water

Review

Practices for Eutrophic Shallow Lake Water Remediation and Restoration: A Critical Literature Review

Antônio Cavalcante Pereira and Catherine N. Mulligan *

Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, QC H3G 1M8, Canada; antoniocp.eng@gmail.com
* Correspondence: mulligan@civil.concordia.ca

Abstract: Lake water has been impaired with nutrients due to the synergic action of human-made activities and climate change. This situation is increasing eutrophication around the globe faster than before, causing water degradation, loss of its uses, and water-associated economic and health effects. Following the Sustainable Development Goal 6, more precisely its target 6.6, nations are already behind schedule in protecting and restoring water-related ecosystems (i.e., rivers and lakes). As concerns with eutrophication are escalating, eutrophic water remediation practices are the keys for restoring those lake waters. Diverse methodologies have been investigated focusing on the nutrient that limit primary productivity (i.e., phosphorus), but few have been applied to in-lake eutrophic water remediation. Thus, the objective of this paper is to provide an overview and critical comments on approaches and practices for facing eutrophic lake water remediation. Information on the successful cases and possible challenges/difficulties in the peer-reviewed literature are presented. This should be useful for supporting further remediation project selection by the stakeholders involved. In summary, for a successful and durable restoration project, external nutrient inputs need to be managed, followed by holistic and region-specific methods to attenuate internal legacy nutrients that are continually released into the water column from the sediment. When aligned well with stakeholder participation and continuous monitoring, these tools are the keys to long-lasting water restoration.

Keywords: eutrophication; total phosphorus; algae; cyanobacteria; lanthanum modified bentonite; dredging; lake water; remediation; surface water

Citation: Pereira, A.C.; Mulligan, C.N. Practices for Eutrophic Shallow Lake Water Remediation and Restoration: A Critical Literature Review. *Water* **2023**, *15*, 2270. https://doi.org/10.3390/w15122270

Academic Editors: Mohammad Mahmudur Rahman, Dibyendu Sarkar, Rupali Datta and Prafulla Kumar Sahoo

Received: 1 May 2023
Revised: 3 June 2023
Accepted: 14 June 2023
Published: 17 June 2023

1. Introduction

Water, an essential resource for humans and economic improvement (i.e., sustainable water), is suffering cumulative pressures from nutrient pollution. Increasing world population and anthropogenic actions [1–3], new climate change circumstances (i.e., changes in nutrient mixing and availability due to increased water temperature) and climate extremes [4–7] are exerting pressure on water resources. In addition, there is frequently a lack of enforcing environmental policies [8,9]. These influences lead to high levels of two macronutrients (i.e., phosphorus and nitrogen) by allochthonous sources (i.e., external sources) and/or autochthonous sources (i.e., internal sources). External sources are characterized by contaminated watershed runoff, direct discharge, and/or incompletely treated effluent release, and internal sources are represented by past catchment-derived emissions that have accumulated in the sediment, releases from sediment disturbances, and/or organic matter decomposition in the water.

With this significant nutrient increase in lakes, there are subsequent eutrophication occurrences [4,5]. In these, lake waters go through chemical and biological changes including decreased dissolved oxygen concentration [10], obnoxious smells and taste [11,12], and blue-green algae/cyanobacteria biota domination [13,14] with potential harmful toxin production (i.e., neurotoxins, hepatotoxins, and endotoxins) [15]. Studies suggest economic and health concerns due to eutrophication related to lake waterfront property value decrease [16,17], recreational use loss [17,18] and increased costs with drinking water treatment as a preventive measure for any negative health effect [17–19].

In this framework, as the concern with eutrophication will be escalating in the following years by the variables suggested, eutrophic lake water remediation is the key for nations to restore those waters not only for the present generation but also for generations to come. This idea aligns well with Sustainable Development Goal 6 (SDG6) (i.e., clean water and sanitation) from the UN (United Nations) agenda, further detailed in the 6.6 target. This target for restoration of the water-related ecosystems was to be achieved by nations in 2020. Thus, following the mentioned concern, in-situ technological practices for water remediation/restoration are of high priority.

The focus is on the primary limiting nutrient, phosphorus (P), the essential component required to constrain primary productivity development [20]. Approaches and practices for reducing eutrophication circumstances, which already have been applied in situ, are based on distinct technologies directly or indirectly used for reducing the phosphorus concentration in the water column. Correspondingly, it is implied that control of the external loadings and the management of sediment legacy phosphorus due to particle settling [21,22] play an important role in successful and sustainable remediation. In this paper, in situ lake remediation procedures that are physical, chemical, biological, combined, and emerging will be discussed.

There are several distinct and well-established eutrophic in-lake water remediation practices in specialized literature. This article will review well-documented practices centered on whole lake restoration in addition to emerging methods. Physical techniques include sediment dredging and hypolimnetic water aeration. Chemical techniques are sediment capping with inert elements or phosphorus inactivation in water and bottom sediments by chemical addition. Comprising the application of pure oxygen into hypolimnetic water and capping with lanthanum-modified bentonite (LMB) and coagulants (aluminum and iron-based). The biological methods underlined are biomanipulation and macrophyte management.

Emerging methods, which support waterbody restoration and take advantage of the ecosystem's natural response to changes [23], will be presented. Those ecological engineering techniques involve primary productivity control by minimally invasive nutrient abstraction. The ones highlighted in this paper will be geotextile filtration and floating wetland use. Combined remediation practices with two or more of all mentioned methodologies will be also discussed as a holistic approach to water restoration.

Thus, the objective of this paper is to provide an overview and critical comments on in-lake/situ approaches and practices for mitigating eutrophication worldwide. Thus, by providing summarized information on the successful cases and challenges in the peer-reviewed literature, the aim is to facilitate other further remediation project selection by stakeholders involved (i.e., environmental managers, and society in general). For guiding this review, two research questions were developed as follows:

1. What in situ practices with plausible results have been applied to address eutrophication in lake waters?
2. What are the major challenges/disadvantages to these water restorations?

2. Human-Induced Eutrophication Processes

Eutrophication is described as a water enrichment process by excess plant nutrients, nitrogen, and phosphorus (P) which can lead to enhanced algae/cyanobacteria growth, periphyton, or macrophytes [24,25] in lake water systems. From an ecological standpoint, this is a natural process in which a waterbody goes through growth-promoting processes [26] over a long-time frame. However, due to the increased nutrient input coming point and diffuse external and internal sources, this timeframe has been reduced. Those nutrients are primarily associated with human activities as presented in Figure 1.

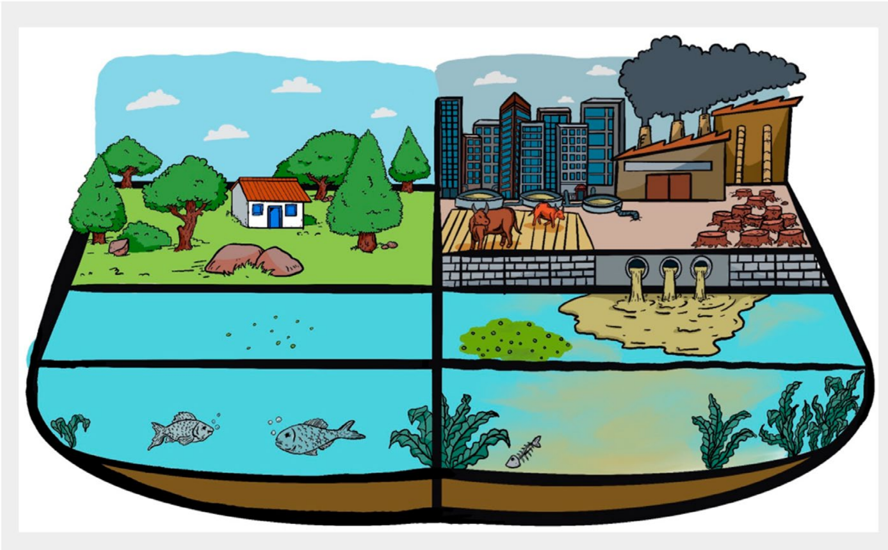

Figure 1. Visual representation of balanced/non-polluted (**left**) and nutrient-polluted (**right**) systems.

Anthropogenic actions synergically associated with the new climate change developments and population growth have been instigating nutrient stresses in aquatic environments. Point sources include direct contaminant discharge, as well as untreated sewage disposal. Diffuse sources originate from agriculture (i.e., fertilizer over(use)) and livestock (i.e., animal feces) as well as increased contaminated watershed runoff due to climate extremes. Internal sources are related to former external sources which have settled and accumulated in the sediment and organic matter degradation in the water column/sediment. As an example, when the excessive phytoplankton degrades and settles to the sediment surface, decomposition can lead to possible low oxygen concentrations in the lower water levels, which could cause releases of P from the same sediment [27]. Thus, the sediment acts as a sink and source of P, an important characteristic in the lacustrine ecosystem health and any possible remediation/restoration practice application.

Various issues are manifested as the total excessive phytoplankton growth effects, the main disturbance on a eutrophication occurrence, leading to imbalanced primary and secondary productivity and a faster succession/ageing rate [26]. Some of the distresses are related to benthic primary productivity (i.e., macrophytes and periphyton) shifting to pelagic primary production (i.e., phytoplankton) [28], causing phytoplankton biomass density to increase. Usually, this upsurge will trigger a change to a cyanobacteria-dominated phytoplankton community [29]. Consequently, with these possible excessive cyanobacteria developments, harmful toxin production [5,30] as well as possible water anoxia, obnoxious scum, and smells will occur. Thus, eutrophication development will not only bring recreational and drinking advisories due to possible harmful toxin production but will also have diverse economic and health effects associated with it.

2.1. Phosphorus Cycle and Water/Sediment Interactions

The phosphorus (P) cycle is formed by this element's interaction between terrestrial and aquatic ecosystems. As shown in Figure 2, the terrestrial phosphorus contribution could be associated with P rich rock/soils as well as fertilizer uses and livestock practices. Thus, by runoff, possible leaching due to chemical weathering reactions and/or physical erosion of soil/rocks can occur, transferring this component from the terrestrial ecosystem to the aquatic one. The mineral P form (i.e., inorganic) mostly present in rocks is apatite, which comprises hydroxyapatite, fluorapatite, and chlorapatite [31], which can then be found in aquatic ecosystems. On the other hand, hydrous ferric oxides such as goethite (FeOOH) and ferrihydrite ($Fe(OH)_3$) are the common form in well-drained soils and important sinks or sources of soluble phosphate in aquatic environments [32]. When related to anthropogenic terrestrial P (i.e., fertilizer and livestock) this will be mostly organic and soluble in water which will runoff from the land.

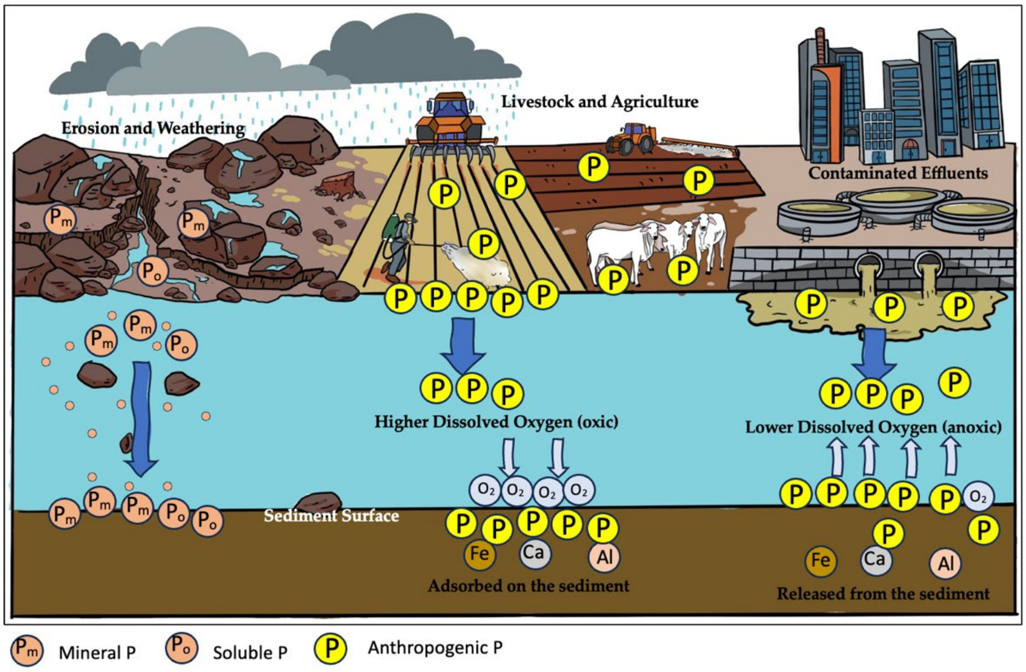

Figure 2. Phosphorus enrichment process in the environment and simplified cycle. Modified from [26].

