Novel Sustainable In-Situ Geotextile Filtration Method for Eco-remediation of Eutrophic Lake Waters

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ABSTRACT

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Antônio Cavalcante Pereira

Climate change and human-made actions are synergically increasing eutrophication cases on inland waters. These augmentation circumstances are not only in places where contamination is higher (i.e., with increased nutrient input) but worldwide due to climate change disruptions. Those excessive nutrients scenarios are augmenting faster trophic status changes to inland waters. Diverse invasive, drastic, intricate, and expensive technologies are applied currently worldwide for eutrophic water remediation, adversely affecting the aquatic biota and reducing its water volume. In order to counterpart this issue, a novel approach method is under study and application, an effective, environmentally safe, and economic eco-remediation technique using a floating filtration system, a silt curtain, and geotextiles (woven and non-woven) as filter media. An in-situ water remediation methodology for the minimally invasive removal of suspended solids and particulate nutrients. A sustainable remediation method supporting the own waterbody's restoration and directly following three of the 17 Sustainable Developments Goals (SDGs), proposed by United Nations (UN) to be reached before 2030: SDG 6 clean water and sanitation, SDG 12 responsible consumption, and production, and SDG 14 life below water. This pilot in-situ experiment was deployed at Lake Caron, a shallow eutrophic lake located in *the Sainte-Anne-des-Lacs* municipality in Quebec from summer until mid-fall for two consecutive years (i.e., 2019 and 2020). Lake water quality monitoring were performed using the following parameters: particle size analysis (PSA), total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), nitrate (NO_3^-), chemical oxygen demand (COD), pH, dissolved oxygen (DO), temperature (Temp.), oxidation-reduction potential (ORP), conductivity, turbidity, total dissolved solids (TDS), chlorophyll a (Chl. a) and blue-green algae-phycocyanin (BGA-PC). Turbidity, total suspended solids (TSS), total phosphorus (TP), blue-green-algae-phycocyanin (BGA-PC), and chlorophyll-a statistically significant average removal efficiencies were 49%, 53%, 22%, 56%, and 57%, respectively in the first-year study and 17%, 36%, 18%, 34% and 32%, respectively in the second year study. Those removal trends prevented primary productivity, in both years. This has demonstrated the hypothesis of sustainable lake water remediation by the method presented. A strong statistically positive correlation was also found, in the second year study, between TSS and turbidity, and with TSS and variables that could represent particles (i.e., total phosphorus, turbidity, chlorophyll-a) same behavior were found with turbidity. Additionally, to comply and strengthen sustainability principles within the project, waste management practices were investigated, based on potential reuse strategies (i.e., for used geotextiles and captured suspended solids) following circular economy principles. After proper washing, the geotextiles exhibited hydraulic proprieties close to a value of the unused ones (related to the flow rate and permittivity) characterizing its possible reuse. Also, liquid waste produced with the captured suspended solids may be classified for future reuse with the high phosphorus content where additional investigation is required. Using this surface water management technique in combination with the proper waste management route as presented, could present this remediation as a promising technique not only for shallow lakes but also for ponds, river sections, coastal regions, bays, and other water types, to ensure proper cleaner water for future generations.

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[…] Ah! don't give me sympathetic intentions!
Don't asks me for definitions!
Don't tells me: "come this way"!
My life is a whirlwind that broke loose,
It's a wave that rose.
It's one more atom that ignited...
I don’t know which way I’ll go,
I don't know where I'm going to,
I know I'm not going that way!

Black Rhythm
(José Régio, in ‘Poemas de Deus e do Diabo’)

[…] Ah, que ninguém me dê piedosas intenções,
Ninguém me peça definições!
Ninguém me diga: "vem por aqui"!
A minha vida é um vendaval que se soltou,
É uma onda que se alevantou,
É um átomo a mais que se animou...
Não sei por onde vou,
Não sei para onde vou
Sei que não vou por aí!

Cântico Negro
(José Régio, no ‘Poemas de Deus e do Diabo’)

CONTRIBUTION OF AUTHORS

CHAPTER 1. INTRODUCTION – Antonio Cavalcante Pereira: Conceptualization, Investigation, writing and original draft, Catherine Mulligan: Supervision, Reviewing and Editing.

CHAPTER 2. COMPREHENSIVE LITERATURE REVIEW – Antonio Cavalcante Pereira: Conceptualization, Investigation, Writing and original draft. Catherine Mulligan: Supervision, Reviewing and Editing.

CHAPTER 3. FIRST ARTICLE – Antonio Cavalcante Pereira: Conceptualization, Methodology, Investigation, Writing – original draft, Dileep Palakkeel Veetil: Methodology, Investigation, Catherine Mulligan: Supervision, Methodology, Writing - Reviewing and Editing, Funding acquisition, Sam Bhat: Provision, Methodology.

CHAPTER 4. SECOND ARTICLE – Antonio Cavalcante Pereira: Conceptualization, Methodology, Investigation, and Writing – original draft, Dileep Palakkeel Veetil: Investigation, Catherine Mulligan: Supervision, Methodology, Writing - Reviewing and Editing, Funding acquisition, Sam Bhat: Provision.

CHAPTER 5. THIRD ARTICLE – Antonio Cavalcante Pereira: Conceptualization, Methodology, Investigation, Writing – original draft, Dileep Palakkeel Veetil: Investigation, Catherine Mulligan: Supervision, Writing - Reviewing and Editing, Funding acquisition, Sam Bhat: Provision.

CHAPTER 6. CONCLUSIONS – Antonio Cavalcante Pereira: Conceptualization, Investigation, writing and original draft. Catherine Mulligan: Supervision, Reviewing and Editing.

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LIST OF ABBREVIATIONS AND SYMBOLS

AOS: Apparent Opening Size (μm)
ASTM: American Society for Testing Materials
BGA-PC: Blue-Green Algae-Phycocyanin (μg/L)
CCME: Canadian Council of Ministers of the Environment
COD: Chemical Oxygen Demand (mg/L)
Chl. a: Chlorophyll a (μg/L)
CDOM: Chromophoric Dissolved Organic Matter
CE: Circular Economy
CM: Commercial Mesh
DOM: Dissolved Organic Matter
DO: Dissolved Oxygen (mg/L)
FDOM: Fluorescence Dissolved Organic Matter (QSU)
FNU: Formazin Nephelometric Units
GIS: Geography Information Systems
HDPE: High-Density Polyethylene
ICP-MS: Inductively Coupled Plasma Mass Spectrometry
IWRM: Integrated Water Resource Management
MELCC: *Ministère de l'Environnement et de la Lutte contre les changements climatiques*
MDGs: Millennium Development Goals
NO_3^-: Nitrate (mg/L)
N: Nitrogen
P: Phosphorus
ORP: Oxidation-Reduction Potential (mV)
PSA: Particle Size Analysis
PET: Polyethylene Terephthalate
PP: Polypropylene
PTFE: Polytetrafluoroethylene
QSU: Quinine Sulphate Units

RSVL: *Réseau de surveillance volontaire des lacs*

SEM: Scanning Electron Microscope

SD: Secchi Depth

SWI: Sediment-Water Interface

SS: Suspended Solids(mg/L)

SDGs: Sustainable Developments Goals

Temp.: Temperature (ºC)

TN: Total Nitrogen (mg/L)

TP: Total Phosphorus (µg/L)

TSS: Total Suspended Solids (mg/L)

TSI: Trophic State Index

UN: United Nations

CHAPTER 1. INTRODUCTION

A world in which poverty and inequity are endemic will always be prone to ecological and other catastrophes. Catastrophes, are not only caused by regional difficulties as an example a contaminant release in a river or lake but in worldwide matters, like climate change. In other words, not always the one who is suffering the problem will be the one who is causing it. Climate change scenarios are increasing the world temperature and climate extremes, augmenting issues not only on organisms and ecosystems but also human systems and well-being. When associated with contemporary anthropic disruptions (i.e., natural resources overuse, production model, population growth, inequality between nations) this is probably triggering disturbances in the biosphere more than its capacity to resist, showing that the human species is the higher threat to the earth's environment.

Water contained in this extremely disrupted biosphere is suffering as well. Constantly polluted when it is present, as well as having its availability highly affected by issues of having too much water in some places (i.e., extreme precipitation events) and scarcity in others (i.e., extreme drought events). In this view, inland waters, aquatic environments located within land boundaries (i.e., lakes, rivers, and their connected wetlands), are the ones that have been increasingly affected by this synergic action of human-made activities and climate change. More precisely lakes, which are considered the climate change sentinels, responding rapidly to any change in the watershed.

One contemporary issue, which has been reaching lakes, and is due to increase of the two variables described (i.e., human-made actions and climate change scenarios) is eutrophication. Eutrophication can be defined as a natural ecological response to excessive nutrient enrichment and is mainly caused by phosphorous and nitrogen augmented by internal and external loads from point and diffuse releases. As a way to attenuate this issue, in-lake nutrient abstraction techniques need to be proposed, focusing on the phosphorus input, the limiting nutrient. Unlike the current remediation techniques which are invasive, drastic, intricate, and expensive, requiring a highly trained person, sustainable remediations methods are techniques that support restoration and are being further investigated.

Measures which are taken in the environment, to follow sustainable thinking, need to be guided by the 17 Sustainable Development Goals (SDGs) objectives to be reached before 2030 as proposed by the United Nations (UN). Based on the eutrophication issue the most relatable SGD is the SDG 6 (i.e., clean water and sanitation goal) and is expanded on the targets 6.6 (i.e., restore ecosystems), 6.a and 6.b (both related to an enabling environment). In other words, a remediation technique for eutrophication inhibition should not only be providing cleaner water but should also restore a diverse ecosystem within it, for the present and future generations. Also, if any material is used on these remediations projects, sustainable consumption and production (SDG 12) and the conservation and sustainable use of the oceans, seas, and marine resources (SDG 14) need to be considered by using circular economy (i.e., sustainable production model) and waste management.

In order to answer the raised concern, towards sustainable remediation methods, a novel approach is under investigation and application. A reactive, ecologically safe, and economic method employs a silt curtain, a floating filtration unit, and geotextiles (non-woven and woven) as filter media. An in-situ minimally invasive remediation methodology for possible removal of suspended solids and particulate nutrients. This method has been used in a pilot in-situ experiment, which was deployed out at Lake Caron, a shallow eutrophic lake located in the *Sainte-Anne-des-Lacs* municipality in Quebec, from summer until mid-fall for two consecutive years (i.e., 2019 the first year and 2020 the second year). Additionally, to strengthen the sustainability outcome of this method, proper ways of waste management for the used filter layers and captured suspended solids are under investigation as well.

Therefore, the aim of this thesis is to develop the methodology proposed for eutrophic lake water sustainable remediation using geotextile filtration. To achieve this aim, this thesis is divided into chapters based on manuscripts, which are planned for future publication. There are five objectives on this thesis, one for each chapter proposed as follows:

- To conduct a comprehensive literature review for in-depth study of remediation techniques and sustainable methods for lake water remediation (CHAPTER 2);
- To evaluate the daily water quality monitoring of the eutrophic study lake, over the 69-day experiment deployment of the remediation proposed (CHAPTER 3);
- To assesses the second-year, follow-up experiment, daily water quality monitoring of the eutrophic study lake, over the 76-day experiment deployment remediation proposed (CHAPTER 4);
- To investigate the potential reuse strategies for waste generated after lake water geotextile filtration considering circular economy (CHAPTER 5); and

- To summarize the information of the previous chapters to draw possible future directions, applications, and investigations to this method (CHAPTER 6).

