Review of existing and new methods of in-lake remediation

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For:

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1. Plain English Summary

This report supports the Plan Change 10 process of the Bay of Plenty Regional Council by reviewing recent developments in lake restoration and management and updating a 2018 review on the same topic by the first author. The current report is part of the 2022 Bay of Plenty Regional Council Plan Change 10 Science Review which is conducted at five-year intervals. The report summarises recent developments in lake modelling, understanding of drivers and patterns of lake degradation, including climate change, and remediation techniques to support adaptive management of lake ecosystems. The focus of the report is on recent developments and new technologies arising since the earlier review.

The report emphasises the importance of monitoring practice to collect data capable of separating natural variations from those due to management interventions, and to support a scientific understanding of observed changes in the lake ecosystems. The Bay of Plenty Regional Council has an excellent programme of 'State of the Environment' monitoring which has been complimented by monitoring to assess effects of land and lake mitigation actions. The report highlights the need to improve understanding of the impacts of climate change on lakes to understand transitions (or pathways) leading to the degradation of lake ecosystems and exert pre-emptive actions to avert or slow the degradation. Lake modelling has an important role to play for anticipating impacts of climate change and generating possible future scenarios and planning mitigation actions appropriately.

Efficacy of the conventional and new remediation techniques is evaluated in the report. A vast body of recent literature exists on a range of materials that can in used in-lake to bind phosphorus but many of these techniques are unlikely to be practical, either because of lack of scalability (e.g., inability to spread large quantities over a lake surface) or cost. Progress has been made in the use of conventional coagulants (e.g., alum; aluminium sulphate) with existing commercial products (e.g., Phoslock®) or novel compounds, and in reducing the potential for non-target or adverse impacts. Oxygen nanobubbles applied directly or in a matrix of modified local soil or other minerals (e.g., zeolite) show promise but are also likely to be constrained by scalability and cost.

Control of invasive submerged weeds is increasingly recognised as having holistic benefits for lake ecosystems, possibly associated with avoiding large biomass that can subsequently collapse and result in anoxia of bottom waters and release of bioavailable nutrients. Control of invasive weeds has been associated with return or reinvigoration of native turf communities, and these communities appear to be associated with improvements in water quality.

2. Executive summary

Griffith University was requested to provide a contemporary review of lake management practices as part of the 2022 Bay of Plenty Plan Change 10 Science Review. The request sought a brief summary of the earlier lake management review provided by Hamilton (2019) and additional detail on emerging technologies, particularly any that have arisen since the previous review. Lake remediation is highly interdisciplinary. Critical elements are a close and continuous relationship between science technical delivery and community consultation, policy development and funding support. Successful lake management programs are adaptive and scientific knowledge often evolves in a similar way, informed by good monitoring. Good time series data are needed to separate intrinsic (natural) variations from responses due to management interventions and to support a scientific understanding of observed changes. Clear goals and end points of restoration are also required to judge the success of restoration actions, including an expected time course for improvement of key variables and a suitable monitoring programme.

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. Lake models can be comprehensively calibrated and validated from the monitoring undertaken in order to anticipate impacts of land use and/or climate change, generating possible future scenarios and planning mitigation actions that inform management.

This report briefly describes recent developments in techniques for lake restoration, many of which are based on modifications of conventional techniques. These include: algicides, coagulants, hydraulic flushing, bioremediation, phytoremediation, oxygen nanobubble technology, invasive submerged weed control, and dredging. Evaluation of some recently published techniques is limited because only lab-based or small experimental-scale trials (e.g., mesocosms) have been undertaken. 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. Efforts have been made to summarise the application and outcomes of lake remediation techniques, particularly those not included in the previous review (Hamilton, 2019) but evidence on efficacy of recent techniques for lake remediation is often limited as in situ evidence of the effect is lacking, the technique is at prototype (lab) stage, or there may not be adequate data to assess the success of the technique.

In recent times there have been several reviews of lake restoration methods and technologies as well as many studies focused on specific treatments, particularly coagulants and flocculants. 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.

Control of invasive submerged weeds is increasingly recognised as having holistic benefits for lake ecosystems, possibly associated with avoiding large biomass that can subsequently collapse and result in anoxia of bottom waters and release of bioavailable nutrients. Control of invasive weeds has been associated with return or reinvigoration of native turf communities, and these communities appear to be associated with improvements in water quality.

3. Project Brief

To improve water quality of Lake Rotorua, as part of the wider Rotorua Te Arawa Lakes Programme of water quality improvement, a plan change was required by the Bay of Plenty Regional Council. Plan Change 10 in its final form, following ratification through the Environment Court and the regional council in 2021, introduced rules to limit the amount (load) of nitrogen entering Lake Rotorua from different properties and land uses. Nitrogen is one of the environmental factors that limits the growth of algae (phytoplankton) in Lake Rotorua. Plan Change 10 is intended to reduce the frequency and magnitude of blooms of phytoplankton, specifically cyanobacteria.

A science review was required under Method LR M2 in 'Plan Change 10 Lake Rotorua Nutrient Management' (PC10), and in agreement with key stakeholders. The review conducted in 2017 led to 12 reports and a summary document, which were reviewed by Professor Warwick Vincent (Laval University, Canada) and submitted to the regional council. One of these documents was a *Review of relevant New Zealand and international lake water quality remediation science* (Hamilton 2019). The science review is stipulated to be at five-year intervals and is designed to assess outcomes from the monitoring programme and to collate recent findings and knowledge of lake processes that are relevant to Plan Change 10. This report is the five-year follow-up to the Hamilton (2019) review.

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. The peer review of the 2019 science review of PC10 identified that climate change should be embedded in considerations of lake management strategies, building upon a statement in 2020 by the Technical Advisory Group (*Climate change, lakes and water resources, Rotorua region*) about the importance of climate change for managing water resources in the region. Acknowledging that lake management throughout the world is increasingly accounting for the effects of climate change, this report includes direct consideration of how climate change may impact management actions undertaken in Lake Rotorua and the extensive body of modelling work that has been undertaken (e.g., Hamilton et al. 2012; Lehmann and

Hamilton 2019; Wang et al. 2018) to simulate water quality of Lake Rotorua under different climate change scenarios.

4. Introduction

Lake eutrophication is a global problem associated with increased external (catchment-based) nutrient loading, most often from nutrients arising from agricultural sources and domestic and industrial wastewater (Jeppesen et al., 2003; Schindler et al., 2012). In shallow lakes, eutrophication often results in the loss of submerged macrophytes, which has been associated with a switch to a turbid, phytoplankton-dominated state (Hilt et al., 2006). Growing human populations have also resulted in increased demand for freshwater globally and particularly escalating eutrophic conditions in water-stressed regions. Climate change, through a shift in temperature and precipitation patterns, may also increase eutrophication of lake systems globally (Anderson et al., 2021; Moralese-Martin et al., 2021).

Current efforts to combat eutrophication by reducing external nutrient loading take time and may not meet water quality expectations of stakeholders due to the slow response (lag time) of complex lake ecosystems (chemical and biological resistance) to external nutrient controls (Jeppesen et al., 2003; Schallenberg 2021). This delay is consistent with persistent high rates of nutrient release from bottom sediments of many lakes, including Lake Rotorua. Several in-lake restoration measures have therefore been developed to reduce nutrient concentrations in lakes, many of which are focused on phosphorus control, in order to circumvent lags and act synergistically with reductions of catchment nutrient loads to hasten the rate of recovery of impaired lake ecosystems (Spears et al. 2022).

Hamilton (2019) provided a critical review of several restoration measures developed for in-situ management of eutrophic lakes. These methods are summarised in Table 1 and include:

- hydraulic flushing for direct algal control,
- inflow diversion,
- phosphorus controls through geoengineering and sediment capping,
- ultrasound and hydrogen peroxide to control cyanobacteria,
- booms for removal of cyanobacterial blooms,
- phytoplankton harvesting by filtration, physical methods such as surface mixing, aeration,
- artificial destratification and oxygenation,
- floating wetlands,

- hypolimnetic siphoning, microbial controls,
- dredging,
- biomanipulation, and
- macrophyte harvesting.

These techniques are commonly categorised into physical, chemical, and biological methods for lake restoration (Fig. 1). Many of the methods provide temporary remediation, which means there is potential for the lake to revert towards its earlier trophic state after the treatment has concluded or if it does not continue to be adequately implemented. In some cases, the response of the lake to these treatments has not met expectations, sometimes because of the limited duration of control, restrictions imposed by the cost of the treatment, or the feasibility of the treatments at various spatial and temporal scales. Social and political aspects are also important including regulatory controls, cultural considerations and available funding, and need to be included at the outset of any lake remediation programme. These factors may limit the application of at least some of the lake remediation methods.

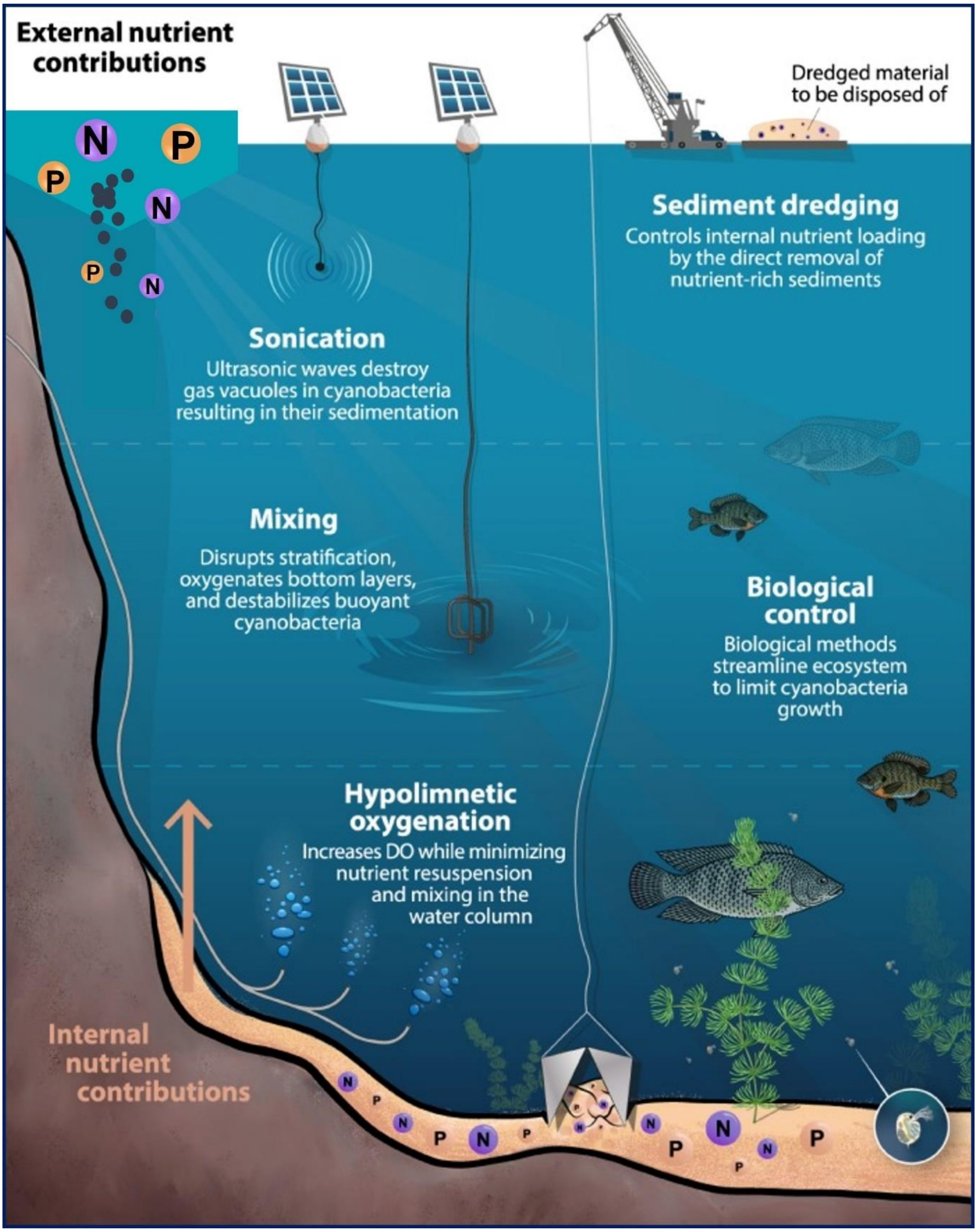

Figure 1 Schematic representation of in-lake restoration methods. Figure modified from Kibuye et al. (2021) under Creative Commons license CC by 4.0.

