OVERCOMING ROTORUA LAKES ECOLOGY CHALLENGES

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ABSTRACT

Over many years the increasing incidence of nuisance algal blooms in some of the Rotorua Lakes has been the catalyst for studies to identify reasons for the general decline in water quality. These studies cite the combined nutrient inputs from anthropogenic and natural sources in regard to their specific contribution to the problems of lake water quality. Over the last decade there has been a strong focus on setting targets to control nitrogen and phosphorus loads, the main drivers for changes in lake trophic condition. In recognition of the importance of the Rotorua lakes, Bay of Plenty Regional Council has set statutory environmental bottom lines in the form of specific Trophic Level Indices (TLIs) for all the Rotorua lakes in the Water & Land Plan (W&LP). This has lead to investigation and implementation of selected restoration methods to overcome the immense challenges of managing and treating large bodies of lake water. This paper briefly covers the reasons and effects of changes in water quality and introduces methods currently in operation to control excess nutrients. Although the Rotorua Lakes programme targets substantial decreases of both nitrogen and phosphorus loads, this paper is primarily concerned with the control of phosphorus.

KEYWORDS

Lake restoration, freshwater nutrient control, sediment capping, stream treatment, alum addition.

1 INTRODUCTION

As early as the 1960's reports of deteriorating water quality of iconic Rotorua lakes identified excess nutrients as a major contributing factor. A definitive report by Fish in 1975 and subsequent reports by others quantified nutrient loads, their source, water shed characteristics and related activities. These studies contributed to an understanding of conditions and circumstances leading to entry of nutrients into the lakes, particularly nitrogen and phosphorus that are viewed as primary drivers causing eutrophication in the lakes measured as changes in trophic state (biological production, especially plant and algal life).

In 1998 the Te Arawa Maori Trust Board (now Te Arawa Lakes Trust), the Bay of Plenty Regional Council and Rotorua District Council established a Lakes Management Working Group that was tasked with coordinating the efforts of interested parties by setting in place a process that would lead to solving lake water quality problems as efficiently as possible. This culminated in the Lake Management Strategy that set goals for the protection, use, enjoyment and management of lakes and surrounding catchments. The strategy was adopted in October 2002.

In 2006, a Rotorua Lakes Strategic Group was formed, comprising two representatives each from the above parties, as a permanent body under the Local Government Act 2002 and Te Arawa Settlement Act 2006. It's purpose is summarised here as working on actions needed to promote sustainable management of named Rotorua Lakes and watersheds while recognising the intrinsic and cultural values of the people[†]. In April 2007 a Memorandum of Understanding (MoU) was signed between the Lake Strategies Group and Central Government formalising a working relationship to jointly engage through the Rotorua Lakes Protection and Restoration Action Programme. The MoU set out responsibilities of group members and actions to be examined and implemented.

The Crown, as owner of the lake waters and air space above the lake beds (the lake beds are owned by Te Arawa), provides a national perspective on lake management and funds half a $144m ten year plan, being about half of the overall 20year restoration programme, with the other half funded by Rotorua District Council and Bay of Plenty Regional Council.

In addition, on 9th May 2011 the government announced it's Fresh Start for Fresh Water 2011 reform that includes a National Policy Statement for Freshwater Management that took effect 1st July 2011. This statement directs that regional policies relating to water quality, quantity and integrated management be implemented through Regional Plans by 2014, or if that is not practicable, such other staged implementation by 2030.

Since 2003 and with the same intent as the Government's National Policy Statement for Freshwater, the Regional Council has developed action plans for Lakes Rotorua and Rotoiti, Rotoehu, Rotoma, Okaro and Okareka using methods and objectives under the Regional Water and Land Plan (W&LP). Action Plans for the remaining six lakes are either in progress or under consideration. Most importantly, Actions Plans are regularly reviewed to allow for changes in approach such as developments in technology and best management practices.

† For exact wording refer Rotorua Te Arawa Lakes Strategy Group – Terms of Reference

2 LAKE CONDITION INDICATORS

2.1 LAKE TROPHIC LEVEL

A frequently used measure of the state of fresh water quality is the Trophic level Index, TLI. It is a calculated value based on measurements taken at selected monitoring sites for each lake. Figure 1 indicates trophic terminology in relation to observed conditions. Microtrophic TLI (0 to 2) is typical of clear glacial melt water where few nutrients are present. TLI's increase by an integer for each trophic state to reach Hypertrophic TLI (6 to 7) that is typical of highly nutrient rich water, e.g. oxidation ponds.

Figure 1: Trophic states in relation to nutrient load and visual appearance.

The TLI formula adopted by BoPRC includes Secchi Disk measurements for water clarity, concentrations of chlorophyll *a*, total nitrogen and total phosphorus. Objective 11 of the W&LP sets TLI targets for each lake as shown in Table 1. These are compared against the most recent three yearly TLI average and annual measurement for 2010/11. Once the three-year average TLI is exceeded by 0.2 units for two consecutive years, Method 41 of the W&LP sets out the process to develop and implement an Action Plan. Most lakes have exceeded this threshold and consequently have operative Action Plans.

