Review of relevant New Zealand and international lake water quality remediation science

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For:

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1. Executive Summary

The Australian Rivers Institute was commissioned by Bay of Plenty Regional Council 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 the Plan Change 10 Lake Science Review.

Implementation of lake remediation actions is usually costly and requires underpinning scientific information derived from a routine lake monitoring programme as well as a programme of monitoring that may need to be set up specifically to examine the before and after effects of remediation and any possible ecotoxicological 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 Trophic Level Index target of 4.2) based on a current climate.

This review included considerations of: hydraulic flushing for direct algal control; inflow diversion; phosphorus locking (geoengineering); sediment capping; ultrasound and hydrogen peroxide to preferentially remove blue-green algae (cyanobacteria); booms to remove cyanobacteria blooms; harvesting phytoplankton by filtration; surface mixers, aerators, artificial destratification and oxygenation; floating wetlands; hypolimnetic siphoning; microbial control; biomanipulation and macrophyte harvesting. 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 methods do not merit further consideration given the evidence to date that that they have limited success for phytoplankton control (including cyanobacteria) and could potentially interfere with aquatic food webs.

A number of lake remediation techniques involving physical modifications – hypolimnetic siphoning, inflow diversion, sediment capping, flushing, filtration, and oxygenation or artificial destratification – are unlikely to be viable or effective for shallow Lake Rotorua.

Of the lake remediation methods that are considered to potentially be feasible for Lake Rotorua, lake geoengineering addresses 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.

Geoengineering using alum dosing has been extremely successful in managing external and internal nutrient loads in Lake Rotorua. A more concerted effort to explore alternative options is required, however, because of uncertainties in obtaining future resource consents and the potential for unforeseen ecotoxicological events or floc accumulations, both of which appear to have been monitored and well managed to this point in time. Costs may be prohibitive for the use of alternate commercial geoengineering materials, while others such as the introduction of sediments modified with oxygen nanobubbles would require a concerted effort to translate promising results in the laboratory and upscale to the whole lake.

As there is no obvious and similarly cost-effective alternative to alum dosing, reductions in catchment nutrient loads are essential. The marked improvements in water quality of Lake Rotorua over the past decade are strongly linked to alum dosing (i.e., lake geoengineering), which appears to have offset some of the urgency to meet the sustainable catchment nutrient loads prescribed in Plan Change 10.

2. Project Brief

Nutrient management in the Lake Rotorua catchment is subject to 'Proposed Plan Change 10' (PPC10) as well as a long-running programme of interventions and science investigations. The PPC10 includes provision for reviewing the science, as detailed in Method LR M2 of the Lake Rotorua Nutrient Management provisions. It specifically requires the following (as clause M2(d)):
Review of New Zealand and international lake water quality remediation science.

The brief for this work is to include lake interventions and restoration techniques that may be suitable for Lake Rotorua. This work will include the potential for climate change effects, changes in nutrient targets through time, techniques to eliminate, replace or augment alum and any other relevant in-lake or catchment-based methods to improve water quality. The review will attempt to update relevant literature and to offer opinion on the efficacy and scale of interventions, product/technique safety, as well as the commercial application and viability of different methods. Where possible relevant costs will be provided. The review will provide an update of the recent NIWA review (Gibbs 2015) of management and restoration options pertaining to all of the Rotorua/Te Arawa lakes.

Examples of remediation topics that will be covered include:

- A context for restoration
- The role of catchment processes and modelling
- The role of lake processes and modelling
- Lake and catchment monitoring
- Artificial destratification
- Oxygenation
- Effects and control of invasive macrophytes
- Relevance of wastewater treatment
- Floating and land-based wetlands
- Geoengineering
- Biological control (including potential for zooplankton and grass carp to control algae)
- Algaecides, ultrasound, hydrogen peroxide and various other agents that may acct directly on algae
- Dredging

The review synthesises information from a number of sources. It does not include detailed information about the socio-economic factors that are required for a successful lake restoration program. Mueller et al. (2015) provide a perspective on this topic and identify significant ecosystem service benefits from maintaining Lake Rotorua in good health, as well as identifying some of the consequences of environmental decision making and delayed decision making that make restoration more problematic. The current report includes an executive summary and commentary on any specific lake remediation methods that warrant further investigation in the context of Lake Rotorua.

3. Context for restoration

3.1 Introduction

Lake Rotorua has a long history of eutrophication, spanning some decades. Consequently, PPC10 requires that a sustainable load of 435 tonnes of nitrogen per annum (t N y^{-1}) is achieved to support a target water quality for the lake, identified as a Trophic Level Index (TLI) value of 4.2. A catchment load of 37 t P y^{-1} has also been identified to support the TLI 4.2 target, as part of the review of Policy WL 3B(c) of the Regional Policy Statement. The current Science Review also takes into consideration what combination of nitrogen and phosphorus catchment loads might be required to achieve the TLI of 4.2. The sustainable lake nutrient loads are also aligned with the implementation by the Bay of Plenty Regional Council of the National Policy Statement for Freshwater Management (MfE 2014). In addition to these identified targets, adaptive management is recognised as a core element of the implementation of nutrient management for Lake Rotorua.

As part of the Science Review in PPC10, Stephens et al. (2018) have examined water quality trends in Lake Rotorua from 2001 to 2017. The focus has been on the TLI and its constituents (total nitrogen, total phosphorus, chlorophyll *a* and Secchi depth). The TLI and each of its constituents show an improving trend which is generally most pronounced from about 2009 to 2017. Alum dosing with aluminium sulphate has been carried out in the Utuhina Stream (from 2006) and Puarenga Stream (from 2010). Evidence has continued to build (e.g., Smith et al. 2016) that the dosing has markedly improved the TLI and each of its constituents. Tempero (2015a, 2018) provides a review of the potential eco-toxicological effects of alum dosing. Evidence of improvements arising from alum is reinforced by reports that are part of the Science Review for PPC10 (Dare 2018; McBride et al. 2018a, 2018b) which have examined trends in nutrient concentrations measured in tributaries for over multiple years extending back for some decades in some cases. These reports indicate that it is highly unlikely that improvements in water quality of Lake Rotorua were due to a reduction in nutrient loads; statistical analysis generally indicated that at most sites deterioration (increases) in total nitrogen concentrations in inflows dominates over improvements, and that phosphorus (total and dissolved forms) has deteriorated (increased) more rapidly than nitrogen.

Restoration has been defined by the Society for Ecological Restoration (2004) as "The process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed".

This statement is taken to mean that it is possible to manage, engineer or otherwise manipulate a lake and its catchment in order to achieve a desired endpoint. The definition of the endpoint is critical and needs to be clearly specified so that it is possible to judge the success (or otherwise) of the restoration actions. In the case of Lake Rotorua the endpoint is taken to be the water quality of the lake in the late 1960s and specifically the attainment of a TLI of 4.2. This TLI value corresponds to the 'sustainable catchment nutrient load' but without the alum dosing that is currently used to manage nutrient levels and eutrophication of the lake. The TLI in this case is used as a proxy for lake water quality, biodiversity and community values and aspirations (see Quinn 2009).

Moss (2018) makes some observations about restoration of aquatic systems that are pertinent to the current report:
"The results of many projects have been disappointing, especially in terms of increase in biodiversity. Most have been adequate in terms of re-creation of geomorphological features or improvement of appearance, but in many, conditions have reverted, and most have not been properly monitored … Success is often assumed; awards are given; but the ecological gain is doubtful…often only one, particularly phosphorus concentration or physical reconstruction, of several mutual impacts, is tackled; the land use of the catchment is largely unaltered and the aspirations of the project are subject to political limitations".

This critical review by Moss highlights several features of a restoration programme that need to be carefully considered. An effective restoration programme needs to include:

- Monitoring that is adequate to support assessments of the success of lake restoration actions.
- Actions of sufficient scale that contribute towards the outcomes and are an efficient use of funds and resources.
- Adaptive management that provides opportunities to tackle multiple issues beyond the one of immediate concern (e.g., a single limiting nutrient).
- Catchment land use change as an integral consideration of any lake management strategy.

3.2 Lake and catchment monitoring

In the same chapter as Moss' synopsis, Zohary (2018) outlines the importance of a monitoring programme to support lake restoration efforts:

"Expensive operations are usually required, but not always do these operations lead to the expected outcome: at times lake restoration efforts result in only partial success, or no positive outcome at all. Some lakes undergo restoration at huge expense, but no money is set aside to initiate and maintain a long-term monitoring program to follow up the outcome. With little or no background or follow-up data, it is practically impossible to assess restoration success in objective terms. In cases of only partial or no success, lack of data will make it extremely difficult to decide whether further steps are required and if so, which should be undertaken."