This report includes recent technological advances in the restoration of eutrophic lakes as well as summarising the material from the report by Hamilton (2019). 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.

Climate change is an emerging threat which can increase the duration and intensity of thermal stratification in lakes due to warming of surface waters from increased air temperature and, potentially, through climate change induced atmospheric stilling, i.e., decreases in wind speed (Ranjbar et al. 2022), and extreme rainfall and runoff events. As shown for Lake Rotorua by Wang et al. (2018), changes in the stratification pattern induced by climate change can be expected to strongly impact the lake trophic status and are likely to be a stronger driver of climate-induced changes in trophic state of Lake Rotorua than impacts on catchment hydrology and nutrient loads. The increased duration of stratification leads to longer periods of anoxia of bottom waters, increased rates of phosphate and ammonium release from bottom sediments into the overlying water, and greater biomass of phytoplankton as these nutrients enter the photic zone (i.e., the upper water layer where photosynthesis occurs) and are taken up. Changes in rainfall patterns are also likely to occur with climate change and are likely to be associated with longer dry periods interspersed with intense rainfall events. These changes will affect the hydrological regime and the delivery of nutrients and sediments to streams and lakes.

Thus, 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. Our focus in this report is mostly on the in-lake treatment methods, extending out as far as the lake riparian zone, but not including catchment controls.

Table 1 Lake restoration strategies and their general purpose, with commentary on the relevance of these strategies to Lake Rotorua. This table summarises many of the methods reviewed by Hamilton (2019).

Restoration strategy	Purpose	Relevance to Lake Rotorua
Weed harvesting	Removes nutrients assimilated in excess weed growth, usually from exotic species (e.g., hornwort)	Has been used to remove biomass and nutrients from smaller, but similarly shallow, Lake Rotoehu, and is shallow Okawa Bay of Lake Rotoiti
Sediment capping	Provides a capping layer to decrease nutrient release from lakebed sediments	Not actively practiced but may be an indirect outcome of alum dosing where there are areas of abundant floc. A central area of Lake Rotorua with fine sediment (~ 20 km^2) would likely be the target (including where anoxia is initiated). Application of Aqual-P^{TM} can be considered as a form of sediment capping and has been used in Lake Okaro where the capping layer was somewhat patchy
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. Constructed floating wetlands may have a secondary purpose of protecting shorelines and reducing wind-wave disturbance of bottom sediments but their application in lakes Rotoiti and Rotoehu has not been linked directly to shoreline protection
Floating wetlands	Wetland plants take up nutrients, nitrogen removed via denitrification	Implemented in Lake Rotorua in 2012. Also used in lakes Rotoiti, Rotoehu and Tikitapu. Quantitative evidence of benefits to water quality at lake scale is lacking
Oxygenation, destratification or mixing propellers	Redistributes oxygen/air to the bottom waters 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 and other Rotorua lakes. Simulations indicated that the scale of infrastructure and operation may be prohibitive. Destratification was used with two aerator devices over some years in Lake Rotoehu but detailed scientific evaluations confirmed limited horizontal range (~ 200 m) of benefits of mixing (e.g., alleviation of bottom-water anoxia)
Inflow diversion	Diversion removes nutrient loads from a lake	Implemented to divert Lake Rotorua outflow away from Lake Rotoiti via the Rotoiti outflow. Simulations of diversion of Hamurana inflow to Lake Rotorua carried out with a lake model and examined by Gibbs et al. (2007). Simulated benefits (nutrient reduction) of this

Restoration strategy	Purpose	Relevance to Lake Rotorua
		technique were not considered to be adequately offset by loss of oxygen in the Hamurana underflow to Lake Rotorua
Chemical methods (algicides, herbicides, coagulants), including phosphorus inactivation or flocculation	Uses chemicals (e.g., aluminium sulphate) to ‘lock up’ phosphorus via adsorption and precipitation or reduces cyanobacterial blooms either directly by killing algae or indirectly by making nutrients inaccessible for algal growth	Alum dosing (coagulation) has been used in the Utuhina Stream (from 2006) and Puarenga Stream (from 2010) that flows into Lake Rotorua (Smith et al., 2016), as well as in Lake Okaro and a geothermally influenced inflow to Lake Rotoehu. A trial of Phoslock took place in Lake Okareka and Aqual-P^{TM} has been used in several one-off treatments in Lake Okaro and when there was a major algal bloom in Okawa Bay of Lake Rotoiti. The use of other treatments such as copper sulphate or algicides and herbicides may not be suitable for the treatment in Lake Rotorua due to ecotoxicological effects, increased secondary pollution (post-treatment), and cultural objections to such chemical treatments.
Dilution and flushing, including increased residence time	Reduces the time for phytoplankton to grow and equilibrate their biomass to the ambient nutrient levels and may reduce releases of nutrients from the bottom sediments due to increased aeration	Not adopted in Lake Rotorua and not possible because there is not an additional freshwater source for dilution.
Biological methods (biofilm, constructed wetlands, aquatic phytoremediation)	Promotes interactions between aquatic flora and fauna to enhance ‘self-purification’ of water (e.g., denitrification to remove nitrogen)	No clear evidence of a specific microbial additive was found in an experiment done in the Bay of Plenty (Scholes 2005). Fish manipulation should be avoided in Lake Rotorua as earlier introductions of grass carp to Lakes Ōmāpere and Tutira have not provided marked improvements in water quality (Hamilton, 2019). Current fish invasions (catfish) in lakes Rotorua and Rotorua should provide a cautionary note for attempts at lake remediation using exotic fish introductions. Phytoremediation methods could increase the risk of establishment of invasive species due to inadvertent introductions associated with the plants.
Oxygen nanobubble technology	Delivers oxygen to restore eutrophic water, either directly to the water or indirectly through nanobubbles added to modified local soils	Not adopted in Lake Rotorua. Scaling may be an issue as nanobubble techniques use extremely large quantities of modified local soil carrier material.

5. Lake monitoring and modelling

Lake restoration is an ambitious goal (Zohary 2019) and the results of many restoration efforts have often been disappointing, sometimes associated with little change in lake ecology or in other cases with temporary improvement followed by a rapid reversion to degraded conditions (Moss 2019). Many restoration efforts have been poorly monitored, sometimes because of a preconception that conventional ‘state of the environment’ monitoring programs may be adequate to identify changes specific to a mitigation action. The result can be uncertainty in the responses to mitigation actions and the efficacy of the investment. Monitoring before, during and after a mitigation action is critical because replication at lake scale is rarely practical. The monitoring should ascertain a pre-restoration baseline, any short-term (acute) response to treatment, including possible adverse impacts, and the longevity of the treatment, including legacy effects.

Figure 2 Monitoring buoy in Lake Tarawera, which supports high-frequency (15-min) meteorological and water quality measurements.

A close and continuous relationship between science technical tools and community consultation, policy development and funding support is critical to implement lake management programs that are adaptive and successful (Hamilton et al. 2016). Good time series data are needed to separate intrinsic (natural) variations from responses due to management interventions and to support a scientific understanding of observed changes. Clear goals and end points are also required to judge the success of restoration actions, including an expected time course for improvement of key variables.

The various lake monitoring types can be divided into categories distinguished on whether water column or sediments are assessed, the frequency at which monitoring is carried out (Table 2), and whether the technique is primarily physically, chemically or biologically based. Hamilton (2019) reviewed the current state of lake monitoring relevant to PC10. Briefly, monitoring plays a vital role in providing data to synthesise long-term lake responses to various environmental (precipitation, air temperature, etc.) and human (land use, management intervention, etc.) stressors. Analysis of these data can provide critical information to decision makers to plan restoration and mitigation actions. As statutory obligations for monitoring increase (refer to obligations on regional councils in the National Policy Statement for Freshwater Management (NPS-FM, 2020), there is an increasing need to manage monitoring data, interpret it, and provide outcomes and knowledge arising from the monitoring to managers and decision makers. These aspects are too often given low priority when planning a monitoring programme.

The NPS-FM (2020) provides direction to local authorities about managing freshwater under the Resource Management Act 1991. It requires that all practicable steps are taken to reduce uncertainty in freshwater assessments by providing robust data, taking steps to improve monitoring, and validating models with suitable data. Policy 13 of the NPS-FM 2020 requires that “The condition of water bodies and freshwater ecosystems is systematically monitored over time, and action is taken where freshwater is degraded, and to reverse deteriorating trends”.

Table 2. Different types, targets, and frequencies of monitoring for assessing lake restoration actions. Note that for assessing biota, a targeted approach may be necessary.

Monitoring type	Target	Typical frequency	Notes
Immediate impact/effectiveness	Water column measurements	Intensive	Before-after monitoring designed to detect short-term (days) effects of flocculant in water column
Time series indicators	Measurements in water column	Monthly (often associated with state of environment monitoring)	Routine monitoring designed to indicate medium to long-term changes in lake water quality
Chemical duration of action including legacy effects	Sediment composition and biota assessments	Annual and possibly longer	Periodic monitoring designed to detect changes in sediment and benthic biota composition (e.g., legacy effects, potentially positive and negative)

Lakes, being a particular focal point for restoration actions, require implementation of reliable, consistent state of the environment monitoring programmes that should be comparable among catchments, regions and at national scale. The Bay of Plenty Regional Council has a comprehensive state of the environment monitoring program for the Rotorua–Te Arawa lakes, with monthly monitoring that provides water column profiles and measurements at discrete selected depths in ten lakes, including supporting assessment of the Trophic Level Index (Burns et al., 1999) which is used as an indicator in the Regional Water and Land Plan to set specific water quality targets for each lake. The ten lakes are monitored at a central (mid-lake) station for several physical, chemical and biological attributes (see Burns et al., 2009). Some of the larger lakes have up to three additional monitoring stations. Autonomous sensors have been set up on buoys in several of the lakes to provide high frequency measurements at fixed depths or variable depths via automated profiling systems. Sensors provide valuable data on temperature stratification, oxygen depletion rates in bottom waters, and changes in levels of chlorophyll, as a surrogate for phytoplankton biomass, or phycocyanin, as an indicator of cyanobacteria biomass.

The Rotorua–Te Arawa lakes monitoring programme should serve as a model for adoption more widely in New Zealand although it has some limitations related to the phenology of phytoplankton and zooplankton, i.e., there are limited taxonomic data for these two groups of biota in the lakes. Key features of the Rotorua–Te Arawa lakes' monitoring programme include (i) routine long-term monitoring in all lakes and high-frequency measurements in several of the lakes, (ii) applications of numerical models to many of the lakes to generate understanding of lake processes and environmental scenarios, (iii) programs adapted specifically to monitor the effects of lake mitigation actions, and (iv) active communication channels among scientists, managers and the community (including Māori) to align expectations over lake water quality outcomes, funding and responsibilities.

State of the Environment monitoring provides the underpinning background to make assessments of changes in lake trophic state. For many in-lake mitigation actions, however, there is a need for targeted monitoring that is usually associated with increased temporal or spatial resolution to assess rapid or spatially specific responses, respectively, to the mitigation. In-situ sensor-based monitoring from the Lake Rotorua monitoring buoy, operational since 2007, has provided near-continuous monitoring of temperature, dissolved oxygen and chlorophyll, as well as other variables. An automated monitoring system in Lake Rotorua has been particularly useful in considerations of the rate of oxygen depletion in bottom waters of the lake during periods of stratification, as the duration of stratification in polymictic Lake Rotorua can be quite variable, influenced by the prevailing meteorological conditions (McBride and Rose 2019). Satellite images also provide comprehensive spatial coverage of temperature, chlorophyll and optical clarity and colour of surface waters (e.g., Allan et al. 2015; Lehmann et al. 2019). Ability to harmonise high-frequency sensor data and satellite data, as well integrating the monthly state of the environment data, provide an emerging opportunity for Bay of Plenty Regional Council to continue its position as the leading regional council in lake monitoring. However, it will require additional substantial investment in data storage and analysis, and skilled assessment. The information arising from such a programme may overlap with the requirements for location-specific and high-frequency monitoring associated with mitigation actions.