Table 1: Lake TLI targets, 3 year averages and Trophic type

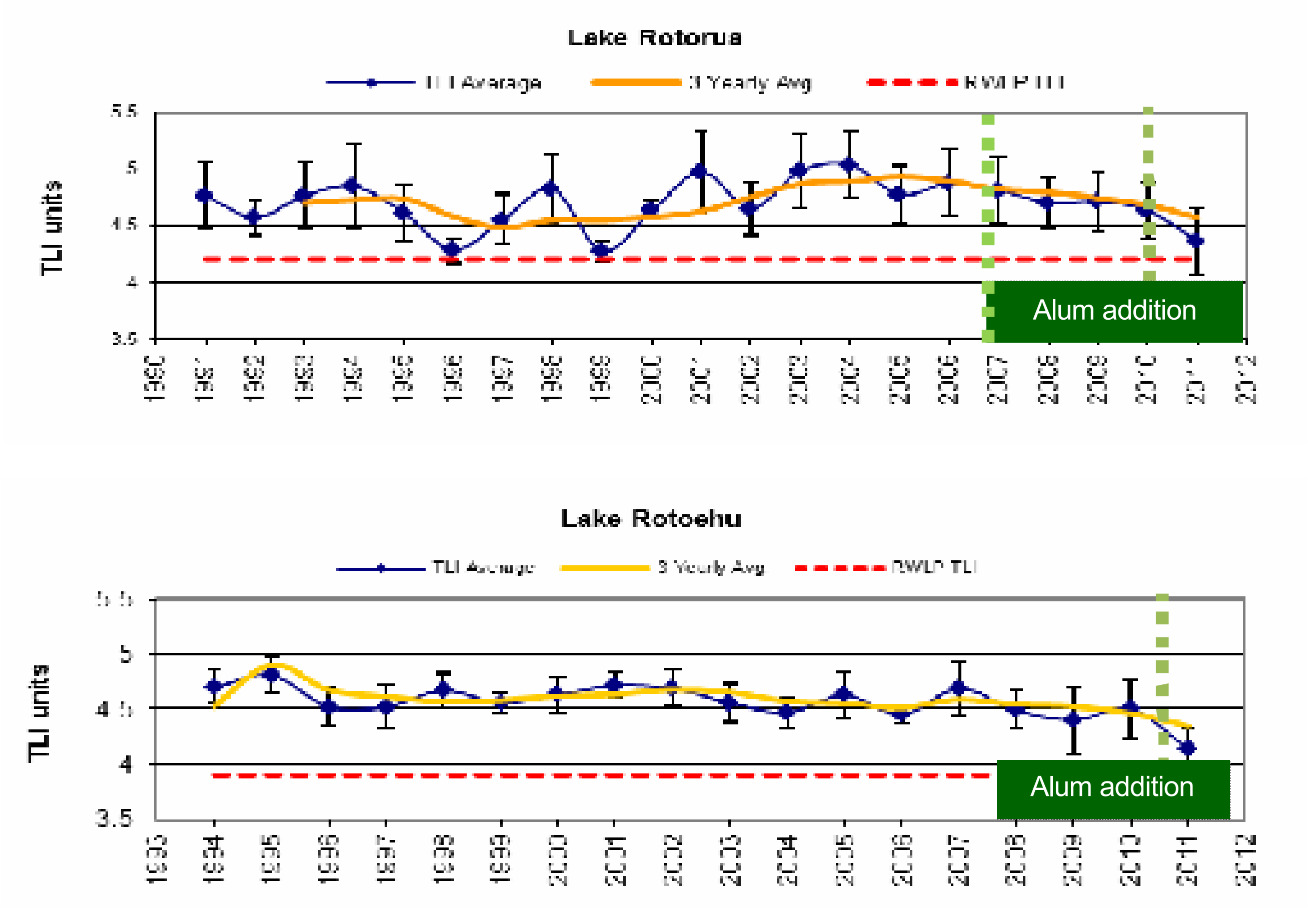
Lake	RWLP $\text{TLI}_{\text{target}}$	2011 3-yearly average TLI	2010/11 TLI	Trophic Type: TLI	
Rotorua	**4.2**	4.6	4.3	Eutrophic:	TLI 4.0 to 5.0
Rotoiti	**3.5**	3.9	3.9	Mesotrophic:	TLI 3.0 to 4.0
Rotoehu	**3.9**	4.4	4.1	Eutrophic;	TLI 4.0 to 5.0
Okaro	**5.0**	5.1	5.2	Supertrophic:	TLI 5.0 to 6.0
Tarawera	**2.6**	2.8	2.9	Oligotrophic:	TLI 2.0 to 3.0

Extract from Table 2.1 of *2011/2010 Rotorua Lakes Trophic Index Update*, BOPRC, December 2011

The Trophic type gives an overall indication of lake condition when examined in conjunction with the Submerged Plant Indicators (SPI). For lakes Rotorua and Rotoehu, the SPI shows plant life to be in poor condition due to proliferation of exotic plants or nuisance plants. Similar conditions exist for Lake Rotoiti where nutrients are generally sufficient (mesotrophic) to support a diverse lake ecology. Lake Tarawera waters are typically low in nutrients (oligotrophic) but support abundant exotic plantlife.

Figure 2 shows annual and 3-year averaged TLI's for lakes that receive alum dosing as part of their restoration action plan. Green flags indicate when alum dosing commenced. Lake Rotorua has two such plants. These lakes show a general improvement in TLI since alum dosing commenced. Of nine other Rotorua lakes with similar TLI records, only Lake Tikitapu (Blue Lake) had a similar TLI drop in 2011.

Figure 2: Lake Rotorua and Lake Rotoehu TLI's from 1990 to 2011



Source: *2011/2010 Rotorua Lakes Trophic Index Update*, BOPRC, December 2011.

The Trophic level Index is a good general indicator incorporating the measurement of **total** nutrients, but does not differentiate between nutrient forms and relative availability for uptake by organisms that make use of them. To overcome this, the Regional Council also monitors dissolved nutrients to better understand their influence as a preferential energy source for organisms. Targeting the removal of, or changing the condition of, dissolved nutrient to make them less bio-available prevents their rapid uptake and requires organisms to expend more energy to win the all important nutrients they need to metabolise and propagate. This leads to a key philosophy of alum dosing, that is to control nutrients within the catchments to which it is currently applied, namely to streams flowing into Lake Rotorua and into Lake Rotoehu.

Alter conditions within a lake to limit the preferential uptake rate of nutrients by nuisance organisms and thereby prevent their proliferation.

The most ideal outcome is to 'lock' sufficient bio-available nutrients to control lake trophic levels at aesthetically desirable levels while maintaining a healthy lake environment.

2.2 NUTRIENT LOADS INTO LAKE ROTORUA

There are various studies estimating nutrient loads that enter Lake Rotorua with predictions ranging from year 1900 to 2055 as summarised by Rutherford, May 2008. The values for nitrogen and phosphorus for years 1965 to 2005 are given in Table 2. These exclude particulate nutrients that are considered to be not available to phytoplankton.

In addition, Lake Rotorua can stratify one or more times per year, typically in the summer, for a duration approaching two weeks per event where hypoxic conditions (DO<3) prevail within the hypolimnion. This results in the release of phosphorus and nitrogen from lake sediments which build up in the hypolimnion layer. When the lake mixes these nutrients are available for uptake by algae that rapidly proliferate to cause eutrophication of lake waters. After the nutrients are consumed the algal die-off and settle which results in nutrients accumulating in the top layer of sediment again. This cycle is shown as 'internal' load in Table 2 and is additional to other nutrient inputs entering Lake Rotorua.

