BAY OF PLENTY REGIONAL COUNCIL TOI MOANA

Lake Rotorua Science Review - Summary Report

Bay of Plenty Regional Council
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Acknowledgments

We are indebted to the authors of the individual science review modules - these people gave their time and expertise freely and are identified in Table 1 of this report.
Professor Warwick Vincent completed the peer reviews in a timely, thorough and efficient manner - this was a significant task and the insights provided by Professor Vincent considerably improved the outputs of the science review.

Executive Summary

Purpose

The purpose of this report is to provide a synthesis of the detailed technical reports produced for the Lake Rotorua Science Review. Short summaries are presented for each technical report while the synthesis of these, including discussion of key findings and recommendations, is provided in this Executive Summary.

Background

This science review is required under Method LR M2 in 'Plan Change 10 Lake Rotorua Nutrient Management' (PC10), and under an agreement with key stakeholders. The review followed a set methodology leading to 12 reports which are summarised here. Each of the technical reports and this summary document were independently peer reviewed by Professor Warwick Vincent from Laval University, Canada (see Appendix 1).

Policy setting

The water quality in Lake Rotorua deteriorated from the 1960s onwards, with algal blooms driven by land use change, farm intensification and city sewage discharges. This decline was due to excess nutrient inputs and caused widespread public concern and support for restoring water quality to levels prevailing in the 1960s, prior to the onset of major decline.

The policy response to these issues is documented by Lamb (2018) and is based on a TLI (Trophic Level Index) target of 4.2 reflecting water quality conditions in the 1960s, with sustainable lake loads for nitrogen and phosphorus of 435 t per year and 37 t per year respectively. These estimates of sustainable lake loads were based on a key paper by Rutherford et al. (1989) and have been supported by subsequent studies, including those presented here.

Lake water quality

As part of this review, the available historical data have been compiled to produce a detailed overview of lake water quality trends for Lake Rotorua, both in terms of the TLI and the individual attributes that make up this index. In McBride et al. (2018a) more than 14,000 individual measurements of water quality were collated for mid-lake sites. A graphical summary of this information shows that the present water quality generally meets the TLI target, and appears comparable to or better than that observed in the late 1960s (Figure 1).

In Stephens et al. (2018), a detailed analysis of water quality trends was carried out on data for the period 2001 to 2017. This revealed that there have been improving trends for all of the TLI attributes (total phosphorus, total nitrogen, chlorophyll-*a*, and Secchi depth). The results were statistically significant at all water depths analysed (surface, mid-depth and bottom), with a striking overall drop in TLI from the range 4.5-5.0 in the early 2000s, to 4.0-4.3 over the last six years (Figure 1).

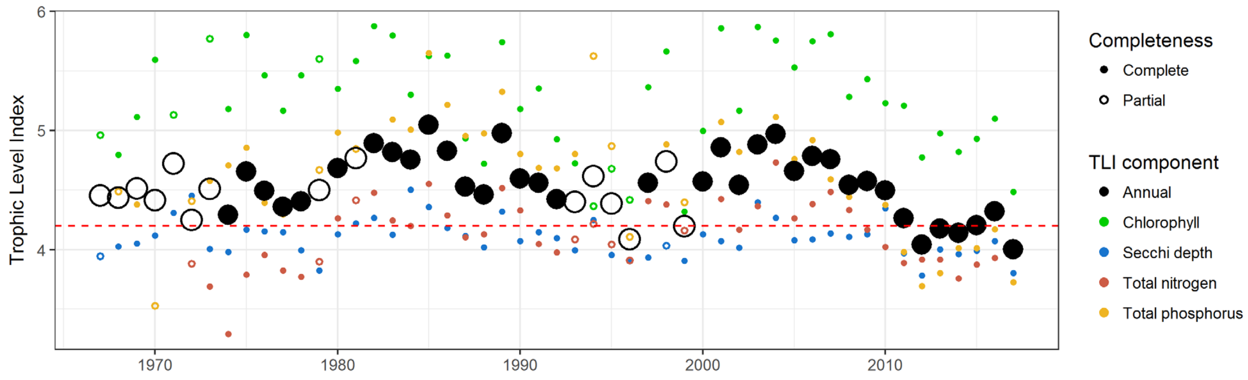

Figure 1 *Annual Trophic Level Index (TLI) and individual water quality components at mid-lake sites in Lake Rotorua. The lake TLI target (4.2) is shown by the dashed red line. See Part 3 of this report for a detailed explanation of this figure (reproduced from Stephens et al., 2018).*

External nutrient loading

Two independent estimates of annual nutrient loading to the lake were made for the period 2002 to 2017 (Dare, 2018), and from the late 1960s to 2017 (McBride et al., 2018a). McBride et al. showed that the total nitrogen load from various sources (including stream inflows, rainfall and geothermal) has increased substantially and steadily since the 1960s. This is principally due to increases in nitrate load, which has approximately doubled over this period. Nitrogen loads were found to be well in excess of the sustainable load, and the annual load target (435 t per year) appears to be higher than that observed in the 1960s (Figure 2).

Similar estimates (for the stream inflows only) were also found by Dare (2018) who calculated that the combined total nitrogen load from these sources has fluctuated at around 400 t per year since 2002, with the estimate for 2016 equating to between 410 and 415 t[1]. The author also showed that a large proportion of the total nitrogen load is contributed by the Waitetī, Hamurana, Awahou, and Puarenga streams.

Dare (2018) used some novel data analysis techniques to reveal that high-flow ammoniacal nitrogen concentrations are increasing over time at some sites. However, the contribution of ammoniacal nitrogen to total nitrogen in most catchments is currently minor, with only the Puarenga and Waiohewa Streams exceeding 10%. Therefore, any increases in ammoniacal nitrogen are unlikely to be solely responsible for increasing total nitrogen trends, which suggests that particulate organic nitrogen may also be a contributor. While the source of ammoniacal nitrogen is unknown, the author suggested that contributors could include farming activity, stormwater discharges, septic tanks, and geothermal activity.

[1] Note that this value is not directly comparable to the sustainable load (435 t per year) because it only accounts for base-mid flow loads from these major inflows.

The total phosphorus load to the lake has varied considerably over time, due to fluctuations in particulate phosphorus loads and the removal of direct inputs of treated wastewater to the lake in 1991 (McBride et al., 2018a). The Hamurana and Awahou streams make up 50% of the dissolved phosphorus to the lake, reflecting the effect of long groundwater residence times on geologically derived phosphorus. Dare (2018) found that the combined total phosphorus load from the nine stream inflows monitored was around 23 t per year between 2002 and 2010, with an increase in subsequent years to between 34 and 36 t in 2016[2]. Trend analysis also showed an overall increase in instream total phosphorus (TP) concentrations, particularly in the period 2009-2016 where eight of nine sites increased.

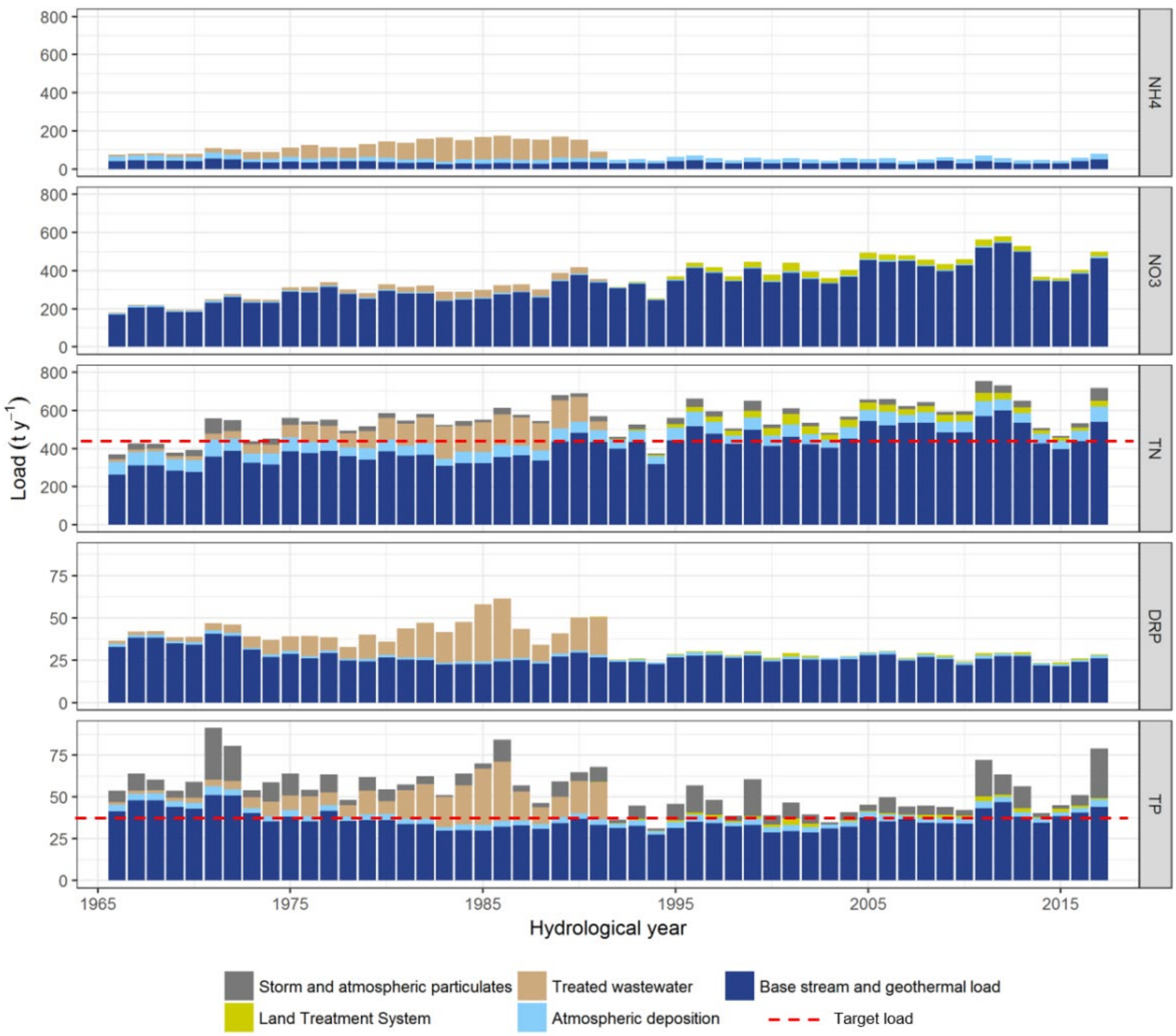

Figure 2 *Summary of nutrient loading to Lake Rotorua 1959 to 2017. Loads from stormflow and particulate deposition are shown in grey. Note, 'NO$_3$' and 'NH$_4$' loads are in terms of N. Sustainable load targets (Rutherford et al. 1989) are shown by the dashed red line (reproduced from McBride et al. 2018a, Figure A - see Part 6 of this report).*

[2] Note as for nitrogen Dare (2018) considered only the monitored stream inflows loads, therefore, phosphorus loads will differ from other authors who considered the total load to the lake (e.g. McBride et al. 2018a).

Nutrient exports

Examination of the lake outflow at Ōhau Channel by Dare (2018) showed that since 2009, an increasingly smaller proportion of inflow total phosphorus has been exported from the lake. This is consistent with the increased supply of particulate phosphorus found at many of the stream inflow sites, and the potential effects of alum dosing of the Utuhina and Puarenga streams. Aside from a wet period between 2010 and 2012, annual rainfall and the number of high intensity rainfall events in the Lake Rotorua catchment is comparable across years. This suggests that other factors may be increasing the supply of particulate phosphorus to Lake Rotorua seen in recent years.

The total nitrogen load at the Ōhau Channel was also found to be low relative to stream inflow loads, implying that a large proportion of total nitrogen becomes stored in sediment or is denitrified within the lake. Total nitrogen export was primarily in the form of organic nitrogen, which suggests that a large amount of bioavailable nitrogen is taken up by planktonic algae and exported as algal biomass.

The impact of nutrients exported from Lake Rotorua and Lake Rotoiti on water quality in the lower Kaituna Catchment is suggested by Dare (2108) to be low. This is because the concentrations of most forms of nitrogen in the lower Kaituna River (except for ammoniacal nitrogen) exceeded that measured at the lake outflow.

Catchment and lake modelling

Computer modelling of the response of water quality in Lake Rotorua to catchment nutrient inputs has been fundamental to the management of the lake since the late 1980s. The available models can now be considered well resolved, having been published in peer reviewed journals and with recent updates to include the latest data and techniques.

ROTAN

As part of this science review, Rutherford (2018) summarised the 2011 and 2016 versions of the ROTAN (ROtorua and TAupō Nitrogen) model. ROTAN is a conceptual catchment model that routes water and nitrogen losses from land through groundwater and streams to the lake, taking account of nitrogen attenuation and groundwater time lags. The output from ROTAN has been important in understanding likely future nitrogen loads, and has also informed the development of the DYRESM-CAEDYM Lake models (see McBride et al. 2018b).

ROTAN-2011 was developed in 2008-2009 and used OVERSEER® v5.4.2 to estimate farm nitrogen losses with a weekly time-step. ROTAN-Annual was developed in 2016 and is a modified version which operates on an annual time-step and uses the latest version of OVERSEER® (v6.2.0). Information on revised groundwater boundaries and recent stream monitoring data was also used for the new model. Land use/cover maps, agricultural statistics and expert opinion from landowners provided input data for OVERSEER® v6.2.0 which predicted historic farm losses from 1900-2015 for input into ROTAN-Annual.

Rutherford (2018) found that the most recent version of the ROTAN model (ROTAN-Annual) gave estimated nitrogen losses on average 88% higher than those of ROTAN-2011. The main influence on this was the change of OVERSEER® versions (from v5.4.2 to v6.2.0). The author concluded that the Version 6 losses are more credible because they match observed stream concentrations, with an average nitrogen attenuation of 42%, which is a plausible value, compared to ROTAN-2011, which gave negligible attenuation.

The author cautioned against the using apparent differences in nitrogen attenuation between sub-catchments to manage each differently because:

- The boundaries of the recharge zones draining to major springs and stream monitoring sites are uncertain (notably in the Awahou and Hamurana).
- The land use history in each sub-catchment is uncertain (e.g., when exactly did dairy farms come into full operation in the Awahou Catchment?).
- OVERSEER® is a steady-state model and there is uncertainty about how long it takes nitrogen losses to adjust to a new equilibrium after a significant land use change (e.g., how long after converting a sheep/beef farm to dairy does the nitrogen loss rate for the dairy farm apply?).

Using ROTAN-Annual the 'most likely' steady state nitrogen load for current land use (i.e. no change) was found to be 750 t per year (range 670 t-840 t per year), which matches closely the ROTAN-2011 estimate of 725 t per year). What differs between models is that in ROTAN-2011 (with nitrogen losses estimated using OVERSEER® v5.4.2) calibrated attenuation was zero in nine of the ten catchments, whereas in ROTAN-Annual (OVERSEER® v6.2.0) attenuation was non-zero in all catchments.

For the loss reduction scenarios developed under Plan Change 10, ROTAN-Annual predicted a steady-state lake nitrogen load of 425 t per year with a range of 390 t-460 t per year (Rutherford and MacCormick 2016). The author calculated that there is a negligible risk that the nitrogen control measures in PC10 will be more than required, but some risk (c. 12-20%) they will be less than required to meet the lake target. The model also predicted that nitrogen reductions specified by Bay of Plenty Regional Council (BOPRC) would reduce lake loads to within 25% of the target within 25 years, although steady-state may not be reached until after 2100. The time-scale of this recovery is similar to that predicted by ROTAN-2011.

DYRESM-CAEDYM

McBride et al. (2018b) build upon a series of modelling studies spanning 12 years to better understand the processes influencing water quality in Lake Rotorua. The existing DYRESM-CAEDYM model was improved by providing empirically derived daily estimates of water, nitrogen and phosphorus inputs to the lake (as per McBride et al. 2018a). The authors sought to increase the number of different nutrient loading scenarios modelled to encompass a 'matrix' involving various combinations of nitrogen and phosphorus loads. This could, for example, give the ability to explore whether a lower target for phosphorus can be offset by a higher target for nitrogen (and vice versa).

By examining these relationships, the authors also aimed to assess the extent that the current relatively good water quality conditions in the lake might have been driven by alum dosing as opposed to changes in catchment loading and/or climate. Several of the model scenarios were designed to assess what level of catchment nitrogen and phosphorus load reductions might be required to meet the TLI target of 4.2 without the need for ongoing, long-term alum dosing.

The performance of the revised model was found to be comparable, and in many cases superior to, previously published applications of DYRESM-CAEDYM to Lake Rotorua and other lakes. Model simulations showed that:

- The TLI could be reduced from approximately 4.8 (as observed from 2001-2007) to approximately 4.3[3] through prescribed catchment nitrogen and phosphorus load reduction, and without the need for alum.
- The catchment nitrogen load prior to 1970 was likely to be less than the target load of 435 t per year, and the lake TLI may possibly have been greater than 4.2 by the late 1960s.
- Substantial further water quality degradation could occur if present trends of increases in the catchment nitrogen load are left unchecked.
- Significant reductions in both nitrogen and phosphorus loads are needed to achieve a TLI near to the target of 4.2.

These important findings are consistent with the weight of scientific evidence that dual nutrient management and reduction are needed for restoration to be effective for Lake Rotorua.

In summary, McBride et al. (2018b) concluded that substantial reductions in catchment nutrient loading will be required to achieve water quality at or near the TLI target in the absence of alum dosing. This is illustrated is Figure 3 which is a matrix showing the combinations of catchment nitrogen and phosphorus loading required to achieve a range of TLI values.

[3] The authors noted that while the TLI reduction from 4.8 to 4.3 appears modest, the absolute reductions in total nitrogen, total phosphorus and chlorophyll-*a* are relatively large due to the logarithmic nature of the TLI component equations. For example mean concentrations of total nitrogen and total phosphorus were reduced by approximately 75% between the maximum and minimum load scenarios.

