Lake Rotorua Science Review Summary

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Special thanks 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. Andy Bruere provided overall leadership and project management, which enabled the completion of the Science Review 2022 effectively and in a timely manner.

Foreword

By Independent Peer Reviewer, Warwick F Vincent.

Introduction to the PC10 Review Process

Under the terms of Rotorua Plan Change 10 (PC10), a science review is mandated at 5-year intervals to provide updated information on water quality trends, land management achievements and challenges, new research findings, new and ongoing issues for the Lake Rotorua ecosystem, and the latest advances in lake remediation science. The initial review was undertaken in 2017/18, and the first of these 5-year reviews took place in 2021/22, resulting in this final report that presents 11 modules and an introductory synthesis chapter. The modules in this report also provide a framework for future 5-year assessments.

As the appointed independent reviewer, I had the task and privilege of reviewing each of the PC10 modules. My primary emphasis was on ensuring that the conclusions were supported by the data obtained and presented, and that the interpretations were well integrated with the current international literature on lake eutrophication and management. Additionally, this was an opportunity to query and correct any apparent errors, for example in scientific units, magnitudes, citations, statistics and consistency, and to make suggestions on ways to present some of the figures and tables in a more accessible and understandable format. I provided each review in writing to the lead author of each report, with a copy to Bay of Plenty Regional Council and was then available for additional exchanges with the authors as needed, and re-review of the revised drafts. I also had the opportunity to comment orally on each report at the Experts meeting in July 2022, and to present my overall impressions at the MoU partners meeting in October 2022.

The scientific quality of each report was uniformly high, and indicative of the professional expertise, experience and standing of each of the consultants. The consultants were receptive to the review corrections and comments, also a hallmark of professionalism, and in several instances, took on board this critical feedback to produce a revised approach that was even better than my suggestions. The result is an impressive set of high-quality reports, that together provide a robust 5-year assessment of PC10.

In standing back from this process, we need to ask the question, how does PC10 compare with the most successful environmental management strategies internationally? In my experience there are several criteria to consider, and the PC10 process ranks highly with respect to each one of these.

Long term vision. There are no quick fixes to lake restoration, despite some commercial promises to the contrary. Lakes are complex systems that are intimately connected to their surrounding watershed, airshed and the global environment, and although some changes can occur rapidly (e.g., the arrival of an invasive species), there is considerable inertia to improvements in water quality. Success in lake restoration requires patience and sustained effort, as is well recognized by the PC10 management plan.

Defined targets. Environmental management requires focused efforts, and the most successful strategies have well defined targets that everyone can get behind and work towards. Considerable effort and consultations have gone into setting the nitrogen and phosphorus loading targets for Lake Rotorua, and this is a notable strength of PC10. This 5-year review has upheld the magnitude and importance of these targets.

Regular reassessment. It is one challenge to set targets. Another is to track progress towards those targets, to evaluate success, consider options and adjust management and monitoring practices appropriately. This also provides a regular opportunity to identify new information, issues and solutions, including from the most recent lake and catchment science from around the world. The 5-year reporting period of PC10 appropriately mandates and formalizes this systematic process. This duration between reports is long enough to be less affected by the usual year-to-year variability associated with weather fluctuations and is short enough to allow a timely response to new conditions.

Sustained monitoring. Progress towards targets, the advent of unexpected new factors, and the need for adaptive management actions to address changes in the environment all rest on the availability of high-quality monitoring data. Lake Rotorua and its catchment benefit from an outstanding monitoring program where there has been attention to seasonal as well as year-to-year, weather-driven variations. Attention has also been given to changes in analytical protocols and consequences for interpreting the data series. This gold standard approach, as adopted in PC10, is essential to continue. It will require an ongoing commitment to maintaining the highest quality of environmental monitoring data, and to augmenting in certain ways (as suggested in some of the reports) the type of data collected.

Preparing for climate change. Global carbon emissions climbed to record new levels in 2022, and annual average temperatures over last 8 years have been the warmest since records began. In recognition of the urgent need to confront the warming climate and the increasing frequency and magnitude of extreme events, environmental management plans throughout the world are paying special attention to climate-related adaptation strategies. This first edition of the PC10 5-year reports includes the first considerations of climate change, and such planning and preparedness will be an increasingly important component of future management plans for the Rotorua Te Arawa lakes.

Targeted research. Each lake plus catchment has its own particularities that change through time, and ongoing research is vital to identify those features and the implications for successful management. The 5-year review process for PC10 is designed to identify new issues and gaps in understanding, and several of these modules make recommendations on specific research topics. This includes the development of climate and land use scenarios that will help prepare for the future.

Working together. Experience throughout the world has shown that the most successful environmental management strategies are those that involve full engagement with local residents, landowners and other stakeholders. Full consultation and engagement have been key elements of the PC10 process, and this respectful and inclusive approach is especially apparent in the BOPRC contributions to this report series. PC10 is a model for successful lake management throughout New Zealand and beyond.

In closing I would like to thank each of the consulting experts for the quality of their work, and their receptiveness to critical feedback. I especially thank Andy Bruere for his expert and affable management of this process, his recruitment of the best environmental expertise, and his continuous guidance to keep the reports on track and focused on pragmatic questions, concerns and solutions. I thank the Lake Rotorua Primary Producers Collective, the Lakes Water Quality Society and the Te Arawa Lakes Trust for their important insights and feedback during this process. Finally, I thank Toi Moana, Bay of Plenty Regional Council for their commitment, vision and leadership, to the enormous long-term benefit of the Lake Rotorua ecosystem.

Biographical information

Dr. Warwick F. Vincent is a professor of biology at Laval University in Quebec City, Canada, where he also holds the Canada Research Chair in aquatic ecosystem studies. Over the last three decades, he has taught freshwater ecosystem science (limnology) at an undergraduate level each year, and limnology and oceanography at a graduate level. Although most of his recent research has been on Canadian lakes and rivers, he has also worked and advised on water quality problems in lakes around the world, including Lake Biwa (Japan), Lake Tahoe (USA) and Lake Geneva (Switzerland/France). He has published around 400 scientific papers and several books, and has been recognized by several awards and distinctions, including election as Fellow of the Royal Society of Canada and as honorary Fellow of the Royal Society of New Zealand.

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 2022. Short summaries are presented for each technical report including discussion of key findings and recommendations.

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 11 reports (see Table 1 in the Introduction section) 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.

Lake water quality

As part of this review, detailed assessments of different aspects of lake water quality have been completed. Consistent long-term water quality information is now available for more than 30 years and provides a reliable foundation for robustly assessing the long-term trajectory of water quality, including Trophic Level Index (TLI) and its individual components, high-frequency monitoring buoy data, and cyanobacteria (to monitor recreational suitability).

The TLI continues to be an important indicator of measuring and reporting progress towards the water quality target in Lake Rotorua (target TLI 4.2), with lower values indicating better water quality. Hamill (2022a) calculated water quality trends for three time periods (31, 21, and 12 years), and found that the TLI (and the individual TLI components) in Lake Rotorua show a very likely decreasing (improving water quality) trend for the 31 and 21-year period. The 12-year period showed mostly uncertain trends for TLI and its components, except for the TLI phosphorus component, which displayed a very likely increasing trend. It is noted that short time-period data in trend testing can lead to uncertain (or statistically insignificant) test results due to the small number of samples used in the test. Based on the three-average TLI, the present water quality generally meets the TLI target, and is comparable to or better than that observed in the late 1960s (Hamill 2022a, McBride 2022b).

The availability of high-frequency monitoring buoy data from 2007 to 2021 in the lake provides new opportunities for exploring the long-term dynamics of stratification patterns in the lake. Because the lake is polymictic, meaning that there are 2-day or longer episodes each year when the lake is no longer fully mixing, and the bottom waters become devoid of oxygen. Although only monthly measurements are available, a strong response of both dissolved nitrogen (N) and phosphorus (P) was observed in the bottom waters to the duration of stratification prior to sample collection. This suggests internal loading may be substantial, with an indication that it makes a greater contribution to total loading for phosphorus than for nitrogen.

Wood et al. (2022) carried out a long-term trend test for cyanobacterial biovolume and demonstrated that total cyanobacterial biovolume was very likely decreasing over the study period in Lake Rotorua, both in the combined and individual site data. When the data were analysed pre- and post-2007 (when alum dosing was initiated), there was a clear pattern of a highly likely increasing biovolume pre-2007, followed by highly likely decreasing biovolume post-2007. The results of the long-term trend test indicate that the portion of the cyanobacteria community that are potentially toxin producers was highly likely increasing in Lake Rotorua. In contrast, the proportion of the cyanobacterial community comprised of species capable of nitrogen fixation showed a highly likely decrease in their relative abundance in Lake Rotorua.

Tempero (2022a) investigated potential changes in nutrient limitation within Lake Rotorua at sub-monthly timescales, and to determine if alum dose rates could be optimised to take advantage of periods of phosphorus limitation. Under the test conditions nitrogen limitation was indicated for most of the summer months (December–March) and nutrient co-limitation (nitrogen and phosphorus) during the spring and late autumn. Only short periods (~2 weeks) of phosphorus-limitation were observed, one of which was associated with an intensive storm event at the end of March 2021. Due to the modest periods of phosphorus limitation indicated by the assays, there appears to be little potential for optimisation of alum dose rates in order capitalise on natural periods of phosphorus limitation. Although these results are limited by the constraints of laboratory incubations that do not completely mimic natural conditions, they provide evidence that both N and P play controlling roles in the Lake Rotorua phytoplankton. The results support the need to manage the catchment loading of both nutrients to the lake.

Catchment nutrient export and management

McBride (2022b) reported long-term nutrient loads to Lake Rotorua. Since July 1999, estimated nitrogen load was lower than the sustainable load for just one of 23 hydrological years, and the average load exceeded this target by approximately 110 t N/yr. For phosphorus, the mean annual load over the past decade was approximately 42 t/yr, or 5 t/yr greater than the estimated sustainable load (note that these figures are exclusive of stormflow particulate loads, which could be more important in the future with ongoing climate change). While catchment loads of nitrogen and phosphorus from 2018 – 2022 were strongly linked to discharge, average concentrations have remained fairly stable since 2000 with, for example, average nitrate concentration oscillating between c. 0.85 and 1.0 g/m3 for 2000-2022. At a whole-of catchment level, this is broadly consistent with predictions of a flattening off of increases in nitrogen load post-2000 as suggested by the ROTAN catchment modelling for Lake Rotorua.

Long-term trends of inflow nutrient concentration and loads were reported by Hamill (2022b). The streams contributing most of the total nitrogen (TN) load are Awahou (71.1 t/yr), Puarenga (67.4 t/yr), Hamurana (66.5 t/yr) and Waiteti (55.8 t/yr). Waiohewa has high NH4-N loads due high concentrations from the geothermal activity. The streams contributing most of the TP load are the Hamurana (7.5 t/yr), Puarenga (5.1 t/yr), Awahou (3.9 t/yr) and Utuhina (3.8 t/yr). The trends in nutrient loads were very similar to trends in nutrient concentrations. For the period 2002 to 2022, the load of TN increased in Hamurana, Awahou and (with less confidence) Waiteti. This increasing trend has continued in the Hamurana and Awahou since 2010. There is reasonable evidence that TN loads in the Puarenga decreased from 2002-2022, but not since 2010. There was reasonable evidence of increasing TP load from the Waiteti, Utuhina, Puarenga, Waingaehe, Waiohewa, and possibly from the Hamurana due to increased flows over the 2002-2022 period.

Kusabs et al. (2022) estimated that the load to land has reduced from 982 tonnes to 761 tonnes between 2017 and 2022. This is a combined nitrogen loss figure of monitoring farm data and scripting and allocation data. The load to land includes the nitrogen reductions achieved on farm through the LRNR and the Incentives Programme. As the improved processes and procedures to effectively implement and monitor the rules and agreements enables the capture of the current state of the catchment (and sub-catchment), reporting on progress towards meeting the sustainable nitrogen target will be improved, which will enable the development of clearer linkages between load to land and load to the lake.

