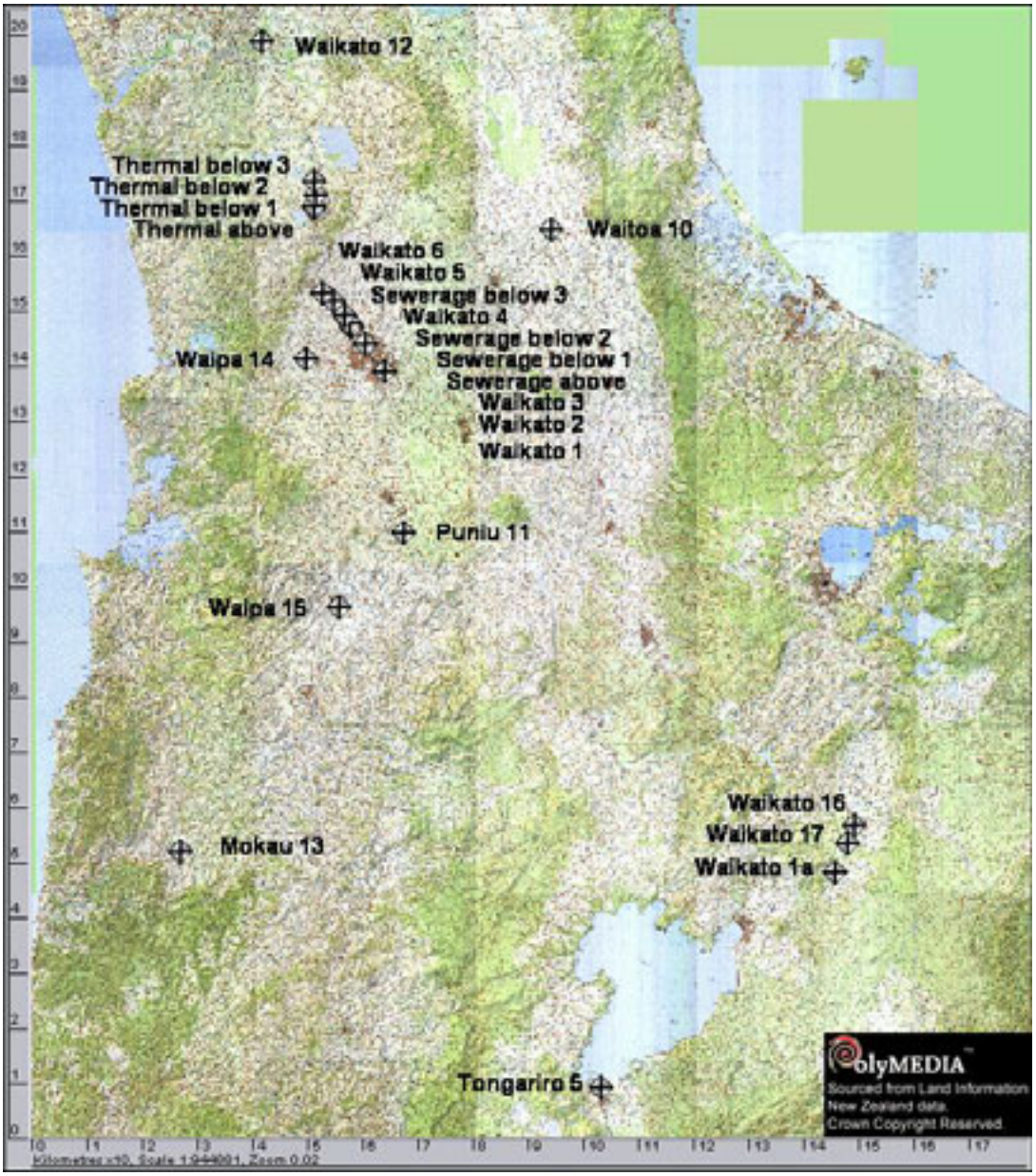

Figure 1. Map showing sites sampled in the Waikato region in 2008 to 2009 for assessing ecosystem function.

2.2. Cellulose decomposition potential

A cotton strip assay was used to assess the ability of a lotic ecosystem to process organic matter (Young 2006; Tiegs *et al.* 2007). At each site, five cotton strip replicates were attached to a 10 m metal chain that was deployed along the stream bed from the wetted edge. Cotton was retrieved after seven 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 (~32 mm) 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 & 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 & 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. Data loggers were deployed for a minimum of 24 hours.

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 & Knight (2005). This model uses the following approach to calculate metabolism values. Mean daily ecosystem respiration (ER) and the reaeration coefficient (k) were determined using the night-time regression method (Owens 1974), which uses only data collected in the dark (<2 µmol m^{-2} s^{-1}). 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 (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 (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:

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

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 (Phinney & McIntire 1965) while the reaeration rate is assumed to increase by 2.41% per degree (Kilpatrick *et al.* 1989). Daily gross primary production (GPP, g O_2 m^{-3} 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. An estimate of average river depth was calculated from five depth measurements using a hand-held depth sounder (Speedtech Depthmate) across the river at each of five transects upstream of 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 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-Table 3). A temperature logger (HOBO, Onset Solutions Ltd) was deployed alongside the cotton strips for seven days at each location. From this data, the daily minimum, maximum and range were ascertained and degree 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. 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 time. Downstream trends in variables were examined using simple linear regression, which was also used to investigate relationships between metabolic and environmental variables. Student's *t*-tests were used to test for differences between upstream and downstream reaches. Where there was a significant difference in variance between treatments, the *t*-test statistics using unequal variances are reported. All diagnostics were checked according to Quinn & Keough (2002), and all analyses were carried out in SYSTAT Version10 (SPSS 2000).

3. RESULTS AND DISCUSSION

3.1. Six sites on the Waikato River

3.1.1. Cellulose decomposition potential

Rates of cotton decay ranged from 0.009 k day^{-1} to 0.074 k day^{-1} (Figure 2) and correspond to loss of tensile strength of 5.98% to 40.43% over the duration of deployment. On average, rates of decomposition in October 2008 were significantly less than rates observed at far-shore sites (*i.e.* farthest from the wetted edge) in April 2008 ($t_{(1, 58)} = 7.869$, $p < 0.001$). However, the same downstream trends observed in April 2008 were also observed in October 2008, with a linear trend for increasing cotton decay downstream from Site 1 to Site 6 ($r^2 = 0.26$, $F_{(1, 58)} = 20.279$, $p < 0.001$) and when grouped, significantly greater cotton decay in the downstream (Sites 4-6) compared to the upstream (Sites 1-3) reach ($t_{(1, 58)} = -4.814$, $p < 0.001$).