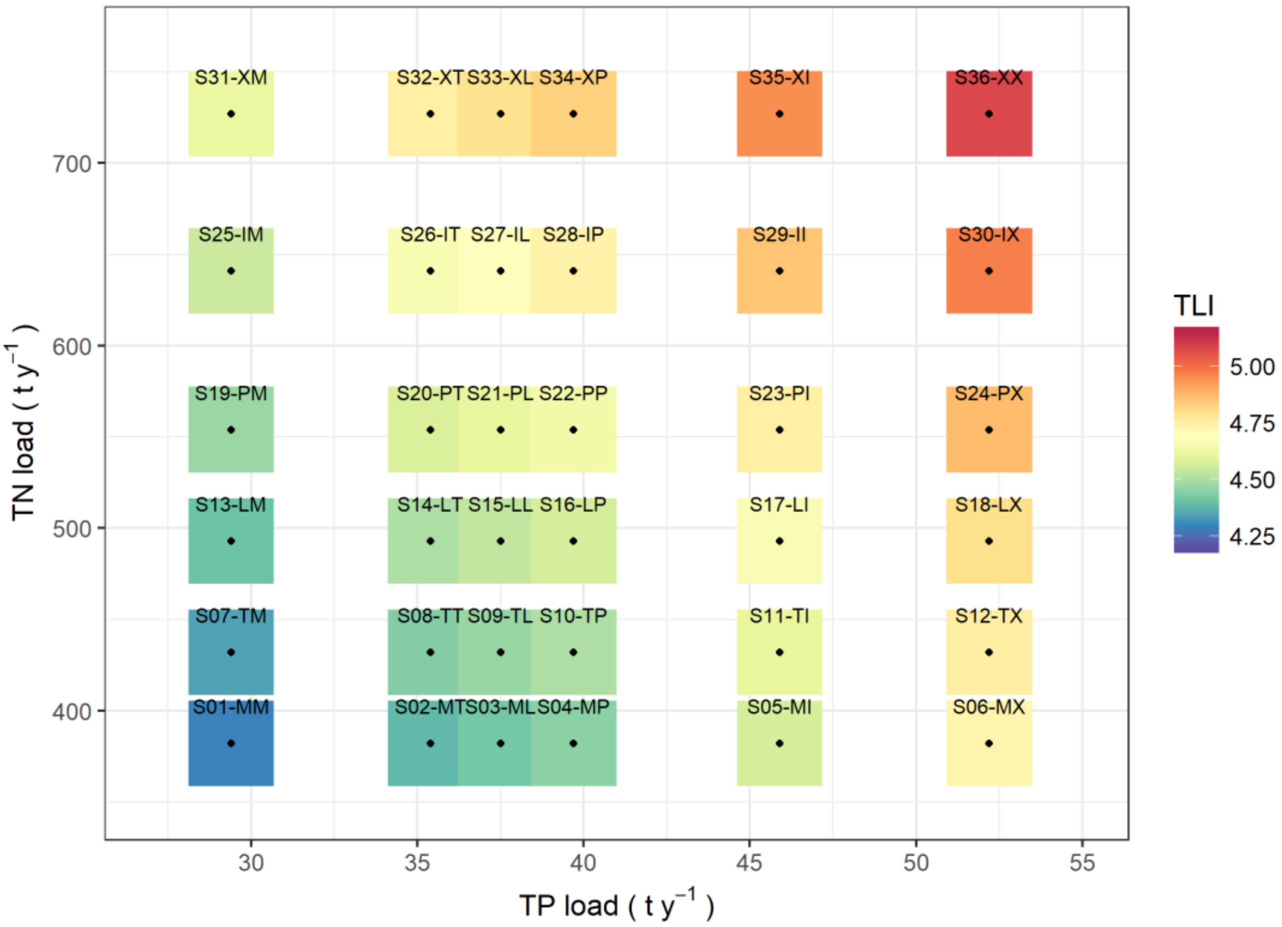

Figure 3 Modelled TLI under 36 scenarios covering various combinations of catchment TN and TP loading. Results presented, demonstrate the influence of TP and TN loading on TLI over the scenario period from July 2000 to June 2007. See Part 7 of this report for a detailed explanation of this figure (reproduced from McBride et al. 2018b, (Figure B).

Nitrogen management

Progress towards the 2022 nitrogen targets

The nitrogen accounting methodology for management of nitrogen loading to the lake under Plan Change 10 (PC10) is described by MacCormick and Miedema (2018). Progress towards the nitrogen reduction targets is reported for both permanent and non-permanent reductions.

Permanent nitrogen reductions from the catchment are achieved through the Incentives Programme, engineering solutions, and the conversion of gorse land to bush or forestry. At the time of writing, the Incentives Programme had achieved 11% of its reduction target while the Engineering Programme achieved 26% of its reduction target. As a result of a better assessment of the gorse coverage in the catchment, the estimated nitrogen load to land from gorse has been reduced from 30 t to 13.9 t per year. Eight agreements to convert gorse areas to forestry or bush and scrub have been completed, representing a reduction to the lake of 0.8 t per year (3% of the original target).

Non-permanent nitrogen reductions are those below the allocated level that are not 'locked-in' through commercial agreements or rules. Approximately 52% of the pastoral area in the catchment has current state information available (based on 99 OVERSEER® assessments), comprising almost all dairy properties and about one third of the dry stock area in the catchment. On average, the nitrogen load from these properties is 17% below their start point allocations[4] and 9% above their 2032 allocations. The authors note that these assessments are not audited and should be considered indicative only.

These modest nitrogen reductions are consistent with the findings of McBride et al. (2018b) who concluded that estimated catchment (external) loads do not reveal reductions over the past 10 years that would explain the recent, and dramatic, improvements in water quality.

Phosphorus management

Alum dosing efficacy and eco-toxicology

The use of aluminium sulphate (alum) as a medium-term measure to improve water quality in Lake Rotorua, appears to be effective despite evidence that the loading of nitrogen, and more recently phosphorus, to the lake continues to increase (e.g. Dare 2018, McBride et al. 2018a). In McBride et al (2018b) it was concluded that low lake phosphorus concentrations at present are likely, due to the alum dosing, possibly coupled with partial exhaustion of historical (legacy) phosphorus from direct wastewater discharge stored in lake sediments. The authors' model simulations also showed that the alum dosing could be producing an effect equivalent to reducing modelled nutrient release rates from lake sediments by approximately 50%. While these findings do not prove that the dominant mode of action of alum is to suppress sediment phosphorus release, it is notable that Stephens et al. (2018) also suggested that alum may have "stronger effects on sedimentary nutrient regeneration than on flocculation of particulate nutrients in overlying waters".

While it is likely that alum dosing has improved the water quality in Lake Rotorua, there has been discussion about the possibility of adverse effects, should this intervention strategy continue in the longer term. To address the potential for ecological impacts, Tempero (2018) produced an addendum to his original report on the eco-toxicological effects of aluminium (Tempero 2015). International studies on aluminium toxicity published since 2015 were reviewed and the implications of these for alum dosing of Lake Rotorua were considered. The author concluded that:

- Acute and chronic toxicological effects from aluminium exposure are unlikely to result under typical pH conditions in the lake, but cautioned that toxicity values are not based on New Zealand species.
- No adverse effects have been observed from alum dosing of the Puarenga Stream.
- The cautious use of continuous low level alum dosing is an ecologically acceptable option for reducing phosphorus loading to Lake Rotorua.

The author also noted that aluminium impacts are unlikely to occur downstream of the lakes (i.e. in the Kaituna River and Ōngātoro/Maketū Estuary) due to low lake aluminium concentrations and further dilution.

[4] A start point can be considered as a property's initial nitrogen allocation from which reductions are made.

Land-based phosphorus loss mitigation

While alum dosing appears to be effective, there remains agreement that reducing phosphorus losses from land-based activities should be the focus in the long-term. To put these losses in perspective, Hamill (2018) provided a detailed review of the information on phosphorus sources for the period 2007 to 2014. The total phosphorus load to the lake was estimated to be 46 t per year after accounting for storm flows and geothermal inputs. The load attributed to anthropogenic sources was 18.1 to 20.7 t per year (39%-45% of the total load) and most of this (71%-79%) was in particulate form.

Information on land-based phosphorus losses and mitigation strategies for pasture, planted forest and indigenous vegetation in the Lake Rotorua Catchment was summarised by Hill (2018). The total estimated catchment phosphorus load was consistent with that of Hamill (2018) at 44.3 t to 45.6 t per year. The most cost-effective phosphorus mitigation strategies for pastoral land use were found to include optimising soil Olsen-P, improving farm dairy effluent management and using low-solubility phosphorus fertilisers. Other mitigation strategies that showed promise included the use of detainment bunds, and a greater focus on Critical Source Areas (CSAs). The author considered that a combination of these phosphorus mitigation strategies could potentially achieve a 40% reduction in losses with minimal impact on farm profit. However, he cautioned that there remains uncertainty around the effectiveness of individual mitigations and implementation costs, largely driven by variable farm system and catchment conditions.

Hill (2018) concluded that adequate phosphorus load reductions to Lake Rotorua would not be achievable through targeting nitrogen alone (i.e. by taking advantage of the phosphorus 'by-catch' associated with nitrogen mitigation). Achieving a phosphorus load of between 30 t and 35 t per year was considered possible through land-based phosphorus mitigation strategies, even if a nitrogen reduction scenario is implemented. However, the author noted that assessment of the effectiveness of phosphorus and nitrogen mitigations is dependent on the capture of finer (farm-scale) data that can be used to refine understanding of losses to the lake.

Lake water quality remediation science

Hamilton (2018) provided a review of relevant New Zealand and international lake water quality remediation science. The review included considerations of a number of lake-remediation actions including hydraulic flushing for direct algal control, phosphorus locking (geoengineering), floating wetlands, bio-manipulation and macrophyte harvesting.

The author found that many of the remediation techniques reviewed are unlikely to be able to be scaled up to be effective for Lake Rotorua (area 80 km^2), or are unsuitable for other reasons (including the shallow lake depth and frequent mixing regime). Several of the techniques remain poorly validated scientifically, including microbial control agents, floating wetlands and some geoengineering materials. Others, such as ultrasound for phytoplankton control, have a limited number of rigorous scientific studies and may interfere with natural aquatic food webs. A number of techniques involving physical modifications (hypolimnetic siphoning, inflow diversion, sediment capping, flushing, filtration, and oxygenation or artificial de-stratification) were considered unlikely to be viable or effective for shallow Lake Rotorua.

The author concluded that while alum dosing appears to have been highly successful in managing external and internal nutrient loads in Lake Rotorua, a more concerted effort to explore alternative options is required to more rapidly attain the sustainable catchment nutrient loads prescribed in Plan Change 10. It was also noted that a 'forward-looking context' is required, because climate change will make it more difficult to attain the water quality goals for the lake. This issue has been highlighted recently in the international literature, for example Jeppesen et al. (2017) state that "Lower nutrient loading is therefore needed in a future warmer world to achieve the same ecological state as today".

Synthesis

Lake Rotorua is one of the most well understood lakes in New Zealand, with a history of scientific research and monitoring since the 1960s. This is well illustrated by the lake water quality monitoring record (more than 14,000 individual measurements to date), and by the vast collection of scientific reports and published papers that have been referenced by the authors who have contributed to this review.

Because of this intense science effort, there are a number of conclusions that can be made with a high degree of certainty. These key conclusions are discussed below and are individually numbered for ease of reference.

With regards to lake water quality it is clear that:

- *Lake Rotorua has shown its vulnerability to nutrient loading, with periods of severe water quality problems in the past that have caused public concern. [Conclusion 1]*
- *Lake management actions, particularly alum dosing, appear to have halted the decline in water quality, and the lake has shown evidence of marked improvement over the period 2001-2017. [Conclusion 2]*
- *The improved water quality state is precarious and will require ongoing careful monitoring and management. [Conclusion 3]*

During the review, there was agreement that careful management of catchment nutrient inputs is the key to improving water quality and this is highlighted by the following conclusions:

- *External phosphorus loading has apparently stayed the same (DRP) or increased (TP), despite the use of alum dosing (see Figure 2). [Conclusion 4]*
- *Nitrate loading today is double that in the 1960s (see Figure 2) and as a result, total nitrogen is well in excess of the sustainable load of 435 t per year. [Conclusion 5]*

Our understanding of the response of water quality in Lake Rotorua to catchment nutrient inputs has been considerably improved through the results of computer modelling. Some of the key conclusions reached from the current modelling using ROTAN and DYRESM-CAEDYM are:

- *Significant reductions in catchment nitrogen <u>and</u> phosphorus loading will be required to achieve water quality at or near the TLI target in the absence of alum dosing. [Conclusion 6]*
- *The catchment nitrogen target of 435 t per year continues to be supported by the present analysis, with the caveat that there is some risk ($\leq$ 20%) that the nitrogen control measures in PC10 will be less than that required to meet the lake water quality target. [Conclusion 7]*

- *The planned nitrogen control measures will reduce lake loads to within 25% of the target within 25 years, although steady-state may not be reached until after 2100. [Conclusion 8]*

- *Climate change will make it more difficult to attain the water quality goals for the lake, meaning that stricter nutrient controls may be needed in the future. [Conclusion 9]*

These important findings are consistent with the weight of international scientific evidence and policies (e.g., EPA, EU), that dual nutrient management and reduction are needed for restoration of lakes to be effective. In addition, the findings confirm that the current sustainable load for nitrogen of 435 t per year is appropriate, although there is some risk that it may need to be lower to achieve the target TLI in the absence of alum dosing. To date, progress towards achieving the nitrogen reduction targets has been modest and this conclusion is supported by the lack of any reductions in the estimated nitrogen loads to the lake.

Given that a dual nutrient approach has been recommended, it is important that the potential for phosphorus mitigation is evaluated. Between 30 and 35 t per year of phosphorus reduction is considered possible through land-based mitigation strategies, even in the absence of nitrogen mitigation (as this normally results in phosphorus 'by-catch'). However, it is noted that assessment of the effectiveness of phosphorus and nitrogen mitigations is dependent on the capture of finer (farm-scale) data that can be used to refine understanding of losses to the lake.

Alum dosing has been confirmed as a useful in-lake phosphorus mitigation strategy and therefore the risks and benefits were an important focus for the review. The key conclusions reached in regard to alum use are:

- *Alum dosing appears to be having a positive effect on lake water quality. [Conclusion 10]*

- *Analysis of the eco-toxicological literature suggests that adverse effects will not occur at the current alum dosing levels; however caution is needed as there is a lack of information about the potential sensitivity of New Zealand aquatic species to aluminium. [Conclusion 11]*

- *Full reliance on phosphorus removal by continuous alum treatment may not be desirable in the long-term. [Conclusion 12]*

The mode of action of alum on phosphorus in the lake remains uncertain. Model simulations indicated than alum dosing may be having an effect equivalent to a 50% reduction in nutrient release rates (internal loading) from the lake sediments. While these findings do not prove that the dominant mode of action of alum is to suppress sediment phosphorus release, there is some suggestion that this may be a more important mechanism than flocculation of dissolved and particulate phosphorus from the water.

The final conclusion of this review is based on a critical analysis of in-lake water quality remediation techniques and further supports a catchment nutrient management approach:

- *In-lake remediation methods are not suitable for a lake the size of Lake Rotorua, and the focus should be on catchment control methods, including promising new approaches that are being trialled by Rotorua farmers. [Conclusion 13]*

Recommendations

A total of 48 individual recommendations for further science work were made by the authors to this review across 10 of the 12 modules. These are reproduced in the short summaries of each technical report which are provided in this report. A table containing all of the recommendations is given in Appendix 2. Prioritisation and implementation of the recommendations will be carried out as a separate process to the science review and this is not considered further here.

Contents

Part 1: **Introduction**

Purpose

The purpose of this report is to provide a synthesis of the detailed technical reports produced to support the Lake Rotorua Science Review (see Table 1). Short summaries are presented for each technical report while the synthesis of these, including discussion of key findings and recommendations, is provided in the Executive Summary. Information on the background to the review and the methodology followed is provided in the following sections.

Background

This Lake Rotorua science review is required under Method LR M2 in 'Plan Change 10 - Lake Rotorua Nutrient Management' (PC10). The need for a science review was first raised in a general way within the 2013 'Oturoa Agreement' that helped resolve the Federated Farmers' appeal on the Regional Policy Statement (RPS). The key RPS appeal points related to the sustainable nitrogen load (435 t per year) and the timeframe to achieve that load (i.e. by 2032).

The broad scope of the science review was refined as part of the 'Stakeholder Advisory Group' (StAG) process. The Stakeholder Advisory Group was tasked with developing a Lake Rotorua nutrient policy package that would deliver the RPS goals – this included advice on science reviews, notably in the July 2014 StAG minutes (see item 4d).

PC10 was publicly notified in February 2016 and only minor changes to Method M2 were made as a result of the 2017 PC10 Hearings. Following notification, the farmers' Collective and the Lakes Water Quality Society (LWQS) sought additional assurances about providing input to the science review process and timing. This resulted in the August 2016 MOU on Lake Rotorua Science and Policy Reviews, signed by BOPRC, the Collective and LWQS.

More generally, the Water Quality Technical Advisory Group (WQTAG)[5] has for many years taken a 'rolling review' approach to assessing science and science needs/gaps related to the Rotorua Lakes Programme. This science review is consistent with the WQTAG's collaborative ethos, albeit triggered by a specific regulatory requirement in Method M2.

Methodology

The PC10 science review is led by Andy Bruere and Rob Donald, with project management and writing support from Simon Park (trading as Landconnect Ltd, under contract to BOPRC).

[5] Information on the WQTAG can be found at www.rotorualakes.co.nz/water-technical-advisory-group

Terms of Reference

The science review terms of reference (ToR) were drafted at a WQTAG workshop in July 2017, resulting in a core list of 10 topics or 'modules'[6]. This process was managed by Andy Bruere, WQTAG convenor and BOPRC's Lake Operations Manager. In addition to PC10's Method M2 and the related Memorandum of Understanding (MOU), the WQTAG took account of the science caucusing that took place in April 2017 during the PC10 hearing process. The WQTAG identified suitable lead authors for each module, drawing mainly on WQTAG members due to their specific expertise and familiarity with each module topic.

Review process

In October 2017, each module author was asked to write a short brief on how they would address their part of the ToR. These briefs were revised after feedback from Andy Bruere, fellow WQTAG members and Simon Park and module writing commenced in November 2017.

Each module is a 'standalone' technical report (see Table 1) comprising: an introduction; key questions; approach/methodology; results/discussion; limitations/gaps in understanding; and where applicable, recommendations for future actions.

Table 1 Science review modules.

Science Review Module – Report Title		Method LR M2 linkage	Authors
1	Setting the water quality and nutrient targets for Lake Rotorua: Rationale and historical background	(c)	Stephen Lamb and Rebecca Burton
2	Lake Rotorua: Trends in water quality (2001-2017)	(a)	Tom Stephens, Keith Hamill and Chris McBride
3	Trends and state of nutrients in Lake Rotorua streams 2002-2016	(a)	James Dare
4	PC10 catchment N accounting	(b)	Alastair MacCormick and Natalie Miedema
5	Long-term nutrient loads and water quality for Lake Rotorua: 1965 to 2017	(a)	Chris McBride, Jonathan Abell and David Hamilton
6	Review and re-run the lake model	(c)(i)	Chris McBride, Matt Allan and David Hamilton
7	Summary of ROTAN results	(c)(ii), part (c)(iv)	Kit Rutherford
8	Rationale and design of a phytoplankton nutrient limitation study	(c)(iii)	Grant Tempero
9	Ecotoxicological review of alum applications to the Rotorua lakes: Supplementary report	(c)(iii)	Grant Tempero

[6] This was later expanded to 12 modules comprising individual reports, (see Table 1).

10	A review of land-based phosphorus loss and mitigation strategies for the Lake Rotorua catchment	(c)(iii)	Reece Hill
11	Anthropogenic phosphorus load to Rotorua: Review and revision	(c)(iii)	Keith Hamill
12	Review of relevant New Zealand and international lake water quality remediation science	(d)	David Hamilton

Peer review and workshop

Method M2 requires that 'Any science review and recommendations completed under Method 2 will be peer reviewed by a suitable qualified independent expert' (clause f). This was discussed in late 2017 amongst WQTAG members before settling upon Professor Warwick Vincent, who holds the Canada Research Chair in Aquatic Ecosystem Studies at Laval University in Quebec City, Canada. Professor Vincent reviewed the ToR and made a number of detailed recommendations in March 2018. These recommendations were conveyed to all module authors.