From the above, it may be surmised that the critical aspects of a lake restoration programme extend beyond implementation of a specific action, and include:

- A sound scientific understanding of lake science, the complexities of lake behaviour and the lag times in lake responses that will vary across individual lakes.
- A clear definition of the end point (i.e., a successful restoration programme) which in some cases may be specific to the group concerned (e.g., the regional council, community group, tangata whenua).

- Avoiding a single objective approach because stressors, knowledge and techniques may change through time (e.g., in response to stressors like invasive species or climate change). The ability to adaptively manage the lake ecosystem alongside policy implementation is therefore important.
- Investment in a monitoring programme that will clearly identify the restoration end point and the trajectory towards that end point.

Lake monitoring generally fits within a broad programme of assessment that may be required for State of the Environment reporting (e.g., related to the Regional Policy Statement or the NPS-FM), detection of environmental trends (e.g., to support identification of long-term environmental change including responses global warming), as well as evaluating the effectiveness of restoration actions and the worthiness of such investments.

Monitoring programmes are increasingly required to be flexible to accommodate advances in monitoring hardware and processing, whilst not disrupting long-term programmes designed to detect trends and provide State of the Environment programmes. Examples of advances in monitoring hardware and processing include:

- Lake monitoring buoys. These buoys provided high-frequency (15-min) data on multiple variables such as water temperature, turbidity, dissolved oxygen, chlorophyll fluorescence, phycocyanin and underwater light. Many monitoring buoys are also equipped with sensors to monitor meteorological variables (e.g., wind speed, air temperature, humidity, light). In the Rotorua/Te Arawa lakes, monitoring buoys have been successfully integrated with the routine monitoring programme and have proven to be particularly useful for polymictic lakes (e.g., Rotorua, Rotoehu, Rerewhakaaitu) to monitor rapid changes (e.g., deoxygenation events) that may take place within the time span of the routine monitoring (i.e., < 1 month). See McBride and Rose (2018) for a detailed evaluation of high frequency monitoring.
- Remote sensing. Allan et al. (2011, 2015) have used Landsat images to inform on the variability of optically active constituents of water, including temperature and chlorophyll. See Allan and McBride (2018) for a comprehensive evaluation of remote sensing applications for lakes.

A National Environmental Monitoring Standard (NEMS) – Water Quality is about to be released by the Ministry for the Environment. This report will provide valuable guidance about establishing and maintaining long-term lake monitoring programmes and how to integrate new methods with established ones, including the need for overlap between the two. The latter issue pertains also to overlap of laboratories that process water samples. The lack of overlap has been particularly problematic for the Rotorua/Te Arawa lakes' nutrient monitoring programme where step changes in nutrient concentrations have been reported and appear to be related to changes in the laboratory processing the samples. Any such future changes of laboratory require *a priori* quality assurance, with suitable overlap of common samples.

3.3 Lake and catchment modelling

Monitoring can also provide input data for models. Models have been shown to be useful for allowing different management scenarios to be simulated for Lake Rotorua (e.g., Abell et al. 2015) as a prerequisite for justifying the high costs of investing in a specific management action (Hamilton et al. 2014). For Lake Rotorua, lake and catchment models have been used (Fig. 1) in conjunction with measurements to provide information about:

- Effect of different farming practices on nutrient losses from farmland using OVERSEER (Park et al. 2014).
- Time scales of delivery of groundwater to Lake Rotorua from different sub-catchments (Morgenstern et al. 2015).
- Time scales on which catchment nutrient loads to Lake Rotorua will largely equilibrate to changes in land use, using ROTAN (Rutherford 2008)
- Catchment nutrient loads required to achieve the TLI of 4.2 using DYRESM-CAEDYM (Hamilton et al. 2015).
- Lake responses (e.g., TLI variations) to climate change using DYRESM-CAEDYM (Hamilton et al. 2012).
- Lake responses to different treatment options by the Rotorua Lakes Council for their Wastewater Treatment Plant operations (Abell et al. 2015). Rotorua Lakes Council is proposing to stop operating its current treated wastewater disposal site in the Whakarewarewa forest. Instead it proposes to upgrade the level of treatment at the wastewater treatment plant and to discharge wastewater to a thermal stream near the edge of the lake. Such a change will be evaluated carefully for a number of reasons including meeting the consent conditions for discharge of nitrogen and phosphorus to the lake.

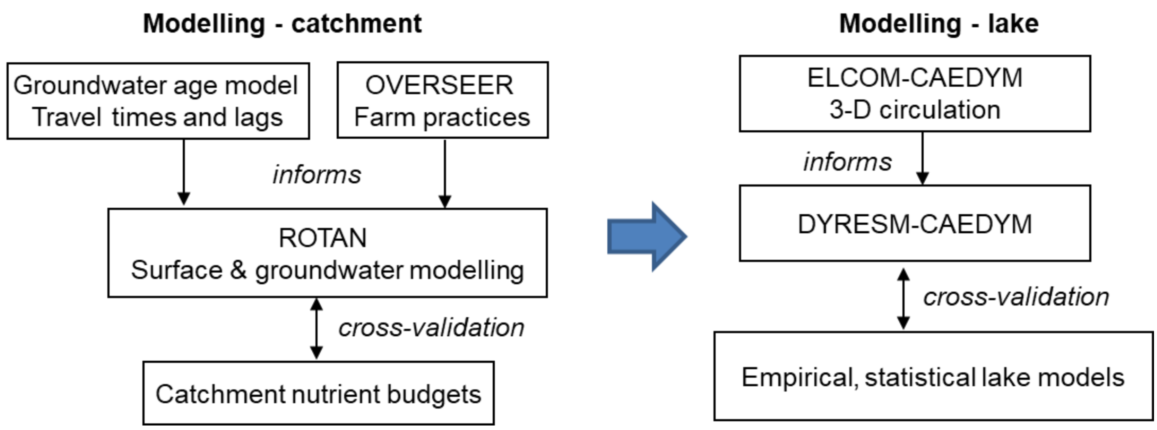

Figure 1. Linked models applied for the case to evaluate sustainable loads of nitrogen required to reach a TLI target of 4.2 for Lake Rotorua.

The models applied to Lake Rotorua and its catchment have been a critical resource for informing PPC10 and will need to continue to be integrated into assessments of restoration actions, including evaluation of how different combinations of nitrogen and phosphorus loads will affect the TLI.

Environmental model applications are increasingly used to guide decision making. These models can take a variety of forms: statistical, biophysical (or mechanistic), Bayesian, Neural Networks, etc. Most of the models applied to the Rotorua lakes and their catchments have been process based (i.e., biophysical) in that they attempt to capture relevant physical processes (in the case of water quantity or transport) and in some cases are combined with biogeochemical processes (e.g., in a lake model such as DYRESM-CAEDYM or ELCOM-CAEDYM; Abell and Hamilton 2014). In some cases there may be a combination of models applied such as using Bayesian techniques to inform values of parameters for a biophysical model.

The process-based nature of biophysical models is useful for exploratory cases, i.e., to generate scenarios that may allow different management regimes to be explored. Multiple models can also be used where these models are coupled (e.g., the ROTAN model output for catchment nitrogen loads can be used as input for DYRESM-CAEDYM lake simulations) or are used to better understand the error and probability of different simulated outcomes. The latter approach may involve ensemble modelling. Increasingly, combinations of models are being used to understand the complex relationships amongst biophysical, economic, social and cultural aspects of the environment (e.g., where a biophysical model is then coupled with an economic model).

Model applications are often extremely valuable because they necessitate a high level of interrogation and questioning of measured data. This can be time consuming but often leads to improvements in the quality of the data that are subsequently collected. Sensitivity analysis is also a valuable means of evaluating whether it is worth collecting data and what additional monitoring data would be most useful.

As indicated above, a variety of models has been used for the Lake Rotorua catchment and for many other catchments in New Zealand. These models vary in a number of key aspects that are critical for developing 'trust' in the simulation output. These aspects include:

- The level of model documentation, including user manuals, justification of science algorithms and the extent of publication in peer reviewed literature.
- The availability of executable and source code, as well as the willingness of the model developers to engage with users of the code and to adapt processes relevant to these users.
- The ability to engage broader cross-sections of modelling communities to contribute knowledge for model algorithm development and testing of the model.
- The level of error analysis and comparison with measured data.
- The continuity of model applications and data generated from the models. In many cases there can be a considerable amount of 'reinventing the wheel' when model

and data repositories are inadequate and institutional knowledge is not adequately transferred.

In view of the above, it is important that model ownership and rights are clearly specified in relation to model executable and source code, as well as input and output data, including suitable repositories for models and data.

