Phosphorus-Enriched Sediment Remediation Practices for Eutrophic Water Bodies Recovery Towards Sustainability: Sediment Capping Investigation

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ABSTRACT
Anthropogenic activities synergically associated with climate change are causing sediments worldwide to become phosphorus-enriched. This augmentation has been occurring due to the increased or former phosphorus discharge into the waters. Subsequently, this discharged nutrient accumulates in the sediments, which can be easily released into the water column, causing recurring eutrophication. Therefore, it is imperative to fully comprehend and enhance practices related to the remediation of phosphorus-enriched sediments for eutrophic water recovery. Therefore, this paper aims to present current practices in sediment remediation, including dredging, capping, and resuspension. Additionally, a case study related to a Quebec mesotrophic lake (Lake Canard) sediment capping investigation will be presented. Thus, for a successful sediment remediation practice, attenuation of external nutrient sources is the first step always followed by a holistic, region-specific, and sustainable sediment remediation to ensure healthy waters and sediment for present and future generations.

RÉSUMÉ
Les activités anthropiques associées en synergie au changement climatique entraînent un enrichissement en phosphore des sédiments du monde entier. Cette augmentation est due à l'augmentation ou à l'ancienneté des rejets de phosphore dans les eaux. Par la suite, ces nutriments rejetés s'accumulent dans les sédiments, qui peuvent être facilement libérés dans la colonne d'eau, provoquant une eutrophisation récurrente. Par conséquent, il est impératif de bien comprendre et d'améliorer les pratiques liées à l'assainissement des sédiments enrichis en phosphore pour la récupération des eaux eutrophes. Par conséquent, cet article vise à présenter les pratiques actuelles en matière d'assainissement des sédiments, notamment le dragage, le recouvrement et la remise en suspension. De plus, une étude de cas liée à une enquête sur le recouvrement des sédiments d'un lac mésotrophe (lac Canard) au Québec sera présentée. Ainsi, pour une pratique réussie d'assainissement des sédiments, l'atténuation des sources externes de nutriments est la première étape, toujours suivie d'un assainissement des sédiments holistique, spécifique à la région et durable afin de garantir des eaux et des sédiments sains pour les générations présentes et futures.

1 INTRODUCTION

Phosphorus (P) pollution is a significant environmental challenge that has far-reaching consequences for aquatic ecosystems worldwide. Due to the increased human activities around surface water, regarding fertilizer overuse, deforestation, current livestock practices, untreated sewage/effluent disposal as well as augmented watershed runoff due to climate extremes, increased phosphorus concentrations are being discharged and/or washed off from land to waterbodies. As this nutrient input always exceeds the outflow, sediment enrichment occurs, thus, causing the sediments to act as an internal source and sink for regulating P availability in the water column (Wang and Liang 2015).

When in the sediment, complex interactions occur between the nutrient-laden sediments and the overlying water column. Some examples are redox conditions (i.e., dissolved oxygen concentration), pH and water column temperature increase due to climate change (Woolway et al. 2022). Those sediment-water interactions are significantly influencing the phosphorus bioavailability and cycling within the aquatic ecosystem thus triggering desorption or dissolution from the sediment matrix. By making this nutrient more accessible in the water column, primary producers are dated to increase in density causing recurring eutrophication scenarios.

Addressing this P enrichment is a crucial practice for the restoration and protection of lakes, rivers, and coastal waters to guarantee healthy and safe waters for present and future generations As nations are trying to cope with this issue, not only the phosphorus-enriched sediment but also eutrophication scenarios, the water-related ecosystems restoration pact has been reaffirmed in the Sustainable Development Goal 6 (SDG6) (i.e., clean water and sanitation) by the United Nations (UN) for its 6.6 targets. Despite this target being behind schedule, it is imperative to completely comprehend and, in some cases, enhance practices related to sediment remediation and eutrophic water management to facilitate water body recovery.