Following discussion with Professor Troy Baisden[7], the module of phosphorus load and mitigation was split, with the latter phosphorus mitigation module contracted to Dr Reece Hill[8].

Individual modules were peer reviewed by Professor Vincent as they became available and detailed feedback given. This resulted in revised second drafts across most modules by early July 2018 and these were made available to everyone involved in the science review.

To help bring and enable broader discussion amongst module authors, WQTAG members and the peer reviewer, a full day workshop was held on 11 July 2018. Each author gave a summary presentation followed by discussion, especially on key recommendations. Workshop notes with draft recommendations for all 11 modules were circulated to all attendees.

MoU parties input

While the MOU parties (the farmers' Collective and LWQS) are not 'peer reviewers', the MOU does provide for their input to the review process and that BOPRC considers their views. PC10's Method M3 also states:

> *Regional Council will respond to the recommendations that result from Method LR M2 science reviews through a formal and public decision-making process. This may include initiation of a plan change and review of resource consent conditions to ensure consents are aligned to the required water quality targets.*

The MOU parties were invited (by Andy Bruere) to comment on the initial ToR and took part in a project update meeting on 22 February 2018. A further MOU parties meeting took place on 12 July 2018. This was arranged as a 'three farms' field trip with Professor Vincent to allow direct discussion with MOU parties on: the science review process; on-farm research that local farmers are involved with; and local challenges and farm systems relevant to managing nutrient losses to Lake Rotorua.

[7] Professor Baisden was appointed in 2017 as the Bay of Plenty Regional Council Chair in Lakes and Freshwater Science.

[8] Landsystems Ltd, also a soil scientist with the Waikato Regional Council.

Part 2:

Module 1 - Setting the water quality and nutrient targets for Lake Rotorua: Rationale and historical background

Stephen Lamb and Rebecca Burton

Introduction

Lake Rotorua has experienced water quality problems due to excess nutrient inputs over many decades. Water quality and nutrient loading targets have been set to improve water quality and this module describes the planning history of those targets.

The water quality in Lake Rotorua deteriorated from the 1960s, driven by land use change, farm intensification and city sewage discharges. This decline caused widespread public concern and support for restoring water quality to levels prevailing in the 1960s. A 1978 science report advised *"that the effect of diverting sewage effluent from Lake Rotorua, provided it is accompanied by the appropriate catchment control measures, would tend to maintain the condition of the lake water quality as it was in the late 1960s and early 1970s..."*

A key science paper (Rutherford et al., 1989) estimated target lake nutrient loads associated with water quality in the 1960s, prior to reticulated sewage discharge, to be 435 t nitrogen per year and 37 t phosphorus per year. When the Rotorua city sewage discharge was moved to land disposal in 1991, lake water quality improved due to the large reductions in nitrogen and especially phosphorus inputs[9]. Rising catchment nutrient inputs and sediment nutrient release (following lake stratification events) overtook gains from improved sewage treatment and water quality declined in the late 1990s and through the 2000s. This led to a series of formal Resource Management Act (RMA) policy development processes to adopt water quality and nutrient targets for Lake Rotorua.

The TLI target

In the early 2000s, the Regional Council began drafting a Regional Water and Land Plan (RWLP) with (TLI) targets for all 12 Rotorua lakes. While most TLI targets related to 'good' 1994 lake water quality, the Lake Rotorua TLI target of 4.2 related to the lake's 'good' 1960s water quality. The formal public consultation process on the Proposed RWLP began with its notification in February 2002. Following the RMA Schedule 1 submissions process, the notified Plan was subject to RMA Hearings and Environment Court appeal processes. No changes were made to Objective 11 and Policy 21(a) that reference the TLI of 4.2 through the appeal process.

[9] When the Rotorua city sewage discharge moved to land disposal, lake water quality expectations were stated in documents associated with the consent, similar to its 1960s water quality.

The RWLP also introduced nitrogen and phosphorus capping rules for rural land uses in five catchments, including Lake Rotorua, known collectively as 'Rule 11'. These relied on using the OVERSEER® model to assess and benchmark individual properties at their average 2001-2004 nitrogen and phosphorus loss rates. Rule 11 was an interim rule to prevent greater nutrient losses and was not expected to achieve the TLI target.

The nitrogen target

Since the 1989 Rutherford et al. paper, a range of scientific studies (including Rutherford 2003, 2008) have also contributed to the understanding of the sustainable load and its relationship to the 4.2 TLI target. The 435 t per year target was formally defined as the 'sustainable lake load' in Policy WL 3B within the Proposed RPS that was formally notified in November 2010. The RPS in Policy WL 6B also defined an annual steady state nitrogen load at 746 t per year (based on Morgenstern and Gordon, 2006). This aligns closely with subsequent NIWA modelling using ROTAN (Rutherford et al., 2011) to give a steady state nitrogen load of 755 t per year. The RPS 435 t per year limit was subject to submissions and appeal and remained unchanged through these processes, although the timeframe to achieve it was extended[10] to 2032 (see Policy WL 6B). The RPS became operative in October 2014 and must be given effect to in regional plans.

Independent modelling undertaken by the University of Waikato was used to ascertain what TLI would result from a range of nutrient interventions, including achieving the 435 t per year target. A TLI close to 4.2 was modelled to be reached at that load (Hamilton et al, 2012). Back calculation of the 1960s nutrient loads modelled in ROTAN 2011 and ROTAN 2016 (Rutherford and MacCormick, 2016) for the 1960s supported an annual nitrogen load over that period in the region of 435 t. Although some research suggested that the 435 t per year value may itself need to be refined (potentially downward[11]) this was not a consideration for the Regional Council at the time of writing.

The phosphorus target

The generally accepted sustainable lake load target for phosphorus is 37 t per year. This figure is again based on the 1989 Rutherford et al. paper. Estimating sustainable in-lake total phosphorus concentrations at that time was problematic. Two models were used and these arrived at values of 17 ppb[12] and 19.7 ppb. A value of 20 ppb was selected as a target (Rutherford et al., 1989). This in-lake target was applied in a lake model which could approximate the corresponding catchment load. It indicated a catchment load target of 37 t per year to achieve the in-lake concentration of 20 ppb. Based on the modelling at the time, the reduction of sewage inputs to 3 t per year would deliver the target load. This also recognised a 30.8 t reduction in phosphorus from sewage inputs in 1984-85.

The 37 t per year target was included within the Lakes Rotorua and Rotoiti Action Plan 2009 but it is not a regulatory target. Policy WL 3B in the RPS requires Council to set a limit for both nitrogen and phosphorus. No statutory limit had been set for phosphorus at the time of writing as there was insufficient evidence to do so. Following the removal of sewage discharges to the lake the "steady state" load was estimated at 39.1 t per year[13]. For the RPS process, the difference between the "steady state" and sustainable loads of phosphorus into Lake Rotorua of 2.1 t per year was not seen as being significant enough to require a RPS limit to be set.

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[10] The timeframe was negotiated through resolving appeals to the Proposed RPS, via the Oturoa Agreement.
[11] Rutherford and MacCormick (2016) pages 7 and 40, and Hamilton et al. (2013) page 359.
[12] ppb = parts per billion (mg/m^3).
[13] Table 6 in "Proposed Lakes Rotorua and Rotoiti Action Plan", Version 5.1, 14 Nov 2007. Environmental Publication 2007/11.

Recent work has provided a more robust view of phosphorus dynamics. For example, the steady state load was estimated by Tempero et al. (2015) at 48.7 t per year – this included storm flow estimates (which were not included in earlier estimates, as it was not considered that particulate attached phosphorus was bio-reactive). Based on this, the required phosphorus load reduction is now estimated at 10 t to 15 t per year (43-64% of the anthropogenic phosphorus load). This indicates the sustainable phosphorus load to reach the TLI of 4.2 (in association with the 435 t target) is 33.7 to 38.7 t per year, similar to the earlier estimate of 37 t per year.

The groundwater reaching Lake Rotorua is naturally enriched with dissolved reactive phosphorus, which has leached from bedrock as a result of long aquifer residence times. To achieve the sustainable phosphorus load is therefore challenging, due to the large proportion of phosphorus entering Lake Rotorua from natural sources (about 52%). This means that only about 48% of the phosphorus reaching the lake is manageable through land use controls.

Part 3:
Module 2 – Lake Rotorua: Trends in water quality (2001-2017)

Tom Stephens, Keith Hamill and Chris McBride

Introduction

This report builds on previous analysis to describe water quality trends in Lake Rotorua at two monitoring sites. Water quality trends were analysed over the long-term (2001-2017) and short-term (2009-2017), and at multiple depths using two different methods. The analysis focused on the four water quality variables that make up the TLI: Secchi depth (SD), total phosphorus (TP), total nitrogen (TN) and chlorophyll-*a* (Chl-*a*).

Key findings

The authors reviewed the long-term water quality history of the lake and confirmed that the TLI has been tracking close to the target of 4.2 since 2012 (Figure 4).

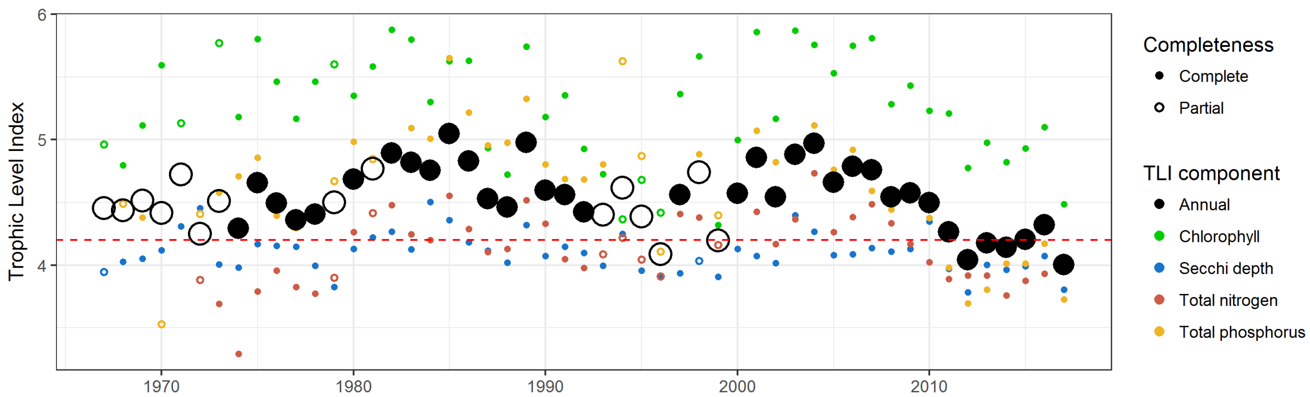

Figure 4 Long-term TLI measurements at mid-lake sites by hydrological year (previous July to present June). Each coloured circle is the mean of seasonal (quarterly) means, with the TLI equation applied (Burns et al., 1999). Solid dots denote years for which at least one measurement was available for all four seasons. Black circles are the overall annual TLI, where solid dots denote "complete" years in which all four seasons were sampled for all four component variables of the TLI. The lake TLI target is shown by the dashed red line (reproduced from Stephens et al. 2018, Figure 1.3).

The trend analysis revealed that:

- There were improving trends for all of the TLI attributes - total phosphorus, total nitrogen, chlorophyll-*a* and Secchi depth (Figure 5, Table 2). The results were statistically significant and substantial at all water depths analysed (surface, mid-depth and bottom). These conclusions also held after correcting the data for laboratory changes.

- Total phosphorus, total nitrogen and chlorophyll-*a* all peaked in late summer-early autumn, while Secchi depth had a more complex seasonal pattern.

- Deconstruction of the trends revealed broadly similar patterns between the TLI components. Chlorophyll-*a* concentration increased from 2001 to 2003 but decreased from 2006 to 2017. The period of greatest improvement in chlorophyll-*a* concentration was 2006 to 2012, and since 2016. Secchi depth appeared to 'decouple' from chlorophyll-*a* for a period from 2006 to 2009 (a decline in water clarity followed by an improvement).

- Since 2009, trends were largely of indeterminate direction, but there was an "extremely likely" improving trend in chlorophyll-*a* between 2009 and 2017.

The trends for each of the water quality variables were broadly similar between sites and between depths. However, at the deeper monitoring site (Site 2), declining trends in total nitrogen and total phosphorus were consistently of greater magnitude with increasing depth. This could imply recent changes to water quality being greater in deeper nutrient reservoirs, including the potential for altered hypolimnetic and/or pore-water nutrient regeneration. The authors suggested that this may mean that alum is having stronger effects on sedimentary nutrient regeneration than on flocculation of particulate nutrients in overlying waters.

Figure 5 Long-term (2001-2017) trend deconstruction output for Sites 2 and 5 combined at "surface" depth for Chl-a, SD, TP and TN (reproduced from Stephens et al. 2018, Figure 4.2.1).

Table 2 Seasonal Kendall trend test output for "surface" water quality indicators from 2001-2017 at Site 2 and 5 within Lake Rotorua. Confidence of direction is classified as "indeterminate" if the 95% confidence interval about median Sen slope estimate includes zero, and otherwise "improving" or "worsening" depending on latter direction. Trend reporting under the outdated nil-hypothesis approach is included, with "significant and meaningful" trends underlined. Trend output for corrected TN and TP is presented in brackets beneath uncorrected TN and TP output (reproduced from Stephens et al. 2018, Table 5.1).

Date	Seasonal Kendall trend test	Site 2				Site 5			
		SD	Chl-*a*	TN adjusted	TP adjusted	SD	Chl-*a*	TN adjusted	TP adjusted
2001-2017	p	<0.01	<0.01	<0.01 (<0.01)	<0.01 (<0.01)	<0.01	<0.01	<0.01 (<0.01)	<0.01 (<0.01)
	SKSE	0.057	-0.939	-11.678 (-7.262)	-1.721 (-1.978)	0.06	-0.968	-11.238 (-6.304)	-1.665 (-1.958)
	RSKE (%/yr)	2.2	-6.4	-3.3 (-1.9)	-7.2 (-8.8)	2.3	-6.9	-3.2 (-1.6)	-6.9 (-8.9)
	Direction (LAWA)	**All trends were "improving" (95% confidence intervals of SKSE do not include zero)**							
	Likelihood of improvement	**All trends were "virtually certain" (>99% probability)**							

Further analysis of the surface water data indicated that from 2001 to 2009 chlorophyll-*a* concentrations were positively correlated with both total phosphorus and total nitrogen (with the correlation slightly stronger for total nitrogen). However, since 2009, chlorophyll-*a* was more strongly correlated with surface water total phosphorus. The authors noted that the analysis is not able to confirm whether nutrients are causing and/or responding to changes in chlorophyll-*a*.

Recommendations

The authors made the following recommendations:

1 Determine trends in dissolved oxygen availability at bottom depths, both throughout the entire record length and for periods of stratification, from which to determine if alum-associated changes influence internal nutrient release.

2 Determine trends in nutrient ratios amongst "surface" waters and assess trend components for association to alum dosing (e.g., to alum mass dosed, to alum concentration instream at point of application).

3 Determine a complementary and appropriate method to analyse for trends in overall TLI score, whether at annual or monthly time-step, that otherwise does not prevent trends in each component cancelling each other when combined.

4 Revise the definition of "meaningful" to be context-specific to the targets set for water quality outcomes in Lake Rotorua and adopt one of the two rather than both trend directional methods currently in use for reporting in New Zealand.

Part 4:

Module 3 - Trends and state of nutrients in Lake Rotorua streams 2002-2016

James Dare

Introduction

This report presents an update on nutrient concentration trends and estimated nutrient loads for the Lake Rotorua stream inflows. The analysis is based on monitoring data at nine sites and the author uses a number of trend analysis and load estimation methods to extract more information from the long-term dataset.

Analysis was carried out over four time periods to understand trends:

- Long (2002-2016) and short (2012-2016) term.
- Pre-laboratory methodology change (2002-July 2008) and post change (July 2009-2016).

The latter two periods were chosen to understand complications associated with a laboratory methodology change that occurred between July 2008 and July 2009.

Key findings

Nitrogen

Trend analysis showed an overall reduction in instream nitrate-nitrite nitrogen (NNN) concentrations since 2009, however, over the long-term dataset (2002-2016), five of nine sites showed an increasing trend (Table 3). In contrast, after July 2009, a pattern of increasing ammoniacal nitrogen (NH4-N) was found at many sites. Analysis of total nitrogen (TN) trends showed more sites with increasing concentrations than decreasing over the long-term dataset and more recently (2002-2016).

Table 3 The number of monitored stream inflows with significant trends (note there are nine sites in total). Red font represents increasing (deteriorating) trends, while green font represents improving trends (modified from Dare 2018, Table 13).

Analyte	2002-2016		2002-July 2008		July 2009-2016		2012-2016	
TN	3	1	1	2	2	2	4	2
NNN	5	1	0	2	1	4	0	2
NH4-N	1	1	0	2	4	0	5	0
TP	6	1	1	2	8	0	6	0
DRP	3	2	0	2	7	0	2	0

An interesting finding was that high-flow ammoniacal nitrogen concentrations were increasing over time at some sites (e.g. see Figure 6). However, the contribution of ammoniacal nitrogen to total nitrogen in most catchments is currently minor, with only the Puarenga and Waiohewa streams exceeding 10%. Therefore, any increases in ammoniacal nitrogen are unlikely to be solely responsible for increasing total nitrogen trends, which suggests that particulate organic nitrogen may also be a contributor. While the source of ammoniacal nitrogen is unknown, the author suggested that contributors could include farming activity, stormwater discharges, septic tanks, and geothermal activity.

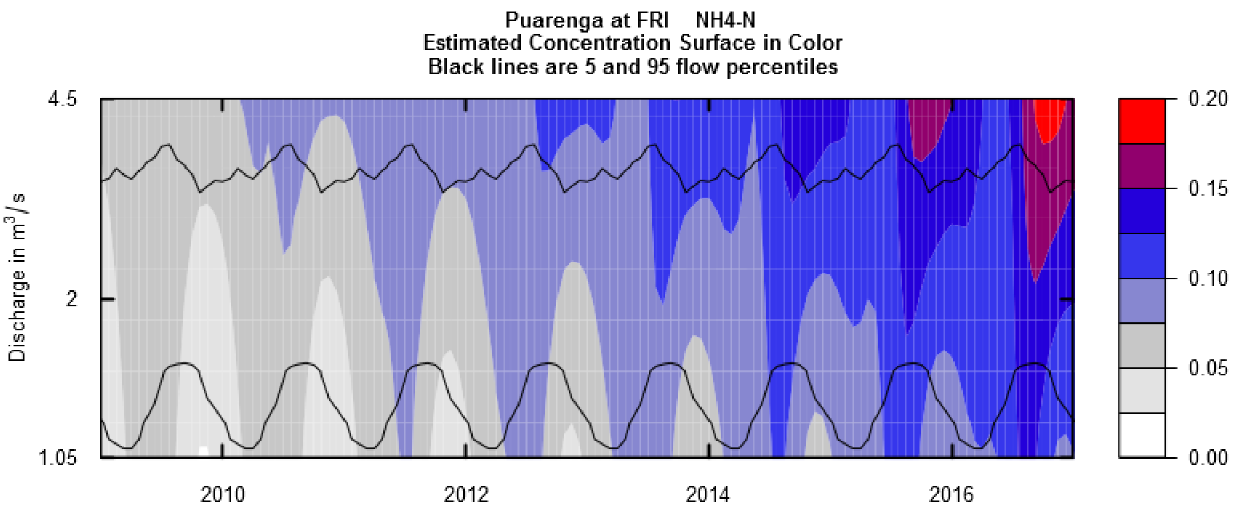

Figure 6 Modelled concentrations versus discharge for the Puarenga at FRI site between 2010 and 2016, for NH4-N (modified from Dare 2018, Figure 28).