Target nutrient input loads for Lake Rotorua (excluding internal loads) have been set at 37 T/yr phosphorus and 435 T/yr of nitrogen, which includes a small allowance for nutrients from treated sewage (3 T P/yr and 30 T N/yr). Currently the lake receives 'Land Use inputs' that are less than 'Land Use exports', the difference being nutrients transported via groundwater which can take multiple decades (predictions for some areas up to 150 years) before groundwater nutrients input to the lake. The ROTAN model predicts about 30 years delay for total nutrient loads to equilibrate, although the mean retention time for water in some Rotorua springs exceeds 100 years. Total inputs include all sources of nutrient entering the lake. Therefore the difference between target loads and future total input loads (as predicted in 2003) will increase for years to come.

The Lake Rotorua and Rotoiti Action Plan set **target nutrient reductions to year 2029 of 10 T/yr phosphorus and 250 T/yr nitrogen.** The phosphorus reduction target includes an allowance for the lake internal loading, groundwater lag time and growth in the area.

Table 2: Nutrient loads to Lake Rotorua (T/yr)

Nutrient	1965 to 2005[1]	Internal[2]	Land Inputs[2]	Land Use & Groundwater[2]	2003 Total Inputs[2]	Target[2]
Nitrogen	206 to 598	360	562	746	783	435
Phosphorus	34 to 42	36	39	39	40	37

1. Rutherford, 2008
2. Lakes Rotorua and Rotoiti Action Plan, 2009

2.3 NUTRIENT SOURCES

After sewage nutrients were irrigated in Whakarewarewa Forest, by far the greatest contribution of nitrogen is from the rural sector, as shown by the nutrient load summary in this section. In the case of phosphorus, natural sources are similar to rural inputs. This fact broadens council's options to control phosphorus. Natural springs are typically phosphorus rich point source flows entering the lake and therefore amenable to adding controls while longer term rural initiatives are developed and implemented.

Approximate source loads in tonnes per year are:-

	Nitrogen	Phosphorus
Rural:		

	- Bush/Forest	19	0.5
	- Sheep / Deer	93	3
	- Dairy	466	14
	- Exotic forest, cropping, etc	41	1.5
Natural:			
	Geothermal, rain, springs and indigenous forest	115	18
Urban:			
	Stormwater, wastewater reticulation and septic tanks	50	4

Assessed from *Lakes Rotorua and Rotoiti Action Plan*, July 2009.

3 NUTRIENT SOURCES AND REDUCTION INITIATIVES

3.1 BRIEF OUTLINE OF NUTRIENT MANAGEMENT INITIATIVES

A broad range of actions are under investigation to control nutrients, with many being ‘in progress’ or ‘in action’ at the present time. Only a brief list of actions can be given within the scope of this paper. It must be recognised that lake water quality changes reflect the cumulative nutrient savings from all actions and are not entirely due to phosphorus locking to which this paper principally refers. However it is equally valid to note that many actions are not yet in place, and consequently, progress on water quality within Lake Rotorua is largely attributed to alum addition for the control of phosphorus.

Expected nutrient reduction loads in tonnes from the various initiatives are:-

		Nitrogen	Phosphorus
Rural:			
	- BPO	30 by 2012	> 0
	- Farm Management	56 by 2019	3.5
	- Research and evolving management practices	84	6.5
Natural:			
	- Tikitere geothermal brines treatment of ammonia	< 20	0
	- Phosphorus locking in streams	Nil	6
Urban:			
	- RDC WwTP improvements	15	4
	- Settlement septic tank improvements	11	0.3
	- Stormwater improvements	3	0.5

Assessed from *Lakes Rotorua and Rotoiti Action Plan*, July 2009.

3.2 STREAM AND SPRING NUTRIENT INPUTS

There are nine significant streams and a number of minor streams contributing flow to Lake Rotorua. Table 3 is derived from BOPRC stream monitoring records that have been averaged over a ten year period prior to alum treatment (1992 to 2003). Only five major streams are noted. Highlighted streams are now treated with alum which started with the Utuhina in 2007 and Puarenga in April 2010. The nitrogen values show that most nitrogen is in the oxidised form nitrate/nitrite (where NNN = TN — TKN), and therefore is little affected by alum treatment. The key initiative for treating stream water with alum is to control Dissolved Reactive Phosphorus, DRP, to curtail it's rapid uptake by organisms when mixed with lake water, particularly types of phytoplankton that cause algal blooms and scums.

Table 3: Stream sources of phosphorus (abridged list)

Stream	Flow (m^3/s)	Nitrogen (T/yr)		Phosphorus (T/yr)		Phosphorus Morgenstern TP - Y2004
		TN	TKN	TP	DRP	
Hamurana	2.53	59.2	5.9	7.3	6.5	6.3
Awahou	1.55	62.3	9.3	4.5	4.1	3.3
Puarenga	1.75	65.5	27.2	6.3	3.6	3.6
Waingaehe	0.22	12.3	5.2	1.7	0.9	0.7
Utuhina	1.96	67.1	24.1	5.4	4.0	2.5