In this view, control measures should be allocated to external and internal practices. Conventional wastewater and contaminated effluents treatment with proper discharge, agricultural/livestock best management practices and reforestation are the main activities around external source control. In contrast, the present current practices in situ sediment remediation practices (i.e., internal sources), include sediment dredging, sediment capping, and sediment resuspension (sometimes followed by filtration).

A large quantity of phosphorus-contaminated sediment is dredged by mechanical means which requires dewatering and proper land disposal which can induce secondary pollution (e.g., heavy metal pollution) in the water system. For sediment capping only chemicals and/or inert elements are added to the sediment to create a thin active layer for reducing sediment-water interactions influencing the bioavailability and phosphorus cycle. This method is only considering a temporary cover transferring responsibility down to possible future generations (Horppila 2019). Lastly, to reduce the amount of wet waste generated, sediment resuspension is a novel method being investigated. The technique allows the removal of the sediments that possibly contain higher phosphorus concentrations, based on the premise that phosphorus is highly associated with smaller particles, which remain suspended in the water for a longer time after an artificial resuspension.

Therefore, there is a growing need for innovative, efficient, and sustainable remediation strategies to mitigate the impacts of P pollution and support the transition towards a more circular economy of nutrient management. Thus, this paper aims to define the best practices and evaluate possible trade-offs with further investigation towards a greener and more sustainable sediment remediation. Additionally, a case study related to a Quebec mesotrophic lake (Lake Canard) sediment capping, located in the *Sainte-Anne-des-Lacs* municipality, will be characterized, and investigated for remediation.

1.1 Best Practices and Trade-Off Evaluation

In this section, specialized literature research was performed to collect information related to the best practices and trade-offs associated with the sediment remediation methods mentioned. To achieve this objective journal papers, company reports and websites as well as websites on this field were used. Additionally, it was observed that there could be potential for sustainability in the methods studied. Summarized outcomes are presented as a table for straightforward understanding.

1.2 Best Practices and Trade-Offs

In-situ sediment remediation has been emerging as a promising alternative, offering the potential to address the issue of P-enriched sediments in some cases, in a more sustainable and environmentally friendly manner. While sediment capping provides a physical/chemical barrier, it requires long-term maintenance and monitoring to ensure its integrity. In contrast, dredging can effectively remove phosphorus from the water body but carries a high risk of disruption to the ecosystem due to secondary pollution requiring careful planning and monitoring to mitigate environmental impacts. Lastly, sediment resuspension can stimulate natural recovery but must be managed to minimize the short-term release of contaminants, possibly making it a more sustainable approach that leverages natural processes when associated with other water treatment techniques. Practices are summarized in Table 1 with their benefits, trade-offs and possible sustainability potential associated with them.

Table 1. Remediation practices with their benefits, trade-offs, and sustainable potential

Remediation Option	Benefits	Trade-off	Sustainability Potential
Sediment Capping	– Physically isolates contaminants from the water column. – Reduces the potential for contaminant flux into the biologically active zone. – Can recreate a healthy benthic environment.	– Contaminated sediment remains in place. – Requires long-term monitoring and maintenance	– Can be designed to enhance habitat and biodiversity. – Developing more durable and self-sustaining capping materials – Integrating circular economy principles in cap design and maintenance
Sediment Dredging	– Permanently removes phosphorus from the system. – Allows for more complete and durable remediation (i.e., external sources attenuated too).	– Costly and disruptive to the ecosystem. – Potential for redistribution of contaminants. – Challenges with disposal of dredged material.	– Improving dredging techniques to minimize resuspension, disturbance and GHG emissions. – Expanding options for beneficial reuse of dredged sediments (i.e., circular economy).
Sediment Resuspension	– Leverages adsorption and surface area to remediate sediments. – Minimizes physical disturbance to the ecosystem	– Increased short-term risk of contaminant release and exposure. – Potential for downstream transport and deposition of contaminants. – Requires longer monitoring.	– Enhancing monitoring and control systems to mitigate short-term risks. – Integrating resuspension with other in-situ treatment methods like water filtration

When the sustainability potential is observed in sediment capping practice, this is related to production, transportation to the site and correct use. Related to the capping media, like LMB or other materials, production is still focused on just specific world regions and monetary costs are still not practical for all nations. (Pereira et al., 2023[a]). This will add greater transportation costs which will carry higher GHG emissions, which need to be prevented. New materials need also to be explored in this field for more durable self-sustaining capping and region-specific remediations not only based on commercial portfolios.