3.4 Climate change

Increases in concentrations of atmospheric carbon dioxide (CO_2) attributable to human activities are almost certainly responsible for global climate change. The future climate will manifest as rising air temperature and alterations in the timing and distribution of rainfall. Climate models project increases in air temperature of 0.7 to 3.7°C by 2110 as a result of increasing atmospheric CO_2 concentrations. The range given above represents model outputs from four different CO_2 emission pathways taken given in the Intergovernmental Panel on Climate Change Fifth Assessment report. The scale of these changes should necessitate that their impacts are included in PPC10 and that these plans be anticipatory, particularly in examining requirements to meet the TLI target of 4.2 for Lake Rotorua. Following from Jeppesen et al. (2009) who noted that greater efforts will be required to achieve lake water quality targets under climate change, 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."

Climate change is likely to alter the seasonality of rainfall by reinforcing wet seasons (winter-spring) and dry seasons (summer-autumn). There is also likely to be increased frequency of extreme (e.g., 1-in-100 year return period) rainfall events. The frequency of large-scale climate oscillations like the El Niño-Southern Oscillation (ENSO) may also be altered by climate warming. With greater seasonality of rainfall, the hydrology will be affected and there may be more floods in the Lake Rotorua catchment. Floods are likely to be most damaging when short-term (hour-to-day) extreme rainfall events are interspersed with more prolonged rainfall, leading to saturated soil conditions. These events occur in a setting of different phases of the Interdecadal Pacific Oscillation (IPO) and ENSO. For example, coincidence of the La Niña phase of the ESNO, a negative phase of the IPO, and cyclones could lead to extreme storms. Increased flooding risk could affect Lake Rotorua through inundation of low-lying built infrastructure, and damage to green infrastructure (e.g., riparian areas, wetlands and detention bunds) that is designed for environmental protection.

Floods increase sediment erosion and losses of particulate phosphorus. Their effect on nitrogen delivery is more variable but increased losses are also expected. Complicating factors relate to interactions of plant growth and microbial activities, and include: how additional atmospheric CO_2 stimulates plant production and nutrient uptake; increased plant growth and microbial degradation and transformation rates from rises in temperature; and interactions of temperature with dissolved organic carbon delivery. 'Brownification' of lakes is now widely recognised as being linked to global change as lakes in the northern hemisphere recover from acidification of the 1970s and 80s, but it has also been linked to increased delivery of terrigenous coloured dissolved organic carbon (CDOM) by storm runoff and shorter lake residence times under a changing climate. One of the effects of brownification has been to amplify stratification and oxygen losses in bottom waters (Williamson et al. 2015) while phytoplankton cells may be increasingly shaded against damaging UVR (Vincent 2009). These effects are complex and some potentially act antagonistically, but it is still widely recognised that a warming climate will lead to greater lake eutrophication. Most of the Rotorua lakes have relatively low levels of CDOM so impacts of climate change on this parameter may be small.

Climate change is likely to increase eutrophication (Paerl et al. 2011; Moss et al. 2011). The effects of climate change on Lake Rotorua may be through three main factors: (1) increased lake surface water temperature, (2) greater vertical stratification and (3) changes in rainfall intensity and frequency. The shallow polymictic nature of the lake makes it vulnerable because of increases in the duration of deoxygenation of bottom waters, leading to nutrient enrichment from increased releases from bottom sediments and stimulations of algal growth (Özkundakci et al. 2012). Cyanobacteria (blue-green algae) have a number of physiological adaptations that provide them with a competitive advantage over other phytoplankton in a warming climate (Carey et al. 2012). For a given nutrient concentration it is likely that there will be increased incidence of blooms and toxin production by cyanobacteria as growth rates of cyanobacteria tend to be optimal at higher temperatures than most other phytoplankton (Wood et al. 2015). Warming of surface waters will intensify vertical stratification and increase the potential for buoyant cyanobacteria to accumulate at the water surface (Hamilton et al. 2013). The most recent modelling study of Lake Rotorua (Me et al. 2018) shows relatively small changes in hydrology and nutrients from the catchment in response to climate change scenarios (out to 2090) but major changes in lake water quality due primarily to extended periods of stratification, leading to increased anoxia of bottom waters and greater sediment nutrient fluxes. Changes in rainfall frequency and intensity may lead to more variable discharge and increased nutrient runoff overall, but impacts on lake water quality are not as great as changes in stratification.

Several noxious alien invasive species (catfish, certain weed species, mosquito fish) are native to sub-tropical and tropical regions, and risks of their spread and growth are more likely in a warming climate (Hamilton et al. 2013). Already there has been a major catfish incursion event in Lake Rotoiti which is connected to Lake Rotorua by the Ohau Channel. Increased surveillance, control and eradication efforts are likely to be necessary for these freshwater invaders. Conversely, habitat of trout may be diminished as trout prefer cooler waters and tend to migrate to coldwater spring-fed tributaries during summer.

Based on model simulations for Lake Rotorua (Hamilton et al. 2012), TLI values can be expected to increase by approximately 0.2 units by 2090, i.e., under PPC10 the TLI will be 4.4 and not 4.2 under the proposed nutrient loading in PPC10. Therefore mitigation actions that are the focus of this report are more likely to be required and catchment nutrient load targets may be conservative as they have been referenced against current climate and not some future climate.

3.5 General comments

Most catchment restoration actions represent long-term investments in the health of receiving waters and have been demonstrated to mitigate the degradation of water quality and eutrophication, including cyanobacteria blooms and toxicity (Hamilton et al. 2016a) and deoxygenation. Catchment-based actions, while being regarded as a proactive and preventative approach, may also potentially be deprioritised when there is a pressing and immediate problem with lake health or water quality (Hamilton et al. 2016a). The current report does not include specific details about catchment restoration actions, many of which are dealt with in the PPC10 Science Review:

1. Evaluation of potential engineering options for reduction of nitrogen inputs to Lake Rotorua (McQueen-Walton and Shaw (2017)). This report includes both in-lake and catchment restoration actions. The in-lake options are dealt with below, as part of the description of in-lake restoration strategies. The catchment restoration actions mentioned by McQueen-Walton and Shaw (2017) include:
    a. Removal/pumping of treated wastewater out of the catchment. This option was rejected as being culturally and/or politically untenable.
    b. A plant to remove 25 t TN y^{-1}. This plant was designed to carry out denitrification, but has now adopted a zeolite adsorption process to remove the nitrogen from geothermal sources in the Waiohewa Stream. This option may be expensive at full scale relative to other nitrogen removal methods (A. Bruere, Bay of Plenty Regional Council, pers. comm.). The initial nitrification (to convert ammonium to nitrate) and pH buffering steps are additional complicating factors.
    c. Protection, maintenance and enhancement of natural (land-based) wetlands. The authors reviewed a number of studies (e.g., Hamill et al. 2010) and found cases of >95% of removal of nitrogen from lake edge wetlands. There are 18 lake-margin wetlands of total area 417 ha, with 12 ha needing to be restored to achieve full nutrient removal functionality. Protection of existing functional wetlands is relatively cheap, being estimated at \$14 kg^{-1} N, while restoring the 12 ha would equate to \$60 kg^{-1} N (Hamill et al. 2010).
    d. Constructed wetlands. The authors reviewed the work of Hamill et al. (2010) who estimated that 145 ha of wetland could be constructed at a cost of \$79 kg^{-1} N removed, and removing 53.3 t N y^{-1}.
    e. Denitrification beds or carbon walls. These are a well proven technology but also reliant on careful positioning to intercept groundwater flow paths to ensure that there is not by-pass of the bed. The authors recommend placement of denitrification beds in a few key places to intercept discharges with high nitrate concentrations.
    f. Watercress beds. The authors recommend upscaling of small-scale trials and identify opportunities to remove considerable nitrogen in the Waingaehe Stream, but they also make a number of cautionary points including the seasonality of watercress growth (and nitrogen uptake) and the planning and earthworks that would be required.

g. Seepage (land-based) wetlands and grass hedges. Kovacova and White (2009) have identified a number of ephemeral streams and seeps that may be suitable as areas to attenuate nitrogen. Hamill et al. (2010) indicate that seepage wetlands would be a low-cost option for nitrogen removal.
h. Anionic Polyacrylamides (PAM) blocks to flocculate and sediment out suspended solids and particulate forms of nitrogen and phosphorus. These would be particularly suitable for use with detention bunds, which are further described in Hill (2018).
i. Removal of N-fixing plants from the catchment. Gorse, as an exotic invasive species, has been the focus of efforts to reduce nitrogen fixed by plants in the Rotorua catchment, but alders, wattles, lupins, and Scotch broom are also identified by McQueen-Walton and Shaw (2017) to be worthwhile as part of a wider N-fixing plant removal strategy.
j. McQueen-Walton and Shaw (2017) identify a number of other strategies for reduction of nitrogen inputs to Lake Rotorua. There appear to be good opportunities to intercept and treat urban stormwater before it enters the lake. Slowing pathways of stormwater close to its source could be inexpensive and highly effective.