Lake models and water quality predictions can help address some of the limitations mentioned above. Models can simulate lake water quality responses at desired spatio-temporal scales to inform lake restoration efforts. Approaches to model lake systems are briefly addressed in Hamilton (2019) and more extensively in Rousso et al. (2020). These include statistical, biophysical (process-based), Bayesian, and Neural Network models. The selection of a suitable model often needs to be linked with the goals of the work, availability of input data, ability to validate model output with measured data, and whether the model is suitable for assessing specific mitigation actions (Hamilton et al., 2019). Calibration and validation are critical components of the modelling process, so that confidence is developed in the ability of different scenarios to realistically project a future condition.

As an example of a process-based model, Qian et al. (2022) outlines a modelling framework (Fig. 3) to track phosphorus sources for a large shallow lake (Taihu) in China. The framework proposed by Qian et al. (2022) is similar to that used for many of the Rotorua–Te Arawa lakes, except that the Taihu application uses a three-dimensional hydrodynamic and water quality model to encompass horizontal variability, while the Rotorua simulations include a broader range of mitigation actions, including evaluating impacts of climate change. The modelling of the Rotorua–Te Arawa lakes represents one of a small number of examples globally where models are used in an operational sense to hindcast and forecast the effects of in-lake mitigation actions (Lehmann and Hamilton 2019). For example, for Lake Rotorua, a one-dimensional lake model (DYRESM-CAEDYM) was adapted to assess the effects of alum dosing in two streams (Puarenga and Utuhina) by adjusting concentrations of P in the streams, as an input to the model, as well as increasing the sedimentation of P in the lake model to represent the effects of flocculation by the alum, and reducing the rate of P release from bottom sediments to represent P-locking as alum affects the sediment P releases (Hamilton et al. 2012). This model application has been used for long-term (multi-year) simulations suitable to evaluate lake water quality changes associated with changes in catchment nutrient loads and climate change (Table 3). Three-dimensional models (e.g., ELCOM-CAEDYM) have also been used to evaluate specific flow patterns or management actions (Gibbs et al. 2016). These models are used to generate environmental scenarios for community consultation purposes. This work is being reinvigorated through the Toihuarewa – Waimāori Chair in Lake and Fresh Water Science (Assoc. Prof. Deniz Özkundakci) based at the University of Waikato.

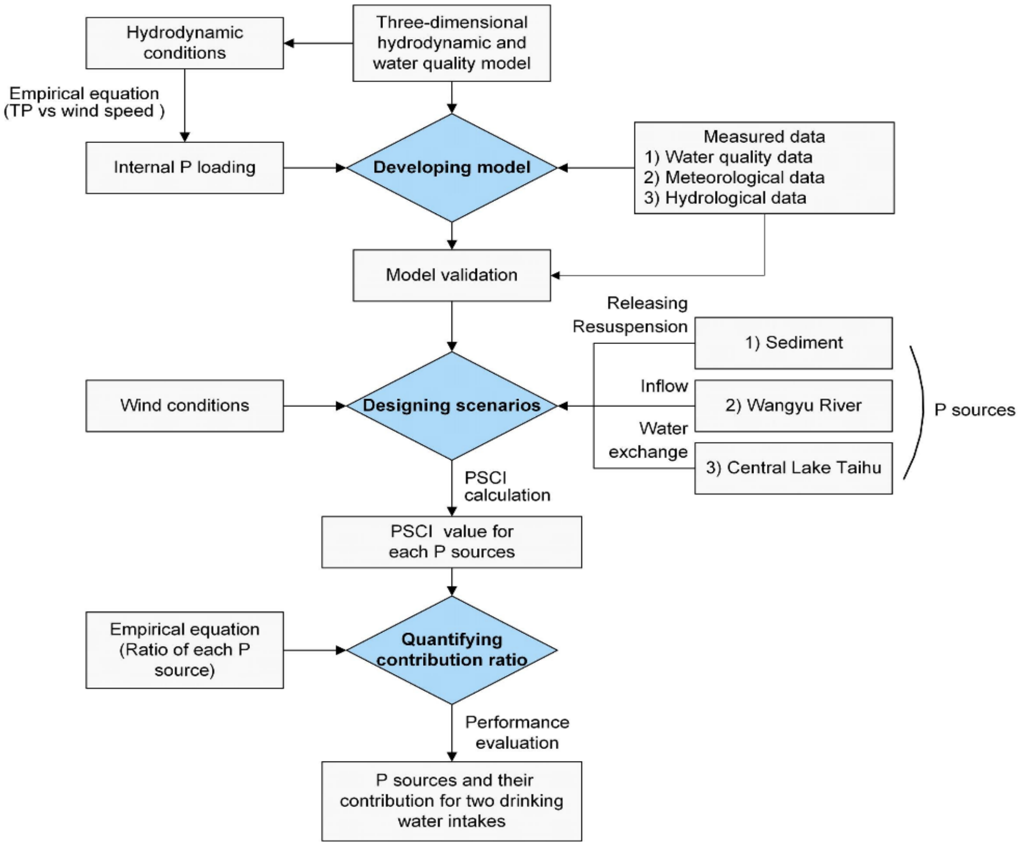

Figure 3 Schematic illustration of a modelling framework to track phosphorus sources in a large shallow lake (TP, total phosphorus; P, phosphorus; PSCI: P source contribution index). Figure adopted from Qin et al. (2022).

Table 3. Monitoring protocols, model deployments, management actions and community consultation processes for the 12 Rotorua–Te Arawa lakes in the Bay of Plenty Regional Council monitoring program. Abbreviations used are Ag = agricultural, MRM = monthly routine monitoring, HFM = high frequency monitoring, WRM = weekly (approx.) routine monitoring in specific periods, BMPs = best management practices. SWAT is the Surface Water Assessment Tool which has been used in the Rotorua catchment for simulations of streamflow and nutrient loads, and MODFLOW is a groundwater model that has been used to assessment groundwater inputs to several of the Rotorua–Te Arawa lakes.

Lake	Monitoring protocol	Model application	Management action	Guiding document or group
Rotorua	MRM, HFM, bottom-sediment composition	SWAT DYRESM-CAEDYM, ELCOM-CAEDYM	Geoengineering (alum dosing), catchment nutrient load reduction policy	Lakes Rotorua and Rotoiti Action Plan
Rotoiti	MRM, HFM, inflow tracers	DYRESM-CAEDYM, ELCOM-CAEDYM	Inflow diversion wall	Lakes Rotorua and Rotoiti Action
Rotoehu	MRM, HFM, WRM	ELCOM-CAEDYM	Destratification, land use change, floating wetlands,	Lake Rotoehu Action Plan

Lake	Monitoring protocol	Model application	Management action	Guiding document or group
			geoengineering (alum dosing)	
Rotoma	MRM, forest harvest monitoring	DYRESM-CAEDYM	None	Lake Rotoma Action Plan
Okareka	MRM	DYRESM-CAEDYM	Replace septic tanks, catchment land use change, geoengineering (Phoslock)	Lake Okareka Action Plan
Rotokakahi	MRM, inflow tracers	DYRESM-CAEDYM, ELCOM-CAEDYM, MODFLOW	None	Lake Rotokakahi Board of Control (Māori owners)
Tikitapu	MRM, bottom-sediment composition	DYRESM-CAEDYM, MODFLOW	Replace septic tanks	Lake Tikitapu Action Plan
Tarawera	MRM, HFM	MODFLOW	None	Lake Tarawera Action Plan
Okaro	MRM, HFM, WRM, bottom-sediment composition	DYRESM-CAEDYM, MODFLOW	Geoengineering (Aqual-P^{TM}, alum dosing), agricultural best management practices	Lake Okaro Action Plan
Rerewhakaaitu	MRM, HFM	DYRESM-CAEDYM, MODFLOW	Ag BMPs	Ag BMPs by farmers

6. Climate change and lake stratification

Lake variables (physical, chemical, and biological) are highly sensitive to changes in climate and anthropogenic pressures (Woolway et al., 2020) and they can also critically contribute to Earth's climate through carbon emissions (Woolway et al., 2022). Including climate change is a priority for designing climate mitigation action plans for ecosystems (Morales-Marin et al., 2021). Climate change impacts on New Zealand lakes are discussed in Hamilton et al. (2012), and include a projected increase in rainfall extremes, a decrease in annual rainfall in most regions, and rising temperature. The increase in surface temperature results in increased intensity and duration of stratification, leading to greater potential for bottom-water anoxia, increased intensity and frequency of algal blooms, and potential for invasions as temperature begins to exceed the tolerance levels of endemic species and may better suit that of the non-native invaders (see e.g., Vincent 2009; Jenny et al. 2020). In this section we summarise recent large-scale evidence of climate change effects on lake stratification, eutrophication, and harmful algal blooms.

Change in the water surface temperature from climate change is well documented. Studies have reported trends of increasing surface water temperature (Coats et al., 2006; Austin and Colman, 2007). Earlier onset of lake stratification may also occur due to a seasonal shift in temperature. This pattern may be affected by changes in precipitation patterns. Surface water temperatures are clearly impacted by increased air temperature and have increased at rates comparable to, or greater than, the rate of increase of air temperature (e.g., O'Reilly et al. 2015). Anderson et al. (2021) have shown that water temperatures have also increased in deep waters of large lakes (e.g., Lake Michigan) although these changes have tended to be less consistent and obvious than in surface waters (Pilla et al. 2020). The three-decade, high-frequency (hourly to three-hourly) continuous subsurface water temperature observations in Lake Michigan (Anderson et al. 2021) revealed that the shortened winter season drives much of the increase in temperature in the lower water layer (0.04 to 0.05 ^{o}C/decade) and earlier onset of summer stratification (cooling period reduced below 100 days and summer stratification extended beyond 200 days). Their thesis is that these changes accelerate eutrophication, increase the probability of algal blooms, and are likely to increase establishment of invasive species.

Woolway et al. (2021) provided additional evidence of the earlier start of stratification in lakes in the northern hemisphere. They predicted that under a scenario of high greenhouse gas emissions, stratification in the lakes would begin 22.0 ± 7.0 (± standard error) days earlier and end 11.3 ± 4.7 days later by the end of this century. In other words, there would be a 33.3 ± 11.7 day increase in the stratified period, which is likely to increase the probability of deoxygenation of bottom waters, with subsequent effects on nutrient mineralisation and phosphorus release from lake sediments. Further misalignment of lifecycle events, with possible irreversible changes for lake ecosystems, is also likely. Morales-Marin et al. (2021) have linked earlier thermal stratification with increasing occurrence of anoxic events and concluded that meteorological variability would generate a nonlinear increase in lake water temperature during summer and autumn in the upper water layers. Sahoo et al. (2016) showed that increase in subsurface temperature reduced deep vertical mixing in Lake Tahoe; a critical part of the process of the annual renewal of dissolved oxygen for deep waters. Their study concluded that a change in mixing properties and depth of deep mixing will affect nutrient supply to the upper waters, affecting primary productivity and food-web dynamics. The study also indicated that curtailing deep mixing could affect the resident salmonid population through deep-water anoxic consequences on ecosystems.

Temperature extremes such as heatwaves can increase the incidence of harmful cyanobacterial blooms (Jöhnk et al., 2008). Hou et al. (2022) showed an increase occurrence of algal blooms based on characterising 248,243 freshwater lakes globally. Their study attributed increased algal bloom incidences to climate change, agricultural practices, and anthropogenic interventions. It also 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 simulating stressors (e.g., climate change) in isolation, as use of single stressors may significantly underestimate the impact of climate change on bloom development (Tewari, 2022). Qin et al. (2021) determined the combined effect of climate warming and nutrient enrichment on cyanobacterial blooms. Their study found that regional climate anomalies exacerbated eutrophication via a positive feedback mechanism, intensifying internal nutrient cycling and aggravating cyanobacterial blooms. Due to the global expansion of eutrophication and blooms, especially in shallow eutrophic lakes, the regional effects of climate anomalies are nested within larger-scale global warming predicted to continue in the foreseeable future. Luo et al. (2022) showed that short-term rainfall significantly reduced cyanobacterial biomass in warm months, while the opposite response was observed in cool months. It was suggested that meteorological factors drive changes in water temperature and the hydrodynamic response, affecting the biomass of cyanobacteria in warmer months specifically. As climate change effects intensify, such varying responses of cyanobacterial biomass to short-term rainfall events in shallow eutrophic subtropical reservoirs may also be expected in temperate lakes (see also Wood et al., 2016). Intense rainfall events, expected to increase in frequency with climate change, erode sediments and transport nutrients (Berger et al. 2006; Dragoni and Sukhija, 2008), as well as decreasing water clarity. A recent paper (Oleksy, 2022) has indicated that climate change has led to widespread change in lake colour (‘browning’) across the world, induced in part by changing hydrology and inputs of optically active components in water, including sediment and chromophoric dissolved organic matter. Collectively, these multiple internal and external stressors have led to a 'warning to humanity' about the rapid degradation of the world's large lakes (Jenny et al., 2020).