Lastly, it is recommended to use this remediation type only for drinking water supply (lakes and reservoirs) and in landscapes where there are only a few lakes in good condition as there is a need for prompt results (Horppila 2019).

Regarding sediment dredging, the first thing which can be considered for sustainability potential is the improvement of the dredging technique. This should be updated to minimize resuspension, in this case, as well as the sediment disturbance and possible GHG emissions from the heavy machinery necessary for operation. Also, as the sediment phosphorus-enriched sediment removed from the lake is still considered to be a waste, there is an opportunity to implant a circular economy principle for beneficial reuse options for sediment dredged as a soil amendment in agriculture (Kiani et al. 2021, 2023) as well as phosphorus element recovery as a struvite mineral (Karunanithi et al. 2016, Yesigat et al. 2022).

For sediment resuspension, the sustainability opportunities are perceived in the enhancement of monitoring and control resuspension systems to mitigate short-term risks, contamination (i.e., secondary pollution), and any ecosystem disturbances which this practice may cause. It is also recommended further investigation of the resuspension integration with other in-situ environmental-friendly water treatment methods for improved results. An example of a possible water treatment that could be associated with this resuspension, is the water filtration with geotextiles as the filter media (Pereira et al. 2023b).

2 METHODOLOGY

2.1 Study Area for Capping Investigation

Located in the Lac Castor watershed, one of the Riviere du Nord watershed contributors (CRE, 2024), the study area of this paper is Lake Canard. A semi-artificial lake located in the *Sainte-Anne-des-Lacs* municipality - 74º 07' 09" W; 45º 50' 34''N, around 75 km from downtown Montreal. Characterized by a mesotrophic state tropic state possibly going towards an initial stage of eutrophication soon if no action is taken.

The nutrient sources associated with this lake are watershed runoff (as an external source) and organic matter degradation (as an internal source). The internal source is recurring as this lake has been enlarged in the past without complete removal of tree stumps and plants from within the waterbody, possibly causing the sediment to get phosphorus-enriched. This may be also the cause of the recurring excessive macrophyte growth near the lakeshore. The sediment phosphorus concentration in this lake is not homogenous ranging from 902 to 1212 mg/kg. Also, this lake of 369,000 m^3 in water volume covers a surface area of 187,000 m^2 with average and maximum depths of 2 m and 3.7 m, respectively (ABVLACS, 2024). Figure 1 (a) shows the visual representation of the studied lake where all the green cover is macrophyte growth, white arrows indicate households and numbered arrows are the sampling stations.

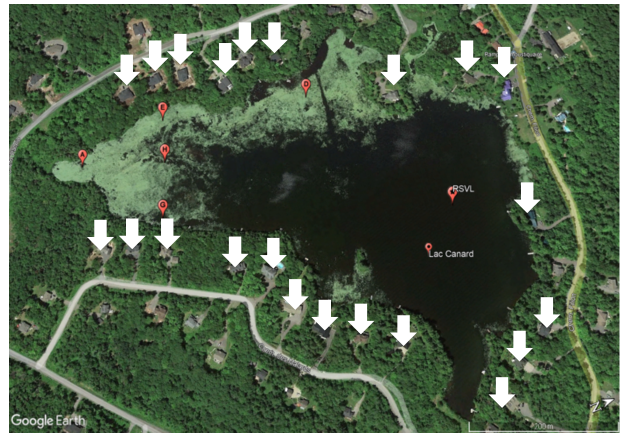

Fig. 1. Lake Canard map with sampling stations and households shown by the numbered and white arrows, respectively.