2. A review of land-based phosphorus loss and mitigation strategies for the Lake Rotorua catchment (Hill 2018). This report deals specifically with agricultural areas to identify where phosphorus mitigation strategies should be focussed and the selection of suitable strategies. The report cites the work of Tempero et al. (2015a) who identified 23.4 t P y^{-1} arising from anthropogenic sources in the catchment, of which about 74% is in particulate phosphorus from. Phosphorus losses vary with land slope, soil type and geology, rainfall, vegetation cover, soil enrichment (phosphorus) concentration status and grazing animals present (type, size, density, etc.). Strategies to manage phosphorus losses may be at different scales and units related to, for example, phosphorus fertiliser and effluent management, grazing regimes, and establishment and management of riparian buffers. Models such as OVERSEER are a key part of the testing and costing of the different strategies. Hill (2018) makes a number of recommendations for reducing losses of phosphorus from agricultural landscapes and concludes that substantial reductions could be achieved via a combination of management strategies. Forestry and other land uses (e.g., horticulture) are not covered in any detail in this report but may require tailored strategies to reduce nutrient loss, particularly given the likelihood for land use change under PPC10 (such as increased forestry) and other pressures (e.g., climate change) that could drive changes in land use (e.g., horticulture with increased air temperature).

Hamilton and Dada (2016) summarised a number of in-lake strategies for managing nutrients and water quality in New Zealand lakes (Table 1). Several of these are directly applicable to Lake Rotorua or, as noted in the column 'relevance to Lake Rotorua' (Table 1), have already been applied to the lake. Others have been applied to other lakes in the Bay of Plenty Region.

Table 2. Lake restoration strategies and their general purpose, with commentary on the relevance of these strategies to Lake Rotorua.

Restoration strategy	Purpose	Relevance to Lake Rotorua
Weed harvesting	Removes nutrients assimilated in excess week growth	Has been used as a means to remove biomass and nutrients from smaller, but similarly shallow, Lake Rotoehu
Sediment capping	Provides a capping layer to decrease nutrient releases from lake bed sediments	Not actively practiced but may be an indirect outcome of alum dosing where there are areas of abundant floc
Wave barriers	Reduces resuspension of sediments and nutrients in shallow lakes through a physical barrier to reduce surface wave propagation	Considered for Lake Rotorua by Stephens et al. (2004), but not implemented
Floating wetlands	Wetland plants take up nutrients, nitrogen removed via denitrification	Implemented by Rotorua Lakes Council in 2012 (see Fig. 2)
Phosphorus inactivation or flocculation	Uses chemicals (e.g., aluminium sulphate) to 'lock up' phosphorus via adsorption and precipitation	Aluminium sulphate (alum) dosed to Utuhina Stream (from 2006) and Puarenga Stream (from 2010)
Oxygenation, destratification or mixing propellers	Redistributes oxygen/air to the bottom of lakes to decrease redox-mediated nutrient releases	Simulations of destratification and pumped water systems have been examined with a lake model for Lake Rotorua
Inflow diversion	Removes nutrient loads from a lake	Implemented to divert Lake Rotorua outflow away from Lake Rotoiti via the Rotoiti outflow (Fig. 3). Simulations of diversion of Hamurana inflow to Lake Rotorua carried out with a lake model and examined by Gibbs et al. (2007)

Figure 2. Photo of Sulphur Point area of Lake Rotorua (looking north) showing the floating wetland installed by Rotorua Lakes Council (see 'ROTORUA' within the lake). Photo: Rotorua Daily Post.

Figure 3. Photo of Lake Rotoiti (foreground) and Lake Rotorua showing the Ohau Channel diversion wall which directs water toward the Kaituna River outflow of Lake Rotoiti (foreground) and away from the main basin of the lake (left-hand side). Photo: Andy Bruere.

Mixed management approaches have been shown to be successful for managing water quality in Lake Rotorua (Bay of Plenty), in an attempt to balance the time scales for achieving long-term reductions in external (catchment) nutrient loads with short-term actions that can relatively rapidly alleviate severe water quality problems (Smith et al. 2016). Attempting in-lake treatments to deal with the acute symptoms of degradation of lake health usually has high levels of risk, high costs and puts managers in a difficult position of trying to evaluate operations or products that can have a strong commercial imperative but limited scientific assessment. One of the objectives of this report is to contribute contemporary information on a wide array of potential restoration actions, including some of which have very limited scientific documentation.

Below we provide literature and a brief commentary on a range of options that may be used to manage lake water quality. The options may be broadly categorised as those that attempt to directly remove algae and cyanobacteria (e.g., by flushing, ultrasound, hydrogen peroxide and booms) and those that attempt to interfere with the environmental conditions that trigger blooms (e.g., by removing nutrients, mixing). In each case the relevance of these options to Lake Rotorua is considered.

4. Restoration techniques

4.1 Hydraulic flushing for direct algal control

Flushing is only effective when the water residence time is reduced to a level where phytoplankton are flushed from the system at rates that exceed their ability to grow and increase in biomass (indicated by doubling times) (Hamilton and Dada 2016). Inability to achieve sufficiently low hydraulic residence time (< 20 days) could increase phytoplankton biomass because it introduces 'new' (external) nutrients to a lake. A higher proportion of the nutrients in inflows is also likely to be in dissolved inorganic or bioavailable form compared with those proportions in a lake, where they are usually reduced to very low levels by biological uptake. In hydro lakes, flushing can be a natural protective mechanism against cyanobacteria blooms due to high through-flows, except where the lakes have poorly flushed side-arms (Hamilton and Duggan 2010). In most natural situations there is limited capacity to increase flushing rates to a level that directly controls cyanobacteria blooms. One high-profile case study of attempted hydraulic flushing is for Lake Taihu (Jiansu province, China) which involves flushing with water from the Yangtze River. Four diversions from the Yangtze River have been implemented since 2002 as an 'emergency stopgap measure' (Li et al. 2013). Modelling by Li et al. (2013) indicated that even the most extreme (high) water transfers did not reduce water residence times in bays of the lake to less than 80 days. Severe cyanobacteria blooms (*Microcystis* spp.) still occurred in Lake Taihu following the diversion, which also delivered additional nutrients.

Relevance to Lake Rotorua: not relevant. The hydraulic residence time of the lake is approximately 1.5 years. Abell et al. (2014) noted, however, that phytoplankton in the littoral (near-shore) region were mostly nutrient replete and may have been transported via lake currents away from this region and into the central lake basin where the phytoplankton were found to be nutrient deficient.

4.2 Inflow diversion

The best known case of a major inflow diversion in New Zealand is the Ohau Channel wall, in Lake Rotoiti (Fig. 3). It receives water from the Ohau Channel and diverts it towards the Kaituna River outflow of Rotoiti. A major driver for the construction of the wall was severe cyanobacteria blooms in Lake Rotoiti in the 2000s and similar blooms (i.e., usually identical species of cyanobacteria) in Lake Rotorua at this time. The diversion has strongly reduced the frequency and severity of cyanobacteria blooms in Lake Rotoiti (Hamilton et al. 2016b) through reduced nutrient loads and removal of a source of cyanobacteria via the Ohau Channel inflow from Lake Rotorua but at the same time the source water from Lake Rotorua has improved markedly, with reductions in nutrient concentrations, chlorophyll *a* and cyanobacteria (Smith et al. 2016).

Relevance to Lake Rotorua: Diversion of the Hamurana Stream was contemplated as a mechanism to reduce nutrient loads on Lake Rotorua. The reduction was estimated to be of the order of 53 t N y^{-1} and 6.3 t P y^{-1} (Burns et al. 2009). A large component of the phosphorus load is bioavailable, associated with the predominance of 'old-age' groundwater in the Hamurana Stream. At the same time this groundwater has been progressively enriched in nitrate from past land use change and intensification, so nitrate levels could be expected to increase for some decades and a diversion wall was a means to alleviate these increases. A computer modelling investigation of the effect of the diversion showed little change in lake water quality, with the reduction in nutrients offset by extended periods of deoxygenation of bottom waters as a result of the loss of the cold, oxygen-saturated inflow that propagated along the bottom of the lake (Hamilton et al. 2012). McQueen-Walton and Shaw (2017) provide a number of other reasons why the Hamurana diversion was not implemented including potential to interfere with trout populations, cost (c. $12 million) and cultural objections.

4.3 Phosphorus locking – lake geoengineering

When phosphorus loading from a catchment is reduced, lake recovery can take several decades. This is because phosphorus that accumulates in the lake sediments when catchment nutrient loads are high is released as an internal load from the sediments during the recovery process (Jeppesen et al. 2005, Spears et al. 2014, Søndergaard et al. 2013). For this reason, the effective control of internal loading can greatly accelerate ecological recovery once external inputs have been reduced significantly (Mehner et al. 2008). This process is known as geoengineering, which has been defined as the deliberate manipulation of lake processes using natural or engineered amendments to induce a desired chemical or ecological outcome (Mackay et al. 2014). Part of the geoengineering process may include phosphorus locking or inactivation (because the primary focus has often been on phosphorus), flocculation (a process by which colloidal material in the water column is made flocculent or bound into flocs), and coagulation and precipitation (e.g., aluminum phosphate precipitation).

