Alum Dosing of two stream discharges to Lake Rotorua

Internal Report

February 2012

Bay of Plenty Regional Council
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Cover Photo:
Alum dosing tank and control facility, Rotorua District Council Wastewater Treatment Plant

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1 Introduction

The phosphorus load flowing into the Rotorua lakes is naturally high due to inputs from cold water springs which have high levels of phosphorus of geological origin. This is particularly true of Lake Rotorua where the groundwater discharged at the springs flows underground for decades and up to a century (Morgenstern *et al* 2004). Phosphorus is dissolved into water from the volcanic sediments and is generally higher in concentration as the age of the groundwater increases. Before the catchment was developed in modern times, the nitrogen load discharged to Lake Rotorua was very low and consequently lake algae would have tended to consume nitrogen to levels that strongly constrained growth, leaving phosphorus in excess. Nitrogen and phosphorus losses from the catchment have increased with urban and rural expansion. In recent times nitrogen and phosphorus have tended to be approximately in balance with respect to limits of algal growth and on rare occasions phosphorus has been consumed to extinction leaving excess nitrogen for short periods (Burger *et al* 2007).

In the 1960s, algal blooms began to occur in Lake Rotorua in summer as the bottom waters became anoxic and nitrogen and phosphorus were released into the lake. On these occasions the phosphorus supply can be in excess of algal requirements compared to the nitrogen supply. During summer and autumn, nuisance blooms of blue-green algae (cyanobacteria) are favoured under calm conditions, and these algae are well adapted to store phosphorus, particularly associated with periodic releases from bottom sediments. Some blue-green algae can also produce their own nitrogen supply by fixing atmospheric nitrogen which is at high levels dissolved within the water.

The Bay of Plenty Regional Council has statutory environmental bottom lines for the Rotorua lakes in the Water & Land Plan to ensure that nuisance blooms would only rarely occur. For Lake Rotorua the environmental bottom line is a Trophic Level Index (TLI) of 4.2. An Action Plan has been developed to reduce nitrogen and phosphorus inputs to Lake Rotorua to lower the TLI to 4.2, as it was in the 1960s.

Alum dosing of streams was identified as a method to reduce phosphorus loads to Rotorua lakes by water resource managers who attended the 2003 Rotorua Lakes Symposium of the Lakes Water Quality Society (Peters, 2003). A series of bench tests were commissioned (Browne *et al* 2004) by the Regional Council. A proposal to develop three alum dosing plants for inflows to Lake Rotorua was discussed with a working party and public consultation was carried out in obtaining resource consents. The first plant on the Utuhina Stream became operational in June 2006 and the second on the Puarenga in January 2010.

Dosing aluminium into the Utuhina Stream water at levels of 1 g Al/m^3 was found to reduce dissolved phosphorus to analytical detection limits. With operation of the Puarenga Stream alum dosing plant in 2010 the load of alum discharged to Lake Rotorua has approximately tripled. Compliance monitoring of the Puarenga Stream, Sulphur Bay and the adjacent Lake Rotorua water and lake monitoring results from the regional monitoring network began to show that the phosphorus abundance was steadily trending downward in the lake. This is coincident with the recent increases in alum loads.

There is an indication that the present dosing regime may at least begin to address the TLI targets for Lake Rotorua by providing a strong degree of ‘phosphorus locking’. Under these circumstances alum dosing the bottom waters of Lake

Rotorua, which has been suggested to reduce releases of phosphorus during anoxic events in bottom waters, may not be required.

2 Quantity of aluminium dosed to Lake Rotorua streams

Continuous alum dosing of the Utuhina Stream started about the beginning of 2007 after mechanical issues with the plant were overcome (all results are expressed in terms of the aluminium content of alum). The alum product discharged from each plant is 47% aluminium sulphate and about 4.2 % of the product is aluminium. In 2010, the amount of aluminium that could effectively lock up phosphorus in Lake Rotorua increased when the Puarenga Stream phosphorus locking plant became operational. Table 1 shows the load of aluminium discharged to the two streams. Effectively the total discharge from the two plants can be considered as a discharge to Lake Rotorua.

Table 1 *Quantity of aluminium (tonnes) dosed into the Utuhina and Puarenga Streams and the combined total load discharged to Lake Rotorua.*

	Utuhina Aluminium (tonnes)	Puarenga Aluminium (tonnes)	total Aluminium (tonnes)
2007	30.17		30.17
2008	17.51		17.51
2009	26.52		26.52
2010	23.97	60.04	84.01
2011	33.24	77.50	110.74

3 Nutrient and aluminium levels in Lake Rotorua

The Regional Council carries out monthly regional monitoring at two sites in Lake Rotorua (Scholes 2011). Data from both those sites is amalgamated in Figures 1 to 3 below. Figure 1 shows the aluminium concentration in Lake Rotorua. The first year (2006-2007) represents pre-alum dosing of the Utuhina Stream. A few higher aluminium concentrations of have been recorded after 2009 and it is not known if these are effects of the dosing programme, errors or natural fluctuations. The majority of the aluminium concentrations are less than 0.055 g/m^3, which is the ANZECC (2000) trigger value for aluminium in freshwater systems. Trigger values are a guideline to give protection from sustained exposure to a toxicant, so occasional minor deviations do not trigger further action.

Lake Rotorua has a high natural load of aluminium from geothermal sources and in historic times this may have protected the waters, to some degree, from potential adverse effects of the naturally high load of phosphorus. It should be noted that total aluminium is recorded in Figure 1, whereas the ANZECC guideline refers to dissolved aluminium.

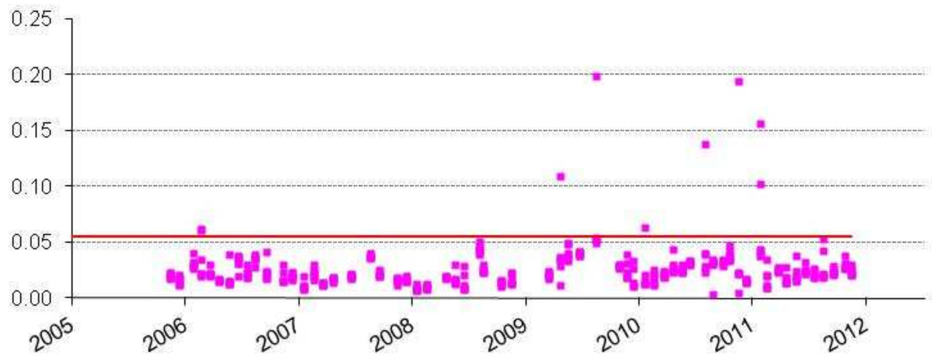

Figure 1 *The total aluminium concentration of Lake Rotorua water from the Bay of Plenty Regional Council regional monitoring data. The ANZECC trigger value for dissolved aluminium is the red line.*

The phosphorus concentration in Lake Rotorua often displays an annual cycle with high levels in the lake following anoxic releases of nutrients from the bottom sediment in the warmer months of the year (Figure 2). Processes such as phytoplankton uptake, sedimentation or transport out of the lake then reduce phosphorus to a lower level by the start of Spring. In the last two years the phosphorus concentration appears to have decreased and it is possible that alum dosing may be instrumental; either by reducing the phosphorus level in the water or by effectively blanketing the bottom sediments to act as a capping agent.

