IN THE MATTER OF	The Resource Management Act 1991
AND	
IN THE MATTER OF	Lake Rotorua Nutrient Management – **PROPOSED PLAN CHANGE 10** to the Bay of Plenty Regional Water and Land Plan

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STATEMENT OF EVIDENCE OF DAVID PHILIP HAMILTON
ON BEHALF OF THE BAY OF PLENTY REGIONAL COUNCIL

Evidence topic: Lake Rotorua Water Quality

Contents:

Qualifications and experience

1. My full name is **DAVID PHILIP HAMILTON**. I hold a position known as the Bay of Plenty Regional Council Chair in Lake Restoration at the University of Waikato. This is a professorial position based at the University of Waikato. I am a Principal Scientist in the Environmental Research Institute (2012-date) at the University of Waikato and hold and adjunct professorial position in the Nanjing Institute of Geography and Limnology at Nanjing, China.

1. I hold the following qualifications: PhD (Zoology, University of Otago, 1991) and BSc (Zoology, University of Otago, 1984).

2. I am a freshwater ecologist with applied and fundamental research interests in lake ecosystem modelling and management, and dynamics of nutrients and algae. I have published more than 200 peer reviewed scientific research papers on this subject matter, as well as more than 100 client reports and several book chapters. This includes more than 10 peer reviewed scientific papers and more than 10 reports on Lake Rotorua.

3. Much of my applied research has involved applications of predictive computer models for water quality assessments. For the Rotorua lakes, these models have been used to generate scenarios of future water quality in response to management actions. Such examples include the Lake Rotoiti diversion wall, Lake Rotoehu artificial destratification and Lake Rotokakahi catchment management. I have been a member of the Water Quality Technical Advisory Group (WQ TAG) convened by the Bay of Plenty Regional Council (BoPRC) since the establishment of the Bay of Plenty Regional Council Chair in Lake Restoration in 2002. As a member of the WQ TAG, I have contributed to statements related to the need for control of both nitrogen and phosphorus loads to Lake Rotorua to improve water quality, and to determine the relevance of nitrogen and phosphorus loads from wastewater on lake water quality.

4. I am a professional member of: the International Society for Limnology (Senior Associate Editor of the Society's journal *Inland Waters*, New Zealand's international representative); New Zealand Freshwater Sciences Society (in 2010 I received the Society's Medal for Outstanding Services to Freshwater and I served as President of the Society from 2010 to 2014); and the Allied Sciences of Limnology and Oceanography (ASLO). Besides editorial roles with *Inland Waters*, I am an Associate Editor with two international scientific journals: *Hydrobiologia* and *Aquatic Ecology.*

5. I have previously presented evidence on the analysis of Lake Rotorua water quality trends: 2001-2012 for an Environment Court mediation hearing on 21st November 2012. I provided evidence to the Environment Court in respect of the Ohau Channel diversion wall [Chapple v Bay of Plenty Regional Council W77/2006 dated 8 September 2006[1]].

6. I am familiar with the Lake Rotorua Nutrient Management – Proposed Plan Change 10, which intends to give effect to and reflect the operative Regional Policy Statement, including the operative policies that apply to the Lake Rotorua groundwater catchment, which seek to:

   (a) Establish limits for the total amount of specified contaminants that enter the receiving waters within the Rotorua catchment and which states the limit of N for Lake Rotorua **[Policy WL 3B]**

   (b) Allocate among land use activities the capacity of Lake Rotorua to assimilate contaminants within the limits established in accordance with Policy WL 3B **[Policy WL 5B],** and

   (c) Require, including by way of rules, the managed reduction of any nutrient losses that are in excess of the limits established under Policy WL 3B **[Policy WL 6B].**

7. As the Bay of Plenty Regional Council Chair in Lake Restoration at the University of Waikato, I have played a central role in coordinating research projects on lakes in the Bay of Plenty region. Some projects are funded directly through the Chair and include support for student and post-doctoral research. Other projects are funded through external organisations, including the Ministry of Business, Innovation and Employment, Lake Tarawera Ratepayers' Association, Beca (as part of the assessment of environmental effects of diversion of the Ohau Channel diversion wall) and Rotorua Lakes Council (assessment of environmental effects of discharge of wastewater from Rotorua wastewater treatment plant). I am also involved in the National Objectives Framework of the National Policy Statement for Freshwater Management, as a member of panels for 'Science Review', 'Lakes' and 'Cyanobacteria'. My expertise therefore includes an understanding of the evolving

[1] The wall's intention was to divert the nutrient rich Lake Rotorua water into Okere Arm in order to reduce nutrient loads to Lake Rotoiti, as the elevated nutrient levels contributed to cyanobacteria blooms in Lake Rotoiti.

water policy framework arising from the National Policy Statement for Freshwater Management (2014) and its subsequent iterations.