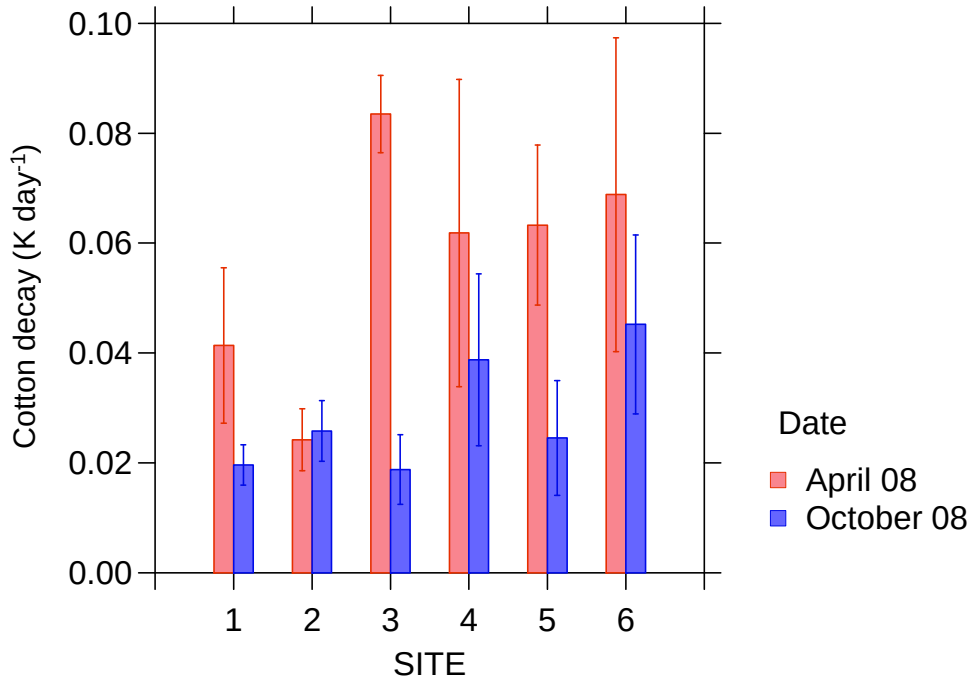

Figure 2. Mean and standard deviation of decay coefficients per day for cotton strips from six sites on the Waikato River in April 2008 and October 2008. Sites labelled upstream to downstream.

The average water temperature in April 2008 was 3.5°C greater than in October 2008 and this may have contributed in part to the greater rates of cotton decay. However, analysis of decay coefficients corrected for degree days (Figure 3) clearly shows the same trends observed when data are expressed per day and illustrates the likelihood that additional factors are contributing to the higher rates of cotton decomposition observed in April 2008. These additional factors

may include lower water levels (average river depth in April 2008 was 2.89 m compared to 4.76 m in October 2008), sustained low flows, and nutrient availability.

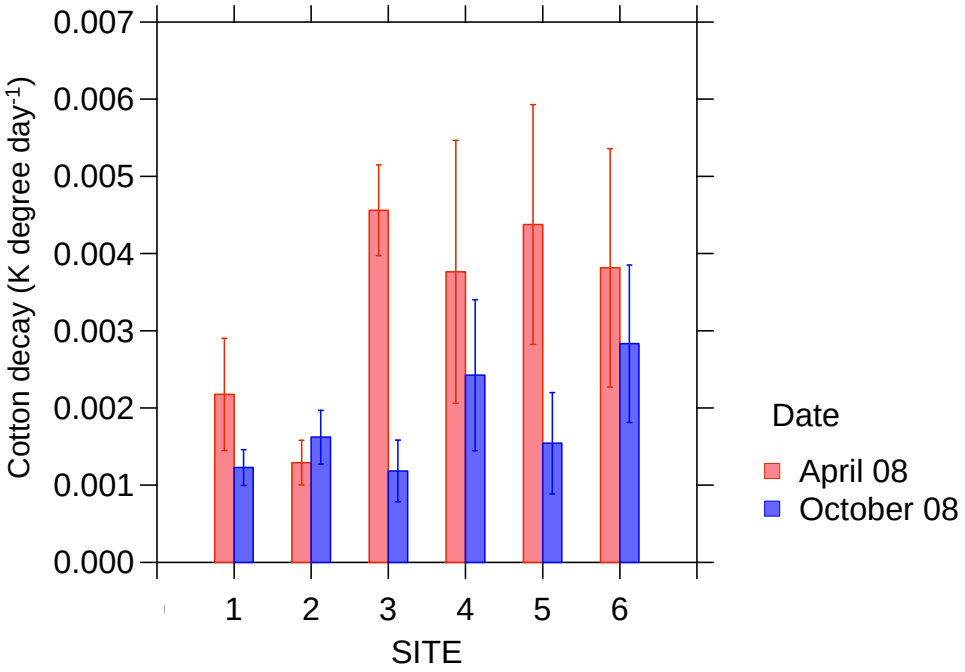

Figure 3. Mean and standard deviation of decay coefficients per degree day for cotton strips from six sites on the Waikato River in April 2008 and October 2008. Sites labelled upstream to downstream.

3.1.2. Ecosystem metabolism

In October 2008, dissolved oxygen concentrations ranged from 96-109% saturation during the 24 hours each site was surveyed (Figure 4). As is typically the case, minimum dissolved oxygen concentrations occurred just before dawn and maximum dissolved oxygen concentrations occurred in the mid/late afternoon. However, at Site 2, dissolved oxygen concentrations did not fall below 100% during the night (Figure 4). This is likely to illustrate a calibration error. To account for this, data were corrected from Site 2 by multiplying by 0.9 before metabolism values were calculated. This correction factor was the minimum amount required to ensure dissolved oxygen concentration fell below 100% saturation at night.

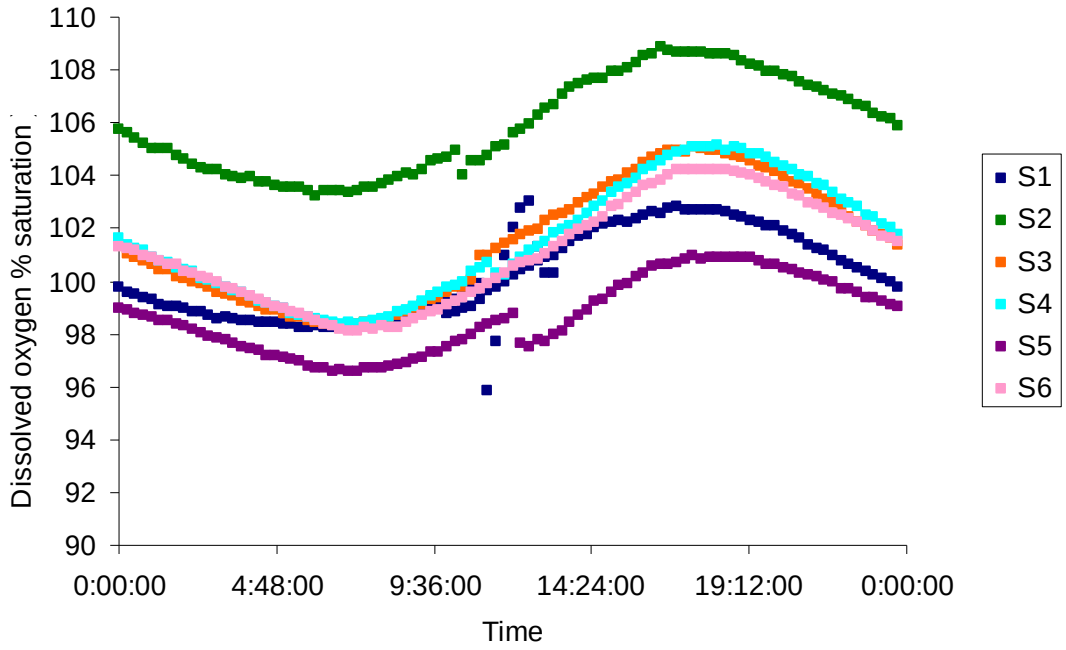

Figure 4. Diel changes in dissolved oxygen at each of the sites on the Waikato River sampled in October 2008.

Rates of gross primary productivity (GPP) ranged from 2.82 g O_2 m^{-2} day^{-1} to 7.84 g O_2 m^{-2} day^{-1} (Figure 5), with the highest values recorded at Site 4. Rates of GPP at all sites reflect 'healthy' to 'satisfactory' conditions according to the criteria of Young *et al.* (2008) and are within the range of values observed in large rivers overseas (Uehlinger 2006; Gawne *et al.* 2007). Unlike April 2008, the general downstream trend in rates of GPP was not significant, mainly due to the high GPP observed at Site 4. Similarly, a Student's *t*-test indicated no difference in rates of GPP between upstream (Sites 1-3) and downstream (Sites 4-6) reaches in October 2008. However, the relationship between distance to an urban confluence or point-source discharge observed in April was apparent as a weak correlation in October (Pearson's correlation: $R = 0.59$, $p = 0.2$).