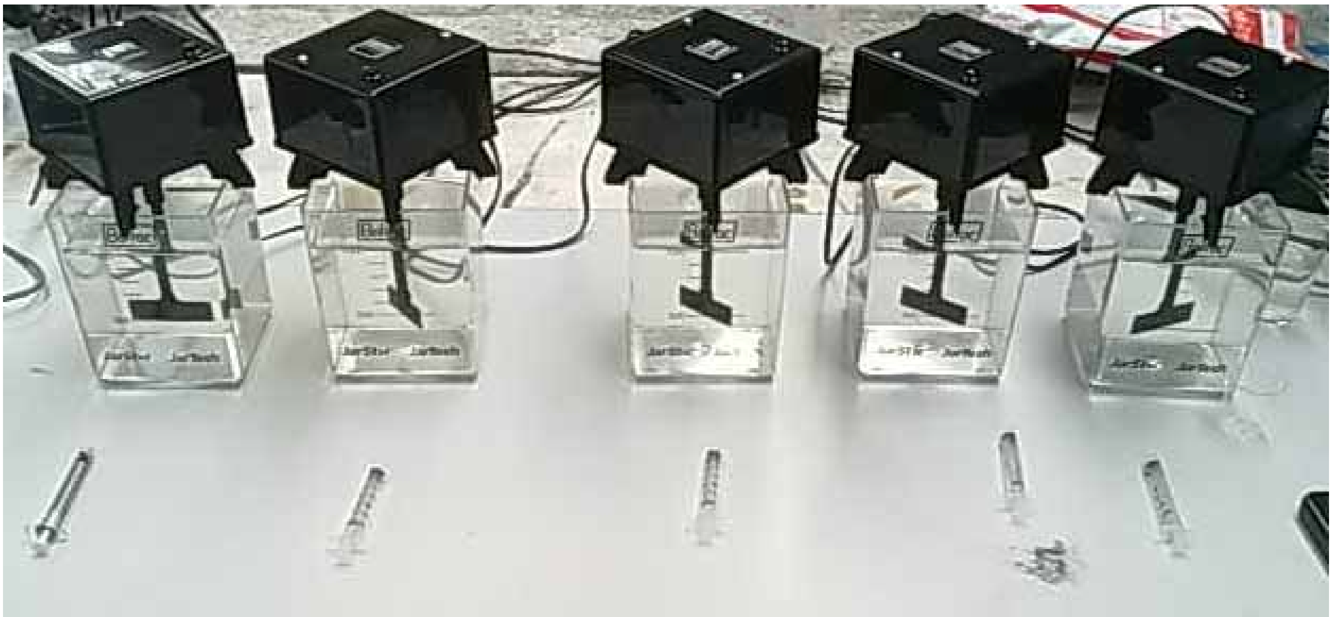
3.3 BENCHTOP WORK TO REDUCE PHOSPHORUS IN STREAM WATER

There have been a number of benchtop tests conducted on waters from various streams in the Lake Rotorua watershed that demonstrate the effectiveness of alum as an efficient phosphorus locking agent. These studies compare commonly used and readily available coagulants of alum and ferric chloride against proprietary products designed for capping of lake sediments such as Phoslock™. The studies clearly demonstrated rapid uptake of dissolved reactive phosphorus , DRP, onto trivalent aluminum oxyhydride and slower performance of proprietary products at equivalent dose rates. However it is important to note that proprietary products are not designed for in-stream treatment of phosphorus and these studies must not be considered to detract from their application as lake sediment capping materials.

During 2004/5 Utuhina and Puarenga Streams were evaluated for the uptake of DRP onto coagulants, alkalinity deficit and the impact of low pH conditions on oxyhydride floc. Later benchtop studies had similar outcomes for water from Waitangi Soda Springs (phosphorus and iron rich thermal water that feeds Lake Rotoehu) and on Lake Rotorua water collected from BoPRC monitoring points. All benchtop chemical trials were sampled at site and pre-treated with analytes measured by a registered analytical laboratory. Analyses included TP, DRP, Alkalinity, pH, Al, Fe and others as necessary to investigate performance of reagents to remove or lock phosphorus.

In later tests a computer controlled Boltac gang-stirring paddle mixers with 1-litre samples were dosed with 1% coagulant to achieve the desired active chemical concentrations. They provided an excellent basis for completing the benchtop work. The mixing energy could be varied to approximately mimic conditions that could be expected to occur over the mixing zone of the stream.

Figure 1: Lake Rotorua and Lake Rotoehu TLI's from 1990 to 2011



Selected results from various benchtop work are given in Figure 4 and Figure 5. Utuhina Stream results show that alum is slightly more effective than ferric chloride for control of DRP when the dose exceeds 0.5ppm. There is little merit in dosing the Utuhina Stream with much more than 1.0 to 1.5 ppm Al^{3+}. At these rates greater than 70 percent binding of DRP onto aluminum can be expected.

Puarenga stream results show that higher alum dose rates are required to bind DRP. The optimal dose rate is between 1.5 to 2.0 ppm Al^{3+}, or up to 20 ppm alum at 47% stock solution.

Figure 4 Utuhina: Phosphorus removal efficiency

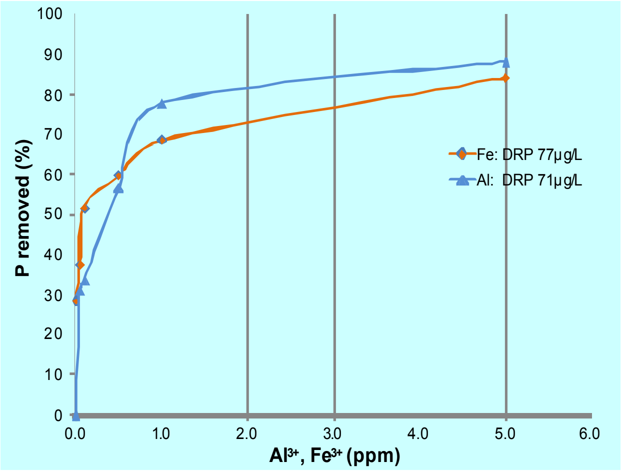
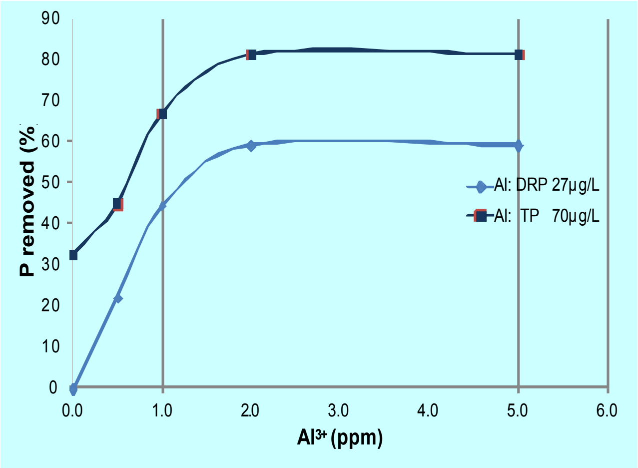


Figure 5 Puarenga: Phosphorus removal efficiency.



The concept of phosphorus locking was developed from observation of results such as Figures 4 and 5 where rapid uptake of phosphorus occurred at only a low dose of aluminum. It was also speculated that low concentrations of aluminum having a long contact time with lake water may have the added benefit of complexing more phosphorus than was demonstrated by short duration contact with stream water.