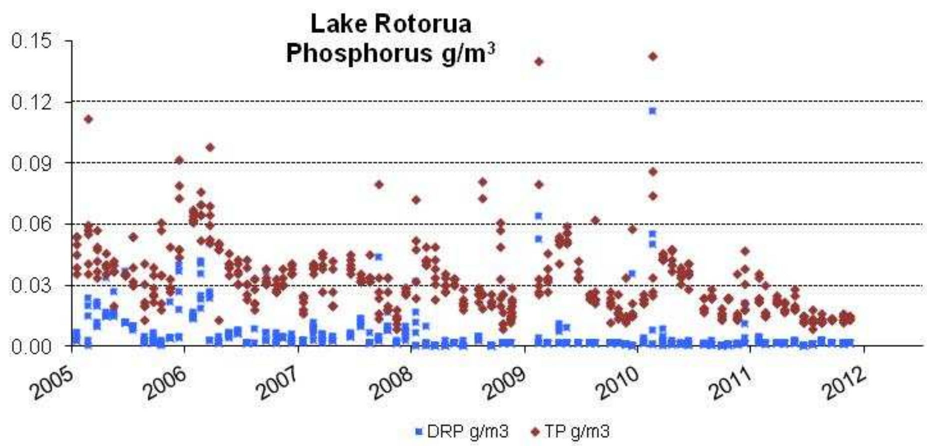

Figure 2 *Dissolved reactive phosphorus and total phosphorus concentrations from two sites in Lake Rotorua.*

The total nitrogen concentration in the lake has been lower in 2010 and 2011 than in the previous four years (Figure 3), despite some obvious periods of sediment nutrient release. In 2011 the nitrate level rose which may suggest that phosphorus limitation was occurring due to less biomass taking up nitrogen, resulting in a build-up of nitrate in the lake.

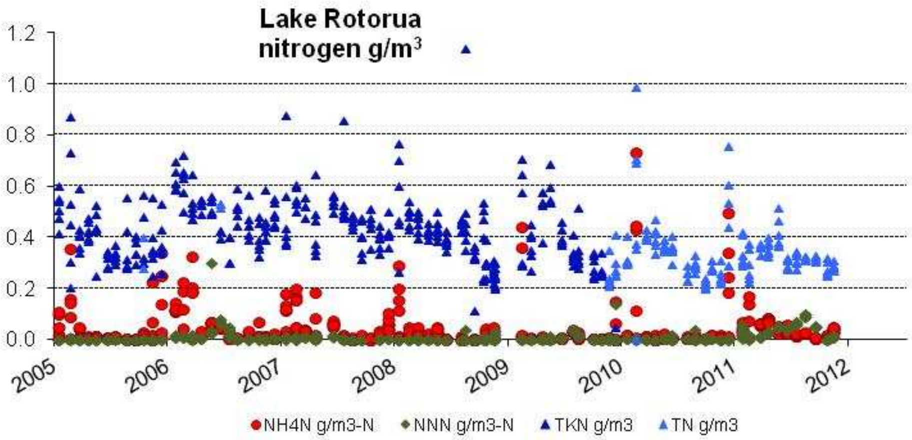

Figure 3 *Nitrogen concentrations in Lake Rotorua with dissolved forms of ammonium nitrogen (red) and nitrate nitrogen (green) and total kjeldahl nitrogen (dark blue) and total nitrogen (light blue). Total nitrogen is total kjeldahl nitrogen plus nitrate nitrogen.*

4 Phosphorus reduction in Lake Rotorua

Lake Rotorua is also monitored close to Sulphur Bay, at the southern end of the lake, as a resource consent monitoring condition. The phosphorus concentration of those waters shows a clear decline as noted at the mid-lake sites (Figure 2). Figure 4 shows data from the clear lake water just outside the boundary with the cloudy silica laden water of Sulphur Bay.

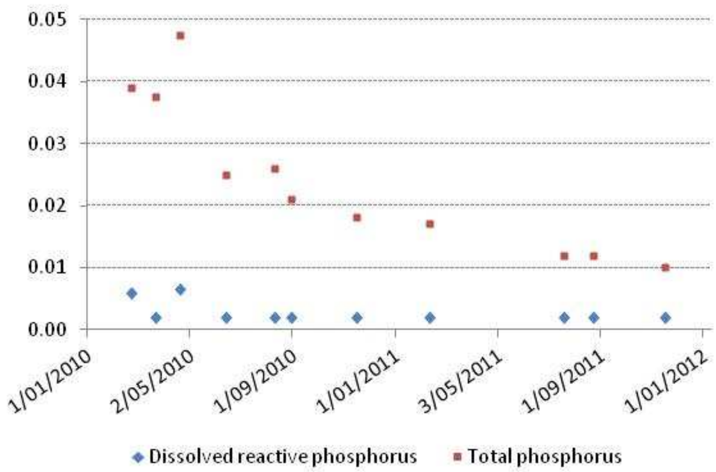

Figure 4 *The total and dissolved phosphorus concentrations in Lake Rotorua close to Sulphur Bay since the Puarenga Stream dosing plant became operative.*

Aluminium discharged to the lower Puarenga Stream mixes in Sulphur Bay before being discharged to Lake Rotorua over the broad interface between Sulphur Bay water and the main body of the lake. It seems highly probable that the phosphorus reduction in the lake water adjacent to the bay is related to the alum dosing of the Puarenga Stream, in particular, and perhaps partly due to dosing of the Utuhina Stream, as well. As the phosphorus reduction close to the bay occured at the same time as the reduction recorded at the mid-lake sites in the regional council's regional monitoring network, it is possible that phosphorus reduction in the whole lake is related to alum dosing of the streams.