2.2 Sediment Capping as a Case of Study

For the preliminary investigation on the sediment remediation performance with different capping materials in Canadian lake sediment, Lake Canard has been chosen as a study area. The lake water, as well as sediment samples, were taken and then combined with a well-known capping material, lanthanum-modified bentonite (LMB) and a byproduct of granular ferric hydroxide production, the granular ferric hydroxide in fine grain (GFHF), a low-cost iron capping material, in a specific deployment. Following the suggestion presented in the literature that for capping layer formation, LMB needs to be applied in a dose of 100:1 for the LMB:P ratio (Lurling & Oosterhout, 2013), this dosage was chosen. As there is no specific information related to GFHF dosage in sediment capping experiments, a similar ratio of 100:1 was used for GFHF:P ratio.

The experiment was performed in glass vessels (Figure 2) containing samples of water (1150 ml) over wet sediment (345 g). The proportion of 5:1.5 and followed the experimental methodology of Cavalcante et al. (2022). Experimental vials were done in duplicate as follows, two with just LMB application, two with just GFHF application, two with a combination of LMB-GFHF (i.e., with half dosage of each one) and two controls where no capping material was added.

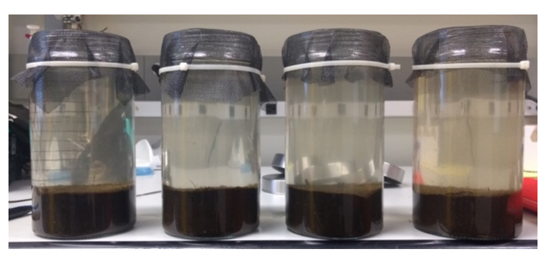

Figure 2. Glass vessels containing samples of lake water and sediment prepared for capping experiments

For the specific capping dosage determination, the average amount of phosphorus found in Lake Canard sediment and water (data not shown) was used. The amount of LMB and GFHF added was based on equations 1, 2 and 3:

$$P_{sediment} = V_{sediment} \times P_{sediment\ analyzed} \times Density_{sediment} \quad [1]$$

$$P_{water} = V_{water} \times P_{water\ analyzed} \quad [2]$$

$$P_{system} = P_{sediment} \times P_{water} \quad [3]$$

Where:

$P_{Sediment}$ = phosphorus in the sediment (g).
V_{Sedim} = volume of sediment in the glass containers (m^3) = 0.000345 m^3.
$P_{Sediment\ analyzed}$ = amount of mobile/available phosphorus determined by analysis (mg /kg); = 980 mg/kg (average obtained on 2022 sediment samples)
$Density_{sediment}$ = Average sediment density (kg/m^3) = 1.3 g/cm^3 or 1300 kg/m^3.
P_{water} = phosphorus in the water (g)
$P_{water\ analysed}$ = amount of phosphorus determined by analysis (µg/L); = 15.0 µg/L (average obtained on 2022)
V_{water} = volume of water in the glass containers (L) = 1.150 L
P_{system} = phosphorus content in the system water and sediment (mg)

In summary, the $P_{Sediment}$ was equal to 0.4459 g, and P_{water} was equal to 0.01725 g thus the P_{system} was equal to 0.4632 g. Consequently, 46.32g was added to the system to maintain the 100:1 ratio for capping material: P. In all cases, a slurry was prepared with the sampled lake water before application to the system.

The capping experiment was then performed for 35 days, with temperature control using an incubator at 21.0ºC ± 0.5, considered an average for the lake water in the summer. The samples were kept in the dark throughout all days to prevent any light interference. Samplings were done on days 0 (i.e., 10 minutes after application), 3, 7, 14, 21, 28 and 35 days for soluble reactive phosphorus (SRP) monitoring. Also, the DO (Thermo Scientific™ Orion Star™ A223 Dissolved Oxygen Portable Meter), ORP (Oakton™ ORPTestr 50), pH (Thermo Scientific Orion 2-Star Benchtop pH Meter) and Turbidity (Oakton TN-100 Turbidity Meter) were followed for understanding the behavior of these parameters.