In-lake restoration activities and new science

The use of aluminium sulphate (alum) as a medium-term measure to improve water quality in Lake Rotorua still appears to be effective in removing dissolved reactive phosphorus (DRP) from the Utuhina and Puarenga inflows, however, Tempero (2022a) argues that its assumed effectiveness in reducing internal phosphorus loading in Lake Rotorua requires further evaluation.

McBride (2022b) used daily aluminium dose rates to the Puarenga and Utuhina Streams for the entire dosing period to estimate the annual phosphorus load bound within each stream. Alum dosing was estimated to remove a substantial proportion (~8%) of DRP load to Lake Rotorua. Given that as little as circa 6 t DRP per year might be derived from anthropogenic sources, the c. 2.3 t DRP per year estimated to be bound by alum represents a very substantial management action compared with other potential phosphorus mitigation approaches available in the Rotorua catchment.

Tempero (2022b) investigated the effects of aluminium (Al) at 2 mg/L in association with diel pH cycling on rainbow trout, common bully, and kōura osmoregulation and respiration. It is concluded that the combined impacts of diel pH cycling and aluminium exposure at twice the current dosing rate (i.e., 1 mg Al/L) are unlikely to significantly impact respiratory and osmoregulatory function in fish and kōura in Lake Rotorua. There was some indication that at circumneutral pH and moderate aluminium concentrations (2 mg Al/L), particulate aluminium may cause erosional damage to kōura gill tissue. However, such conditions are highly unlikely to be encountered within the lake where the mean total aluminium concentrations are approximately one hundred times lower (0.02 mg Al/L).

Hamilton and Patil (2022) provided a comprehensive review of relevant New Zealand and international lake water quality remediation science. The review included considerations of a number of lake remediation actions including algicides, herbicides (relevant to invasive weed species in the Rotorua Te Arawa lakes), coagulants, flocculants (i.e., geochemical engineering), flushing including reducing water residence time, biological remediation and biomanipulation, aquatic phytoremediation (including in constructed and lakeside wetlands), oxygen nano-bubble technology, ultrasound treatment, dredging, inflow diversion, filtration of phytoplankton, and hypolimnetic siphoning. Of these, algicides, coagulants, dredging and bioremediation can be considered as conventional techniques for lake restoration, but the relevant active materials and techniques are being continuously altered. Other techniques are newer or still in a development phase. It was concluded that many novel lake remediation technologies fail to progress beyond laboratory scale and there is often not adequate investment by the product company to provide an evidence base to warrant their consideration. Based on the recommendation in the previous PC10 review that climate change should be given consideration, this report describes the projected changes in New Zealand climate and implications for Lake Rotorua water quality. This new climate section now provides a template for the future 5-yearly updates.

Impact of Plan Change 10 on rural land values within the Lake Rotorua catchment

Craven (2022) provided an update on previous reports that focused on the economic impacts on farming and/or property values following the introduction of nutrient regulation in the form of Rule 11 for the Lake Rotorua catchment.

Sales data do not show any discernible negative impact from the introduction of Plan Change 10 which was notified in 2017, rather the certainty/incentives provided by the regulatory framework may have in certain instances reinforced value. The effect of Plan Change 10 on rural land values is largely dependent on individual property characteristics and as such can be positive and negative. Land use change incentives and additional economic factors such as a buoyant lifestyle market and demand from forestry/carbon market have softened any negative effect of Plan Change 10 on land values within the catchment. The value of New Zealand Carbon Units is now an overriding value consideration for lesser contour pastoral blocks, irrespective of any nitrogen allocation.

Some market participants and landowners have taken advantage of the incentives to activate land use change. The ability to sell supply nitrogen and/or obtain additional development rights is not fundamental to value considerations. Introduction of environmental regulations by central government has resulted in similar restrictions on rural land use nationwide which now dilutes any negative perceptions specific to Lake Rotorua.

Synthesis

Lake Rotorua remains one of the most well understood lakes in New Zealand, with a history of scientific research and monitoring since the 1960s and the technical reports highlighted in this summary report are building on a substantial body of scientific reports and published papers. Multiple studies during the Science Review 2022 have utilised decades worth of data and information and employed state of the art statistical methods to interrogate long-term trajectories of lake water quality. Considering the above, several reasonable conclusions can be drawn from the Science Review 2022:

1. Long-term water quality trends (including TLI and cyanobacteria biovolumes) appear to be improving (>20 years) in Lake Rotorua. However, more recent trends (~10 years) are indetermined. Although determining short to medium-term trends are generally more uncertain from a statistical perspective, ongoing monitoring and data analysis will be required to improve the confidence in the trends.

2. Water quality (i.e., TLI in the context of the science review) varies somewhat with broadscale climatic drivers, as evidenced by correlations between TLI and Southern Oscillation Index, annual rainfall, and sunshine hours. While it is reasonable to assume that some of the year-to-year variation in TLI can be explained by climate and may have to be accounted to report water quality changes against the TLI target, the causal links between climate and in-lake water quality are not straightforward and will require further attention.

3. Alum is effective in reducing phosphorus loads from the Utuhina and Puarenga inflows, but its assumed effectiveness in reducing internal phosphorus loading in Lake Rotorua is less certain.

4. There appear to be no significant adverse ecological effects of alum based on the species tested, although this may need to be confirmed for less mobile species.

5. The nitrogen load to land has reduced from 982 tonnes to 761 tonnes between 2017 and 2022. Ongoing improvements of processes and procedures to effectively implement and monitor the rules and agreements will enable the development of clearer linkages between load to land and load to the lake.

6. Conventional and novel techniques for in-lake restoration are generally not suitable for a lake the size of Lake Rotorua.

As many authors have highlighted during the science review, the lake and catchment monitoring programme for Lake Rotorua is evidently one of the most comprehensive and consistent programmes in New Zealand. The long-term record of a comprehensive suite of water quality parameters has substantially reduced uncertainties of long-term trajectories of water quality. However, during the course of long-term data collection there can be analytical method changes and improvements, and changes in accepted statistical analyses to understand long-term trends. As highlighted by Hamill (2022a, 2022b), these changes can result in step changes in the data (even after adjustments), and problems such as this may compromise trend detectability. Ensuring the collection of high-quality data and analysis requires ongoing scrutiny.

Cumulative impacts facing Lake Rotorua (and other lakes across New Zealand) have received limited attention and there is uncertainty regarding how different impacts interact in the face of current and future pressures, notably climate change. Climate change is predicted to exacerbate eutrophication and there is a general consensus that increasing efforts will be required to achieve desirable lake water quality outcomes. Hamilton and Patil (2022) highlighted the need to combine multiple stressors (including anthropogenic activities) acting in combination in predicting climate change impacts on lake stratification, deoxygenation, and species composition instead of assessing stressors (e.g., climate change) in isolation, as a focus of single stressors may significantly underestimate the impact of climate change on, for example, cyanobacteria bloom development.

Recommendations

A total of 25 individual recommendations for further science work and monitoring activities were made by the report authors. A table containing all the recommendations is given in Appendix 1. 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

Introduction

Purpose

The purpose of this summary report is to provide a synthesis of the detailed technical reports produced to support the Lake Rotorua Science Review 2022. Short summaries are presented for each technical module report, including a discussion of key findings and recommendations. Detailed information on the background and the methodology used in each study can be found in the respective report (Table 1).

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 initial science review of Plan Change 10 was completed in 2018. It was summarised into Lake Rotorua Science Review- Summary Report February 2019. The Science Review report summarised the findings and recommendations of the 11 module reports that provided a review of specific aspects of the Science Review 2018. Each module included recommendations for action, or further work. The Summary Report February 2019 listed 48 individual recommendations for further science work. While the review team and independent reviewer supported the outcomes of each module, the recommendations were included but not assessed against cost of action or timeframe to undertake each of the actions (discussed in detail in Module 1 of the present science review; Table 1). Due to the potential cost, time and specific expertise required to undertake each recommendation, priorities for action were set to ensure progress on the highest priority recommendations. Professor Troy Baisden, Andy Bruere and James Dare undertook this priority setting. The present science review comprises 11 modules (Table 1).

More generally, the Water Quality Technical Advisory Group (WQTAG) 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 The Regional Natural Resources Plan Method LR M2.

Table 1: Science Review 2022 modules

Module	Report title	Author(s)
1	Progress on Recommendations from 2018 Review	Andy Bruere
2	Trophic Level Index Review of targets and variability for the Rotorua Lakes	Keith Hamill
3	Temperature stratification and dissolved oxygen dynamics in Lake Rotorua	Chris McBride
4	Rotorua lakes cyanobacterial data analysis - 2022	Susie Wood, Eric Goodwin, Laura Kelly, Jonathan Puddick
5	Trend and State of nutrients in Lake Rotorua Streams 2002 - 2022	Keith Hamill
6	Long-term nutrient loads and water quality for Lake Rotorua: 1965 to 2022	Chris McBride
7	Nutrient management within the Lake Rotorua catchment	Scott Kusabs, Stephanie Fraser, Penny MacCormick
8	Phytoplankton nutrient limitation in Lake Rotorua	Grant Tempero
9	Toxicological effects of aluminium in relation to diel pH changes on fish and kōura	Emily Fensham, Nick Ling, Grant Tempero
10	Review of existing and new methods of in-lake remediation	David Hamilton, Rupesh Patil
11	Impact of Plan Change 10 on rural land values within the Rotorua lake catchment	Martyn Craven

Methodology

The PC10 science review is led by Andy Bruere. Professor Warwick F. Vincent was appointed independent reviewer for each of the PC10 modules (excluding the land values module 11).

Terms of Reference

The science review terms of reference (ToR) were drafted at a WQTAG workshop in November 2021, resulting in a core list of topics or ‘modules’ (based on the discussions and justifications in Module 1). Andy Bruere, WQTAG convenor and BOPRC’s Lake Operations Manager, managed this 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 November 2021, each module author was asked to write a brief on how they would address their part of the ToR. These briefs were revised after feedback from Andy Bruere, fellow WQTAG members and Professor Warwick F. Vincent.

The scope of some reports included other Rotorua Te Arawa lakes to provide a wider context of the findings and conclusions derived for Lake Rotorua, and to take advantage of the opportunity to analyse the long-term record that exists for some of the other lakes. This summary report focuses almost exclusively on the key findings and implications for Lake Rotorua.

The authors of these reports have worked diligently to gather and analyse the most recent scientific literature within the context of the respective module, and to distil this knowledge into a comprehensive and accessible format. As such, only the module references are listed at the end of this summary report and the reader is encouraged to seek further information on key references of the wider literature cited within each module.

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.

Peer review and workshop

Method LR M2 requires that 'Any science review and recommendations completed under Method 2 will be peer-reviewed by a suitably qualified independent expert' (clause f). This requirement was met by appointing Professor Warwick F. Vincent as an independent peer reviewer, who holds the Canada Research Chair in Aquatic Ecosystem Studies at Laval University in Quebec City, Canada. The peer review process was carried out in the same way as was done for the Science Review 2018.

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, 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 29 July 2022. Each author gave a summary presentation followed by a discussion, especially on key recommendations.

MoU partner 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 BOPRC considers their views. The MoU partners were consulted on the Draft ToR prior to the final ToR being set. Plan Change 10'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 initiating a plan change and reviewing resource consent conditions to ensure consents are aligned with the required water quality targets. The MoU parties were invited (by Andy Bruere) to participate in a science review meeting on 14 October 2022. Lead authors of 5 modules gave presentations, while all other draft reports were made available to the MoU parties before the meeting to discuss them.

Module 1 is a summary of progress on recommendations from the previous review. It is not summarised in this report as it does not form part of the current review but is available online.