8. I have read the Expert Witness Code of Conduct set out in the Environment Court's Practice Note 2014 and I agree to comply with it. I confirm that the issues addressed in this statement of evidence are within my area of expertise, except where I state I am relying on the specified evidence of another person. I have not omitted to consider material facts known to me that might alter or detract from my expressed opinion.

Scope of Evidence and Summary

9. My evidence addresses the outcomes of the work that I have done on nitrogen and phosphorus in respect of Lake Rotorua and focuses on these questions:

   (a) How might changes in external (catchment) loads of N and P affect water quality in Lake Rotorua?

   (b) What effects have in-stream interventions (such as alum dosing for phosphorus removal) had on observed water quality at Lake Rotorua?

   (c) What are the sources of N and P in the catchment and the sustainable load?

10. When I refer to nitrogen and phosphorus in this context, it is to the analytical forms of total nitrogen and total phosphorus.

11. The nutrients nitrogen and phosphorus have been identified as the primary ones of concern for Lake Rotorua because:

   (a) They show statistically significant relationships to concentrations of chlorophyll *a* (viz., phytoplankton biomass; the concentration of suspended microscopic algae).

   (b) Dissolved forms of nitrogen and phosphorus have usually been found to stimulate phytoplankton growth in small-scale experiments (known as bioassays or mesocosms) compared with controls (no added nutrients). Concurrent nutrient additions (i.e., nitrogen plus phosphorus) usually stimulate phytoplankton growth to a greater extent than individual nutrient additions. The nature of this stimulatory response can vary in time (e.g., seasonally with water temperature) and space (e.g., proximity to inflows) (Abell et al. 2014). The dissolved forms of nutrients – nitrate and/or ammonium, and phosphate commonly used for these experiments are constituents of nitrogen and phosphorus in their total form.

(c) Dissolved (viz.,bioavailable) forms of nitrogen and phosphorus are commonly depleted to very low levels in Lake Rotorua during periods of increased growth of phytoplankton, often associated with elevated water temperature and high light levels (e.g., summer-autumn). This is consistent with these nutrients being available at concentrations that are limiting the growth of phytoplankton at these times.

12. Between 2011 and 2014, I have carried out the following studies:

(a) Modelling of the effects on water quality of alum dosing of two inflows to Lake Rotorua and comparisons with external nutrient load reductions (Hamilton et al. 2015). Alum (aluminium sulfate) is used as a remediation (geoengineering) material to bind phosphorus and render that phosphorus unavailable for phytoplankton growth (see Douglas et al. 2016). The study by Hamilton et al. (2015) found that: (1) alum dosing of two stream inflows (Utuhina Stream commencing 2006 and Puarenga commencing 2010) was responsible for recent improvements in water quality of Lake Rotorua, enabling the Trophic Level Index (TLI) target (4.2) in the Regional Water and Land Plan to be attained in 2012, and (2) major reductions[2] in catchment phosphorus loads would be required to similarly replicate the impacts of alum dosing, assuming nitrogen loads remained unchanged.

(b) A study into the environmental effects of treated wastewater discharge to Lake Rotorua (Abell et al. 2015). This report was aligned with a decision of the Rotorua Lakes Council to remove treated wastewater discharges from the Whakarewarewa forest of the Puarenga catchment of Lake Rotorua, and seek an alternative discharge option. This study updates the modelling described in 12(a). It provides a comprehensive documentation of the major assumptions involved in the model set-up. Twenty-eight model scenarios were run to simulate different nitrogen and phosphorus loads to the lake associated with a variety of wastewater treatment and discharge options, and different alum dosing regimes. The effects of the different wastewater

[2] The reductions required to naturally replicate the effects of alum dosing are much greater than the reductions required to meet the sustainable lake load of P in conjunction with the reductions in N. In lay terms, we just could not remove enough P from inputs to the Lake to achieve this, and so need to also reduce N.

treatment options, representing slightly different nitrogen and phosphorus loads to the lake from variations in wastewater treatment methods, were negligible to minor as expressed by the TLI value. The nitrogen load reductions proposed under PC10 are more than an order of magnitude larger than those associated with the total load from treated wastewater.