Related to the aquatic ecosystem, sediments play a crucial role in controlling P availability in the water column in water environments by acting as an internal source and sink [20]. As shown in the phosphorus enrichment process (Figure 2), phosphorus (P) can enter waterbodies in two ways, continuously in runoff water and by diverse inlet streams [26]. This nutrient input nearly always exceeds the output, thus causing the settling of it and enrichment in the sediments [33]. When accumulated in the sediment, some interactions between sediments and overlying waters (i.e., based on dissolved oxygen concentration) will occur, which can determine the bioavailability of this element in the water column.

Different P forms in sediments have different bioavailability and are released by changes in lake environmental conditions to become a potential source contributing to lake eutrophication [34]. An example is related to dissolved oxygen concentration. If there is oxygen in the bottom water, P is strongly bound to metals in the sediment such as iron, aluminum, and calcium. These complexes are difficult to dissolve and make the P unavailable to phytoplankton and other plants and do not contribute to eutrophication [27]. In the absence of oxygen, for example, redox-dependent P species may still be released within the anoxic bulk sediment and diffuse into the water column. As an example, the sediment geochemical cycling of P is tightly coupled to the cycling and redox dynamics of Fe [35,36] shown in Figure 3.

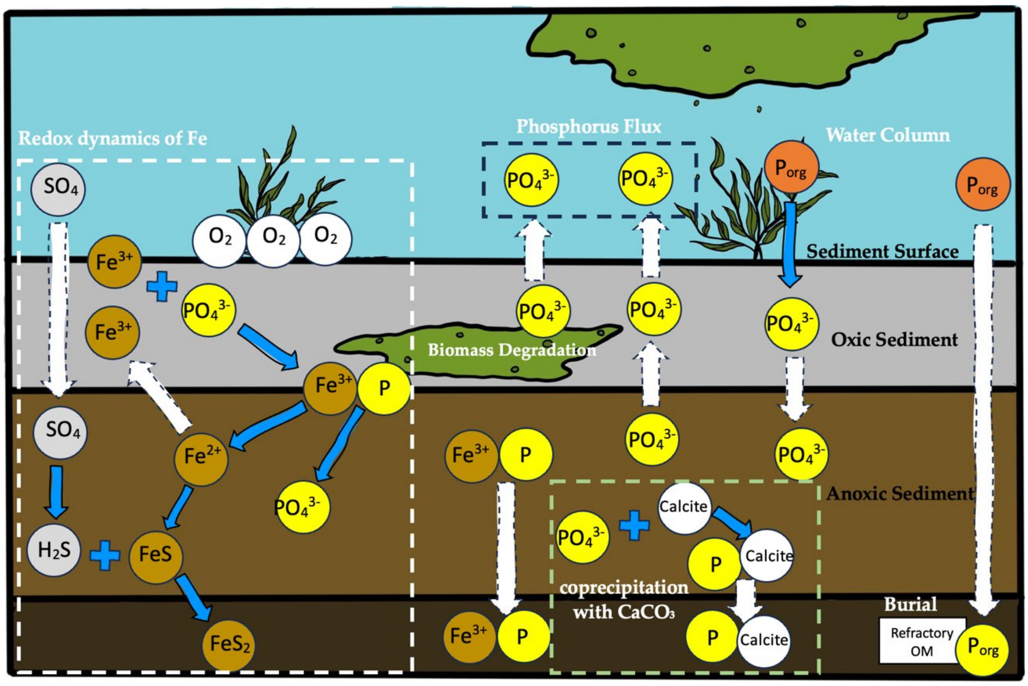

Figure 3. Simplified sediment Fe-P cycling and coprecipitation with $CaCO_3$ schematic. Modified from [36].

This iron-bound phosphorus accounts for a substantial fraction of total P in sediments (~30%) and is regarded as active P (i.e., readily released under anoxic conditions) [37]. In this diagram, since Fe III (hydr)oxide is redox sensitive and its surface is unevenly charged, P sorption on the Fe III (hydr)oxide surface becomes reliant on the redox potential and pH of the environment [38]. Under anoxic conditions in the pore or bottom water, the oxidized iron is reduced to a ferrous ion (Fe (II)) that subsequently diffuses into the water column and is re-oxidized to Fe (III). Sulphate also strongly interferes with iron-phosphorus chemistry and stimulates organic matter anaerobic decomposition. The main product of sulphate reduction under anoxic conditions is dissolved sulphide, which may react with dissolved reduced iron and particulate iron (hydr)oxides under the same condition. The results of this reaction between sulphide and iron under anoxic conditions are the highly insoluble iron sulphide (FeS_2) minerals while phosphate adsorbed to the iron (hydr)oxides or present as iron phosphates become mobilized [39]. Another example is related to the P form which cannot be affected by environmental changes, formed by the phosphate coprecipitation with $CaCO_3$ and considered the most important endogenous process in removing P from the water column [40]. This form is found at the stream bottom and might not easily be suspended [41].

2.2. External Measures: A Primary Step for Reducing Nutrient Loading

Ceasing, attenuating, and regulating external phosphorus nutrient loadings into eutrophic lakes should be the first and foremost action, in the order mentioned, taking into consideration in any lake remediation/restoration practices. These actions are considered the most prominent action for possible further in situ corrective measures. Without this step, even in the case of a possible in situ restoration within the lakes, minimal to no results will occur [42]. As lake catchments are characterized by large differences in hydrology, climate, geology, soils, land cover, and ecosystem type [43], diverse practices could be suggested.

Practices are mainly characterized by four possible actions: land-use modifications, wastewater (domestic/industrial) treatment, planned urban development around water-bodies and their possible water uses, and modification changes in agricultural/livestock management approaches. These strategies are the central focus for mitigating the external nutrient input in lacustrine ecosystems. In more detail, land use changes within forestry practices can contribute for reducing any uncovered land which can erode due to watershed runoff to a water body. Additionally, increasing vegetation buffer zones on lakes will play a large part in acting as a filter for capturing nutrients. Wastewater tertiary treatment processes focused on nutrient removal should also be implemented in places where the effluents are discharged directly into water bodies.

It is worth mentioning that water management/protection is not a straightforward action and specific methodologies should be adapted depending on the region and by always prioritizing external nutrient remediation. This is strongly reliant on the contribution of diverse sectors and the stakeholders involved, and the practices must be adjusted on a case-by-case basis. Thus, the contribution of representative local stakeholders who are affected by the eutrophic water must be included, promoting inclusive and transformative change in valuing this water [44]. If an internal lake water restoration practice is applied without any external load control/attenuation, the eutrophic aquatic environment will not improve over the long term, mainly because the waterbody is going to have a continuous phosphorus input which is dated to be stored in the sediment, acting as a source of P for the waterbody. P migration from the sediment into the overlying water can be reported as a persistent phenomenon, thus delaying the water quality improvement for a considerable time even after the control of external sources [36]. Thus, for further improvement of any eutrophic waterbody, which suffers from external nutrient inputs, internal nutrient sources should be managed.

2.3. Lakes Trophic States Classification and World Eutrophic Waters Overview

Lakes are often classified by their “trophic status”, which can be determined via measures of productivity or nutrient load [45]. In the most used classifications, water quality parameters are used to roughly assess waterbody primary productivity status. For example, these parameters can include the concentration of the limiting nutrient (phosphorus), chlorophyll-a (an indicator of phytoplankton biomass), and transparency (dependent on both algal biomass and sediment resuspension), expressed as Secchi depth [24]. Diverse indices are proposed such as the Carlson-type TSI (trophic state index), which assumes algal biomass to be the basis for trophic state classification. It is calculated by three hydro-ecological characteristics mentioned as follows: the chlorophyll-a concentrations, total phosphorus (TP) in water, and the Secchi depth (SD) [46]. For classification criterion, waters with low productivity are termed oligotrophic and waters with high productivity are eutrophic. The other trophic categories are mesotrophic, the one located between low- and high-productivity waters, and hypertrophic, the one higher than eutrophic water.

Eutrophication occurrences have not only been prevalent in economically developing nations but also in economically developed countries. Freshwater basins are becoming oversaturated with phosphorus [47], causing anthropogenic eutrophication to become a primary water quality issue worldwide [48,49]. Roughly 50% of the world’s largest lakes (including Asia, Europe, and North and South America) are eutrophic because of high TP loadings [50]. Additionally, surveys have shown that 54% of lakes in Asia are eutrophic in Europe, 53% in North America, 48% in South America, 41% and in Africa, 28% [51]. Large eutrophic lakes such as Lake Erie (North America), Lake Winnipeg (Manitoba, Canada), Lake Taihu (China), Lakes Biwa and Kasimagaura (Japan), Lake Victoria (Africa) [52], Lake Jacarepaguá (Rio de Janeiro, Brazil), and others are a small worldwide snapshot of this issue. Other smaller and shallow waterbodies not well monitored and documented are also increasingly exhibiting eutrophication characteristics. Nutrient releases to waterbodies are the main factor. As little to no efforts have been made to reduce this contamination, the number of affected waterbodies will tend to increase even more. In both scenarios, in economically emergent and economically developed nations, the lack of enforcement of environmental policies is associated with increased eutrophication.

3. In Situ Practices for Eutrophic Water Restoration

Eutrophication restoration of lakes has been undertaken by simple algal killing and reduction in the endogenous nutrient concentration by multiple technologies in the lake ecosystem [53]. The in situ remediation techniques mainly involve phosphorus concentration management, either in the water column and sediment. This is because P is typically the most cost-efficient nutrient for abatement measures [43]. Presently, there is no international agreements for classifying in situ techniques for lake water remediation [54]. Thus, the following classification presented in Figure 4 will be used in this paper. In situ lake remediation techniques technologies are allocated into physical, chemical, biological, combined, and emerging methods.

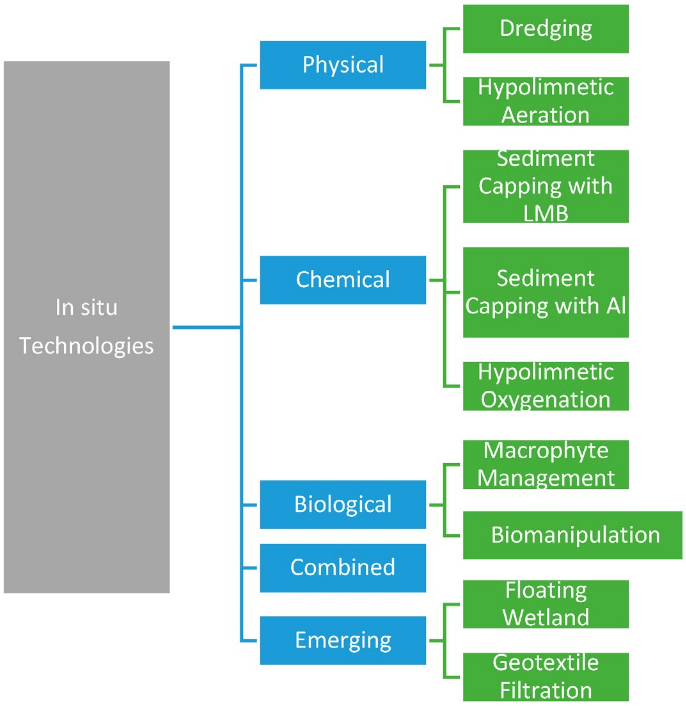

Figure 4. In situ lake remediation techniques classification.