3 RESULTS AND DISCUSSION

3.1 Sediment Characterization

The basic physiochemical properties of the original sediment used in the sediment capping case study are presented in Table 2. The sediment contains a higher phosphorus concentration, which may be linked to the amount of organic matter that is still decaying on it. Also, in terms of particle size, this material is classed between fine sand and silt.

Table 2. Lake Canard's basic physicochemical properties of the sediment sample

Parameters	Sediment Sample
Bulk density (mg/L)	1.1 ± 0.1
Sediment TP (mg/kg)	1011.55 ± 58.33
D90[a] (µm)	251.33 ± 20.0
D50[a] (µm)	94.60 ± 4.0
D10[a] (µm)	20.36 ± 0.5

[a]D10, D50, D90 represent the 10/50/90 % of particles smaller than that size, respectively.

3.2 Case of Study: Lake Canard Sediment Capping

For investigating the behavior of possible sediment capping methods, Lake Canard water, as well as sediment samples, were combined with a well-known capping material, lanthanum-modified bentonite (LMB) as well as with a granular ferric hydroxide production byproduct, the granular ferric hydroxide in fine grain (GFHF), a low-cost iron capping material.

The experiment was performed during the 35 days proposed without any disruption. It was perceived that some organic matter present in the control system started to degrade from 7 days of incubation which was captured on the ORP, DO and SRP results. This has increased the SRP value to an amount of 13 µg/L and DO has decreased to 7.11 mg/L on this system. Also, it was observed that better capping layer stability of the LMB was obtained when compared to GFHF. The second one presented a more gel-like behaviour easily shaken by any glass vessel movement. A summary of the results is presented in Table 3.

Table 3. Capping experiment summary with averages of investigated parameters

Exp./ Vial	ORP (mV)	DO (mg/L)	pH	Turbidity (NTU)	SRP (µg/L)
Control	216.89 ± 26.95	7.20 ± 0.18	5.97 ± 0.39	1.65 ± 1.72	7.90 ± 2.93
LMB	216.44 ± 24.19	7.93 ± 0.28	6.87 ± 0.32	6.63 ± 3.61	3.12 ± 2.24
GFHF	248.11 ± 44.73	7.93 ± 0.28	5.22 ± 0.41	5.57 ± 2.97	2.81 ± 1.86
LMB - GFHF	229.56 ± 34.60	7.95 ± 0.14	6.53 ± 0.30	3.70 ± 2.00	3.00 ± 2.24

When related to the system pH investigated, distinctive behaviours were shown. The pH for the LMB and LMB/ GFHF was kept near neutral with an average of 6.87 ± 0.32 and 6.53 ± 0.30, respectively. In contrast, the pH on the GFHF decreased to near pH 5.4 long after the capping material application and was kept at an average of 5.22 ± 0.41 during the 35-day experiment. Thus, these treatments (LMB/LMB-GFHF) are the first choice for possible in-lake remediation, as the pH in the aquatic environment did not change substantially. The pH modification could affect this material's use in real-world scenarios applications.

Shortly after the capping material addition to the systems, there was a drastic turbidity increase due to capping slurry interactions in the water column. On the LMB, GFHF and LMB-GFHF systems, the values monitored were 926 NTU, 222.67 NTU and 789 NTU, respectively. These values were removed from the graphic representation in Figure 3 and the reporting started on day 3. As expected, all proposed treatments showed decreased turbidity throughout the 35 days of the experiment when compared to the control system. This could be explained as all capping material settled and formed the expected capping layer in the system and the combination of GFHF and LMB had performed better on this parameter as well. The LMB-GFHF treatment presented the lower turbidity value in all treatments (3.70 ± 2.00 NTU).