The combined total nitrogen load from the nine inflows has fluctuated around 400 t per year since monitoring began, with the estimate for 2016 equating to between 410 and 415 t (Figure 7). Note that this value is not comparable to the sustainable load (435 t per year) because it only accounts for base-mid flow loads from these major inflows. Further estimates of ungauged inflows and rainfall contribution need to be included before direct comparison with the sustainable load can be made.

A comparison of nitrogen loads from each monitoring site revealed that a large proportion of the total load is contributed by the Waitetī, Hamurana, Awahou, and Puarenga streams (Figure 9). Nearly 75% of the total ammoniacal nitrogen load is sourced from the Waiohewa Stream. The next greatest contributor is the Puarenga Stream where the ammoniacal nitrogen load has been steadily increasing since 2010.

The total nitrogen load at the Lake Rotorua outflow (Ōhau Channel) has remained consistently low relative to stream inflow loads (Figure 10), implying that a large proportion of total nitrogen is sedimented or denitrified within the lake. Total nitrogen export was primarily in the form of organic nitrogen, which suggests that a large amount of bioavailable nitrogen is taken up by planktonic algae and exported as algal biomass. The impact of nutrients exported from Lake Rotorua and Lake Rotoiti on water quality in the lower Kaituna Catchment is suggested to be low. This is because the concentrations of most forms of nitrogen (except ammoniacal nitrogen) in the lower river at Maungarangi Road exceeded that measured at the lake outflow.

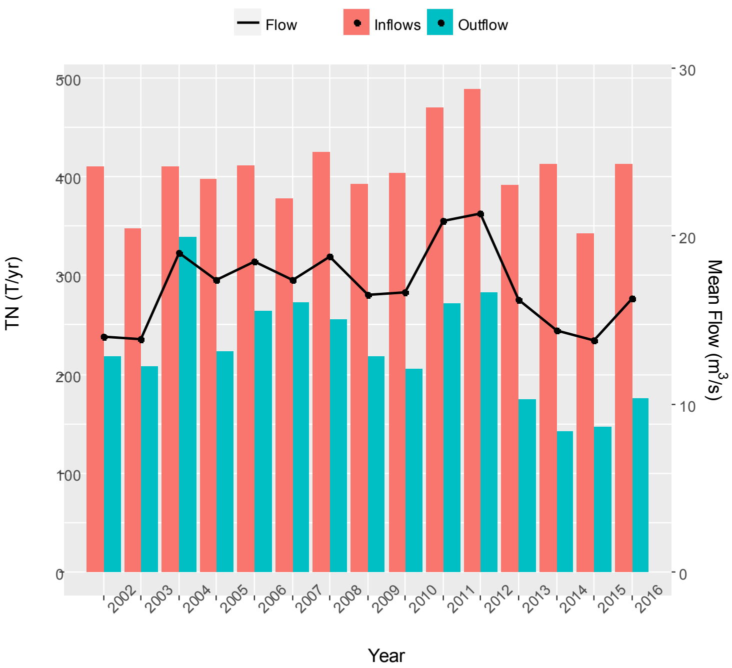

Figure 7 *Comparison of major inflow and outflow TN loads throughout the duration of the study. The black line represents the mean annual flow for the Ōhau Channel (Lake Rotorua Outflow), as calculated from mean daily flows corresponding with each water quality sample (reproduced from Dare 2018, Figure 58).*

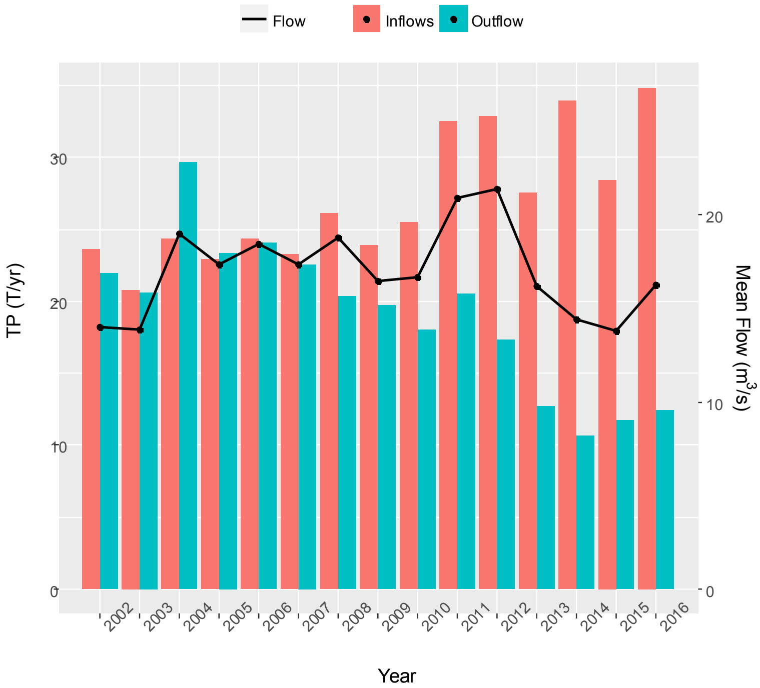

Figure 8 *Comparison of major inflow and outflow TP loads throughout the duration of the study. The black line represents the mean annual flow for the Ōhau Channel (Lake Rotorua Outflow), as calculated from mean daily flows, corresponding with each water quality sample (reproduced from Dare 2018, Figure 59).*

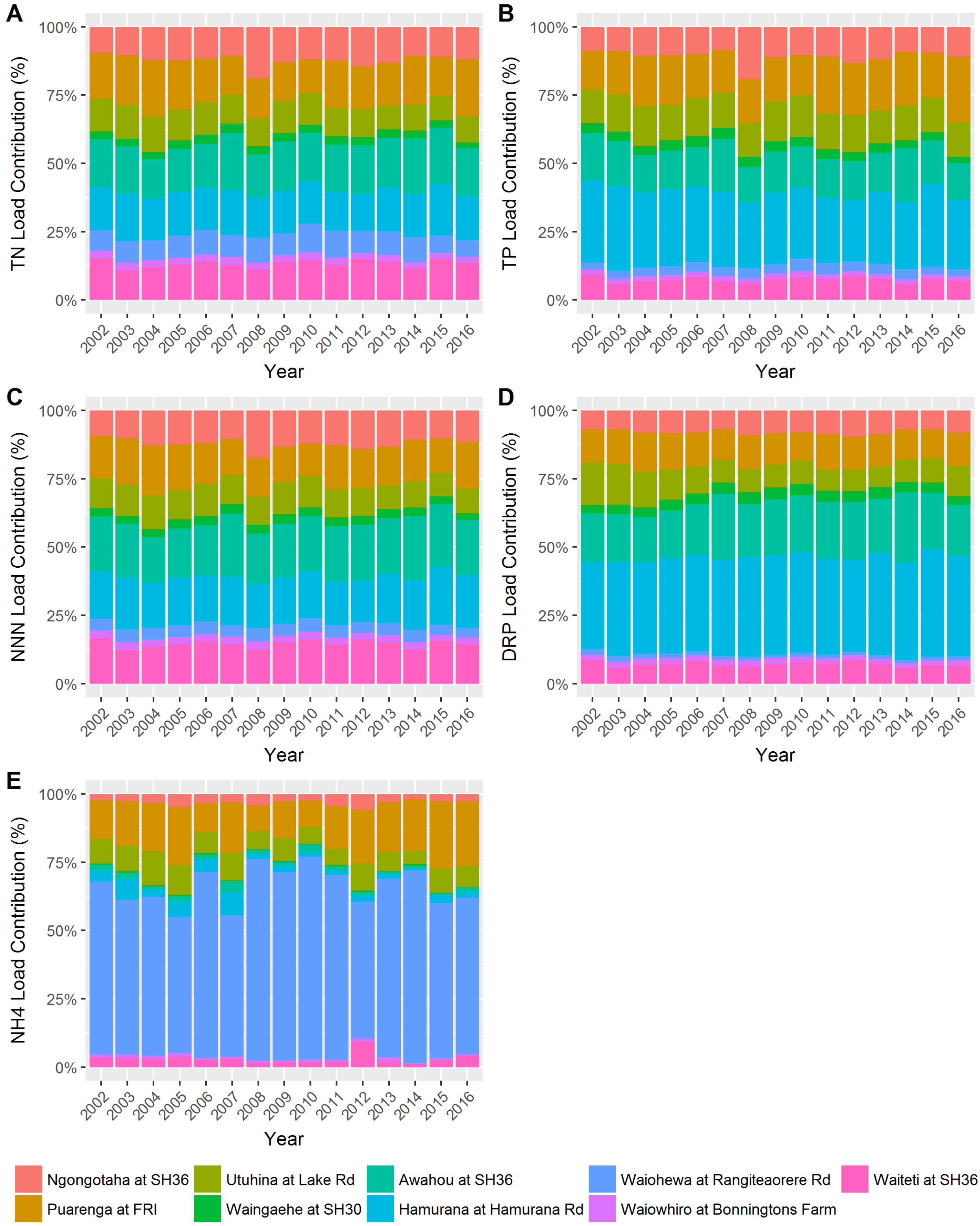

Figure 9 *Relative load contribution per analyte for each of the main Rotorua inflows. TN, NNN, TP, and DRP are calculated using the LOADtEST model. NH4-N is calculated using Numeric Integration (reproduced from Dare 2018, Figure 64).*

Phosphorus

Trend analysis showed an overall increase in instream total phosphorus (TP) concentrations, particularly in the period 2009-2016 where eight of nine sites increased (Table 3). Increasing trends were also identified for dissolved reactive phosphorus (DRP) with seven sites increasing after July 2009. No site showed any reduction for total or dissolved reactive phosphorus after July 2009.

Increasing dissolved reactive phosphorus concentrations contributed to the number of increasing total phosphorus trends identified, particularly after July 2009. However, many sites have also experienced an increase in particulate phosphorus in recent years. These forms of phosphorus are typically mobilised via overland flow pathways caused by high intensity rainfall events. Aside from a wet period between 2010 and 2012, annual rainfall and the number of high intensity rainfall events in the Lake Rotorua Catchment is comparable across years. This suggests that other factors may be increasing the supply of particulate phosphorus to Lake Rotorua seen in recent years.

The combined total phosphorus load from the nine inflows was around 23 t per year between 2002 and 2010, while the estimate for 2016 equated to between 34 and 36 t (Figure 8). Ratios of inflow to outflow phosphorus load show that after 2009, an increasingly smaller proportion of inflow total phosphorus has been exported from the lake (Figure 10). This is consistent with the increased supply of particulate phosphorus found at many of the inflow sites, and the effects of alum dosing of the Utuhina and Puarenga streams.

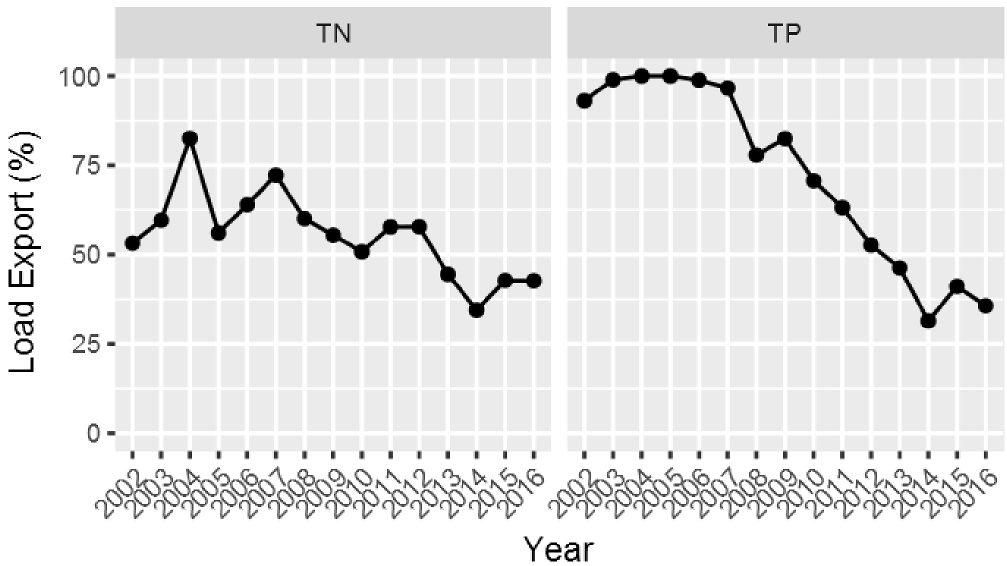

Figure 10 The percentage of TN (left) and TP (right) loads calculated from major inflows, which are exported from the lake via the Ōhau Channel, over time (reproduced from Dare 2018, Figure 60).

Over 50% of the dissolved reactive phosphorus load can be attributed to the Hamurana and Awahou catchments alone, reflecting the extended groundwater residence times in these catchments. Other major contributors include the Puarenga and Utuhina catchments, the latter of which contributed a smaller proportion of dissolved reactive phosphorus load after 2006, coinciding with the start of alum dosing. The Hamurana Catchment was the largest single contributor making up close to 25% of the total phosphorus load. Particulate phosphorus was more prevalent in the Puarenga, Utuhina, and Ngongotahā catchments compared to dissolved reactive phosphorus.

Recommendations

The author made the following recommendations to improve the data and information available for future analyses:

Improvement of scientific data

1 Increase high flow sampling events to provide more robust load estimates and inform concentration-discharge analyses. Results indicate contaminants may be responding differently at different parts of the hydrograph (e.g. base flow versus high flow). Accurate high flow measurements would provide more certainty around high flow predictions, while also benefiting regression load estimates.

2 Improve continuous flow measurements. Continuous flow records can provide useful data for additional analysis. Installation of water level loggers is a relatively simple task, enabling flow-water level relationships to be developed for non-hydrology sites. This data could also increase certainty around some of the spot gauging data which appears to be biased towards low flows in recent years.

Additional Investigations

1 Investigate the increasing trend of ammoniacal nitrogen in the Puarenga Catchment. Results show the ammoniacal nitrogen concentrations have increased in this catchment, particularly after 2009. A small scale investigation may provide answers about the source of this contamination and enable it to be minimised.

2 Identify hydro-chemical signatures to clarify contaminant sources and pathways. The identification of discrete hydro-chemical signatures could provide information about the source and pathway of contamination, allowing for targeted mitigation methods to be applied.

Part 5:
Module 4 - PC10 catchment N accounting

Alastair MacCormick and Natalie Miedema

Introduction

This module describes the nitrogen accounting methodology that supports Plan Change 10 (PC10). It provides a revised version of the ROTAN 2011 nitrogen budget using OVERSEER® 6.2.3 and current understanding of measured loads. Progress towards nitrogen reduction targets is reported for both permanent and non-permanent reductions.

Key findings

The ROTAN 2011 nitrogen budget has been updated to include revised land use areas, the latest groundwater boundary, and OVERSEER® 6.2.3 average land use nitrogen (N) discharge coefficients based on the Rule 11 benchmarking. The budget estimates a catchment pre-attenuation annual load of 1274 tN and calculates an attenuation factor of 44% to achieve the ROTAN 2011 steady state load of 755 tN. Adjusting the Integrated Framework (I.F.) reductions to use the same attenuation factor and reflect our current understanding of the gorse area in the catchment results in a post mitigation load of 446 tN which is reasonably close to the sustainable load of 435 tN. This N accounting approach is illustrated in (Table 4).

Permanent N reductions from the catchment are achieved through the Incentives Programme, engineering solutions, and the conversion of gorse land to bush or forestry. The Incentives Programme has achieved 11% of its OVERSEER® 6.2.3 reduction target and the Engineering Programme has removed 26% of its OVERSEER® 6.2.3 reduction target. As a result of a better understanding of the gorse coverage in the catchment, the estimated load from gorse has reduced from 30 t N to 13.9 t N. Of the 30 t target reduction, 3% has been permanently removed through commercial agreements to convert gorse areas to forestry or bush and scrub (Table 5).

Non-permanent N reductions are reductions below the allocated level that are not locked-in through commercial agreements or rules. Current state information has been used to indicate the level of non-permanent reductions in the catchment, based on 99 OVERSEER assessments by BOPRC contractors (Land Use Advisors). The current state period covered 2013-2017, with most assessments (55 properties) based on the 2015/2016 year. Approximately 52% of the pastoral area in the catchment has current state information available, comprising almost all dairy properties and about one third of the dry stock area in the catchment.

Table 4 Updated nitrogen budget for Lake Rotorua using losses modelled in OVERSEER® 6.2.3, measured loads and attenuation factors calculated to achieve 755 tN. Applying the same attenuation factors to the land load after reductions gives a 2032 lake load of 446 tN (reproduced from MacCormick and Miedema 2018, Table 2).

Land use	Area (ha)	Load to land (tN/y)	Pre-attenuation reductions (tN/y)				Load to land before attenuation and after reductions (tN/y)	Attenuation factor	Load to lake after attenuation and before reductions (tN/y)	Load to lake after attenuation and reductions (tN/y)
			Rules	Incentives	Engineering	Gorse				
Dairy	**4,990**	**473**	-167.0	-93.4	-5.0		208	44%	267	117
Dry stock	**15,873**	**551**	-94.8	-93.4	-11.0		352	44%	311	199
Grazed trees	**1,346**	**12**					12	44%	7	7
Forestry	**9,163**	**23**					23	44%	13	13
Bush and scrub	**9,994**	**30**					30	44%	17	17
House	**396**	**27**			-8.8		19	22%	21	14
Reticulated housing	**2589**	**13**					13	44%	7	7
Urban Open Space	**522**	**11**			-2.0		9	44%	6	5
Lake or waterway	**8,145**	**0.0**					0.0	0%	0.0	0
Non-productive	**237**	**0.1**					0.1	44%	0.1	0
Roading	**534**	**0.3**					0.3	0%	0.3	0
										0
Gorse	*882*	**14**				-10	4	44%	8	2
Rain on lake	*8,082*	**30**					30	0%	30	30
WWTP 2001-2004	*1*	**56**			-18.0		38	40%	34	23*
Tikitere	*1*	**25**			-20.0		5	0%	25	5
Urban stormwater	*2,589*	**8**			-2.0		6	0%	8	6
Whakarewarewa	*44*	**0.3**					0.3	44%	0.2	0
Totals	**53,790**	**1,274**	**-262**	**-187**	**-66.8**	**-10**	**749**		**755**	**446**

*This is a hypothetical load to the lake after assuming 7 t N removal between the WWTP outflow and the lake through algal farming or other N removal process. This is additional to the WWTP treatment and N removal processes.