The underlying concept behind the use of geoengineering materials is that they can help to address phosphorus legacies (Sharpley et al. 2013). General principles for the use of geoengineering have been developed based on several New Zealand case studies (Hickey and Gibbs 2009; Douglas et al. 2016), primarily because of scientific experiences in the Rotorua/ Te Arawa lakes that has been supported through the Bay of Plenty Regional Council. Lake Okaro has been a particular focal lake for trialling flocculants, and experiences related to efficacy, ecotoxicity and evaluations of different flocculants have been documented in a special section of the *Hydrobiologia* (Hamilton and Landman 2011). A decision support framework based on a flow diagram of relevant considerations for geoengineering is given by Hickey and Gibbs (2009) who also provide a 'tool box' for complementary strategies for lake restoration (Hickey and Gibbs 2009). The array of geoengineering materials is increasing but selection of the most appropriate material is considered to remain problematic (Douglas et al. 2016).

The geoengineering framework of Hickey and Gibbs (2009) can assist with conceptual understanding of geoengineering and details related to timing, quantity of geoengineering material, etc. for specific lakes. The framework also provides guidance for assessing ecological risks associated with restoration options. *A priori* testing of the geoengineering materials is important to examine reaction kinetics, ascertain phosphorus uptake capacity and understand the influence of other chemical species, as well as to consider the range of in-lake physicochemical conditions and the most suitable time to apply the material. Douglas et al. (2016) identify where the material is effective (i.e., sediment vs water) and the relative time scales on which the material acts: (i) the water column (days to weeks), (ii) the reactive sediment capping layer (weeks to months) and (iii) the buried or redistributed reactive capping (months to years). Ecotoxicological testing is essential so as not to induce acute toxicity (e.g., with excessive or unbuffered high-alum dosing that could cause acidification) or leave a chronic legacy in bottom sediments that might also affect the benthos and have impacts on the food web. Modelling can play an important complementary role to laboratory and field investigations preceding a lake-scale geoengineering application (Spears et al. 2014).

Table 2 provides additional information on geoengineering materials that have been used for experimental purposes or for whole lake treatments. Longevity of a one-off treatment appears to be variable depending on a number of lake-specific variables including morphology of the lake, phosphorus loading (linked to ratio of catchment area to lake area), and presence of benthic organisms that may reactivate phosphorus in the bottom sediments (Huser et al. 2016). Geoengineering needs to be tailored to each specific lake based on volume to be treated, presence of competing cations and anions, CDOM, etc. (Hamilton and Dada 2016). For each lake is it important to evaluate efficacy based on jar tests, laboratory experiments and small-scale field trials, costs, ecotoxicity, and physical effects related to smothering and potential impacts on benthos (e.g., benthic invertebrates).

Lake geoengineering using alum ($KAl(SO_4)_2 12(H_2O)$) has been practiced for many decades, including in Lake Rotorua for more than one decade (McBride et al. 2018b). The charged metal cation (Al^{3+}) in alum binds with and precipitates phosphate (PO_4^{3-}). Fine colloids and suspended solids are also coagulated and flocs are formed within the water column that enhance sedimentation rates. Under alkaline conditions a dissociation product of alum ($KAl(SO_4)_2 \cdot 12(H_2O)$) or poly aluminium chloride (PAC) is $Al(OH)_4^-$ which can be toxic to biota (Gensemer and Playle 1999). This observation was one of the reasons why alternate materials have been explored. Such materials include Phoslock®, a patented material that uses the rare earth lanthanum (La^{3+}) instead of aluminium (Al^{3+}) to lock up phosphorus and Aqual-P, which uses a zeolite carrier but has aluminium as the active phosphorus-locking compound. Lanthanum has also been examined for its potential to have eco-toxicological effects (Herrmann et al. 2016).

In some cases coagulation and flocculation may be enhanced intentionally by additions of other flocculants like powdered aluminium chloride (PAC), to achieve floc formation in combination with alum or Phoslock® to adsorb phosphorus in the flocs (Oosterhout and Lürling 2011). The application of geoengineering materials has often been linked to the need to reduce the incidence of cyanobacteria blooms. Algaecides (e.g., hydrogen peroxide) have therefore sometimes been used prior to phosphorus locking (e.g. by Phoslock®). Cyanobacteria are lysed and killed by the algaecide rather than potentially sedimenting out with the floc and re-emerging to form blooms in the surface layer, presumably as buoyant cells and colonies detach from the floc soon after it has settled to the bottom of the lake (Lürling, pers. comm.).

Douglas et al. (2016) review a number of potential geoengineering materials. These include a range of naturally occurring and processed (often by industrial by-product) materials:

- Carbonates
- Soils, sands, suspended particles
- Allophane and imogolite
- Fe–Al (oxy)hydroxides
- Hydrotalcite
- Aluminosilicates calcined to form porous aggregates
- Hydrocalcite
- Expanded/thermally treated clay aggregates
- La-modified bentonite, vermiculite, zeolite or soils
- Red mud/sand
- Slags
- Neutralised used acid (NUA)

Recently, Zhang et al. (2018) have modified various natural compounds (zeolite and lake sediments) using a novel oxygen nanobubble technique, to test their effectiveness at laboratory scale as a potential lake geoengineering material. The primary mode of action of this material is to oxygenate the bottom sediments as the material sediments out, thereby increasing the oxidation status of the bottom sediments and reducing the release of redox-sensitive dissolved constituents (e.g., phosphate). Some materials suitable for nanobubble modification may provide additional benefits related to flocculation and coagulation as they settle. Nanobubble-modified sediments clearly have potential as a variant of geoengineering materials but there is still considerable work to do to scale from laboratory trials to field applications, including consideration of the costs involved.

Table 3. Lake geoengineering materials used as phosphorus flocculation and inactivation agents in lake treatments.

Flocculant	Active com-pound	Carrier	Requirements	Cost (approx.)	Side effects/toxicity	Application difficulty
Alum, PAC	Al^{3+}	None.	Mostly used with a buffer; careful checks required to avoid acidification	Low	Free (uncomplexed) Al ion toxicity to biota (primarily a gill toxicant), highly pH dependent (Gensemer and Playle 1999)	Low-medium
Phoslock®	La^{3+}	Bentonite	-	Medium-high	Low-alkalinity waters could lead to greater susceptibility of biota to side effects from La^{3+}	Medium
Chitosan (Zou et al. 2006)		Has been used in association with flocculants for sinking (ballast) purposes	Check for contaminants released by flocculant (if used)	High	Benign: toxicity to higher organisms highly unlikely but appears to act as an algaecide to cyanobacteria	High
Oxygen nanobubble modified natural particles (Zhang et al. 2018)	-	A local mined soil is often used, to which oxygen nanobubbles are impregnated	Has not been scaled up; still experimental (laboratory-scale)	Likely to be high	Benign unless the modified soil releases contaminants	Medium
Aqual-P	Al^{3+}	Zeolite	-	Medium	Evidence to date indicates Aqual-P is relatively benign	Medium

Relevance to Lake Rotorua: Geoengineering with alum has been used in the Utuhina Stream inflow to Lake Rotorua (Bay of Plenty) since 2006 and in the Puarenga Stream inflow since 2010 (Smith et al. 2016). The alum has multiple effects: precipitating phosphate, flocculating and coagulating colloids and suspended solids and removing them from the water column via sedimentation, and continuing to bind and precipitate phosphorus in the bottom sediments of the lake. Alum dosing in Lake Rotorua is regarded as an interim measure while 'excess' catchment nutrient loads are addressed. The protocol for stream dosing has been refined by Bay of Plenty Regional Council, who seek to maintain total phosphorus concentrations at 17-20 mg m^{-3} in surface waters of the lake. The early stages of operating both alum dosing plants was characterised by more variable dose rates based on stream aluminium concentrations. It is likely that some 'overdosing' takes place, where unspent alum (i.e., that not locking phosphorus or otherwise inactivated) enters the lake and continues to lock up phosphorus. A synthesis of the water quality effects of alum on Lake Rotorua is given in McBride et al. (2018b) and ecotoxicological considerations are given by Tempero (2015a, 2018). More work is required on alternative approaches because of cultural objections to the use of alum and potential for ecotoxicological effects.