Due to the water qualities heterogeneity in eutrophic waterbodies, the decision on the option(s) to be applied to a disturbed aquatic ecosystem will depend on the following: (1) water quality characteristics, (2) nutrient pollution source, (3) sediment phosphorus bioavailability, (4) lake nuisance concerns (i.e., macrophyte overgrowth, harmful primary productivity), (5) available capital, (6) possible stakeholders involved/affected, and the (7) method's sustainability. With this understanding, decision-support frameworks for these restorations have been created and are diverse [27,55,56]. They are indicated for facilitating not only the selection but also further requirements for a successful and durable restoration (i.e., monitoring and continuous external loading reduction).

A simplified decision support framework is presented in Figure 5, which shows the necessary steps to be taken in a possible eutrophic lake water remediation project. The first step to be taken is lake water/sediment characterization with the identification of external and internal sources. External load attenuation should always be followed by an in-lake remediation practice for accumulated nutrients in the lake sediment. In the remediation option management parameters such as chemical dose, waste disposal, monitoring, and others need to be defined. Thus, after the remediation procedure takes place, continuous monitoring needs to be performed to investigate not only the restoration outcomes, but also continuously verify if the water needs additional treatments.

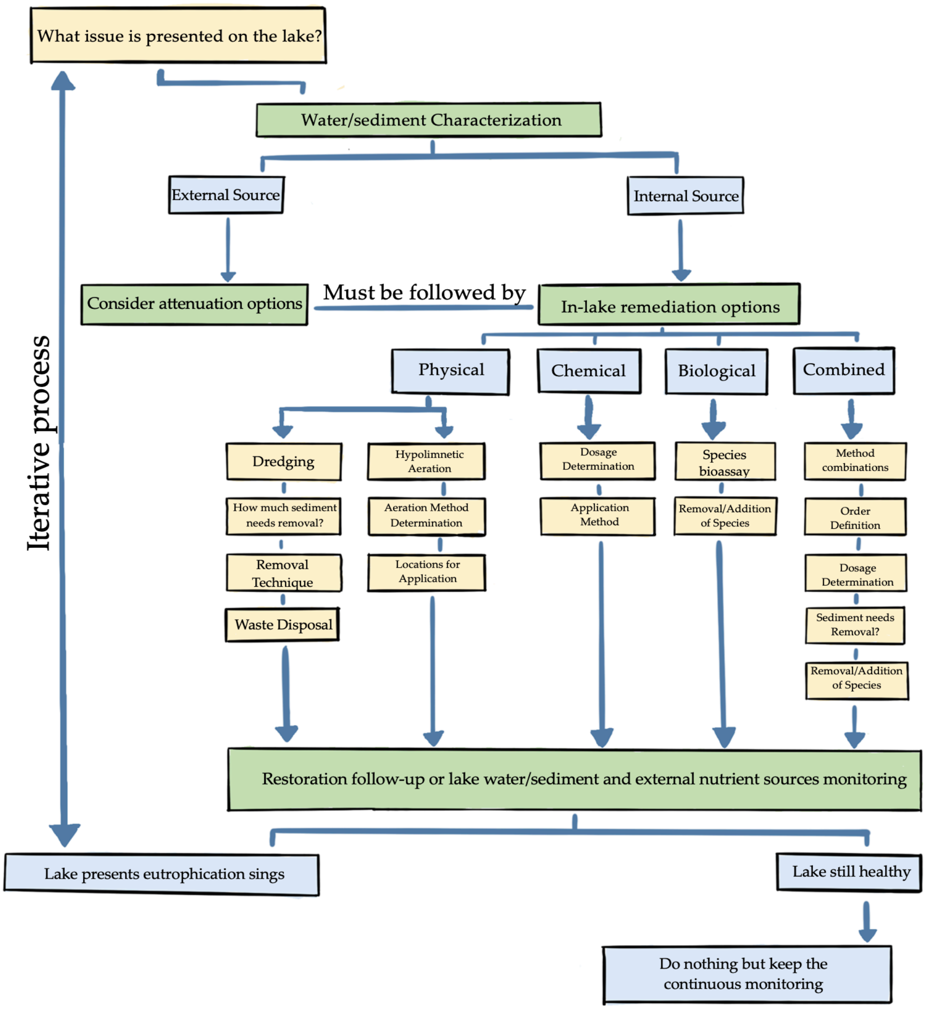

Figure 5. Simplified decision support framework for eutrophic water restoration selection.

In any case, the decision support frameworks as well as selected methodologies must always be tailored to the region's perspective regarding affected stakeholders' insights and needs. This paper has been completed to provide an overview of addressing eutrophication in lake waters. It is expected not only to emphasize major challenges/disadvantages but also the necessary parameters for effective and durable lake water restoration practice. Thus, a guided overview has been completed for providing and facilitating further remediation project investigations by stakeholders involved in various lakes.

3.1. Physical Remediation

3.1.1. Dredging

In this treatment category, phosphorus (P) rich sediment is removed from the lake as a restoration method. Sediment is excavated by mechanical means with specific equipment and brought to the surface and dewatered in geotextile bags prior to disposal. Generally, this sediment removal will reduce the internal P loading immediately and substantially. The positive effects on lake water quality included a decline in water column nutrients, reduction in phytoplankton, the disappearance of cyanobacterial blooms, and increased coverage of macrophytes [57]. Although there are benefits, several trade-offs have been presented by this remediation. The removal of lake water sediment can cause secondary pollution due to leaching metals/contaminants from the sediment into the water column. Additionally, an imperative concern is waste disposal, which needs to be evaluated. Some dredging projects have been analyzed and are presented in Table 1.

Table 1. In situ remediation studies of dredging.

Reference	Lake Name	Country	Mean Depth	Area Excavated/Excavated Depth	Treatment Year	TP Before/TP After
			[m]	[ha]/[m]	[Year]	[µg/L/µg/L]
[57]	Lake Mustijärv	Estonia	1.1	1/1.1	2016–2017	44/100
[58]	Dongqian Lake	China	2.2	1991/0.50	June 2009 to January 2013	142/100
[59]	Lake Wuli	China	2.5	560/0.30	June 2002 to November 2003	n.d *
[60]	Lake Yuehu	China	n.d *	61/1 m	June 2006, to October 2006	431 ± 236/254 ± 84
[61]	Lake Nanhu	China	1.2	n.d *	August 2017 to March 2018	3470/470

Note: * n.d—Not determined.

Generally, it was observed that dredging projects only have short-term positive effects on lake ecosystems even though there are changes in the sediment phosphorus content, as well as the water column, directly after the removal [57,58]. The projects reviewed have no external nutrient attenuation plan or action performed, which has affected the proposed remediation performance/durability. Additionally, no mention of dredged sediment disposal has been given, which should be a strong concern regarding the sustainability of those projects. For the results reviewed, dredging should be only recommended if combined with other ecological lake restoration techniques, which will be further discussed [59–61].

Related to this remediation practice's possible cost, a range from 20,000 to 75,000 USD per acre dredged could be presented. Contaminated sediment final disposal is not included, which will bring an additional significant amount depending directly on the disposal site distance from the water body [62]. Not only the value for the actual dredging process but also the risks associated with the technique application, workers' safety, equipment transportation to the site, vegetation, and bathymetric assessment should also be considered and included, if necessary.

3.1.2. Hypolimnetic Withdrawal

Hypolimnetic withdrawal is a practice based on the mixing of deep anoxic waters with shallow oxygenated epilimnion waters to prevent low dissolved oxygen water near the sediment surface, which could increase phosphorus bioavailability for a possible eutrophication occurrence. For this objective, several methods have been used such as air compression water mixers as well as new technologies of solar-driven aeration units (SolarBee®). In the specialized literature reviewed, there are variable results regarding the capacity of this water remediation. Some studies have been analyzed and are shown in Table 2.

Table 2. In situ remediation studies of hypolimnetic withdrawal.

Reference	Lake Name	Country	Mean Depth	Treatment Year	Aeration Type	TP Before/TP After
			[m]	[year]		[µg/L/µg/L]
[63]	Lake Durowskie	Poland	4.6	2009–2017	Pulverizing aerator	40/30
[64]	Fossil Creek Lake	United States	2	2009–n.d *	Submerged aeration	1150-90/76-40
[65]	Lake Długie	Poland	5.3	1987, 1999, 2000	Destratification	58/48
[66]	Greenfield Lake	United States	1.5	February 2005	Solar Bee Unit **	145 ± 425/ 96.1 ± 69.7

Note: * n.d—Not determined; ** Additional treatments have been done.

Frequently, the water aeration technique must counteract high organic levels in the sediment [63], and most times the oxygen demand for microorganisms is greater than the oxygen supply capacity of the aerator. Therefore, the oxygen deficit is going to be reduced each year as the mineralization of accumulated organic matter instigated by the oxygen presence reduces its demand. In other cases, even though phosphorus is immobilized in the bottom sediments, high concentrations will remain in the water due to continuous external pollution, and the low sediment sorptive capacity (i.e., low concentrations of iron and manganese, which bind phosphorus) which prevents further association with phosphorus [65].

This sorption capacity is an important parameter to be evaluated if water aeration is a selected remediation method in the lake. Additionally, TP inputs to the water column vary from year to year depending on the ecosystem, a factor not considered by the present lake management efforts [66]. Nevertheless, hypolimnetic aeration seems to alleviate eutrophication symptoms, and thus it should be used in combination with other methods [63]. External nutrient sources are a recurring issue, and attenuation should be performed to enhance the potential of this remediation. Cost-wise, this practice will depend on the type of aerator chosen. An average monetary value evaluated in a recent study has shown 3800.00 USD per acre for the capital cost [67] and 700.00 USD per acre for operation and maintenance.

3.2. Chemical Remediation

3.2.1. Sediment Capping with LMB

The lanthanum-modified bentonite (LMB) use has been a highly implemented approach on the market and literature for eutrophic waterbody remediation. This method has been used when a higher internal nutrient source remains to sustain recurrent eutrophication occurrences in lakes. This method is based on modified clay addition in a slurry form or granules in the eutrophic water column which will sorb phosphorus present on it and settle it, creating a thin barrier that will retain and reduce phosphorus sediment bioavailability. The quantity of LMB necessary to inactivate phosphorus in aquatic systems is based on the supplier-recommended mass ratio (La/P) 100:1 (100 kg Phoslock®/1 kg phosphorus), which needs to be calculated based on the TP measured in the water column and potentially releasable phosphorus in the sediments (labile, reductant-soluble, metal oxide). Some LMB lake application studies have been reviewed in Table 3.

Table 3. Sediment capping studies with LMB application.