Table 5 *OVERSEER® 6.2.3 reductions achieved to date through Integrated Framework reduction programmes (reproduced from MacCormick and Miedema 2018, Table 4).*

Reduction Programme	Number of agreements	N removed from lake by 2022 (OVR 6.2.3 tN/y)	2022 in Lake Reduction Target (OVR 6.2.3 tN/y)	Percentage removed
Incentives	9	11.4	105.6	11%
Engineering	*N/A*	12.8	50	26%
Gorse	8	0.8	30.0	3%

On average, the N load from these properties with current state assessments is 17% below their start point[14] allocations and 9% above their 2032 allocations. These N 'reduction' numbers shown in Table 6 are not audited and are indicative only because the different assessment years, OVERSEER® versions and incomplete data are all likely to affect the results.

Table 6 *Dominant 2001-2004 land use and average percentage reductions calculated by property. Percentage reductions are calculated for start point to NDA and start point to current state (reproduced from MacCormick and Miedema 2018, Table 7).*

2001-2004 Dominant Land use	Number of properties	Effective area (ha)	Average property reduction from SP to NDA (%)	Standard deviation SP to NDA (%)	Average property reduction from SP to CS (%)	Standard deviation SP to CS (%)
Dairy	31	5679	27%	26%	17%	23%
Dry stock	68	5865	9%	17%	0%	46%
All	99	11543	14%	22%	5%	41%

Recommendations

Consideration of the gaps and limitations identified in this N accounting analysis leads to six recommendations for further work:

1. Define reporting requirements. The reporting requirements determine the information collected and the systems to manage that information.
2. Complete development of NDMS (Nutrient Data Management System). The N accounting system must be able to accurately and reliably track changes to allocations arising from N buy outs, trading between properties and shifts within properties.
3. Work with OVERSEER® Limited to improve the N loss predictions in the Rotorua Catchment and the model's reliability.
4. Investigate catchment attenuation and the uncertainties in measured loads, modelled loads and groundwater travel times.

[14] Start Points are defined in PC10. For the purposes of this report a start point can be considered as a property's initial allocation from which reductions are made.

5 Investigate N losses from lifestyle blocks. Understanding the N losses from lifestyle blocks will help inform where resources should be focused.

6 Measure loads and trace losses from stormwater and sewerage systems to identify areas where reductions can be made.

Part 6:
Module 5 - Long-term nutrient loads and water quality for Lake Rotorua: 1965 to 2017

Chris McBride, Jonathan Abell and David Hamilton

Introduction

This study collated and analysed water quality data from all available sources for the lake and inflows over the period 1965 to 2017[15]. The author used consistent methods to obtain estimates of long-term loading and lake water quality, so that the information could be evaluated in the context of the established sustainable nutrient loads (total nitrogen 435 t per year; total phosphorus 37 t per year[16]).

To undertake the analysis, a lake water balance was first constructed, accounting for all sources and losses of water on a daily basis from July 1964 to June 2017. Daily stream nitrogen and phosphorus concentrations were estimated either by interpolating measurements or modelling discharge-concentration relationships during stormflows, using available data. Volume and concentration of additional sources, including geothermal fluid, groundwater and atmospheric deposition, were estimated from additional monitoring data and literature review.

Key findings

This study provides estimates of external (catchment) nutrient loading only. The authors acknowledge that internal nutrient recycling can greatly increase total loading to the lake water column on an annual basis, and can also reduce the rate that lake water quality improves following external load reduction. Annual estimates of nutrient loading from various sources are presented in (Figure 11).

The authors found that total nitrogen load has increased substantially and steadily since the 1960s, principally due to increases in nitrate concentrations. Direct discharge of wastewater from Rotorua City to the lake (pre-1991) was a smaller component of total nitrogen load than for phosphorus. Nitrogen loads were found to be well in excess of the sustainable load, and the annual load (435 t per year) appears to be higher than that observed in the 1960s (as estimated in this study).

[15] Note: while this work was not originally identified as a module of the Science Review it has been treated as such.

[16] From Rutherford et al. (1989).

Stream phosphorus concentrations have been relatively stable since the 1970s, however, total phosphorus load to the lake has varied considerably over time, reflecting fluctuations in particulate phosphorus loads and removal of direct inputs of treated wastewater to the lake in 1991. Groundwater-dominated inflows (Hamurana and Awahou) were the largest sources of dissolved phosphorus to the lake, and a substantial proportion of phosphorus loading is likely to be geologically-derived. Total phosphorus concentrations have increased in several inflows since 2010.

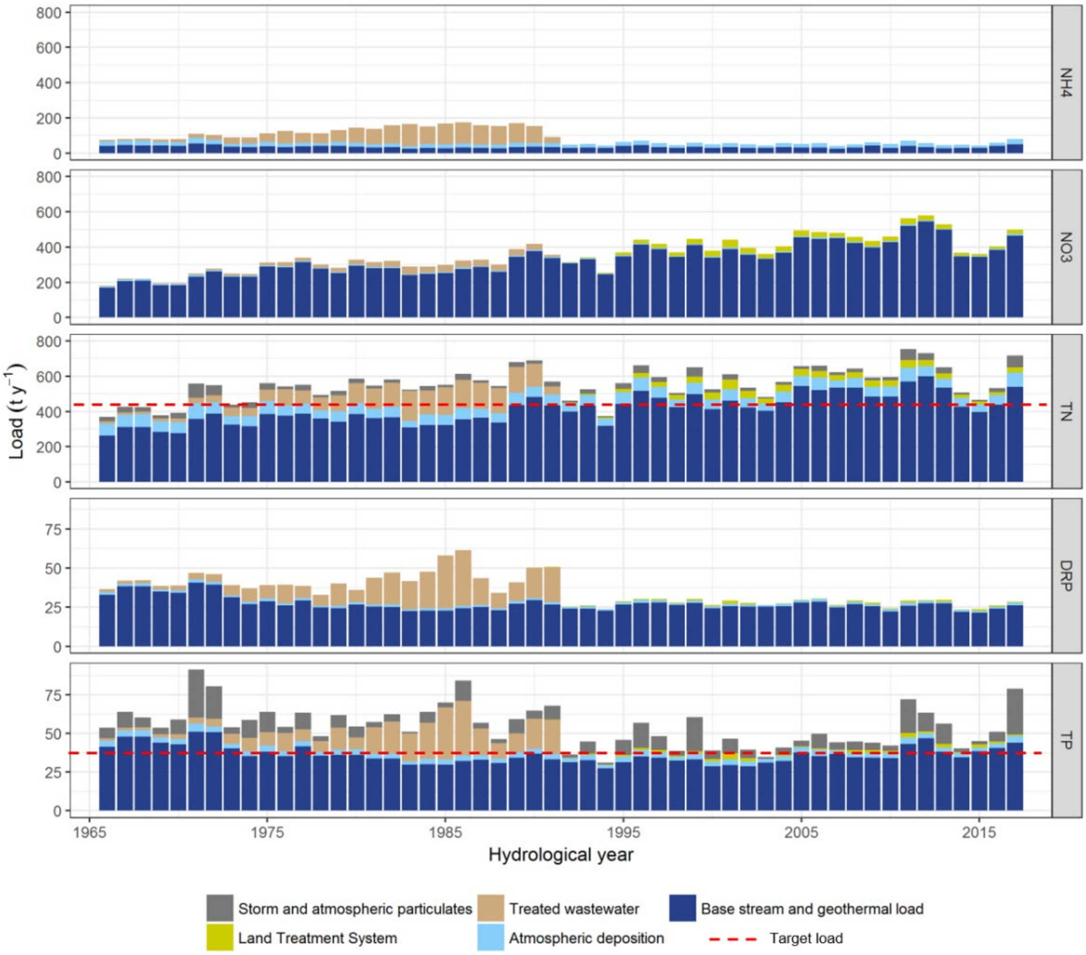

Figure 11 Summary of nutrient loading to Lake Rotorua 1959 to 2017. Loads from storm flow and particulate deposition are shown for in grey. Note 'NO_3' and 'NH_4' loads are in terms of N. Sustainable load targets (Rutherford et al. 1989) are shown by the dashed red line (reproduced from McBride et al. 2018a, Figure A).

Lake water quality data from 1967 to 2017 were collated from a variety of sources. Due to gaps and inconsistent frequency of sampling, an aggregation approach was adopted to reduce seasonal bias in annual mean values. Mid-lake water quality data collected from the late 1960s (early 1970s for nitrogen) until present, and annual estimated water quality and TLI values are presented in Figure 12 and Figure 13. Present water quality generally meets the TLI target, and appears comparable to, or better than that observed in the late 1960s, with the possible exception of nitrogen. Annual phosphorus concentrations measured since 2010 are generally lower than any earlier observations. High phosphorus concentrations in the 1980s to early 2000s appear to be pulse-like during warmer months, suggesting that particularly high internal loading associated with stratification occurred during that period.

In summary, the authors concluded that estimated catchment (external) loads do not reveal reductions over the past 10 years that would explain the recent, and dramatic, improvements in water quality. In the absence of external catchment drivers, low lake phosphorus concentrations at present are likely due to the alum dosing, possibly coupled with partial exhaustion of historical (legacy) phosphorus from direct wastewater discharge stored in lake sediments. The authors also concluded that substantial reductions in catchment loading, particularly for nitrogen, will be required to meet the sustainable load targets. This would reduce dependence on active in-lake and in-stream management strategies (such as alum dosing) that may carry greater ecological risk than management by sustainable land use practices alone.

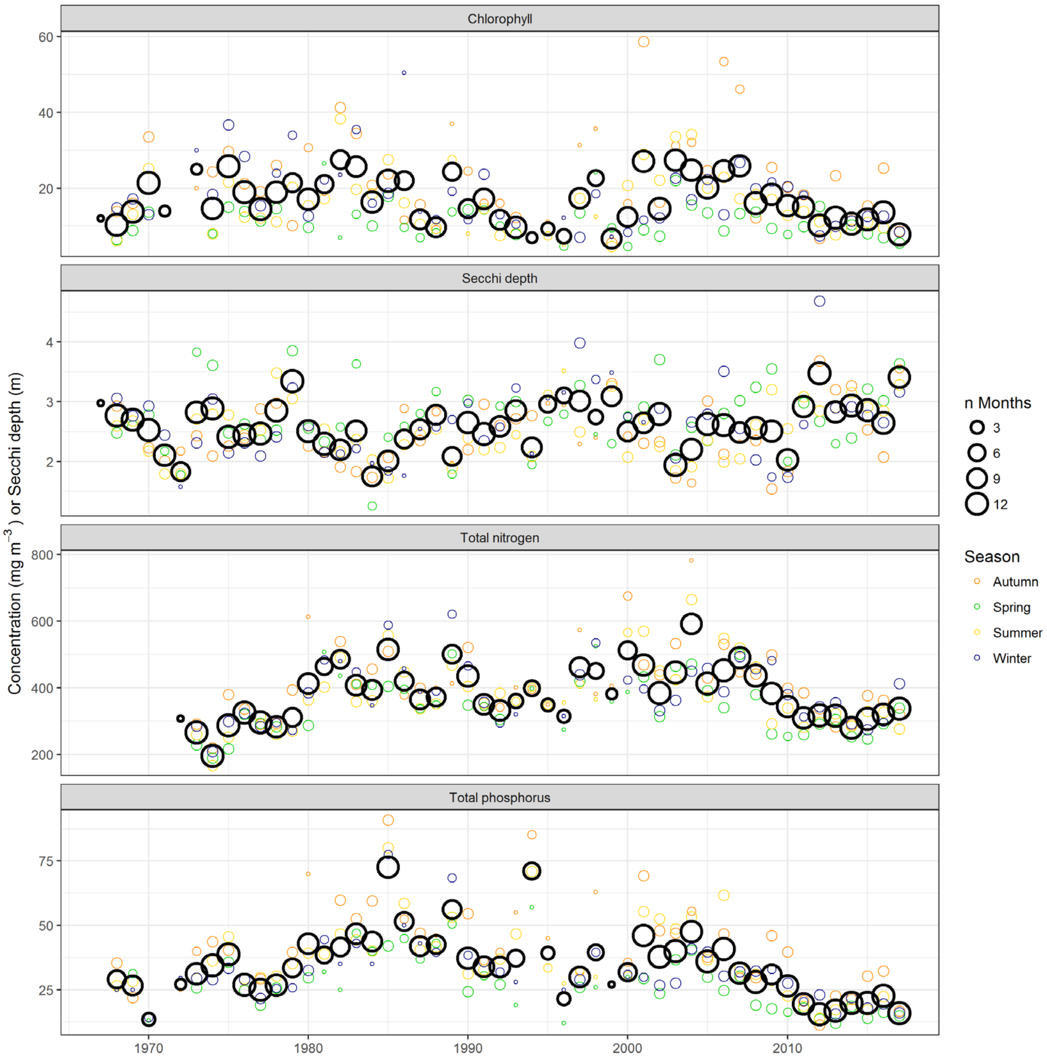

Figure 12 Measurements of TLI variables at mid-lake sites in Lake Rotorua. Individual samples were aggregated, retaining only the median value for each month and variable. Monthly medians were then averaged seasonally, shown by the coloured circles. Black circles are the mean value of all available seasonal averages, and may differ slightly from values reported by BOPRC due to the 'average of seasonal averages' approach used here. The diameter of all circles is scaled by the number of monthly median measurements aggregated (reproduced from McBride et al. 2018a, Figure B).

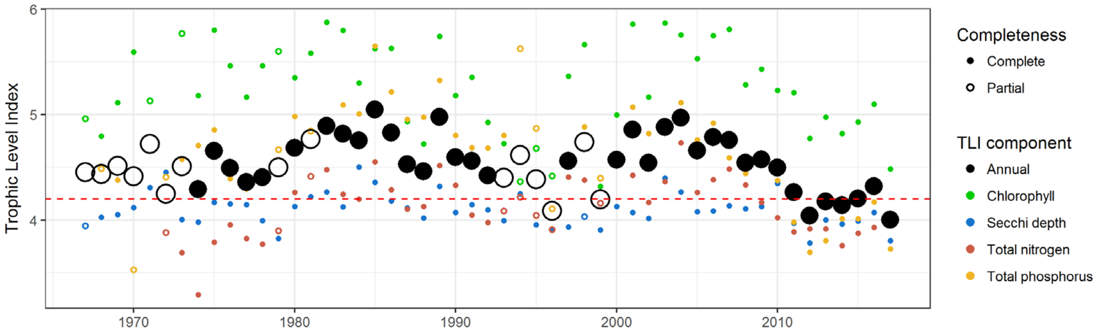

Figure 13 *Annual TLI at mid-lake sites by hydrological year (previous July to present June). Each coloured circle is the mean of seasonal means, with the TLI equation (Burns et al. 1999) applied. Large black circles are the annual TLI (average of four components). Solid circles denote years for which at least one measurement was available for all four seasons (solid black circles denote that all four component variables of the TLI were sampled each season). Open circles denote that measurements were missing for at least one season. The lake TLI target (4.2) is shown by the dashed red line. Values may differ from those routinely reported by BOPRC due to the aggregation method used here (reproduced from McBride et al. 2018a, Figure B).*

Note: *This figure is identical to that presented in Part 3 (from Stephens et al. 2018).*

Part 7:
Module 6 - Review and re-run of the Lake Rotorua model

Chris McBride, Mathew Allan, and David Hamilton

Introduction

This report builds upon a series of modelling studies spanning 12 years to better understand the processes influencing water quality in Lake Rotorua. The existing DYRESM-CAEDYM model was improved by providing empirically derived daily estimates of water, nitrogen and phosphorus inputs to the lake. The authors sought to increase the number of different nutrient loading scenarios to encompass a 'matrix' involving different combinations of nitrogen and phosphorus loads. This matrix allowed insights into:

- Water quality outcomes for the lake arising from a variety of management strategies that may alter the relative loads of nitrogen and phosphorus to the lake,
- The effects of catchment load reductions on internal loading to the lake, and
- The degree to which alum dosing of the Puarenga and Utuhina streams (post-2006) has altered internal loading to the system, thus reducing the 'total load' (external plus internal) to the lake.

By examining these relationships, the authors hoped to assess the extent that the current relatively good water quality conditions in the lake might have been driven by alum dosing, as opposed to changes in catchment loading and/or climate. Several of the model scenarios were designed to assess what level of catchment nitrogen and phosphorus load reductions might be required to meet the TLI target of 4.2, without the need for ongoing, long-term alum dosing.

Key findings

The performance of the revised model was found to be comparable, and in many cases superior to, previously published applications of DYRESM-CAEDYM to Lake Rotorua and other lakes. Model simulations showed that:

- The TLI could be reduced from approximately 4.8 (as observed from 2001-2007) to approximately 4.3[17] through catchment nitrogen and phosphorus load reduction, and without the need for alum.
- The catchment nitrogen load prior to 1970 was likely to be less than the target load of 435 t per year, and the lake TLI may possibly have been greater than 4.2 by the late-1960s.

[17] The authors noted that while the TLI reduction from 4.8 to 4.2 appears modest, the absolute reductions in total nitrogen, total phosphorus and chlorophyll-*a* are relatively large, due to the logarithmic nature of the TLI component equations. For example, total nitrogen and total phosphorus mean concentrations were reduced by approximately 75% between the maximum and minimum load scenarios.

- Substantial further water quality degradation could occur if present trends of increases in the catchment nitrogen load are left unchecked.

- Significant reductions in both nitrogen and phosphorus loads are needed to achieve a TLI near to the target of 4.2.

These important findings are consistent with the weight of scientific evidence that dual nutrient management and reduction are needed for restoration to be effective for Lake Rotorua.

The calibrated model was also used to test the proposition that alum dosing of the Puarenga and Utuhina streams, has positively impacted lake water quality over and above any benefit caused by direct adsorption of dissolved reactive phosphorus by alum in the two streams. This arose from the observation that since 2010, there has been a reduction in dissolved reactive phosphorus concentrations in the lake, and that surface water dissolved inorganic nitrogen concentrations have sometimes been strongly elevated compared with historical levels. Although both dosing rates and water quality varied widely from 2007-2017, the model simulations indicated than alum dosing may be having an effect equivalent to a 50% reduction in nutrient release rates (internal loading) from the lake sediments[18] (see Figure 14).

[18] In making this conclusion the authors noted that internal nutrient loads are dominated by dissolved (largely bioavailable) nutrients, whereas catchment loads contain relatively more particulate and organic forms of nitrogen and phosphorus, only some of which may become bioavailable at longer time-scales.