3.4 COST TO REMOVE OR LOCK PHOSPHORUS FROM STREAM WATER

An early initiative of the chemical reagent program looked to totally remove phosphorus from stream water to achieve a reduction of phosphorus into Lake Rotorua. This required a dose rate somewhere between 3.0 to 5.0 ppm Al^{3+} to create a floc of sufficient size to be readily removed by filtration and/or sedimentation.

The treatment facilities required to achieve phosphorus removal would involve the following main processes:-

i. Chemical reception, storage and dosing including coagulant, flocculent and alkalinity correction chemicals.

ii. Stream intake/return structures.

iii. Chemical mixing and flocculation.

iv. Sedimentation (and possibly filtration)

v. Compliance pond

vi. Solids thickening and dewatering

vii. Solids load-out facilities

viii. Control centre.

While plant capital costs could be distributed over the life time of the facility, chemical cost is an annual amount that is subject to market fluctuations. An estimate of this cost for a stream of around 2 cumecs flow in 2004 indicated $7,000,000$^+$ capital and $2,500,000 chemical cost annually. As these costs are 'per stream' they are replicated for each stream treated, i.e. three streams would have a total combined chemical cost of around $7.5m annually. This illustrated that chemical costs over a 10-year minimum expected operating life would far out way any other cost. Other matters such as sophistication of the plant and disposal of sludge further discouraged adopting the complete removal of phosphorus. This can be compared to the far more cost efficient and less invasive strategy of a phosphorus locking plant, which cost in the order of $200,000 to $350,000.

3.5 LAKE SEDIMENT CAPPING AND WATER CIRCULATION

Lake Rotorua stratifies for short periods with hypoxic conditions below 12 metres depth. During this time depleted oxygen below the thermocline deters water life from staying in a barren landscape that is typical of the lake depths. This promotes the concept of capping lake sediments below the 15 m contour that contribute most strongly to the internal recycling of nutrients. In this way only the most barren areas of the lake would be affected by the cap, with more ecologically rich margins left untouched. Invaluable work by Gibbs *et al* (2008) studied the concept of permanently encapsulating nutrients beneath a thin cap of phosphorus adsorbing material to eliminate recycling of phosphorus between the sediments and water column. Of the four substances studied, alum performed well at an application rate of 80g/m^2 to control phosphorus that leaches from the top 4 cm of sediment at a rate close to 3.2 gP/m^2 at pH 6.8. The alum application rate includes a margin of close to twice the amount implied by the binding capacity of alum that is around 45g P/kg alum at pH 7, an excellent binding ratio of close to 1:1 Al^{3+}:P. However, despite this being the most effective material studied for controlling phosphorus, it was not preferred because the light floc layer formed by aluminum oxyhydride was thought to be susceptible to the actions of currents that might relocate or re-suspend significant areas of the cap. Furthermore alum does little to control nitrogen, a key parameter of concern to the eutrophication of Rotorua lakes.

Apart from the significant cost and supply logistics, other key deterrents to applying a sediment cap are public perception of such a large scale application operation and the fact that deposition of sediments will gradually bury the cap over a period of around ten years to the point where the nutrient internal cycle would completely re-establish itself. This would require the lake sediments to be capped at intervals of less than ten years to maintain control of the internal nutrient cycle.

A later study by Gibbs *et al* (2011) examined lake currents to understand the movement of lake water in relation to wind direction and other contributing environmental factors. These studies found during non-stratified conditions that the entire lake water body uniformly circulates around the island of lake Rotorua at between 100 to 700 m/h depending on wind speed. The higher velocity (0.2 m/s) is noted as being sufficient to suspend fine sediment. A reverse in wind direction forced the direction of water rotation to also reverse within a day or two. During stratified conditions surface waters continued to respond to the wind as for fully mixed conditions, however water below the thermocline the water rotated in the opposite direction and at a similar velocity to that above. These studies confirmed that targeting selected areas of the lake sediments would need to be done while there is little current and the capping material will need to withstand the action of low velocity currents.

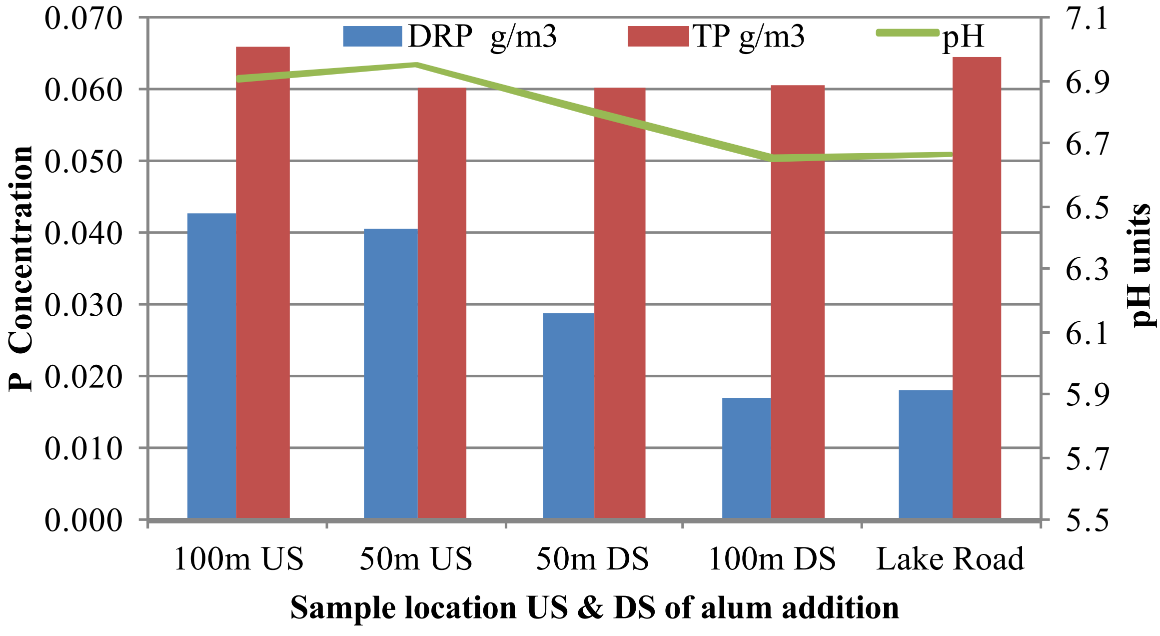
Though many of these studies were not done when stream application trials of alum began they demonstrate that any method of applying a substance that could continually control at least one of the key nutrients and have minimal effect on the habitat and water quality would overcome many obstacles of a comprehensive capping plan, particularly if it avoided the need to add other chemicals designed, for example, to sustain lake water alkalinity (i.e. consumed in the formation of an oxyhydride complex when applied in bulk).