Module 2 - Trophic Level Index Review of targets and variability for the Rotorua Lakes

Background

The management of twelve Rotorua Te Arawa lakes is directed by Bay of Plenty Regional Council (BOPRC) through the Regional Natural Resources Plan (RNRP), and the Regional Natural Resources Plan (RNRP). The Rotorua Te Arawa lakes are identified as "Catchments at Risk", and Objective 11 (RL 01) of the RNRP requires that water quality of these lakes is maintained or improved to meet water quality targets, as expressed using the Trophic Level Index (TLI). Values of TLI are determined annually from annual mean surface water concentrations of chlorophyll *a*, total nitrogen and total phosphorus, and Secchi depth.

The TLI targets set in the RNRP were based on achieving historic water quality conditions. For Lake Rotorua this was based on achieving water quality state that existed in the 1960s, while for the other Rotorua lakes the target was equivalent to water quality in the early 1990s.

Objectives

This report provides a review of TLI data and the TLI targets set in Objective 11 of the RNRP for each of the Rotorua Te Arawa Lakes. This includes:

- Collating all long-term data for each lake relevant to assessing the TLI.
- Adjusting the phosphorus (P) data to account for laboratory changes. This is to address historic analytical issues associated with P data due to changes in laboratory methods and the interference of arsenic (As) and silica (Si) when measuring phosphorus by some methods.
- Analysis of water quality trends for each lake as measured by the TLI and its component parts.
- Assessment of TLI state and temporal variability for each lake.
- Review of the TLI targets along with recommended options to express TLI targets to reduce their sensitivity to natural variability.

Methodology

Water quality data was collated from BOPRC and the University of Waikato. The dataset compiled by the University of Waikato for Lake Rotorua for modelling purposes had already been checked and this was used to provide a consistent basis of analysis.

For a period of about August 2010 to October 2019, the total phosphorus results of samples from most Rotorua lakes were elevated due to interference of the analysis by silica and arsenic. To address this issue, a new BOPRC laboratory method was trialled from early October 2018 and adopted in October 2019. Corrections factors were developed for each lake that were used to correct the data for the period August 2010 to October 2019 and these corrections were applied to total phosphorus data used in this report.

The TLI and its component parts for total nitrogen, total phosphorus, chlorophyll *a*, and Secchi depth (TL-n, TL-p, TL-c and TL-s, respectively) were calculated for each monthly sampling event from surface samples. Trends were calculated using the seasonal Kendall trend analysis over time periods of 31-years (1991-2021), 21-years (2001-2021) and 12-years (2009-2021).

TLI state and temporal variability were evaluated by comparing annual TLI values to the banding stipulated under the National Objectives Framework in the National Policy Statement for Freshwater Management (NPS-FM) 2020, exploring different time periods used for averaging TLI values, assessing the influence of the mathematical method used to calculate the TLI, and comparing interannual variability of TLI with climatic variables.

Key findings

The trophic state attribute bands of A, B, C and D under the National Objectives Framework in the NPS-FM 2020 approximately correspond to oligotrophic (or better), mesotrophic, eutrophic and supertrophic (or worse), respectively. However, the grading of lake trophic state using the NPS-FM 2020 attributes tends to be more stringent than the TLI because the TLI is calculated as an average of scores derived from total nitrogen, total phosphorus, chlorophyll *a*, and Secchi depth, while the NPS-FM attributes can fail a bottom-line for any individual variable. Also, the NPS-FM maximum statistic for chlorophyll *a* sets bands based on individual algal blooms, as opposed to high concentrations occurring on average. For the 3-year period 2018/19 to 2020/21, the attribute band for total nitrogen, total phosphorus, chlorophyll *a* (maximum) was B. However, the attribute band for chlorophyll *a* (median) was C, which renders the overall NPS-FM 2020 band for Lake Rotorua for the 3-year period 2018/19 to 2020/21 C.

Overall, the TLI and its components show a very likely decreasing trend for the 31 and 21-year period (Table 2). The 12-year period showed mostly uncertain trends for TLI and its components, except for TL-p, which displayed a very likely increasing trend. It is noted that short time-period data in trend testing can lead to uncertain (or statistically insignificant) test results due to the small number of samples used in the test. Lake Rotorua is eutrophic with its TLI currently just at its target value. TL-c is consistently high relative to TLI values. TLI has substantially decreased (improved) in the lake since 2001 (Figure 1). Most of the improvements in water quality occurred between about 2004 and 2013, and there has been little change in more recent years. Interventions to improve lake water quality include land disposal of the city's wastewater since 1991, sewage reticulation of lakeside communities, alum dosing to lock phosphorus from Utuhina Stream (commenced in 2006) and Puarenga Stream (commenced in 2010), rules to cap land-based inputs.

Table 2: Trend direction, statistical confidence, and percent annual change (PAC) in the TLI for time periods of c. 31-years, 21-years, and 12-years. Arrows indicate the trend confidence and direction as follows: "very likely increasing" ↑, "uncertain" → , "likely decreasing" ↘, and "very likely decreasing" ↓. Table is adapted from Hamill (2022a).

Period	TLI		TL-n		TL-p		TL-c		TL-s	
	Trend	PAC	Trend	PAC	Trend	PAC	Trend	PAC	Trend	PAC
31-year period, 1991-2021 inclusive	↓	-0.5	↓	-0.4	↓	-1.1	↓	-0.3	↓	-0.2
21-year period, 2001 - 2021 inclusive	↓	-1.0	↓	-0.7	↓	-1.6	↓	-1.2	↓	-0.5
12-year period, 2010 - 2021 inclusive	→	0.0	→	0.1	↑	0.8	→	-0.3	↘	-0.2

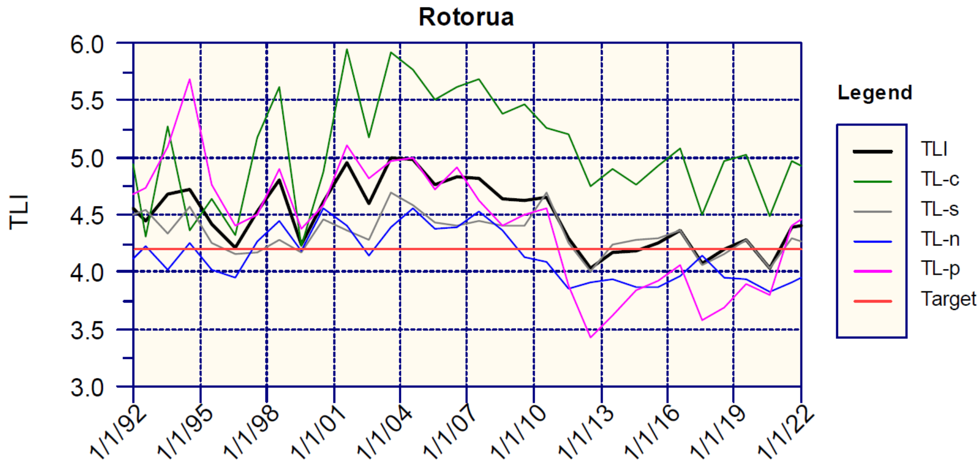

Figure 1: Annual mean TLI and target (horizontal red line) for Lake Rotorua. Dates are the end of the hydrological year. Figure reproduced from Hamill 2022a.

The influence of the assessment period used for averaging TLI values was assessed by calculating the rolling average TLI for durations of 1- to 8-years. As expected, averaging the TLI over longer periods provides more smoothing and less variation between years. However, longer durations also cause more of a time-lag, which could potentially delay triggering an action plan in response to poor water quality. The current approach of using a rolling mean TLI over a three-year period is reasonable from a statistical perspective. Regular monthly sampling provides 36 data points over three years, and as the sample sizes increases above 30 there are diminishing returns with respect to improved confidence in estimates. Alternatively, a 5-year mean may be a better option to fit with the 5-year reporting periods used for Lake Rotorua.

The comparison of calculation methods for the TLI confirms the conclusions of previous reports about the importance of following a consistent method for calculating TLI scores and for reporting against the target values.

Spearman correlation analysis between the 12-month mean TLI and annualised climate variables (2009-2022) indicates that variations in TLI in Lake Rotorua are influenced by the Southern Oscillation Index, rainfall patterns, and sunshine hours.

Recommendations

While no specific recommendations were made in the report, ongoing discussions pertaining to Lake Rotorua amongst WQTAG members include:

1. Interpretation of interannual variability and trends in context of statistical trends (10-20 year) vs Interpretation in context of statistical analysis of 5-year time periods.

2. Reduce influence of interannual variability by using a tolerance before triggering management action, e.g., no tolerance vs tolerance of 0.2 TLI before triggering action.

3. If target is triggered, investigate possible climate reasons using multiple line of evidence, e.g., “paired” lakes. Interpret TLI in context of “paired’ lakes with statistical correlation – not strong correlation between some lakes.

Module 3 - Temperature stratification and dissolved oxygen dynamics in Lake Rotorua

Background

Lake Rotorua is polymictic, meaning that more than once per year its surface waters become isolated from bottom waters due to density differences and subsequently mix again after days or weeks. During these periods of stratification oxygen is consumed in bottom waters and cannot be replenished by atmospheric exchange. This can stimulate remineralisation of dissolved nutrients that would otherwise have been retained within lake sediments, back into the water column ('internal loading') which can enhance phytoplankton growth. It is important to understand stratification pattern within each year and across several years to help with predicting and managing the physical, chemical, and biological processes that occur in the lake.

Objectives

High-resolution monitoring buoy data present a unique opportunity to better understand the drivers of water quality in Lake Rotorua. This report synthesises a complete best-estimate of the number, duration, and timing of stratification events in the lake 2007-2017 and presents an exploration of water chemistry data in this context, as well as nutrient and alum loading.

Methodology

A combination of high frequency monitoring data and 1-D hydrodynamic modelling was used to calculate key indicators of water column stratification in Lake Rotorua. Statistical analysis was used to explore the relationships between stratification patterns and overall water quality expressed as annual mean surface concentrations of total nitrogen and total phosphorus.

Key findings

Patterns of stratification are highly variable interannually in Lake Rotorua (Figure 2). Sustained periods of stratification are relatively rare but can last for as long as 8 weeks (maximum observed 58 days).