Many New Zealand lakes, including Lake Rotorua, are eutrophic and can have severe blooms of toxic cyanobacteria. Lake Rotorua may become even more eutrophic under future climate change (Smith et al., 2016). Global warming and subsequent changes in water quantity and quality are likely to aggravate the lake eutrophication process and occurrences of cyanobacterial blooms (Paerl and Huisman, 2008). Hamilton et al. (2012) noted that the effect of a warming climate may be accentuated in polymictic shallow lakes compared with deep lakes. In polymictic lakes, periods of temporary stratification will become more regular and prolonged, with potential for increased deoxygenation of bottom waters in eutrophic systems. Many shallow lakes in New Zealand are highly impacted by anthropogenic activities and any increase in anoxia or decrease in water levels may lead to higher rates of release of nutrients from the bottom sediment, which is likely to make the lakes more vulnerable to eutrophication (Abell et al. 2019). Management of New Zealand lakes needs to account for long-term climate change and short-term extreme climate events in future management plans.

Changes in dissolved oxygen of freshwater lakes induced by global warming and anthropogenic pressures are of concern as they affect habitat availability for aerobic organisms (Kraemer et al., 2021) and have sequential effects on key biogeochemical processes that affect concentrations of nutrients and metals (Breitburg et al., 2018). The changes in the upper water column with warming are primarily associated with decrease in gas solubility and increased biological activity (Seki et al., 1980). Declining trends in concentrations of dissolved oxygen have occurred in deeper waters due to rising surface and subsurface water temperatures and reduced vertical mixing (Keeling et al., 2010; Long et al., 2016; Jane et al., 2021). Temperature extremes, such as heat waves, induce a high degree of thermal stability resulting in greater hypolimnetic oxygen depletion and increasing the risk of occurrence of deep-water anoxia (Jankowski et al., 2006). Oxygen losses are amplified by increased decomposition rates resulting from warming (Jankowski et al., 2003; Yvon-Durocher et al., 2010). Based on an analysis of 45,148 dissolved oxygen and temperature profiles for temperate lakes spanning the period 1941 to 2017, it was surmised that there was an overall decline in dissolved oxygen in surface and near-surface waters, primarily associated with reduced oxygen solubility from warming temperature (Jane et al., 2021). The study found that dissolved oxygen decline in deep waters is mostly associated with stronger thermal stratification (due to climate change) and loss of water clarity, but not with changes in gas solubility. Declines in dissolved oxygen in freshwaters are 2.75 to 9.3 times greater than observed in the world's oceans which could threaten essential lake ecosystem services (Schmidtko et al., 2017; Schindler, 2017; Breitburg et al., 2018).

It is evident from the projected changes described above that lake ecosystems across the globe have already been affected by climate change, and the magnitude of these changes is likely to increase in forthcoming decades (Jenny et al. 2020). Some of the effects of climate change include increased stratification, deoxygenation, harmful cyanobacterial blooms, and reduced water column mixing. Climate-induced shifts in lake water balances and nutrient transport mean that the effects of climate change are likely to be diverse and will affect multiple variables in lakes (Butcher et al., 2016). Significant advances have been made to understand the patterns, drivers, and consequences of stratification, deoxygenation and harmful algal blooms on lake ecosystems, and the lake responses to remediation techniques designed to counter these occurrences, but there is a need to improve predictions that inform lake restoration and management at large temporal and spatial scales.

Improved modelling frameworks are needed to integrate anthropogenic and climatic stressors and better predict the lake ecosystem responses to restoration measures (including feedbacks and lessons learnt that inform the management actions). This knowledge will increasingly be informed by in-situ and remote sensing observations to support model validation at a variety of scales. The improved mechanistic understanding of lake systems, together with communication, policy formulation, conservation, and engineering tools, can form critical elements of holistic lake restoration strategies (Magee et al., 2019).

Conventional catchment-based lake management strategies alone may not be able to fully reverse or prevent the eutrophication of freshwater lakes, and additional interventions using geoengineering may be required (Osgood, 2017; Morabito et al., 2018). Engineering strategies may increasingly be sought and can often involve complex design, infrastructure and consent processes (e.g., destratification operations), hinting that early planning and consultation are vital components of implementation. Strategies may also need to be 'outside of the box' and adaptive because unforeseen changes in lake behaviour may occur as a results of future climate change (Magee et al., 2019). Multi-faceted approaches, which may range from traditional conservation/restoration practices to novel technological and engineering solutions, may need to be adapted on a case-by-case basis. Adaptation approaches should focus on enhancing the resistance and resilience of lakes to climate change and anthropogenic stressors (Miller et al., 2007), noting that lakes close to a reference or baseline state (often linked to low trophic status) are more likely to be resilient to climate change (Brookes and Carey 2008; Visconti et al., 2008; Paerl, 2014).

Addressing the impacts of climate change on freshwater ecosystems requires collective action by local and national government agencies. Local communities are also important agents of change and incorporating human dimensions of climate adaptation can be important for gaining acceptance of proposed geoengineering and other lake management approaches. To tackle climate change impacts on freshwater lakes, decision-making requires both 'top-down' and 'bottom-up' assessments to help design and implement adaptation measures (Barruffa et al., 2021). Improved understanding of the synergies, conflicts, and trade-offs between adaptation practices and climate change effects on lake ecosystems can significantly contribute to integrated climate policy and effective climate adaptations for the freshwater lake systems.

Table 4 gives a summary of projections associated with climate change and potential impacts on lake water quality. Climate change will have multiple effects; at an external (catchment) and internal (in-lake) scale; on the mixing and transport dynamics within lakes; on the volume of water and loads of constituents entering a lake; on dissolved oxygen in surface and bottom waters, on biogeochemical interactions; on habitat availability for biota and opportunistic introductions of invasive species; and on the productivity of macroalgae, phytoplankton, and macrophytes.

Table 4 Predicted effects of anthropogenic climate change in NZ and key limnological impacts; predicted changes in key climatic drivers.

Effect	Predicted magnitude of effect	Reference	Limnological impact	Reference
Warming	0.1- 1.4 ^{0}C by 2030s	Wratt et al. (2004)	Eutrophication	Visconti et al. (2008), Trolle et al. (2011)
	0.2- 4.0 ^{O}C by 2080s	Wratt et al. (2004)	Phenology of mixing, eutrophication	Winder and Schindler (2004)
Precipitation	Increase except in eastern North Island and northern South Island	Hennessey et al. (2007)	Decreased water residence times Increased external nutrient loading	Hamilton et al. (2012) Schallenberg and Hamilton (2013)
Wind	Midrange projections by 2080: 60% increase in mean westerly component of wind speed	Wratt et al. (2004)	Increased turbulence and resuspension	Hamilton and Mitchell (1997) Schallenberg and Hamilton (2013)
			Deeper mixing	Davies-Colley (1984)
			Increased aeolian dust (phosphorus)	McGowan et al. (1996) Brahney et al. (2019)
Sea level	By 2100: 0.18-0.59 m increase relative to year 2000	Hennessey et al. (2007)	Salinization of coastal lakes and lagoons and disappearance of some	Schallenberg et al. (2003), Duggan and White (2010), Hamilton et al. (2012)

7. Restoration techniques

7.1 Algicides

Chemical algicides are not generally recommended for lake restoration, fundamentally because they fail to address causal agents of blooms (usually nutrient levels) and treat the symptoms (lysing cyanobacteria cells and sometimes causing en-masse releases of cyanotoxins if the bloom is toxic). Mass release of cyanobacterial toxins into the water when there are large blooms usually limits the use of many algicidal treatments in drinking water reservoirs (Stroom and Kardinaal, 2016). To minimize potential harm to human health and aquatic biota, chemical algicides need to be selected to minimise potential toxicity, long-term persistence, and for their ability to target the species (e.g., cyanobacteria) of concern. Jar and in situ experimental tests should be used to understand the influence of key environmental factors that influence the efficacy of algicides and their potential side effects, for example pH and dissolved organic and inorganic forms of carbon. Mixing and hydrodynamic models are also valuable for considering the dispersion of the algicide and therefore whether the desired concentrations and contact times are achieved for the algicide to effectively inactivate cells (see Lehmann and Hamilton et al. 2019).

Biological algicides have been used to remove or control red tide (marine and estuarine) harmful algal blooms (Balaji-Prasath 2022). The reactive chemical agents are produced biologically and include chemicals like lipids, tannins and acids that have some form of biocidal activity. We are not aware of similar biocidal applications to freshwater systems and at the present time these biocidal agents remain a promising research avenue. Burford et al. (2020), for example, have been examining terrestrial dissolved organic matter from vegetation as a suppressant of cyanobacterial blooms, raising the possibility that revegetation around lakes could target certain tree species known to produce high levels of organic compounds that suppress blooms.

For the reasons given above we do not go into extensive detail about use of algicides, providing a brief contemporary review below. Readers should refer to the review by Matthijs et al. (2016) of existing and emerging cyanocidal compounds for cyanobacterial bloom mitigation and the recent review by Balaji-Prasath (2022) which is focused mostly on marine and estuarine algal bloom species. We also note that control of invasive macrophytes with herbicides is a separate topic, with around 50 problematic aquatic weeds costing an estimated $27m per annum (2010 figure) for control using a range of chemicals such as Diquat, endothall and glyphosate (Champion et al. 2019). Herbicidal treatments are likely to have non-target effects on phytoplankton also (Ni et al., 2014).

Copper: Chemical control methods using copper have been used for many years and have sometimes been employed in a pre-emptive mode to prevent or restrict the size of algal blooms (Zhang et al., 2020). Most copper based algicides use copper sulphate ($CuSO_4$) which is relatively cheap and limits the growth, metabolism, and photosynthesis of algae, and more generally promotes cell stress (Schindler, 2006; Ebenezer et al. 2014; Bishop et al., 2018). A variety of copper algicidal variants are available including registered products with copper in chelated form.

In shallow Fairmont Lakes in Canada, copper compounds have been used for 58 years to prevent excessive algal growth (Hanson and Stefan, 2010). Hullebusch et al. (2002) provide an example of use of copper sulphate as an algicide to control cyanobacteria in a small shallow polymictic lake in France, but it was only effective against the cyanobacterial genus *Microcystis* for a limited period (two months). The large-scale and continuous application of copper sulphate is usually restricted due to harmful side effects to many non-target aquatic organisms and the potential for build-up of copper in bottom sediments. En masse release of intracellular compounds from algae is a concern as the substances released can be toxic (e.g., cyanotoxins) or causal agents of taste and odour that impairs the quality of drinking water supplies; this issue is not unique to copper and all potent algicides will lyse and kill cells. Concerns have also been expressed about the potential for copper-resistant harmful cyanobacteria species and some bloom-forming species with high tolerance to copper, especially in response to repeated doses (Hobson et al., 2021).

Ozone: Dissolved ozone is a highly reactive molecule that can oxidise and degrade a wide range of organic compounds. Concentrations of 1-5 mg L^{-1} and a contact time of 5-10 minutes are usually required for effective oxidation in water treatment processes. Ozone produces hydroxyl radicals and peroxides that are generally short-lived but can be expected to be harmful to biota generally, not only the target bloom species. The process of oxidation may, however, be highly effective for oxidising cyanotoxins (Ponnusamy et al. 2019). In marine and brackish waters, ozone has been effective in inactivating red-tide blooms species such as *Karenia brevis*, *Amphidinium* sp. and *Cochlodinium polykrikoides* (Oemcke and Hans van Leeuwen 2005; Shin et al. 2017). Ebenezer and Ki (2013) found the oxidised species from ozone rapidly killed ten different algal bloom species through lipid peroxidation, cell membrane rupture and disruption of gene structure. The use of ozone treatment of cyanobacteria blooms in natural waters has mostly been experimental in nature and not widely reported in international academic journals. Jar tests are a critical part of any consideration of use of ozone in the natural environment because there is a wide variety of compounds present in lake water that may be preferentially oxidised before the target organisms (e.g., cyanobacteria) are inactivated.