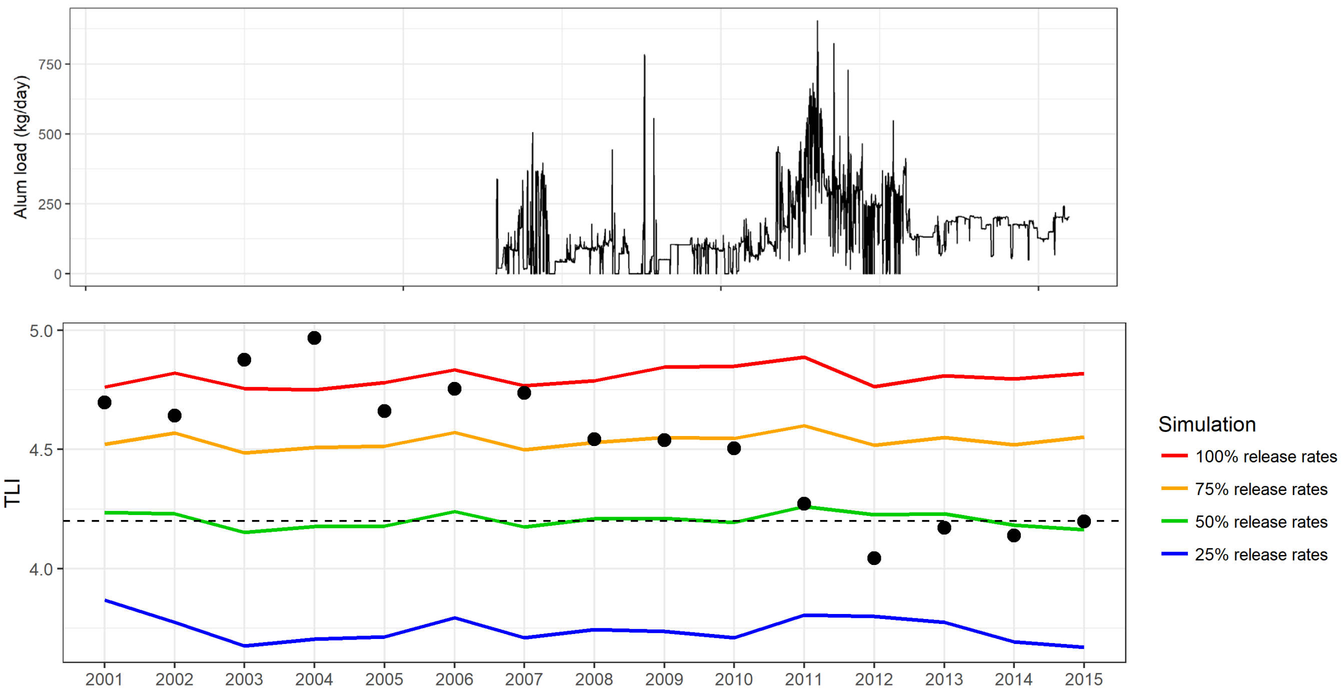

Figure 14 *Alum dose rate (top, expressed as kg Al per day), and bottom, observed TLI (black dots) along with TLI simulated under four different scenarios of sediment nutrient flux rates. Release rates of 100% represent the 'baseline' calibrated DY-CD lake model, and other scenarios represent reductions in modelled sediment nutrient flux rates. Simulations show that stream alum dosing may have had an effect similar to a reduction of c. 50% of internal nutrient load, and that this effect varies with dose rate (reproduced from McBride et al. 2018b, Figure A).*

In summary, the authors concluded that substantial reductions in catchment nutrient loading will be required to achieve water quality at or near the TLI target in the absence of alum dosing. This is illustrated in Figure 15, which shows the combinations of catchment nitrogen and phosphorus loadings required to achieve a range of TLI values.

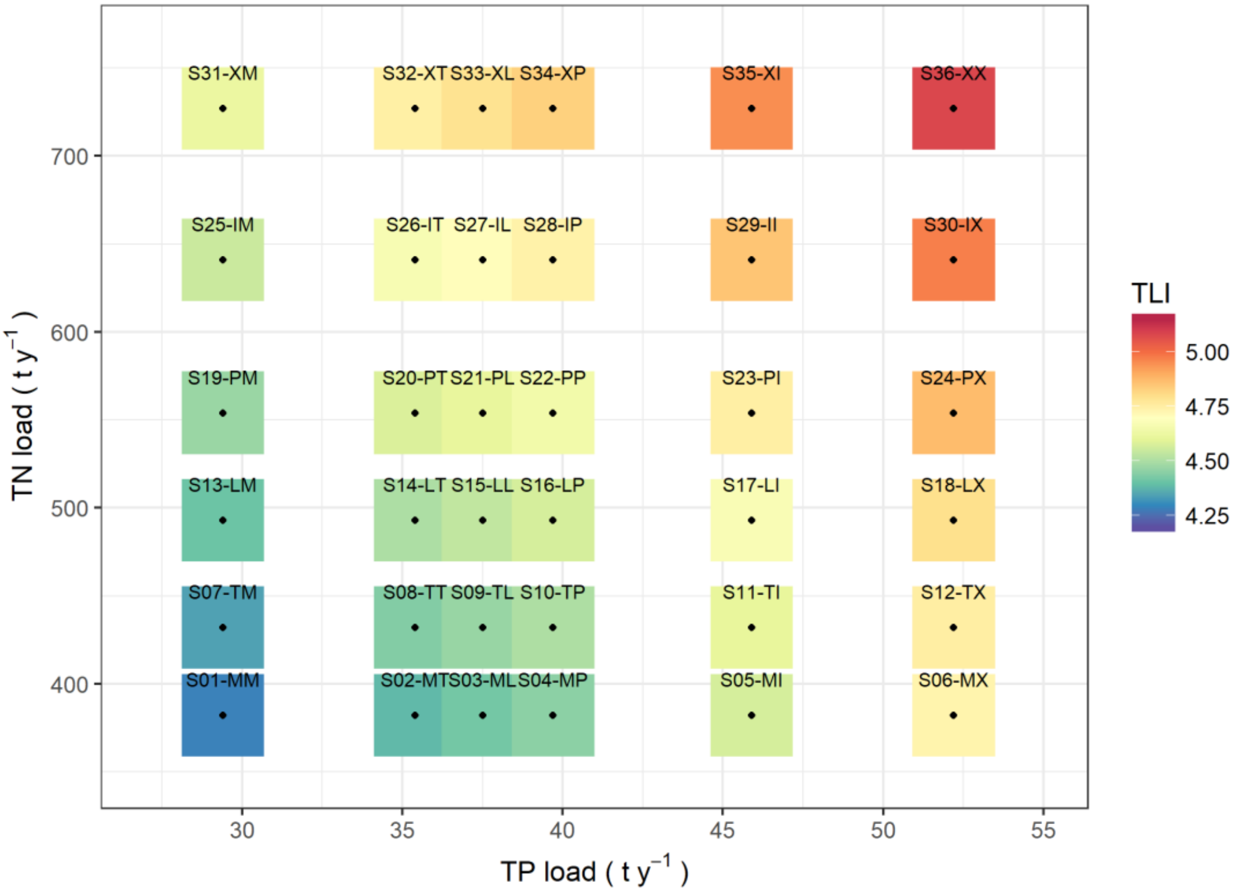

Figure 15 *Modelled TLI under 36 scenarios covering various combinations of catchment TN and TP loading. Results presented demonstrate the influence of TP and TN loading (t y^{-1}) on TLI over the scenario period from July 2000 to June 2007. The lowest simulated TLI was 4.29 (S01-MM) and the highest simulated TLI was 5.08 (S36-XX). Each point and coloured tile on the plot represents one nutrient loading scenario corresponding to its position on the X and Y axes. The last two letters of each scenario name represent the N and P load, respectively, where: M = minimum load and T=Target load, L = lower load, P = Present load (2001–2007), I = Increased load, and X = Maximum load (reproduced from McBride et al. 2018b, Figure B).*

Recommendations

The authors identified the following additional studies to improve the scope and robustness of catchment and lake modelling for Lake Rotorua:

1. Modelling of climate change effects on load delivery and in-lake processes.
2. Model ensemble, including multiple models with different process representations of internal load (nutrient recycling). This approach would likely generate a wider, but potentially more realistic, range of potential outcomes resulting from management strategies.
3. Modelling additional food web groups and higher trophic levels.
4. More detailed uncertainty estimation, including Monte Carlo (MC) or Bayesian Markov Chain Monte Carlo techniques, to further improve confidence in outputs by generating an envelope of expected outcomes.
5. Coupled catchment-lake modelling, including a catchment model such as the Soil and Water Assessment Tool (SWAT), capable of modelling the role of contaminant mobilisation and delivery as well as associated mitigation options.

Part 8:

Module 7 - Summary of ROTAN results

Kit Rutherford

Introduction

In this report the author summarises the 2011 and 2016 versions of the ROTAN (ROtorua and TAupō Nitrogen) model. ROTAN is a conceptual catchment model that routes water and nitrogen losses from land through groundwater and streams to the lake, taking account of nitrogen attenuation and groundwater time lags. The output from ROTAN has been important in understanding likely future nitrogen loads, and has also informed the development of the DYRESM-CAEDYM lake models (see Part 7).

ROTAN-2011 was developed in 2008-2009 and used OVERSEER® v5.4.2 to estimate farm nitrogen losses with a weekly time-step. ROTAN-Annual was developed in 2016 and is a modified version which operates on an annual time-step and uses the latest version of OVERSEER (v6.2.0). Information on revised groundwater boundaries and recent stream monitoring data was also used for the new model. Land use/cover maps, agricultural statistics and 'expert opinion' from landowners provided input data for OVERSEER® v6.2.0 which predicted historic farm losses from 1900-2015 for input into ROTAN-Annual.

Previous work had shown that groundwater makes a significant contribution to water and nitrogen loads to Lake Rotorua, and ranges in mean age from 14-170 years. In the ROTAN models, water and nitrogen travel to the lake by three pathways: 'quickflow' (surface flow and interflow), 'slowflow' (deep groundwater) and 'streamflow'. Nitrogen removal along each pathway (termed attenuation) is quantified in ROTAN-Annual using three separate coefficients whose values were calibrated to match monitored stream concentrations from 1967-2015 using groundwater residence times and aquifer boundaries published by GNS-Science.

It was not feasible to determine the nitrogen attenuation coefficients directly, and hence they needed to be estimated by model calibration. Calibration relied heavily on measured stream concentrations because there were only limited groundwater concentration data. The author noted that there is uncertainty about which land parcels drain to each monitoring site and the associated groundwater travel times. There is also uncertainty in the timing of land use intensification, and historic farm nitrogen losses.

Key findings

The ROTAN-Annual model gave estimated nitrogen losses on average 88% higher than those of ROTAN-2011, the main influence on this was the change of OVERSEER® versions (from v5.4.2 to v6.2.0). The author noted that the reliability of OVERSEER® estimates of nitrogen losses from farmland is a key issue for many stakeholders and considered a number of factors that contribute to uncertainty in the ROTAN estimates. These included soil characteristics, rainfall estimates, and farm input data. Based on the information available, the uncertainty in historic nitrogen losses was estimated to be ±50%.

The 88% difference in average nitrogen losses between OVERSEER® Version 5 and Version 6 raised concerns about the accuracy of the input data used in ROTAN-2011 and ROTAN-Annual. Updating to Version 6 included changing from an annual to a monthly time step, accounting for seasonal changes in animal numbers, estimating nitrogen losses using drainage rather than rainfall, including a wider range of soils/rainfall/drainage classes, and revising the cropping model. The author concluded that the Version 6 losses are credible because they match observed stream concentrations with an average attenuation of 42%, which is a plausible value, compared to ROTAN-2011 which gave negligible attenuation.

The author cautioned against the using apparent differences in nitrogen attenuation between sub-catchments to manage each differently because:

- The boundaries of the recharge zones draining to major springs and stream monitoring sites are uncertain (notably in the Awahou and Hamurana).
- The land use history in each sub-catchment is uncertain (e.g., when exactly did dairy farms come into full operation in the Awahou Catchment?).
- OVERSEER® is a steady-state model and there is uncertainty about how long it takes nitrogen losses to adjust to a new equilibrium after a significant land use change (e.g., how long after converting a sheep/beef farm to dairy does the nitrogen loss rate for the dairy farm apply?).

Using ROTAN-Annual the 'most likely' steady state nitrogen load for current land use (i.e. no change) was found to be 750 t per year (range 670 t-840 t per year), which matches the ROTAN-2011 estimate of 725 t per year). What differs between models, is that in ROTAN-2011 (with nitrogen losses estimated using OVERSEER® v5.4.2) calibrated attenuation was zero in nine of the ten catchments, whereas in ROTAN-Annual (OVERSEER® v6.2.0) attenuation was non-zero in all catchments.

For the loss reduction scenarios developed under Plan Change 10, ROTAN-Annual predicted a steady-state lake nitrogen load of 425 t per year with a range of 390 t-460 t per year (see Figure 16).The author calculated that there is a negligible risk the nitrogen control measures in PC10 will be more than required, but some risk (c. 12-20%) they will be less than required to meet the lake target. The model also predicts that nitrogen reductions specified by BOPRC, will reduce lake loads to within 25% of the target within 25 years, although steady-state may not be reached until after 2100. The time-scale of recovery is like that predicted by ROTAN-2011.

Recommendations

The author identified the following additional studies to improve the scope and robustness of catchment and lake modelling for Lake Rotorua:

- There is little that can be done to refine historical information on stocking rates and nitrogen losses. However, routine monitoring of groundwater at key locations would allow future nitrogen concentration changes over time to be quantified. Initially, concentrations are expected to increase as groundwater affected by high nitrogen drainage from recent land use intensification arrives at the monitoring sites, but as mitigation measures take effect they are expected to decrease.
- Additional synoptic surveys of groundwater would better quantify the spatial distribution of nitrogen concentration, together with iron, manganese, oxygen, carbon and redox (indicators of the likely groundwater attenuation rate). Routine monitoring of groundwater concentrations would allow the effectiveness of remediation to be tracked over time.

- Longitudinal surveys of stream flow would indicate where shallow and deep groundwater re-emerges into streams. This would enable refinement of flow pathways and aquifer boundaries – critical in the ROTAN modelling. Measuring water age in longitudinal surveys would help refine current estimates of groundwater flow pathways and residence times. Longitudinal surveys of flow and nitrogen concentration would allow stream attenuation to be calculated, to constrain current estimates based on Viner (1986).

- In other parts of New Zealand, groundwater models have been used to estimate flow pathways and residence times. The hydro-geology of Rotorua is complex and although GNS-Science has developed a groundwater model, only preliminary results have been sighted to date. Further refinement of the groundwater model would help refine current estimates of groundwater attenuation, aquifer boundaries and the likely response time of lake loads to the mitigation measures proposed under PC10.

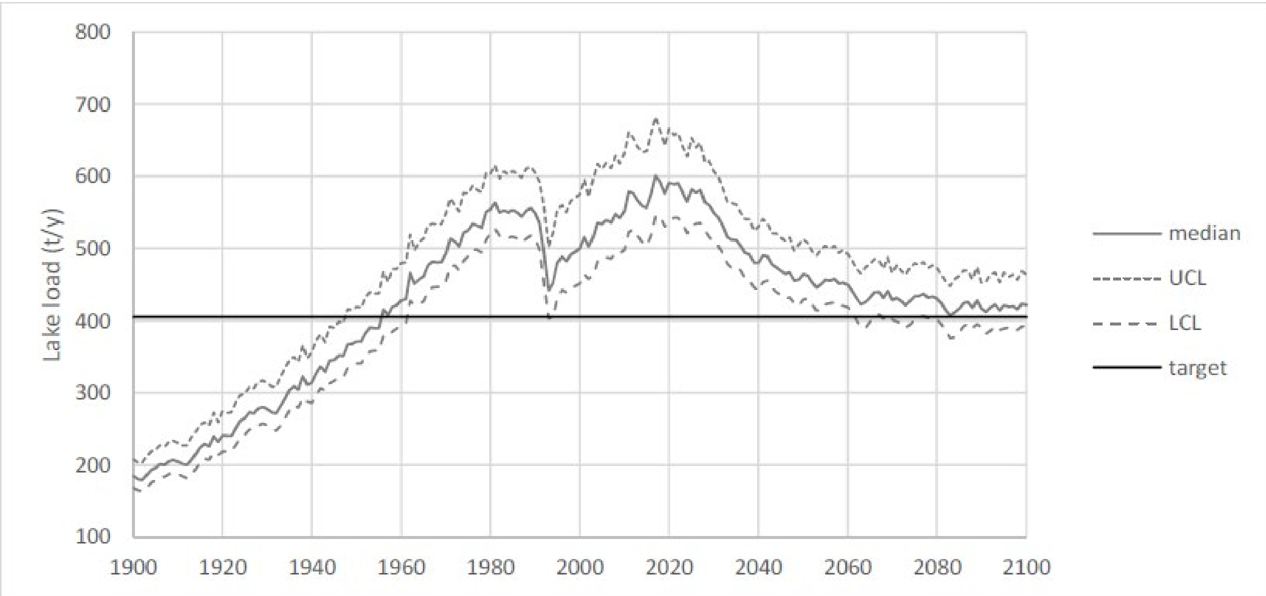

Figure 16 *Predicted lake loads 1900-2100. From 2010 staged reductions in nitrogen loss are modelled. Results show the 'most likely' (median) loads together with approximate upper (UCL) and lower (LCL) bounds. The 'target' of 405 t y-1 excludes rain falling directly on the lake (Figure 3-11 reproduced from Rutherford and MacCormick 2016).*

Part 9:
Module 8 - Rationale and design of a phytoplankton nutrient limitation study

Grant Tempero

Introduction

The purpose of this report is to provide a monitoring protocol to determine seasonal phytoplankton nutrient limitation in Lake Rotorua. The proposed work would have the following objectives:

1 Determine the limiting macronutrient (nitrogen or phosphorus) or macronutrients (nitrogen and phosphorus) of the phytoplankton community assemblage in Lake Rotorua on a seasonal scale.

2 Determine the concentrations of inorganic and total nutrients in relation to phytoplankton community composition at a seasonal scale.

3 Based on the findings of Objectives 1 and 2, make recommendations as to the alum dosing rates of the Utuhina and Puarenga stream inflows.

Key findings

The report essentially provides a recommendation for future work. This would involve targeted sampling of the lake and laboratory based bio-assays.

The author considered that the challenges of conducting assays within the lake (in-situ) were significant and therefore proposed a laboratory based approach for the assays. This would reduce sampling costs, the potential for contamination, and allow greater control of environmental variables. However, this also increases the risk of producing results that are not representative of the original environment. For this reason, the author stressed that extrapolation of laboratory results to an understanding of nutrient limitation in the lake must be conservative.

A number of significant methodological challenges were also discussed. These are related to culturing and quantification of algal species, the use of mixed phytoplankton assemblages to determine nutrient limitation, and measurement of phytoplankton growth. Methods were proposed to mitigate the risk posed by these challenges.

Recommendations

As noted above, this report provides a recommendation for future work. This work will be considered along with the other recommendations arising from the Lake Rotorua Science Review.

Part 10:

Module 9 - Ecotoxicological review of alum applications to the Rotorua lakes: supplementary report

Grant Tempero

Introduction

This report is intended to supplement the original report “Ecotoxicological Review of Alum Applications to the Rotorua Lakes” (Tempero 2015). It reviews a number of relevant studies published since 2015 regarding the toxicological effects of aluminium (Al), and addresses several questions specific to Lake Rotorua including:

1. Are the aluminium concentrations used in toxicological testing relevant to the low concentration of aluminium measured in the main waters of Lake Rotorua?

2. Given Lake Rotorua has a low buffering capacity, are pH shifts driven by algal bloom photosynthesis likely to result in toxic aluminium complexes?