(c) A report on anthropogenic phosphorus loads to Lake Rotorua (Tempero et al. 2015a). Phosphorus loads originate from natural sources (e.g., weathering of bedrock which releases phosphorus) and anthropogenic sources (e.g., fertiliser use, intensive land uses). This report quantified the relative contributions of phosphorus from natural and anthropogenic sources in the catchment, so that phosphorus management options could be considered with the aim of reducing phytoplankton biomass in Lake Rotorua. The report provides an understanding of the fraction of catchment phosphorus loads which may be amenable to land use management and controls, and how these sources can be managed concurrently with nitrogen load reductions envisaged under PC10, to achieve the TLI target of 4.2 for Lake Rotorua.

13. These studies are presented in three reports (Hamilton et al. 2015; Abell et al. 2015; Tempero et al. 2015a). Copies of these reports have been uploaded to the "Rotorua Te Arawa Lakes Programme" website, and form part of the Science reports library. The reports are also referenced and summarised in the section 32 report produced by the Regional Council in support of the Proposed Lake Rotorua Nutrient Management Rules Plan Change 10: Appendix 12.

14. My evidence is based upon these reports.

15. Conclusions arising from the report by Hamilton et al. (2015) are given below:

(a) *Improvements in TLI with alum dosing:* Since the mid-2000s, there has been a general decline in the TLI of Lake Rotorua (i.e. improved water quality; Abell et al., 2012; Smith et al., 2016), and the annual average TLI reached the target value of 4.2 in 2012 and 2014 (BoPRC, 2015a). The TLI is derived from equally-weighted, scaled measurements of total nitrogen concentration, total phosphorus concentration, chlorophyll *a* concentration and Secchi depth. The TLI target for Lake Rotorua is 4.2 (BoPRC et al., 2009), which is at the lower end of the eutrophic category (4.0–5.0; Burns et al., 1999). Lower values of TLI correspond to higher levels of water quality.

(b) *Concentrations of nitrogen and phosphorus in lake water have declined but stream loads and concentrations have not declined since c. 2006.* Based on our findings, a significant factor contributing to recent improvements in water quality is the action of dosing aluminium sulfate (alum) to Utuhina Stream (2006) and Puarenga Stream (2010). Concurrently, concentrations of nitrogen and phosphorus in stream inflows to Lake Rotorua showed no indication of decrease.

(c) *Alum dosing has been highly effective in reducing levels of dissolved reactive phosphorus in the two stream inflows where the dosing takes place.* The alum dosing regime at Lake Rotorua inflows has been highly effective in adsorbing ('locking up') dissolved reactive phosphorus (DRP) in the stream inflows, particularly above certain threshold dosing concentrations (c. 100 kg day^{-1} Al in Utuhina Stream and 75 kg d^{-1} Al in Puarenga Stream). Alum dosing has resulted in low dissolved reactive phosphorus concentrations and low ratios of DRP to total phosphorus (DRP:TP) in the stream inflows below the dosing point.

(d) *The effectiveness of the alum dosing has extended beyond stream inflows and into the lake.* On the basis of DYRESM-CAEDYM[3] model simulations, it can be surmised that alum dosing has impacted on lake concentrations beyond immobilising DRP in the Utuhina and Puarenga Steam inflows. Alum dosing of these inflows not only reduces DRP loads from the inflows, but also results in 'excess' alum entering the lake where it continues to 'lock up' phosphorus and remove it from the water column via sedimentation to the lakebed sediments.

(e) *Alum dosing may bring about high rates of sedimentation of organic matter in the lake, thereby removing particulate nitrogen and phosphorus.* Considering the relatively low levels of DRP in the lake compared with levels in the two stream inflows above the respective dosing plants, it is possible that the mode of action of the aluminium may be slightly different between the inflows and the lake. Flocculation of organic material and subsequent sedimentation of

[3] DYRESM-CAEDYM comprises a hydrodynamic model (DYRESM – Dynamic Reservoir Simulation Model) coupled to a water quality model (CAEDYM – Computational Aquatic Ecosystem Dynamic Model). DYRESM-CAEDYM is the most widely cited aquatic ecosystem model in the scientific literature (Trolle et al., 2012) and Hamilton was the original developer of the CAEDYM model. The model has been applied to several lakes in New Zealand for long-term (multi-year) simulations, to understand in-lake processes and inform management decisions.

the floc may increase under the relatively quiescent conditions in the lake and there is evidence for this effect in the marked decreases in both total phosphorus and total nitrogen concentrations after 2010, when high rates of alum dosing were undertaken in the two streams.