Hydrogen peroxide: In recent times hydrogen peroxide has become popular as an algicide, in part because of reduced side effects and low impacts on non-target organisms compared with many other algicides, as well as relatively simple breakdown products, i.e., water (Lürling and Mucci, 2020). Hydrogen peroxide efficacy is affected by environmental factors in a similar way to ozone, with effective does-response relationships from 2 to 100 mg L^{-1}. A recent paper (Weenink et al. 2022) has developed a species sensitivity distribution for phytoplankton, zooplankton and macroinvertebrate taxa based on EC50 and LC50 values. As expected, three cyanobacterial taxa were highly sensitive to hydrogen peroxide, but the rotifer *Brachionus calyciflores* and the cladocerans *Ceriodaphnia dubia* and *Daphnia pulex* were also highly sensitive. They concluded that there is a trade-off between successful suppression of cyanobacteria at the expense of sensitive species in the zooplankton community.

There is emerging evidence that hydrogen peroxide targets benign phytoplankton (e.g., chlorophytes) over harmful cyanobacteria (Yang et al. 2018; Fan et al., 2013, 2019). Pokrzywinski et al. (2022) found a substantial reduction in biomass (including chlorophyll *a*, and cyanobacteria) after the application of a peroxide-based algicide (sodium carbonate peroxyhydrate) in Lake Okeechobee, Forida, USA and concluded that the peroxide-based algicide was a strong candidate for scalable field trials in cyanobacterial control. Hydrogen peroxide treatment can be considered as inducing an extreme form of photosynthesis, i.e., mimicking the reactive oxygen species, including hydroxyl, produced internally during photosynthesis, and which exceed the capacity for their removal by antioxidant enzymes, such as superoxide dismutase, catalase, reduced glutathione and peroxidase. Naturally the application of hydrogen peroxide is to the bulk water, however, and safety considerations are an important part of handling and applying this chemical. Matthijs et al. (2012) consider that diluted hydrogen peroxide could be useful for recreational lakes and drinking water reservoirs when there is a need for urgent and immediate action to control cyanobacteria on short time scales not commensurate with the time required to control nutrients and limit cyanobacteria by nutrient limitation.

Other chemicals: There is an abundance of chemicals with various biocidal efficacies. Chlorine, permanganate and sodium hypochlorite are mostly associated with conventional water treatment processes but have been used in some natural situations to control blooms, e.g., the marine species *Prorocentrum minimum* (Ebenezer and Ki 2013). The oxidative reagent potassium monopersulfate apparently prevents cyanobacteria from multiplying (Wu et al., 2014). Salicylic acid is an algicide that is considered to provide long-term prevention of algae growth (Guo et al., 2015). Biodegradable polymer foam can be used as a carrier of algicides to improve the efficiency of the biocidal process (Bae et al., 2015). In a recent review, Balaji-Prasath et al. (2022) stated that algicides loaded on cationic particles can enhance algicidal effects. Their table 3 summarises a range of oxidants that have been used to control red tide (estuarine and marine) bloom species with values given for the efficacy and the required concentration of oxidant.

7.2 Coagulants

Using coagulants to aggregate cyanobacterial cells and sinking the aggregate out of the water column, sometimes through biocidal effects of the coagulant, is a chemical treatment used to reduce cyanobacterial biomass (Lürling and Mucci, 2020), but most coagulants are intended primarily to reduce nutrient levels and address the excess concentrations that lead to algal blooms and eutrophication. It may be difficult, however, to distinguish remediation focused solely on phosphorus control strategies from beneficial side effects related to direct removal of cyanobacteria (e.g., Thongdam et al. 2021). Coagulants in common use (e.g., Phoslock®, Aqual-P^{TM} and aluminum salts) have little to no direct biocidal effect compared with algicides, including hydrogen peroxide, and chitosan (see below) (Kang et al., 2022). Literature covered in the previous review (Hamilton, 2019) is still highly relevant to this review, noting a review of coagulants by Douglas et al. (2016) that examined a range of naturally occurring and processed materials, including materials commercialised for use in lake restoration, that could be useful for nutrient removal:

- 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).

Aluminium: Alum (aluminium sulphate) is a common coagulant used for removing cyanobacteria from the water column, adsorbing phosphate, and flocculating and sedimenting material from the water column (Abell et al., 2022). Tempero (2015a, 2015b, 2018) has provided extensive reviews of the low potential for ecotoxicity of alum under the dosing regime used in Lake Rotorua, while Smith et al. (2016) document some impressive impacts from alum dosing of inflows to Lake Rotorua, which are associated with reductions in cyanobacteria biovolume and concentrations of total phosphorus in the lake. Various iron compounds have been used for binding phosphorus, but these are not covered in this review because most of these compounds are reduced in anoxic conditions, i.e., they liberate phosphorus, whereas materials like alum and Phoslock® are much more stable under anoxic conditions.

The efficacy of alum for phosphorus control is not in question. A recent review (Agstram-Norlin et al. 2021) points to some of the success factors influencing eutrophication control with alum, as well as focusing attention on the importance of long-term monitoring programs, including determination of external loads to properly evaluate the effects of treatment on sediment phosphorus release and lake water quality. A comprehensive review of international lake studies of alum dosing, including Lake Okaro, is given in Kyriakopoulos et al. (2021) and, interestingly, documents several alum dosing cases where planktonic and benthic biodiversity has been improved through alum dosing, with few issues of ecotoxicity provided pH is circumneutral and excessive smothering of benthic biota from floc deposition is avoided. Targeted application of alum can also improve efficacy and avoid non-target issues, such as injecting dissolved aluminium into anoxic bottom sediments of lakes (Rydin, 2014) or 'pre-capture' (Lyu et al., 2020).

Other recent literature has focused on optimising treatment efficiency for reduction of internal loads (Agstam-Norlin et al., 2020) and including aluminium in novel compounds that provide synergistic effects on phosphorus removal (Yin et al. 2020), as well as use of aluminium in combination with other phosphorus inactivation agents. For example, trials have been carried out of modified zeolite in combination with poly aluminium chloride (PAC) and lanthanum-modified bentonite (assumed to be similar or identical to Phoslock®) (Yang et al. 2021). It has been shown that Phoslock® may increase the release of ammonium under anoxic conditions (Zeller and Alperin 2021). Similarly, Pan et al. (2020) has evaluated a granulated lanthanum/ aluminium hydroxide composite adsorbent that was considered potentially scalable for mesotrophic systems with moderate phosphorus loads.

Other methods have included 'floc and sink' (Fig. 4) using alum to floc phosphorus and *Microcystis* sp., and a local soil as a ballast to sink the floc (Thongdam et al. 2021). Liu et al (2022) suggested using a combination of flocculants and oxygenators for treating high-concentration cyanobacterial blooms for emergency purposes. A study by Agstam-Norlin et al. (2020) developed a model for optimising alum applications based on the applied dose, mobile sediment phosphorus fraction in the sediment and lake morphology, which could be useful for future considerations of alum dosing in the Rotorua Te Arawa lakes. Kuster et al. (2016) suggest that a fixed mass ratio between aluminium and mobile plus labile organic sediment phosphorus of 11:1 could be used as a conservative guideline to avoid overdosing of aluminium relative to the available phosphorus. Such a guideline could also be used to check current and past alum dosing levels of Lake Rotorua.

Figure 4 Small-scale experiments using controls and various concentrations of flocculants are essential to build a body of evidence on the efficacy of flocculants at different doses.

Chitosan: Chitosan is a readily biodegradable coagulant which has algicidal effects (Kang et al., 2022). It may be preferable to metal-based coagulants in pH-sensitive (low-alkalinity) lakes (Li and Pan, 2013), but it can cause cell lysis with longer exposure (Mucci et al., 2017). This cell-damaging effect reduces the potential of cyanobacteria to recolonise the water column, but slower rates of cell lysis may lead to more controlled (slower) releases of cyanotoxins (Li and Pan, 2015).

Clays: Lu et al. (2015) report on different types of clays to flocculate phosphorus and control harmful algae in a wide variety of waterbodies, from freshwater to marine. Modified clays are widely used in controlling harmful algal blooms (Lu et al. 2016; Yu et al. 2017). Modified clays produce cationic hydrolysis products that suppress growth of algal blooms cells directly through collisions inducing cell flocculation and indirectly by removing soluble nutrients (Balaji-Prasath et al. 2021). Studies have found that modified clay technology inhibits the germination of cysts (Wang et al. 2014) which is critical factor in the formation of harmful algal blooms from sediments. Thus, modified clay has potential to provide long-term reduction in harmful algal blooms.

Summary: Although many chemicals have been shown at laboratory scale to be promising candidates for lake restoration, their application is usually limited by cost, secondary pollution, and harmful effects on non-target aquatic organisms, humans, livestock, and wildlife. Our review has highlighted that there are many phosphorus inactivation materials in development but very few get to commercial stage, either because of logistical issues, costs (which are almost always greater than for alum), inability to scale practically to lake ecosystems, or unforeseen regulatory impediments. It usually takes many years until a commercial product can be developed, so our focus on new coagulants developed in the past 4-5 years may have underestimated their potential to get to market.

7.3 Hydraulic flushing

There is little new information on the effects of flushing following the previous review by Hamilton (2019) and, as noted previously, it is unlikely that hydraulic flushing could be used for any of the Rotorua lakes because there are no large upstream lakes or reservoirs to provide a sustained supply of good-quality water. For algal control, water residence times need to be reduced to around 20-30 days so that phytoplankton are washed out of the surface mixed layer, preventing net growth (Hamilton and Dada 2016; Zhang et al., 2020).

Many cyanobacteria grow more slowly than other phytoplankton taxa and harmful blooms usually occur at the surface, so they may be able to be preferentially targeted by hydraulic flushing, especially in the surface mixed layer. Hamilton and Duggan (2010) noted in the Waikato hydro lakes how high flushing rates prevent cyanobacteria blooms in the main channel but not necessarily in the poorly flushed side-arms. Recent literature (Giani et al. 2020) has focused attention on the use of flushing to control cyanobacteria biomass relative to other phytoplankton and noted that in tropical lakes (though not isolated to tropical lakes), periodic rainstorms induce flushing and mixing can attenuate the development of cyanobacteria blooms. Cyanobacterial blooms in stratified lakes may therefore be able to be targeted for control by reducing residence time (Cha et al., 2017), with concurrent reductions in phosphorus concentrations in the surface layer (Romo et al., 2012). Four diversions from the Yangtze River into Lake Taihu (Jiansu province, China) have been implemented since 2002 but these are considered ineffective as a control measure for cyanobacteria blooms (*Microcystis* spp.) because water residence times in the lake remain greater than 80 days and there are high nutrient concentrations in the diverted water (Li et al. 2013).

Olsson et al. (2022a, 2022b) noted that reduced water residence times may shorten and weaken summer stratification, reducing the duration of hypolimnetic anoxia in eutrophic lakes and can therefore combat the problem of high rates of internal P loading (see Fig. 5). Olsson et al. (2022b) applied this technique for the restoration of Elterwater, a shallow lake in the English Lake District, UK, which stratifies for several months each year. The study found that reducing annual water residence times by 4.9 days shortened the summer stratification length by 2 days. The study also recommended that larger reductions in water residence times would help to reduce the summer stratification period. The recent literature therefore suggests that the effects of shorter hydraulic residence time should be considered more broadly than as a flushing control for cyanobacteria blooms, and that ability to alter patterns of mixing and stratification may provide an additional eutrophication control measure. A combination of increased flushing and use of artificial mixing during warm periods may similarly disrupt formation of cyanobacteria blooms (Paerl, 2008;

Carvalho et al., 2011). Water level fluctuations also offer an opportunity to manage flushing to mitigate cyanobacterial blooms but the success is likely to depend on specific ecosystem properties, including the quality and retention of water, and climate conditions (Romo et al., 2012; Bakker and Hilt, 2016).