CHAPTER 2. COMPREHENSIVE LITERATURE REVIEW

2.1 CLIMATE CHANGE AFFECTING WATER RESOURCES

Climate change is defined as the shift in climate patterns mainly caused by greenhouse gas emissions (i.e., from natural systems and human activities) (Fawzy et al., 2020), which has been causing several effects worldwide. The effects are triggering temperature increases, changes in irradiance and UV-B levels, changes in the amount of precipitation and humidity patterns, and also alterations in the incidence of abiotic and natural disturbances (Netherer & Schopf, 2010; Cavicchioli et al., 2019). In this way, the modification of these parameters is favoring an increased likeability of extreme events (Moore & Allard, 2011), (i.e., storms, record-breaking rainfall events, heat waves prolonged droughts, and tropical cyclones) in the world. They are affecting, even more, the already anthropized environment that we live in and causing disruptions which the environment is not able to support.

It is well understood that human activities have caused about 1.0°C of global warming, temperature increase, above the pre-industrial levels, which is likely to reach 1.5°C between 2030 and 2052 if this continues to increase at the current rate (IPCC, 2018). These warming scenarios presented are affecting not only organisms and ecosystems but also human systems and well-being (Hoegh-Guldberg et al., 2018). Thus, when these scenarios are associated with contemporary issues of natural resources overuses, the production model (i.e., take-make-consume-dispose), and population growth, the answer is the biosphere disruption more than its capacity to resist. Contained in the biosphere, the hydrosphere is one of the most vulnerable living spheres in it, due to its quantity, unequally divided around the globe.

However, how will climate change scenarios disturb the hydrosphere, more precisely water resources systems. Climate change is going to affect water probably related to the following parameters: runoff water quality and quantity, evaporation, precipitation, wind stress, sea level fluctuations and other ocean properties (Najjar et al., 2010). Changes brought by these circumstances will probably add excess sediments and nutrients, will cause natural sediment resuspension (i.e., sediments will be more presented in the water column), and other pollution types to the water. In addition, an increased air temperature could result in higher water temperature, and consequently stimulate the algal blooms growth and dissolved oxygen decrease, thus deteriorate the ecological environment (Luo et al., 2020).

2.1.1 Inland Water Resources

Inland waters are defined as surface waters that are non-coastal above-ground open fresh or brackish waterbodies (Davies & Moss, 1999). In other words, they are aquatic-influenced environments located within land boundaries (CBD, 2008). Being considered the most vulnerable and important water sources on the planet, these inland waters are composed of lakes, rivers, and their connected wetlands (Devlin & Manjur, 2021).

Recipients of matter and energy from the watershed and the atmosphere (Tranvik et al., 2018), inland waters in the modern circumstances are introduced and directly affected by climate change. Those warming scenarios are affecting inland waters parameters, as mentioned, causing e.g., warming of waters, oxygen reduction, biological rates acceleration, substantial restructuring of aquatic communities, increasing evapotranspiration due to climate extremes (i.e., droughts), increased emissions of CO_2, CH_4, and N_2O to the atmosphere, and nutrients release (Rinke et al.,2019).

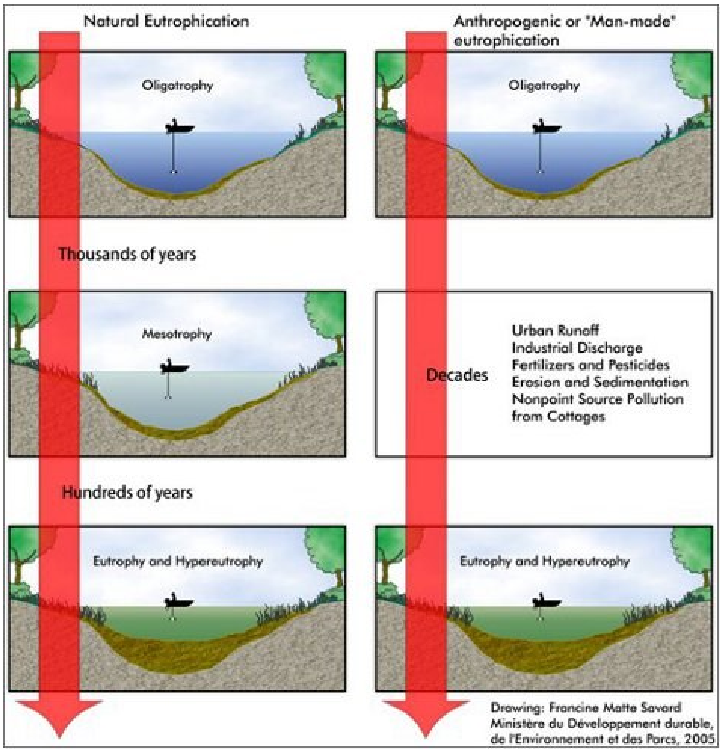
It is worth commenting, that inland waters are affected not only by climate change but also by human-made interactions, which have been higher than before, thus causing water resources deterioration and putting organisms under stress. Those issues which inland waters are suffering are, the accelerated release of dissolved organic matter (DOM) to inland and coastal waters through increases in precipitation, thawing of permafrost, and changes in vegetation (Williamson et al., 2017), increasing in water browning (Kritzberg et al., 2019), and higher internal nutrient releases (Yidong et al., 2021) from past human activities causing irreversible conditions.

Inside the inland water resources named, lakes have their spotlight. Being peculiar water types, which show unusual behavior for the issues presented, they are being strongly affected by the mentioned issues. As they are sensitive to the climate and respond rapidly to any change (i.e., a wide range of physical, chemical, and biological responses to climate variance), and incorporate changes in the catchment (Adrian et al., 2009) lakes are effective sentinels for climate change (Woolway & Merchant, 2019).

2.1.2 Lake Aging, Increased Nutrient Input and Eutrophication

Lakes (also known as lentic systems) are a diverse set of inland freshwater habitats that exist across the globe and provide essential resources and habitats for both terrestrial and aquatic organisms. (Hoverman & Johnson, 2012). Like any living organism, they age naturally, but the timeframe for this is about hundreds to thousands of years (Zhang et al., 2020). However, human interaction within the land synergistically associated with climate change scenarios and population growth is accelerating this process. This acceleration is transforming low nutrient lakes (i.e., oligotrophic lakes) to high nutrient lakes (i.e., eutrophic lakes) faster than before (Pereira et al., 2020).

As presented in Figure 2-1, being drinkable and/or navigable and/or recreational, lakes are suffering increasing stresses which have been degrading them, probably causing loss of their uses. Anthropogenic actions such as urban runoff, point and diffuse pollution, industrial discharges as well as lake water warming, and increased internal nutrient releases (due to climate change circumstances) are increasing lakes' primary productivity, turbidity, and reducing their volume favoring harmful phytoplankton development over other species within this environment.



Drawing: Francine Matte Savard
Ministère du Développement durable,
de l'Environnement et des Parcs, 2005

Figure 2-1: Scenarios exacerbating aging of lakes (MDDEP, 2012)

External and internal loads of nitrogen (N) and phosphorus (P) from point and diffuse sources are the ones responsible for this possible aging. When those nutrients are present in high concentrations in the water, eutrophication occurs, a water pollution issue. As N and P are the key nutrients essential for the growth and sustainability of different microorganisms and aquatic lives that constitute the surface water ecosystem (Bhagowati et al., 2019; Nazari-Sharabian et al., 2018), they are considered key substances in the water column to be present when there is an increasing primary productivity (Guinard et al., 2017).

Eutrophication can be understood as the process of water enrichment by excess plant nutrients, leading to enhanced growth of algae/cyanobacteria, periphyton, or macrophytes (Istvánovics, 2009) in the natural system. By nature, this is an ecological response to excessive nutrient enrichment. Undesirable symptoms of this ecological response primarily occur during the plant growing season (spring and summer), when low flow, high water residence times, sufficient light levels and high-water temperature promote rapid algae growth (Nazari-Sharabian et al., 2018).

Eutrophication symptoms are responsible for probable recreational and drinking water advisories in lakes caused by high cyanobacteria productivity, along with harmful toxins development (Freeman et al. 2020; Yindong et al. 2021 and Burford et al. 2020). Additionally, in some eutrophication cases, volume reduction (Braga & Becker 2020), browning (Hayden et al., 2019 and Kritzberg et al., 2020) and anoxia can occur in these systems. Also, it is worth commenting that when external sources of nutrients are reduced, the release of historically accumulated (legacy) phosphorous (P) from lake sediment can maintain excess nutrient levels and high primary productivity in lakes (Schütz et al., 2017).

2.1.3 Trophic Classification and Trophic Levels Changes

Lakes are often classified by their “trophic status” which can be determined via measures of productivity or nutrient load (Schlesinger & Bernhardt, 2020). In the most used classifications, water quality parameters are used to roughly assess waterbody trophic status. For example, with information about 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) (Istvánovics, 2009) diverse indices are proposed. For classification criterion, waters with low productivity are termed oligotrophic and waters with high productivity eutrophic (Beiras, 2018). If only the main ones are considered, the trophic categories are four, namely, oligotrophic, mesotrophic, eutrophic, and hypertrophic (Concepcion et al., 2020).

An interpretation of this classification method is used by the MELCC (*Ministère de l'Environnement et de la Lutte contre les changements climatiques*) of Quebec, which is the one used in this project to classify the studied lake. In this classification, each parameter is treated as a unique variable with proper subdivisions for the different trophic classification stated, as presented in Figure 2-2. As there is no proper correlation in the parameters evaluated, misinformation could be given. For example, shallow lakes (i.e., < 2.0m) can be located in the eutrophic state when related to transparency (m) but could be in the oligotrophic state when related to total phosphorus (TP) concentration at the same time. In this case, the results from this classification method need to be inferred with precaution and require additional analysis.

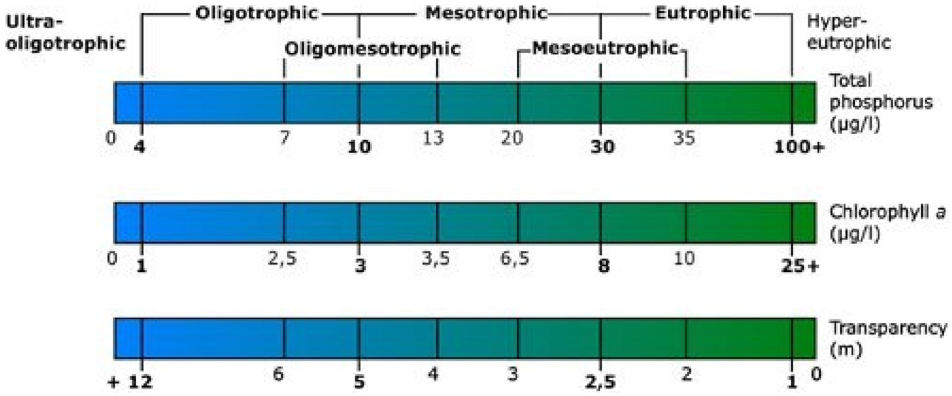


Figure 2-2: Diagram of the trophic level of lakes (MDDEP, 2012)

Several other trophic state classifications can be used; indices based on several biological, chemical, and physical indicators are the most recommended. One of them is the Carlson-type TSI (trophic state index), which is one of the most used in the trophic studies. This index offers a suitable and acceptable method for trophic classifications of lakes (Xu, 2008). The Carlson-type TSI index assumes algal biomass to be the basis for trophic state classification and is calculated by three hydroecological characteristics: the chlorophyll-a (Chl.a) concentrations, TP in water and the Secchi depth (SD) (Adamovich et al., 2016; Carlson, 1977) in specific equations.