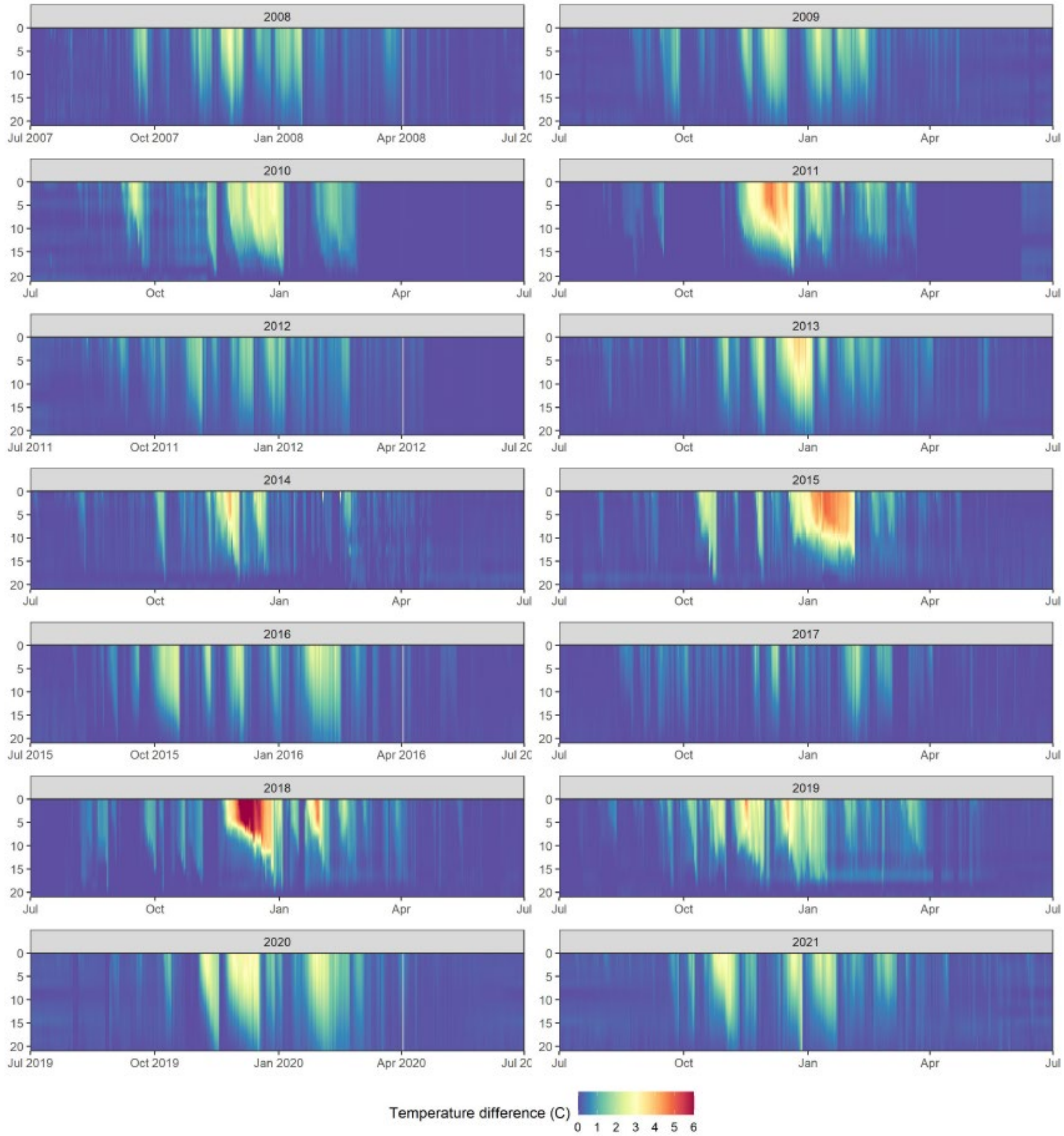

Figure 2: Combined record of surface and bottom water temperature, using modelled water temperature to fill gaps in the monitoring record. Each panel represents a hydrological year. (Figure reproduced from McBride 2022a).

The lake is frequently hypoxic to anoxic during warmer months, and a strong response of both dissolved nitrogen and phosphorus was observed in the hypolimnion to the duration of stratification prior to sample collection (Figure 3). This suggests internal loading may be substantial in Lake Rotorua. Total alum dose was a strong predictor of both nitrogen and phosphorus concentrations. However, the influence of the few pre-dosing years as outliers cannot be ruled out.

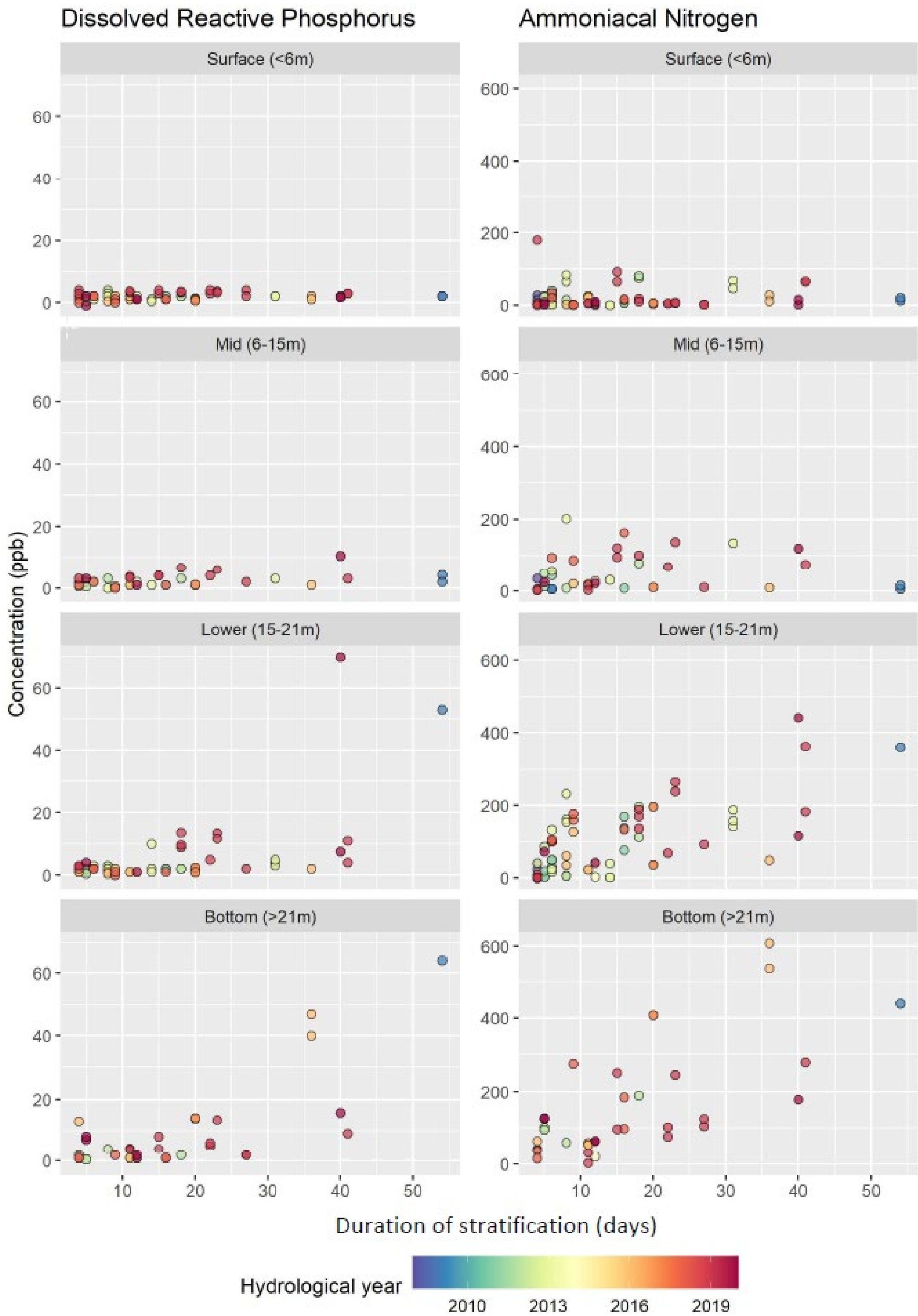

Figure 3: Observations of dissolved reactive phosphorus (left column) and ammoniacal nitrogen (right column) concentrations at different depth ranges (plot rows) against the number of consecutive days of stratification prior to sample collection. Only those measurements collected during a stratification event are presented. Points are coloured by the year of observation. (Figure reproduced from McBride 2022a).

Under a changing climate, the duration and timing of stratification are likely to change. The findings in this report suggest that if long-duration events become more common under changing climate then internal loading may drive increased nutrient supply (particularly phosphorus) to surface waters.

Recommendations

The author did not include specific recommendations for further studies in the report, but general suggestions on improving on the current approach were proposed throughout the discussion section in the report:

1. An opportunity exists for further analysis to estimate the total internal load by assessing daily hypolimnion volume against the average rate of concentration increase identified in this report.

2. Future studies could employ a biogeochemical model to fill the (relatively fewer) gaps in the dissolved oxygen record of the lake buoy in the same fashion as the hydrodynamic model was used in the report for filling gaps in the temperature record.

3. High-frequency monitoring remains essential to understanding Lake Rotorua, and targeted water chemistry sampling over the duration of stratification events could be a useful addition to its monitoring program.

Module 4 - Rotorua lakes cyanobacterial data analysis - 2022

Background

Cyanobacterial blooms have occurred in some of the Rotorua lakes since at least the 1970s. These blooms create a suite of water quality issues and because some species produce cyanotoxins, they also pose a health risk to recreational users.

Objectives

Evaluate trends in the abundance and composition of cyanobacteria in four Rotorua lakes (Ōkaro, Rotoehu, Rotoiti, Rotorua) and one site in the Kaituna River.

Collate and analyse data on health warnings, measurements of cyanotoxins, and shifts in the presence of potentially toxic species, with a focus on Lake Rotorua.

Provide recommendations on further monitoring or analysis that could assist with obtaining a robust understanding of future trends in cyanobacterial blooms and their toxins.

Methodology

Cyanobacteria data collected as part of the BOPRC recreational monitoring programme between 1998 and 2022 was analysed for Lake Rotorua. Trends were statistically determined using the seasonal Kendall test and generalised additive models for identifying shorter periods of statistically significant change in cyanobacterial biovolume. The data was also analysed to determine how many times a site breached the alert level / action mode thresholds, and in each instance whether this was caused by the biovolume of potentially-toxic cyanobacteria.

Key findings

In terms of shifts in dominant cyanobacteria genera in Lake Rotorua, *Pseudanabaena* was most abundant in 2012 and 2013, whilst *Cuspidothrix* was most abundant in 2015, *Synechococcus* in 2017, *Planktothrix* in 2018, with all other years dominated by either *Dolichospermum* or *Microcystis*.

The long-term trend test results show that total cyanobacterial biovolume was very likely decreasing over the study period in Lake Rotorua (Figure 4), both in the combined and individual site data. When the data were analysed pre- and post-2007 (when alum dosing was initiated), there was a clear pattern of a highly likely increasing biovolume pre-2007, followed by highly likely decreasing biovolume post-2007.

The results of the long-term trend test indicate that the portion of the cyanobacteria community that are potentially toxin producers was highly likely increasing in Lake Rotorua. In contrast, the proportion of the cyanobacterial community comprised of species capable of nitrogen fixation showed a highly likely decrease in their relative abundance in Lake Rotorua.

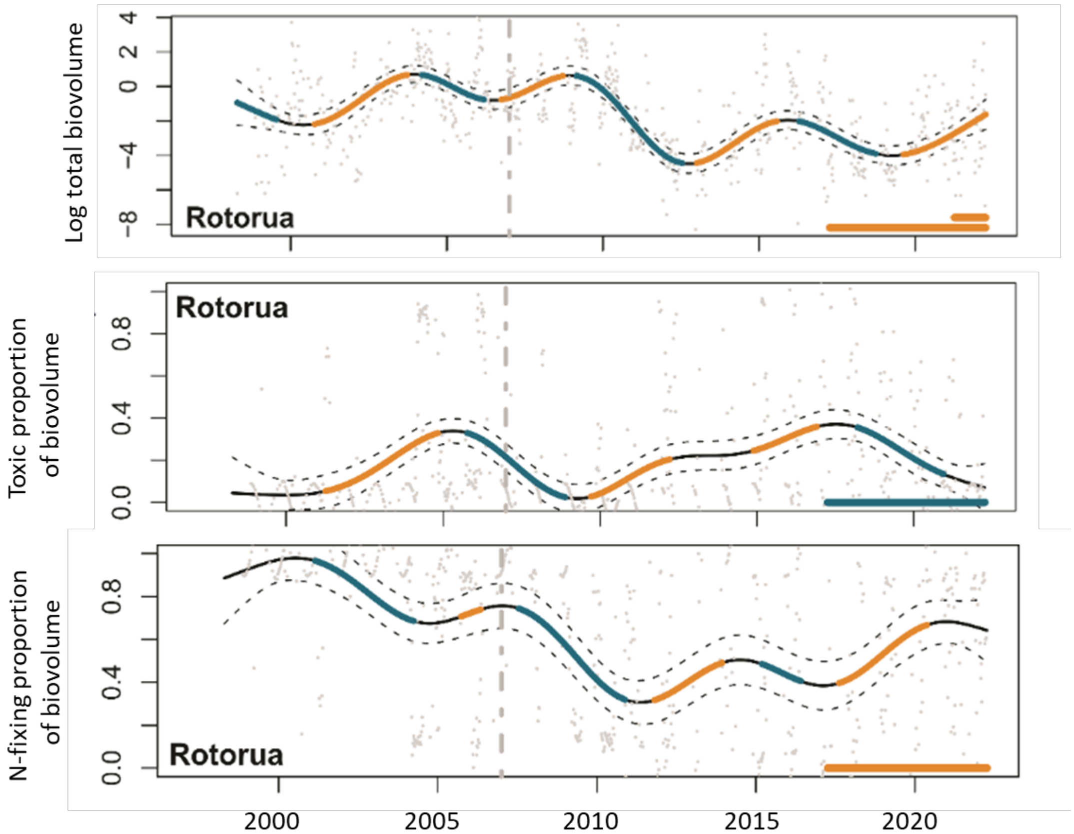

Figure 4: Results of generalised additive models for total cyanobacterial biovolume (top), portion of the cyanobacterial community that are potential toxin producers (middle), and cyanobacterial community that are capable of nitrogen fixation (bottom) with all sites combined for each lake. Plots show raw data in grey and fitted generalised additive mixed models (black line) with 95% confidence intervals shown by the dashed black line. Dashed vertical lines show interventions—alum dosing in Lake Rotorua. Significant changes are denoted by blue (decreasing) and orange (increasing) line segments. Horizontal orange or blue bars at the right-hand end of the x-axis summarise whether the cyanobacterial biovolume in the last year (short bar) or five years (longer bar) has been overall increasing (orange) or decreasing (blue). Figure reproduced from Wood et al. 2022.