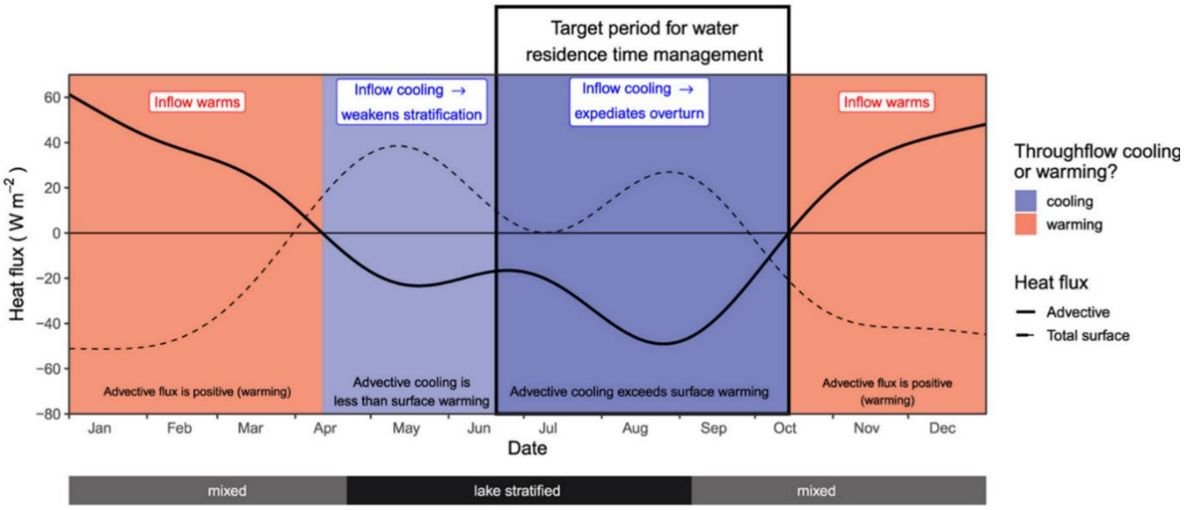

Figure 5 Impact of increasing throughflow on lake heat fluxes and thermal structure. Figure adapted from Olsson et al. (2022a).

7.4 Biological remediation

Biological remediation methods promote interactions between microorganisms and target organisms, to degrade, absorb, and transform lake nutrients to control eutrophication. These methods include microbial remediation and aquatic phytoremediation. The premise of microbial remediation is to settle out organic matter, nitrogen and phosphorus through increasing natural nutrient cycling processes and sedimentation of particulate material. Microbial bioremediation is accomplished by adding specific microorganisms (e.g., strains or species) to accelerate the decomposition of pollutants (Smith & Schindler, 2009). During the microorganism reproduction process, nutrients are absorbed by microorganisms, with the premise that higher rates of microbial productivity and biomass generation will remove bioavailable forms of nutrients (in dissolved form) and increase particulate forms, thereby leading to higher rates of sedimentation (Qin et al., 2013). Microbial remediation is affected by the physicochemical environment and competition (Blackburn & Hafker, 1993). As noted in the review by Hamilton (2019) microbial remediation is difficult to achieve and few well documented case studies exist. Scholes (2005) considered that a whole-lake trial of a microbial additive to Lake Sullivan (Bay of Plenty) was inconclusive and a trial of the additive in the northern arm of Lake Rotoehu also did not show significant changes in lake water quality.

Boopathy (2000) noted that in some cases, microbial metabolism of contaminants produced toxic metabolites. At a whole lake scale, it seems unlikely that a single strain or species of microbe, or even a blend of microbes, could multiply to exert the desired controls on nutrient transformations that would effect eutrophication control at a whole lake scale.

Microorganisms can disrupt the processes that make nutrients available for generating harmful algal blooms (Iannino et al., 2021; Ren et al., 2022). Artificial surfaces in the form of filters with a large specific surface area and a polymer material as a carrier can be used to promote biofilm-forming microorganisms, allowing pollutants to be intercepted, adsorbed, and degraded. When properly designed, these filters promote a wide diversity of microorganisms, improving degradation efficiency and pollutant removal rates. For example, Wu et al. (2005) used algal–bacterial biofilms in artificial aquatic mats to mitigate algal blooms. Huang et al. (2011) used three active barrier materials (zeolite, ceramic, and a lightweight porous media) to support biofilms to prevent nitrogen release from eutrophic lake sediments, with a bio-zeolite capping being the most effective. Yuan et al. (2014) used filamentous bamboo and plastic filling as a biofilm carrier for bioremediation of nitrogenous compounds from eutrophic water. The premise of floating wetlands (see below) is for plants and microorganisms to take up nutrients in dissolved form into plant or microbial biomass or to make the nutrients unavailable in other ways (e.g., as gaseous forms of nitrogen via denitrification or plant uptake (with the exception of nitrogen-fixing plants)).

The aim of targeted biomanipulation programs is to improve the lake environment by deliberately altering food web structure (Shapiro et al., 1975). This method is usually based on manipulating food-web interactions to ultimately reduce phytoplankton biomass and nutrient levels. Biomanipulation of fish has been common, involving removal of benthic-feeding species (e.g., carp and catfish) that resuspend sediments and nutrients from the bottom (Klinge et al., 1995; Mäler, 2004), or carnivorouss species to increase populations of target organisms such as zooplankton that can exert top-down control on algae (Søndergaard et al., 2010; Tang et al., 2015). In some cases, biomanipulation has involved adding planktivorous fish (e.g., silver carp) that feed directly on phytoplankton (Wang et al., 2017). Liu et al. (2018) used fish manipulation to provide long-term reductions in total phosphorus and phytoplankton biomass and reduce turbidity in a shallow subtropical lake (Fig. 6). They concluded that fish removal and stocking of piscivorous fish, combined with transplantation of submerged macrophytes, had major benefits on water clarity in the lake. However, removal of invasive benthivorous fish from highly degraded lakes needs exceptional effort and may not be economically if not accompanied by strong external load reductions (Abell et al., 2020). Khan (2021) studied pelagic food web structure and dynamics in two New Zealand Lakes (Lake Hayes and Lake Johnson) but did not find evidence of significant phytoplankton biomass control from introduced *Daphnia pulicaria* that increased the total biomass of *Daphnia* species. Studies on removal of benthivorous fish (predominantly common carp) from shallow hypertrophic Lake Ohinewai (surface area 0.17 km^2, maximum depth 4.5 m), in the Waikato River floodplain yielded no clear improvements in lake trophic status over five years, despite reducing the carp biomass from 308 kg/ha in 2011 to a minimum of 14 kg/ha in 2014 (Tempero & Hicks, 2017; Tempero et al., 2019). The recent widespread invasion of lakes Rotoiti and Rotoiti by catfish (*Ameiurus nebulosus*) is a major concern, however, with their ability to alter food web dynamics through benthic feeding and resuspension of bottom sediments and nutrients.

Bivalves can achieve high rates of filtering of phytoplankton and reduce their biomass (up to 60% reduction), resulting in a reduction of nutrients through filtration and excretion of nutrients as relatively refractory pseudofaeces (Jiang et al., 2016; Lucas et al., 2016; Marroni et al., 2022), although most cases are documented in the marine environment. More work is required to understand and support habitat for the native species kākahi (*Echyridella menziesi*) and kōura (*Paranephrops planifrons*) in the Rotorua-Te Arawa lakes. Kōura are recognised as a keystone species (Kusabs et al., 2015) with potential to impact lake food webs. Kākahi are filter feeders and filtering rates need to be used to consider potential for whole-lake, or at least localised, potential to control of phytoplankton at different kākahi population densities *(*Ogilvie and Mitchell, 1995), and ability to re-introduce or enhance natural populations.

Figure 6 Southwest Lake before and after restoration using fish manipulation. Figure from Liu et al. (2018).

Constructed wetlands: Wetlands play a key role in improving water quality and protecting biodiversity (Fisher et al., 2009). The aim of constructed wetlands is to enhance biodegradation potential through biogeochemical and physical processes associated with wetland plants and soil matrix composition. Constructed wetlands are of three types: i) vertical flow, ii) subsurface flow, and iii) surface flow. Vertical constructed wetlands are considered to be highly effective for removing ammoniacal nitrogen (NH_3/NH_4^+), total nitrogen and total phosphorus. Subsurface flow constructed wetlands may provide consistent removal rates of contaminants as they are better thermally insulated and subject to less hydrological variation (Nie et al., 2007). Surface flow constructed wetlands provide a combination of physical, chemical, and biological processes occurring simultaneously and contributing to natural reoxygenation, which is important for degradation and supporting the presence of oxidised species (e.g., nitrate) that can subsequently be removed, e.g., through denitrification.

Constructed wetlands have frequently been used in developing countries for nutrient removal from polluted lakes (Li et al., 2010) and are favoured due to modest cost, proven pollutant removal efficacy, and easy operation and maintenance. For pollutant removal, however, they operate at modest rates compared with expensive conventional wastewater systems designed specifically to handle high pollutant loadings (Shutes, 2001; Chakraborti and Bays, 2020). A recent review of constructed wetlands for wastewater treatment by Vymazal (2022) identified their value for treating agricultural wastewaters and runoff.

Floating wetlands: Floating wetlands (mats) constructed from vegetation such as rushes (e.g., *Juncus* spp.) or sedges (e.g., *Schoenoplectus* spp.) (Pavlineri et al., 2017; Bi et al., 2019) can be used for restoring eutrophic lakes. Floating wetlands constructed from *Typha angustifolia* are considered better alternatives to some other wetland species where there are space and cost constraints (Weragoda et al., 2012). Constructed floating wetlands are used for removing nutrients from lake water via uptake into plant tissues, as well as through denitrification in root mats (Zhang et al., 2014; Pavlineri et al., 2017). Additionally, floating wetlands can be used for providing habitat along with nutrient management (Huang et al., 2017). They can reduce wave action, which increases settling of sediments beneath the wetlands and significantly contributes to nutrient removal (Sukias et al., 2010), however, this reduces mixing and could prolong stratification in polymictic lakes, leading to internal nutrient loading mediated by anoxia (Abell et al., 2022). Constructed floating wetlands may have limited nitrogen and phosphorus uptake capacity and their performance is often overestimated due to extrapolation from small-scale experiments (Bi et al., 2019) but they can be effective at modest scale for storm water ponds (e.g., Tanner and Headley, 2011) or domestic wastewater (Zhang et al., 2014). They are effective in both tropical and temperate climates but low temperature may reduce their performance in winter in temperate regions (Arab et al., 2021). Constructed floating wetlands are mostly insensitive to changes in water level (Pavlineri et al., 2017). Modest performance in nutrient removal, cost involved, potential for faecal contamination and nutrient enrichment by aquatic birds, and incompatibility with some recreational uses should be important for considering establishment of floating wetlands and can make them a poor alternative to enhancing or establishing lakeside wetlands (Hamilton & Dada, 2016).

7.5 Filtration methods

Filtering of phytoplankton using mechanical filtration methods is largely dependent on the phytoplankton size distribution and density (Trindade de Castro and Veldhuis, 2019). Czyżewska and Piontek (2019) reported significant removal of plankton and cyanobacteria, including microcystins, using microstrainers (stainless steel wire cloth in a partially submerged stainless-steel drum). In Lake Taihu, filtration has been used to remove very high concentrations of cyanobacteria (Fig. 5), targeting specific areas (e.g., water treatment plant intakes). A trial has previously been run by Bay of Plenty Regional Council to mechanically filter water from the Ohau Channel outlet of Lake Rotorua to remove algae and nutrients. The conclusions from the trial were that filtration rates were inadequate to achieve the desired rates of removal of algae and nutrients (Scholes et al. 2010). Similar to considerations of flushing, filtration is only effective if the relevant water mass can be filtered in time periods of c. <20 days, so filtration is unlikely to be effective for cyanobacteria control at whole-lake scale.

Relevance to Lake Rotorua: Mechanical filtering of phytoplankton from Lake Rotorua is unlikely to be effective because low concentrations 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.

7.5 Aquatic phytoremediation

Aquatic plants can effectively absorb nutrients from the water column and sediments during their growth and may be effective as a remediation measure if these nutrients are not substantially recycled in the water column (Glick, 2003; Abed et al., 2017; Spangler et al., 2019). These plants may be emergent, floating, or submerged, and can have higher nutrient removal potential than terrestrial plants (Wang et al., 2011; Zhang et al., 2020).

Table 5 Plant species and their phytoremediation potential (adopted from Wang et al., 2011; Bu & Xu, 2013; Zhang et al., 2020). Note: several of these species are noxious plant pests in New Zealand (see footnotes).