(f) *Alum dosing may have altered the composition of lakebed sediments, which would reduce loads of nutrients from lakebed sediments.* High-frequency dissolved oxygen measurements from 19 m depth at the lake buoy site show a substantial decrease in the frequency of anoxia[4] over the past 2-3 years. The consistency of this reduction indicates that alum has directly or indirectly altered the composition of the bottom sediments, in a way that has resulted in lower rates of oxygen consumption and reduced rates of nitrogen and phosphorus release from the sediments. The direct mode of action of alum may be due to changes in the chemical composition of bottom sediments from alum floc deposition. The modified bottom sediments may have lower rates of oxygen consumption. In addition, improvements in lake trophic status and reductions in the rate of organic matter deposition (lake-wide as opposed to adjacent to the inflows) may reduce oxygen consumption rates.

(g) *Persistence of the benefits of alum dosing might be expected for 2-3 years following its discontinuation.* Based on a conservatively estimated (i.e., low) sedimentation rate of 0.3 m d^{-1} for alum flocs and a mean depth of 10 m for Lake Rotorua, calculations indicate that around 40% of the alum floc would persist after 30 days and about 7% after 90 days. More persistent effects (i.e., >90 days) are likely to be associated with the way in which deposited alum flocs alter the bottom-sediment composition. Based on the progressive reduction in the rate of oxygen consumption in the bottom waters over 2-3 years following intensive stream alum dosing, legacy effects of alum dosing may persist over a period of around 2-3 years following termination of dosing.

(h) *Alum dosing was the primary factor identified in the progressive reduction in TLI values in Lake Rotorua from 2008-12.* Lake model simulations without the stream alum dosing resulted in a TLI3 value approximately 0.5 units higher than for the simulation without alum. This three-parameter TLI value (including nitrogen, phosphorus and chlorophyll *a*) was calculated as a mean from a multi-year simulation period as Secchi depth is not a direct output from

[4] Absence of free dissolved oxygen in water. Other oxidised species (e.g., nitrate, sulphate) have generally not been reduced and are still present in water.

the lake model. Without the inclusion of Secchi depth the TLI3 is approximately 0.1 units higher than the four-parameter TLI value which is commonly reported. The simulations suggest that the reduction of TLI in Lake Rotorua through the period of 2008 to 2012 would not have occurred without the dosing of alum, and thus the improvements in water quality are directly attributable to its effects.

(i) *Attaining the TLI target in 2012, while nitrogen loads were comparatively high, was associated with large reductions in lake water phosphorus concentrations as a result of alum dosing.* Simulations were undertaken with the model DYRESM-CAEDYM to encompass different scenarios of catchment nutrient loads, alum dosing, and additional measures to reduce the phosphorus load to the lake. They indicated that for a scenario of increased nutrient load without any dosing of alum or phosphorus load mitigation (N730; equivalent to a total nitrogen load to the lake of 730 tonnes per year), mean TLI3 for the simulation period would be 5.57. This TLI represents strongly impacted (i.e., degraded) water quality relative to the RLWP TLI targets of 4.2 for Lake Rotorua. Therefore, in the absence of the alum dosing, the TLI would have been much higher than the actual value, and the lake water quality would have been strongly degraded.

(j) *Model simulations indicate that a nitrogen load of 435 t y^{-1}, together with a proportional reduction in phosphorus load, will achieve the target TLI for Lake Rotorua of 4.2.* DYRESM-CAEDYM model simulations presented in the report indicated that a reduction of catchment total nitrogen loads from 641.5 to 435 t y^{-1} and TP loads from 34.5 to 23.4 t y^{-1} (DRP reduction from 23 to 15.6 t y^{-1}) led to a reduction in the Trophic Lake Index (TLI) to the RLWP target value of 4.2 (equivalent to TLI3 of 4.3). These simulations correspond to the nitrogen load target of 435 t/yr in the PC10 Managed Reduction Target and conform approximately to the nominal phosphorus external catchment load of 37 t yr^{-1} mentioned in LR M2(c) of PC10.

