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# Decision Support Framework and Principal Components Analysis Applied to Eutrophic Shallow Lake Water Remediation Selection

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**Abstract:** A general methodology for a possible assessment of best practices in eutrophic lake water remediation based on principal component analysis (PCA) was developed with a decision support framework. The PCA method was used to examine variations within different procedures used in eutrophic water remediation and their major qualities and trade-offs. Also, this was used for understanding the effects of measures on various dimensions of sustainability (i.e., the triple bottom concept). Results showed the strategy's applicability of PCA for possibly defining the sustainability of the remediation and the decision framework to support its applicability. Remediation methods combination represents the options with higher sustainability. Lastly, it is advised that the final choice should be based on region-specific characterises with the assistance of the stakeholders involved. Even though the method proposed will guide/assist the remediation choice it is extremely advised deep planning for a positive impact.

**Keywords**: Eutrophication; PCA; Phosphorus

Inland waters have been extremely distressed by anthropic actions as well as new climate change circumstances. As the first recipients of matter and energy from watersheds and the atmosphere (Tranvik et al., 2018), those waters are the first to experience distress in their quality and possibly become polluted. In this, a never-ending list of possible quality distress, a natural process called eutrophication could be emphasized. Defined as the water/sediment enrichment with plant macronutrients (i.e., phosphorus and nitrogen), this is aggravating the eutrophication scenarios faster than before. In a eutrophication occurrence, waters go through different modifications such as algae/cyanobacteria biota domination with possible toxins production, odour and taste complaints, and low dissolved oxygen concentration. Those changes are causing water loss of use and are followed by recreational and drinking advisories as well as economic and possible health effects. With this possible development, to safeguard healthy water sources for present and future generations, the Sustainable Development Goal 6 (SDG6) (i.e., clean water and sanitation) from the UN (United Nations) agenda was crafted, further detailed in the 6.6 targets (i.e., restoration of the water-related ecosystems) and was to be achieved in 2020.

To transmute the goal of actions physical, chemical, and biological procedures have been employed for lessening the phosphorus sources of the external and internal nutrients, the possible limiting nutrient (Golterman, 1975), in waterbodies, from the water column and sediment. Following the specialized literature, the physical techniques include sediment dredging and hypolimnetic water aeration, chemical techniques are sediment capping with inert elements (i.e., lanthanum modified bentonite) or chemical addition (i.e., coagulants) and biological methods underlined are biomanipulation and macrophyte management (Pereira & Mulligan, 2023). With the understanding that water resources are a heterogeneous entity, decisions on which procedures(s) need to be employed in a disturbed aquatic ecosystem are based on diverse factors from water quality, lake nuisance concerns, available capita, possible stakeholders involved/affected, and possible method sustainability. Thus, the objective of this paper is to present an improved understanding practically and visually of the applicability of the main methods used nowadays for eutrophic shallow water remediation to facilitate informed stakeholders' choosing.

In the practical view, diverse decision-support frameworks for these restorations have been developed (Pereira & Mulligan, 2023; Hickey & Gibbs, 2009; Rast & Holland,1988). The first result/finding of this research is an updated framework based on best practices for further environmental development applied in the procedures previously presented shown in Figure 1.1. In the specified framework, the first step is comprehending what nuisance the eutrophic waterbody presents (i.e., excessive algae production, lake browning or macrophyte overgrowth). Then, sediment and water characterization should be done. With this complete characterization, it is possible to determine where the issue is coming from and possibly address it. If any external load nutrient reduction is necessary, it should always be followed by an in-lake remediation practice for lake sediment accumulated nutrients attenuation. In the remediation option, not only management parameters such as chemical dose, waste disposal, and monitoring but also waste reuse, energy source, GHG emission and others need to be defined. Before the remediation procedure takes place, impacts must be defined and mitigated/compensated when necessary. Thus, after the remediation, continuous monitoring needs to be performed to investigate not only the restoration outcomes but also continuously verify if the water needs additional treatments.

The second outcome of this research was a visual representation of the sustainability/feasibility of common in situ eutrophic water remediation procedures based on Pereira & Mulligan (2023). This was obtained by a graphic general representation of the PCA (Principal Component Analysis) method. The PCA is a technique for reducing the dimensionality of large datasets, increasing interpretability while minimizing information loss (Jolliffe & Cadima, 2016). This technique uses the original variables (i.e., sometimes normalized), and then PCA calculates a set of new variables that describe as much as possible of the variance of the data (Hellness et al., 2019).

On this understanding, 8 remediation methods (sediment dredging, hypolimnetic water aeration, hypolimnetic water oxygenation, sediment capping with lanthanum-modified bentonite, and sediment capping with aluminium, biomanipulation, macrophyte management and procedures combination) and 14 assessment parameters (normalized) related to the: environment perspective (water quality, sediment quality, lake biodiversity, impacts on natural habitat, carbon footprint, waste generation, waste management), economic perspective ((energy consumption, feasibility, installation cost, lifetime, maintenance cost) and social perspective ( (community perception, workers, and public safety). A preliminary sample of the data is presented in Table 1.1. Using PCA to reduce dimensionality it was able to emphasize variation and differentiate ‘clusters’ within methods to further advance the sustainability/feasibility of procedures assisting stakeholders involved in informed selection.