Although cyanobacteria were almost always present in the samples collected from Lake Rotorua (Figure 5), health warnings were only issued for 2% of the samples collected between 2012 to 2022 (the period analysed for health warnings does not span the full dataset). In all instances the health warnings were triggered by exceedance of the potentially toxic biovolume threshold (> 1.8 mm^3/L; Situation 1 in the planktonic cyanobacteria alert-level framework).

Cyanotoxin data are extremely limited for Lake Rotorua with data available for 12 samples, two of which contained low levels of the hepatotoxic (affecting the liver) microcystin. The occasional presence of high concentrations of the toxin producers *Microcystis* sp. and *Cuspidothrix issatschenkoi* suggest cyanotoxins could reach levels which are dangerous to human users of the lake.

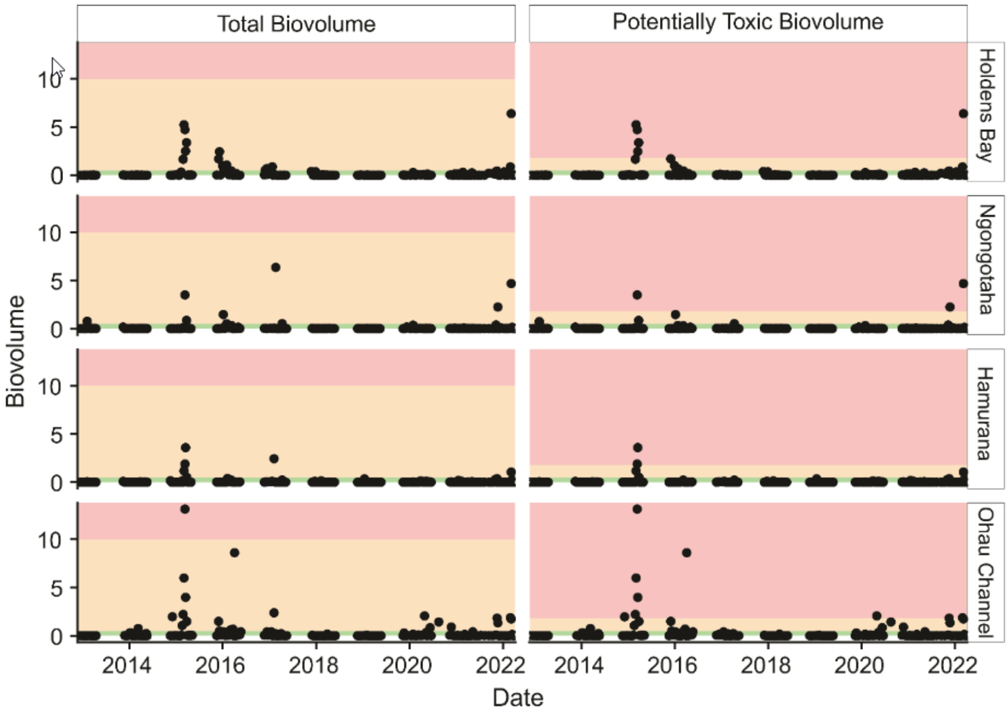

Figure 5: Total cyanobacterial biovolume (mm³/L) for the four monitoring sites in Lake Rotorua. Shading shows the three biovolume thresholds as given in the alert-level framework for planktonic cyanobacteria in recreational freshwaters (MfE and MoH 2009). The left column shows the thresholds for total cyanobacterial biovolumes (green/surveillance ≤ 0.5 mm³/L; orange/alert > 0.5 mm³/L to < 10 mm³/L; red/action ≥ 10 mm³/L; Situation 2). The right column shows the biovolume for potentially toxic cyanobacteria (green/surveillance ≤ 0.5 mm³/L; orange/alert > 0.5 mm³/L to < 1.8 mm³/L; red/action ≥ 1.8 mm³/L; Situation 1). A health warning is issued when the action level threshold is breached by either the total cyanobacterial biovolume or the biovolume of potentially toxic cyanobacteria. Figure reproduced from Wood et al. 2022.

Recommendations

1. Improvements to the current recreational cyanobacterial monitoring programme, including:
   - modernise how cyanobacteria monitoring is undertaken by incorporating technologies such as field-portable fluorometers that could be used on the lakeshore to measure phycocyanin,
   - continuing training procedures for microscopy analyses to reduce inconsistencies between taxonomists,
   - implementing an inter-laboratory comparison as part of their annual quality control process.
2. Incorporate cyanotoxin analysis into the recreational cyanobacterial monitoring programme by including cyanotoxin gene and chemical analyses into the cyanobacterial recreational monitoring programme.
3. Develop a robust algal monitoring programme by developing an algal monitoring programme for a selection of lakes in the Rotorua region that would allow long-term patterns in all algae to be assessed, not just cyanobacteria.
4. Analyse high frequency data and explore drivers of change and to gain further insights into cyanobacterial dynamics in these lakes.

Module 5 - Trend and State of nutrients in Lake Rotorua Streams 2002 - 2022

Background

This report updates previous analysis on the state and trends in nutrients of the nine major streams flowing to Lake Rotorua.

Objectives

The aim of this report is to describe the state and trends of water quality (and particularly nutrients) in streams entering Lake Rotorua.

Methodology

Trends were statistically determined using the seasonal Kendall test routine taking the median of monthly seasons. The trend analysis was undertaken over three different time periods determined by the period of water quality sampling for all streams and when there were changes in analytical method used for phosphorus (P). The time periods used were: July 2002 to June 2022 (Long term -), July 2002 to June 2010 (pre-2010 P-method change), and September 2010 to August 2019 (post-2010 P-method change).

Key findings

Lake Rotorua catchment streams with the highest concentration of total nitrogen (TN) were Waiohewa (2839 mg/m^3), Waingaehe (1544 mg/m^3), Waiteti (1484 mg/m^3), Awahou (1365 mg/m^3). The streams with the highest concentration of total phosphorus (TP) were Waingaehe (123 mg/m^3), Hamurana (89.5 mg/m^3), Puarenga (81.8 mg/m^3), Waiohewa (80.3 mg/m^3) and Awahou (74.6 mg/m^3).

Over the period of 2002 to 2022, the concentration of TN increased in Hamurana, Awahou and Waiteti due to increasing nitrate-nitrite-nitrogen (NNN). These increasing trends have continued in each of these streams since 2010 and was particularly large in the Awahou and Waiteti. Over the 2002-2022 period, there is reliable evidence of TN decreasing in the Puarenga and possibly in the Ngongotaha, but this decrease does not appear to have continued since 2010.

There is reliable evidence that, over the period of 2002 to 2022, the concentration of TP increased in the Hamurana, Ngongotaha, Utuhina, Puarenga, Waingaehe, and Waiohewa; with this trend continuing since 2010 in each stream except the Waingaehe.

The trends in nutrient loads (Figure 6) were very similar to trends in nutrient concentrations. For the period 2002 to 2022, the load of TN increased in Hamurana, Awahou and (with less confidence) Waiteti. This increasing trend has continued in the Hamurana and Awahou since 2010. There is reasonable evidence that TN loads in the Puarenga decreased from 2002-2022, but not since 2010.

There was reasonable evidence of increasing TP load from the Waiteti, Utuhina, Puarenga, Waingaehe, Waiohewa, and possibly from the Hamurana due to increased flows over the 2002-2022 period.

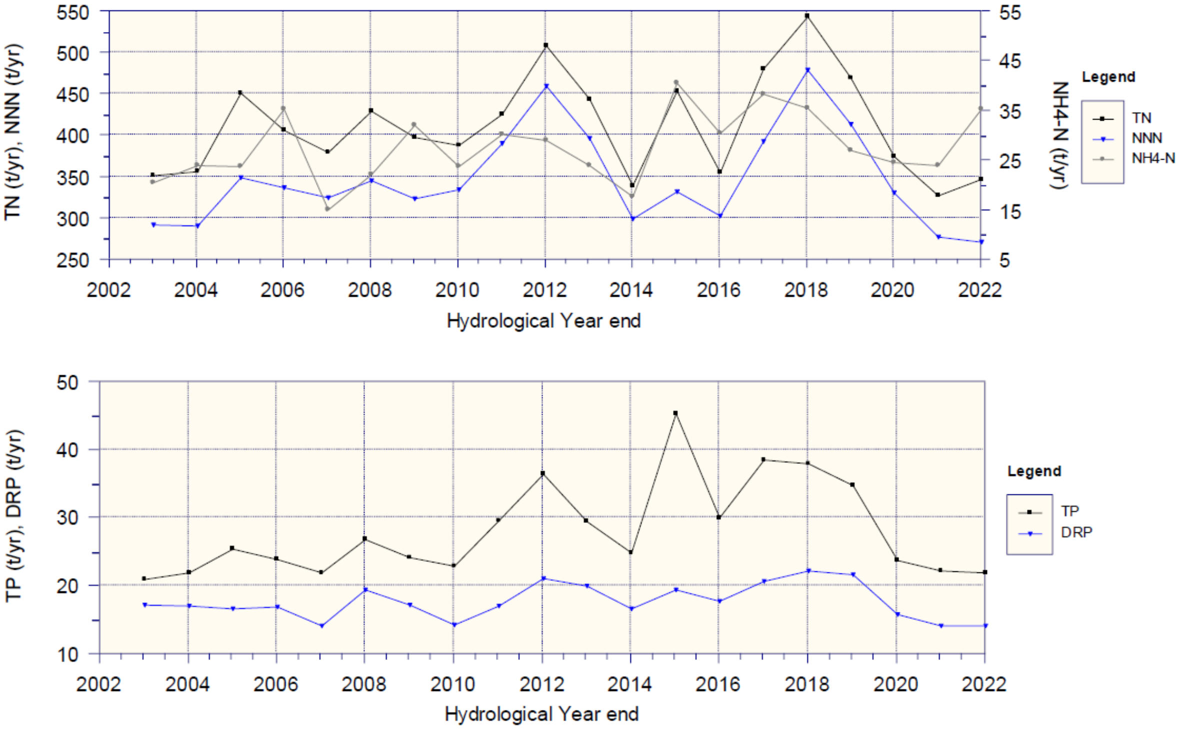

Figure 6: Total annual nutrient load from the nine monitored streams entering Lake Rotorua. Figure adopted from Hamill 2022b.

Recommendations

No specific recommendations were made in this report.

Module 6 - Long-term nutrient loads and water quality for Lake Rotorua: 1965 to 2022

Background

By assessing nutrient loading and water quality in Lake Rotorua using all available data and consistent-as-possible methods, this report aims to generate insight into long-term changes in the catchment-lake complex, and to potentially identify drivers of changes to catchment loading and their effects on lake water quality.