Three sites (Sites 2, 3, 4) had higher rates of GPP in October compared to April, whereas three sites (Sites 1, 5, 6) had lower rates of GPP in October; consequently there was no significant overall difference between April and October 2008 rates of gross primary productivity.

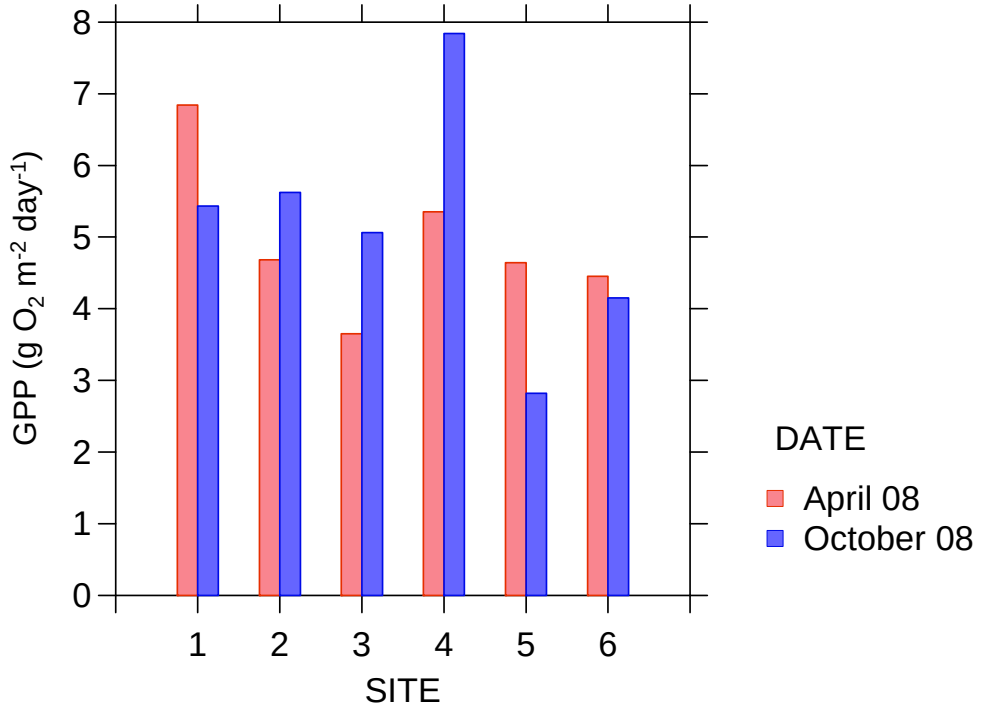

Figure 5. Rates of gross primary productivity (GPP) measured in April and October 2008 at six sites on the Waikato River. Sites labelled upstream to downstream.

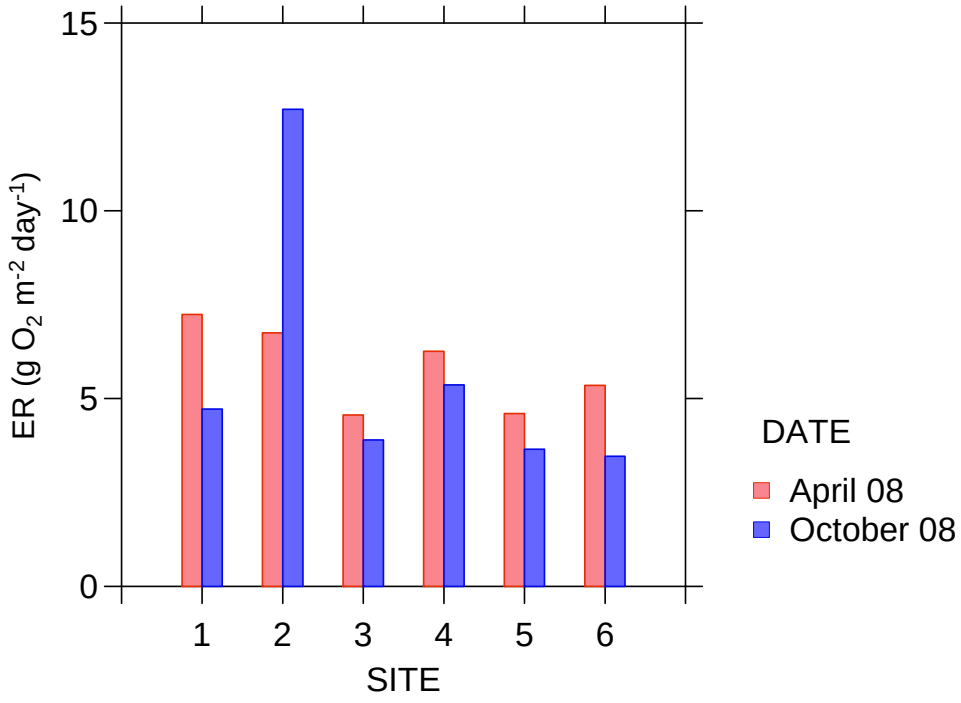

Figure 6. Rates of ecosystem respiration (ER) measured in April and October 2008 at six sites on the Waikato River. Sites labelled upstream to downstream.

Rates of ecosystem respiration (ER) ranged from 3.46 g O_2 m^{-2} day^{-1} to 12.70 g O_2 m^{-2} day^{-1} (Figure 6). Ecosystem respiration was greatest at Site 2 and indicative of poor ecosystem health according to the criteria of Young *et al.* (2008). Despite this, there was a weak trend of decreasing ER downstream (R^2 = 0.48; $F_{(1, 5)}$ = 1.22, p = 0.3), but there was no significant difference between upstream and downstream reaches. Similar to GPP, there was a weak correlation between ER and the downstream distance to an urban confluence or point-source impact (Pearson's correlation: R = 0.59, p = 0.2).

All sites had lower rates of ER in October compared to April, except Site 2 where ER was substantially higher in October. Subsequently, there was no significant difference between April and October 2008 rates of ecosystem respiration.

The ratio of gross primary productivity to ecosystem respiration (P/R) ranged from 0.44 to 1.46 (Figure 7). According to the criteria of Young *et al*. (2008), all sites showed healthy P/R ratios, except Site 2 which indicated satisfactory rates. Four out of six sites displayed net autotrophy, which suggested in-stream productivity was stimulated during October. This is surprising because large rivers are expected to be heterotrophic (Vannote *et al.* 1980). Furthermore, we would expect primary productivity to contribute a greater amount to metabolism in April when days are longer, temperatures are higher (average 7-day temperature = 19.32 °C) and flows are lower (average reach depth = 2.81 m) and more stable, compared to October when temperature are lower (average 7-day temperature = 15.94 °C) and flows are higher (average reach depth = 4.79 m) and more subject to floods and freshes. It is possible that ER is more sensitive than GPP to changes in temperature and flow, and this is reflected in higher rates of ER relative to GPP in April. In April 2008 all sites displayed net heterotrophy. These results highlight the potential temporal variability between autochthonous and allochthonous contributions to river processes, as demonstrated in other systems (Young & Huryn 1996; Chester & Norris 2006; Uehlinger 2006; Clapcott & Barmuta In press). The results also illustrate the need for more regular temporal assessments of in-stream metabolism to fully understand the temporal variability of this in-stream process, in relation to flow as well as season.