A confounding factor is that nitrogen also appears to show a reducing trend over the same period. This might occur due to a number of reasons and several factors could act in concert. Alum dosing has no direct effect on nitrogen. An indirect effect could occur if the biology of the lake was limited by phosphorus, reducing the biomass of algae. This would in turn reduce the rate of de-oxygenation of the bottom waters during stratification events and reduce the rate of release of nitrogen and phosphorus from the sediment.

De-oxygenation rates at depth of 19 m in the middle of the lake have been calculated from several events recorded by the monitoring buoy since it was placed in Lake Rotorua (Figure 5) providing data every 15 minutes. The data and periods are recorded in Appendix I. The de-oxygenation rate was initially very high. High rates of sedimentation of algae on the bottom sediments (e.g. following a bloom) could contribute to high rates of deoxygenation (*eg* Burger *et al* 2007). For the later period the de-oxygenation rate (VHOD – volumetric hypolimnetic oxygen demand) varies between 0.5 and 1 g/m^3/day. A similar range has been common for Lake Rotorua over several decades, although measurement was sporadic and at daily intervals before the monitoring buoy was established. Rutherford *et al* (1989) reported the de-oxygenation rate (VHOD) as varying from 0.4 g/m^3/day in 1976-77 to 0.9 g/m^3/day in 1984-85. In the summer of 1988-89 VHOD varied between 0.9 g/m^3/day – 1.3 g/m^3/day (Bay of Plenty Catchment Board data). The objective de-oxygenation rate for a restored Lake Rotorua is 0.25 g/m^3/day. At this rate a stratification event of 20 days duration would fail to result in anoxia and its associated increased rates of nutrient release (Rutherford *et al* 1989). Commonly, stratification occurs over periods of less than 20 days.

At this time it is not possible to conclude that the de-oxygenation rate has been reduced sufficiently to reduce the load of nitrogen and phosphorus released into the lake from bottom sediments. Two short-lived de-oxygenation events in November 2011 displayed a very high rate of de-oxygenation.

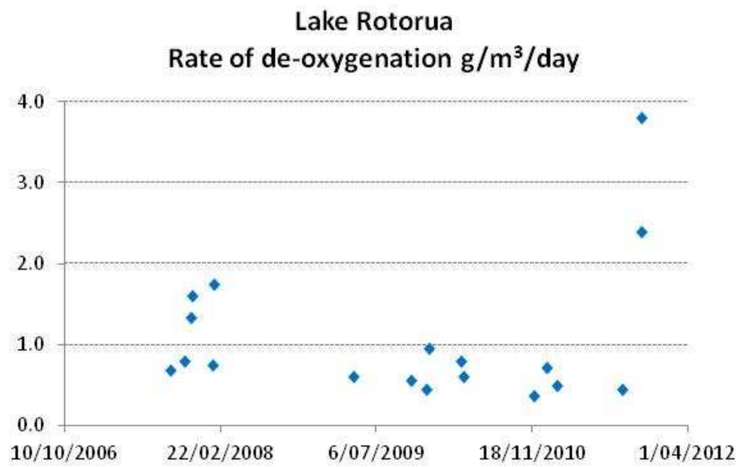

Figure 5 The de-oxygenation rate of Lake Rotorua from separate events recorded by the monitoring buoy (web site).

5 Phosphorus locking in Lake Rotorua

A bench test, carried out in the design stage of the first phosphorus locking plant, measured a reaction ratio of 30:1 Al:P for alum dosing of Utuhina Stream water *ie* 30 parts of aluminium removed 1 part of phosphorus. It is difficult to estimate the reaction ratio of aluminium with phosphorus in the Utuhina Stream but there is an annual load of approximately 2 tonne per year of dissolved reactive phosphorus. With the median dose rate of 26.5 tonnes aluminium the reaction ratio could be around 13:1 Al:P. However, the reduction of phosphorus in Lake Rotorua suggests that more phosphorus is being locked in the lake by the alum floc.

Hoare (1980) used a phosphorus balance model to relate the input load M to Lake Rotorua to the concentration C of phosphorus at the lake outlet, which can be assumed to be the concentration in the lake.

$$C_P = (1 – R) M/Q \qquad (1)$$

Q is the discharge rate of the outflow and R is the proportion of phosphorus retained in the lake. He measured about 70% of the phosphorus entering the lake stayed in the sediments. The average flow of the Ohau Channel, Q, is 16 m^3/s. This model is used to calculate the load M of phosphorus entering the lake (Table 2) in the 5 year period before alum dosing, in the initial period of alum dosing in the Utuhina Stream and for 2011 when a large reduction in phosphorus was measured. The periods used in Table 2 are 2001 – 2006 for pre-alum dosing, 2007 – 2010 for dosing from the Utuhina Stream plant and 2011 for dosing from the Puarenga Stream plant. Dosing started at the Puarenga plant at the start of 2010 and assuming that this aluminium suppressed some sediment phosphorus release that would not have occurred until the summer in early 2011.

Table 2 The average concentration of total phosphorus C_P in Lake Rotorua and the input load to the lake calculated using equation (1) above (using R=0.71).

Period	C_P g/m^3	M tonnes/year
2001 - 2006	0.043	75
2007 - 2010	0.031	54
2011	0.022	38

The theoretical ratio for phosphorus removal using aluminium is 1:1, however, the ratio is always greater than 2 (Bann *et al*, 2008) due to reaction of other elements with aluminium in situ.

A ratio of 5:1 Al:P has been recorded in Lake Delavan, Wisconsin, USA, from an alum treatment in 1991 (Cooke *et al* 2005). The dose rate for Lake Delavan was 12 g Al/m^2. The dose rate in Lake Rotorua based on 84 and 110.7 tonnes of alum floc (2010 and 2011, respectively) settling out into the portion of the lake below 15 m (surface area 22 $x10^6$ m^2), equates to 3.8 g Al/m^2 and 5 g Al/m^2.

Biologist, Ian Kusabs has studied koura on the lake bottom of Lake Rotorua and observed that their sandy habitat extends to the 15 m contour, below which fine sediments accumulate. Pearson (2007) found that fine sediments covered 40% of the lake bottom area, which corresponds to the area below the 15 m contour. Currents in Lake Rotorua have also been studied by Gibbs *et al* (2011). They found that the whole water column tended to rotate in the same direction around Mokoia

Island when the lake was fully mixed and when stratified the top and bottom waters tended to rotate in opposite directions. Wind direction was the key determinant of whether the water rotated clockwise or anti-clockwise. The currents are likely to keep fine particles, such as alum floc, in suspension for a long time and the circular motion is likely to encourage movement of this floc to deeper parts of the lake. The alum floc should disperse throughout the fine sediments as they settle out below 15 m.