Eager (2018) provides a comprehensive review of why alum dosing has been relatively ineffective in Lake Rotoehu compared with Lake Rotorua. Interference by anions and cations derived mostly from geothermal waters and flocculation within hornwort (*Ceratophyllum demersum*) beds have prevented broader-scale phosphorus reductions similar to Lake Rotorua. In any geoengineering application with alum, consideration therefore needs to be given to a range of anions and cations that may interfere with the phosphorus flocculation process by alum, the potential to acidify poorly buffered stream and lake waters (in which case a buffer may need to be applied concurrently), and localized in-lake accumulations from sedimentation of flocs around the inflows that are dosed with the flocculant. In the case of whole-lake applications, repeat dosing at intervals of a few years to a decade or more are common and often reflect inability to adequately manage excess nutrient loads on lakes.

4.4 Sediment capping

The objective of sediment capping is primarily to provide a physical barrier between the remnant, nutrient-enriched sediments and the water column (Theis 1979; Spears et al. 2018), resulting in altered physico-chemical conditions at the sediment-water interface. A capping layer can decrease sediment oxygen demand, nutrient releases and sediment resuspension. Many of the issues associated with dredging are also relevant to sediment capping: loss or impairment of benthic fauna, temporary resuspension of remnant sediments as the capping layer establishes, and rapid return to an organic-rich sediment layer if excess external loads have not been adequately addressed beforehand. The capping layer generally needs to be at least a few centimetres in depth to ensure that the existing organic-rich sediment layer will degrade anaerobically beneath the capping layer, although areas of a lake can be targeted where sediments are most enriched (Hickey and Gibbs 2009). The capping material also needs to be evaluated carefully, to ensure that it does not itself leave an undesirable chemical legacy and that it does not release compounds, including nutrients, back into the water column.

Relevance to Lake Rotorua: A preliminary consideration of sediment capping would involve (i) the area to be targeted (likely c. 30 km^2 based on the area of organically enriched sediments), (ii) the depth of the layer (at least 2-3 cm to fully cover the organic-rich sediment layer), (iii) the material used (e.g., sand, gravel, zeolite, etc.), (iv) the ability to source the large amount of material required (2.25 million tonnes based on an area of 30 km^2, a layer depth of 3 cm and a density of the material of 2,500 kg m^{-3}), the duration over which the capping layer is effective and (v) the costs involved (including extraction of the material, transportation and application).

4.5 Ultrasound to preferentially remove cyanobacteria

The use of ultrasound is being promoted for cyanobacteria control by some distributors of ultrasound equipment. There are no New Zealand-specific reviews of ultrasound treatments but research and reviews have been carried out overseas (Lürling and Tolman 2014a, 2014b). Ultrasound devices are purported to produce collapse of gas vesicles and inhibit photosynthesis in cyanobacteria, with lysis and damage of cells. The most authoritative and scientifically based research on ultrasound indicates, however, that it is highly unlikely to have any control effect on cyanobacteria in natural systems unless extremely high-intensity ultrasound is applied within a very small body of water. Such high-intensity ultrasound has been found to kill zooplankton grazers (Lurling and Tolman 2014a, 2014b) and could potentially affect fish populations and behaviour.

Relevance to Lake Rotorua: Based on the most rigorous scientific investigations, ultrasound is not going to be viable to selectively remove cyanobacteria in Lake Rotorua.

4.6 Hydrogen peroxide

Like ultrasound, there are no working examples in New Zealand of hydrogen peroxide for cyanobacteria control. In the international scientific literature it has been reported that hydrogen peroxide can selectively target removal of cyanobacteria over other algae (Drábková et al. 2007). Hydrogen peroxide may also oxidise and degrade cyanobacteria toxins, for example, microcystins (Lurling et al. 2014). A major advantage of hydrogen peroxide is its rapid breakdown to harmless by-products (water and oxygen) so that there is no chemical legacy from dosing with this compound. Effective dose-response relationships vary from c. 2 up to 100 mg L^{-1} of hydrogen peroxide. The wide variation may be caused by variations amongst lakes in the concentration and array of compounds that interfere with the efficacy of action by hydrogen peroxide. Specialist boats and equipment are required to apply hydrogen peroxide in lakes in order that health and safety risks are minimised.

Relevance to Lake Rotorua: Hydrogen peroxide may offer an opportunity for short-term bloom control as an algaecide. Lab trials or small-scale tests would be essential, particularly as geothermally influenced waters may interfere with treatment efficacy. A specialist boat would probably be necessary for hydrogen peroxide application to a lake. Hydrogen peroxide has not before been applied to a lake as large as Rotorua and the logistics and cost of such an operation would require more detailed consideration.

4.7 Booms to remove cyanobacteria blooms

Booms have occasionally been used for the purpose of concentrating and removing cyanobacteria. The technique exploits the buoyancy of many cyanobacteria as a potential control measure. Booms were used as an emergency measure for a *Microcystis* bloom in the

Swan River in Western Australia in 2000 (Fig. 4a) but their efficacy was not quantitatively evaluated (Atkins et al. 2001). The algal scum that was collected was discharged to the sewer system.

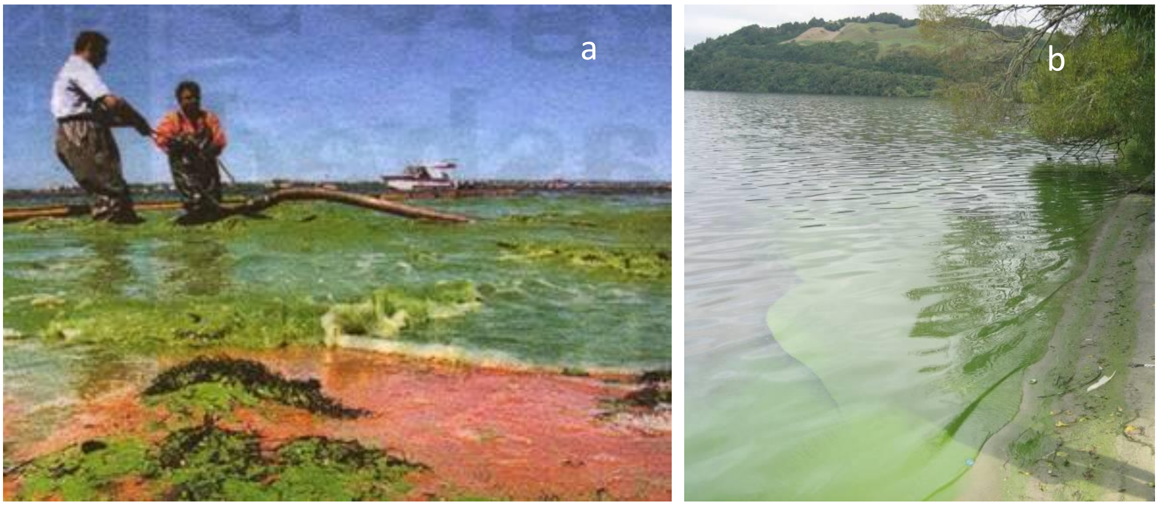

Figure 4. Buoyant blooms of cyanobacteria showing (a) use of a boom to attempt to remove Microcystis sp. from the Swan River, Western Australia (2000) (photo: The West Australian), and (b) an opportunity to use a boom to remove a bloom of *Dolichospermum* sp. from Lake Rotorua (2005) (photo: D. Trolle).

Relevance to Lake Rotorua: Booms may offer opportunities to remove unsightly blooms in nearshore areas under calm conditions (e.g., Fig. 4b) but the effort required to remove these blooms would need to be weighed up against the likelihood of the blooms being dispersed rapidly under windy conditions and to re-form quickly as the proportion of cyanobacteria removed would be small at a whole lake scale. For a lake of the size of Rotorua (area = 80 km^2) it is highly unlikely that booms would harvest cyanobacteria from a sufficiently large area to be effective as a lake management tool.

4.8 Harvesting phytoplankton by filtration

In natural systems very high filtration rates are required to achieve control of phytoplankton. In Lake Taihu filtration is used to remove very high concentrations of cyanobacteria (Fig. 5), targeting specific areas (e.g., water treatment plant intakes), but filtration is not effective for cyanobacteria control at whole-lake scale. Similar to considerations of flushing, filtration is only effective if the relevant water mass can be filtered in time periods of c. <20 days. A trial has previously been run by Bay of Plenty Regional Council to filter water from the Ohau Channel outlet of Lake Rotorua to remove algae and nutrients. The conclusions from this trial were that filtration rates were inadequate to achieve the desired rates of removal of algae and nutrients (Scholes et al. 2010).

Relevance to Lake Rotorua: Harvesting phytoplankton from Lake Rotorua is unlikely to be effective because low concentrations of phytoplankton and large lake size would render the filtration process ineffective for biomass control. For example, to replicate the effect of a 20-day flushing period (i.e., filtering the entire lake volume in 20 days) would require filtering approximately > 450 m^3 s^{-1}, substantially more than the mean flow rate of the Waikato River (340 m^3 s^{-1}).

Figure 5. Example of harvesting and concentrating cyanobacteria (mostly *Microcystis* spp. from Lake Taihu where concentrations are extremely high and the lake area is 2,390 km^2. Photo: M. Burford.