One of the method limits is that the TP-based index variable would not correlate well with the Chl.a in situations where phosphorus was not limiting algal/cyanobacteria growth, nor would

Secchi depth correlate well with Chl.a if the major light scattering in the water were clay particles or dissolved humic color (Carlson & Havens, 2005). Other alternatives for lake trophic state classification are based on tree-artificial neural network (Concepcion et al., 2020), statistical analysis (Köklü & Alkış, 2021), and Geography Information Systems (GIS) data analysis (Gidudu et al., 2021; Rivani & Wicaksono, 2018; Kumar et al., 2019).

2.1.4 Cultural Eutrophication Exacerbation

Being the unpleasant recipe for the eutrophic lakes' numbers magnification around the globe (Beiras, 2018), cultural eutrophication takes place when the nutrient supply is anthropogenic (agriculture fertilizers, detergents from domestic effluents, among others) or the nutrient being internally released is from a former human action. The overall effect with cultural eutrophication is anthropogenic activities on watersheds, causing water bodies to fill in faster with sediment and nutrients supply for abundant aquatic plant growth (Kang & Chung, 2017). With warmer waters, caused by climate change, more nutrient availability scenarios in the water column in those systems increases the eutrophication likelihood.

In this way, cultural eutrophication has been creating dense phytoplankton blooms that are reducing water quality, light penetration, and causing die-offs of various life types (Chislock et al., 2013) in water resources. Induced by climate change, massive algal blooms are prompting bacterial respiration, consuming O_2 and generating high turbidity water (Wurtsbaugh et al., 2019), and possibly in some cases releasing toxins. This relationship is evidenced in several studies (i.e., between temperature and cyanobacterial dominance) from laboratory and field observations for individual lakes or lakes in a confined region (Kosten et al., 2011).

2.1.5 Harmful Algae Blooms

As a consequence of increased nutrient input linked with warmer waters, triggered by climate change scenarios, augmented water mixing scenarios on aquatic systems will be favored, producing higher nutrient availability in the water column. In those situations, some species decrease in diversity and some usually fewer desirable species increase in biomass. These changes will lead to a decrease in biological diversity with the exclusion of many ecologically sensitive species (Boyd, 2019) causing the prevalence of the most resistant species to the modifications presented, the cyanobacteria.

Cyanobacteria are photoautotrophic aerobic bacteria belonging to the Bacteria domain, according to the classification of Woose et al. (1990). Species of these genera are particularly harmful, often surface scums former, obnoxious odors producer, and causers of taste problems, being sometimes toxic to living organisms (Boyd, 2019). Some possible toxins produced by them cited in the literature, intra- and extracellular by toxic cyanobacteria strains are anatoxin-a (neurotoxin), cylindrospermopsin (neurotoxin), and microcystin (hepatotoxin). As a rising concern, several studies have shown that harmer climates associated with human impacts are going to cause a higher production of cyanotoxin-producing cyanobacteria strains (Kosten et al., 2011; Yan et al., 2017; Paerl, 2018; Burford et al., 2020; Weber et al., 2020) triggering in this way further toxic contamination around the world.

2.2 CONTROL AND REMEDIATION METHODS FOR EUTROPHIC LAKES

The eutrophication management of lakes has undertaken a change from simply algal killing and reduction of the endogenous nutrient concentration to multiple technologies of lake ecosystems restoration (Zhang et al., 2020). These several methods have guaranteed robust literature on this process when applied to laboratory experiments. In contrast, few techniques are being applied in-situ with follow-up studies.

As stated, the most important nutrients for eutrophication are N and P. Those two chemical elements present distinct behaviors in the water column of lake systems. Nitrogen may be retained or lost to the atmosphere in gaseous forms by the denitrification process (e.g., N_2, NH_3, N_2O), due to higher sediment area to water volume ratio in shallow lake systems (Chen et al., 2012; Paerl et al. 2020). Phosphorus (P), in contrast, is often called the limiting nutrient and a primary controller of eutrophication in freshwater systems (Pant, 2020) and can be found in the water column, suspended solids, sediment and external releases. Furthermore, the phosphorus form found within lake water is of critical importance.

External loads of phosphorus, that come from watersheds, which enter water systems are partly in the particulate form, which will be possibly settling in the water column and remain within the sediment used only by phytoplankton if released for biological and/or chemical reactions (Sandström et al., 2020; Zhang et al., 2018). Internal loads, on another hand, predominantly occur in the dissolved form directly bioavailable for algal/cyanobacteria growth (Bormans et al., 2015).

As a result, it is compulsory to propose removal methods for external and internal phosphorus loads exacerbated into lakes due to synergistic climate change and human actions. As this thesis is presenting an in-situ remediation project, perceived in its objective and methodology given, preference will be for remediation technologies that can be applied in-situ or on-site.

2.3 INVASIVE REMEDIATION TECHNIQUES

At present, there is no international agreement for classifying in-situ techniques for lake water remediation. However, to the best of our knowledge, they include physical, biological, and chemical immobilization techniques (Wang & Jiang, 2016). Based on the previous classification, the more popular engineering methods for lake water remediation includes one or the combination of the following: hypolimnetic withdrawal, bottom sediment removal, sediment capping, phosphorus inactivation to the water and bottom sediments, and artificial aeration (Dunalska, 2021). Being invasive, drastic, intricate, and expensive, those methods require highly trained personal and specific materials as a proposed remediation project. Also, it is worth mentioning that these techniques' application has been heavily affecting lake water uses and their natural biota.

2.3.1 Chemical Addition

In this treatment category, several metals are used to inactivate sediment P, including flocculation agents like aluminum (Al), iron (Fe), and calcium (Ca) (Jilbert et al., 2020) as well as to capture phosphorus on the water column and bind them to sediment. The mechanism for this removal is similar to the addition of a flocculant agent in water treatment to aggregate suspended particles, creating larger flocs, which settle more easily. It is worth commenting that large treatment chemicals doses may cause a sharp decline in biodiversity in a lake due to coagulation or lethal effects (Gołdyn et al., 2014).

Aluminum (Al) salt application has been used to reduce phosphorus (P) concentrations in lakes since the 1960s (Huser et al., 2016). Aluminum-based compounds, such as aluminum sulphate ($Al_2(SO_4)_3$), aluminum chloride ($AlCl_3$), polyaluminum chloride, and sodium metaphosphate ($NaAlO_2$), have all been tried or tested for lake internal P loading control (Wang & Jiang, 2016). Al is typically applied to the water column in the Al-hydroxides form, which settles to the sediment surface and binds P in the sediment (Schütz et al., 2017). In other words, aluminum compounds (mainly referred to as $Al_2(SO_4)_3$) when added to water undergo rapid hydrolysis reactions. Initially, a moderate reactivity polymeric Al species with ferron is formed, which is transformed to a colloidal form rapidly (Wang & Jiang, 2016). Technical constraints of this method are related to dose determination, management challenges in external load control, and regulatory limitations related to potential Al toxicity (Wagner et al., 2017).

Iron-based compounds, such as ferric chloride ($FeCl_3$), ferric sulphate ($Fe_2(SO_4)_3$), solid ferric hydroxide ($Fe(OH)_3$), ferric chloride sulphate ($FeClSO_4$), ferrous chloride ($FeCl_2$), ferrous sulphate ($FeSO_4$), and ferric oxide (Fe_2O_3), have all been tried or tested for lake internal P loading (Wang & Jiang, 2016) as well. Upon dissolution into the aqueous phase, Fe^{3+}/Fe^{2+}precipitates with phosphate directly, the Fe^{3+}/Fe^{2+} hydrolyzes to become an iron hydroxide gel and iron oxide are removed by chemical precipitation and adsorption (Wang et al., 2021). When added in excess, iron could also negatively affect organisms as iron in high doses can be toxic (Bakker et al., 2015)

Calcium-based compounds, such as calcium chloride ($CaCl_2$), calcium hydroxide ($Ca(OH)_2$, including slaked lime), gypsum ($Ca_2SO_4 \bullet 2H_2O$), calcium oxide (CaO, including lime), calcium carbonate ($CaCO_3$, mainly referring to calcite), and limestone, have all been tried or tested for lake internal P loading control (Wang & Jiang, 2016). Calcium cations and hydrogen carbonate anions which at elevated concentrations, form carbon dioxide and $CaCO_3$ precipitate and coprecipitate P to the sediment in the process (Zamparas et al., 2014) retrieving some phosphorus from water column and locking in the sediment. These calcium compounds have low solubility in fresh water; and therefore, these compounds are not suitable for effective phosphate ion removal when dissolved in fresh water.

2.3.2 Inert Elements Addition

Some recently developed solutions are currently being tested as alternative binding methods. Many of these solutions involve the addition of P-binding metals to clay material that is then added to lake water and allowed to precipitate and mix with the sediment. These are called capping methods. The first one, being extensively studied is Phoslock® a lanthanum (La) modified bentonite clay that is being increasingly used as a geo-engineering tool for the control of legacy phosphorus (P) release from lakebed sediments to overlying waters (Spears et al., 2013). The Phoslock® has been applied in around 200 environments worldwide and has undergone extensive testing at laboratory, mesocosm, and whole lake scales (Copetti et al., 2016).

Related to other inert element addition material, there is zeolite application. Two zeolite types have been used for lake internal P loading control, namely raw zeolites (nature or artificial) and modified zeolites (Jilbert et al., 2020). While unmodified zeolite phosphate anions are not removed because of its negative surface charge; modified zeolites properties can be tuned by incorporating different metals into the matrices which serve as the primary binding sites for phosphate ions (Saifuddin et al., 2019). The removal is achieved due to adsorption of phosphate on the zeolite surface or phosphate precipitation (Naghash & Nezamzadeh-Ejhieh, 2015).

2.3.3 Contaminated Sediment Dredging

As an extremely costly recovery method, this technique has been applied on shallow lakes where internal loads should be the principal contributor to lake water eutrophication. As sediments act as sinks and sources of pollutants in aquatic environments, the P accumulated in the sediments can be released into the overlying water easily (Chen et al., 2018). By this premise, the contaminated sediment can be removed from the system to prevent further contamination. However, projects with dredging to restore eutrophic lakes have shown mixed results (Kiani et al., 2020) when related to their actual application.

Theoretically, the dynamic phosphorus (P) release from sediments to the overlying water is subjected to two basic processes: 1) the diffusion process of pore water P, which depends on the concentration gradients between the sediment-water interface (SWI); and 2) the resupply process of solid P to the pore water by the release of P from the binding sites of the sediment solids (Ding et al., 2015). A hypothesis indicated that after dredging, with the significant decline in organic matter in the post-dredged sediments, the internal P release is reduced because of the lower rates for the decomposition of organic matter (Oldenborg et al., 2019).