(k) *Phytoplankton species composition may be altered with nutrient reduction strategies. It is important to decrease phosphorus loads together with nitrogen loads to reduce the potential for potentially nitrogen-fixing cyanobacteria blooms.* Aside from the simulation mentioned above (paragraph 15j), only model scenarios with alum dosing consistently met or bettered the TLI target for Lake Rotorua. A TLI below target levels was simulated by maintaining the current nitrogen load and using a full range of phosphorus reduction measures (a combination of phosphorus external load reductions, alum treatment of inflows, elevated in-lake flocculation of particulate organic material and reduced release of phosphate from the lake sediments). These simulations indicated a shift in the nutrient limitation of phytoplankton from co-limitation by nitrogen and phosphorus to predominance of phosphorus limitation under the phosphorus reduction strategies. Indirect evidence of a shift towards phosphorus limitation is indicated in field observations from Lake Rotorua after 2010, specifically very low DRP concentrations and occasional elevated concentrations of nitrate in surface waters.

(l) *The intensity and sustainability of alum dosing need to be carefully weighed against the management of present and future loads of both nitrogen and phosphorus from catchment land use.* Specifically, in the absence of alum dosing, nitrogen reductions to meet the 435 t/yr PC10 Managed Reduction Target are required because of the large component of natural phosphorus in the total load to Lake Rotorua. This unusually large natural phosphorus load fraction (relative to most other non-volcanic catchments in New Zealand) limits the extent to which the total catchment load of phosphorus can be reduced. This phenomenon is attributable to the large volume of groundwater discharge to the lake, which is DRP-enriched due to dissolution of phosphorus in the rhyolitic pumice bedrock associated with long storage times in the groundwater aquifer. Therefore, without alum dosing, the TLI target will not be attained without reaching the 435 t/yr PC10 Managed Reduction Target as well as the afore-mentioned phosphorus reduction (paragraph 15j). Conversely, phosphorus load reductions need to be achieved in concert with nitrogen load reductions in to reduce dominance by cyanobacteria (blue-green algae) amongst the phytoplankton species assemblage (Smith et al. 2016). This is important to avoid occurrences of blooms and nitrogen-fixation, which are associated with some of the bloom-forming cyanobacteria under low water column nitrogen: phosphorus mass ratios.

(m) *Dual nutrient limitation of phytoplankton (by nitrogen and phosphorus) is common in Lake Rotorua and reaching the 435 t/yr PC10 Managed Reduction Target along with proportional reductions in phosphorus loads will ensure the highest probability of attaining of TLI for Lake Rotorua of 4.2 in the* *absence of alum dosing.* In considerations of managing nutrient loads for eutrophication control, it has been postulated that if either nitrogen or phosphorus is controlled to growth-limiting levels, then control on the other nutrient can be less stringent or negligible. In the case of sole focus on nitrogen, this would be a risky strategy because of potential for proliferation of cyanobacteria (paragraph 15l). In the case of sole focus on phosphorus, this would also be risky because (i) the study by Abell et al. (2014) using field observations and model simulations suggested that in Lake Rotorua there are locations and times when either nutrient or both can limit phytoplankton growth (i.e., dual limitation), and (ii) periods of strongly N-limited phytoplankton growth were demonstrated in experimental bioassays undertaken during a period of intense alum dosing in 2012. The efficacy of controlling a single nutrient to limit primary production is therefore not well supported by direct measurements (e.g., using bioassays), or model simulations (see Smith et al. 2016).

16. Conclusions arising from the report by Tempero et al. (2015a) are given below:

(a) Anthropogenic phosphorus loads to Lake Rotorua are estimated to be 22% (expressed as a catchment areal rate of 0.12 kg DRP ha^{-1} y^{-1}) of the total DRP load and 48% (0.47 kg P ha^{-1} y^{-1}) of the total phosphorus load. This fraction of the respective dissolved and total loads is potentially amenable to reductions from catchment management actions.

(b) In Rotorua stream sub-catchments where groundwater discharge to the lake is volumetrically dominant, e.g., Hamurana (89.3%) and Awahou (79.6%), the natural contribution to DRP and total phosphorus loads was high, despite extensive agricultural land-use in these catchments. By contrast, sub-catchments dominated by surface water discharges, e.g., Ngongotaha (34% groundwater) and Waiteti (15% groundwater), had comparatively high anthropogenic total phosphorus loads, with elevated concentrations of particulate phosphorus.

(c) The minor and ungauged catchments contributing to Rotorua, representing drains, small streams (both coldwater and geothermal), overland flow, groundwater discharge to the bed of the lake, discharge below gauged stream sites and a residual term, were estimated to contribute 33% of anthropogenic particulate phosphorus loads[5] to Lake Rotorua.