4.9 Surface mixers, aerators, artificial destratification and oxygenation

There are many different options and associated with the use of surface mixers, aerators, artificial destratification and oxygenation, and these may have slightly different purposes. For example, surface or mechanical mixers can be mounted at a water surface to pump water from the surface towards the bottom of a lake, ideally creating sufficient flow to stop buoyant algae (usually consisting mostly of cyanobacteria) from accumulating at the water surface and forming blooms (Visser et al. 2016). Trials have taken place on some Rotorua lakes to test a device called a WaveKatcher (http://www.eko-rx.com/main/wpump.html) which used wind-wave energy to transport water downwards from the lake surface. Simulations by the author and colleagues indicated that this device would not provide sufficient energy to be effective at a lake scale. Mechanical mixers also deepen the surface mixed layer, creating lower levels of light exposure for phytoplankton in this layer and reducing growth rates. Surface mixers generally require considerable energy to achieve basin-wide circulation cells and effectively mix at a basin scale. Solar-powered devices (e.g., SolarBee®) operate in a slightly different mode, floating on the lake surface and drawing water from depth up through a draft tube and discharging water to the surface of the lake.

SolarBee® devices have operated on Lake Virginia (Whanganui) (Burgraaf 2008) and Pegasus Lake (North Canterbury) (author's personal obs.) but their impact has not been well described scientifically. Based on more detailed scientific studies overseas, they likely have minimal impact (e.g., Dukes 2016).

Bubble plume destratifiers use compressed air which is usually pumped near the bottom of the water column to entrain and lift deep water and mix it with surface waters. They can create large-scale circulation through bubbles entraining water from different depths and spreading this water laterally in the form of a jet. Destratifiers have been found to have limited horizontal extent in relatively large Lake Rotoehu (8.1 km^2), Bay of Plenty (see McBride et al. 2015, Fig. 6; Tempero 2015b), but have been used for water quality control in water supply dams managed by Auckland Council (Gibbs and Howard-Williams 2018). In these waterbodies they have reduced the occurrence of anoxic waters adjacent to water offtakes, leading to reduced levels of iron and manganese. This effect is likely to be localised, targeted specifically to water removed at the offtake.

Destratification should not be confused with oxygenation which involves direct supply of oxygen (or occasionally air) to the bottom waters of lakes whilst attempting not to interfere with the seasonal temperature stratification. Very small oxygen or air bubbles (sometimes referred to as micro- or nano-bubbles although the prefix is not indicative of actual bubble size) or liquid oxygen can be used to increase the dissolution of oxygen in bottom waters. Hawkes Bay Regional Council is currently trialling methods of oxygenating Lake Waikopiro (http://gisborneherald.co.nz/environment/3020672-135/lake-put-on-life-support). An unsuccessful attempt was made in the 1970s to destratify the larger, adjacent Lake Tutira. It is strongly recommended that models be used in considerations and design capacity of destratification or oxygenation systems. Coupled hydrodynamic-ecological models like DYRESM-CAEDYM have process representations of artificial destratification and mechanical mixers.

Hypolimnetic aeration or oxygenation has been used in a number of lakes in Europe, Canada (Ashley 1985) and USA (Gantzer et al. 2009). While it may be appropriate for several of the smaller monomictic lakes in the Bay of Plenty region (e.g., Lake Okaro), it is not suitable for Lake Rotorua because periods of stratification are temporary (commonly several days), which may limit the duration on which oxygen could be distributed through the deeper waters; this much of the oxygen could be 'wasted' when the lake mixes naturally and deeper waters are re-oxygenated. Bormans et al. (2016) indicate that hypolimnetic aeration or oxygenation is not suitable for lakes <15 m depth although this generalisation could be adjusted according to the area of the lake.

Relevance to Lake Rotorua: Mechanical mixing, artificial destratification or hypolimnetic aeration/oxygenation is not considered to be viable as a restoration technique for polymictic Lake Rotorua. Natural wind and convective mixing would continue to dominate the physical dynamics of the water column of the lake. Lake Rotorua fits outside of the depth range (> 15 m) for which Bormans et al. (2016) indicate that these techniques may be worthy of consideration.

Figure 6. Commissioning of a destratification device designed to fully mix the water column using air-lift of bottom waters. Photo: D. Hamilton.

4.10 Floating wetlands

The primary purpose of installation of floating wetlands in lakes is purported to be for nutrient control. This occurs primarily through plant uptake and denitrification, which involves microbial conversion of nitrate (a plant nutrient) to nitrogen gas. Ideally, plants are harvested from a floating wetland to remove nutrients. Floating wetlands have been used in the Rotorua/Te Arawa lakes in Lake Rotorua (Fig. 2) and Lake Rotoehu (Fig. 7). Considering the scale of investment of installing floating wetlands in lakes, there is scant scientific evidence for their benefit as a nutrient control method. Nutrient removal rates appear to be modest (Sukias et al. 2010) and may be compromised by birds that utilise the new terrestrial habitat. A review of floating wetlands for nutrient removal (Pavlineri et al. 2017) included one lake study and four mesocosm studies relevant to considerations of floating wetland applications for lakes. This review emphasised the importance of plant harvesting for effective nutrient control and also appeared to show very little reduction in total nitrogen concentrations when the water supporting associated with the floating wetland had concentrations <5 mg L^{-1}.

Relevance to Lake Rotorua: One of the largest known floating wetlands has been established in Lake Rotorua by the Rotorua Lakes Council, at a cost of approximately $1 million. A large floating wetland was also established in Lake Rotoehu (Fig. 7). No studies have been carried out to establish whether there are any benefits of either of these wetlands. Establishment of floating wetlands should not be considered or justified for the purpose of improving water quality. Floating wetlands may incur ongoing costs related to maintenance and repair.

Figure 7**.** Floating wetlands have been installed in Lake Rotoehu as part of the nutrient management plan for that lake. Photo: D. Hamilton.

4.11 Hypolimnetic siphoning

Hypolimnetic siphoning uses gravitational siphoning of water from the bottom of a lake to an outlet positioned below the bottom of a lake. The objective is to preferentially remove nutrient-enriched bottom waters (Hickey and Gibbs 2009). This technique is not known to have been used in New Zealand although it has been investigated as one of a range of potential management options for Lake Okāreka (Bay of Plenty Regional Council 2004).

Relevance to Lake Rotorua: For Lake Rotorua, hypolimnetic siphoning would involve using a large pipe to transfer water from the bottom of the lake to a less elevated position, likely partially down the Kaituna River outflow of Lake Rotoiti. This would appear to be impractical. Consideration would need to be given to impacts on the Kaituna River as during periods of stratification in Lake Rotorua there may be higher levels of nutrients discharged to the Kaituna River via the siphon. It is recommended that this option not be investigated at this stage.

4.12 Microbial control

One form of microbial control involves introducing bacteria to water. The objective of this technique is to enable bacteria to proliferate, and take up nitrogen and phosphorus, outcompeting phytoplankton, particularly cyanobacteria, for these nutrients. The problem with the theory of this technique is that nitrogen and phosphorus associated with bacteria are not refractory and, while flocs may sediment out, recycling of these nutrients is expected. There appears to be very little scientific documentation on microbial control methods that have produced significant changes in water quality at a lake scale. This viewpoint does not necessarily pertain to heavily organically loaded systems, for instance oxidation ponds, where breakdown of organic material could be constrained by the availability of suitable microbes and their ability to rapidly generate biomass. Huisman et al. (2018) outline methods to control blooms, including biological controls, but do not strongly endorse this approach and note that they are rarely successful in the long term.

Other related treatments may involve adding macronutrients or micronutrients to the water column. Macronutrients include nitrogen and phosphorus, as well as silica required to build silicified cell walls in diatoms. Micronutrients may include trace minerals such as molybdenum that can limit cyanobacteria, particularly those that fix nitrogen, because of the key role some micronutrients have in the nitrogen fixation process. Additions of either macronutrients or micronutrients are not recommended. Additions of a limiting nutrient can be expected to increase productivity, organic load and oxygen depletion in bottom waters as the organic matter is broken down.

A trial of a microbial control agent (composition unspecified) has been conducted using mesocosms in Lake Sullivan (Whakatane) but there was no clear outcome (Scholes 2005). A subsequent whole-lake trial in Lake Sullivan proved to be inconclusive and a trial in the northern arm of Lake Rotoehu did not show significant results.

Relevance to Lake Rotorua: The results of microbial control agent trials are inconclusive. Together with the large size of Lake Rotorua and significant remobilisation of bottom sediments via resuspension and releases of dissolved nutrients, microbial control agents are unlikely to be useful for water quality control in the lake.