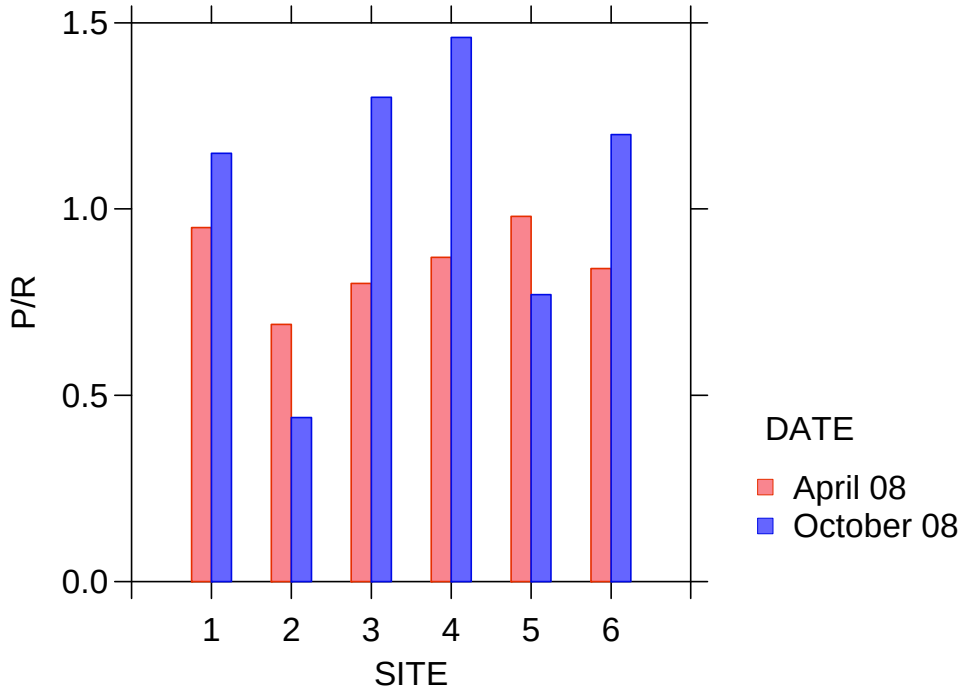

Figure 7. The ratio (P/R) of gross primary productivity to ecosystem respiration measured in April and October 2008 at six sites on the Waikato River. April rates are an average of four readings, where available. Sites labelled upstream to downstream.

3.2. The effect of point-source impacts

3.2.1. Cellulose decomposition potential

Organic matter processing rates ranged from 0.008 k day^{-1} to 0.142 k day^{-1} at sites sampled in April 2009 above and below point-source impacts (Figure 8). There were significantly greater rates of cotton decay above the thermal impact compared to below ($t_{(1, 38)} = 5.76$, $p < 0.001$) and there were significantly greater rates of cotton decay below the sewerage impact compared to above ($t_{(1, 35)} = 3.11$, $p = 0.008$). There was no significant relationship between cotton decay and the distance downstream of either point-source impact.

Surprisingly, there was a negative correlation between cotton decay rates and average water temperature during incubation (Pearson's correlation: $R = -0.40$, $p < 0.001$), driven primarily by high decay rates associated with low temperatures above the thermal impact and low decay rates associated with high temperatures above the sewerage impact, respectively. Patterns in decay rates when examined in k degree day^{-1} (*i.e.* standardised by temperature) were the same as that observed for k day^{-1}.

The results suggest organic matter processing rates are significantly affected by both thermal and nutrient point-source impacts. Previous studies have observed similar findings with accelerated organic matter processing rates associated with increased nutrient concentrations.

However, high rates are usually associated with higher temperatures and conversely, low rates associated with lower temperatures (for review see Young *et al.* 2008).

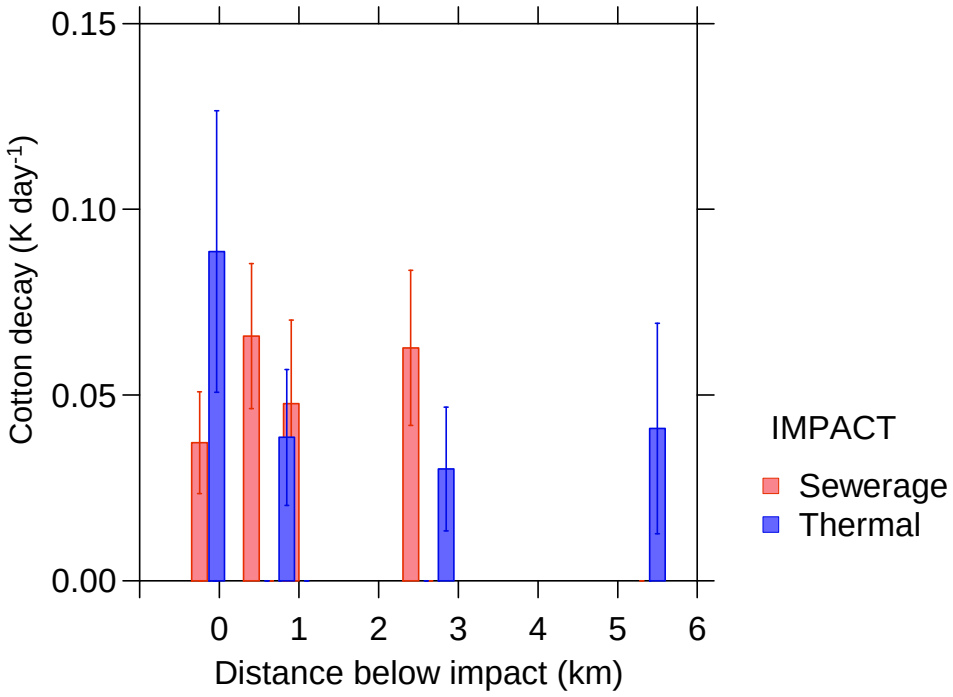

Figure 8. Decay coefficients for cotton strips measured in April 2009 at eight sites on the Waikato River above and below point-source impacts.

3.2.2. Ecosystem metabolism

Dissolved oxygen concentrations ranged from 94-107% saturation in sites related to the thermal discharge and from 93-105% saturation in sites related to the sewerage discharge. On average, there was a much wider daily range in saturation values at sewerage sites (7.7%) compared to thermal sites (4.5%) and thermal sites maintained higher values of saturation throughout the day (Figure 9). In particular, Site 1 and Site 2 below the thermal discharge maintained levels of dissolved oxygen above or close to 100% saturation throughout the day. This may illustrate a calibration error, or it may illustrate the effect of elevated temperatures (sites below the thermal discharge were between 1.5 and 3 degrees C greater than above). These values were corrected by multiplying by 0.9 and 0.95 respectively, to allow for the calculation of metabolism. An unusual rise in saturation during the night time was evident at the site above the sewerage discharge. There was no way to 'correct' these values, but it is likely to contribute to the high rates of metabolism observed at this site.