3.6 STREAM TRIALS OF ALUM APPLICATION

Stream trials involved the construction of an alum storage and dosing facility at Depot Road, Rotorua. The facilities include a 30,000 L chemical grade tank with secondary containment bund and a chemical metering system to an outfall diffuser in the Utuhina Stream. The outfall position was selected for it's proximity to downstream bridge buttresses and stream directional changes that promote mixing of alum added to the stream water. Monitoring by BoPRC during August 2006 to March 2007 from above and below the outfall point is shown in Figure 6 as averaged results. Total nitrogen remains reasonably consistent throughout the study area despite various drain and minor stream inputs. Dissolved Reactive Phosphorus, DRP, results are consistent for the upstream monitoring points and show that alum mixing and reaction is well in progress by 50 metres downstream and complete by 100 metres downstream. Monitored results suggest that 1 mg/L Al^{3+} will give DRP of between 0.002 to 0.02 mg/L when treating Utuhina Stream water. The treated water result for the target dose rate of 1 mg/L Al^{3+} is therefore slightly better than indicated in Figure 6 giving a 75 percent reduction in DRP at a concentration ratio of aluminum to DRP is 33:1, which is less than achieved during the benchtop work of 18:1. This is due to the stream DRP start value of 0.042 and benchtop DRP start value of 0.071mg/L, and stream water having a pH value outside of the maximum efficiency range of alum.

These ratios fall well short of the binding ratio of 2:1 achieved for sediment trials, which suggests additional binding capacity exists for stream dosed alum that can be exerted once mixed with lake water, particularly where aluminum oxyhydride meets more favourable pH conditions when in contact with sediments. Alum added to stream water drops the pH by 2 points causing little if any effect. Normal stream water pH is close to pH 7, well above the optimal range for alum of 5.5 to 6. Despite this, the trials proved effective in control of DRP. The dosing facility trial finished in 2008 and now functions as a key lake restoration project. Success of the Utuhina facility lead to implementing a second facility situated within Rotorua Wastewater Treatment Plant grounds that adds alum to the Puarenga Stream.

Figure 6: Utuhina Stream phosphorus and pH profile

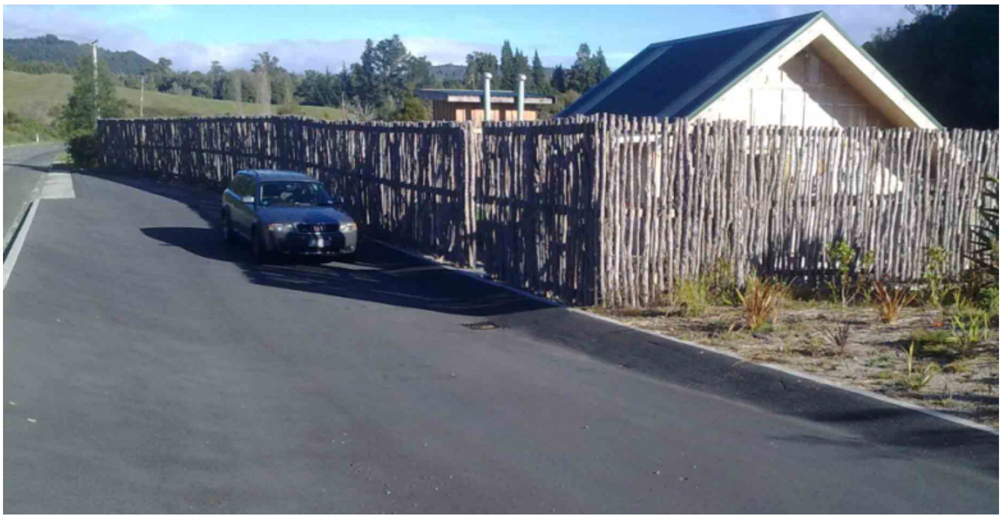


The Puarenga facility in Figure 7 is conceptually similar to the one at Utuhina. It was commissioned in 2010 to deliver 2 ppm Al^{3+}, as indicated by benchtop work results shown in Figure 5 above. The Puarenga facility is an existing disused wastewater plant alum dosing system that was refurbished for the purpose of a phosphorus locking plant.

Figure 7: Puarenga Stream phosphorus locking facility

The Waitangi Soda Spring phosphorus locking facility is situated in the immediately vicinity of a commercial bathing complex. The building is essentially a covered bund where all operational activities are completed without any need to enter the building.

Figure 8: Lake Rotorua and Lake Rotoehu TLI's from 1990 to 2011



3.7 BIO-MONITORING OF UTUHINA STREAM

In August 2008 Scion produced results of two surveys studying the condition of various Rotorua streams in regard to fish abundance over the period November 2006 to July 2008. For the Utuhina Stream notable changes in fish abundance were recorded during the first year of alum dosing. The common bully (*Gobiomorphus cotidianus*) greatest decrease in density coincided with the highest dose rate of alum over months of the plants early operation. The latest survey however shows these populations have re-established which suggests they have either acclimatised or the decline in population was associated with other factors.

Interestingly, Rainbow and Brown Trout (*Oncorhynchus mykiss and Salmo trutta*) and Koura (*Paranephrops planifrons*) populations generally increased during the study period suggesting alum had no clear effect on stream biota despite two years of alum dosing. Aluminum increased in tissue samples of biota in the Utuhina Stream compared with that of other Rotorua streams with the most significant being in the animals liver. There was minimal increase in flesh.

It is also noted that toxicological studies focus on a pH<5.5, where aluminum is more likely to adversely affect fish by adhering to gill surfaces. Stream and lake water pH is close to pH 7 where aluminum does not exhibit strong toxicity. Fish are also able to move away from water conditions that they sense as unfavourable, e.g. stream mixing zones, too warm, too bright, etc.