Lower reaction ratios of aluminium and phosphorus have been recorded (Cooke *et al* 2005). A ratio of 2.1:1 was found for the Susser See in Germany, which was treated over a period of years, and this led to the suggestion that treating a lake over many years with a very low dose of alum was more effective than one large dose (Cooke *et al* 2005).

For the period 2007–2010 in Lake Rotorua there appeared to be a reduction in phosphorus concentration. From Table 2 this is calculated as a reduction of 21 tonnes /year of phosphorus, compared to the average load for the period 2001–2006. A reduction of 16 tonnes/year of phosphorus occurred in 2011. It is possible that the reduction in 2011 is related to the discharge of 84 tonnes aluminium in 2010 (Table 1). This implies an Al:P reaction ratio of 5.3:1.

Climate variation does result in fluctuations in the water quality of lakes, especially for a shallow lake such as Lake Rotorua where mixing of lakewater by the wind plays a major role in the frequency and duration of sediment nutrient release events. Since 2010 when the Puarenga Stream dosing plant began operations La Nina conditions with northerly winds have been more prevalent. Rainfall affects lake nutrient levels by increased storm runoff or by changing the flushing rate. Over the period 2007-2010, the eastern urban and semi-urban area was reticulated for sewage, removing septic tank effluent from local inputs to the lake. The Wharenui dairy farm was converted to drystock farming removing a potentially large source of nutrients from the Waingaehe Stream and from local groundwater in that area. Alum dosing would have played some part in that nutrient reduction (2007-2010). From Table 1 the average aluminium discharge before 2010 was 25 tonnes /year. If the Al:P reaction ratio was 5.3:1 then a reduction of 4.7 tonnes /year of phosphorus in the incoming load could be attributed to the alum dosing in the period 2007-2010.

A target phosphorus reduction of 10 tonnes /year was set in the Rotorua-Rotoiti Action Plan. Using the relationship derived above it would require an application of 53 tonnes of aluminium/year to Lake Rotorua to achieve the target reduction. This target assumes that the lake condition is stabilised so that only a small quantity of phosphorus is released from the bottom sediments per year.

Scholes (2011) reported the Bay of Plenty Regional Monitoring Network data for the Rotorua lakes and calculated the annual average Trophic Level Index (TLI). In the 2010-11 year, both the average nitrogen and phosphorus concentrations for Lake Rotorua were the lowest on record since 1990. Only two annual TLI values for the 21 year period were lower than the TLI for 2010/11. With the potential for ongoing reduction in phosphorus levels with alum dosing in Rotorua, it is possible that the TLI could be reduced further.

6 Conclusion

It is not known how much the low phosphorus concentration in Lake Rotorua in 2011 is attributable to natural variation, alum dosing or a combination of the two. A speculative analysis suggests that an Al:P reaction ratio of about 5.3:1 may be achieved, in the lake-wide environment, by alum dosing over an extended period of time.

In the summer of 2010/11 a peak in phosphorus can be noted in Figure 2 implying that a sediment nutrient release event occurred. The quantity of aluminium deposited on the lake bottom may not have been sufficient at that time to act as a complete capping layer but the phosphorus release rate may have been partially reduced compared with releases of pre-alum dosing sediments. The load of aluminium discharged to the lake has increased in 2011 and the state of the lake over the summer of 2011/12 will add more information to test the assumptions made in this report.

Gibbs *et al* (2008) measured 3.17 g P/m^2 in the top 4 cm of Lake Rotorua sediment and concluded that a capping layer of 80 g/m^2 alum (3.2 g/m^2 aluminium) would be sufficient to cap Lake Rotorua sediments. They suggested that about four years 'effectiveness' could be expected until the phosphorus uptake capacity of alum was saturated. In section 5, it has been estimated that the alum dose in 2011 could effectively contribute 5 g/m^2 aluminium as part of a capping layer to Lake Rotorua sediments below the 15 m depth contour.

In achieving the phosphorus reduction the level of aluminium concentration in the lake is consistent with the ANZECC (2000) trigger value for aluminium in freshwaters and the lake aluminium concentration has not increased since alum dosing began.

Although strong conclusions cannot be drawn yet, it appears that alum dosing of the Utuhina and Puarenga Streams is having a beneficial effect on the quality of Lake Rotorua by reducing the phosphorus content of the lake water. Because the fine material in the lake is moved to the zone below the 15 m contour the alum floc is likely to be deposited in this region after a period of time. This is the area where the sediment nutrient releases predominantly occur so the stream dosing may be effectively applying a thin capping to this layer to reduce phosphorus releases, termed the "legacy" source in the Lake Rotorua and Lake Rotoiti Action Plan (BoPRC, 2009). The estimate of the phosphorus load on Lake Rotorua in 2011 (Table 2) is very close to the phosphorus load objective of the Action Plan. However, a longer monitoring period is needed to determine if the changes observed in the past year or so will continue.

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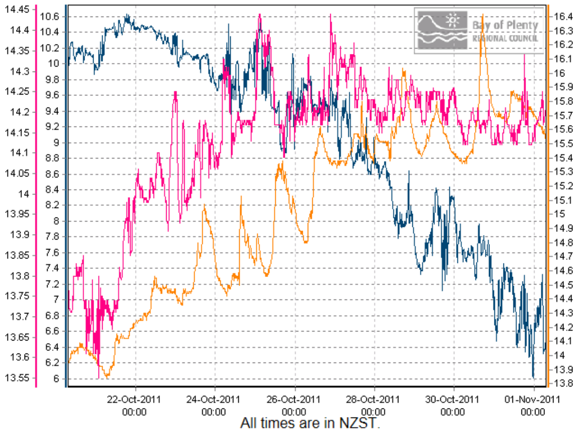
Appendix 1

The table shows the periods over which the de-oxygenation rate was calculated. Each period is plotted in the following figures. Very few periods of de-oxygenation are uninterrupted by re-oxygenation events. The blue line is the oxygen concentration. The temperature record was erratic with the near surface temperature being the yellow line and the near bottom temperature being the red line.