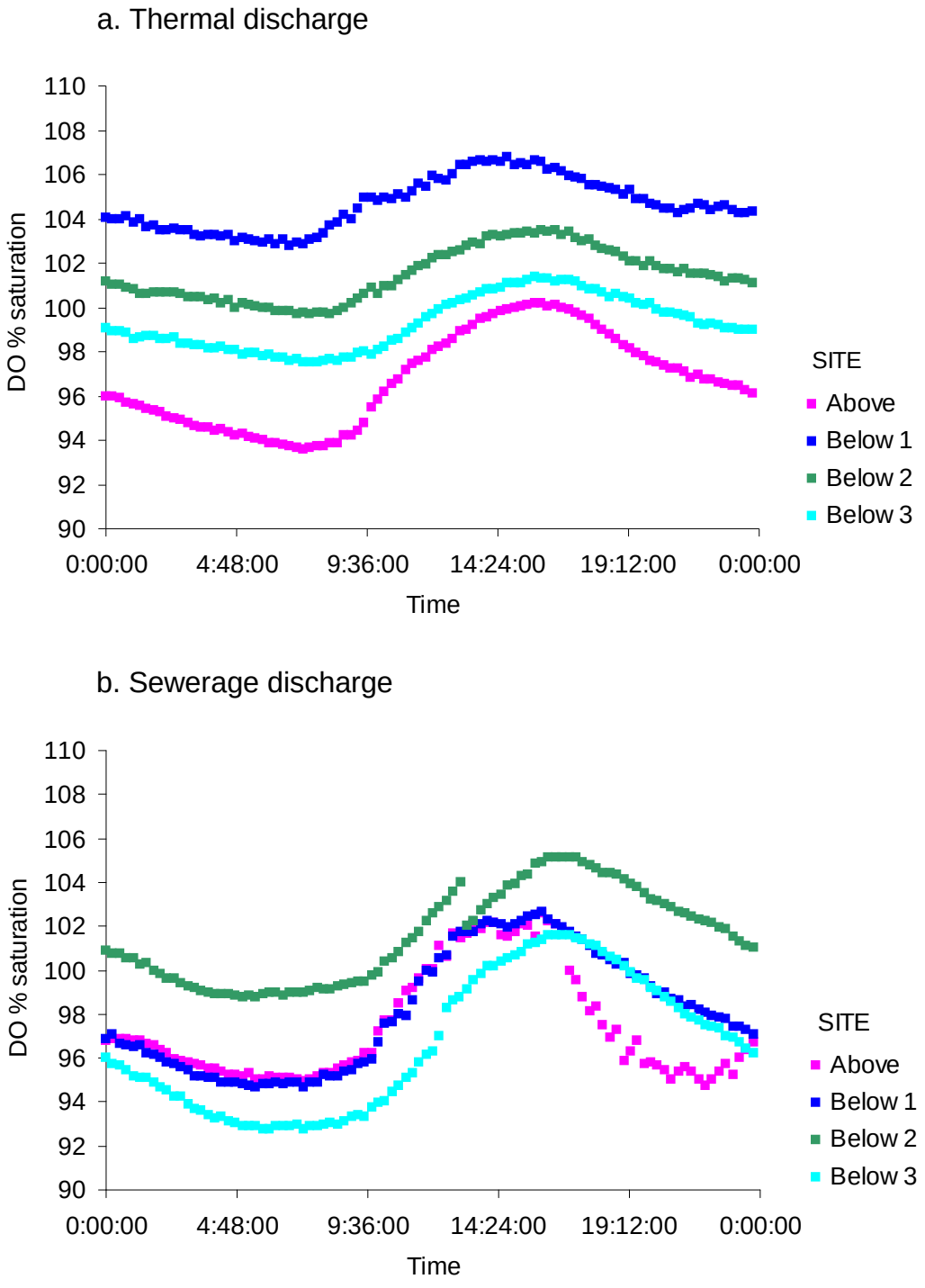

Figure 9. Diel changes in dissolved oxygen at each of the sites above and below point-source impact measured in April 2009, a. thermal discharge from Huntly power station, and b. sewerage discharge from Pukete sewerage treatment plant.

Rates of gross primary productivity (GPP) ranged from 0.42 g O_2 m^{-2} day^{-1} to 1.61 g O_2 m^{-2} day^{-1} above and below a thermal point-source impact in the Waikato River (Figure 10). Rates of gross primary productivity (GPP) ranged from 3.07 g O_2 m^{-2} day^{-1} to 9.25 g O_2 m^{-2} day^{-1} above and below a sewerage point-source impact in the Waikato River (Figure 10), with the highest values observed above the impact. There was no apparent downstream trend in rates of GPP below the point-source impacts.

In comparison, rates of ecosystem respiration (ER) ranged from 1.02 g O_2 m^{-2} day^{-1} to 13.94 g O_2 m^{-2} day^{-1} above and below a thermal point-source impact, and from 4.42 g O_2 m^{-2} day^{-1} to 20.57 g O_2 m^{-2} day^{-1} above and below a sewerage point-source impact in the Waikato River (Figure 11). The highest rate of ER was observed above the sewerage treatment plant suggesting this site is subject to some other environmental factors supporting high metabolic rates. There was no apparent trend in rates of ER below the sewerage discharge. At the two sites immediately below the thermal discharge very high rates of ER were observed suggesting 'poor' ecosystem health according to the criteria of Young *et al.* (2008).

The influence of point-source impacts on downstream metabolism was most evident in the ratio of gross primary production to ecosystem respiration (P/R) (Figure 12). Whilst no general downstream trend was evident, P/R indicated increased autotrophy (more productivity) below the sewerage impact compared to above and enhanced heterotrophy (more respiration) below the thermal impact compared to above.

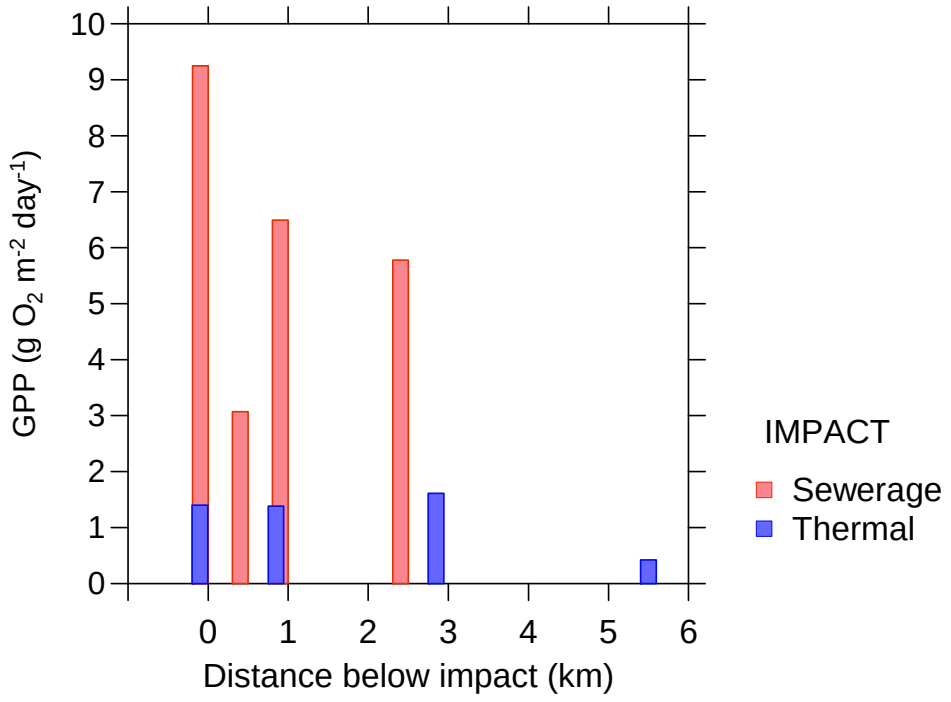

Figure 10. Rates of gross primary productivity (GPP) measured in April 2009 at eight sites on the Waikato River above and below point-source impacts.