Objectives

A concise report to augment the previous studies, using similar methods, with the period 2017-2022, i.e., corresponding to the 5-year review cycle of the Rotorua Plan Change 10 Science Review. An analysis of alum dosing rates to the Puarenga and Utuhina streams and estimate annual load of dissolved reactive phosphorus bound by the aluminium added to the streams is also presented.

Methodology

A lake water balance was constructed accounting for all sources and losses of water on a daily basis from July 1964 to June 2017. Daily stream nitrogen (N) and phosphorus (P) concentrations were estimated either by interpolating measurements or modelling discharge-concentration relationships during stormflows, using available data.

Volume and nutrient concentration of additional inflow sources, including geothermal fluid, groundwater and atmospheric deposition, were estimated from monitoring data and literature review.

Historical water quality data and metadata were collated from a variety of sources, standardised and analysed using a consistent calculation method for Trophic Level Index to minimise bias due to inconsistent sampling intervals over the years.

Key findings

Water quality over the past five years has exceeded the TLI target every year except for 2020 (for which reduced summer sampling probably biased the TLI towards lower values; Figure 7). The change in TLI over the past four to five years has been driven mostly by increases in phosphorus concentrations in the lake. Notably, recent years with elevated lake total P (2021-22 in particular) do not correspond to the wet years with high loading observed in Figure 8 (2018-19). This suggests internal loading may be responsible for the observed increases in the lake, consistent with high concentrations of dissolved reactive P observed in bottom waters observed in the late 2010s and early 2020s.

Figure 7: Anomaly plot for TLI variables and overall TLI. Values represent the difference between the annual observed trophic level of each component, and a Trophic Level Index of 4.2 (target value). (Figure reproduced from McBride 2022b)

Catchment loads of nitrogen and phosphorus from 2018-2022 were again strongly linked to discharge. Despite very high loading years in 2018-19 (Figure 8), catchment-wide (volumetric) average concentrations have remained fairly stable since 2000 with, for example, average nitrate concentration oscillating between c. 0.85 and 1.0 g/m^3 for 2000-2022. At a whole-of catchment level, this is broadly consistent with predictions of a flattening off of increases in nitrogen load post-2000 as suggested by ROTAN catchment modelling for Rotorua.

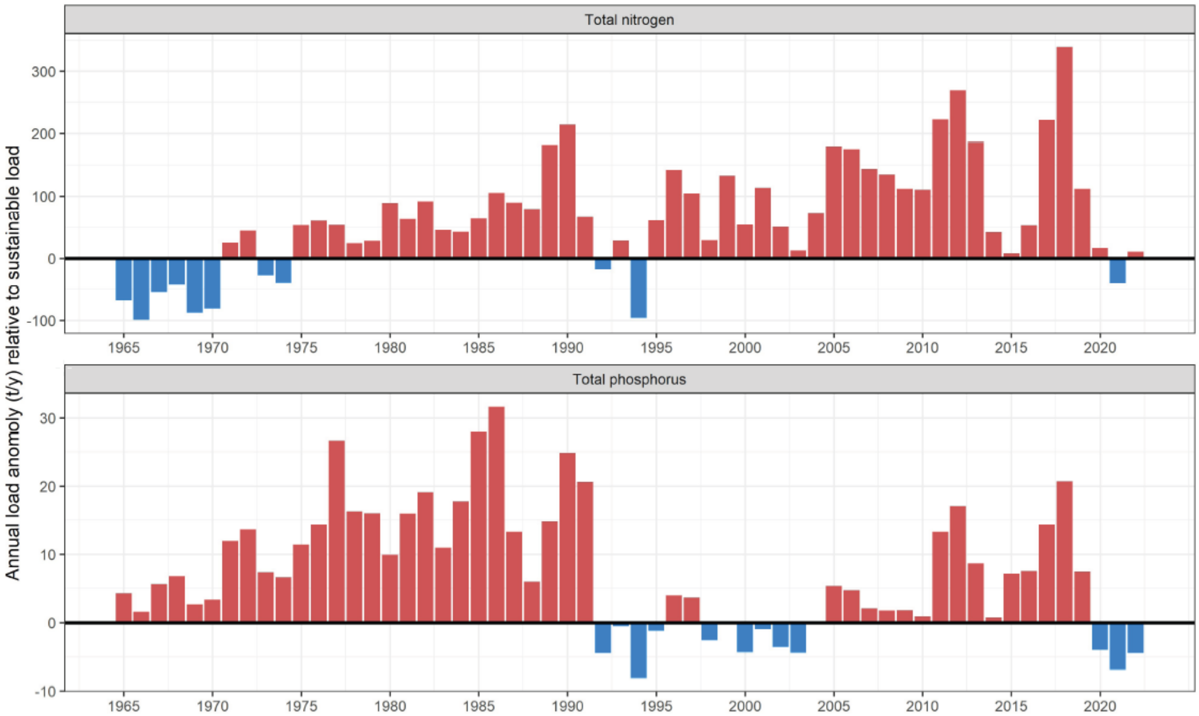

Figure 8: Annual estimated loads of total nitrogen and phosphorus to Lake Rotorua, presented as the difference between estimated load and the 'sustainable load'. (Figure reproduced from McBride 2022b)

On the balance of evidence presented here, an average catchment target load of 435 t N/y appears somewhat higher than estimated loading for the 1960s (the period to which water quality targets were set). The analysis presented in this report suggests that meeting or exceeding catchment nutrient load targets will be vital to maintaining water quality at or near TLI targets in the long-term in order to reduce the need for ongoing active management and/or geoengineering approaches such as inflow alum dosing.

Recommendations

A review and update of an aluminium budget for Lake Rotorua could be useful to reassess observed relationships between dose rates and in-lake water quality. Understanding the capacity to manage water quality with alum dosing, and the relative importance of internal and external loading is critical to the ongoing management of the lake.

Module 7 - Nutrient management within the Lake Rotorua catchment

Background

The purpose of this report is to discuss the monitoring methodology that has been used to keep track of nutrient loss from farms and will present all sources of nutrient reductions across the Rotorua Catchment between 2017 and 2022.

Objectives

- Discuss the terms of reference based on the high-priority recommendations made in Module 4 of the 2017 Science Review, which was concerned with the methodology used to calculate nitrogen loss.
- Discuss the high-priority recommendations made in Module 10 of the 2017 review, which outlined sources of phosphorus and potential mitigation strategies.
- Provide an overview of nitrogen loss from rural land use in the Lake Rotorua catchment.
- Provide a report on the progress and future opportunities for reducing nitrogen loss from rural land use.
- Provide an overview of how phosphorus mitigations are monitored within the Lake Rotorua Nutrient Rules.
- Provide a sub-catchment breakdown that shows the different characteristics within the Lake Rotorua catchment.
- Find and analyse the gaps within our current monitoring methodology.
- Make recommendations for future work needed to improve our knowledge before the next science review in 2027.

Methodology

The methodology below is a description of the actions taken after the Science Review 2017, which has resulted in processes and procedures to effectively implement and monitor the rules and agreements. The collected data enables the capture of the current state of the catchment and report on progress towards meeting the sustainable nitrogen target.

By implementing the Lake Rotorua Nitrogen Rules (LRNR), data has been collected from monitored farms within the Lake Rotorua catchment. Collection of this data enables Toi Moana to track progress towards Lake Rotorua nitrogen (N) targets set through the Integrated Framework using the ROTAN (Rotorua and Taupō Nitrogen) 2011 modelling process.

The NDMS (Nutrient Data Management System) is a blend of multiple applications (such as GIS), spreadsheets, databases and models (such as OverseerFM). This blend enables reporting of the LRNR allocation accounting and compliance monitoring in the current version of OverseerFM. The NDMS is updated when a new version of Overseer is released.

Olsen P values are required to be included within consented farm Nutrient Management Plans (NMPs). Olsen P values are commonly used to calculate phosphate fertiliser requirements on pastoral blocks to assist with understanding the plant-available phosphorus in soils. Farmers are required to maintain soil phosphorus fertility within the recommended range described by the

Fertiliser Association in its Fertiliser Use booklets. Olsen P values are entered into OverseerFM as farm systems are entered, but we do not maintain a central database. Olsen P actions are captured, monitored and regulated as part of individual consents.

Effluent management on farms is monitored by the Toi Moana compliance team when monitoring the dairy effluent consents. Effluent storage and land application records are required to be documented by the consent holders as a condition of the effluent consents. When NMPs are submitted to us the dairy effluent section is assessed to make sure they align with the effluent consent.

An independent farmer led governance group, the Phosphorus Mitigation Project Inc. (PMP) was established in 2016 to enable and direct continued applied research on detainment bund mitigation performance. Toi Moana was one of nine co-funders supporting the PMP.

Phosphorus mitigation is prioritised by targeting Critical Source Areas (CSAs) of individual farms when the farm NMPs are being developed. As CSAs are identified, they are captured geospatially and are then monitored as part of the process to monitor land use consents. We have developed an effective process to capture CSAs geospatially to allow the effective monitoring of phosphorus mitigation strategies over time.

Key findings

The load to land has reduced from 982 tonnes to 761 tonnes between 2017 and 2022 (Figure 9). This is a combined nitrogen loss figure of monitoring farm data and scripting and allocation data. The load to land includes the nitrogen reductions achieved on farm through the LRNR and the Incentives Programme as at the time of this report.

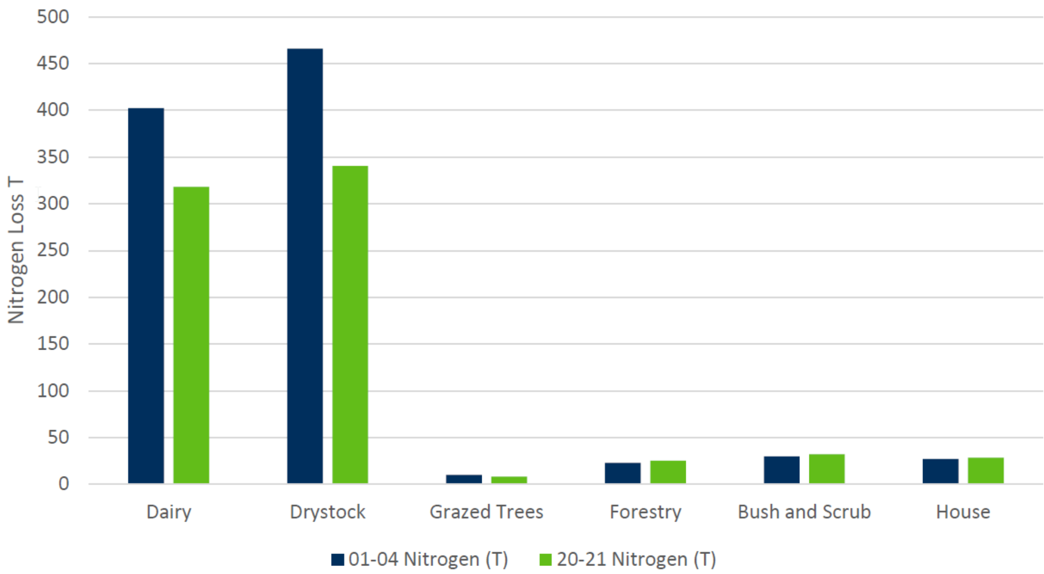

Figure 9: Change in nitrogen loss by land use between 2001 and 2004 and 2020 and 2021. Figure adapted from Kusabs et al. 2022.

The 100 tonnes of nitrogen reduction required by the Incentives Programme was included as part of the Integrated Framework adapted from ROTAN in 2011. There has been land use change on 4626 hectares of land by 24 landowners in the catchment to reach 30% of the incentives target for the Incentives Programme. These figures only include the legal agreements that have been encumbered. There are a number of agreements still being worked through.