Plants	**N removal (%)**	**P removal (%)**	**COD_{MN} removal (%)**	**Purification ability (%)**
Water hyacinth[1]	>75	>75	-	>75
Azolla japonica	65-75	65-75	-	65-75
Water peanut	>75	<65	-	65-75
Arrowhead	>75	65-75	-	>75
Water caltrop	<65	<65	-	>75
Sleeping lotus	<65	<65	-	>75
Ceratophyllum demersum[2]	65-75	<65	-	65-75
Canna lilies (*Canna* spp.)	30-50	20-25	20-40	>75
Elodea canadensis[3]	>75	>75	-	>75
Calamus (*Acorus calamus*)	30-45	15-45	20-35	-
Cyperus alternifolius	25-40	15-45	15-35	-
Vetiveria zizanioides	25-30	15-45	15-30	-

[1] Unwanted and notifiable aquatic plant, highly aggressive invader
[2] Hornwort, widespread and highly invasive in North Island
[3] Widespread, moderately invasive in New Zealand

Native species of lakeweed in New Zealand include turf communities, isoetes, native pondweeds and milfoils and charophyte species. Invasive aquatic plants often displace and replace native lakeweeds and have significant environmental consequences including loss of biodiversity, degradation of native fish and aquatic habitats, and restriction of recreational activities such as swimming and boating. Invasive lakeweeds can be quick to establish and form solid bands of dense weed around the margins of the lake. Nutrient (N and P) enrichment, near-bed anoxia, loss of native species, and changes in flow are features of dense invasive weed growth in waterways.

Methods to control invasive weeds are of three types: physical, chemical, and biological. Physical control methods include mechanical or manual harvesting of vegetation or biomass and habitat manipulation (which creates barriers to plant growth). Manual harvesting includes hand-weeding, raking and netting. Mechanical harvesting is carried out by using suction dredges, excavators, mowing, or cutting. Chemical control methods involve use of herbicides such as diquat, endothall, and glyphosate. Biological control methods use biocontrol techniques or grass carp to graze on and control or suppress the growth of target weeds. The latter method using grass carp has had mixed results in New Zealand, likely due to very large stocking levels of grass carp that appear to have been associated with a transition to a low-clarity, phytoplankton-dominated state (e.g., Lake Ōmāpere, as described by Hofstra 2014). Use of multiple possible control options, including, for example, herbicides, containment zones and biosecurity checks, are regarded as the best option for invasive aquatic plant control (Hofstra et al., 2018)

Figure 7 Harvesting of invasive floating macrophytes (Salvinia sp.) in a shallow urban lake in Brisbane, Australia. This operation was highly successful in removing the weeds and a large quantity of nitrogen and phosphorus. In New Zealand it is a notifiable and unwanted organism under the Biosecurity Act 1993 and efforts seek to eradicate it. Incursions of Salvinia have been common in the Northland region and it has been occurred as far south as Christchurch.

Horne (2020) investigated the feasibility of weed harvest in Lake Rotorua and considered it was uneconomic for nutrient reduction purposes although it could have removed c. 50 t of nitrogen. However, hornwort harvesting of dense hornwort beds in Lake Rotoehu, has been considered worthwhile at a cost of about $52,800/yr comprised of $22/kg N and $165/kg removal cost. In Lake Ōkareka, considerable work has been done to control submerged invasive weeds and allow native turf species to recover. The results have been better that anticipated considering only the plant removal (Hofstra, pers. com.) and suggest that there may be changes in biodiversity and 'naturalness' that extend to water quality, with diverse communities having increased resilience and nutrient processing capacity.

7.6 Oxygen nano-bubble technology

Conventional aeration used in water restoration for delivering oxygen, an essential life-sustaining component for aquatic life and substrate for oxidative degradation, often has relatively low energy transfer efficiency (see Hamilton 2019). Nanobubbles and microbubbles, with diameters less than 1000 nm, have low buoyancy and can slowly diffuse oxygen into the surrounding water (Lyu et al., 2019) (Fig. 8). Oxygen nanobubbles have oxygen utilization rates and volumetric mass transfer coefficients in synthetic wastewater treatment systems double that of conventional bubble aerated systems, i.e., it may require less than half the retention time required for the degradation of organic matter in conventional systems.

Nanobubbles may also be capable of supplying oxygen via a modified clay, to alleviate anoxia in lake sediment to maintain dissolved oxygen at concentrations > 6 mg L^{-1} for over 6 months (Zhang et al., 2018). The use of a sediment carrier for nanobubbles can allow for targeted actions in the bottom sediments of eutrophic lakes. Nanobubble-treated zeolites have also been used in laboratory-scale tests in two case studies in New Zealand where sediment samples were taken from Lake Ngaroto (Zhang et al., 2018) and a Waikato peat lake (Lake Millicich) (Woodward et al. 2017). Zhang et al (2020) demonstrated an effective application of nanobubble oxygen-carrying materials modified from natural zeolites and local soils to combat simulated internal P loading at laboratory scale. Following this treatment, sediment anoxia was reduced along with the release of nutrients and greenhouse gases from the bottom sediments (Pan et al., 2019; Waters et al., 2022). In-situ evidence about efficacy of this technology is not yet available at whole-lake scale and it appears to lack the level of investment required to progress it from lab or small-scale trials to a cost-benefit analysis, including practicality of the modified clay application, that would make it viable as a whole-lake commercial restoration material.

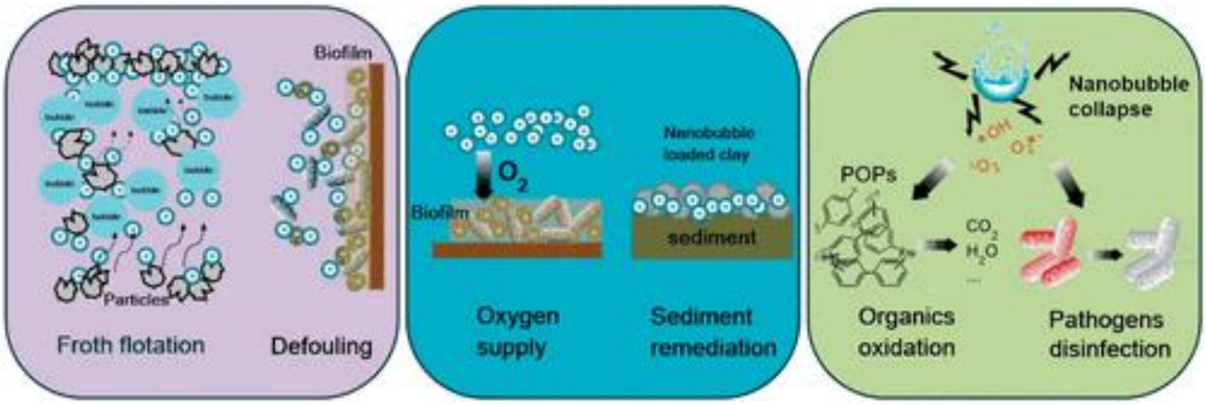

Figure 8 Potential contributions of nanobubble technology in environmental engineering due to their unique physical, biological, and chemical characteristics. Figure from Lyu et al. (2019) and reproduced under Creative Commons Attribution License.

7.7 Ultrasound treatment

Ultrasound treatment has been suggested to control cyanobacterial biomass at lake scale by collapsing of gas vesicles and inhibiting photosynthesis, and through lysis and damage of cells (Sukenik and Kaplan, 2021). Low frequency ultrasound may slow cyanobacteria growth (Asadi et al., 2013), while it is claimed by some manufacturers that ultrasound frequencies may need to be tuned to target different cyanobacteria due to varying levels of gas vesicles. Natural ability to recover gas vesicles may also strongly impact the efficacy of the ultrasound treatment (Sukenik and Kaplan, 2021). Several studies have found that low-frequency ultrasound is not effective at all in cyanobacterial control (Leclerq et al., 2014; Lürling et al., 2016). High-frequency ultrasound is more effective in killing cyanobacteria (Lürling & Tolman, 2014), but it will also kill zooplankton (Holm et al., 2008), and has high energy costs that make field-scale applications impractical (Lurling et al., 2016). Haocai et al. (2020) suggest adopting low-frequency, low-density, and short-duration ultrasound to reduce energy consumption. Their study found that an increase in ultrasound frequency can reduce effective distance of ultrasound treatment on algal cells, but cells were able to repair themselves when exposed to low ultrasonic frequencies (Haocai et al., 2020). Ultrasound treatment has gained popularity because of its ease of operation, lack of residuals, and minimal ecological impact (Schneider et al., 2015; Park et al., 2019), but all evidence from systematic studies suggests that it is ineffective at whole lake scale (Lürling and Mucci, 2020). Most studies are limited to laboratory tests, and information on optimization and scalability to larger waterbodies is lacking despite implementation of commercial devices in some lakes.

7.8 Dredging

Dredging can remove nutrients that have accumulated due to a legacy of high external loading (Hamilton, 2019). Dredging has most commonly been applied to shallow lakes where it has the potential to substantially increase the water volume to surface area ratio, and to therefore assist in controlling internal loads (Bormans et al. 2016). Several studies have shown that beneficial impacts of dredging can be quite short-lived, perhaps only 1-2 year unless it is combined with other ecological lake restoration measures, especially reductions of sediment and nutrient loads in the catchment and other active in-lake techniques like use of coagulants (Jing et al., 2019; Li et al., 2020; Wen et al., 2020). Dredging removes phosphorus and nitrogen-rich sediments (Li et al., 2020), leading to reduction in internal loads, removal of cyanobacteria that germinate and reinoculated the water column from akinetes (e.g., *Dolichospermum* or *Rhaphidiopsis* species) or vegetative cells (e.g., *Microcystis* spp.), and it can assist with habitat restoration (Oldenborg and Steinman, 2019). After sediment dredging in Lake Taihu, China, there was a decline of c. 30% in abundance of cyanobacteria (Yu et al 2016).

Hydrodynamic conditions and temperature patterns can significantly influence the risk of internal nutrient release after dredging. For instance, a lab experiment in northern Lake Taihu, China, showed that dredging under strong mixing conditions may not remove the potential risk of internal release in the long term (Chen et al., 2021). This study suggested adopting a combination of ecological and engineering measures with dredging to minimize the release of pollutants from the bottom sediments (Chen et al., 2021). Dredging can also lead to ammonia release to the water column in the short term and may reduce nitrogen removal by reducing denitrification rates (Jing et al., 2013). Dredging operations should be carried out during low-temperature seasons including when efforts have been made to avoid excessive external sediment and nutrient loadings that effectively re-set the contaminant release potential of the sediments (Jing et al., 2013).

In the lake management report to Bay of Plenty Regional Council by Hamilton (2019), reference is made to a report, also to Bay of Plenty Regional Council, by Miller (2007), which examined the potential of dredging as a restoration measure for Lake Rotorua. Readers should refer to this report for a comprehensive assessment of dredging for the lake, including the duration, disposal of spoil and approximate costs of an operation. Assessment of these factors meant that dredging was not considered to be practical or economic for restoration of the lake. Hamilton et al. (2014) documented costs for dredging involving substantial dredging of small lakes of the order of $100,000 per hectare.

Figure 9 A sediment removal operation in Forest Lake, Brisbane, Australia. Dredged spoil is contained within a slightly porous bag and the runoff contained within a bunded area.

7.9 Inflow diversion

Inflow diversion has increasingly been applied, in some cases as an emergency measure, to remove highly polluted inflows, remove nutrients, and reduce the occurrence of cyanobacterial blooms in eutrophic lakes (Dai et al., 2020). Water diversion instantaneously reduces nitrogen and phosphorus loads to lakes (Zhang et al., 2016). A hydrodynamic model simulation of Lake Dianchi, Yunnan Province, China showed high probability of improvements in water quality through inflow diversion (Zhang et al., 2016). Inflow diversion affects the physicochemical and biological characteristics of lakes in different ways. Liu et al. (2014) found a significant decrease in organic pollutant concentrations due to seasonal inflow diversion in Gonghu Bay of Lake Taihu. It can be considered a better alternative to mitigate internal phosphorus loading and intercept dissolved phosphorus in water when other phosphorus inactivation methods (e.g., coagulants) are not available, not practical, or too costly (Osgood, 2017). The effectiveness of inflow diversion is directly related to discharge, nutrient concentration, location of the freshwater inlet, the amount and quality of in-lake water, and the change in in-lake flow field (Yang et al., 2021). It is effectively the opposite of flushing, which is less concerned about the composition of the inflow and more about obtaining a water residence time that is reduced (as opposed to increased) sufficiently to flush phytoplankton before their growth potential is realised. The diversion of the Ohau Channel inflow from Lake Rotorua to Lake Rotoiti remains the largest major diversion undertaken in New Zealand and cyanobacteria bloom incidence has decreased in Lake Rotoiti (Hamilton and Dada 2016; Lehmann and Hamilton 2019). The Sandy Creek inflow diversion from Lake Tutira was substantial, however, reducing the effective catchment size from 2717 to 843 ha. In major stormflow events, the diversion is compromised and nearly the whole catchment (2717 ha) is considered to contribute to the inflow (Johnstone and Robinson, 1987).