Reference	Lake Name	Country	Mean Depth	Treatment Year	Dosage Used	TP Before/TP After
			[m]	[Year]	[ton/ha]	[µg/L/µg/L]
[68]	Swan Lake	Canada	1.86	Spring 2013	4.6	247/99 (1st year) and then 60 (2sd year)
[69]	Laguna Niguel Lake	United States	3.66	29 April 2013 to 2 May 2013	4.13	(>80% decrease)
[70]	Lake Bromont	Canada	4.88	Fall 2017	3.77	23.63 ± 4.12/18.20 ± 3.19
[71]	Lake Bärensee	Germany	2.63	June 2007/May 2010/March 2013	1.9/0.5/0.5	80/35
[72]	Mere Mere *	United Kingdom	2.8	9 March 2013	5.1	76.6/49.8
[73]	Hatchmere **	United Kingdom	1.4	11 March 2013, to 13 March 2013	5.3	83.2/64.4

Notes: * 18 lakes study (most recently selected); ** 10 lakes study (most recently selected).

Dosage determination plays an important role in the definition and results obtained with this remediation application. An appropriate LMB application can bind soluble reactive phosphorus (SRP) in the water column and cap bioavailable forms of P in the sediments [71]. However, it is important to mention that humic substances can be a strong complexing agent for lanthanides, causing the clay to underperform in those scenarios [74]. Additionally, this compound could react with hydroxyl species under high pH conditions (>8.35) and decrease the potential binding efficiency [69].

In circumstances where external nutrient inputs have not been attenuated in the waterbodies before LMB application, it is understood that these are going to possibly accumulate on the sediment surfaces above the La barrier and are expected soon to trigger eutrophication reoccurrences due to P release. In those scenarios, even though costs will increase, reapplications of the product are recommended as a feasible way to ensure long-term water quality when the applied dosage was or has become insufficient [68,73]. The monetary cost of this remediation practice will depend on the water body size which directly affects the amount of LMB required. As presented in [75], total costs ranging from 152.00 to 253.00 USD per pound of phosphorus mitigated should be expected depending on the water body size. Additionally, another example [76] showed provided the material cost of LMB was 3100.00 CAD/t or 2279.00 USD/t (metric ton) in 2015, and the application cost was 200 CAD/t or 147.00 USD/t for Elk Lake, Canada. The cited cost only includes a one-time application; if any reapplication is necessary, additional costs will incur.

3.2.2. Sediment Capping with Al

This method involves adding an aluminum solution to the lake water, which settles in the sediment and binds phosphorus to it, preventing its release into the water column. Surface complexation–sorption reactions are the primary binding mechanism for phosphate by Al hydroxides [71]. Additionally, for this compound, there is an optimal pH range (i.e., 6–8). In the case of acidic water pH, the form Al^{3+}, which is toxic to organisms, dominates in the solution [74]. Increasing concerns are still not well explained regarding the chronic toxicity of aluminum exposure to humans, which affects the selection for this treatment method. Some in situ lake aluminum applications are presented in Table 4.

Table 4. In situ remediation studies of sediment capping with Al.

Reference	Lake Name	Country	Mean Depth	Treated Area	Treatment Year	Dosage Used	TP Before/TP After
			[m]	[m^2]	[Year]	[g/m^2]	[µg/L/µg/L]
[77]	Lake Harriet	United States	8.7	littoral zone	May 2001	32	n.d
[78,79]	Lake Barleber	Germany	6.7	whole lake	1986 ****	36	SRP: 180/3
[80]	Lake Klasztorne Małe	Poland	8.1	2 m isobath for iron portion of the lake PAC	2021	73.2 (iron)/49.7 (PAC)	211 ± 131/31 ± 72
[81]	Trekanten *	Sweden	3.6	whole lake	2011	60 (PAC)	n.d
[82]	Starodworskie Lake	Poland	9.4 m	area below isobath 10 m	1994–1995	18.6	1700/700
[83]	Lake Vedsted **	Denmark	5.0	whole lake	2009	26.6	n.d
[84]	Nordborg ***	Denmark	5.0	whole lake	2006	44	231/26 (2007), 37 (2008)

Notes: n.d—Not determined; PAC: Poly-Aluminum-Chloride; SRP: Soluble Reactive Phosphorus * 7 lakes studied (most recently selected); ** 114 lakes treated with aluminum (most recent selected); *** 6 lakes treated with aluminum (most recent selected) **** results after 30 years of remediation presented.

Similar to LMB remediation, a high requirement is needed to adequately address the dosage. This should be performed to achieve an active barrier (i.e., capable of binding SRP in the water column and to cap bioavailable forms of P in the sediments) and for addressing possible external nutrient sources for which attenuation has not been performed. Additionally, this phosphorus inactivation method does not directly affect the content of organic phosphorus [78–80]. Any reduction in the phosphorus organic form is the result of reduced primary production in the water body. The cost of this remediation practice will depend on the amount of aluminum solution and its type required. A study has suggested [67] an average of 4812.00 USD per acre for capital costs and a range of 0 USD to 619 USD operation and maintenance costs if continuous monitoring is added to the practice application.

3.2.3. Hypolimnetic Oxygenation

This treatment/remediation option is based on the introduction of oxygen in deep anoxic water to prevent low dissolved oxygen concentrations. The main goal is to satisfy the sediment oxygen demand (SOD) and increase the redox potential at the water-sediment interface, limiting the seasonal release of nutrients from the bottom sediments into the water column [85]. The common effect of hypolimnetic oxygenation has been to eliminate hypoxic conditions with strong suppression of sediment solubilization of TP, Fe, and Mn [86,87]. Some in situ hypolimnetic oxygenation practices applications are presented in Table 5.

Table 5. In situ remediation studies of hypolimnetic oxygenation.

Reference	Lake Name	Country	Mean Depth	Method Used	Treatment Year	Dosage Used	TP Before/TP After
			[m]		[Year]	[kg O_2/d]	[µg/L/µg/L]
[84]	Lake Vedsted *	Denmark	5.0	Bubble diffusers	1995/2003–2007	50	25/16
[86]	Lake Pleasant	United States	8	Bubble linear diffusers	2014–2018	1775	552/53
[87]	Lake Serraia	Italy	7	Octagonal diffusers 1 m above sediment	2006 and 2007	144	40/n.d **
[88]	Aha Reservoir	China	13	Bubble plume diffusers	2017	28.58	40/20

Note: * 6 lake studies (most recently selected) additional treatment with Al, ** n.d—Not determined.

As with hypolimnetic aeration, sediment with low sorptive capacity (low amount of binding phosphorus substances such as iron and manganese) will affect the phosphorus attenuation. If the lake has a high content of organic matter (OM) accumulated on the sediment, oxygen concentration demand will increase at the start of the procedure, playing an important role in this remediation. Additionally, when further OM oxidation in the superficial layer of the lake sediments takes place, reduction in the sediment oxygen demand throughout the application and improvement of the trophic state if accompanied by reduction in the external nutrient load [87] will be noted. If this methodology is required, it should be combined with other ecological lake restoration techniques. Capital, operational, and maintenance costs for the implementation of this method vary depending on many site-specific parameters such as oxygenation equipment chosen, type of oxygen generator employed, or transportation of pure oxygen tanks and practice maintenance. For a better perspective, a diffuser oxygenation system installation is between $0.5 M and $2.5 M ($40 to $800 per hectare meter), with annual operating costs between $30 K and $140 K ($5 to $36 per hectare meter) [89] with values in USD.

3.3. Biological Remediation

3.3.1. Macrophyte Management

Macrophyte management is characterized by plant biomass removal from the lake water as well as the repopulation of endogenous species. The first one can be performed with specific equipment, which can either remove the macrophyte or cut it down as much as possible, and the second is performed with small enclosed aquatic gardens which will be used to spread a certain macrophyte species on the waterbody. Both have been investigated for in-lake applications, and the results have been variable. Removing macrophyte biomass from lakes is often an effective treatment to control a nuisance macrophyte problem [90]. Harvesting these submerged macrophytes has four distinct effects on water quality: leaching of soluble compounds from macrophyte organs, sediment resuspension, reduction in macrophyte litter in the lake [91], and plant fragment dispersal. Macrophyte repopulation or phytoremediation, on the other hand, is a new approach which is still under investigation and is based on the large-scale cultivation of a macrophyte species (indigenous in the area), which can assimilate some of the nutrients in the water. Some in-lake studies have been highlighted in Table 6.

Table 6. In situ remediation studies of macrophyte management.

Reference	Lake Name	Country	Mean Depth	Method Used	Treatment Year	TP Before/TP After
			[m]		[Year]	[μg/L/μg/L]
[91]	Lake Biwa	Japan	3.5	Annual macrophyte harvesting	July to September (every year)	n.d *
[92]	Lake Caohai	China	2.5	Large-scale cultivation of water hyacinths	2011–2013	54/15
[93]	West Lake	China	2.27	Sediment covered by a layer of modified clay minerals (10 cm)	July 2013–2019	70 ± 30/20 ± 10

Note: * n.d—Not determined.

In this procedure, it is recommended for the macrophyte harvesting, a method to avoid sediment resuspension [91] to further reduce metal ion (i.e., Ca, Mg, Sr, and Fe) and nutrient dissolution in the water. In other words, instead of removing rooted plants, the technique recommended is to just cut the upper plant part. With the macrophyte repopulation, it is highlighted that P is assimilated from lake water and partially in the sediment. Thus, this method could be performed on sites with large algae concentrations, for declining assimilated nutrients and removing endogenous sources.

3.3.2. Biomanipulation

Biomanipulation or the aquatic food chain manipulation is a procedure to reduce phytoplankton biomass and is achieved by planktivorous fish removal and the introduction of piscivorous fish into a lake [92]. Removal could be performed with the use of nets and/or electric fishing. The main objectives of this technique are to decrease the high concentration of toxic phytoplankton in the water bodies as well as reduce sediment disturbance. Well-studied methodologies have presented variable results. In reviewed papers, improvement in water clarity is mainly due to reduced sediment disturbance by fish [94,95]. It is worth mentioning that a reduction in turbidity will possibly cause a reduction in nutrient concentration in the water column, but this will not remove it from the sediment. Because of that, some of the papers have combined biomanipulation with the transplantation of macrophytes (to create a more stable sediment surface) [94–96]. Some in situ biomanipulation practices are presented in Table 7.

Table 7. In situ remediation studies of biomanipulation.

Reference	Lake Name	Country	Mean Depth	Method Used	Treatment Year	TP Before/TP After
			[m]		[Year]	[μg/L/μg/L]
[94]	Meishan Dongpo Lake	China	2.5	Biomass screening/Removal of Fish/Macrophyte Addition	November 2015 to July 2016	379/lower than 50
[95]	Lake Eymir	Turkey	3.1	Multiple mesh-sized gill nets	August 1998–1999	324 ± 31/381 ± 21

Table 7. *Cont.*

Reference	Lake Name	Country	Mean Depth	Method Used	Treatment Year	TP Before/TP After
			[m]		[Year]	[µg/L/µg/L]
[96]	Lake Wuli	China	2.1	Gillnets and electric fishing/Richardson, and piscivorous fish addition with macrophytes	2010	n.d *
[97]	Huizhou West Lake	China	1.6	Plankti-benthivorous fish was followed by the planting of submerged macrophytes and stocking of piscivorous fish	-	126/lower than 50

Note: * n.d—Not determined.

As a possible disadvantage of biomanipulation, the water has a higher clarity after manipulation, and the sediments which thus retain more P. Aquatic species could disturb the sediment, causing further nutrient releases from the sediments. Usually, three specific activities will define the cost of biomanipulation: the fish removal, the stocking, and the fish population monitoring. For giving a perspective on costs for biomanipulation of the Twin Lakes in Golden Valley, Minnesota, amounts have been shared as follows: 8000 USD for the combination of netting and electrofishing fish removal, and 45,000 USD was used for stocking (i.e., which will directly be dependent on the species). This included a fish population yearly monitoring cost of 1000 USD per year [98].

3.4. Combined Remediation Techniques

In this type of practice, more than one remediation technique is used to achieve the desired objective of a healthy water body without signs of eutrophication. This is considered a rounded methodology, well established in the specialized literature for treating eutrophic aquatic ecosystems. An overview of possible combinations is summarized in Table 8.