The Integrated Framework sustainable water quality solution for Lake Rotorua was agreed to by all partners of the Te Arawa Lakes Programme and the Stakeholder Advisory Group in approximately 2015. Part of that framework was that 50 tonnes of nitrogen reduction (toward the 320-tonne reduction target) was to be made through engineering solutions. The viable solutions to contribute to the 50-tonne target have evolved over time, at the time of writing this report they are sewerage reticulation and wetlands.

The Lake Rotorua Gorse Programme was expected to reduce the amount of nitrogen leaching to Lake Rotorua by 30 tonnes. The way to achieve this was by converting mature gorse (existing in the benchmarking period), to either forestry, native bush or other land uses where nitrogen leaching is low. As of 2019, Gorse Agreements (through the Lake Rotorua Gorse Programme) controlled about 267 hectares of gorse in the catchment. Alternative channels (such as Incentives Agreements, Environmental Programmes and landowner led interventions) have managed to control a further 596 hectares. An estimated 226 hectares remain as uncontrolled gorse, which has not otherwise been classified.

The approach to date to monitor how CSAs are managed on farm has relied on the farmer taking the lead. Often the farmer has suggested timely mitigation strategies, leading to real progress towards managing CSAs effectively. In several instances work has been done collaboratively with farmers to manage problem areas on the farm.

As part of the Nutrient Management Plans (NMP), consent holders must keep Olsen P test results between the recommended range, as described by the Fertiliser Association. If farm Olsen P tests are identified as being too high, then strategies need to be identified to bring the results back within the recommended range. Dairy farmers must test soils every two years and drystock farmers every three. Farmers considered to be compliant through permitted activity rules do not need to test soils for P and are not required to produce an NMP. The NMP has a table that identifies good management practices on-farm that help to reduce nutrient loss from farms. The reason for good management practices is to manage the farm activities in a way that will prevent CSAs developing on-farm and reduce nutrient loss. The practices are divided into required and recommended practices. Most management actions described in the table focus on ongoing farm practices that rain and overland water flow paths can affect.

Recommendations

1. Assess the impact of updated S-map data on nitrogen allocations.

   The physical attributes of soils have the potential to affect the actual loss of nutrients from farm systems. The project being undertaken by Manaaki Whenua will update the soils in S-map using modern methodology and more accurate measurements. The due date for the project to be completed and S-map updated will be spring of 2024. Once this has been completed, there is a need to carry out work to help understand the implications of the changed soil parameters on the nitrogen discharge allocations and how this may affect individual farms within the catchment.

2. Assess new climate data and effects on nitrogen allocations.

   The climate data in OverseerFM uses 30-year averages from NIWA and is updated every 10 years. The climate data set has recently been updated and the effect of this needs to be assessed in regard to benchmark, reference files and allocations.

3. Engage in new science to improve OverseerFM modelling in the Lake Rotorua catchment.

   Continue to identify opportunities to improve and support work that will increase knowledge of nutrient loss from farms in the Lake Rotorua catchment. For instance, the new initiative for Plantain Potency and Practice Programme – DairyNZ. Find references to recent research on the topic and a link to the DairyNZ website in the Reference section of this report.

4. Monitor and map gorse growth in the catchment area.

   Gorse mapping will be carried out once in the next five years before the next science review. This will be important to help monitor areas where gorse may be increasing so work with landowners can ensure it is controlled.

5. Conduct a physical assessment of the efficacy of wetlands for assisting towards the engineering nitrogen targets.

   Significant potential exists in using wetlands to remove nitrogen from groundwater and surface water before it enters the lake. A Toi Moana commissioned report identified suitable sites where wetlands could be constructed in the Lake Rotorua catchment. Progress the design and construction of at least one wetland within the catchment is expected. At that time monitoring will be undertaken to test the efficacy of the constructed wetland to remove nitrogen from water.

Module 8 - Phytoplankton nutrient limitation in Lake Rotorua

Background

The quantity and ratios of external and internal nutrient (nitrogen and phosphorus) loading to lakes can vary seasonally, which can drive changes in nutrient concentrations in the lake that promote algae growth. Understanding nutrient limitation, which occurs when additions of an essential nutrient in biologically available forms cause an increase in the rate of a biological process, is important to understand the response of Lake Rotorua to seasonal changes in external and internal loading.

Objectives

1. Determine the likely limiting macronutrient (nitrogen or phosphorus) or macronutrients (nitrogen and phosphorus) of the phytoplankton community assemblage in Lake Rotorua on a fortnightly basis over the spring-summer-autumn period.

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

3. Based on the findings of objectives 1 and 2 make recommendations as to the potential for adaptive alum dosing of inflows to Lake Rotorua in response to phosphorus limitation status.

Methodology

Phytoplankton growth assays were conducted a total of 16 times with water collected from Lake Rotorua between October 2020 to May 2021.

Key findings

Algae growth appeared to be nitrogen limited for most of the summer months (December–March) and nutrient co-limitation (nitrogen and phosphorus) during the spring and late autumn (Table 3). Only about two weeks of phosphorus limitation was observed during the study. One was associated with an intensive storm event in the Rotorua catchment at the end of March 2021. Because of the short periods of phosphorus limitation in Lake Rotorua during the study, optimisation of alum dose rates to take advantage of natural periods of phosphorus limitation in the lake is limited.

The author discussed that despite the observed improvements in Trophic Level Index in Lake Rotorua, likely due to the alum dosing and improvements in catchment management, cyanobacterial blooms are still likely to occur under favourable environmental conditions as the system remains within a eutrophic state. The data collected during this study support this conclusion, during which the author found that changes in phytoplankton community composition were more strongly driven by physical environmental factors such as temperature, light and wind speed rather than nutrient availability.

Table 3: Summarised results from 16 nutrient limitation assays conducted fortnightly from October 2020 to May 2021. Results include ratio of total nitrogen to total phosphorus, chlorophyll *a* concentration, phytoplankton biovolume and net phytoplankton growth. *Indicates a nutrient limitation was present but the difference was not statistically significant (Table reproduced from Tempero 2022).

Assay date	Surface mass TN:TP	Mass TN:TP	Chlorophyll *a*	Phytoplankton Biovolume	Net biomass growth
19 October 2020	8.42	Co-limitation	Simultaneous co-limitation	P limitation	P limitation*
1 November 2020	7.33	Co-limitation	Simultaneous co-limitation	Simultaneous co-limitation*	Inconclusive
16 November 2020	21.67	P limitation	Simultaneous co-limitation	Inconclusive	Inconclusive
29 November 2020	10.95	Co-limitation	Serial N limitation	Simultaneous co-limitation	No limitation
13 December 2020	23.85	P limitation	Serial N limitation	Serial N limitation*	No limitation
5 January 2021	7.62	Co-limitation	Serial N limitation	Serial N limitation	N limitation
18 January 2021	8.33	Co-limitation	Serial N limitation	Independent co-limitation	N limitation
2 February 2021	8.80	Co-limitation	Serial N limitation	Serial N limitation	N limitation
14 February 2021	8.75	Co-limitation	Serial N limitation	Serial N limitation	Serial N limitation
1 March 2021	4.33	N limitation	Serial N limitation	N limitation	N limitation
14 March 2021	4.62	N limitation	N limitation	Serial N limitation	Inconclusive
28 March 2021	7.69	Co-limitation	N limitation	N limitation	N limitation
9 April 2021	11.39	Co-limitation	Serial P limitation	P limitation	P limitation*
26 April 2021	6.76	N limitation	N limitation	Simultaneous co-limitation	Simultaneous co-limitation*
9 May 2021	17.10	P limitation	Independent co-limitation*	Independent co-limitation	Independent co-limitation*
23 May 2021	5.93	N limitation	Inconclusive	Inconclusive	P limitation*

Recommendations

1. The effectiveness of alum dosing on lake internal P-loading remains an open question. Quantification of lake-wide sediment P release rates would assist in determining whether declines in lake DRP are due to sequestration of P or a natural decline in the sediment P pool from reduced catchment loading.

2. Phosphorus limitation during the winter-early spring may occur and further nutrient limitation assays conducted at sub-monthly intervals would help to determine whether optimisation of alum dosing is possible for this period. Such fine-scale temporal resolution would be required in order to differentiate the effects of environmental perturbance on nutrient availability.

3. Current nutrient monitoring systems do not have the required resolution to provide guidance regarding nutrient availability in Lake Rotorua. In addition, simple TN:TP ratios are not reliable indicators of phytoplankton nutrient requirements. Further investment into the development of environmental forecasting systems such as hydro-dynamic models and real-time nutrient monitoring may provide the temporal resolution to achieve adaptive management of dosing within the Rotorua alum dosing programme.

Module 9 - Toxicological effects of aluminium in relation to diel pH changes on fish and kōura

Background

Since 2006, alum (aluminium sulphate; Al2(SO4)3) has been applied to the Utuhina and Puarenga Streams at a targeted dose rate of 1 mg Al/L to control phosphorus loading to Lake Rotorua. This module is addressing an important knowledge gap related to toxicological impacts of aluminium during transient exposure of aquatic organisms to alkaline pH. Under typical conditions, the pH of Lake Rotorua is near pH 7, but due to its limited buffering capacity may reach pH 10 during intensive algal blooms. These diel increases in pH have the potential to create conditions that increase toxicity of aluminium to aquatic organisms.

Objectives

This report examines the cumulative impacts of transient alkaline pH (7–10) and aluminium (2 mg L-1) on rainbow trout, common bully, and kōura.

Methodology

Osmotic (the maintenance of ion concentrations within the body) and haematological (blood analysis to understand organism health) disruption were tested in rainbow trout and kōura in response to exposure to 2 mg Al/L aluminium and cyclic pH (7-10-7) under laboratory conditions over 10 days. Toxicity tests were conducted in four 60 L flow-through glass tanks, divided into two control and two treatment tanks, each containing three test subjects using a variety of osmotic and haematological indicators.

Key findings

Cyclic changes in pH driven by algal blooms in combination with current alum dosing levels are highly unlikely to result in acute osmoregulatory impacts on common fish and macroinvertebrate species in Lake Rotorua. There were no significant impacts on metabolic oxygen consumption under similar exposure conditions. There was some evidence that extended exposure to 2 mg Al/L may damage gill tissue from particulate aluminium, with kōura being more susceptible than rainbow trout.

Overall, it was concluded that diel pH cycling and exposure to 2 mg Al L-1 were unlikely to significantly impact osmoregulatory function in rainbow trout and kōura in Lake Rotorua.

Recommendations

The tests in this report were carried out with relatively mobile species with the ability to ‘escape’ stressful environmental conditions. Furthermore, some results indicated that kōura gills may be more susceptible to erosional damage from precipitated aluminium hydroxide. These discussion points lead to two recommendations for further work:

1. Further investigation of aluminium exposure on more susceptible and less mobile life stages (i.e., larval rainbow trout) which would help to define potential impacts and species tolerances.

2. Further testing of potential impacts on gill tissues from particulate aluminium is recommended, particularly with regard to kōura.

Module 10 - Review of existing and new methods of in-lake remediation

Background

This report includes recent technological advances in the restoration of eutrophic lakes as well as summarising the material from Module 12 of the Science Review 2017. Many of the newer methods are experimental, so there may be limited evidence in terms of their efficacy, costs, and spatio-temporal coverage. Additionally, the report summarises recent approaches to in-lake ecosystem modelling to inform management for lake restoration.

Objectives

The aim of the present report is to provide a brief update of the extensive review in 2019, and to target specific emerging issues in lake management and examine their applicability and relevance to Lake Rotorua, rather than directly repeating material from the earlier review. The updated review includes considerations of scalability to Lake Rotorua, commercial elements (e.g., costs), and the risks of new technologies.

Methodology

Systematic literature review on the topics of lake restoration, climate change effects on lake ecosystems, and monitoring and modelling to inform management for lake restoration

Key findings

Many novel lake remediation technologies fail to progress beyond laboratory scale and there is not adequate investment by the product company to provide an evidence base to warrant their consideration. Some new methods are also limited by their secondary effects, such as pollution, increased nutrient content, ecotoxicological effects, cultural concerns, and cost. Selecting a combination of methods (ideally to provide synergistic effects) can be more effective in combating eutrophication and cyanobacterial blooms.