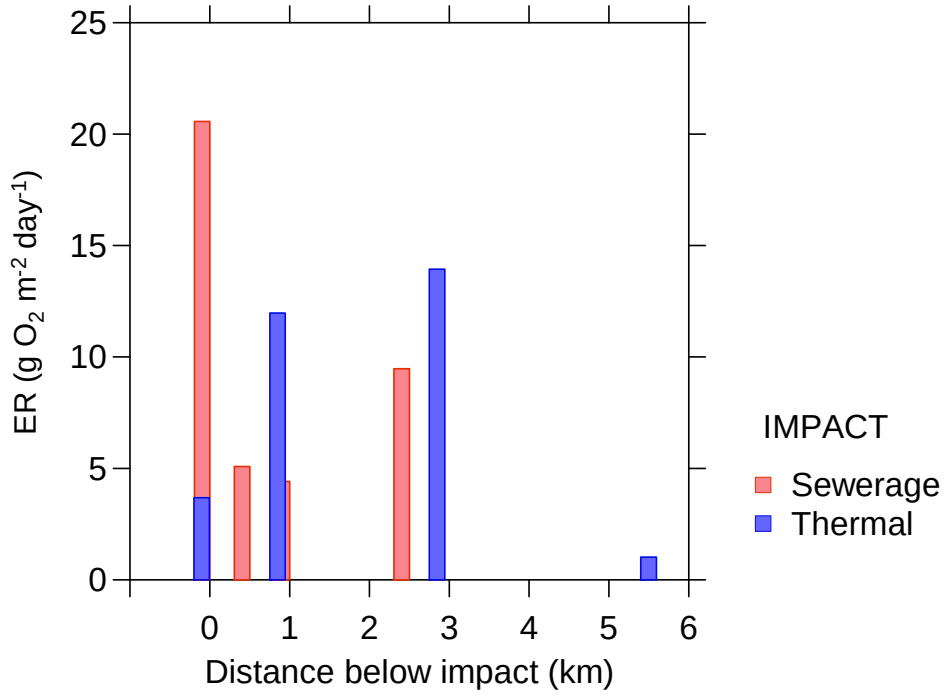

Figure 11. Rates of ecosystem respiration (ER) measured in April 2009 at eight sites on the Waikato River above and below point-source impacts.

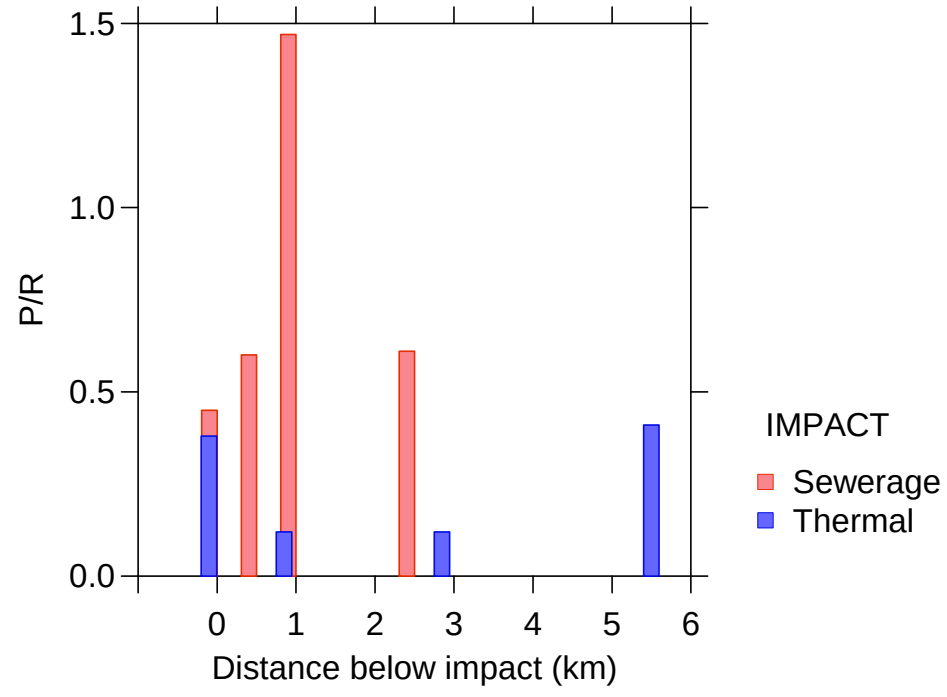

Figure 12. The ratio of gross primary productivity to ecosystem respiration (P/R) measured in April 2009 at eight sites on the Waikato River above and below point-source impacts.

3.3. Broad spatial trends in ecosystem function in Waikato rivers

3.3.1. Cellulose decomposition potential

Organic matter processing rates ranged from <0.001 k day^{-1} to 0.376 k day^{-1} in 10 rivers surveyed in the Waikato region in December 2008 (Figure 13). There was a negative linear relationship between cotton decay rates and native vegetation cover in the catchment upstream ($F_{(1, 116)} = 76.4$, $p < 0.001$). However, residual diagnostics showed a significant increase in variance associated with lower levels of vegetation cover. A Student's t-test with unequal variances confirmed a significant difference between cotton decay rates at sites with <50% native cover and sites with >60% native cover ($t_{(1, 71)} = 7.76$, p <0.001), although it should be noted that this relationship is influenced by three sites with similar catchment attributes on the upper Waikato River. There was also a negative linear relationship between cotton decay rates and increasing impervious cover in the catchment ($F_{(1, 116)} = 42.4$, p <0.001), with equal variances. There was no relationship between cotton decay rate and average water temperature and similarly a strong correlation ($R = 0.998$, $p < 0.001$) between k day^{-1} and k degree day^{-1}.

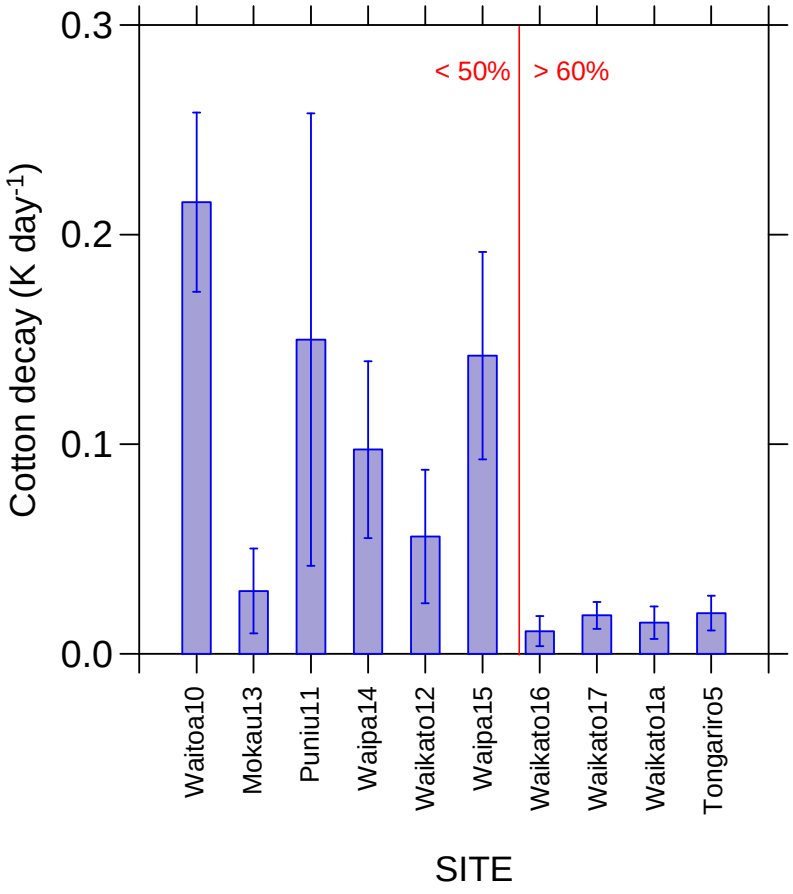

Figure 13. Mean and standard deviations of decay coefficients for cotton strips measured in December 2008 at ten sites in the Waikato region. Sites are ordered by the percent of native vegetation in the catchment and separated by a red line into groups with less than 50% or greater than 60% native vegetation cover.

3.3.2. Ecosystem metabolism

Dissolved oxygen concentrations measured in December 2008 ranged from 85-131% saturation at 10 sites in the Waikato region. There was a wide range in diel variation among sites from only 2.1% at Waipa14 to 22.6% at Mokau13. Dissolved oxygen values did not fall below 100% for Waikato16 and Waikato17 and these data were corrected by multiplying by 0.9 and 0.8 respectively.