PCA results presented in Fig 1.2 have shown that methods which generate large amounts of waste such as dredging, biomanipulation and macrophyte removal were grouped nearby. This could be explained as those procedures need to be well thought out before their application due to several variables related to removal and disposal (i.e., more precisely GHG emission, secondary pollution, and environmental impacts). Also in this group, the only one which presents a larger lifetime is dredging. The others due to continuous application costs as well as public perception present lower feasibility. The second group which involves continuous air and/or pure oxygen introduction onto sediment as a method for alleviating phosphorus from sediment needs to be well thought out on the possible application due to high energy consumption. Those methods presented better public perception but as it is continuous the cost could be over the roof. Environmental-wise those methods will not strongly affect the waterbody ecosystem.

The third group, which involves chemicals addition for sediment capping showed the best lifetime apart from dredging and the lowest installation/maintenance cost compared to the others, which are continuous/annually. Public perception of this method is still not as strong as should be due to concerns related to human health due to lanthanum and aluminium presence in the water. Environmental-wise related to aluminium/lanthanum this procedure should be further followed for the chemical presence during the years following their application. For the procedure's combination considered in the study, the sustainability could be increased as methods which score lower (i.e., generate larger GHGs, have higher energetic consumption or higher cost and reduced public perception) are replaced for others who score better on the variables mentioned.

The objectives of this research have been achieved as a visual and practical recommendation for stakeholders involved in the eutrophic water remediation selection has been presented. Even though this research provided some directions for indicating the remediation method to be used, it is worth advising that no best or go-to option exists in the literature due to the heterogeneity of waterbodies and individuals involved. What works for one scenario could not easily apply to another. It is endorsed that further selection be based on the region-specific choice with the assistance of the stakeholders involved. This is suggested because in this case, it is extremely advised deep planning for a positive impact not only on the environment but also on society, and the economy.