(d) Modelling results reported in Hamilton et al. (2015) indicate that a reduction in total nitrogen loads from 641.5 to 435 t y^{-1} and total phosphorus loads from 34.5 to 23.4 t y^{-1} (DRP reduction from 23 to 15.6 t y^{-1}) would be needed to achieve the TLI target of 4.2. These scenarios used inflow nitrogen concentrations derived from ROTAN (Rutherford et al. 2011) and inflow phosphorus concentrations derived (interpolated) from monthly sampling as no catchment-wide phosphorus model is currently available. The model inputs may therefore have underestimated total phosphorus and DRP loads from stormflow events as these nutrients tend to respond positively to increases in discharge (Abell et al. 2013). The study by Tempero et al (2015a) included stormflow total phosphorus and DRP loadings from the Puarenga, Ngongotaha and Utuhina Streams, resulting in a calculated lake TP load of 48.7 t y^{-1} (23.4 t y^{-1} anthropogenic) and DRP load of 27.7 t y^{-1} (6.1 t y^{-1} anthropogenic). Hence, to achieve a TLI target of 4.2 in the absence of alum dosing would require both the 435 t y^{-1} nitrogen load target (PC10) and an estimated reduction in TP of 10–15 t y^{-1}, i.e., anthropogenic TP loading would need to be reduced from c. 23 t y^{-1} to 8–13 t y^{-1}.

17. Since the publication of these two reports (Hamilton et al. 2015; Tempero al. 2015a), no new information has come to my attention that might alter my conclusions. However, some studies on Lake Rotorua have emerged that further consolidate my stance. Information from these studies is summarised in paragraphs [18] to [19] below.

18. Tempero et al. (2015b) undertook a study entitled "Ecotoxicological Review of Alum Applications to the Rotorua Lakes". This report was commissioned by the Bay of Plenty Regional Council to provide guidance on a number of concerns associated with alum dosing of the Rotorua lakes, particularly non-target side effects. The findings from this report are that:

(a) A conservative dosage of total aluminium that does not exceed 200 µg l^{-1} at pH >6.0 - 8.0, 75 µg l^{-1} at pH 5.0 - 6.0 and 25 µg l^{-1} at pH 4.0 - 5.0 was suggested, to minimise potential for acute lethal effects. Bioaccumulation and

[5] At this stage the modelling suggests that future management strategies to address this source of phosphorus could target urban areas and minor and ungauged catchments. This 'residual' load could be investigated further to delineate relative contributions from different sources.

biomagnification of aluminium do not generally occur in biota and pH-dependent dosing guidelines should help to avoid such occurrences.

(b) Current alum dose rates and measured water column total aluminium concentrations are below these proposed threshold values. The current alum dosing programme for Lake Rotorua needs to continue to be conservative to avoid the risk of aluminium toxicity due to the low buffering capacity of the lake water. Excess dosing could risk lake water acidification and acute toxicity for biota, either through direct exposure to reduced forms of aluminium (Al^{3+}) or indirectly from pH.

(c) There is still relatively little information examining the ecological effects of Al-floc formation and deposition. Current dose rates to the Rotorua lakes are unlikely to form significant quantities of Al-floc but effects of floc deposition on biota (e.g., lake bed smothering) have not been studied.

(d) pH can be elevated in the presence of algal blooms, and this may also render alum dosing not only ineffective but also toxic to biota. A pH sensor was recently positioned on a fixed monitoring buoy in Lake Rotorua to continuously monitor pH and provide evidence of the potential for high pH to interfere with the efficacy of alum use.

(e) The report noted concerns of Te Arawa Lakes Trust and iwi and hapū in regard to alum dosing; from a cultural perspective and for provision of mahinga kai. The authors did not have expertise to provide commentary on these cultural matters. Nor did the report provide details of plans relating to resource consents for ongoing use of alum.

(f) It is my opinion that inflow alum dosing has been responsible for major improvements in water quality of Lake Rotorua since its implementation in 2006, and particularly with dosing of a second inflow in 2010. It is also my opinion that alum dosing has led to a delay in actions to reduce catchment nutrient loads because of perceptions that lake water quality is ‘satisfactory’ and beginning to reach that RLWP target of a TLI value of 4.2. I consider it highly unlikely that catchment phosphorus loads can be controlled to the same degree as has been achieved with alum dosing, in part because alum dosing provides capacity to inactivate both natural and anthropogenic sources of phosphorus. As a consequence, the changes to nutrient loading proposed under PC10 are a critical, long-term sustainable solution to meeting the RLWP targets for water quality of Lake Rotorua.