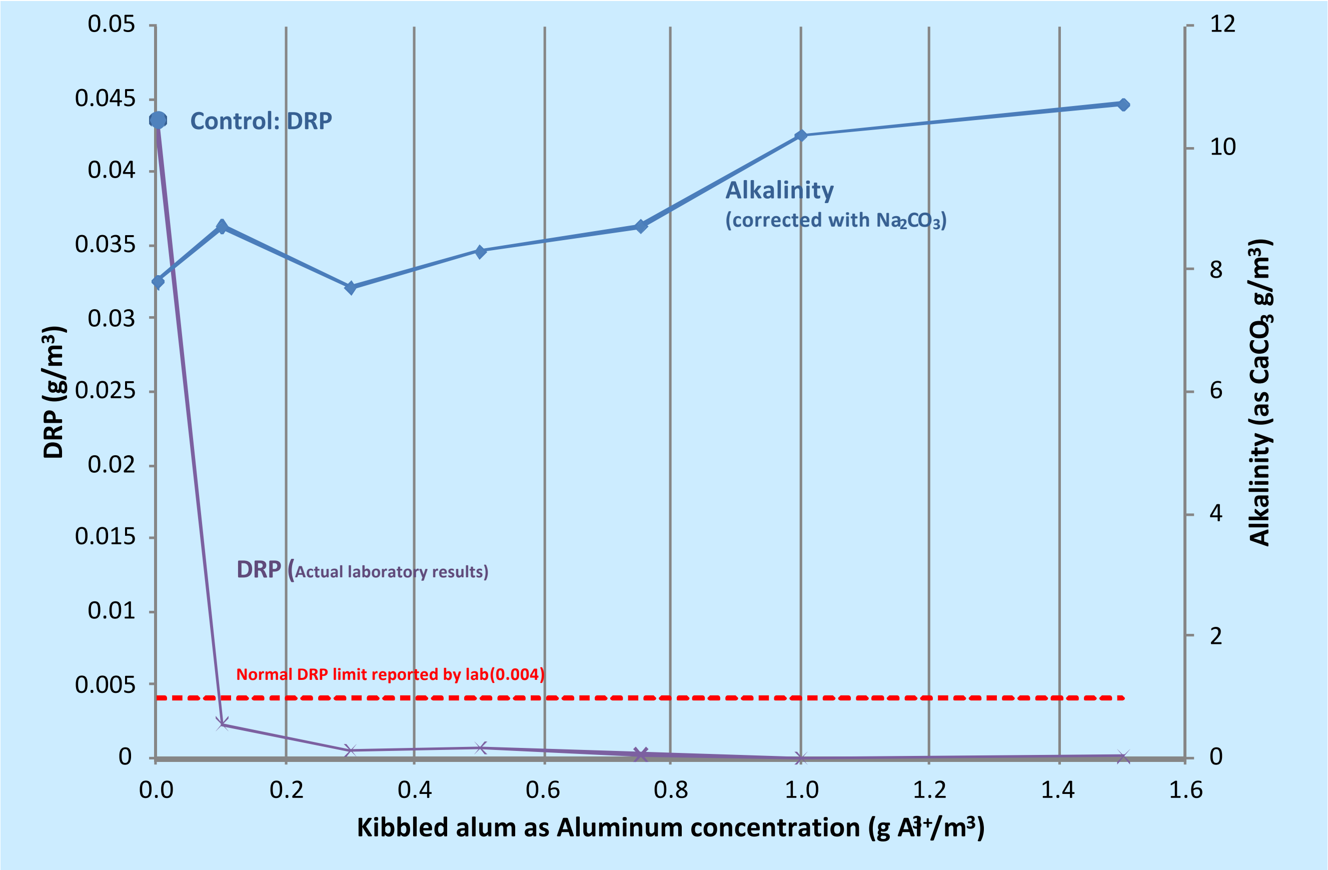
Overall, the study concludes there is no loss of fish population density attributable to aluminum dosing into Utuhina Stream water.

4 EFFECTS ON LAKE ROTORUA

4.1 LAKE ROTORUA BENCHTOP WORK

Benchtop work on Lake Rotorua water confirmed that low concentrations of aluminum addition will form a settleable floc. A 24-hour settling column test showed that aluminum at 0.3mg/L was sufficient to form a thin layer of settled material and 0.1mg/L locked the available DRP. Figure 9 shows rapid locking of DRP to beyond the detectable limit of the laboratory test. The alkalinity of each sample was maintained relative to the control sample by adding sodium carbonate during the rapid mix stage to hold the pH at 6.5. Even at one percent solution sodium carbonate continued to adjust pH for some time after it was added making it difficult to match that of the control. This caused the final pH of more heavily dosed samples to be half a pH unit higher than required, and consequently alkalinity of 3 mg/L higher than the control. It is also noteworthy that adding 0.3 mg/L aluminium only reduces the lake water pH by 0.1 units which implies an alkali buffer is not required when adding alum at these low rates.

Figure 9: Locking of DRP in Lake Rotorua water treated with 1% solution kibbled alum



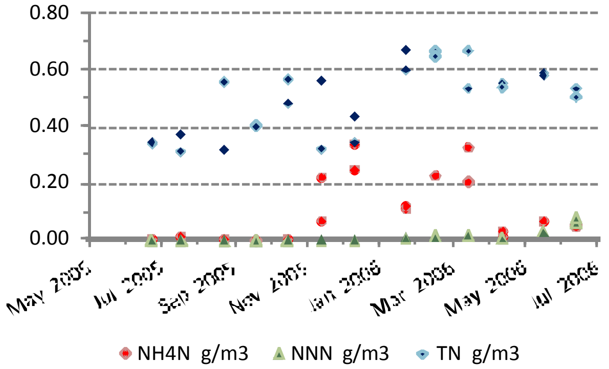
This suggests that aluminum oxyhydride resulting from alum addition to Lake Rotorua streams will precipitate to settle with algae and be deposited at the lake bed, gradually and continuously integrating with sediments. If enough aluminum is deposited, phosphorus released from the sediment during degradation of settled algae will instead be substantially locked onto aluminum, thereby minimising it's bioavailability. There are some early monitoring results in support of the hypothesis that this mechanism may be taking effect. Recent results from the Regional Council for nitrogen and phosphorus indicated a normal seasonal hypoxic release of nitrogen and subdued release of phosphorus from lake sediments. Also noteworthy is that proliferation of blue-green algae was suppressed which is tentatively attributed to a deficiency of excess phosphorus in the water column. Ongoing work is planned to determine the amount of aluminum accumulating in lake bed sediment and to confirm the extent of changes in the algal population. The mass of accumulated aluminum can then be compared against the amount needed to effect capture of phosphorus.