7.10 Surface mixers, aerators, artificial destratification and oxygenation

Surface mixers, aerators, artificial destratification and oxygenation are often lumped together although their mechanisms of operation can be quite different. Top-down surface mixers are increasingly used for preventing near-surface stratification and controlling cyanobacteria, and less so for limiting sediment nutrient releases (Slavin et al., 2022). Top-down surface mixers typically have an effective range of over 20 m radius but usually not extending beyond a 60 m radius from the mixer (Slavin et al., 2022). Artificial water circulation techniques such as conventional water circulation can replicate natural mixing and break thermal stratification to suppress algal blooms (Lee et al., 2022). They operate in a similar way to lake mixing technology such as a “Gradual Entrainment Lake Inverter (GELI)” which reduces stratification to improve oxygenation of the water column and prevent hypoxia and anoxia. It has higher application efficiencies compared with other aeration techniques, but its cost may still limit large-scale applications (Smith et al., 2018). Destratification of Lake Rotoehu (8.1 km^2) was also noted to have limited horizontal extent (McBride et al. 2015; Tempero 2015b) but has been used for water quality control in water supply dams managed by Auckland Council (Gibbs and Howard-Williams 2018) where the focus has been on oxygenating reduced forms for iron and manganese adjacent to the water offtake.

Mixing techniques such as bubble diffusers and paddle wheels have modest energy transfer efficiencies for breaking stratification. In lakes with hypoxic or anoxic bottom waters, pumps with Venturi tubes or ultrafine oxygen bubble condensers can be suitable to mix and aerate the water (Boys et al., 2021). However, this technology is not necessarily effective to control cyanobacterial blooms. Han et al. (2020) used a parsimonious one-dimensional (1D) turbulent diffusion model with an artificial circulation term along with a multi-objective calibration approach to explore effects of mixing on cyanobacterial blooms, attempting to optimise the control of cyanobacterial blooms. Mixing, aeration, and oxygenation are promising control strategies, but their wide application is mainly limited by energy costs (Kibuye et al., 2021).

Hypolimnetic aeration or oxygenation has been used in many lakes (Gantzer et al. 2019). It may be suitable for smaller monomictic lakes in the Bay of Plenty region (e.g., Lake Okaro) but not for Lake Rotorua because of its large size and brief periods of stratification, i.e., much of the oxygen could be ‘wasted’ when the lake mixes and deeper waters are naturally re-oxygenated. Gantzer et al. (2019) noted that hypolimnetic oxygen consumption rates declined following oxygenation, possibly with many redox-sensitive compounds being oxidised in the bottom sediments, i.e., meeting the existing oxygen demand in the sediments (Gantzer et al., 2019). A linear bubble plume diffuser hypolimnetic oxygenation system has been verified as a cost-effective treatment option for water supply reservoirs in which anoxia induces water quality problems (Mobley et al., 2019). However, hypolimnetic oxygenation for the restoration of nutrient-loaded dimictic lakes can be an excessively costly option unless P loading is controlled (Kuha et al., 2016). Horne (2019) reported a successful application of hypolimnetic oxygenation by reducing hydrogen sulfide levels and avoiding toxicity to fish in Camanche Reservoir, California.

Figure 10 Example of harvesting and concentrating cyanobacteria (mostly Microcystis spp.) in water from Lake Taihu where concentrations are extremely high and the lake area is 2,390 km2. Photo: M. Burford.

7.11 Hypolimnetic siphoning

Hypolimnetic siphoning uses gravity to remove hypolimnetic water using an outlet positioned at a level below the bottom of a lake. It is a low-cost method with potentially long-term effectiveness (Zamparas, 2021). The monitoring of the operational variables of hypolimnetic siphoning and water quality in the source and receiving waters can help to improve the efficiency of this method (Nürnberg et al., 2020) including optimising its ability to remove phosphorus (Silvonen et al., 2020, 2021, 2022). One of the major drawbacks of hypolimnetic siphoning is the potential for water quality issues downstream (i.e., if hypolimnetic water contains high concentrations of phosphorus, nitrogen and hydrogen sulphide, and low concentration of oxygen). There is potential for warming of bottom waters as colder bottom waters are withdrawn (Zamparas, 2021). 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).

8. Summary of lake remediation techniques

Several new measures have been developed for restoration of eutrophic lakes. Major purposes, advantages, and disadvantages of these methods are summarized in Table 6.

Table 6 Main purposes, advantages, and drawbacks of new methods for in-lake remediation.

Restoration methods	Purpose	Application	Examples	Advantages	Disadvantages
Algicides	Reduce cyanobacterial biomass directly by killing algae or indirectly by making nutrients inaccessible for algal growth.	May be suitable as an in-situ emergency control measure (algicides) but only addresses symptoms rather than causal factors (e.g., nutrients)	Courtille Lake, France (Hullebusch et al., 2002); Fairmont Lakes, Canada (Hanson and Stefan, 2010); Lake Koetshuis, the Netherlands (Matthijs et al., 2013); Lake Okeechobee, USA (Pokrzywinski et al., 2022)	Algicides effective for the rapid, short-term treatment of algal blooms with usually high doses of algicide.	Toxic effects on non-target biota. Sediment contamination. Culturally or socially sensitive Algicides or herbicides not recommended for planktonic applications and long-term lake restoration. Can bring unforeseen ecological risks
Herbicides (relevant to invasive weed species in the Rotorua-Te Arawa lakes)	Control of invasive weed species for reasons of habitat improvement, biodiversity, recreational and amenity value, reducing spread of invasive weeds to other lakes	Commonly, applications of diquat (dibromide) and endothall (dipotassium salt).	de Winton et al. (2013), Hofstra et al. (2018)	Rapid knock-down of invasive species Allows native species, including low-growing turf species, to re-grow and stabilise bottom sediments	Potential persistence through the food chain Potential for long-term contamination in lake sediments
Coagulants, flocculants (i.e., geochemical engineering)	Control internal P loading (coagulants), flocculate P from the water column		IMDEA Water Institute, Spain (Oliveira dos Anjos et al., 2021)	• Effective for P adsorption.	• Coagulants tend to be a costlier treatment of eutrophication control.

Restoration methods	Purpose	Application	Examples	Advantages	Disadvantages
		In-situ P removal (coagulants).	Lake Groot Vogelenzang, the Netherlands (Quaak et al., 1993; Controlled experiment - containing algal water collected from Lake Taihu, China (Li & Pan, 2015); Lake Terra Nova, the Netherlands (Immers et al., 2015) Simulated lab experiments (Cheng et al., 2018; Pan et al., 2020).	Effective at controlling internal P loading.	
Flushing including reducing water residence time	Reduce algal and nutrient levels to limit algal biomass. Combat internal P loading.	In-situ measure to control blooms and improve water clarity. In-situ measure for controlling internal P loading released from the sediment.	Limited success (Zhang et al., 2020) except in small or hydro lakes Lake Elterwater, UK (Olsson et al., 2022a; Olsson et al., 2022b).	Rapid technique to treat small water bodies Significantly attenuate stratification by reducing residence times Control the length of the hypolimnetic anoxic period Reduce P loading from the sediments into the water column	Not usually suitable for larger lakes because it requires significant investment to reduce flushing time to levels impacting cyanobacteria and nutrients More significant changes in water residence time (WRT) manipulations are needed during particular times of the year, which can have undesirable effects on ecosystem function

Restoration methods	Purpose	Application	Examples	Advantages	Disadvantages
Biological remediation and biomanipulation	Promotes the interaction between microorganisms and aquatic plants and self-purification ability Alters food web to influence nutrient transformations and inactivation that reduced trophic state	Temporary in-situ measures to control eutrophication in lakes by establishing near-natural ecological conditions or supporting food webs beneficial to nutrient attenuation	Lake Ohinewai, New Zealand (Tempero et al., 2019; Tempero & Hicks, 2017); Huizhou West Lake, China (Liu et al., 2018); Lab experiments (Ren et al., 2022; Iannino et al., 2021; Chakraborti & Bays, 2020; Wu et al., 2005; Huang et al., 2011; Yuan et al., 2014)	Little environmental impact. Broad application prospects Ability to attenuate pollutant concentrations Low cost, effective, and easy to operate/apply Can treat agricultural wastewaters and runoff waters	Affected by both the physicochemical and environmental parameters. Long-term remediation action Needs contaminant-specific biological microbial populations, which may produce toxic metabolites. Less effective without external load reduction measures. Food webs can be difficult to manipulate
Aquatic phytoremediation (including in constructed and lakeside wetlands)	Plant uptake and denitrification of nitrogen suited for eutrophic lakes.	In-situ bioremediation for eutrophic lakes.	Lab experiments (Wang et al., 2011; Abed et al., 2017; Spangler et al., 2019)	Plants can accumulate high nutrient concentrations and root systems support denitrification. Create favourable conditions for microbial organic degradation, essential for restoring polluted lakes	Regular biomass harvesting is necessary, or the absorbed nutrients may re-enter the water body.
Oxygen nano-bubble technology	Degradation of organic matter and maintaining elevated dissolved oxygen level (>6 mg/L)	In-situ technique to maintain dissolved oxygen levels similar to the natural water for longer times (> 6 months)	Controlled experiment - containing soil from Lake Ngaroto, New Zealand (Zhang et al., 2018).	Greater gas (oxygen) transfer efficiency and requires half the retention time for the degradation of organic matter compared to oxygenation conventional systems.	Needs more scientific, practical and cost-benefit evidence to support wide-scale application to eutrophic lakes.

Restoration methods	Purpose	Application	Examples	Advantages	Disadvantages
				Cost-effective and time-saving approach	
Ultrasound treatment	Control cyanobacterial biomass	Collapse of gas vesicles and inhibit photosynthesis in cyanobacteria.	Lab experiments on cyanobacterial biomass using low-frequency ultrasound (Asadi et al., 2013) and high frequency ultrasound (Haocai et al., 2020)	Ease of installation and operation of ultrasound technique. Lack of residuals.	Needs field-based evidence for introduction, optimization and scalability of this method for treatment of large water bodies. Detailed lake-scale studies indicate no effect.
Dredging	Nutrient removal	Direct removal nutrients accumulated in lakebed sediments	Physically control internal loads (Bormans et al. 2016); remove phosphorus-rich sediments (Li et al., 2020); support habitat restoration (Oldenborg & Steinman, 2019)	Directly removing nutrients that have accumulated due to a legacy of high external loading	Provides only short-term benefits unless accompanied by other in-lake restoration techniques such as use of coagulants.
Inflow diversion	Emergency measure to remove polluted inflows	Polluted inflows are diverted to reduce nitrogen and phosphorus loading to lakes	Water diversion (Zhang et al., 2016); circulation of flow field (Yang et al., 2021)	Provides an instantaneous way to reduce nitrogen and phosphorus loading to lakes.	The effectiveness is mostly influenced by discharge, nutrient concentration, position of the freshwater inlet, the amount and quality of in-lake water to be diluted, and direction of flow field in the lake.
Filtration of phytoplankton	Remove cyanobacteria	Cyanobacteria, phytoplankton removed by using mechanical or biological filtration methods	Bivalve farming for phytoplankton filtration (Jiang et al., 2016; Marroni et al., 2022); microstrainers (Czyżewska and Piontek, 2019)	May provide effective filtering of high concentration of cyanobacteria and phytoplankton depending on the size distribution and density of phytoplankton.	Very high filtration rates are required to achieve control of phytoplankton.
Hypolimnetic siphoning	Remove nutrient-enriched bottom waters	Uses gravitational siphoning of water from the bottom of a lake to an outlet positioned below	Remove phosphorus (P) from eutrophic lakes (Silvonen et al., 2022); recovering and recycling P accumulated in eutrophied lakes (Silvonen et	Low-cost method with potentially long-term effectiveness for removal of P from eutrophic lakes.	Significant water quality issues downstream (if hypolimnetic water contains high concentrations of phosphorus, ammonia, hydrogen sulphide and low oxygen).

Restoration methods	Purpose	Application	Examples	Advantages	Disadvantages
		the bottom of a lake.	al., 2020; Silvonen et al., 2021)		Potential warming of the lakes as bottom waters increasingly become similar in temperature to those of the surface

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