Date	period days	initial DO g/m^3	final DO g/m^3	difference g/m^3	de-oxygenation rate $g/m^3/day$
15/09/2007	6	9.6	5.5	4.1	0.68
29/10/2007	2	10.0	8.4	1.6	0.80
20/11/2007	0.6	7.8	7.0	0.8	1.33
21/11/2007	1	7.2	5.6	1.6	1.60
27/01/2008	2	7.5	6.0	1.5	0.75
2/02/2008	2	3.5	0.0	3.5	1.75
22/04/2009	1	9.4	8.8	0.6	0.60
24/10/2009	2	10.2	9.1	1.1	0.55
11/12/2009	6	6.7	4.0	2.7	0.45
22/12/2009	4	7.8	4.0	3.8	0.95
2/04/2010	3	9.6	7.2	2.4	0.80
10/04/2010	2	9.0	7.8	1.2	0.60
24/11/2010	8	5.0	2.0	3.0	0.38
1/01/2011	7	7.0	2.0	5.0	0.71
6/02/2011	2	6.5	5.5	1.0	0.50
2/09/2011	2	11.0	10.1	0.9	0.45
3/11/2011	0.5	7.2	6.0	1.2	2.40
4/11/2011	0.5	7.5	5.6	1.9	3.80

There is a large degree of uncertainty in the calculated de-oxygenation rates but it is certain that the rate is not at the target rate of 0.25 $g/m^3/day$ and nutrient release events were obvious in the nutrient data plotted in Figures 2 and 3.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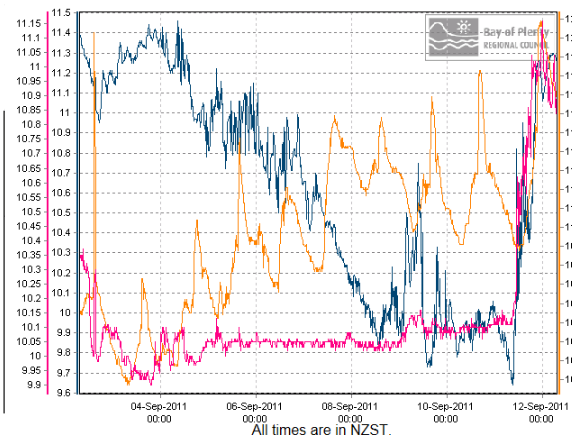