This can significantly decrease the capacity of the non-dredged sediments to retain P, resulting from the reduction and/or dissolution of iron oxides in a more anoxic condition (Yu et al., 2017). Sediment dredging can produce a large quantity of waste, which will require dewatering and land disposal. In many cases, the dredged sediments may be reactive once dried requiring further management (Yin et al., 2021). Additionally, the sediment disturbance may cause the co-contaminants to be released such as heavy metals and therefore induce secondary pollution (Yu et al., 2019).

2.3.4 Water Aeration

Increased phosphorus and nitrogen concentrations can stimulate algal/cyanobacteria growth, which then leads to additional oxygen demand due to the mineralization of dead algal biomass (Bierlein et al., 2017). Hypolimnetic aeration (i.e., pumping of epilimnion water into the hypolimnion) involves the addition of oxygen to bottom waters to promote binding of sediment P with oxides of redox-sensitive metals such as Fe and manganese (Mn). These systems inject air or oxygen either into the hypolimnion or into water withdrawn from it (Wagner, 2019; Jilbert et al., 2020; Niemistö et al., 2019). Well-oxidized sediment surface can be a sink of P via sorbing settling P and thus prevents P of deeper sediments from escaping (Tammeorg et al.,2020). Hypolimnetic withdrawal has been rarely applied, likely due to the major drawback that the method in its traditional form only moves the nutrient problem downstream (Jilbert et al., 2020).

2.4 SUSTAINABILITY, SUSTAINABLE DEVELOPMENT GOALS AND SDG 6

In the report, Our Common Future published in 1967 by Brundtland Commission, it is stated that in a world in which poverty and inequity are endemic, it will always be prone to ecological and other catastrophes. As we are evolving as nations, measures must be taken to prevent or in some cases at least attenuate those possible crises. In order to answer the possible concerns presented, sustainable development is a raising suggestion. This sustainable development can be defined as the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. In other words, by meeting the basic needs of all and extending to all the opportunity to satisfy their aspirations for a better life (Brundtland & Khalid, 1987), only by this path sustainability is achieved.

To be able to fully access this idea, nations have shaped specific objectives in order to transmute concepts into actions and called the Sustainable Development Goals (SDGs). Created by the United Nations (UN) General Assembly in 2015, they are the successor of the Millennium Development Goals (MDGs), which were considered ambiguous. This agenda document consists of 17 SDGs, as presented in Figure 2-3, which among the many other tasks, are intended to eradicate poverty and create better health conditions in countries that do not have full access to education and improved living conditions in countries that have (Leal Filho et al., 2018). As this project is presenting a lake remediation method, SDGs related to water will be focused on, more precisely SGD 6 that presents clean water and sanitation as the objective to be reached by nations in 2030.

Figure 2-3: Sustainable Development Goals defined by UN (UN, 2021)

The sustainable future of water resources, lakes and reservoir is being endangered by emerging global threats, such as biological invasions, climate change, land-use intensification, and water depletion (Ho & Goethals, 2019). When the SDG 6 is looked at in depth, it is well understood that there is coverage of all possible contemporary issues of water resources. The SDG 6 adopts a broader set of water-related targets extending well beyond just improving access to it (Sadoff et al., 2020).

Beyond targets related to drinking water supply and sanitation (targets 6.1. and 6.2), it includes aspects of water quality and wastewater (target 6.3), water use and efficiency (target 6.4), integrated water resources management (IWRM) (target 6.5), restoring ecosystems (target 6.6) and an enabling environment (targets 6.a and 6.b). Presenting reliable answers to all those water-related difficulties, the objectives of this target create a future not only with cleaner water but also with a restored and diverse ecosystem. When associated to the presented thesis, which proposes a methodology of lake water sustainable remediation, the SDG 6 can be expanded on the targets 6.6, 6.a and 6.b and used as investigation justification.

2.5 SUSTAINABLE WATER REMEDIATION TECHNIQUES

Sustainable remediation techniques are methods supporting the own waterbodies' restoration (Dunalska et al., 2021). In other words, they are methods, which take advantage of a lake ecosystem's natural response to changes made within it (Gołdyn et al., 2014; Rosińska et al., 2018). By using minimally invasive measures for lake restoration, a gradual reconstruction of the aquatic communities' composition, from phytoplankton and zooplankton to benthic macroinvertebrates and macrophytes, is enabled (Gołdyn et al., 2014). Examples of these methods are ecological engineering techniques involving the primary productivity control (i.e., by minimally invasive nutrient abstraction), biocides application, macrophyte harvesting, macrophyte re-establishment, and the use of floating wetlands, and artificial substrates (Dunalska, 2021; Gołdyn et al., 2014).

When technical contemporary solutions have been applied for lake water remediation currently, they are chosen haphazardly and implemented by companies focusing on making profits (Dunalska, 2021) In contrast, sustainable methods are considered less invasive, easily deployed and cheaper when compared with actual technologies. Additionally, when sustainable methods are applied in-situ, this methodology should be effective, in reducing nutrients for the entire recreational season, environmentally safe, and relatively easy to apply (Lürling & Mucci, 2020). Lastly, as water sustainable remediation is a recent topic in the literature, knowledge on its application is still being formed, and modern sustainable in-lake restoration methods are yet under investigation to fulfill this gap.

It is well understood that several years of sustainable restoration application at the beginning of lake water deterioration can easily reduce ecosystem degradation due to eutrophication and maintain good lake water quality (Dondajewska et al., 2019). In this case, acting in advance, treating symptoms, not the disease (i.e., disease metaphorically related to eutrophication with harmful algae/cyanobacteria bloom) water quality status can be maintained. By guaranteeing the water quality status, the most important change when using sustainable methods is applied is to reduce harmful plankton organisms (i.e., cyanobacteria) attributable to a significant reduction on phosphorus concentration in the water column (Gołdyn et al., 2014). This allows other water uses even if other groups of phytoplankton organisms are still frequent.

2.6 FILTRATION PROCESS

Originated by the Latin word *filtrum*, which means a piece of felt (i.e., a type of textile) this process occurs when a liquid is strained for particle removal and this method have been used for centuries. Following the word etymology stated, when scientifically defined, filtration is the mechanical or physical process used for the separation of one substance from another, such as solids, liquids, and gases, with the aid of an interposing medium (filter) (Shah & Rawal, 2016). In other words, filtration is any process for the removal of solid particles from a suspension (a two-phase system containing particles in a fluid) by the passage of the suspension through a porous medium (Crittenden et al., 2012). The fluid that passes through is called the 'filtrate' and the retained solid is collected as a 'cake'.

As explained by word etymology and definitions, filtration when related to liquid filtration (i.e., water filtration), the main outcome to be achieved is particle removal. This process when applied in water can not only remove or reduce the particulate matter concentration including suspended particles, parasites, bacteria, algae, viruses, and fungi but can also remove other undesirable chemical and biological contaminants from contaminated water to produce safe and clean water for specific purposes (Mao, 2016). Removing particles in the influent suspension has the objective of producing a filtrate with high clarity (Amirtharajah, 1988) clean of undesirable components to be used in diverse ways. Media types commonly used for producing high clean filtrate are charcoal, carbon, sands, gravels, zeolites, or clean, insoluble, and mechanically resistant material such as any textiles, geotextile, polymers, and others.

2.7 FILTRATION MECHANISMS

When particles are larger than the void spaces in the filter, they are removed by straining. When particles are smaller than the voids, they can be removed only if they contact and stick to the grains of the media (Crittenden et al., 2012) previously accumulated on the media surface which reduces media opening sizes. The main mechanisms where particles are removed are, surface filtration or straining and depth filtration or cake filtration (Brandt et al., 2017; Eyvaz et al., 2017). Transport to the media surface occurs by interception, sedimentation, and diffusion, and attachment occurs by attractive close-range molecular forces such as van der Waals forces (Howe, et al., 2012).

In the surface straining filtration mechanism, any particle that is larger than the pores of the medium deposits on the surface and stays there until it is removed. Particles that are smaller than the pores pass quickly through the medium (Sutherland, 2008; Ebnesajjad et al., 2017). As presented in Figure 2-4 a) in surface filtration, particles are collected on the surface of the membrane. Additionally, the solid particles penetrating the surface of the media close off the open pores, thus forming a filter cake on the media surface called depth filtration, reducing its opening size and increasing the water head pressure on the media. In-depth filtration mechanics shown in Figure 2-4 b), particles penetrate the structure of the media and form a filter cake layer on the surface (Crittenden et al., 2012). Particles are removed continuously throughout the filter through a process of transport and attachment to the filter grains. (Howe, et al., 2012), or in other words, a combination of those two mechanisms.

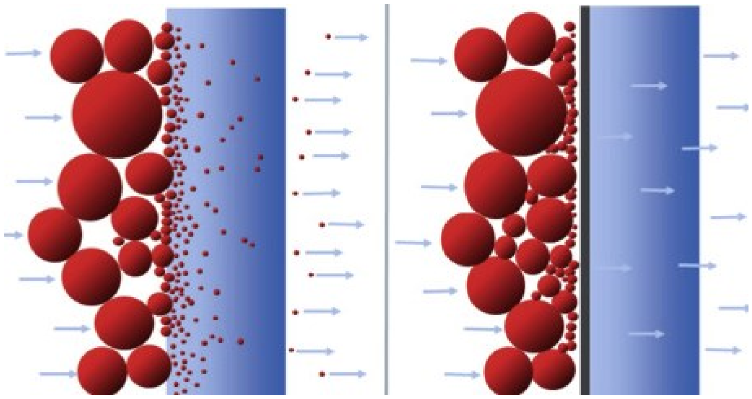


Figure 2-4: Filtration mechanisms: (a) surface filtration versus (b) depth filtration (adapted from Donaldson Corp, 2015)

2.8 TEXTILES AS FILTER MEDIA

Textile fibers are obtained from many synthetic and natural sources being extensively used as filter media. Various fiber types could be used in the making of the filter media including glass fibers, synthetic fibers, cellulosic fibers, wool fibers, metal fibers, ceramic fibers, high-performance polymer fibers, microfibers, and nanofibers (Mao, 2016). Those varied textiles are used in several ways, for separating, and purifying liquids and solids, cleaning gases and effluents, absorbing dirt, fumes, and oil (Zerin, & Datta, 2018). Also, textile filtration has been used for particle and bacterial removal in drinking water treatment (Siwila & Brink, 2018).

Fabric filters' advantages include high collection efficiency over a broad range of particles sizes and flexibility in design provided by the availability of various cleaning methods and filter media (Miller, 2011). With smaller opening sizes, textile elements are the most commonly used filter material for fine-size filtration and can be easily compared with modern paper filters in terms of performance. The fabrics may contain a range of materials, in a woven and nonwoven presentation, and may be modified by impregnation with synthetic resins or the like (Eyvaz et al., 2017).

Related to the fibers, woven fabrics can be understood as a material made from either the interlacement by two or more yarn sets. In contrast, nonwoven textiles are produced from short-staple fibers, invariably possess surfaces with protruding fiber ends (Shah & Rawal, 2016). When both are compared, nonwoven fabric filters offer many unique technical characteristics over woven ones, including greater permeability, greater specific surface area, and controllable pore size distribution, as well as smaller pore sizes (Mao, 2016).

2.9 GEOTEXTILES AS FILTER MEDIA

Geotextiles are textile fabrics, which are permeable to fluids such as water and gases (Ingold, 2013). Polymeric fabrics that are extensively used as filters in geotechnical and geoenvironmental works (Palmeira et al., 2019). Application examples of this material could be in road construction, drains, harbor-works, breakwaters, land reclamation, and many other civil engineering purposes (Spencer, 2001). The main reasons for this large utilization are due to the easiness of transport and installation in the field, besides being manufactured products, which guarantees uniformity and reproducible properties (Palmeira et al., 2019).