The Bay of Plenty Regional Council lake monitoring programme provides excellent data to support detailed evaluations of the effect of mitigation actions for lake water quality, including 'State of the Environment' monitoring to provide long-term time series data at central lake stations, high-frequency sensor monitoring from central lake buoys, and monitoring targeted specifically at identifying change from lake mitigation actions. This report highlights the need to address the impacts of climate change and understand transitions (or pathways) leading to the degradation of the lake ecosystems, thereby exerting pre-emptive actions to avert or slow the degradation.

Climate change is likely to increase the risk of degradation of lake ecosystems. Under such scenarios, applying a single technique to control lake eutrophication and cyanobacterial blooms may not be adequate to restore the lake ecosystem to a desired state. Long-term planning is needed to integrate catchment controls on nutrient loads with specific in-lake nutrient control measures.

Recommendations

The authors included recommendations throughout the report:

1. Investigate harmonisation of high-frequency sensor data and satellite data, as well integrating the monthly state of the environment data to improve understanding of lake response to specific mitigation actions.

2. Improve predictions related to stratification, deoxygenation and harmful algal blooms to inform lake restoration and management to counter these occurrences.

3. Improve modelling techniques to integrate anthropogenic and climatic stressors, as well as the responses to the restoration measures.

4. Explore the use of hyporheic restoration and pre-capture techniques to understand their effectiveness against nutrient enrichment.

5. Test other restoration techniques to develop multiple pieces of evidence about the effectiveness of these methods in Lake Rotorua.

Module 11 - Impact of Plan Change 10 on rural land values within the Rotorua lake catchment

Background

Bay of Plenty Regional Council on behalf of the stakeholders have requested an update on previous reports that focused on the economic impacts on farming and/or property values following the introduction of nutrient regulation in the form of Rule 11 for the Lake Rotorua catchment.

Objectives

This report seeks to identify the economic impact (if any) of Plan Change 10 on Land Values within the Lake Rotorua catchment. The report also discusses changes in market conditions and government policies affecting land values and land use change in the Lake Rotorua catchment.

Methodology

The methodology used the following analysis:

- Sales (property search, numbers of farm blocks 40+ hectares sold in Rotorua District, apportion in/out catchment, collate sales per annum 2005-2021 for each category, report sales activities in/out of Lake Rotorua catchment)
- Values / Rural land (Individual analysis of sales 2005-2021 to land value per hectare - pastoral and dairy farms 40+ hectares, analysis of before and after land values for farms that have engaged in sale of N to incentive board)
- Lifestyle land value drivers (Median value differential in/out of catchment over relevant period and analysis of value drivers, impact of Plan Change 10)
- Nature and source of information relied upon

Key findings

Sales data does not show any discernible negative impact from the introduction of Plan Change 10 which was notified in 2017, rather the certainty/incentives provided by the regulatory framework may have in certain instances underpinned value.

The effect of Plan Change 10 on rural land values is largely dependent on individual property characteristics and as such can be positive and negative.

Land use change incentives and additional economic factors such as a buoyant lifestyle market and demand from forestry/carbon market have softened any negative effect of Plan Change 10 on land values within the catchment. The value of New Zealand Carbon Units is now an overriding value consideration for lesser contour pastoral blocks, irrespective of any nitrogen allocation.

Some market participants and landowners have taken advantage of the incentives to activate land use change. The ability to sell supply nitrogen and/or obtain additional development rights is not fundamental to value considerations.

Introduction of environmental regulations by central government has resulted in similar restrictions on rural land use nationwide which now dilutes any negative perceptions specific to Lake Rotorua.

Recommendations

No specific recommendations have been made.

Science Review module references

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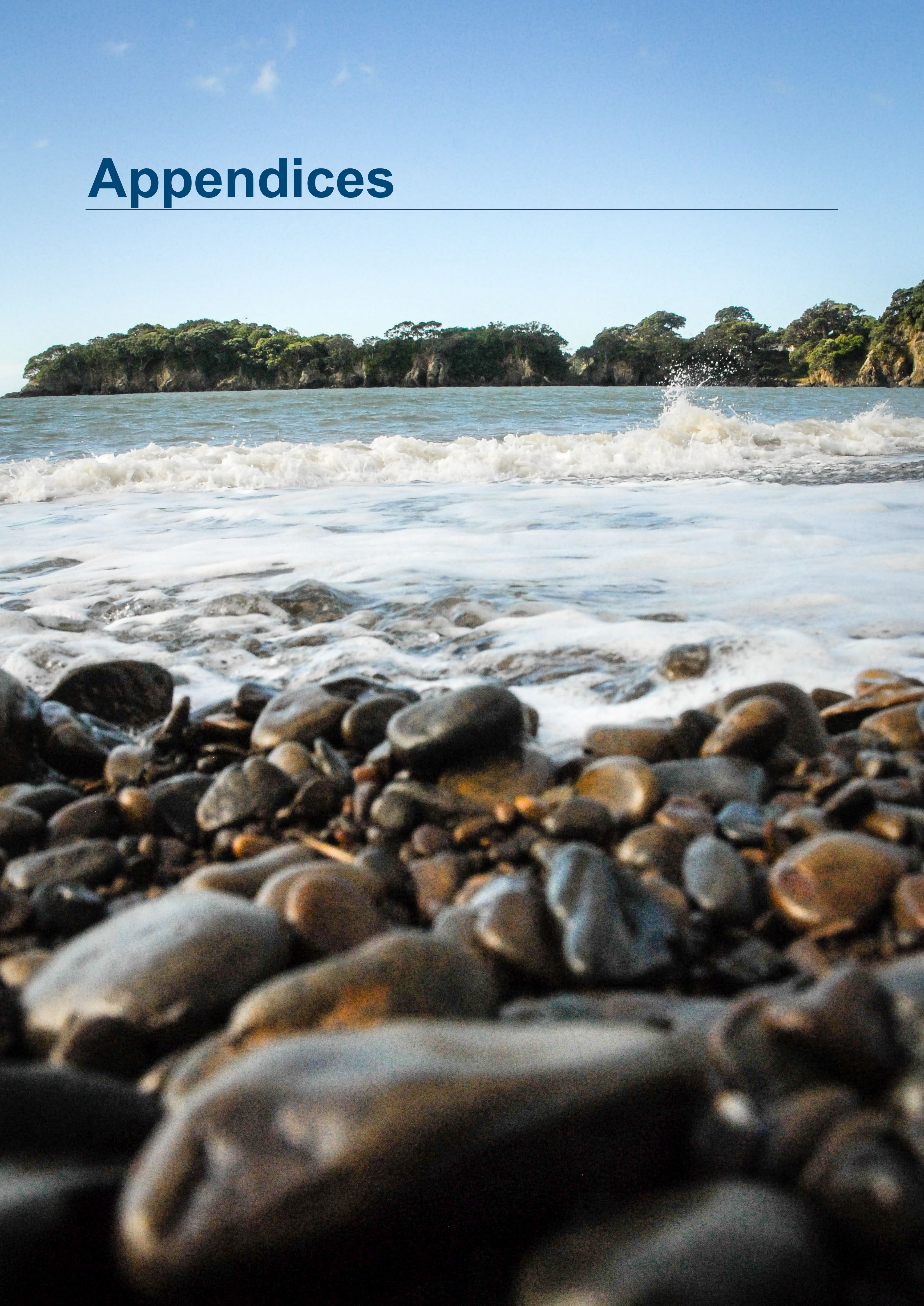
Appendices



Appendix 1: **Overview of Science Review 2022 recommendations**

Module	Recommendation	Comment	Priority
2	Further consider the analysis of interannual variability and trends in context of statistical trends (10-20 year) versus statistical analysis of 5-year time periods.	Ongoing discussion point pertaining to Lake Rotorua amongst WQTAG members include	High
2	Reduce influence of interannual variability by using a tolerance before triggering management action; e.g., no tolerance vs tolerance of 0.2 TLI before triggering action.	Ongoing discussion point pertaining to Lake Rotorua amongst WQTAG members include	High
3	Estimate the total internal load by assessing daily hypolimnion volume against the average rate of concentration increase as identified in this report.	General suggestions on improving on the current approach	High
3	Apply biogeochemical modelling to fill the (relatively fewer) gaps in the dissolved oxygen record of the lake buoy in the same fashion as the hydrodynamic model was used in the report for filling gaps in the temperature record.	General suggestions on improving on the current approach	Medium
3	Maintain high-frequency monitoring as an essential approach to understanding Lake Rotorua dynamics, with targeted water chemistry sampling over the duration of stratification events.	General suggestions on improving on the current approach	High
4	Improve the current recreational cyanobacterial monitoring programme, including by: • incorporating new technologies such as field-portable fluorometers that could be used on the lakeshore to measure phycocyanin, • continuing training procedures for microscopy analyses to reduce inconsistencies between taxonomists, • implementing an inter-laboratory comparison as part of their annual quality control process.		Medium
4	Incorporate cyanotoxin analysis into the recreational cyanobacterial monitoring programme by including cyanotoxin gene and chemical analyses into the cyanobacterial recreational monitoring programme.		Medium
4	Develop a robust algal monitoring programme for a selection of lakes in the Rotorua region that would allow long-term patterns in all algae to be assessed, not just cyanobacteria.		Medium
4	Analyse high frequency data and explore drivers of change and to gain further insights into cyanobacterial dynamics in these lakes.		Medium
6	Review and update the aluminium budget for Lake Rotorua to reassess observed relationships between dose rates and in-lake water quality. Improve understanding about the capacity to manage water quality with alum dosing, and the relative importance of internal and external loading.		High
7	Assess the impact of updated S-map data on nitrogen allocations.		High
7	Assess new climate data and effects on nitrogen allocations.		Medium

7	Engage in new science to improve OverseerFM modelling in the Lake Rotorua catchment.		*
7	Monitor and map gorse growth in the catchment area.		High
7	Conduct a physical assessment of the efficacy of wetlands for assisting towards the engineering nitrogen targets.		Medium
8	Quantify of lake-wide sediment P release rates. This would assist in determining whether declines in lake DRP are due to sequestration of P or a natural decline in the sediment P pool from reduced catchment loading.		High
8	Conduct nutrient limitation assays at sub-monthly intervals, to help determine whether optimisation of alum dosing is possible for specific periods (e.g., winter-early spring).		Low
8	Continue to improve environmental forecasting systems such as hydro-dynamic models and real-time nutrient monitoring, to optimize the Rotorua alum dosing programme.		Medium
9	Investigate the effects of aluminium exposure on more susceptible and less mobile life stages (e.g., larval rainbow trout).		Low
9	Conduct further tests of potential impacts on gill tissues from particulate aluminium, particularly with regard to kōura.		Medium
10	Investigate harmonisation of high-frequency sensor data and satellite data, as well integrating the monthly state of the environment data to improve understanding of lake response to specific mitigation actions.		Low
10	Improve predictions related to stratification, deoxygenation and harmful algal blooms to inform lake restoration and management to counter these occurrences.		Medium
10	Improve modelling techniques to integrate anthropogenic and climatic stressors, as well as the responses to the restoration measures.		Medium
10	Explore the use of hyporheic (stream based) restoration and pre-capture techniques to understand their effectiveness against nutrient enrichment.		Medium
10	Test other restoration techniques to develop multiple pieces of evidence about the effectiveness of these methods in Lake Rotorua.		Low

* Further discussions required, including appraisal of ongoing improvements and clarification of OverseerFM at a national level.

Note: Science investigation projects can require considerable investment in expertise and funding. Consequently, the priorities against each recommendation in the table have been set high, medium, or low in accordance with perceived value from investing in each project. In general, it is expected that high priority recommendations will be undertaken before the next 5-year review. Medium and low priority recommendations will be addressed where suitable funding and expertise becomes available.