Table 8. Combined in situ remediation studies.

Reference	Lake Name	Country	Mean Depth	Method Used	Treatment Year	Dosage Used	TP Before/TP After
			[m]		[year]		[µg/L/µg/L]
[99]	Lake De Kuil	Netherlands	4	Coagulation/Flocculation/LMB Capping	18 May to 22 May 2009	65.35 $FeCl_3$ g/m^2, 2.03 tLMB/ha superficially and 4.17 tLMB/ha	50/20
[100]	Lake Głębokie	Poland	2.4	Aeration/coagulation (iron sulphate III)/biomanipulation	2008–2012	A total of 7.90 g/m^2 divided in 8 applications	140/65
[101]	Swarzędzkie Lake	Poland	2.6	Aeration/coagulation (iron sulphate III) and magnesium chloride ($MgCl_2$)/biomanipulation	2012–2014	15 kg/ha ($FeSO_4$)	114.6/76
[102]	Lake Kleine Melanen	Netherlands	1.0	Biomanipulation/dredging/sand capping/LMB application and flocculant	2010–2012	4.14 t LMB/ha	300/110
[103]	Lake Rauwbraken	Netherlands	8	Coagulation and LMB capping	April 21st to 23rd 2008	(0.8 t LMB/ha + 77 g/m^2 PAC *) + 6.4 t LMB/ha	134/14
[104]	Lake Schmaler	Germany	14.7	$Ca(OH)_2$ injection and hypolimnetic aeration	1996–1998	300 t of $Ca(OH)_2$	n.d **

Note: * PAC: Poly-Aluminum-Chloride; ** n.d—Not determined.

The holistic approaches presented in the reviewed articles are well-known doses of coagulant and LMB to achieve the desired objective of a healthy lake free of eutrophication signs [99,102,103]. This practice is based on coagulant addition, and in some cases was followed by water column aeration. Then, LMB is supplemented to increase flocculation in the applied water body, thus causing particles to settle more easily and sorb phosphorus on them, thus capturing P as an active capping layer on the sediment surface. Investigation into the order of addition is needed to obtain the best attenuation scenario. Additionally, as presented after the particles settle, biomanipulation can take place during this treatment. As this procedure is well studied in the literature with positive results, this in-lake practice application could be a future preference for dealing with eutrophic waterbodies soon. These coagulation and flocculation practices reported monetary values as a total amount including all the steps required. For example, Lake De Kuil had a cost of €140,000 or 150,800 USD [99] and Lake Rauwbraken [105] was €50,000 or 53,854 USD.

Another option presented is the procedure of dredging followed by imposing a sand capping layer for the exposed dredged sediment [102], then addition of the P fixative modified clay and flocculant poly-aluminum chloride. Both methods have presented reliable results for eutrophication control. Some other examples such as the addition of $Ca(OH)_2$ and hypolimnetic aeration [104], which has induced calcium carbonate precipitation, combined with deep water aeration lower P flux in the sediment, but further investigation is needed.

3.5. Emerging Remediation Techniques including Geotextile Filtration and Floating Wetlands

Emerging remediation measures are based on minimally invasive lake restoration techniques which take the benefits of the natural response of lake water to changes made within it. This has been used for nutrient abstraction or algae suppression. When compared with implemented technologies, these methods are considered less invasive, easily deployed, cheaper, and more sustainable, characterizing them as an environmentally friendly remediation option. While the floating wetland (i.e., ecological floating beds) uses floating plant units, which can uptake nutrients from the water column and thus decrease the incidence of harmful algae blooms, the lake water filtration technique is based on using custom-made geotextiles, generally used in layers for strata separation, soil improvement, reinforcement, and drainage as filter layers for attenuating suspended solids and thus particulate phosphorus. A significant improvement in lake water has been found in investigations performed with geotextiles onsite and in situ [106–108]. However, additional investigations are still required for both methods for any further scale-up and whole lake applications.

3.6. Critical Overview of Practices for Eutrophic Shallow Lake Water Remediation

As previously mentioned, water management/protection is not a straightforward action and technologies must be adjusted on a case-by-case basis. The same understanding should be taken into internal nutrient remediation practices selection and further application. On those, there is no better remediation than the other, as well as no go-to manual for selection—just recommendations to be followed. This is mainly due to water/sediment quality heterogeneity in eutrophic waterbodies. With this thinking, frameworks for selection should always be applied with the perspective on issues presented on the eutrophic waterbody for its attenuation. It is well known that cost plays an important role in this procedure, but it should also be taken into consideration that if the remediation is not performed promptly, the eutrophic water body will not return to its original condition, and costs will tend to increase yearly (i.e., external nutrient attenuation is not performed) or will reach a point of no return.

Summarized information on in situ remediation practices is presented in Table 9. Apart from sediment dredging, all other procedures do not remove higher sediment phosphorus accumulated inside the aquatic ecosystem; thus, the other methods may not permanently reduce eutrophication occurrences. However, this should not be the first and foremost recommended methodology for lake water remediation, mainly because of its associated byproducts generated (i.e., possible metal leaching and waste). This methodology needs to be further investigated and refined to precisely remove less sediment, causing less disturbance and secondary pollution.

Table 9. Overview of practices for eutrophic shallow lake water remediation.

Practice	Procedure	Advantage	Disadvantage/Challenge	Estimated Capital and/or Operating Costs
Dredging	Sediment is excavated mechanically and removed from the waterbody.	Reduction in the internal P loading immediately and substantially.	• Secondary pollution due to leaching metals/contaminants. • Imperative concern for waste disposal.	20,000 USD to 75,000 per acre dredged + Waste disposal cost.
Hypolimnetic Aeration	Mixing of deep anoxic waters with shallow oxygenated epilimnion waters.	Alleviation of eutrophication symptoms.	• Oxygen deficit at start will be high due to accumulated organic matter mineralization. • Does not deal with the issue and combination with other methods is required.	Average of 3800.00 USD per acre for the capital cost and 700.00 USD per acre for operation and maintenance.
LMB Capping	Modified clay addition in a slurry form or granules in the water column which will sorb phosphorus and settle creating a thin barrier.	Sequestration of phosphorus and retention in the sediment and reduced phosphorus sediment bioavailability.	• Dosage determination plays an important role in the results obtained. • Humic substances can complex with lanthanides. • Under high pH conditions (>8.35) the potential binding efficiency decreases. • Reapplication of the product could be required.	2279.00 USD/t for LMB and 147.00 USD/t for application in some cases.
Aluminium Capping	Involves adding an aluminum solution to the lake water which settles in the sediment and binds phosphorus, preventing its release into the water column.	Sequestration of phosphorus and retention in the sediment and reduced phosphorus sediment bioavailability.	• Dosage determination plays an important role in the results obtained. • Optimal pH range is needed (i.e., 6–8). • Acidic water pH, the form Al^{3+}, which is toxic to organisms. • Concerns are still not well explained regarding the chronic effects. • Method does not directly affect the content of organic phosphorus.	Average of 4812.00 USD per acre for capital costs and a range of 0 USD to 619.00 USD operation and maintenance costs in some cases.

Table 9. *Cont.*

Practice	Procedure	Advantage	Disadvantage/Challenge	Estimated Capital and/or Operating Costs
Hypolimnetic Oxygenation	Oxygen introduction in the deep anoxic water to prevent low dissolved oxygen concentrations.	Increased redox potential at the water–sediment interface, limited seasonal release of nutrients from the bottom sediments into the water column.	• Dosage determination plays an important role in the results obtained. • If high content of organic matter accumulated on the sediment, oxygen concentration demand will increase. • It should be combined with other ecological lake restoration techniques.	System installation: 40.00 to 800.00 USD per hectare meter) and operation and maintenance: 5.00 to 36.00 USD per hectare meter in some cases.
Macrophyte Management	Characterized by plant biomass from aquatic ecosystem removal by plunking or cutting it down. Or macrophyte repopulation with endogenous species.	Reduction in macrophyte litter in the lake.	• Leaching of soluble compounds from macrophyte organs • Sediment resuspension and dispersal of plant fragments. • No reduction in phosphorus in the sediment.	Will depend on the price of the equipment acquired/or endogenous plant species to be introduced.
Biomanipulation	Aquatic food chains manipulation achieved by planktivorous fish removal and introduction of piscivorous fish into a lake.	Decreased high concentration of toxic phytoplankton in the water bodies as well as reduced sediment disturbance.	• More P retention in the sediments could lead to further P release into the water.	Removal by netting and electrofishing (8000 USD), 45,000 USD to stock populations, with a yearly monitoring of 1000 USD in some cases.

Sediment capping practices, on the other hand, could be considered a direct and quick solution to decrease eutrophication occurrences, which in some cases is what the stakeholders involved want. The fast application of this active layer on the sediment would have representative direct results, but the higher sediment phosphorus remains. Resuspension or sediment disturbances would easily decrease its effectiveness. Additionally, some capping materials, aluminum and LMB, are well received in some countries and not in many others due to policy restrictions that could affect their selection and application. Additionally, material production of LMB or other specific materials are still focused on just specific world regions and monetary costs are still not practical for all nations.

As with the hypolimnetic oxygenation and aeration method, this technique will just limit the seasonal release of nutrients from the bottom sediments into the water column and is thus a temporary eutrophication alleviation practice. This means that with the interruption of the mentioned technologies, the waterbody could possibly return to its initial eutrophic condition. For macrophyte removal and repopulation, caution should be used. Phytoplankton biota domination or macrophyte dispersal could be worsened due to plant fragments depending on the macrophyte population. Thus, this should be avoided for all unnecessary scenarios (i.e., visual impairment) and if truly needed, the only removal method recommended is cutting the macrophytes to guarantee fewer negative effects on water body quality.

Treatment combinations should be the future practice for eutrophic shallow lake water remediation. Firstly, methods attempting to remov higher phosphorus content sediments from the lake should be followed by methods dealing with the remaining phosphorus concentration in the water column. These practices need to be increased in the remediation market. It is worth commenting that further enhancement of these remediation techniques must include circular economy and waste management approaches for addressing material production as well proper waste reuse or disposal. Additionally, sustainability frameworks need to be developed for ensuring proper application. Environment government bodies must act now on either providing funding for research or allowing pilot studies on lakes by specialized personnel, which can further be expanded to full scale lake restoration.

4. Discussion and Future Perspectives

It is better to prevent than to treat the disease (i.e., eutrophication occurrence). When this premise cannot be applied, it is necessary first to remove/attenuate external nutrient sources followed by a holistic, region-specific, and sustainable remediation method for internal phosphorus load reduction to ensure healthy waters and assurance of all its possible uses for present and future generations. This is achieved by setting targets in close consultation with local authorities and the stakeholders to safeguard a pragmatic and realistic communication of the remediation process [71]. The affected society's involvement should be present not only prior to but also during and after the remediation measures, acting as a valuable promotion of restored water value and if required possible supervision.

Related to external nutrient sources, even though radical and rapid elimination, in many cases, is not possible, especially in the case of non-point sources [63], actions in this direction need to be promoted and documented. These could be achieved using proper land use planning or employing/increasing buffer strips (i.e., to prevent erosion and act as a filter to intercept contaminated watershed runoff). Environmental regulatory government bodies must also present and enforce stricter restrictions/policies for nutrient apport/emission on water bodies to stop the increase in eutrophication scenarios. By designing harsher nutrient removal and emission strategies/guidelines for external sources (i.e., untreated/incompletely treated effluents/sewage disposal) on lakes, the actual eutrophic waterbodies and the ones increasing nutrient concentration will have a time frame to be dealt with it. Past/present nutrient emitters should also be strongly financially accountable for any nutrient attenuation/monitoring of the affected water body.