19. Abell et al. (2015) produced a report entitled: “Lake Rotorua Treated Wastewater Discharge: Environmental Effects Study”. This report was commissioned by the Rotorua Lakes Council to provide guidance on the potential impacts of discharging wastewater to the Puarenga Stream or directly to the lake, upon the expiration of irrigation operations at the Land Treatment System (LTS) in the Whakarewarewa Forest. This study involved modelling a number of scenarios of treated wastewater discharges, both with and without the current inflow alum dosing regime. Conclusions from the study were:

(a) DYRESM-CAEDYM model simulations emphasised the significant positive contribution that stream alum dosing has had towards achieving TLI targets for the lake, in line with findings in the earlier study (Hamilton et al. 2015).

(b) There appears to have been a transition from dominance by nitrogen limitation (only) as was reported in the early 1980s (White et al. 1985) to increased co-limitation. The shift towards dominance of primary limitation by phosphorus when alum effects were included in the model (i.e., the baseline scenario) reflects reduction of dissolved reactive phosphorus in the water column, both in the treated stream inflows, and in the lake due to downstream transport of free aluminium from the alum dosing stations. These results are in agreement with our previous study (Hamilton et al. 2015).

(c) The effects of alum were represented ‘statistically’ by altering parameters that control the rates of bed sediment phosphorus release and particulate organic matter settling. Although these changes were based on mechanistic principles, there was a lack of representation of daily fluctuations in alum dosing rates and dynamic changes to sediment nutrient stores. This may have contributed to model uncertainty in the earlier study (Hamilton et al 2015).

Basis of my opinion

20. The studies that provided the basis of my opinion on the subject matter are derived from intellectually proven methodologies, as well as the use of predictive models that have been extensively documented and published both locally and internationally.

(a) In **Paper 1** (Hamilton et al. 2015)**,** modelling was informed on the basis of the DYRESM-CAEDYM model. The 1-D model DYRESM-CAEDYM comprises a hydrodynamic model (DYRESM- Dynamic Reservoir Simulation Model) that is coupled to a water quality model (CAEDYM- Computational Aquatic Ecosystem Dynamic Model). DYRESM-CAEDYM is the most widely cited aquatic ecosystem model in the scientific literature (Trolle et al., 2012) and Hamilton was the original developer of the CAEDYM model. The model has been applied to several lakes in New Zealand for simulations over many years, to understand in lake processes and inform management decisions.

(b) Specifically, the DYRESM-CAEDYM model was used to predict how Lake Rotorua will respond to reductions in external loads, using various nitrogen and phosphorus loading with and without inflow alum dosing. DYRESM-CAEDYM was calibrated against field data for a three-year period between July 2004 and June 2007 for variables of temperature, dissolved oxygen, DRP, TP, ammonium, nitrate and TN concentrations. Monthly samples collected and analysed by BoPRC were used to assess model performance. Scenarios were simulated using runs of the model over the period July 2007 to December 2012, corresponding to the period of alum dosing to inflows.

(c) In **Paper 2,** mean annual discharge (MAD) was estimated individually for nine major stream sub–catchments of Lake Rotorua, and a combined MAD was estimated for other minor and ungauged stream sub–catchments. Natural stream phosphorus concentrations were derived from published values based on the River Environment Classification (REC) land classes within the lake catchment. Natural groundwater phosphorus concentrations were derived from published relationships between groundwater age and phosphorus concentrations in the Rotorua sub–catchments.

(d) Total phosphorus and DRP loads were calculated for each inflow for the period 2007–2014 (‘contemporary loads’) using the daily discharge estimates and time series of estimated daily mean concentrations of each nutrient species (TP, DRP) for each inflow. Daily loads were then summed to calculate annual loads. Natural loads for each inflow were subtracted from contemporary loads to estimate anthropogenic loads.

Reports/Update

21. A report (Morgenstern et al. 2015) presents a different opinion from our earlier submission in terms of the nutrient dynamics of Lake Rotorua. Specifically, in the Morgenstern et al. (2015) study, authors analyse hydrochemistry data and conclude that "the only effective way to limit algae blooms and improve lake water quality in such environments is by limiting the nitrate load". While the paper provides an important contribution to understanding groundwater processes in the lake catchment, it contradicts the current strategy of limiting both phosphorus and nitrogen loads to Lake Rotorua and advocates only for nitrogen control. Based on literature that supports our assessment, we presented a peer-reviewed and published rebuttal that the conclusions reached by the study about lake water quality should be disregarded. These reasons are highlighted below.