4.13 Dredging

Dredging involves removing lake bed sediments and therefore has the advantage of directly removing nutrients that have accumulated due to a legacy of high external loading. In shallow lakes, dredging is a well-established method to physically control internal loads (Bormans et al. 2016). It may be particularly useful when the bottom sediments of a lake are exposed to anoxic overlying waters resulting in resupply of nutrients to the water column. It could also reduce re-inoculation of cyanobacteria to the water column by removing akinetes of cyanobacteria (e.g., of *Dolichospermum* or *Rhaphidiopsis* species) or overwintering vegetative cells (e.g. *Microcystis* spp.).

Dredged spoil has to be disposed of according to the local or regional environmental regulations and options may be restricted according to how the spoil is classified. Costs for small lakes may be of the order of $100,000 per hectare (Hamilton et al. 2014). The efficacy of dredging varies with a number of factors including the dredging depth, the composition of underlying exposed sediments (as dredging is based on the premise that deeper sediments have lower levels of nutrients and organic matter), the scale of disturbance and resuspension of sediments from the operation, the disruption of benthic biota and the ability to accurately target the deeper organic-rich sediments. Removal and death of benthos is relevant to Lake Rotorua where there are taonga species such as kākahi (*Echyridella menziesi*) and kōura (*Paranephrops planifrons*) that are either resident in the sediments or scavenge the benthos for food. An early and detailed critique of dredging is given by Peterson (1982) who considered its ability to remove phosphorus-rich bottom sediments and thereby reduce internal loading, as well as the potential offsets from the harmful side effects mentioned above.

Dredging has been used to remove nutrient enriched sediments from specific areas of hypertrophic Lake Taihu Lake (mean depth = 2 m, area ca. 2,350 km^2). Early reports were mostly positive (Cao et al. 2007; Zhong et al. 2008) and indicated that dredging had potential as a whole lake restoration method. However, it has largely been abandoned, with concerns expressed about the amount of spoil and its disposal, as well as the creation of relatively deep areas where bottom waters may potentially go anoxic (Yiping Li, Hohai University, pers. comm.). The popularity of dredging as a lake restoration tool appears to have waned through the past two decades or so. It is still, however, still used occasionally in The Netherlands in a mode of a complete system 're-set', where the depth is increased substantially (often several metres), the soil is used as a means to develop riparian areas and geoengineering is also used to minimise the persistence of dredged sediments and their ecological impact. This highly intensive restoration is extremely expensive and restricted to smaller lakes in densely populated areas.

Relevance to Lake Rotorua: Miller (2007) provided an excellent report to Bay of Plenty Regional Council on the potential of dredging as a restoration tool for Lake Rotorua. This report was generally positive about the potential of dredging to improve water quality of the lake, but indicated a need for further more detailed investigation. It also recommended carrying out a small-scale dredging trial to assess the practicality, cost and procedures for a full-scale operation. Miller (2007) recommended testing the spoil to examine its potential for dewatering and assess other potential uses, but this material may have elevated arsenic and mercury concentrations derived from geothermal sources. One of the concerns raised in the report was that bottom sediments exposed by dredging may also release nutrients, similar to the surficial sediments being removed. This concern is supported on the basis that deeper sediments (up to 0.5 m depth) have similar nutrient concentrations to surficial sediments. Given the cost and size of a dredging operation (c. 30 km^2 central area out of 80 km^2 total lake area being targeted) as well as cultural concerns, which include removal of taonga species, prototype dredging operations have not been carried as a first step to a whole-lake operation.

Figure 8. Dealing with dredged spoil can be a major operational issue and expense; a lake dredging operation in China.

4.14 Biomanipulation

Biomanipulation is the deliberate alteration of an ecosystem by adding or removing species, especially predators. Manipulation of food webs in aquatic systems most often relates to efforts to reduce predation on zooplankton (e.g., by adding fish that are predators on zooplankton-feeding fish, or by directly removing zooplankton-feeding fish), thereby maximizing the population size of zooplankton and their grazing pressure on algae. In New Zealand alteration of lake ecosystems has also occurred with both intentional and unintentional introductions of species, and because these have been so frequent they are also dealt with in the section. Hamilton and Dada (2016) summarise opportunities for biomanipulation in New Zealand lakes and report on a number of case studies including Lake Ōmāpere, where more than 40,000 grass carp (*Ctenopharyngo donidella*) were introduced to the lake in 2000. This lake has gone through major transitions of clear water with exotic macrophytes and turbid water with cyanobacteria blooms from 2000 to present. Other biomanipulation techniques include seeding of mussels (*Echyridella menziesi*), introductions of planktivorous fish such as silver carp (e.g., Ma et al. 2012), and filter-feeding zooplankton (Burns et al. 2014) including the recent unintentional introductions of large-bodied herbivorous zooplankton (Balvert et al. 2009).

Relevance to Lake Rotorua: Introductions of grass carp and silver carp should be avoided. Introductions of grass carp to Lakes Ōmāpere and Tutira have not provided marked improvements in water quality although for Lake Tutira the primary purpose of grass carp introductions was related to an incursion of the exotic weed *Hydrilla.* More work is required to understand and support habitat for kākahi (*Echyridella menziesi*) and kōura (*Paranephrops planifrons*) – the latter identified by Kusabs et al. (2015) as a keystone species.

4.15 Macrophyte harvesting

In the 1960s there was a major problem with growth of invasive macrophytes, mostly *Lagarosiphon major*, in Lake Rotorua. It affected the littoral zone of the lake, smothering the lake bed and creating surface-reaching growths that were unsightly and impaired recreational activities. Storms led to massive accumulations on the shoreline. The prolific spread of plants in the 1960s has not continued, possibly due to increased light attenuation and active management of invasive weeds with Diquat®. In Lake Rotoehu, however, there has been prolific growth of the invasive macrophyte *Ceratophyllum demersum*, and this has been dealt with through a harvesting programme that is designed to remove the unsightly surface-reaching plants (Fig. 8) and to contribute to attaining nutrient reduction goals for the lake. The harvesting is estimated to remove c. 320 kg yr^{-1} of phosphorus, 2,400 kg yr^{-1} of nitrogen, at a total cost of approximately $53,000/yr (Hamilton and Dada 2016) though recent correspondence indicates this figure may be conservative (A, Bruere, Bay of Plenty Regional Council, pers. comm.). The success of this programme is obviously highly reliant on the biomass of plants present, which will vary with a number of environmental factors as well as the harvesting regime itself. Somewhat counter-intuitively, Dai et al. (2012) examine the presence of hornwort from a restoration perspective, where weed beds maintain clear water and reduce sediment resuspension (i.e., maintain a clear-water regime) in the lake. They recommend an ideal coverage of 20% to address eutrophication issues in shallow Chinese lakes. This recommendation makes no consideration of the highly invasive nature of hornwort, such as in New Zealand. Quilliam et al. (2015) provide a perspective on weed harvesting related to 'closing the loop' and providing multiple downstream benefits from the weed harvest (e.g., stock feed, fertiliser) in addition to addressing lake eutrophication.

Relevance to Lake Rotorua: Weed harvesting is probably not relevant as a nutrient management tool for Lake Rotorua. Allowing invasive species to establish high biomass could be problematic in terms of the area that may need to be controlled and the potential for radiation of invasive species to other lakes. Greater benefit may accrue from actively controlling invasive species to low levels and attempting to re-establish the natural submerged macrophyte communities. These communities would help to stabilise sediments, provide refuge for zooplankton grazers and other fauna, and take up nutrients.

Figure 9. Weed harvesting in Okawa Bay, Lake Rotoiti. Photo source: Lakes Water Quality Society.

5. Conclusions

In-lake remediation options need to be selected carefully based on a comprehensive knowledge of the lake which is to undergo treatment. Many options that may apply to deeper lakes that are continuously seasonally stratified can be ruled out for shallow Lake Rotorua. Other options will not scale appropriately for the large area of Lake Rotorua. Reductions in catchment nutrient loads will help to feed back to reductions in internal loads by reducing the organic content of the bottom sediments and ultimately should elicit a feedback that maintains a resilient, relatively clear-water state. It is critical that geoengineering treatments (e.g., stream alum dosing) do not offset the urgency of addressing catchment nutrient loads. The littoral (lake-edge) zone where there is enough light to support photosynthesis on the lake bed, is beginning to be recognised as a very important area for lake health and function. It supports a number of species that have important ecological and cultural values like kākahi and koura. It is where nutrients in inflows are initially 'processed', and it is where both exotic and native submerged plant communities grow. More work is required to examine ways in which the littoral zone can be enhanced to improve biodiversity and resilience, in addition to reducing eutrophication. Climate change may bring about a discordance between the current sustainable nutrient load targets and the Trophic Level Index, with lower nutrient loads likely to be required to meet TLI targets as climate warms. Modelling allows for better understanding of this discordance but it is critical that there is no further delay in efforts to attain the current sustainable nutrient load targets for the catchment and progressively reduce the reliance on geoengineering through alum dosing.

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