In the case of internal nutrient remediation strategies selection, this decision must be only based on well-known decision frameworks sustained by prior monitoring results of lake water and sediment. This prior investigation should comprise phosphorus and organic matter content in the water column and sediment, as well as phosphorus bioavailability in the sediment with some other important parameters for best treatment selection, which are pH, DO, turbidity, and chlorophyll-a. The determination of whether internal P load is important relative to external P inputs needs to be understood by the quantification and their contribution to lake P concentration established [68]. In addition, scientifically reliable data on the efficacy of proactive approaches need to be provided to assist water resource managers in making informed decisions [69]. Technologies should be chosen according to their suitability for the site and not solely on an economic basis [23]. Thus, remediation corporation portfolios could and should be used, but compulsory caution on region-specific presented results needs to be included. Even though costs for the various practices are quite different, the final selection will depend on the probable recommendation of environmental government body and the responsible payers to that, which will take into consideration the cost/benefit perspective.

Monitoring actions should always be integrated into the lake restoration practices with a proper definition of follow-up steps and actions if there is a deviation from the expected remediation results. This could be completed by direct guidelines on reapplications, increasing mixing or chemical addition concentration (e.g., O_2 concentration), and rigorous actions to further attenuate the external source if this is the issue. The sustainability of remediation projects also needs to be further investigated and increased in some cases because generating a large quantity of waste without proper disposal (i.e., biomanipulation, sediment dredging) or using non-renewable energy for applications (i.e., diverse chemical addition application, sediment dredging, biomanipulation) are not sustainable. Emergent remediation techniques should be further investigated, and if presented, reliable results used with well-established options for healthy lake water.

With the understanding that every person has the right to clean and safe water, eutrophication must be prevented/attenuated on a global scale promptly. Even though the essential awareness and financial aspect for remediation projects will not be presented equally around world nations, as was noticed throughout the cases presented in Tables 1–8, this lack is mainly occurring in economically developing nations. It is implicit that those nations also suffering from this matter receive all attention and assistance required. Additionally, to assure equitable access to essential knowledge and technologies development/application for water remediation restoration, international environmental organizations must further cooperate not only in the exchange of realities/experiences/perspectives but also for financial and technical support. Only with proper policies and programs for training and development and further investments can nations develop their practices and policies, and remediate their eutrophic waterbodies.

5. Conclusions

Concern with eutrophication in lakes is escalating and in-situ, holistic, and region-specific approaches are the only possible option for the restoration of eutrophic aquatic ecosystems for present and future generations. By the combination of attenuation and regulation of external phosphorus loads with diverse internal nutrient source control and proactive technologies, this is going to be accomplished. In this paper, the principal procedures being applied for in situ eutrophic water remediation has been emphasized in association with possible parameters and disadvantages/challenges encountered by various water restoration techniques. By reviewing these in-situ approaches around nations, a guided summary has been completed, providing concise information on the in-situ restoration cases and challenges in the peer-reviewed literature to facilitate further remediation project investigation, studies, and further selection by stakeholders involved (i.e., environmental managers, and society in general). Two additional steps are compulsory for successful and durable water remediation which are external nutrient attenuation and continuous monitoring. It is also imperative that the affected society participates prior to, during and after the eutrophic remediation measures as a possible way of valuing this water and for long-term and effective water management.

Author Contributions: Conceptualization, A.C.P.; investigation, A.C.P.; writing—original draft preparation, A.C.P.; writing—review and editing, C.N.M.; visualization, A.C.P.; supervision, C.N.M.; project administration, C.N.M.; funding acquisition, C.N.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by NSERC ALLRP 549706-19 grant, Concordia University and Titan Environmental Containment.

Data Availability Statement: The data for this study are available from the authors upon reasonable request.

Acknowledgments: The authors are also grateful to the visual artist Alisson Clebson Nogueira Siqueira for assistance with the diagram and figures included in this paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Beaulieu, J.J.; DelSontro, T.; Downing, J.A. Eutrophication will increase methane emissions from lakes and impoundments during the 21st century. *Nat. Commun.* **2019**, *10*, 1375. [CrossRef] [PubMed]
2. Tong, Y.; Sun, J.; Uddin, M.; Kong, X.; Lin, Y.; Wang, M.; Zhang, H.; Xu, X.; Wu, Z. Perspectives and challenges of applying the water-food-energy nexus approach to lake eutrophication modelling. *Water Secur.* **2021**, *14*, 100095. [CrossRef]
3. Scherer, L.; Pfister, S. Global biodiversity loss by freshwater consumption and eutrophication from Swiss food consumption. *Environ. Sci. Technol.* **2016**, *50*, 7019–7028. [CrossRef] [PubMed]

4. Paerl, H.W.; Gardner, W.S.; Havens, K.E.; Joyner, A.R.; McCarthy, M.J.; Newell, S.E.; Qin, B.; Scott, J.T. Mitigating cyanobacterial harmful algal blooms in aquatic ecosystems impacted by climate change and anthropogenic nutrients. *Harmful Algae* **2016**, *54*, 213–222. [CrossRef]
5. Yindong, T.; Xiwen, X.; Miao, Q.; Jingjing, S.; Yiyan, Z.; Wei, Z.; Mengzhu, W.; Xuejun, W.; Yang, Z. Lake warming intensifies the seasonal pattern of internal nutrient cycling in the eutrophic lake and potential impacts on algal blooms. *Water Res.* **2021**, *188*, 116570. [CrossRef]
6. Woolway, R.I.; Kraemer, B.M.; Lenters, J.D.; Merchant, C.J.; O'Reilly, C.M.; Sharma, S. Global lake responses to climate change. *Nat. Rev. Earth Environ.* **2020**, *1*, 388–403. [CrossRef]
7. Woolway, R.I.; Merchant, C.J. Worldwide alteration of lake mixing regimes in response to climate change. *Nat. Geosci.* **2019**, *12*, 271–276. [CrossRef]
8. Häder, D.P.; Banaszak, A.T.; Villafañe, V.E.; Narvarte, M.A.; González, R.A.; Helbling, E.W. Anthropogenic pollution of aquatic ecosystems: Emerging problems with global implications. *Sci. Total Environ.* **2020**, *713*, 136586. [CrossRef]
9. Chowdhary, P.; Bharagava, R.N.; Mishra, S.; Khan, N. Role of industries in water scarcity and its adverse effects on environment and human health. In *Environmental Concerns and Sustainable Development: Volume 1: Air, Water and Energy Resources*; Springer: New York, NY, USA, 2020; pp. 235–256. [CrossRef]
10. Le Moal, M.; Gascuel-Odoux, C.; Ménesguen, A.; Souchon, Y.; Étrillard, C.; Levain, A.; Moatar, F.; Pannard, A.; Souchu, P.; Lefebvre, A.; et al. Eutrophication: A new wine in an old bottle? *Sci. Total Environ.* **2019**, *651*, 1–11. [CrossRef]
11. Li, H.; Gu, X.; Chen, H.; Mao, Z.; Shen, R.; Zeng, Q.; Ge, Y. Co-occurrence of multiple cyanotoxins and taste-and-odor compounds in the large eutrophic Lake Taihu, China: Dynamics, driving factors, and challenges for risk assessment. *Environ. Pollut.* **2022**, *294*, 118594. [CrossRef]
12. Smith, V.H.; Sieber-Denlinger, J.; de Noyelles, F., Jr.; Campbell, S.; Pan, S.; Randtke, S.J.; Blain, G.T.; Strasser, V.A. Managing taste and odor problems in a eutrophic drinking water reservoir. *Lake Reserv. Manag.* **2002**, *18*, 319–323. Available online: https://www.tandfonline.com/doi/abs/10.1080/07438140209353938 (accessed on 30 April 2023). [CrossRef]
13. Wang, Z.; Akbar, S.; Sun, Y.; Gu, L.; Zhang, L.; Lyu, K.; Huang, Y.; Yang, Z. Cyanobacterial dominance and succession: Factors, mechanisms, predictions, and management. *J. Environ. Manag.* **2021**, *297*, 113281. [CrossRef] [PubMed]
14. Brasil, J.; Attayde, J.L.; Vasconcelos, F.R.; Dantas, D.D.; Huszar, V.L. Drought-induced water-level reduction favors cyanobacteria blooms in tropical shallow lakes. *Hydrobiologia* **2016**, *770*, 145–164. [CrossRef]
15. Kaur, S.; Srivastava, A.; Ahluwalia, A.S.; Mishra, Y. *Cyanobacterial blooms and Cyanotoxins: Occurrence and Detection. Algae: Multifarious Applications for a Sustainable World*; Springer: New York, NY, USA, 2021; pp. 339–352. [CrossRef]
16. USEPA (US Environmental Protection Agency). A Compilation of Cost Data Associated with the Impacts and Control of Nutrient Pollution. 2015. Available online: https://www.epa.gov/sites/default/files/2015-04/documents/nutrient-economics-report-2015.pdf (accessed on 30 April 2023).
17. Dodds, W.K.; Bouska, W.W.; Eitzmann, J.L.; Pilger, T.J.; Pitts, K.L.; Riley, A.J.; Schloesser, J.T.; Thornbrugh, D.J. Eutrophication of US freshwaters: Analysis of potential economic damages. *Environ. Sci. Technol.* **2009**, *43*, 12–19. [CrossRef]
18. Pretty, J.N.; Mason, C.F.; Nedwell, D.B.; Hine, R.E. *A Preliminary Assessment of the Environmental Costs of the Eutrophication of Fresh Water in England and Wales*; University of Essex: Colchester, UK, 2002. Available online: https://buckinghamcanal.org.uk/wp-content/uploads/resources/EAEutrophReport.pdf (accessed on 30 April 2023).
19. Walker, W.W., Jr. Significance of eutrophication in water supply reservoirs. *J. Am. Water Work. Assoc.* **1983**, *75*, 38–42. [CrossRef]
20. Golterman, H.L. Chapter 17 Nutrient Budgets and Eutrophication. In *Physiological Limnology—An Approach to the Physiology of Lake Ecosystems*; Elsevier: Amsterdam, The Netherlands, 1975; pp. 357–402. [CrossRef]
21. Sharpley, A.; Jarvie, H.P.; Buda, A.; May, L.; Spears, B.; Kleinman, P. Phosphorus legacy: Overcoming the effects of past management practices to mitigate future water quality impairment. *J. Environ. Qual.* **2013**, *42*, 1308–1326. [CrossRef] [PubMed]
22. Song, K.; Adams, C.J.; Burgin, A.J. Relative importance of external and internal phosphorus loadings on affecting lake water quality in agricultural landscapes. *Ecol. Eng.* **2017**, *108*, 482–488. [CrossRef]
23. Dunalska, J.A. How the integrated engineering solutions can support the lakes restoration? *Ecohydrol. Hydrobiol.* **2021**, *21*, 36–45. [CrossRef]
24. Istvánovics, V. Eutrophication of Lakes and Reservoirs. In *Encyclopedia of Inland Waters*; Elsevier: San Diego, CA, USA, 2009; pp. 157–165. [CrossRef]
25. O'Hare, M.T.; Baattrup-Pedersen, A.; Baumgarte, I.; Freeman, A.; Gunn, I.D.; Lázár, A.N.; Sinclair, R.; Wade, A.J.; Bowes, M.J. Responses of aquatic plants to eutrophication in rivers: A revised conceptual model. *Front. Plant Sci.* **2018**, *9*, 451. [CrossRef]
26. Khan, F.A.; Ansari, A.A. Eutrophication: An ecological vision. *Bot. Rev.* **2005**, *71*, 449–482. [CrossRef]
27. Sellergren, M.; Li, J.; Drakare, S.; Thöns, S. Decision Support for Lake Restoration: A Case Study in Swedish Freshwater Bodies. *Water* **2023**, *15*, 668. [CrossRef]
28. McCormick, A.R.; Phillips, J.S.; Botsch, J.C.; Ives, A.R. Shifts in the partitioning of benthic and pelagic primary production within and across summers in Lake Mývatn, Iceland. *Inland Waters* **2021**, *11*, 13–28. [CrossRef]
29. Senar, O.E.; Creed, I.F.; Trick, C.G. Lake browning may fuel phytoplankton biomass and trigger shifts in phytoplankton communities in temperate lakes. *Aquat. Sci.* **2021**, *83*, 21. [CrossRef]