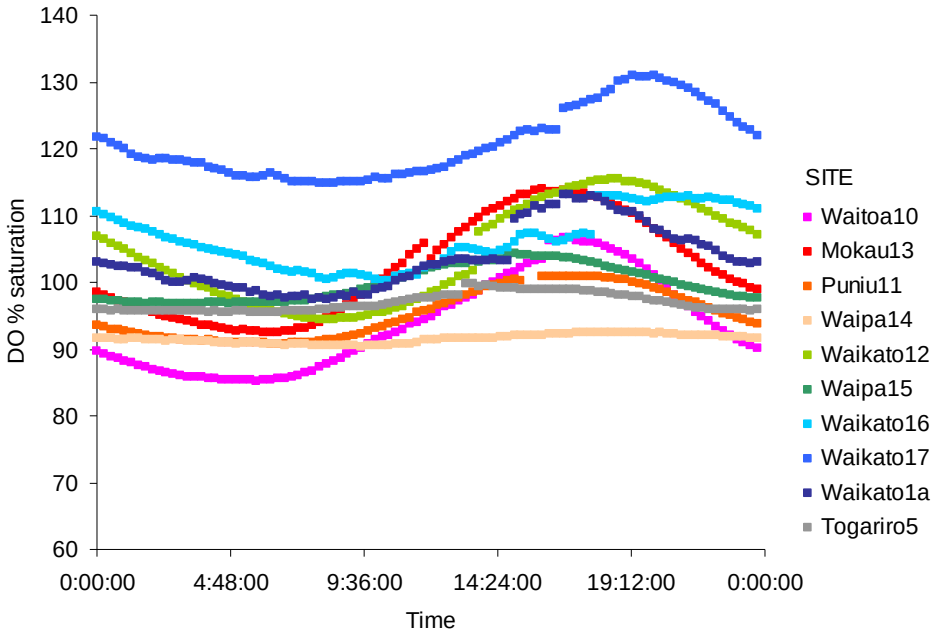

Figure 14. Diel changes in dissolved oxygen concentration measured in December 2008 at ten sites in the Waikato region.

Rates of gross primary productivity (GPP) ranged from 0.54 g O_2 m^{-2} day^{-1} to 10.91 g O_2 m^{-2} day^{-1} at the 10 sites measured in December 2008 (Figure 15). Rates of GPP >8 g O_2 m^{-2} day^{-1} at Waikato12 and Waikato17 sites were indicative of poor ecosystem health according to the criteria of Young *et al*. (2008). There was no significant relationship between rates of GPP and the percent of native vegetation in the catchment, as has been observed in smaller rivers elsewhere in New Zealand (Clapcott *et al.* In review).

Rates of ecosystem respiration (ER) ranged from 1.32 g O_2 m^{-2} day^{-1} to 15.73 g O_2 m^{-2} day^{-1} at the 10 sites measured in December 2008 (Figure 16). Four sites had rates of ER greater than 10 g O_2 m^{-2} day^{-1}, indicative of poor ecosystem health (Figure 16). As with GPP, there was no significant relationship between rates of ER and the percent of native vegetation in the catchment. It is possible that local (*i.e.* reach-scale) environmental variation and point-source impacts are more influential than, or confound the effects of, catchment land-use in shaping ecosystem metabolism in these rivers.

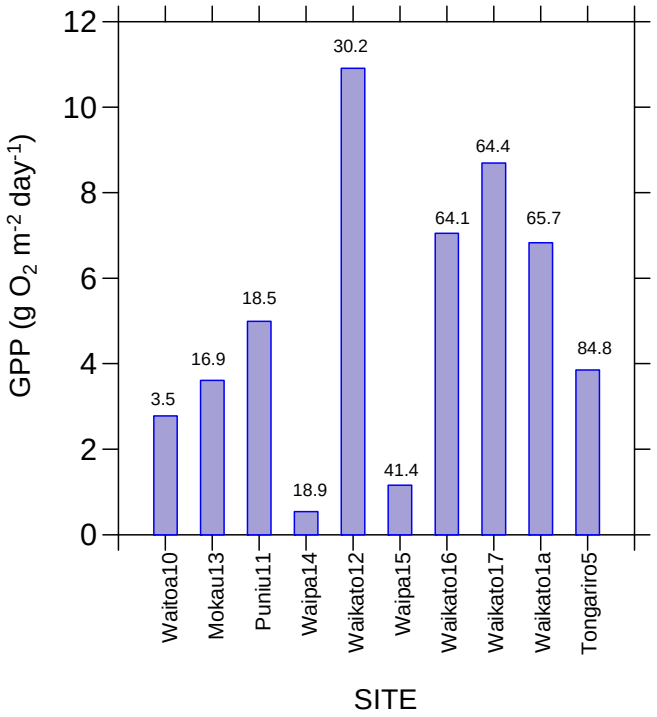

Figure 15. Rates of gross primary productivity (GPP) measured in December 2008 at ten sites in the Waikato region. Sites are ordered by the percent of native vegetation in the catchment and these values are noted above the bars.

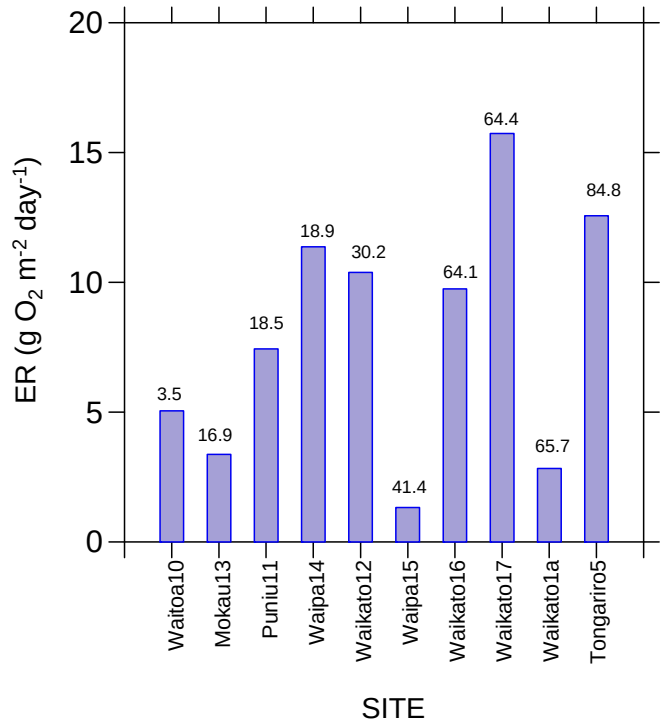

Figure 16. Rates of ecosystem respiration (ER) measured in December 2008 at ten sites in the Waikato region. Sites are ordered by the percent of native vegetation in the catchment and these values are noted above the bars.

The ratio of gross primary productivity to ecosystem respiration (P/R) ranged from 0.05 to 2.42, suggesting a wide range in energy sources fuel the metabolism at the 10 sites sampled in the Waikato region in December 2008 (Figure 17). Significant autotrophic conditions were observed at site Waikato 1a. This is not unusual given that this site is the closest to the outlet of Lake Taupo and similarly high P/R ratios have been observed at other lake outlets (Author's unpublished data).