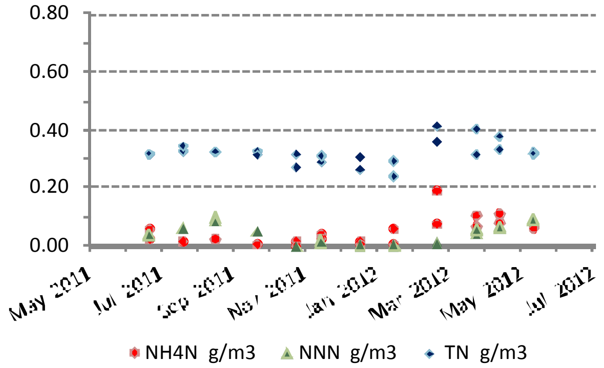
Aluminum in the colloidal form is unlikely to settle and will continue to circulate within the water column for long-term contact with phosphorus until it either grows sufficiently to precipitate and settle, or is ultimately flushed from the lake.

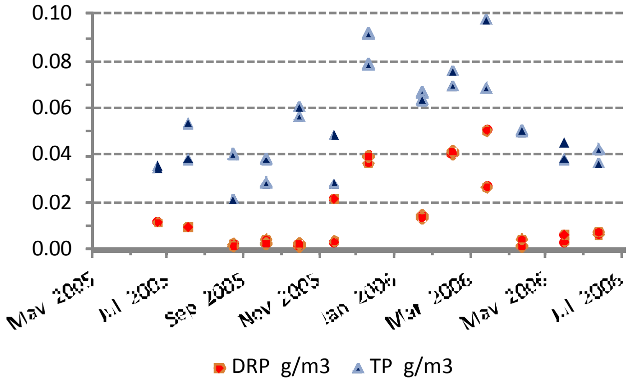
4.2 LAKE ROTORUA WATER MONITORING RESULTS

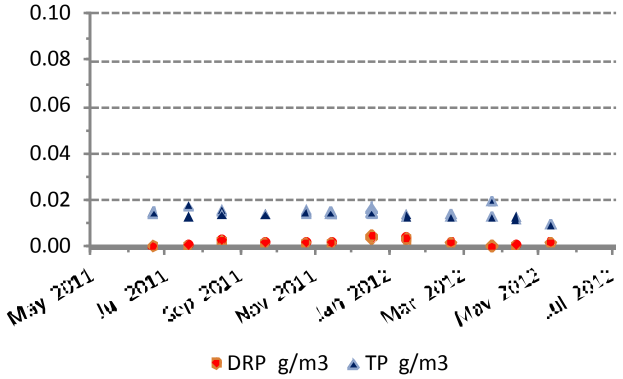
Figure 10 shows lake water nutrient analyses from samples taken as part of Regional Councils lake monitoring program. Plots to the left are nutrient concentrations in Lake Rotorua water during the period May 2005 to July 2006, prior to the addition of alum. Plots to the right are nutrient concentrations over the period during 2011/12. There is a clear trend of lower phosphorus concentrations for both total and dissolved reactive forms with a 7-fold reduction in DRP and nearly 4-fold reduction in TP which represents a massive reduction of phosphorus available to algae. While aluminum will not directly lock nitrogen, it is plausible that secondary effects are causing a change here as well. Some decline in nitrogen values will be due to initiatives to control land and urban inputs to the lake. However the bulk is likely due to disruption of the lake internal nutrient cycle and some flushing of soluble nitrogen by discharge through the lake outlet. Work is ongoing to determine the mechanisms occurring.

Figure 10 Comparison of Lake Rotorua Nutrient concentrations









5 CONCLUSIONS

The present objective of dosing alum to streams goes beyond the initial concept of locking phosphorus in the stream flow. Natural circulation of lake currents are utilised to distribute the aluminum, and long contact times are used, to continue locking phosphorus within the lake body itself. The greatest benefit however is not limited to locking of phosphorus within the streams, but also the locking of at least part of the 36 tonnes of phosphorus recycled internally from lake sediments. The uniform integration of aluminum into lake sediment promotes maximum opportunity for control of benthic phosphorus, a distinct advantage over the alternative of capping the sediments. Should the locking capacity of lake water phosphorus by aluminium prove as effective as tests indicate, then alum dosing to the contributing streams alone will be a most economic means of improving the lake TLI to target levels and also an excellent means to control it at the desired level while other catchment wide initiatives take effect.

6 OPPORTUNITIES

There is an obvious opportunity for absorptive materials to be used to control excess phosphorus at other freshwater bodies, though extensive study is needed to balance the likely effects and benefits and a comprehensive program is required to monitor changes in the water body, sediments and life forms.

For a number of years alum has been applied to treated wastewater, with significant capital invested to remove, concentrate and dispose of precipitated phosphorus. An interesting aspect of the phosphorus locking strategy is that only small additions of aluminum are needed to effect control of phosphorus and complete removal of this phosphorus is therefore not required. There is an opportunity to investigate the suitability and acceptability of phosphorus locking of treated effluent without removing it from the discharge. A well planned environmental monitoring program would be needed as part of an overall management plan to confirm environmental aims are met. Phosphorus locking could also be an interim measure while plans and finances are confirmed for the typically heavy expenditure on additional sedimentation and sludge handling facilities. Phosphorus locking facilities cost only a small part of a total phosphorus removal plant.

The control of blue-green algae could also be of interest at water treatment plants especially where pre-oxidation of water is needed and may otherwise cause release of toxic substances associated with these organisms. Low doses of alum to reservoir storages may assist to control algae and assist with locking of phosphorus in sediments. The effect that sustained aluminum accumulations might have on raw water storage turnover conditions cannot be commented on, but is likely to be favourable to treated water quality and therefore worthy of further study.

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