3. What is the potential for long-term chronic toxicological effects, particularly on down-stream receiving ecosystems?

4. What is the effect of natural geothermal sources of aluminium in Sulphur Bay?

Key findings

Since 2015, significant advances have been made in determining toxic thresholds for Al, particularly chronic effects. The United States Environmental Protection Agency (USEPA) has recently conducted acute and chronic toxicological testing on eight aquatic species under a wide range of environmental conditions and total aluminium concentrations, including those conditions common to Lake Rotorua[19]. Using previously published data, a multiple linear regression (MLR) model was constructed to predict chronic Al toxicity under varying conditions of dissolved organic matter (DOM), pH and water hardness.

The MLR model was run using the DOM and water hardness values for Lake Rotorua to calculate toxicity potential for a range of pH values. All but one value (pH 6, 0.045 mg L^{-1}) exceeded both the ANZECC (2000) trigger value for dissolved Al (0.055 mg L^{-1}) and mean total Al concentration in Lake Rotorua (0.020 mg L^{-1}). Therefore, it was concluded that chronic toxicological effects from Al exposure are unlikely to result under typical pH conditions in Lake Rotorua. However, the author noted that caution should be used in applying these values as the data is not based on New Zealand species.

[19] Specifically - water hardness 14 mg L^{-1} (as $CaCO_3$); dissolved organic matter 2 mg L^{-1}, pH 6.8; total Al ~0.020 mg L^{-1}.

The author also considered the potential for acute Al toxicity resulting from phytoplankton driven diel (day-night) shifts in pH. This is possible in poorly buffered eutrophic systems, such as Lake Rotorua, where pH changes of up to 3 pH units (i.e. pH 6.5 – 9.5) are common. However, given the low total Al concentrations in Lake Rotorua and comparatively short exposure times to high pH during algal blooms, acute effects were considered unlikely.

There is currently no requirement to monitor for potential impacts from alum dosing to the Kaituna River. However, the concentrations of Al in the lake are currently below toxicity thresholds and the author noted that the lake water is further diluted by combination of flow from Lake Rotoiti, before entering the Kaituna River. Once discharged to the Ōngātoro/Maketū Estuary, it is further diluted by tidal exchange.

The concentrations of total aluminium in the Sulphur Bay area of Lake Rotorua are naturally high (>1 mg L^{-1}) due to the geothermal influence. This has produced an area of naturally low aquatic biodiversity, due to the low pH (~pH 3) and the prevalence of highly toxic Al^{3+}. However, these effects are negated at the mouth of bay where the geothermally influenced waters mix with water from the main lake body and at this point normal lake diversity can be observed. The author also noted that no adverse effects have been observed from alum dosing of the Puarenga Stream.

The author concluded that the cautious use of continuous low level alum dosing is an ecologically acceptable option for reducing phosphorus loading to Lake Rotorua.

Recommendations

The author has identified the following additional studies to better understand the potential for Al toxicity:

1 Further evaluation of potential toxic effects during phytoplankton driven diel pH cycling.

2 Continue monitoring the effects of alum dosing.

3 Consider work to better understand Al speciation.

Part 11:

Module 10 - A review of land-based phosphorus loss and mitigation strategies for the Lake Rotorua Catchment

Reece Hill

Introduction

This module summarises information on land-based anthropogenic phosphorus losses and mitigation strategies for pasture, planted forest and indigenous vegetation in the Lake Rotorua catchment. These phosphorus losses are influenced both spatially and temporally by biophysical factors such as soil type, rainfall and topography (see Figure 17). Land use and its management influence phosphorus loss, either exacerbating or mitigating losses.

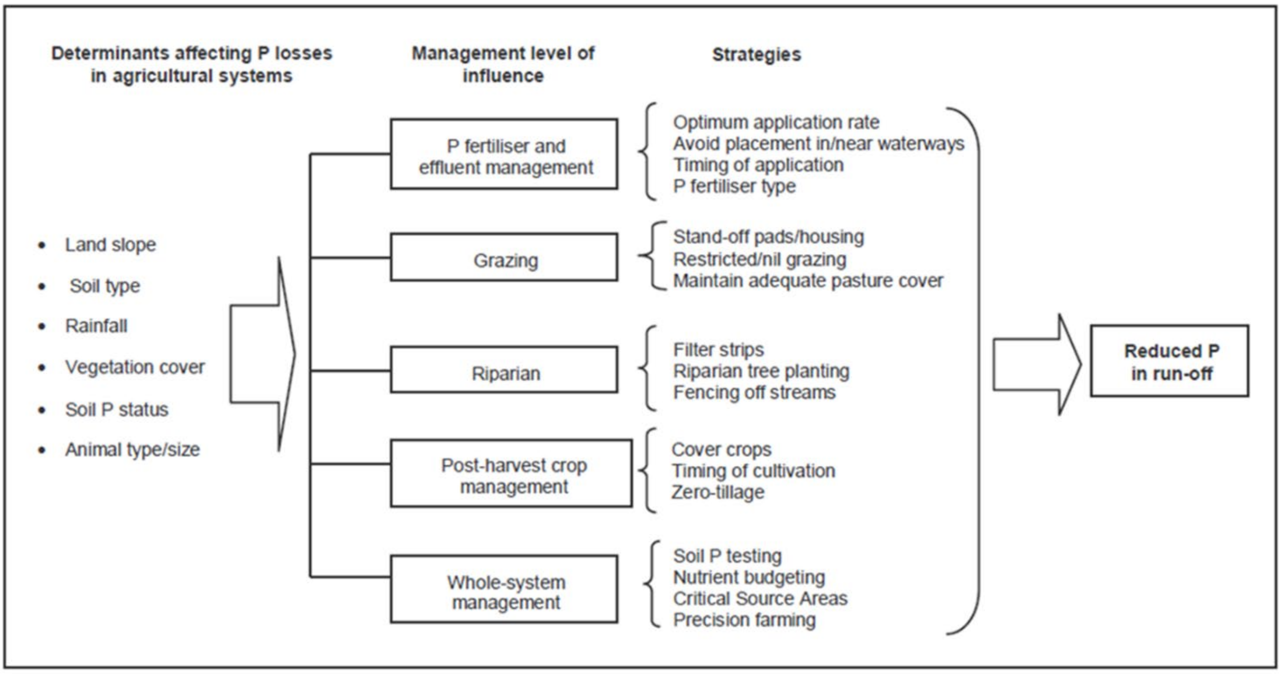

Figure 17 Main determinants affecting P losses in agricultural systems and key management strategies for mitigating losses (from Menneer et al., 2004).

Key findings

The range of catchment phosphorus (total P) loads to Lake Rotorua has been reported and assessed in a concurrent science review by Hamill (2018), with the 2007-2014 load averaging 46 t per year, or 42.2 t per year, when adjusted for long-term rainfall and stream runoff data. That result is consistent with this report's assessment of 44.3 t-45.6 t per year.

The most cost-effective phosphorus mitigation strategies that have minimal or positive impact on farm profit include optimising soil Olsen P, improving farm dairy effluent management and using low-solubility phosphorus fertilisers. Other phosphorus mitigation strategies are worth future consideration, including detainment bunds, and a greater focus on critical source areas (CSAs).

The effectiveness of different phosphorus mitigation strategy combinations was explored, based on existing publications and OVERSEER® scenarios. A combination of phosphorus mitigation strategies can potentially achieve a 40% reduction in phosphorus with minimal impact on profit. However, there remains uncertainty around the effectiveness of individual mitigations and implementation costs, largely driven by variable farm system and catchment conditions. The broad range of cumulative phosphorus mitigation effectiveness is shown in Table 7 and Table 8.

Table 7 The high and low effectiveness point cumulative phosphorus reductions for dairy, dry-stock and lifestyle land use mitigation combinations (reproduced from Hill 2018, Table 7).

Land use category	**Cumulative P reduction (%)**	
	High-point	Low-point
Dairy	65.1	15.0
Dry stock	61.7	12.4
Lifestyle	46.8	9.2

Of the land use phosphorus loss coefficients used, the forestry coefficients were the most variable across the literature and had the most associated uncertainty. Given the suggested changes from pasture to forestry in the future scenarios, the impact of the forestry phosphorus loss values used will impact on the results and follow through to any subsequent decisions based on the results.

Adequate phosphorus reductions to achieve a phosphorus load target are not achievable through targeting nitrogen load alone (i.e. there is a reduced phosphorus load associated with nitrogen mitigation - termed phosphorus "by-catch") and targeted phosphorus mitigation strategies area required.

Achieving a phosphorus load of between 30 t and 35 t per year seems possible through phosphorus specific land-based phosphorus mitigation strategies, even if a future nitrogen based reduction scenario is implemented. However, caution is still required around the estimates, especially around the assumptions associated with the land use phosphorus loss coefficients and mitigation % effectiveness estimates used. For example, an assessed potential phosphorus load of 31.6 t per year following a reduction of 12.7 t per year (from a status quo 44.3 t per year) is based on multiple assumptions, including:

- Land use change corresponding to scenario 'S8' in Parsons et al (2015) which approximates the long-term outcome of PC10, including substantial new forest plantings.

- The most commonly used phosphorus loss coefficients across a range of studies.
- Sector phosphorus loss reductions of: dairy - 50%; dry-stock - 41%; lifestyle - 30%.

Key to the ongoing assessment of PC10 implementation effectiveness for phosphorus loss reductions (but also nitrogen loss reductions) is the capture of finer (farm scale data) that can be used to refine catchment scale modelling of nitrogen and phosphorus load to Lake Rotorua.

Table 8 Description of two P mitigation combinations using refined effectiveness estimates from OVERSEER® and potential mitigations (reproduced from Hill 2018, Table 8).

	Main features		
P mitigation combination	**Mitigations**	**Effectiveness**	**Relevant farm area**
Original + OVERSEER® (adjusted effectiveness)	No additional mitigations	Reference files for dairy and dry stock were modified in OVERSEER® - the difference provided the effectiveness percentage.	Either based on commonly used areas (e.g. fertiliser and effluent mitigations) or estimated (e.g. CSA management)
		Olsen P mitigation from high level to optimum production Olsen P level.	Applicable to whole farm
		Low solubility P fertiliser used (RPR replaced phosphate).	Applicable to whole farm
		Low effluent application effectiveness from Park (2012) OVERSEER® assessment.	15% of farm area
Original + additional mitigations	**In-paddock CSAs**: Includes minimising bare ground (usually by re-grassing or revising paddock management) around gateways, troughs and animal camp areas (McDowell, 2010).	(40%)[1] Estimated at between 30% and 50% (midpoint 40%). Similar range to "restricting grazing of cropland"	Estimated combination of gateway, trough and camp areas at 3% of farm area
	Strategic grazing: Directional grazing to maximise the buffering effect of un-grazed grass closer to waterways and water flow paths (McDowell et al., 2016).	(10-80%) McDowell et al., 2016 indicated up to 80% effective. No low point effectiveness provided but have assumed at least 10%	Estimated that applicable to 1 in 4 paddocks on average (25% farm area); depends on topography
	Tracks and lane management: Includes adding berms to tracks to divert runoff to grassed areas, good track surface maintenance, and use of side of track sorbents to intercept P in runoff (McDowell, 2010).	(40%)[1] Estimated conservatively; similar to stream fencing, lower than in-paddock CSAs because tracks still retain erosion risk with bare ground (track surface) and batters.	Estimates of the area of tracks on dairy and dry stock farms was from a 2012 Waikato Regional Council assessment of soil stability (Taylor, 2016); 8% for dairy and 5% for dry stock farms.

[1] 2016 Land TAG P mitigation workshop.

Recommendations

Recommendations for improving data and information on phosphorus loss and phosphorus mitigation strategies specific to the Lake Rotorua Catchment include:

1. Improved monitoring data for Olsen P (via soil tests and preferably in a maintained database) for all farms (potentially at block level for use in OVERSEER®).
2. Maintain the current soil testing frequency as suggested in the NMP template, with the expectation that soil Olsen P will decrease by 1-2 units per year once the mitigations are implemented.
3. Ensure good capture (preferably in a maintained database) of and monitoring of the state of Farm Dairy Effluent (FDE) storage and land application data.
4. Continue to maintain connections with phosphorus mitigation research and promote and support mitigation research within the Lake Rotorua Catchment to assess the local applicability of phosphorus mitigations (for example, detention bunds).
5. Support the development of multiscale spatial approaches to prioritising phosphorus (and nitrogen) mitigation placement to better target phosphorus sources, phosphorus form and phosphorus loss pathways.
6. Support research to better understand the changes in phosphorus loss associated with the different stages of forestry, from harvest to forest maturity. Research across the range of forest soils in the Lake Rotorua Catchment is likely requirement as well.
7. Explore the opportunity to improve data on phosphorus mitigation associated with forestry management (possibly via the NPS-PF).
8. Support the investigation of the increasing trend in particulate phosphorus identified in Dare (2018) with a focus on long-term drivers (e.g. climate change), and phosphorus generation sources and transfer pathways.
9. Target phosphorus reductions alongside nitrogen reductions (i.e. a dual nutrient reduction approach) given that the phosphorus load target is not achievable through phosphorus "by-catch" associated with nitrogen focussed mitigation alone.
10. Build on the existing Nutrient Management Plan template to increase the quantitative and measurable capture of phosphorus nutrient inputs, mitigations and outputs, similar to nitrogen capture.
11. Improve and support soil map information, regionally and where possible, at farm scale, to improve nutrient budget estimates as well as NMP implementation.
12. Monitor and report phosphorus mitigation implementation and loss data (initially via nutrient budgets in the NMP) for all farms in the Lake Rotorua Catchment and refine the criteria around the collection, recording, storage of data, as well as NMP implementation monitoring and auditing.
13. Develop Council's geospatial database to include implemented phosphorus mitigation actions and phosphorus losses through time.

Part 12:
Module 11 - Anthropogenic phosphorus load to Rotorua: Review and revision

Keith Hamill

Introduction

This module is a review and revision of the estimated anthropogenic phosphorus loads to Lake Rotorua. A previous report by Tempero et al. (2015) calculated a total external phosphorus load to Lake Rotorua of 48.7 t per year with 23.4 t per year due to anthropogenic sources and the balance due to natural 'baseline' sources, predominantly dissolution of phosphorus minerals within volcanic rock into groundwater. The Tempero et al. (2015) estimates accounted for particulate phosphorus entering the lake during stormflow events, resulting in higher loads than many past estimates. This approach is continued and updated to account for revised groundwater catchment areas, geothermal inputs and long-term average loads over two time periods.

The total load of phosphorus from the catchment has been estimated by different researchers over different time periods; these estimates typically fall in the range 34 t per year to 42 t per year when excluding particulate phosphorus from flood flows (Rutherford 2008), as shown in Table 9 below.

Table 9 Previous estimates of catchment phosphorus loads to Lake Rotorua (modified from Rutherford 2008). TP = total P, DRP = dissolved reactive P, PP = particulate P (reproduced from Hamill 2018, Table 1.1).

Source	Year	DRP (t/yr)	TP (t/yr)	Notes
Hoare 1978	1976-1977	25-26	34-35	Excluding sewage and flood flow PP
Hoare 1980a	1976-1977		35.6-37.4	Excluding sewage and flood flows, but including septic tanks
Hoare 1980a	1976-1978		42.6-44.9	Excluding sewage but including septic tanks, flood flow PP
Rutherford et al. 1978	1967-1977		33-44	Excluding sewage and flood flow PP
Rutherford et al. 1989	1967-1977		34	Excluding sewage and flood flow PP
Morgensten	2005		39.1	Including sewage
BOPRC 2009			39.8	
Hamilton et al. 2015	2001-2012		33	
Tempero et al. 2015	2007-2014	27.7	48.7	Including sewage and flood flow PP

A phosphorus target of 37 t per year was derived by Rutherford (2008) from a catchment load of 34 t per year, plus an additional allowance for sewage of 3 t per year. These catchment loads did not include particulate phosphorus from flood events because, at the time, this fraction was considered to be predominantly not bioavailable.

Key findings

For the period 2007-2014, the total phosphorus load to Lake Rotorua was estimated to be 46.0 t per year after accounting for storm flows and geothermal inputs. The total phosphorus load attributed to anthropogenic sources was 18.1 t to 20.7 t per year (39%-45% of the total load). Most (71%-79%) of the anthropogenic total phosphorus load was in the particulate form – which points to managing erosion as an effective way of reducing anthropogenic phosphorus loads to the lake. Most came from the following catchments: 'ungauged' (30%), Puarenga (23%), Utuhina (18%) and Ngongotahā (11%) – reflecting their relative size. It would also be useful to know the proportion of particulate phosphorus that may become bioavailable.

For a drainage factor of 0.5 (weighted by relative groundwater catchment area) and accounting for geothermal inputs, the sub-catchment distribution of baseline and anthropogenic phosphorus load is shown in (Figure 18).

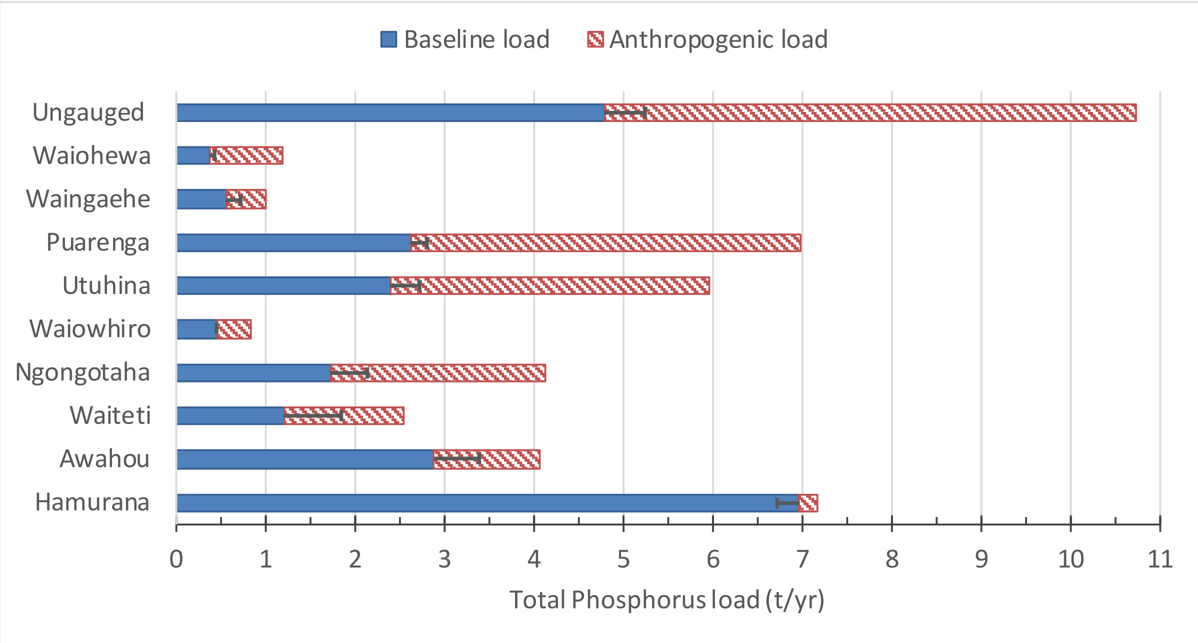

Figure 18 Total phosphorus load to Lake Rotorua (2007-2014) with the baseline and anthropogenic contributions indicated for drainage factor D2 and accounting for geothermal inputs. Error bars show scenario D1 (reproduced from Hamill 2018, Figure 3.3).