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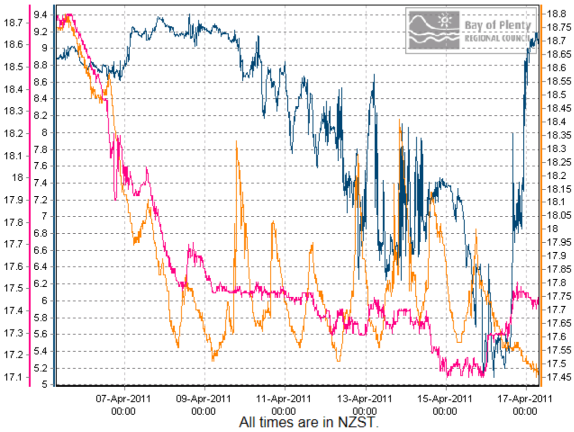
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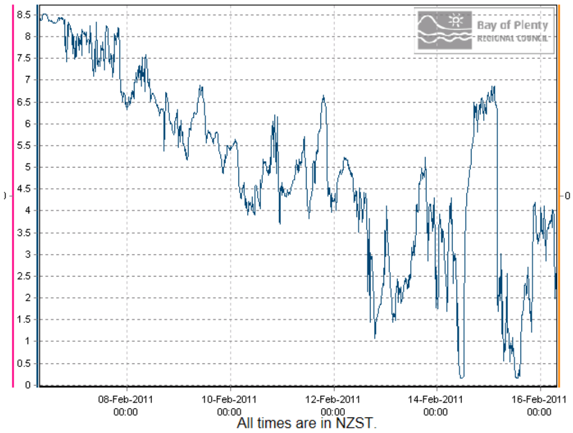
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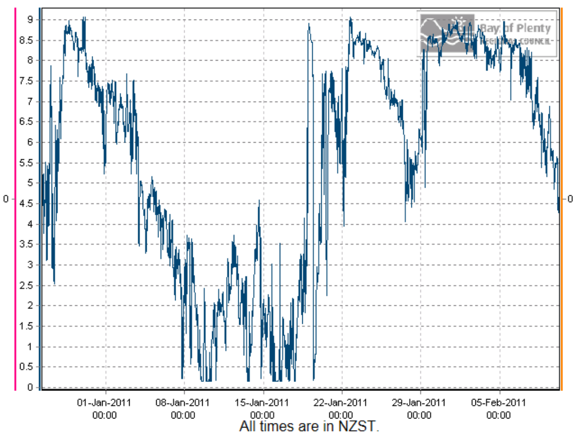
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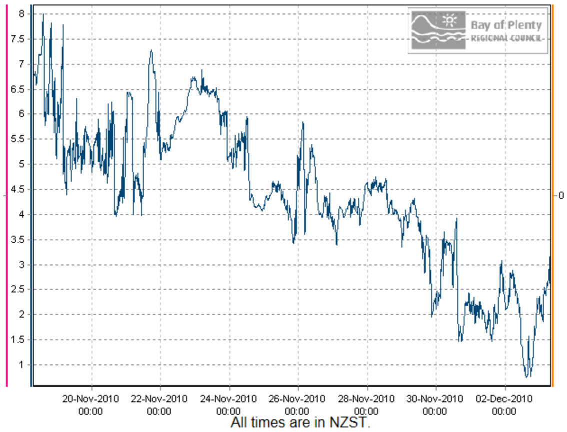
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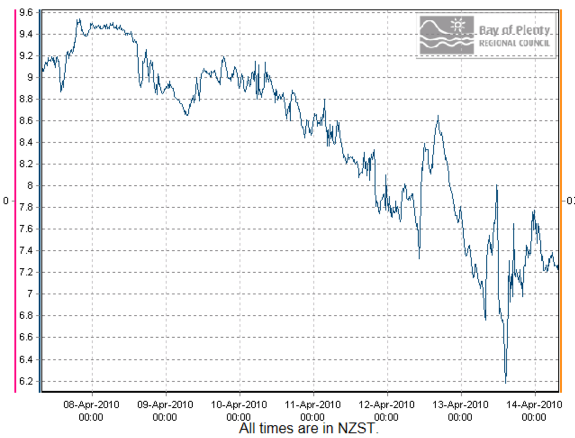
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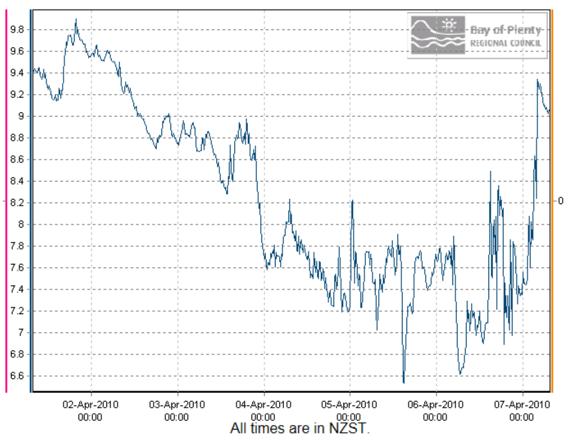
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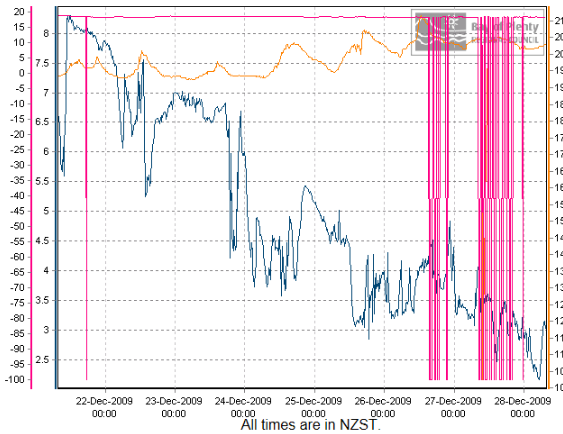
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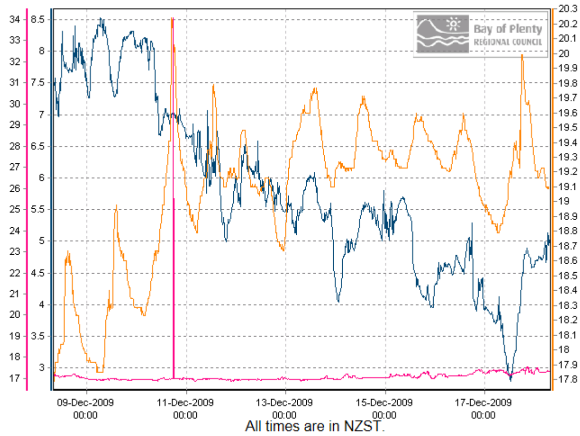
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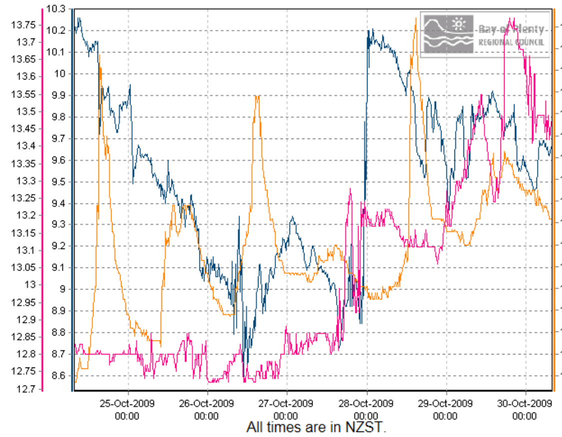