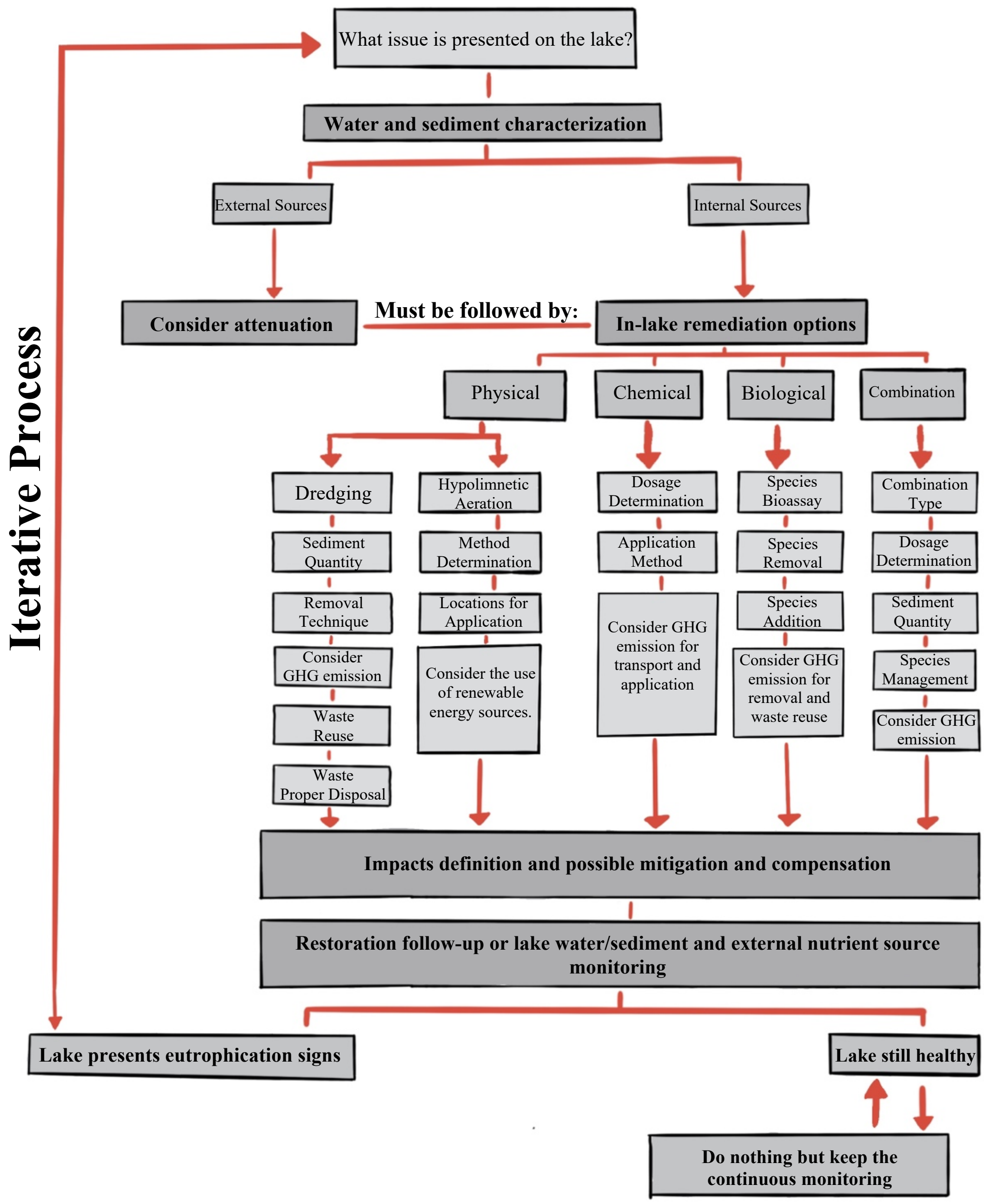


**Figure 1.1** Decision support framework for eutrophic water restoration selection considering further environmental aspects.

**Table 1.1** Preliminary Sample Assessment for Dredging Remediation Procedure

| Parameter | Classification | Score |
|---|---|---|
| Water Quality | Likely impairment/Possible impairment/No change/Possible improvement/Likely improvement | 3 |
| Sediment Quality | Likely impairment/Possible impairment/No change/Possible improvement/Likely improvement | 3 |
| Lake Biodiversity | Likely impairment/Possible impairment/No change/Possible improvement/Likely improvement | 3 |
| Impacts on Natural Habitat | Likely impairment/Possible impairment/No change/Possible improvement/Likely improvement | 2 |

| | | |
|---|---|---|
| Carbon footprint | Sequestration/Unknown/GHG emitted during application only/GHG emitted during application and material production | 3 |
| Waste generation | Large amount of waste/ Slightly amount of waste/no waste | 1 |
| Waste management | Waste no needs disposal/Waste need disposal/Waste need special disposal/No disposal required. | 3 |
| Energy consumption | Approximately 3750 MWh | 2 |
| Feasibility | Untested technology/Used in other jurisdiction/Used minimally in jurisdiction /Local contractor expertise | 1 |
| Installation cost | Ranges from 20,000 USD to 75,000/acre (log scale 0-1) | 2 |
| Lifetime | Range 5-50 years (scaled linear 0-1) 30 years | 1 |
| Maintenance | None/Required every 10-20 years /Required every 5-10 years /Required annually | 1 |
| Community perception | Worsened/Slightly worsened/No change Slightly improved/Improved | 1 |
| Workers and public safety | Worsened/Slightly worsened/No change Slightly improved/Improved | 1 |

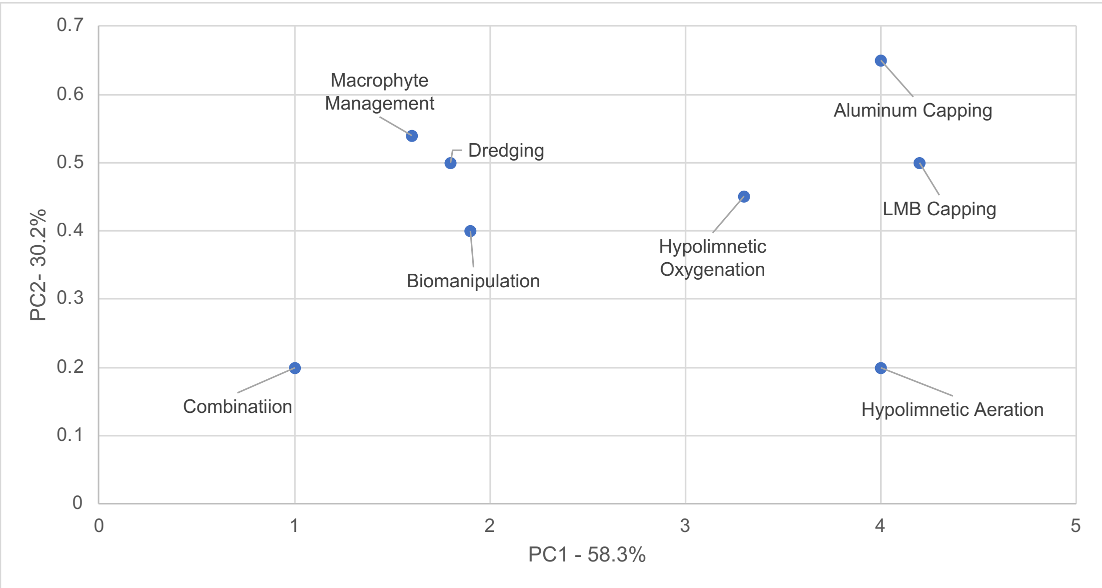


**Figure 1.1** Preliminary PCA method for the in-situ eutrophic lake water remediation variables proposed

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