30. O'Keeffe, J. *Cyanobacteria and Drinking Water: Occurrence, Risks, Management and Knowledge Gaps for Public Health*; National Collaborating Centre for Environmental Health: Vancouver, BC, Canada, 2019. Available online: https://ncceh.ca/documents/evidence-review/cyanobacteria-and-drinking-water-occurrence-risks-management-and (accessed on 30 April 2023).
31. Mackey, K.R.M.; Paytan, A. Phosphorus Cycle. In *Encyclopedia of Microbiology*; Elsevier: Oxford, UK, 2009; pp. 322–334. [CrossRef]
32. Denver, J.M.; Cravotta, C.A.; Ator, S.W.; Lindsey, B.D. *Contributions of Phosphorus from Groundwater to Streams in the Piedmont, Blue Ridge, and Valley and Ridge Physiographic Provinces, Eastern United States*; US Department of the Interior, US Geological Survey: Denver, CO, USA, 2010; Volume 2010. Available online: https://pubs.usgs.gov/sir/2010/5176/support/sir2010-5176old2282011.pdf (accessed on 30 April 2023).
33. Slomp, C.P.; Mort, H.P.; Jilbert, T.; Reed, D.C.; Gustafsson, B.G.; Wolthers, M. Coupled dynamics of iron and phosphorus in sediments of an oligotrophic coastal basin and the impact of anaerobic oxidation of methane. *PLoS ONE* **2013**, *8*, e62386. [CrossRef] [PubMed]
34. Yu, W.; Yang, H.; Chen, J.; Liao, P.; Chen, Q.; Yang, Y.; Liu, Y. Organic Phosphorus Mineralization Dominates the Release of Internal Phosphorus in a Macrophyte-Dominated Eutrophication Lake. *Front. Environ. Sci.* **2022**, *747*, 812834. [CrossRef]
35. Zhou, Z.; Henkel, S.; Kasten, S.; Holtappels, M. The iron "redox battery" in sandy sediments: Its impact on organic matter remineralization and phosphorus cycling. *Sci. Total Environ.* **2023**, *865*, 161168. [CrossRef] [PubMed]
36. Kapsalis, V.C.; Kalavrouziotis, I.K. Eutrophication—A worldwide water quality issue. In *Chemical Lake Restoration: Technologies, Innovations and Economic Perspectives*; Springer: New York, NY, USA, 2021; pp. 1–21. [CrossRef]
37. Søndergaard, M.; Jensen, J.P.; Jeppesen, E. Role of sediment and internal loading of phosphorus in shallow lakes. *Hydrobiologia* **2003**, *506*, 135–145. [CrossRef]
38. Li, Y.; Yu, S.; Strong, J.; Wang, H. Are the biogeochemical cycles of carbon, nitrogen, sulfur, and phosphorus driven by the "Fe III–Fe II redox wheel" in dynamic redox environments? *J. Soils Sediments* **2012**, *12*, 683–693. [CrossRef]
39. Smolders, A.J.; Lucassen, E.C.; Bobbink, R.; Roelofs, J.G.; Lamers, L.P. How nitrate leaching from agricultural lands provokes phosphate eutrophication in groundwater fed wetlands: The sulphur bridge. *Biogeochemistry* **2010**, *98*, 1–7. [CrossRef]
40. Avilés, A.; Rodero, J.; Amores, V.; De Vicente, I.; Rodríguez, M.I.; Niell, F.X. Factors controlling phosphorus speciation in a Mediterranean basin (River Guadalfeo, Spain). *J. Hydrol.* **2006**, *331*, 396–408. [CrossRef]
41. House, W.A. Geochemical cycling of phosphorus in rivers. *Appl. Geochem.* **2003**, *18*, 739–748. [CrossRef]
42. Wetzel, R.G. 26—Inland waters: Understanding is essential for the future. In *Limnology*, 3rd ed.; Elsevier: Oxford, UK, 2001; pp. 825–841. [CrossRef]
43. Jilbert, T.; Couture, R.M.; Huser, B.J.; Salonen, K. Preface: Restoration of eutrophic lakes: Current practices and future challenges. *Hydrobiologia* **2020**, *847*, 4343–4357. [CrossRef]
44. UNESCO. The United Nations World Water Development Report 2021: Valuing Water. 2021. Available online: https://unesdoc.unesco.org/ark:/48223/pf0000375724 (accessed on 30 April 2023).
45. Schlesinger, W.H.; Bernhardt, E.S. Inland Waters—Chapter 8. *Biogeochemistry* **2020**, *132*, 293–360. [CrossRef]
46. Carlson, R.E. A trophic state index for lakes. *Limnol. Oceanogr.* **1977**, *22*, 361–369. [CrossRef]
47. Mekonnen, M.M.; Hoekstra, A.Y. Global anthropogenic phosphorus loads to freshwater and associated grey water 671 footprints and water pollution levels: A high-resolution global study. *Water Resour. Res.* **2018**, *54*, 345–358. [CrossRef]
48. Smith, V.H.; Schindler, D.W. Eutrophication science: Where do we go from here? *Trends Ecol. Evol.* **2009**, *24*, 201–207. [CrossRef]
49. Ho, J.C.; Michalak, A.M.; Pahlevan, N. Widespread global increase in intense lake phytoplankton blooms since the 1980s. *Nature* **2019**, *574*, 667–670. [CrossRef]
50. Kakade, A.; Salama, E.S.; Han, H.; Zheng, Y.; Kulshrestha, S.; Jalalah, M.; Harraz, F.A.; Alsareii, S.A.; Li, X. World eutrophic pollution of lake and river: Biotreatment potential and future perspectives. *Environ. Technol. Innov.* **2021**, *23*, 101604. [CrossRef]
51. International Lake Environment Committee, (I.L.E.C.); Lake Biwa Research Institute. *1988–1993 Survey of the State of the World's Lakes*; International Lake Environment Committee, Otsu and United Nations Environment Programme: Nairobi, Kenya, 2002; Volume I–IV.
52. Paerl, H.W.; Xu, H.; McCarthy, M.J.; Zhu, G.; Qin, B.; Li, Y.; Gardner, W.S. Controlling harmful cyanobacterial blooms in a hyper-eutrophic lake (Lake Taihu, China): The need for a dual nutrient (N & P) management strategy. *Water Res.* **2011**, *45*, 1973–1983. [CrossRef]
53. Zhang, Y.; Luo, P.; Zhao, S.; Kang, S.; Wang, P.; Zhou, M.; Lyu, J. Control and remediation methods for eutrophic lakes in the past 30 years. *Water Sci. Technol.* **2020**, *81*, 1099–1113. [CrossRef]
54. Wang, C.; Jiang, H.L. Chemicals used for in situ immobilization to reduce the internal phosphorus loading from lake sediments for eutrophication control. *Crit. Rev. Environ. Sci. Technol.* **2016**, *46*, 947–997. [CrossRef]
55. Rast, W.; Holland, M. Eutrophication of lakes and reservoirs: A framework for making management decisions. *Ambio* **1988**, *17*, 2–12. Available online: https://www.jstor.org/stable/4313411 (accessed on 30 April 2023).
56. Hickey, C.W.; Gibbs, M.M. Lake sediment phosphorus release management—Decision support and risk assessment framework. *N. Z. J. Mar. Freshw. Res.* **2009**, *43*, 819–856. [CrossRef]
57. Kiani, M.; Tammeorg, P.; Niemistö, J.; Simojoki, A.; Tammeorg, O. Internal phosphorus loading in a small shallow Lake: Response after sediment removal. *Sci. Total Environ.* **2020**, *725*, 138279. [CrossRef] [PubMed]

58. Jing, L.; Bai, S.; Li, Y.; Peng, Y.; Wu, C.; Liu, J.; Liu, G.; Xie, Z.; Yu, G. Dredging project caused short-term positive effects on lake ecosystem health: A five-year follow-up study at the integrated lake ecosystem level. *Sci. Total Environ.* **2019**, *686*, 753–763. [CrossRef] [PubMed]
59. Liu, C.; Zhong, J.; Wang, J.; Zhang, L.; Fan, C. Fifteen-year study of environmental dredging effect on variation of nitrogen and phosphorus exchange across the sediment-water interface of an urban lake. *Environ. Pollut.* **2016**, *219*, 639–648. [CrossRef]
60. Zhang, S.; Zhou, Q.; Xu, D.; Lin, J.; Cheng, S.; Wu, Z. Effects of sediment dredging on water quality and zooplankton community structure in a shallow of eutrophic lake. *J. Environ. Sci.* **2010**, *22*, 218–224. [CrossRef]
61. Wan, W.; Zhang, Y.; Cheng, G.; Li, X.; Qin, Y.; He, D. Dredging mitigates cyanobacterial bloom in eutrophic Lake Nanhu: Shifts in associations between the bacterioplankton community and sediment biogeochemistry. *Environ. Res.* **2020**, *188*, 109799. [CrossRef]
62. Natural Technique for Dredging a Pond or Lake—Clean-Flo. Available online: https://clean-flo.com/alternative-dredging-techniques-muck-removal (accessed on 28 May 2023).
63. Dondajewska, R.; Kowalczewska-Madura, K.; Gołdyn, R.; Kozak, A.; Messyasz, B.; Cerbin, S. Long-term water quality changes as a result of a sustainable restoration—A case study of dimictic Lake Durowskie. *Water* **2019**, *11*, 616. [CrossRef]
64. Zhang, X. Restoration of a Small, Shallow, Eutrophic Lake by Submerged Aeration and Comparison with a Similar Lake. Ph.D. Dissertation, Colorado State University, Fort Collins, CO, USA, 2013. Available online: https://www.proquest.com/docview/1416433047 (accessed on 30 April 2023).
65. Grochowska, J.; Brzozowska, R.; Parszuto, K. The influence of different recultivation techniques on primary production processes in a degraded urban lake. *Oceanol. Hydrobiol. Stud.* **2014**, *43*, 211–218. [CrossRef]
66. Mallin, M.A.; McIver, M.R.; Wambach, E.J.; Robuck, A.R. Algal blooms, circulators, waterfowl, and eutrophic Greenfield Lake, North Carolina. *Lake Reserv. Manag.* **2016**, *32*, 168–181. [CrossRef]
67. ITRC. *Review of Strategies for Preventing and Managing Harmful Cyanobacterial Blooms*; Interstate Technology and Regulatory Council: Washington, DC, USA, 2020; Available online: https://hcb-1.itrcweb.org/c-2-cost-compilation-for-several-mitigation-strategies/ (accessed on 28 May 2023).
68. Nürnberg, G.K.; LaZerte, B.D. Trophic state decrease after lanthanum-modified bentonite (Phoslock) application to a hyper-eutrophic polymictic urban lake frequented by Canada geese (Branta canadensis). *Lake Reserv. Manag.* **2016**, *32*, 74–88. [CrossRef]
69. Bishop, W.M.; McNabb, T.; Cormican, I.; Willis, B.E.; Hyde, S. Operational evaluation of Phoslock phosphorus locking technology in Laguna Niguel Lake, California. *Water Air Soil Pollut.* **2014**, *225*, 1–11. [CrossRef]
70. Neweshy, W.; Planas, D.; Tellier, E.; Demers, M.; Marsac, R.; Couture, R.M. Response of sediment phosphorus partitioning to lanthanum-modified clay amendment and porewater chemistry in a small eutrophic lake. *Environ. Sci. Process. Impacts* **2022**, *24*, 1494–1507. [CrossRef]
71. Epe, T.S.; Finsterle, K.; Yasseri, S. Nine years of phosphorus management with lanthanum modified bentonite (Phoslock) in a eutrophic, shallow swimming lake in Germany. *Lake Reserv. Manag.* **2017**, *33*, 119–129. [CrossRef]
72. Spears, B.M.; Mackay, E.B.; Yasseri, S.; Gunn, I.D.; Waters, K.E.; Andrews, C.; Cole, S.; De Ville, M.; Kelly, A.; Meis, S.; et al. A meta-analysis of water quality and aquatic macrophyte responses in 18 lakes treated with lanthanum modified bentonite (Phoslock®). *Water Res.* **2016**, *97*, 111–121. [CrossRef] [PubMed]
73. Dithmer, L.; Nielsen, U.G.; Lürling, M.; Spears, B.M.; Yasseri, S.; Lundberg, D.; Moore, A.; Jensen, N.D.; Reitzel, K. Responses in sediment phosphorus and lanthanum concentrations and composition across 10 lakes following applications of lanthanum modified bentonite. *Water Res.* **2016**, *97*, 101–110. [CrossRef]
74. Lürling, M.; Faassen, E.J. Controlling toxic cyanobacteria: Effects of dredging and phosphorus-binding clay on cyanobacteria and microcystins. *Water Res.* **2012**, *46*, 1447–1459. [CrossRef] [PubMed]
75. Tetra Tech. Assessment of Nutrient Management Technology Submission Phoslock®Phosphorus Locking Technology. 2022. Available online: https://h2.ohio.gov/wp-content/uploads/2022/09/H2Ohio-Technology-Assessment-Final-Report-Phoslock-Jan-2022.pdf (accessed on 30 April 2023).
76. Nürnberg, G.K. Attempted management of cyanobacteria by Phoslock (lanthanum-modified clay) in Canadian lakes: Water quality results and predictions. *Lake Reserv. Manag.* **2017**, *33*, 163–170. [CrossRef]
77. Huser, B.J. Aluminum application to restore water quality in eutrophic lakes: Maximizing binding efficiency between aluminum and phosphorus. *Lake Reserv. Manag.* **2017**, *33*, 143–151. [CrossRef]
78. Dadi, T.; Schultze, M.; Kong, X.; Seewald, M.; Rinke, K.; Friese, K. Sudden eutrophication of an aluminum sulphate treated lake due to abrupt increase of internal phosphorus loading after three decades of mesotrophy. *Water Res.* **2023**, *235*, 119824. [CrossRef] [PubMed]
79. Rönicke, H.; Frassl, M.A.; Rinke, K.; Tittel, J.; Beyer, M.; Kormann, B.; Gohr, F.; Schultze, M. Suppression of bloom-forming colonial cyanobacteria by phosphate precipitation: A 30 years case study in Lake Barleber (Germany). *Ecol. Eng.* **2021**, *162*, 106171. [CrossRef]
80. Kowalski, H.; Grochowska, J.K.; Łopata, M.; Augustyniak-Tunowska, R.; Tandyrak, R. A Unique Application Methodology for the Use of Phosphorus Inactivation Agents and Its Effect on Phosphorus Speciation in Lakes with Contrasting Mixing Regimes. *Water* **2022**, *15*, 67. [CrossRef]
81. Agstam-Norlin, O.; Lannergård, E.E.; Futter, M.N.; Huser, B.J. Optimization of aluminum treatment efficiency to control internal phosphorus loading in eutrophic lakes. *Water Res.* **2020**, *185*, 116150. [CrossRef] [PubMed]