All times are in NZST.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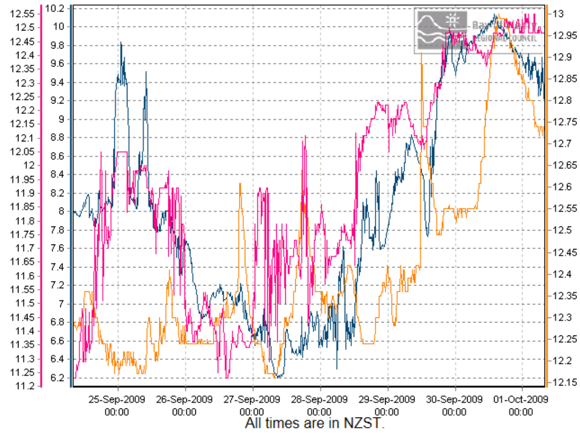
All times are in NZST.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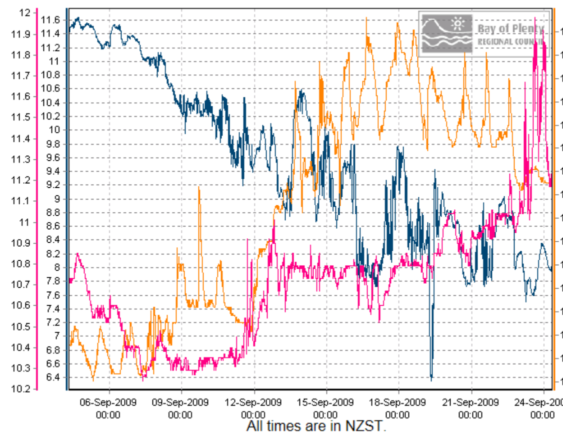
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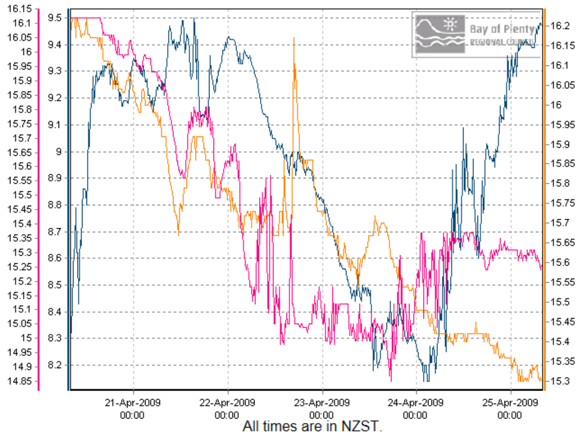
All times are in NZST.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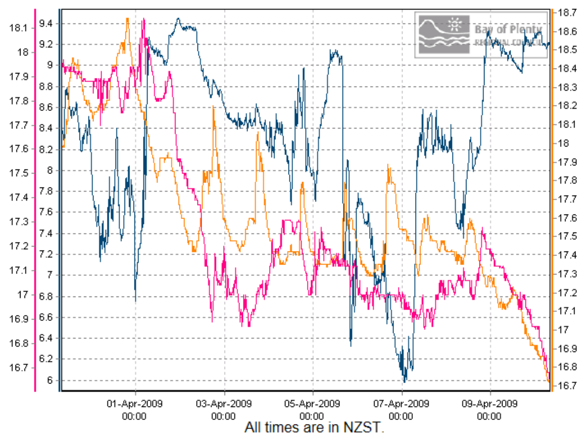
All times are in NZST.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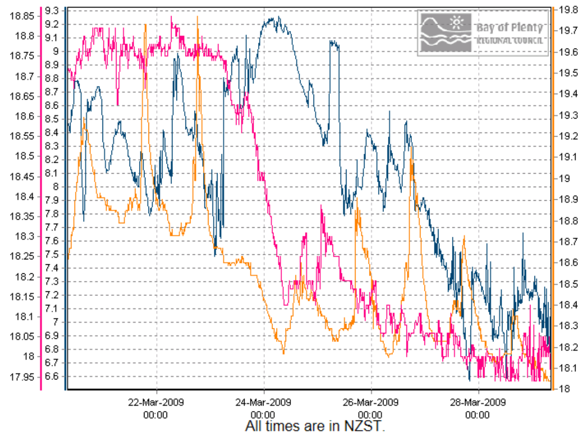
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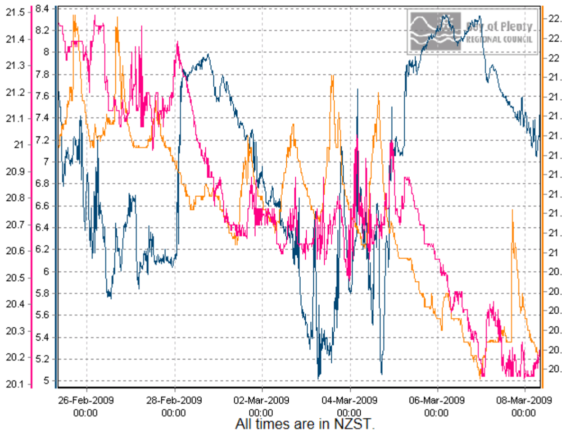
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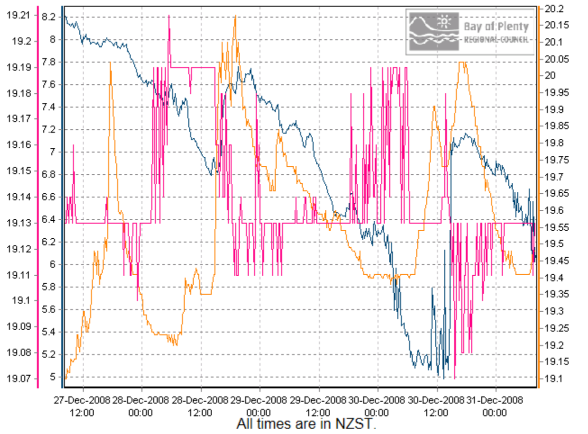
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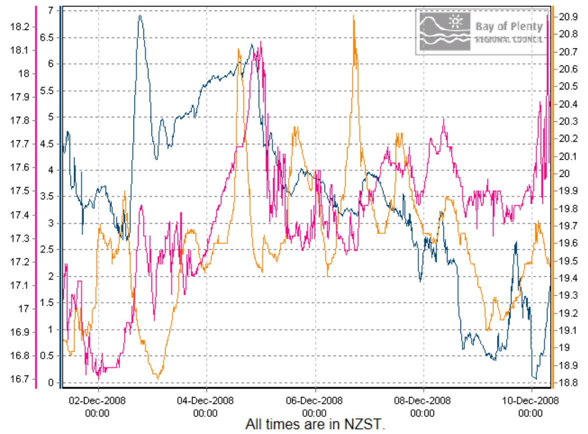
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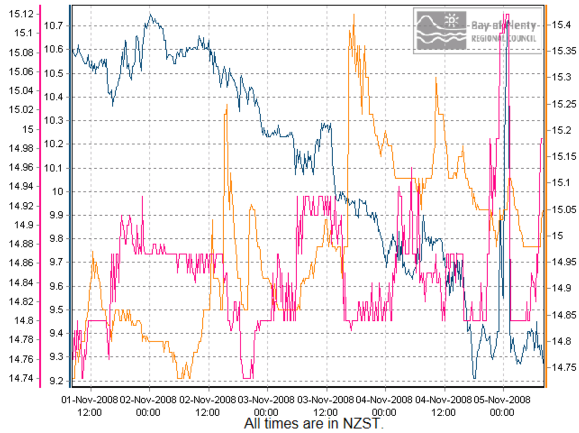