About 98% of the currently used geotextiles are made of non-degradable polymers from the polyolefin, polyester, or polyamide family (Wu et al.2020). Being textiles, they can be woven (i.e., the interlacement of yarn) and nonwoven (i.e., composed of staple fibers). In their functions, geotextiles are employed for at least one of the following: separation, reinforcement, filtration, drainage, stabilization, barrier, and erosion protection (Wu et al.2020). It is worth mentioning that only filtration uses will be focused on this topic as it is the objective of this thesis presented. In this process, water passes through the geotextile blocking any sediment/suspended particles larger than the pore size from passing through (Paul & Tota-Maharaj, 2015).

By using the principle explained for employing geotextiles as a filter media, has brought attention to the feasibility of this application in real scenarios and some studies have been developed to address this literature gap. Some studies on this topic have been focusing on remediating lake water by removing suspended solids and their associated contaminant. In this thinking, further investigations have been done on applying this media (i.e., different opening sizes geotextiles) to filter lake water using a floating filtration unit for addressing and removing suspended solids and their associated particulate nutrients (Palakkeel et al., 2021; Pereira et al., 2020; Ghasri, 2019; Sarma, 2016; Mulligan et al., 2009) showing high potential as flexible, effective and economic filtration each study has its unique methodology and results. Different from previous work procedures, this thesis will cover the application of in-situ long term geotextile filtration for eutrophic lake water sustainable rehabilitation.

2.10 PARAMETERS INFLUENCING LAKE WATER QUALITY

In this topic, a brief explanation of the chemical, physical, and biological parameters which influence lake water quality is given. Details on what the parameter is and where it can be derived from will be presented, followed by how its absence or presence in large amounts can affect lake waters. Those expanded explanations presented will be employed as a reference for results and discussion in this thesis.

2.10.1 Phosphorus

Phosphorus (P) is an essential element for life and is often considered either the primary limiting or collimating nutrient in water ecosystems (Steinman et al., 2017). This element can be found in the aquatic environment in several forms including organic phosphorus, water-soluble inorganic, and insoluble inorganic forms of phosphorus. Of these different forms, the water-soluble inorganic form is the most important because it can be consumed by phytoplankton directly and contributes to surface water productivity (Sengupta, 2014).

The main sources of P to aquatic systems are surface runoff from varying land uses (e.g., arable land, native grassland, forested, urban), septic tanks, groundwater seepage, atmospheric deposition (dust fall and precipitation), internal sediment release, waterfowl and other wildlife, and the decomposition of organic matter (Riemersma et al., 2006). If the P presence in natural water is too great, eutrophication occurs (Boyd, 2015; Pal, 2017; Senthil Kumar & Yaashikaa, 2019). Normally this scenario will stimulate aquatic plant growth and especially phytoplankton growth. In other words, high nutrient concentrations can cause harmful algal/cyanobacteria blooms this will leads to a lake environment prone to hypoxia, fish kills, and the production of toxins (Wilkinson, 2017).

As mentioned, in lake water, P exists as total dissolved, represented by inorganic water soluble, and particulate forms by inorganic insoluble phosphorus and organic, where the total of those forms represents the total phosphorus concentration. In a real lake scenario, phosphorus from catchments (external sources) is partly in the particulate form that possible settles in the water column and is only used by phytoplankton if released (Sandström et al. 2020). Internal loads in lakes are predominantly in the dissolved form directly bioavailable for algal/cyanobacteria growth (Bormans et al., 2015. Fractions are operationally defined and determined by filtration through 0.2 or 0.45 µm filters (Paytan & McLaughlin, 2007). The dissolved fraction (which passes through the filter) and particulate P (retained on the filter).

2.10.2 Nitrogen

Nitrogen is an essential element for life and is the fourth most abundant element in the living biomass (by moles) after hydrogen, carbon, and oxygen (Howarth, 2009; Hanrahan & Chan, 2005). This element enters aquatic ecosystems via surface and groundwater runoff, atmospheric deposition, nitrogen fixation by prokaryotes (cyanobacteria), dissolution of nitrogen-rich material, and decomposition (van den Berg & Ashmore, 2008). In aquatic ecosystems, nitrogen compounds are naturally present at low concentrations usually as NH_3-N, NO_2^-, and NO_3^- (Ryskie et al., 2021). An increase in nitrogen availability in water can stimulate or enhance the growth and proliferation of primary producers (phytoplankton, benthic algae, and macrophytes) in combination with phosphorus. The eutrophication of aquatic environments can result in the huge expansive growth of primary producers (van den Berg & Ashmore, 2008).

2.10.3 Nitrate

The nitrate ion (NO_3^-), the oxidized form of dissolved nitrogen, is the most common contaminant worldwide, high soluble (Keeton, 2017) found in the natural waters at moderate concentrations (Shrimali & Singh, 2001). Contaminant sources of this include nitrogen fertilizers, manure from animal feeding operations, septic systems, plant nitrification of and other organic matter, and atmospheric deposition. (Ward & Brender, 2019; Pärn et al., 2012). Elevated nitrate concentrations in conjunction with P increases can also result in natural water bodies' eutrophication affecting the aquatic environment and reducing water quality. Additionally, high nitrate concentrations in the case of drinking water supplies can cause acute toxic effects in human beings, notably methemoglobinemia in infants (also known as “blue baby syndrome”) (Cashman et al., 2017).

2.10.4 Turbidity

Turbidity, a measure of water cloudiness, is caused predominantly by suspended material such as clay, silt, organic and inorganic matter, plankton, and other microscopic organisms, which scatter and/or absorb light (Scholz, 2016). The solid particles of the micron or submicron size order, which are miscible in water, are responsible for the water to appear turbid (Nvs & Saranya, 2020). For measurements, the nephelometric method is used and represented in nephelometric turbidity units (NTUs). A nephelometer measures the intensity of light scattered by a sample and compares it to the intensity of light scattered by a reference standard. Sample turbidity is proportional to the intensity of the scattered light (Popek, 2018).

Turbidity can be caused by soil erosion, waste discharge, urban runoff, bottom feeders like carp that stir up sediments, household pets playing in the water, and algal growth (Patel & Vashi, 2015). Any modification of water turbidity will cause modifications of dissolved oxygen concentration in the water column through affecting living organisms. More precisely changes in water turbidity can cause modifications of photosynthesis rates (Gómez et al., 2017). Turbid waters also become warmer as suspended particles absorb more heat, causing oxygen levels to fall (warm water holds less oxygen than cool water) (Patel & Vashi, 2015). High turbidity can also mean higher concentrations of bacteria, nutrients, pesticides, or metals. Therefore, a sudden change in turbidity, by the information mentioned, may indicate the presence of a new pollution source (biological, organic or inorganic) in natural waters (Sadar, 2017). Turbidity is also often assumed as a surrogate for total suspended solids (TSS). It is generally true that the higher the TSS then the more particles are expected in suspension, and the higher the turbidity (Bratby, 2015).

2.10.5 Particle sizes

Particles are ubiquitous in natural waters and in water and wastewater treatment streams. Through particle counting and size distribution analysis it is possible to determine the makeup of natural waters when related to suspended particles (SMWW, 2020). In other words, it is possible to define which particle sizes are causing cloudiness and/or contamination on it. Depending on its size, particles can hide harmful organisms like plankton, virus and bacteria as well as substances or nutrients that can cause problems to this environment. In addition, the size and distribution of these particles are important to the structure and functioning of aquatic ecosystems, as it influences trophic interactions within the planktonic community (Reynolds et al., 2010).

Total suspended particles sizes are one of the most important parameters for removal efficiency of basic water treatment/remediation processes (Zielina et al., 2007). In this understanding, particle size analysis characterizes the quality of treated water more precisely than turbidity, TSS, or any other parameters. For doing its measurements, particle-counting instruments are employed. Those equipment types allow particles to pass through a sensing zone where they are measured individually. By the instrument's measurement of an electronic pulse (voltage, current, or resistance) particle size is characterized (SMWW, 2020).

2.10.6 Total Suspended Solids

Suspended particles, particularly in natural waters are composed of a large variety of materials that could include clays, silts, inorganic matter, organic matter, vegetation, and living organisms with various particle sizes and optical characteristics (Bratby, 2015). With this understanding, total suspended solids (TSS) are defined as solids in water that can be trapped by a filter. Solids that will not pass through a specific size filter (i.e., 0.45μm filter) are referred as the portion called total suspended solids (Woodard & Curran, Inc., 2006). To measure TSS, the water sample is filtered through a pre-weighed filter. The residue retained on the filter is then dried in an oven at 103–105°C until the weight of the filter no longer changes (Ismail et al., 2019).

Higher concentrations of suspended solids serve as carriers of toxics, which readily sorb to suspended particles, which reduces the treatment efficiency and operation of industrial processes. (Spellman, 2003). The excess of this parameter also decreases the light through the waters slowing photosynthesis by aquatic plants. Additionally, water will heat up more rapidly and hold more heat when higher TSS concentration is present, which in turn, might adversely affect aquatic life that has adapted to a lower temperature regime (EPA, 2012).

2.10.7 Water Temperature

Water temperature is a measure of the water molecule kinetic energy and is expressed in degrees Fahrenheit (ºF) or Celsius (ºC). Temperature is considered a critical water quality and environmental parameter as it governs all types of aquatic life, regulates the maximum dissolved oxygen concentration of the water, and influences the rate of chemical and biological reactions (Oram, 2012). Elevated temperatures resulting from discharges of heated water may have a significant ecological impact (SMWW,2020a).

2.10.8 Dissolved Oxygen

Dissolved oxygen (DO) is the amount of elemental oxygen (chemical symbol O_2, molecular wt. 31.99 g/mol) dissolved in the water (Deacutis, 2015). In freshwater this parameter reaches 14.6 mg/L at 0 °C and approximately 9.1, 8.3, and 7.0 mg/L at 20, 25, and 35 °C, respectively, and 1 atm pressure (Patel & Vashi, 2015). When DO levels in water drop below 5.0 mg/L, aquatic life is put under stress. The lower the concentration, the greater the stress. For living organisms, a minimum of about 4 mg/L of DO should be in water (Patel & Vashi, 2015). As temperature and salinity increase, dissolved oxygen saturation decreases. Increases in atmospheric pressure increase saturation concentration of DO.

Dissolved oxygen concentration is not conservative and is strongly affected by biological processes such as photosynthesis and respiration (Deacutis, 2015). When water is eutrophic, a known consequence of it could be hypoxia (i.e., reduced dissolved oxygen concentration in water which stresses organisms), caused by blooms of blue-green algae (i.e., algae and/or cyanobacteria). In other words, this is caused when dense algae bloom eventually dies and microbial decomposition starts to occur, severely depleting dissolved oxygen in the water column, creating a hypoxic or anoxic ‘dead zone' lacking sufficient oxygen to support most organisms (Chislock et al., 2013).