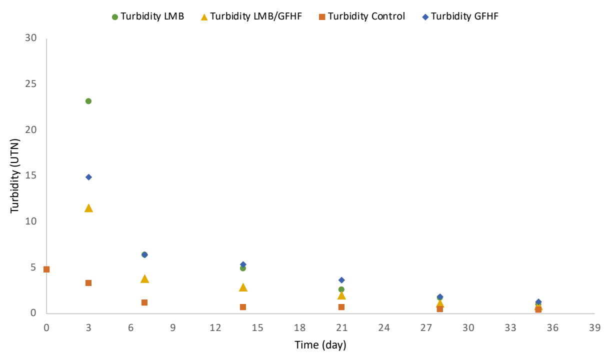

Figure 3. Turbidity (NTU) follow-up in the capping experiment

When related to SRP, all treatments proposed (LMB, GFHF and LMB-GFHF) promoted a reduction in the SRP in the system when compared to the average found in the control (average concentration of 7.90 ± 2.93 µg/L) as presented in Figure 7. Despite being significantly lower than the control, the SRP concentrations found in this study were positive in all treatments, with averages of LMB of 3.12 ± 2.24 µg/L, GFHF of 2.81 ± 1.86 µg/L and LMB/GFHF of 3.00 ± 2.24 µg/L or 60%, 64% and 62%. This means that there was still a release of P from the sediment after applying the LMB, GFHF and/or LMB-GFHF layer with the dosages used, so this was deemed insufficient.

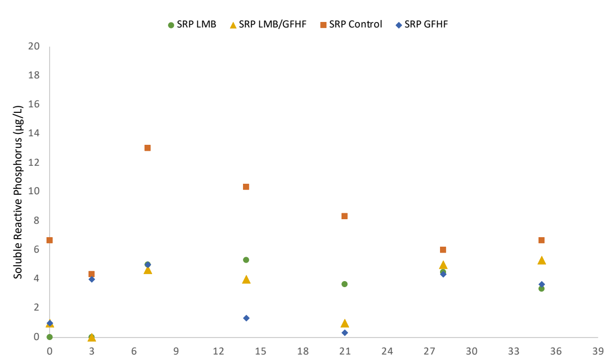

Figure 4. Soluble Reactive Phosphorus – SRP (µg/L) follow-up on the capping experiment

Therefore, something may have interfered with the total functioning of the modified bentonite and granular ferric hydroxide in the experiment. Some explanations could be associated with organic matter present in the water and sediment, as lanthanides can combine with those compounds instead of phosphorus reducing its effectiveness. Another pertinent factor that may have affected the functioning of the LMB/GFHF is the amount of P concentration in the sediment adopted to calculate the capping clay dose, which could have been underestimated. As presented by the results, the LMB-GFHF treatment combination performed better in maintaining the pH near neutrality as well as in turbidity reduction and SRP attenuation. When considered, this is a combination of a well-known capping material with an iron production by-product. This would be the suggested capping material for remediation of this phosphorus-enriched sediment.

4 CONCLUSIONS

For a successful phosphorus-enriched sediment remediation practice, no standard options in the specialized literature exist, only recommendations. This remediation needs to always start with external nutrient source attenuation followed by in-lake holistic, region-specific, and sustainable techniques for reducing high sediment phosphorus concentration and ensuring healthy water systems for present and future generations. Those in-lake practices have full potential for tackling this over-accumulated nutrient in a more sustainable and environmentally friendly manner either by addressing the GHGs emitted, waste produced or updating equipment, materials, or processes employed. By presenting a case study in a Canadian mesotrophic semiartificial lake, the reality of phosphorus-enriched sediment was brought to Canada. As well the combination of an iron byproduct (i.e., integrating circular economy principles) with a well-known lake capping material is the approach to developing a more durable and self-sustaining capping material. Further studies would be related to changing the ratios of LMB-GFHF on the treatment options, as well as increasing the sediment mass being remediated.

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