All times are in NZST.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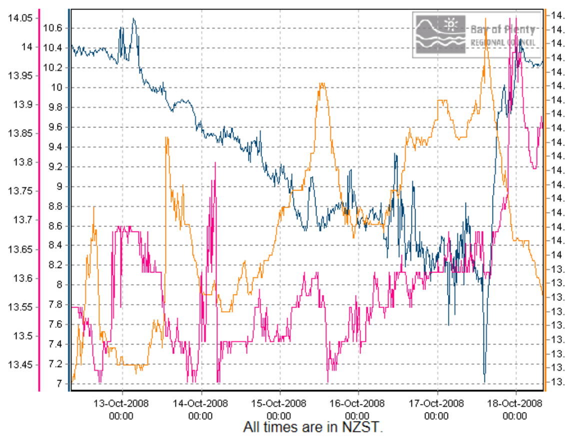
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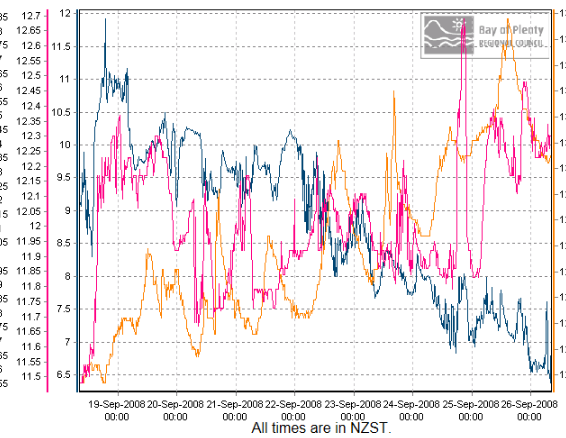
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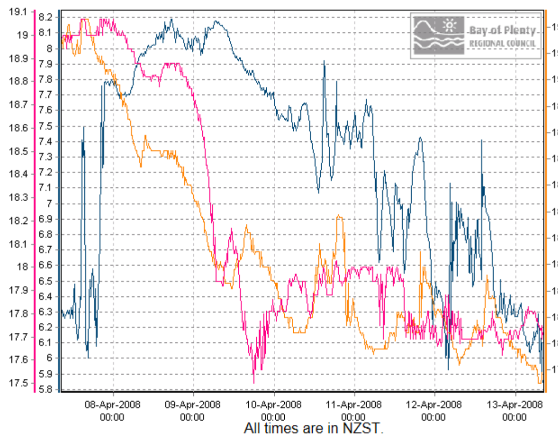
All times are in NZST.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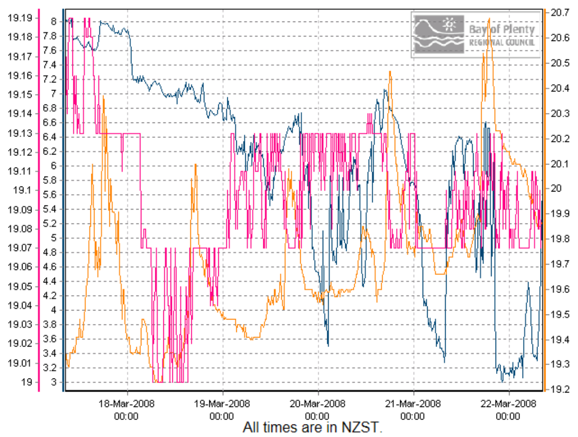
All times are in NZST.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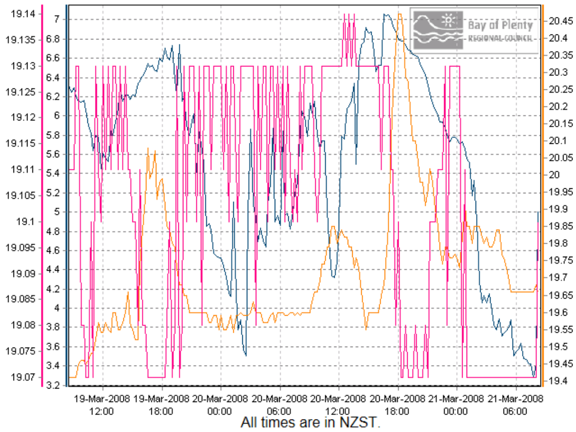
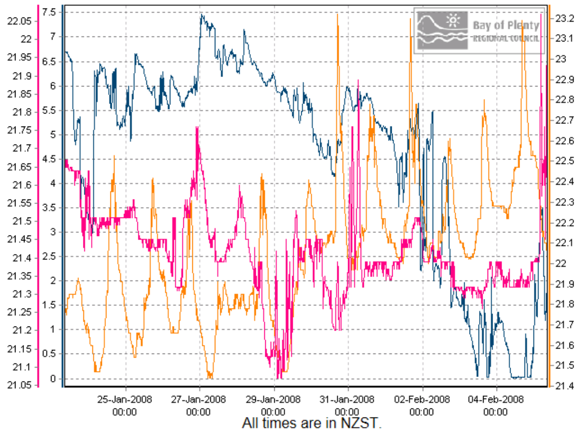
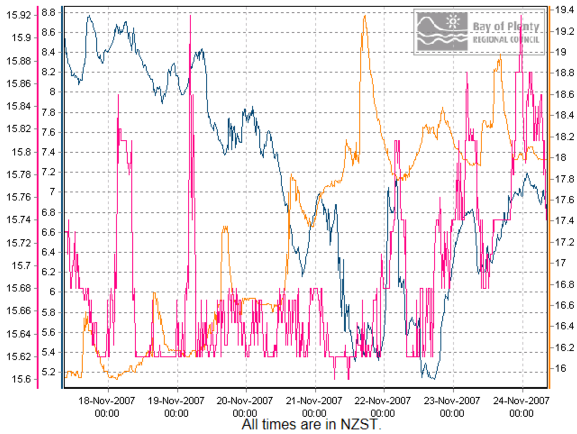
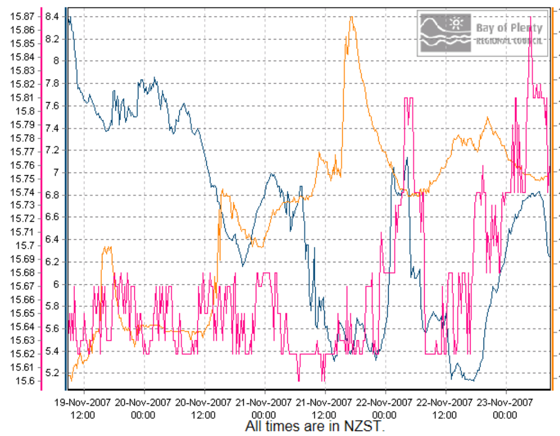
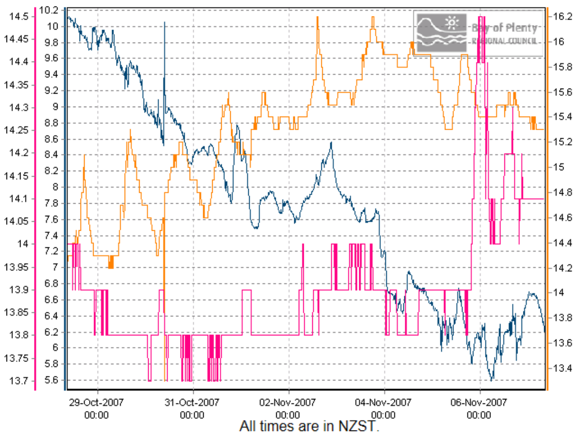
All times are in NZST.

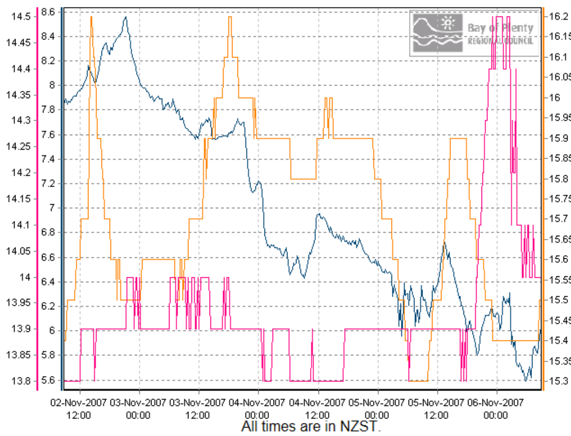












Default | Today | This Week | This Month | Yesterday | Last Week | Last Month | Custom Range | Show Summary