2.10.9 Fluorescence Dissolved Organic Matter (FDOM)

Dissolved organic matter (DOM) is a heterogeneous class of water-soluble compounds that contain reduced (organic) carbon from a variety of biological and geological sources with a wide range of chemical reactivity (Hartnett, 2017). This organic matter consists of the elements C, H, O, N, P, and S configured into millions of different organic molecules and occurs in every compartment of the hydrologic cycle from oceans and rain to surface water and groundwater. Researchers commonly refer to the major DOM components in stream water as “humic” and “fulvic” materials (Lamberti, & Hauer, 2017). This DOM and its constituents’ fractions can be derived both from terrestrial sources external to the aquatic system (allochthonous) and from sources within the aquatic system (autochthonous) (Hood et al., 2005).

Between the DOM portions, some of those substances are called colored/chromophoric dissolved organic matter. Chromophoric dissolved organic matter (CDOM) is an important optically active substance in aquatic environments and plays a key role in light attenuation and the carbon, nitrogen and phosphorus biogeochemical cycles (Zhang et al., 2018). In other words, organic matter in water absorbs strongly in the ultraviolet (UV) spectrum, which is important in the nutrient cycle. Those substances cause color in the water and indicate that the environment has organic matter degradation. In addition, the fluorescent fraction of CDOM referred to as CDOM fluorescence or fluorescence dissolved organic matter (FDOM), has been widely used to trace CDOM distributions, sources, compositions, and cycles (Zhang et al., 2021) and has been used as a surrogate for dissolved organic carbon.

2.10.10 Chemical Oxygen Demand

Chemical Oxygen Demand (COD) is defined as the amount of oxygen equivalents consumed in the chemical oxidation of organic matter (organic and inorganic) by a strong oxidant (e.g., potassium dichromate) (Hu & Grasso, 2005). It is generally used to indirectly determine the number of organic compounds in aquatic systems (Islam et al., 2019). High COD indicates the presence of all forms of organic matter, both biodegradable and non-biodegradable and hence the degree of pollution in waters. The COD concentrations observed in surface water resources typically range from 20 mg/L or less in unpolluted waters to greater than 200 mg/L in waters receiving effluents. Industrial wastewaters may have COD values ranging from 100 mg/L to 60,000 mg/L (Chapman, 1996).

2.10.11 Oxidation-Reduction Potential (ORP)

The oxidation-reduction potential (ORP) (abbreviated as redox potential) is the tendency measurement of an environment to oxidize or reduce substrates. ORP provides a snapshot of redox potential by applying a low voltage current to the sample (Pepper & Gentry, 2015). This is a measure of the ease with which a molecule will accept electrons, which means that the more positive the redox potential, the more readily a molecule is reduced (Doble & Kumar, 2005). Positive values for ORP indicate oxidizing conditions, whereas negative values indicate reducing conditions (Myers, 2019). Redox potentials of less than −100 mV indicate anaerobic environments, while values greater than + 100 mV indicate aerobic environments (Suthersan, 2001; Scholz, 2019). The inorganic oxidants include oxygen, nitrate, nitrite, manganese, iron, sulphate, and CO2, while the reductants include various organic substrates and reduced inorganic compounds (DeLaune & Reddy, 2005).

2.10.12 pH

The pH of a solution equals the negative of the logarithm to the base 10 of its hydrogen ion concentration, $pH= - \log_{10}[H+]$ (Blackstock, 1989). Being a measurement of the acid-base equilibrium and, in most natural waters. This parameter is controlled by the carbon dioxide–bicarbonate–carbonate system. An increased carbon dioxide concentration will therefore lower pH, whereas a decrease will cause it to rise (WHO, 2007). pH influences the position of the chemical equilibrium of the majority of chemical reactions in aqueous solutions (Głąb & Hulanicki, 2005). Also, the water pH determines the solubility (the amount that can be dissolved in the water) and biological availability (the amount that can be utilized by aquatic life) of chemical constituents such as nutrients (phosphorus, nitrogen, and carbon) and heavy metals (lead, copper, cadmium, etc.) (USGS, 2019).

2.10.13 Chlorophyll-a

Chlorophyll-a absorbs light in the violet to red spectrum (approximately 400-700 nm wavelength range) and reflects green light (500-570 nm wavelength), which imparts the characteristic green color to land plants. Being an essential component for oxygenic photosynthesis (NCBI, 2021) all land plants, green algae, and prochlorophytes possess chlorophyll-a (Tanaka et al., 1998). Chlorophyll-a (Chl.a) serves a dual role in oxygenic photosynthesis: in light harvesting as well as in converting energy of absorbed photons to chemical energy. No other chlorophyll pigment is as omnipresent in oxygenic photosynthesis as Chl.a (Björn et al., 2009). In water, Chl.a concentration is considered a proxy for phytoplankton biomass, in other words, a rapid increase of this concentration indicates an increase in photosynthetic organisms in the water column. This increase, in the majority of cases is caused by increased nutrient concentration and leads to issues such as hypoxia, high turbidity levels, and high dissolved organic matter.

2.10.14 Cyanobacteria or Blue-Green Algae (BGA)

Cyanobacteria or previously called blue-green algae constitute a phylogenetically coherent group of evolutionarily ancient, morphologically diverse, and ecologically important phototrophic bacteria. They are defined by their ability to carry out oxygenic photosynthesis (water-oxidizing, oxygen-evolving, plant-like photosynthesis) (Garcia-Pichel, 2009). Cyanobacteria are present in a wide range of habitats viz. marine, freshwater, soil, biological soil crusts, snow, cryoconites, etc. Further, they are found in symbiotic association with different hosts and also occur in extremely stressed conditions like volcanic ash, salted soils, and anthropogenically disturbed areas (Gaysina et al., 2019). In aquatic environments, cyanobacteria are important primary producers and form a part of the phytoplankton and they may also form biofilms and mats (benthic cyanobacteria) (Sivonen, 2009).

Wherever conditions of temperature, light and nutrient status are conducive, surface waters (both freshwater and marine) may host an increased growth of algae or cyanobacteria. Where such proliferation is dominated by a single (or a few) species, the phenomenon is referred to as an algal or cyanobacterial bloom (Chorus & Welker, 2021). Mass occurrences of cyanobacteria can be toxic as they can release toxins as byproducts (external toxins) or when there is cellular lysis as they die off (internal toxins). The mainly cyanobacterial toxins which have been present in the specialized literature studies are of three main types: hepatotoxins, neurotoxins and lipopolysaccharide (LPS) endotoxins. It has been reported that several animal poisonings have occurred and there is also a threat to human health (Sivonen, 2009).

2.11 CRITERIA FOR SURFACE WATER QUALITY FOR AQUATIC LIFE

Surface waters are extremely affected by the nutrient pollution and warming scenarios presented. In order to follow their status, federal, provincial and territorial authorities, in the case of Canada, must properly monitor them for protecting water quality and aquatic life. This monitoring is based on chemical, biological and physical parameters, where guidelines values are presented, and used to provide information about how the surface water quality change through time, and how to support water resource management.

In Canada, even though there is a federal guideline, every province has its own guidelines, based on the federal one or with other references. As the study lake is located in Quebec, the

Critères de la qualité de l'eau de surface guideline from *Ministère du Développement durable, Environnement et Lutte contre les changements climatiques* (MDDELCC), have been followed, when possible. For the parameters not presented in the guideline federal guidelines such as Canadian Council of Ministers of the Environment (CCME), the guideline of the Government of Canada (2008) was employed. For specific parameters not covered by both of them specialized literature was used. Guideline values are presented in Table 2.1.

Table 2.1: Water quality guidelines for surface water used in Quebec

Parameter	**Form**	**Guideline**	**Source**
Nitrogen	total	1 mg N/L	Government of Canada (2008)
Nitrate and nitrite	total dissolved	2.93 mg N/L	CCME (2018); Government of Canada (2008)
pH	n/a	between 6.5 and 9 1	MDDELCC, 2017
Phosphorus	total	0.03 mg P/L	MDDELCC, 2017
Turbidity	n/a	10 NTU	Government of Canada (2008)
Chlorophyll a	n/a	8 mg/L	Government of Canada (2008)
Oxygen	dissolved	5 mg/L	Government of Canada (2008)
Suspended sediments	total	Maximum increase of 25 mg/L for high flow and turbid waters above background levels 4	Government of Canada (2008)
COD	total	20 mg/L	(Chapman & Kimstach, 1996)

2.12 WASTE MANAGEMENT FOR PLASTIC MATERIAL

Waste management is a conduit at the crossroads of inputs from producers, users, and outputs to environmental compartments, with the overall goal to clear the residues and reutilize cleared materials when possible (Rajendran et al., 2019). In other words, waste management is the step that should be taken when any residue is produced for proper handling and if necessary final disposal of it. For this matter, several waste management routes could be proposed and the chosen one will depend on the residue type, amount, and current legislation.

Waste hierarchy management set by the European Union Waste Framework Directive (European Parliament Directive, 2008) is also followed by the Québec Residual Materials Management Policy. The 4R-D says that on residual materials management priority should be given to source reduction, reuse, recycling (including by biological treatment or land spreading), other forms of material reclamation, energy production, and disposal, in that order. This means that any waste should primarily be minimized or prevented to exist and when this is not possible products should be reused as they are, or their materials should be recycled. If this step is not possible as well, waste should be recovered for energy, a good alternative to using fossil fuels or harvesting biological materials. The least favorable option for waste is to dump it in a landfill. As this is an important step on any project that is been applied in the environment, this topic will be briefly explained in the understanding of the possible waste routes on the highest quantity waste produced on this thesis, plastic waste.

Proper management of solid waste lessens or fully abolishes various adverse impacts on the environment and human health and supports economic development along with the life quality improvement (Hannan et al., 2020). In order to environmentally answer to this issue, sustainable waste management practices have been used, even though it is challenging due to our consumption behavior and changing socioeconomic conditions (Rajendran et al., 2019). This is a possible road being offered. As waste is composed of diverse materials, with different degrading times and behaviors, different routes need to be used for each component present. As the global political agenda now views plastic waste as a serious solid waste management problem (Hahladakis et al., 2020) ways of attenuating this issue need to be planned. With this understanding, the proposed method in this thesis, as sustainable tracks are going to be suggested, management of the residues produced, plastic waste, by this filtration process will be addressed.

2.12.1 Circular Economy for Plastic Material

The current linear economy is based on converting natural resources into waste via production. This traditional model, in which goods are manufactured and then discarded as waste is according to the pattern of “take–make–consume and dispose of” (Landaburu-Aguirre et al., 2016). This is deteriorating the environment (Garcés-Ayerbe et al., 2019) due to the assumption that resources are abundant. In this view, an alternative model to the linear economy, which is considered sustainable, surges as a model to denominate the circular economy. A circular economy (CE) is explained as an economic model of keeping resources in a closed loop by maximizing their consumption and minimizing waste (Yusuf et al., 2020). CE suggests an economic model regulated according to the laws of nature, interacting components networks, exchange of material and energy flows, recycling patterns, and environmental mimicry (Ghisellini et al., 2016). It is a perspective for how industries could deal with a lack of resources today and in the future (de Jong & Mellquist, 2021).

Focusing on the plastic industry that has been producing a prosperous durable material, it has in some way provided an evolution to diverse food packages, containers and textiles. In some way, the plastic that has been produced fifty years ago is still degrading onto the environment currently. In this view, a plastics circular economy needs to be proposed, being a prosperous economy that recirculates materials, keeping plastics out of the environment and in the economy. Using as an example the material used on the proposed remediation method as a filtration geomembrane (i.e., plastic) there is a need to change from our current linear plastic use model to a plastic circular economy model.