The 2007-2014 period had higher outflows and inflows compared to previous years. The long-term average total phosphorus load to Lake Rotorua was estimated to be 42.2 t per year, and the long-term average total phosphorus load attributed to anthropogenic sources was 16.6 t per year to 19.0 t per year. Overall, the analysis results are consistent with previous estimates of the catchment phosphorus load to Lake Rotorua (i.e. about 39 t-49 t per year).

The calculation of anthropogenic phosphorus load was particularly sensitive to the drainage factor used (i.e. the proportion of net rainfall that enters lakes and stream via groundwater) and the calculation of net rainfall (i.e. rain less evapotranspiration) for the lake. For a drainage factor of 0.5 (weighted by relative groundwater catchment area) and accounting for geothermal inputs, the area-specific anthropogenic phosphorus loads are shown in (Figure 19).

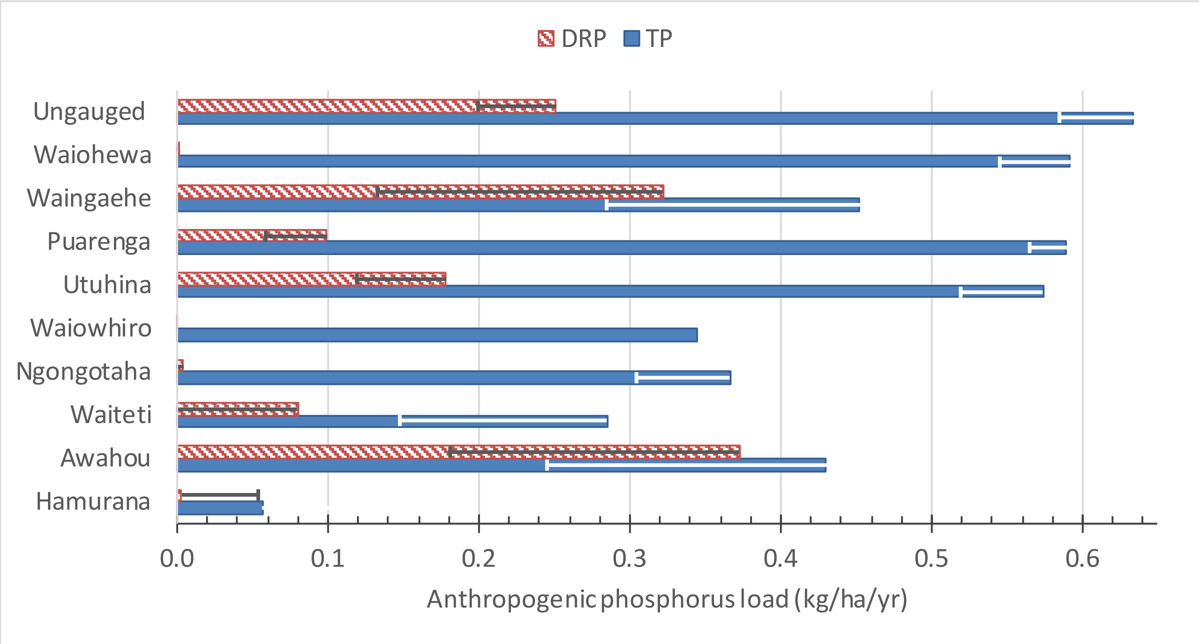

Figure 19 Area-specific anthropogenic phosphorus load to Lake Rotorua (2007-2014) assuming drainage factor D2 and accounting for geothermal inputs. Error bars show scenario D1 (reproduced from Hamill 2018, Figure 3.5).

There was an indication that there might be additional groundwater contributions (from outside the defined catchment) to the south of the lake via geothermal inputs. This is speculative and was based on more water being assigned to ungauged catchments than could be explained by the available rainfall data, and higher estimates of geothermal inflows from the south of the lake than could be explained by rainfall in catchments. If there was additional groundwater entering via geothermal inputs, then the calculations for anthropogenic loads from 'ungauged catchments' would be over-estimated.

Recommendations

Recommendations are made for further work to fill information gaps relating to the phosphorus load to Lake Rotorua and its bioavailability, as follows:

- Investigations to improve our understanding of sediment sources and phosphorus concentrations in particulate phosphorus from gauged and ungauged catchments (e.g. sampling of 'settleable' sediment to differentiate areas with relatively higher total phosphorus concentrations associated with the sediment).

- A major fraction of the anthropogenic phosphorus load is in the particulate form, much of which is transported during storm events. Additional storm event monitoring would be helpful to better quantify total phosphorus loads to the lake.

- The estimates of anthropogenic phosphorus load from ungauged catchments would be more accurate if the estimate of groundwater mean residence time (MRT) was refined.

- Improving our estimates of geothermal inflows to Lake Rotorua. One part of this is to incorporate chloride as part of the analysis suite for the lake, Ōhau Channel outflow and inflowing streams.

- Past estimates of geothermal contribution to Waiohewa Stream have wide variability. This report has adopted the lower estimates, and this may explain the correspondingly high estimates of area-specific anthropogenic phosphorus for Waiohewa Stream. To resolve discrepancies in geothermal inputs to Waiohewa, it is recommended that future monitoring of Waiohewa Stream include gauging and water quality samples (including phosphorus) at locations to differentiate the geothermal inputs.

- Better quantification of the extent to which particulate phosphorus derived from the human activity in the catchment is bioavailable and its contribution to internal phosphorus release from lake sediments.

- This report gives an indication of sub-catchments that contribute most phosphorus load to Lake Rotorua using total loads and area-specific loads; however, these estimates contain a high degree of uncertainty. A complementary approach to understanding the location of phosphorus loss within parts of the Rotorua Catchment could be used to develop a risk map of phosphorus loss from the catchment based on landform, land use and catchment processes.

Part 13:
Module 12 - Review of relevant New Zealand and international lake water quality remediation science

David Hamilton

Introduction

The Australian Rivers Institute was commissioned to undertake a review of relevant New Zealand and international lake water quality remediation science. The review did not include socio-economic or cultural evaluations of the feasibility of lake restoration. It also did not include catchment management actions for nutrient control as these are documented elsewhere as part of this Science Review.

Key Findings

Implementation of lake-remediation actions is usually costly and requires underpinning scientific information derived from a routine lake monitoring programme. Monitoring may also need to be set up specifically to examine the 'before and after' effects of remediation and any possible eco-toxicological effects. Process-based modelling to simulate remediation a priori can be extremely useful as part of a decision support system. A forward-looking context is also required because climate change will make it more difficult to attain water quality goals (e.g., the TLI target of 4.2) based on a current climate.

This review included considerations of a number of lake-remediation actions including hydraulic flushing for direct algal control, inflow diversion, phosphorus locking (geoengineering) and sediment capping, harvesting phytoplankton by filtration, floating wetlands, bio-manipulation and macrophyte harvesting. The author concluded that many of these techniques can be disregarded because they are unlikely to be able to be scaled up to be effective for Lake Rotorua (area 80 km^2) or are unsuitable for other reasons, including the relatively shallow lake depth (mean = 10 m) and mixing regime (i.e., polymictic, with frequent complete water column mixing).

Several of the remediation techniques remain poorly validated scientifically, including microbial control agents, floating wetlands and some geoengineering materials. Others such as ultrasound, fail to be worthy of further consideration based on a limited number of rigorous scientific studies, that have dismissed their potential for phytoplankton control (including cyanobacteria), and raised an issue of interfering with natural aquatic food webs. A number of lake-remediation techniques involving physical modifications (hypolimnetic siphoning, inflow diversion, sediment capping, flushing, filtration, and oxygenation or artificial de-stratification) were considered unlikely to be viable or effective for shallow Lake Rotorua.

Of the lake remediation methods that were considered to potentially be feasible for Lake Rotorua, lake geoengineering was thought to address causal factors related to internal nutrient loads and is already practiced successfully through alum dosing of the Utuhina and Puarenga tributaries to the lake. Hydrogen peroxide or booms could address symptoms of eutrophication related to blue-green algae (cyanobacteria) blooms but these methods may be limited to areas where the blooms are obvious and acute. Hydrogen peroxide may have additional use, however, to complement geoengineering to ensure that cyanobacteria are permanently removed when geoengineering operations are carried out when there are cyanobacteria blooms.

Recommendations

The author concluded that while alum dosing appears to have been extremely successful in managing external and internal nutrient loads in Lake Rotorua, a more concerted effort to explore alternative options is required to more rapidly attain the sustainable catchment nutrient loads prescribed in Plan Change 10.

Part 14: **References**

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Appendix One

Peer review letter

The Chief Executive
Bay of Plenty Regional Council
PO Box 364
Whakatāne
New Zealand

3 December 2018

Attention: Fiona McTavish

Dear Fiona,

Peer Review of the Lake Rotorua Science Review

Thank you for the opportunity to be the independent science peer reviewer for the Lake Rotorua (Plan Change 10) Science Review.

I am a Professor in the Department of Biology at Laval University in Quebec, Canada (since 1990), and have conducted ecological research on lakes and rivers in several parts of the world, including North and South America, Europe and Asia. I was initially attracted to the invitation from your science team as I had previously undertaken research projects on Lake Rotorua in the 1980s. As an ex-patriot of New Zealand, I am also very interested in the progress your council has made in developing policy to restore Lake Rotorua.

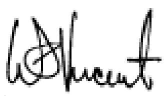
My review followed a set process that involved:

- Scientific peer review of each of the 11 technical reports, with comments and recommendations provided for the authors to consider;
- Attendance at a workshop in Rotorua to discuss the key science findings and the implications of these. This workshop was attended by the authors of the technical reports and Regional Council staff; and
- Peer review of the final summary report prepared by your staff to confirm that it is a fair and accurate record and synthesis of the findings of the science review.

My initial observation from this work is that Lake Rotorua is probably one of the most intensively researched lakes nationally, if not internationally. This has been confirmed by the summary report, which is an impressive distillation of a large amount of data, information, modelling and analysis. The report contains 13 key science conclusions, which I have reviewed and support. I expect these conclusions will be useful in communicating the outcomes of the science review to councillors, staff and the community. Finally, the individual authors have made recommendations for future work and I understand that these will be prioritized for action to support the 2022 Lake Rotorua Science Review.

I trust this review will be helpful in your future management of Lake Rotorua and I commend your Council for the scope and quality of work that has been undertaken to date.

Yours sincerely,



Warwick F. Vincent, PhD, FRSC, hon. FRSNZ
Professor of Biology & Canada Research Chair
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Quebec City, Quebec, Canada

Appendix Two

Science review recommendations

Recommendation		Module (see Table 1)
1	Determine trends in dissolved oxygen availability at bottom depths, both throughout the entire record length and for periods of stratification, from which to deter mine if alum-associated changes influence internal nutrient release.	2
2	Determine trends in nutrient ratios amongst “surface” waters and assess trend components for association to alum dosing (e.g., to alum mass dosed, to alum concentration instream at point of application).	2
3	Determine a complementary and appropriate method to analyse for trends in overall TLI score, whether at annual or monthly time-step, that otherwise does not prevent trends in each component cancelling each other when combined.	2
4	Revise the definition of “meaningful” to be context-specific to the targets set for water quality outcomes in Lake Rotorua and adopt one of the two, rather than both trend directional methods currently in use for reporting in New Zealand.	2
5	Increase high flow sampling events to provide more robust load estimates and inform concentration-discharge analyses. Results indicate contaminants may be responding differently at different parts of the hydrograph (e.g. base flow versus high flow). Accurate high flow measurements would provide more certainty around high flow predictions, while also benefiting regression load estimates.	3
6	Improve continuous flow measurements. Continuous flow records can provide useful data for additional analysis. Installation of water level loggers is a relatively simple task, enabling flow-water level relationships to be developed for non-hydrology sites. This data could also increase certainty around some of the spot gauging data which appears to be biased towards low flows in recent years.	3
7	Investigate the increasing trend of ammoniacal nitrogen in the Puarenga Catchment. Results show the ammoniacal nitrogen concentrations have increased in this catchment, particularly after 2009. A small scale investigation may provide answers about the source of this contamination and enable it to be minimised.	3
8	Identify hydro-chemical signatures to clarify contaminant sources and pathways. The identification of discrete hydro-chemical signatures could provide information about the source and pathway of contamination, allowing for targeted mitigation methods to be applied.	3

9	Define reporting requirements. The reporting requirements determine the information collected and the systems to manage that information.	4
10	Complete development of NDMS (Nutrient Data Management System). The N accounting system must be able to accurately and reliably track changes to allocations arising from N buy outs, trading between properties and shifts within properties.	4
11	Work with OVERSEER® Limited to improve the N loss predictions in the Rotorua Catchment and the model's reliability.	4
12	Investigate catchment attenuation and the uncertainties in measured loads, modelled loads and groundwater travel times.	4
13	Investigate N losses from lifestyle blocks. Understanding the N losses from lifestyle blocks will help inform where resources should be focused.	4
14	Measure loads and trace losses from stormwater and sewerage systems to identify areas where reductions can be made.	4
15	Modelling of climate change effects on load delivery and in-lake processes.	6
16	Model ensemble, including multiple models with different process representations of internal load (nutrient recycling). This approach would likely generate a wider, but potentially more realistic, range of potential outcomes resulting from management strategies.	6
17	Modelling additional food web groups and higher trophic levels.	6
18	More detailed uncertainty estimation, including Monte Carlo (MC) or Bayesian Markov Chain Monte Carlo techniques, to further improve confidence in outputs by generating an envelope of expected outcomes.	6
19	Coupled catchment-lake modelling, including a catchment model such as the Soil and Water Assessment Tool (SWAT), capable of modelling the role of contaminant mobilisation and delivery as well as associated mitigation options.	6
20	There is little that can be done to refine historical information on stocking rates and nitrogen losses. However, routine monitoring of groundwater at key locations would allow future nitrogen concentration changes over time to be quantified. Initially, concentrations are expected to increase as groundwater affected by high nitrogen drainage from recent land use intensification arrives at the monitoring sites, but as mitigation measures take effect they are expected to decrease.	7
21	Additional synoptic surveys of groundwater would better quantify the spatial distribution of nitrogen concentration, together with iron, manganese, oxygen, carbon and redox (indicators of the likely groundwater attenuation rate). Routine monitoring of groundwater concentrations would allow the effectiveness of remediation to be tracked over time.	7
22	Longitudinal surveys of stream flow would indicate where shallow and deep groundwater re-emerges into streams. This would enable refinement of flow pathways and aquifer boundaries – critical in the ROTAN modelling. Measuring water age in longitudinal surveys would help refine current estimates of groundwater flow pathways and residence times. Longitudinal surveys of flow and nitrogen concentration would allow stream attenuation to be calculated, to constrain current estimates based on Viner (1986).	7

23	In other parts of New Zealand, groundwater models have been used to estimate flow pathways and residence times. The hydro-geology of Rotorua is complex and although GNS-Science has developed a groundwater model, only preliminary results have been sighted to date. Further refinement of the groundwater model would help refine current estimates of groundwater attenuation, aquifer boundaries and the likely response time of lake loads to the mitigation measures proposed under PC10.	7
24	Investigate seasonal phytoplankton nutrient limitation.	8
25	Further evaluation of potential toxic effects during phytoplankton driven diel pH cycling.	9
26	Continue research and monitoring on the effects of alum dosing.	9
27	Consider work to better understand Al speciation.	9
28	Improved monitoring data for Olsen P (via soil tests and preferably in a maintained database) for all farms (potentially at block level for use in OVERSEER®).	10
29	Maintain the current soil testing frequency as suggested in the NMP template, with the expectation that soil Olsen P will decrease by 1-2 units per year once the mitigations are implemented.	10
30	Ensure good capture (preferably in a maintained database) of and monitoring of the state of Farm Dairy Effluent (FDE) storage and land application data.	10
31	Continue to maintain connections with phosphorus mitigation research and promote and support mitigation research within the Lake Rotorua Catchment, to assess the local applicability of phosphorus mitigations (for example, detention bunds).	10
32	Support the development of multiscale spatial approaches to prioritising phosphorus (and nitrogen) mitigation placement to better target phosphorus sources, phosphorus form and phosphorus loss pathways.	10
33	Support research to better understand the changes in phosphorus loss associated with the different stages of forestry, from harvest to forest maturity. Research across the range of forest soils in the Lake Rotorua Catchment is a likely requirement as well.	10
34	Explore the opportunity to improve data on phosphorus mitigation associated with forestry management (possibly via the NPS-PF).	10
35	Support the investigation of the increasing trend in particulate phosphorus identified in Dare (2018) with a focus on long-term drivers (e.g. climate change), and phosphorus generation sources and transfer pathways.	10
36	Target phosphorus reductions alongside nitrogen reductions (i.e. a dual nutrient reduction approach) given that the phosphorus load target is not achievable through phosphorus "by-catch" associated with nitrogen focussed mitigation alone.	10
37	Build on the existing Nutrient Management Plan template to increase the quantitative and measurable capture of phosphorus nutrient inputs, mitigations and outputs, similar to nitrogen capture.	10

38	Improve and support soil map information, regionally and where possible, at farm scale to improve nutrient budget estimates as well as NMP implementation.	10
39	Monitor and report phosphorus mitigation implementation and loss data (initially via nutrient budgets in the NMP) for all farms in the Lake Rotorua Catchment and refine the criteria around the collection, recording, storage of data, as well as NMP implementation monitoring and auditing.	10
40	Develop Council's geospatial database to include implemented phosphorus mitigation actions and phosphorus losses through time.	10
41	Investigations to improve our understanding of sediment sources and phosphorus concentrations in particulate phosphorus from gauged and ungauged catchments, e.g. sampling of settleable sediment to differentiate areas with relatively higher total phosphorus concentrations associated with the sediment.	11
42	A major fraction of the anthropogenic phosphorus load is in the particulate form, much of which is transported during storm events. Additional storm event monitoring would be helpful to better quantify total phosphorus loads to the lake.	11
43	The estimates of anthropogenic phosphorus load from ungauged catchments would be more accurate if the estimate of groundwater mean residence time (MRT) was refined.	11
44	Improving our estimates of geothermal inflows to Lake Rotorua. One part of this is to incorporate chloride as part of the analysis suite for the lake, Ōhau Channel outflow and inflowing streams.	11
45	Past estimates of geothermal contribution to Waiohewa Stream have wide variability. This report has adopted the lower estimates, and this may explain the correspondingly high estimates of area-specific anthropogenic phosphorus for Waiohewa Stream. To resolve discrepancies in geothermal inputs to Waiohewa, it is recommended that future monitoring of Waiohewa Stream include gauging and water quality samples (including phosphorus) at locations to differentiate the geothermal inputs.	11
46	Better quantification of the extent to which particulate phosphorus derived from the human activity in the catchment is bioavailable and its contribution to internal phosphorus release from lake sediments.	11
47	This report gives an indication of sub-catchments that contribute most phosphorus load to Lake Rotorua using total loads and area-specific loads; however, these estimates contain a high degree of uncertainty. A complementary approach to understanding the location of phosphorus loss within parts of the Rotorua Catchment could be used to develop a risk map of phosphorus loss from the catchment based on landform, land use and catchment processes.	11
48	The author concluded that while alum dosing appears to have been extremely successful in managing external and internal nutrient loads in Lake Rotorua, a more concerted effort to explore alternative options is required to more rapidly attain the sustainable catchment nutrient loads prescribed in Plan Change 10.	12