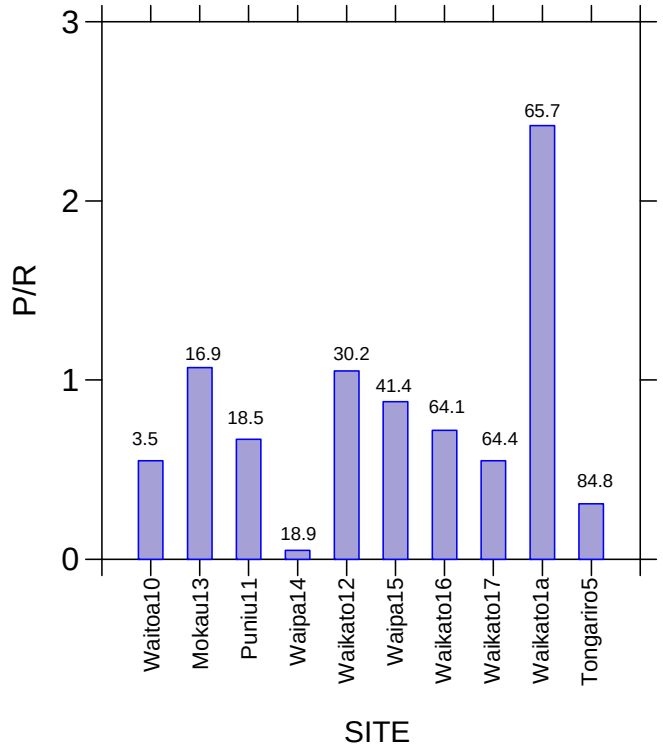

Figure 17. The ratio of gross primary productivity to ecosystem respiration (P/R) measured in December 2008 at ten sites in the Waikato region. Sites are ordered by the percent of native vegetation in the catchment and these values are noted above the bars.

4. SUMMARY

Estimates of ecosystem metabolism were more variable throughout the 21 km of the Waikato River surveyed in October compared to April 2008. In particular, two sites showed extremely high rates of ecosystem respiration and gross primary productivity, respectively. However, there is limited confidence in the results from Site 2 because these data required correction of dissolved oxygen percent saturation and there is no way of knowing whether data was under- or over-corrected. Consequent high rates of ecosystem metabolism meant that the weak downstream trend of decreasing productivity and respiration observed in April was not evident in October, although the relationship between distance from a point-source impact and rates of ecosystem metabolism was still suggested by a weak correlation. This consistent pattern in

both April and October suggests that the methodology may be sensitive to detecting effects from point-source impacts. Unfortunately the upstream-downstream surveys in April 2009 did not support the earlier observations because of unexpected high rates above Pukete sewerage treatment plant and suppressed rates above Huntly power station. Combined, these results suggest greater temporal sampling is necessary to confirm the effect of point-source impacts on river metabolism and to confirm that estimates of ecosystem metabolism are a suitable tool for assessing the effects of point-source impacts on the function of large rivers.

The range of metabolic rates observed at 10 sites in large rivers throughout the Waikato region suggested rivers ranged in their ecosystem health, with eight out of 10 sites showing healthy to satisfactory rates in December 2008.

Cotton decay coefficients showed consistently in April and October 2008 an increase in decomposition potential associated with increasing downstream stressors. The results of the cotton strip assay also showed that point-source impacts affect the organic matter processing of large rivers. Higher processing rates were observed below Pukete, presumably associated with higher nutrient loads. Lower processing rates were observed below Huntly despite sites below Huntly having greater average temperatures.

Similarly, rates of organic matter processing were related to catchment-scale measures of land use in the survey of 10 randomly selected large river sites throughout the Waikato region. These findings are similar to those observed in recent national surveys and confirm the suitability of this measure to assess the effects of both reach-scale and catchment-scale impacts on river function. Cotton strip assays have the advantage of incorporating a longer temporal response to disturbance than one-off measures. Similar confidence may be gained in ecosystem metabolism measures, if data are collected for a longer temporal sequence, *i.e.* at least seven days.

5. RECOMMENDATIONS

1. Consider using a cotton strip assay as a regular State of the Environment monitoring tool for assessing the ecosystem function in large rivers. If so, include sampling at a regional reference site(s); by necessity this may be defined as ‘best available condition’.
2. Deploy and maintain (including regular calibration protocols) permanent dissolved oxygen loggers in some large river sites to better assess the temporal variability in the ecosystem metabolism of large rivers. Use intermittent dual deployments or spot measures to validate dissolved oxygen concentrations.
3. Consider re-examining the effects of point-source impacts on ecosystem metabolism using longer temporal deployments. The current open-system single-station methodology does not appear suitable for sites where the thermal regime significantly affects dissolved oxygen concentrations *e.g.* Huntly power station, dairy condensation

plants, immediately downstream of air-conditioning outflows. In these situations, a two-station approach may be more suitable for assessing the effects of point-source impacts.

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7. APPENDIX

Appendix 1. Daily metabolism estimates from sites on rivers in the Waikato region. 'Corrected' refers to whether DO data needed to be corrected before metabolism calculation – see methods section; 'k data' refers to the number of data points used in the calculation of the reaeration coefficient (k); 'R2' is the strength of the regression equation used to calculate k.

Site	Date	Depth	ER	GPP	PR	k	k data	*R*2	Corrected
Waikato 1	04/04/2008	3.45	-7.24	6.84	0.95	2.31	45	0.67	No
Waikato 2	04/04/2008	3.65	-6.75	4.68	0.69	1.56	51	0.75	No
Waikato 3	04/04/2008	2.05	-4.56	3.65	0.80	1.95	49	0.77	No
Waikato 4	04/04/2008	3.38	-6.26	5.35	0.87	1.80	48	0.80	No
Waikato 5	04/04/2008	2.41	-4.60	4.64	0.98	1.82	44	0.84	No
Waikato 6	04/04/2008	2.38	-5.35	4.45	0.84	1.22	48	0.64	No
Waikato 1	30/10/2008	5.70	-4.72	5.43	1.15	3.39	41	0.85	No
Waikato 2	30/10/2008	4.96	-12.70	5.62	0.44	3.19	31	0.74	-10%
Waikato 3	30/10/2008	4.17	-3.90	5.06	1.3	2.42	34	0.89	No
Waikato 4	30/10/2008	5.51	-5.36	7.84	1.46	2.45	35	0.83	No
Waikato 5	30/10/2008	3.96	-3.65	2.82	0.77	2.80	15	0.66	No
Waikato 6	30/10/2008	4.27	-3.46	4.15	1.20	1.54	19	0.57	No
Thermal A	22/04/2009	1.58	-3.69	1.40	0.38	5.82	17	0.89	No
Thermal B1	22/04/2009	1.46	-11.97	1.38	0.12	15.91	11	0.92	-10%
Thermal B2	22/04/2009	2.30	-13.94	1.61	0.12	18.84	30	0.96	-5%
Thermal B3	22/04/2009	1.70	-1.02	0.42	0.41	7.95	33	0.56	No
Sewerage A	23/04/2009	2.89	-20.57	9.25	0.45	13.88	19	0.99	No
Sewerage B1	23/04/2009	2.94	-5.08	3.07	0.60	2.66	28	0.70	No
Sewerage B2	23/04/2009	4.92	-4.42	6.49	1.47	2.05	39	0.48	No
Sewerage B3	23/04/2009	4.21	-9.47	5.78	0.61	1.97	45	0.63	No
Waikato 1a	08/12/2008	3.97	-2.83	6.83	2.42	3.55	50	0.41	No
Tongariro 5	08/12/2008	2.59	-12.56	3.85	0.31	10.30	15	0.67	No
Waitoa 10	10/12/2008	0.55	-5.05	2.78	0.55	6.72	38	0.98	No
Punui 11	04/12/2008	1.64	-7.43	4.99	0.67	4.87	19	0.96	No
Waikato 12	10/12/2008	3.72	-10.38	10.91	1.05	2.08	43	0.58	No
Mokau 13	05/12/2008	1.12	-3.37	3.61	1.07	4.01	39	0.96	No
Waipa 14	04/12/2008	3.70	-11.36	0.54	0.05	3.64	44	0.43	No
Waipa 15	04/12/2008	0.90	-1.32	1.16	0.88	8.48	31	0.97	No
Waikato 16	08/12/2008	3.64	-9.75	7.05	0.72	1.75	33	0.50	-10%
Waikato 17	08/12/2008	3.44	-15.73	8.69	0.55	6.66	40	0.75	-20%