Using old materials or products as material or shared products is an excellent instrument that supports sustainability goals by improving raw material availability, decreasing environmental impacts, and also increases economic advances (Kalmykova et al., 2018). Particularly, out of the 17 goals mentioned earlier, sustainable consumption, production (SDG 12) and the conservation and sustainable use of the oceans, seas, and marine resources (SDG 14) are most relevant to plastic and plastic waste. Therefore, a greater focus is needed not only on reducing overreliance on plastics but also on finding ways to promote their circularity potential in the system, given that this is the best way of minimizing the environmental, economic, technical, and social impacts associated with plastic waste. In this view, the possible routes to be applied to plastics material produced in this thesis is going to be reuse. This waste management route prevents waste to be produced by extending the lifetime of the layers used.

2.12.2 Possible Waste Routes for Plastic Material

Plastic waste management faces severe challenges and opportunities worldwide, with regard sustainability awareness and technological advances (Kaur & Misra, 2014). Recent methodologies for this material are reuse, mechanical recycling, feedstock (chemical) recycling, incineration, and lastly landfilling. In order to better understand the full subject, each route will be presented with possible details to guarantee that the choice made in the management of the possible residues generated for the lake water remediation technique proposed is the most applicable.

By contributing with the first R, reduction, could be explained as prevent waste to be generated, when this is possible. The second R is related to the reuse route meaning using a product again for the originally intended purpose or other purpose which this material can be applied with no or minimal modification. These options are only a form of lifecycle extension, rather than a true end-of-life scenario.

Recycling, on the other hand, is another method in which the plastic waste is converted into other usable plastic forms. However, in this method, energy will be consumed, and the plastic will remain as it is or it is converted into other forms (Shahnawaz et al., 2019). Plastic solid waste treatment and recycling can be separated into four major categories, primary (re-extrusion), secondary (mechanical), tertiary (chemical) and quaternary (energy recovery). Mechanical recycling is currently the most common method used to recycle plastic waste (Ragaert et al., 2017). The mechanical recycling of plastic waste consists of remelting the material, either alone or in admixture with raw material, to produce granules or finished marketable products, such as bottles (Payne et al., 2019). Chemical recycling is used to describe chemical processes which depolymerase and degrade plastic waste into monomeric units or directly into other useful materials (Lamberti et al., 2020).

Energy recovery involves complete or partial oxidation of the material (Troitsch, 1990), producing heat, power and/or gaseous fuels, oils and chars besides by-products that must be disposed of, such as ash. Plastic waste is considered a good fuel source because they have a heating value almost equivalent to that of the coal (Lawler et al., 2015). In the application of incineration, plastic solid waste can be reduced in volume by 90–99%, greatly reducing the strain on landfill (Lawler et al., 2012). If in plastic incineration the temperature is lower than 800 °C, the value required to completely burn off these wastes, this burning can produce a great number of dioxins. (Kamaruddin et al., 2017).

Lastly, the landfill disposal is seen as the last option for managing both hazardous and nonhazardous solid waste (Horodytska et al., 2019; Butti et al., 2018). Landfilling of plastic waste is considered the least preferable method because it requires a large space, reducing the landfill lifespan and causes persistent pollution complications. (Kamaruddin et al., 2017). As the putrescible organics decay with time, the proportion of plastic waste increases since plastics do not decompose and thus their proportion of the total waste increases with time. After complete decomposition the waste body will be mainly plastics and inert materials which has implications for landfill mining (Owusu-Nimo et al., 2019).

2.13 OVERALL SUMMARY

Presented in this comprehensive literature review, lake water quality has been increasingly deteriorating by human-made actions and/or climate change scenarios which subsequently cause eutrophication cases to intensify worldwide. Several methods are being suggested for the possible attenuation or remediation of this issue. However, most of these intricate techniques are chosen haphazardly and implemented by companies focusing on making profits affecting, even more, the environment, in which they are applied. Following sustainable thinking, more precisely the 3 SDGs deeply related to water remediation (i.e., SDG 6 clean water and sanitation, SDG 12 responsible consumption, and production, and SDG 14 life below water), a minimally invasive suspended solids removal technique, should guarantee the gradual reconstruction of the aquatic system in a sustainable way. Therefore, using the method presented in this thesis, geotextile filtration, it is hypothesized that by removing suspended solids, water deterioration will be reduced (i.e., most of the pollutants in the water are adsorbed onto the surface of suspended solids) and water quality parameters will be improved. Lastly, after remediation of lake water, wastes produced by this treatment need to be dealt with in a proper way. Possible routes were presented with a focus on strengthening the sustainability of the process and will be further highlighted, based on the circular economy.

CHAPTER 3. NOVEL SUSTAINABLE IN-SITU PILOT POLYPROPYLENE GEOTEXTILE FILTRATION METHOD FOR ECO-REMEDIATION OF EUTROPHIC LAKE WATER

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Abstract:

Climate change and human-made actions will exacerbate in the near future eutrophication cases on inland waters. By external or internal inputs, there will be an increase in nutrient concentration in those systems worldwide due to climate change extremes linked directly with environmental anthropogenic modifications. When excessive, those nutrients will bring faster trophic status changes to inland waters as lakes and possible cyanobacteria/cyanotoxin development followed by health, and recreational advisories. At this moment, diverse invasive technologies are applied worldwide for eutrophic lake water remediation, adversely affecting the lake biota in the water column and reducing its volume. A novel approach method for an effective, environmentally safe and economic eco-remediation technique using a floating filtration system, a silt curtain and geotextiles (woven and non-woven) as filter media. An in-situ water treatment methodology for the particulate nutrients and suspended solids removal is under study. This pilot *in-situ* experiment was deployed at Lake Caron, a shallow eutrophic lake located in the *Sainte-Anne-des-Lacs* municipality in Quebec. Turbidity, total suspended solids (TSS), total phosphorus (TP), blue-green-algae-phycocyanin (BGA-PC) and chlorophyll-a statistically significant average removal efficiencies were of 53%, 22%, 49%, 57% and 56%, respectively. Those removal trends prevented primary productivity, even considering the nutrients replenishment due to concentration gradient in natural systems. A strong statistically positive correlation was found with TSS and turbidity with variables that could represent particles (total phosphorus (TP), turbidity, chlorophyll-a). Using the management of surface water quality, in situ suspended particles and particulate phosphorus removal by geotextiles could be promising remediation for not only shallow lakes (average depth < 2m) but also for ponds, rivers, coastal regions, bays and other water types, to enable cleaner water for future generations.

Keywords: Eutrophication; Total Phosphorus Algae; Cyanobacteria; Suspended solids; Woven geotextile; Lake Water; Remediation; Surface Water

3.1 INTRODUCTION

Pressure on inland waters, more precisely on lakes, is expected to be increasing soon due to human-made actions and new climate change scenarios (LeMoal et al., 2019; Yindong et al., 2021 and Woolway & Merchant, 2019). Issues triggered by those new variables or mechanisms will age lakes more quickly and will bring potential recreational and drinking advisories due to high cyanobacteria productivity along with harmful toxin production (Freeman et al., 2020; Yindong et al., 2021 and Burford et al., 2020). Also, in some cases lake anoxia, lake volume reduction (Braga & Becker 2020) and lake browning (Hayden et al., 2019; Meyer-Jacob et al., 2019 and Kritzberg et al., 2020) will result.

Actual driving forces for this succession and eutrophication are expected to be exacerbated by extreme weather events (Paerl et al., 2019; Jeppesen et al., 2021) and actual consuming behaviours (Eimers et al., 2020). In other words, not only events like storms, record-breaking rainfall events, heat waves, prolonged droughts tropical cyclones and hydrological manipulation of waterbodies but also land-use changes, deforestation and fertilizer (over)use will probably produce more eutrophic waters than before.

Those processes will increase organic matter input from point and non-point sources within inland waters by catchment (e.g., watershed runoff after increased precipitation) (Sinha et al., 2017; Huo et al., 2019; Stockwell et al., 2020) and increase internal nutrient lake release due to lake warming (Yindong et al., 2020; Woolway & Merchant, 2019) bringing physical mixing of the water column and sediment resuspension. Higher organic matter presence due to degradation should be observed as well (Zhang et al., 2019b; Senar et al., 2021), and increased input by human activities (e.g., sewage discharge and fertilizer/detergent use) (Le Moal et al., 2019).

In the rising nutrient pool mentioned, within lake ecosystems, phosphorus is often the limiting nutrient related to trophic level changes and a determinant factor for eutrophication (Knoll et al., 2016; Kong et al., 2019). While nitrogen may be retained or lost to the atmosphere in gaseous forms by denitrification (e.g., N_2, NH_3, N_2O) in shallow lake systems, due to higher sediment area to water volume ratios (Paerl et al., 2020; Maberly et al., 2020).

Furthermore, within the lake water column, the phosphorus form found is of crucial importance. While phosphorus from catchments is partly in the particulate form that possibly settle in the water column and are only used by phytoplankton if released (Sandström et al., 2020; Zhang et al.,2019b), internal loads in lakes are predominantly in the dissolved form directly and bioavailable for algal/cyanobacteria growth (Bormans et al., 2015). As a result, it is compulsory to propose removal methods for external and internal phosphorus loads exacerbated in lakes due to climate change and human actions, a challenge to be achieved by nations by 2030 as described in SDG (Sustainable Development Goals) number 6 (i.e., clean water and sanitation) on of the UN (United Nations) agenda.

Numerous intrusive remediation methodologies are used for this removal such as hypolimnetic aeration (Niemistö et al., 2020; Ruuhijärvi et al., 2020), sediment dredging (Jing et al., 2019), lanthanum-modified bentonite addition (Spears et al., 2015; Waajen et al., 2017), cement addition (Liu et al., 2020), and aluminum addition (Huser et al., 2016; Agstam-Norlin et al., 2020). These remediation approaches can adversely affect the lake biota in the water column, and in some cases are very costly (Lürling et al., 2016) and also can reduce the lake volume, in the case of additives or sorbents and should not be used as in situ remedial options.

Consequently, in-lake non-invasive and sustainable remediation techniques need to be proposed. These in-situ methods should be effective, in reducing those nutrients, if possible, for the entire recreational season, environmentally safe, relatively easy to apply, and should not be too expensive (Lürling & Mucci, 2020). With this understanding, geotextiles have been employed as membranes for inland water remediation for particulate nutrient and suspended solids removal by filtration (Palakkeel et al., 2021; Pereira et al., 2020; Mulligan et al., 2009), indicating their strong potential as a flexible, potentially economically efficient and reactive environmental remediation that can be implanted at shallow lakes and other surface water types.

To this date there is no similar in-situ treatment being proposed for remediation of lake water. This in-situ pilot experiment can potentially be used for remediating the surface water quality of a shallow eutrophic lake, Lake Caron, study lake on this project. It uses custom-made woven and non-woven geotextiles as a filter media in an active floating filtration unit straightforwardly deployed inside a turbidity curtain enclosed area. By removing suspended solids, it is hypothesized an indirect reduction in nutrient availability. This will decrease in the lake system the eutrophication likelihood and will suppress algal/cyanobacteria blooms in an environmentally safe way. Thus, the main objectives of this study are to present the daily monitoring of lake water quality, over the 69-day experiment deployment, evaluate the effectiveness of geotextiles in-situ floating filtration unit, correlate variables for better remediation understand and to present the potential applicability and challenges for inland water Eco remediation.