82. Augustyniak, R.; Tandyrak, R.; Łopata, M.; Grochowska, J. Long Term Sediment Modification Effects after Applications of P Inactivation Method in Meromictic Lake (Starodworskie Lake, Olsztyn Lakeland, Poland). *Land* **2021**, *10*, 411. [CrossRef]
83. Huser, B.J.; Egemose, S.; Harper, H.; Hupfer, M.; Jensen, H.; Pilgrim, K.M.; Reitzel, K.; Rydin, E.; Futter, M. Longevity and effectiveness of aluminum addition to reduce sediment phosphorus release and restore lake water quality. *Water Res.* **2016**, *97*, 122–132. [CrossRef]
84. Jensen, H.S.; Reitzel, K.; Egemose, S. Evaluation of aluminum treatment efficiency on water quality and internal phosphorus cycling in six Danish lakes. *Hydrobiologia* **2015**, *751*, 189–199. [CrossRef]
85. Gantzer, P.A.; Bryant, L.D.; Little, J.C. Effect of hypolimnetic oxygenation on oxygen depletion rates in two water-supply reservoirs. *Water Res.* **2009**, *43*, 1700–1710. [CrossRef]
86. Austin, D.; Scharf, R.; Chen, C.F.; Bode, J. Hypolimnetic oxygenation and aeration in two Midwestern USA reservoirs. *Lake Reserv. Manag.* **2019**, *35*, 266–276. [CrossRef]
87. Toffolon, M.; Ragazzi, M.; Righetti, M.; Teodoru, C.R.; Tubino, M.; Defrancesco, C.; Pozzi, S. Effects of artificial hypolimnetic oxygenation in a shallow lake. Part 1: Phenomenological description and management. *J. Environ. Manag.* **2013**, *114*, 520–529. [CrossRef]
88. Lan, C.; Ji, Y.; Wang, J.; Yang, H. Water Quality Restoration of a Drinking Water Outlet Area in a Eutrophic Reservoir Using Hypolimnetic Oxygenation in Southwest China. *Pol. J. Environ. Stud.* **2021**, *30*, 1237–1246. [CrossRef] [PubMed]
89. Mobley, M.; Gantzer, P.; Benskin, P.; Hannoun, I.; McMahon, S.; Austin, D.; Scharf, R. Hypolimnetic oxygenation of water supply reservoirs using bubble plume diffusers. *Lake Reserv. Manag.* **2019**, *35*, 247–265. [CrossRef]
90. Cooke, G.D.; Welch, E.B.; Peterson, S.; Nichols, S.A. *Restoration and Management of Lakes and Reservoirs*; CRC Press: Boca Raton, FL, USA, 2016.
91. Ban, S.; Toda, T.; Koyama, M.; Ishikawa, K.; Kohzu, A.; Imai, A. Modern lake ecosystem management by sustainable harvesting and effective utilization of aquatic macrophytes. *Limnology* **2019**, *20*, 93–100. [CrossRef]
92. Zhang, Y.; Liu, H.; Yan, S.; Wen, X.; Qin, H.; Wang, Z.; Zhang, Z. Phosphorus removal from the hyper-eutrophic Lake Caohai (China) with large-scale water hyacinth cultivation. *Environ. Sci. Pollut. Res.* **2019**, *26*, 12975–12984. [CrossRef]
93. Bai, G.; Zhang, Y.; Yan, P.; Yan, W.; Kong, L.; Wang, L.; Wang, C.; Liu, Z.; Liu, B.; Ma, J.; et al. Spatial and seasonal variation of water parameters, sediment properties, and submerged macrophytes after ecological restoration in a long-term (6 years) study in Hangzhou west lake in China: Submerged macrophyte distribution influenced by environmental variables. *Water Res.* **2020**, *186*, 116379. [CrossRef]
94. Chen, Z.; Zhao, D.; Li, M.; Tu, W.; Liu, X. A field study on the effects of combined biomanipulation on the water quality of a eutrophic lake. *Environ. Pollut.* **2020**, *265*, 115091. [CrossRef]
95. Beklioglu, M.; Ince, O.; Tuzun, I. Restoration of the eutrophic Lake Eymir, Turkey, by biomanipulation after a major external nutrient control I. *Hydrobiologia* **2003**, *490*, 93–105. [CrossRef]
96. Yu, J.; Liu, Z.; Li, K.; Chen, F.; Guan, B.; Hu, Y.; Zhong, P.; Tang, Y.; Zhao, X.; He, H.; et al. Restoration of shallow lakes in subtropical and tropical China: Response of nutrients and water clarity to biomanipulation by fish removal and submerged plant transplantation. *Water* **2016**, *8*, 438. [CrossRef]
97. Liu, Z.; Hu, J.; Zhong, P.; Zhang, X.; Ning, J.; Larsen, S.E.; Chen, D.; Gao, Y.; He, H.; Jeppesen, E. Successful restoration of a tropical shallow eutrophic lake: Strong bottom-up but weak top-down effects recorded. *Water Res.* **2018**, *146*, 88–97. [CrossRef]
98. Chandler, K.L. *Feasibility Report for Water Quality Improvements in Twin Lake CIP Project TW-2*; Barr Engineering Company: Minneapolis, MN, USA, 2013.
99. Waajen, G.; van Oosterhout, F.; Douglas, G.; Lürling, M. Management of eutrophication in Lake De Kuil (The Netherlands) using combined flocculant–Lanthanum modified bentonite treatment. *Water Res.* **2016**, *97*, 83–95. [CrossRef]
100. Kozak, A.; Gołdyn, R.; Dondajewska, R.; Kowalczewska-Madura, K.; Holona, T. Changes in phytoplankton and water quality during sustainable restoration of an urban lake used for recreation and water supply. *Water* **2017**, *9*, 713. [CrossRef]
101. Kowalczewska-Madura, K.; Rosińska, J.; Dondajewska-Pielka, R.; Gołdyn, R.; Kaczmarek, L. The effects of limiting restoration treatments in a shallow urban lake. *Water* **2020**, *12*, 1383. [CrossRef]
102. Waajen, G.; Lürling, M.; van de Sande, R. The unfulfilled promise of urban Lake Kleine Melanen (The Netherlands): Diagnostics, experiment on reduction of sediment P-release and in-lake restoration. *Lake Reserv. Manag.* **2019**, *35*, 8–24. [CrossRef]
103. van Oosterhout, F.; Waajen, G.; Yasseri, S.; Marinho, M.M.; Noyma, N.P.; Mucci, M.; Douglas, G.; Lürling, M. Lanthanum in Water, Sediment, Macrophytes and chironomid larvae following application of Lanthanum modified bentonite to lake Rauwbraken (The Netherlands). *Sci. Total Environ.* **2020**, *706*, 135188. [CrossRef]
104. Dittrich, M.; Gabriel, O.; Rutzen, C.; Koschel, R. Lake restoration by hypolimnetic $Ca(OH)_2$ treatment: Impact on phosphorus sedimentation and release from sediment. *Sci. Total Environ.* **2011**, *409*, 1504–1515. [CrossRef]
105. van Oosterhout, F.; Yasseri, S.; Noyma, N.; Huszar, V.; Manzi Marinho, M.; Mucci, M.; Waajen, G.; Lürling, M. Assessing the long-term efficacy of internal loading management to control eutrophication in Lake Rauwbraken. *Inland Waters* **2021**, *12*, 61–77. [CrossRef]
106. Inoue, T.; Fukue, M.; Mulligan, C.N.; Uehara, K. In situ removal of contaminated suspended solids from a pond by filtration. *Ecol. Eng.* **2009**, *35*, 1249–1254. [CrossRef]

107. Veetil, D.P.; Arriagada, E.C.; Mulligan, C.N.; Bhat, S. Filtration for improving surface water quality of a eutrophic lake. *J. Environ. Manag.* **2021**, *279*, 111766. [CrossRef]
108. Pereira, A.C.; Mulligan, C.N.; Veetil, D.P.; Bhat, S. An In-Situ Geotextile Filtration Method for Suspended Solids Attenuation and Algae Suppression in a Canadian Eutrophic Lake. *Water* **2023**, *15*, 441. [CrossRef]