(a) A key issue is that the authors have considered only nutrient sources and have neglected to consider nutrient sinks in drawing their conclusion. In-lake processes typically reduce ambient lake surface water concentrations of PO_4^{-3} to levels much lower than those in the main inflowing streams; one such important process is biological uptake and subsequent sedimentation of particulate organic material. Thus, while concentrations of PO_4^{-3} in inflows may exceed some defined threshold at which P does not limit net phytoplankton production (based on other limiting factors), concentrations in the lake may be considerably below this threshold, with phytoplankton biomass accumulation in the lake P-limited at times.

(b) The authors' conclusion that N-only control should be adopted is based on their inference that natural P loads greatly dominate those from anthropogenic sources, and the fact that anthropogenic loads are much easier to reduce than natural loads.

(c) The authors' conclusions are based only on consideration of groundwater processes. A strategy of only "limiting the nitrate load" would unduly inhibit the timelines over which lake water quality objectives could be achieved. This is due to the unresponsive nature of catchment nitrate loads, which the authors have effectively demonstrated. In our paper we indicate that wider consideration of nutrient pools and transport processes (e.g. internal loading and overland flow) leads to the conclusion that dual control of N and P is more efficient than focusing solely on controlling nitrate loading to address eutrophication.

(d) Focusing only on controlling external nitrate loads to the lake is likely to reduce the N : P ratio in lake water. This has the potential to promote greater relative abundance of undesirable cyanobacteria in the lake.

(e) A recently published study (Dada and Hamilton 2016) demonstrated strong positive relationships between *E. coli* counts at Lake Rotorua and particulate inorganic phosphorus or total phosphorus concentrations in water samples from Lake Rotorua inflows.

(f) Based on an approach that wholly focuses on nitrogen reduction, most recent ROTAN-Annual modelling (Rutherford 2016), it was predicted that it will take nearly 25 years for nitrogen reductions specified by BoPRC to reduce lake loads to within 25% of the target (405 t y^{-1}). Even then, steady-state may not be reached until after 2100 (as will be detailed in Dr Rutherford's evidence).

22. **Conclusion**

(a) Since the mid- 2000s, there has been a general decline in the TLI of Lake Rotorua (i.e. improved water quality; Abell et al., 2012; Smith et al., 2016), and the annual average TLI reached the lake target in 2012 and 2014 (BoPRC et al., 2015a).

(b) Based on our findings, a significant factor contributing to recent improvement in water quality is the action of dosing aluminium sulfate (alum) to two stream inflows, initiated in one inflow in 2006 and the second in 2010.

(a) This action has reduced dissolved phosphorus concentrations in the two treated streams, while excess alum has also contributed to further reducing ambient dissolved P concentrations in the lake to a level where phosphorus limitation of phytoplankton biomass accumulation is likely to occur.

(b) Despite this success, there are long-term risks associated with the technique (Tempero, 2015) and there is recognition that, although such geoengineering solutions can be a useful component of a wider range of restoration actions, they are not a substitute for long-term sustainable reductions in nutrient loads from the wider catchment. The intensity and sustainability of alum dosing need to be carefully weighed against the management of present and future loads of both nitrogen and phosphorus from catchment land use.

(c) A strategy of controlling both nitrogen and phosphorus loads to Lake Rotorua provides the safest and most sustainable mechanism to improve water quality and increase water clarity in Lake Rotorua, by increasing the duration and area over which phytoplankton are strongly nutrient limited.

Background materials and reports referenced

23. In the course of preparing this evidence I have had regard to the following documents and materials:

(a) Abell J, Stephens T, Hamilton DP, McBride C, Scarsbrook M. 2012. Analysis of Lake Rotorua water quality trends: 2001-2012.ERI Report No. 10. Report prepared in response to Environment Court mediation, 21 November 2012. Environmental Research Institute, University of Waikato, Hamilton. Available at: http://www.waikato.ac.nz/eri/research/publications.

(b) Abell, J. M., Hamilton, D. P., and Rutherford J. C. 2013. Quantifying temporal and spatial variations in sediment, nitrogen and phosphorus transport in stream inflows to a large eutrophic lake. Environmental Science - Processes & Impacts 15: 1137-1152.

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Name: (Professor) DAVID PHILIP HAMILTON

Date: 11 January 2017

Appendices:

Four reports (Hamilton et al. 2015; Abell et al. 2015; Tempero et al. 2015a and 2015b).