3.2 MATERIALS AND METHODS

3.2.1 Study Area

The present study focused on improving the Lake Caron water quality (45°50'28″N; 74°08'50"W), a shallow eutrophic lake located in the *Sainte-Anne des-Lacs* municipality in Québec situated around 75 km north from downtown Montréal in the *Laurentian* Mountains. The lake is located in the *Lac Ouimet* watershed mainly occupied with wild trees and a few residents (Coutore et al., 2013), represented in a graphic map on Figure 3-1 with sampling stations and households.

Lake Caron has maximum, minimum and average depths of 2.6, 0.5 and 1.4 m, respectively and approximate surface area and water volume of 35,300 m^2 and 48,400 m^3 (ABVLacs Org. 2018). The average annual temperature of *Sainte-Anne des-Lacs* is 2.6 °C (- 20 – 24 °C), and the average annual precipitation is 1039.2 mm.

Figure 3-1: Lake Caron with sampling stations and households

This lake is an artificial and closed water body where the main sources of water renewal are precipitation, surface runoff and snow. Its renewal time is 0.86 years and flows to a large lake, *Lac Ouimet*. Lake Caron has exhibited floating algal/cyanobacteria biomass every summer since 2008, and it is currently with a swimming advisory. The Quebec *Réseau de surveillance volontaire des lacs* (RSVL) report (MELCC 2018) recommends adoption of measures to limit nutrient inputs for avoiding further degradation of and loss of uses.

Regarding phosphorus input in this lake, while external phosphorus loading on the lake is linked to possible septic tank discharges and decomposition of vegetation in the water. Internal loading is associated with past lake enlarging with incomplete tree cutting (i.e., stumps and roots remaining within the lake), and phosphorus sediment release. In some parts of the lake, sediment phosphorus concentrations varied between 908-1310 mg/kg (Palakkeel et. al. 2018).

3.2.2 Pilot In-situ Geotextile Filtration Setup

The pilot in-situ filtration deployment was based on two enclosed circular areas inside the lake, delimited with floating turbidity curtains (14.6 m x 1.2 m) (L x W), approximately with same diameter of 1.54 m (Figure 3-2 (a)). One of the enclosed areas was used for the experiment control and the other one was where the floating filtration unit was deployed. The location chosen near station 4, represented by St. D in Figure 3-1 due to the accumulation of cyanobacteria colonies in this area and easy access for sampling and maintenance.

Turbidity curtains were provided by Titan Environmental Containment Inc., to contain and control suspended solids including the algae/cyanobacteria and fine sediment particles within the enclosures. By employing enclosing areas, the project wanted to investigate how the presence of continuous geotextile filtration will modify the water quality parameters in this natural system.

The filtration unit was made of Plexiglas, Figure 3-2 (b) with possible details, an open square vessel, with a galvanized copper grid at the base to support the filters with dimensions of 30.5 x 30.5 x 20 cm (W x L x H). Additionally, a Plexiglas frame wall of 20 cm height which were fixed individually by clamps for preventing the filter membrane from moving while deployed. The material type and open unit style was chosen to provide easy filter media access as well as to follow the geotextile clogging status.

The whole unit was tied up and floated with the aid of an inflated synthetic rubber tube, Figure 3-2 (c) represents the in-situ deployment. Also, for water recirculation on the filters two submersible water pumps (DC 12V, 4.8 W) having flow rates of 240 L/h were used for pumping. The nearest outlet present provided electrical supply. Additionally, a plastic prefilter was used to guarantee that the pumped water was uniformly distributed in the geotextile. All treated water was returned to the enclosed area and the filtration unit was able to move freely inside the contained water.

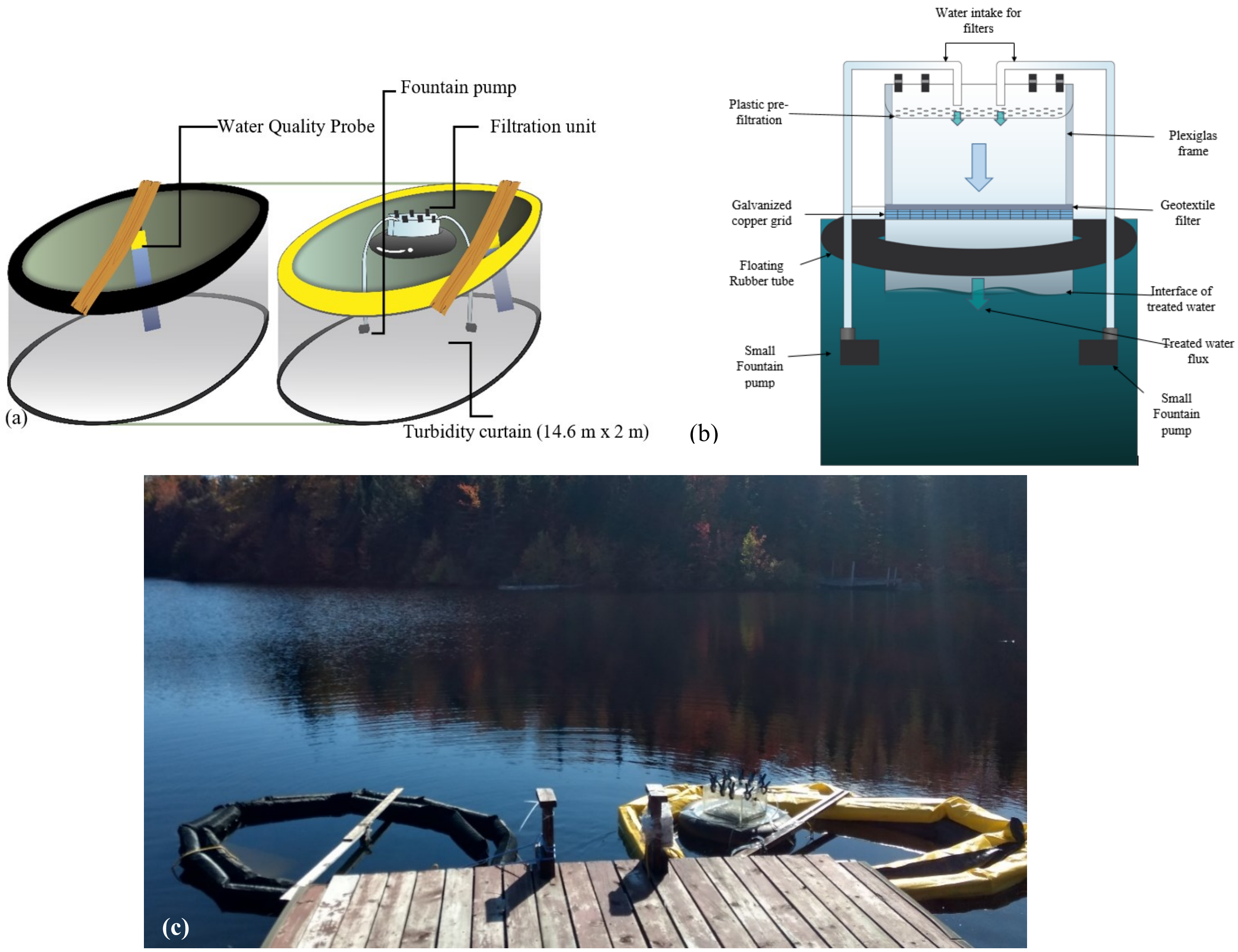

Figure 3-2: (a) In-situ filtration setup (b) Schematic of floating filtration unit (c) Actual in-situ deployment.

3.2.3 Filter Media

One non-woven (TE-GTT170) and one woven (TE-GMW35) custom-made geotextile filters were developed and received from Titan Environmental Containment Ltd., MB to be employed as a filtration media in this in-situ lake remediation project, for suspended particle and nutrient removal. In addition, those geotextiles were combined with a commercial mesh (CM) used as prefiltration layer. In Table 3-1, geotextile physical characteristics (based on the datasheets obtained from Titan Environmental Containment Ltd.) and CM are detailed.

Table 3.1: Woven and non-woven geotextile characteristics used in this study

Filters	Material	Apparent Opening Size (AOS) (µm)	Flow rate (L/m^2/min)	Permittivity (sec^{-1})	Mass per unit area (g/m^2)
Commercial Mesh	-	900-450 µm	-	1.62	180
TE-GMW35	[a]PP	425 µm	2039	0.70	
TE-GTT170	[a]PP	350 µm	4800	-	350

[a]PP: Polypropylene

TE-GTT170 is a nonwoven black geotextile filter made in 100% virgin staple, UV resistance, and thermally bonded polypropylene (PP) fibers with 350 µm apparent opening size (AOS). The TE-GMW35 (AOS: 425 µm) is a multifilament woven geotextile gray/black colour, made in 100% virgin high tenacity polypropylene fibers with UV resistance and resistant to biological degradation. Those geotextiles were dimensionally stable fabric highly flexible and outstanding material for use a filtration membrane. Lastly, the CM is composed of PP was only employed as a layer for removing large material present in the water that is not suspended solids and can affect the geotextile filtration performance.

For filtration experiment, geotextiles and CM was cut to a 30 cm square and arranged in descending order of their AOS with combinations, when necessary, Figure 3-3 presents the woven and nonwoven geotextiles before the filtration process. Filter selection and combination were based on the previous on-site experiment during 2017-2018 and the particle size distribution in the contained filter area. The combination proposed were 1 layer of the CM, 4-5 layers of TE-GMW35 with the addition of one TE-GTT170 when found needed. The set of filter layers was entirely changed every week or when clogged, whichever occurred first. Also, these filter combinations mentioned, from 5 to 7 layers, were used throughout the entire experiment.

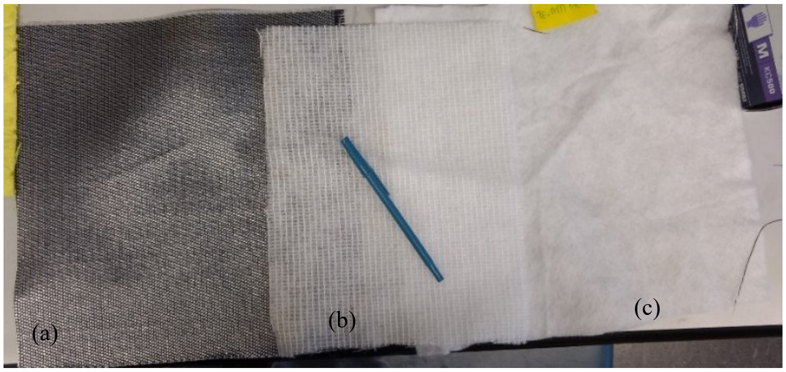

Figure 3-3: Geotextiles and mesh used in the experiment: (a) woven geotextile TE-GMW35 – AOS: 425µm (b) CM and (c) non-woven geotextile TE-GTT170 – AOS: 350 µm before the filtration process

3.2.4 Field Sampling and Experiment Sampling

Field sampling was performed throughout the entire lake at selected stations (St. S, St. 1, St. 4, St.7, St.8 and St.9) over the 2019 summer/fall to access the water quality of this shallow eutrophic lake water. In addition, during the filtration experiment deployment, water samples were collected from each contained area, each 2-3 days, for capturing the variations in the water quality. Water samples in this project were collected in 50 ml sterilized polypropylene test tubes (chemical analysis) and previously cleaned 1L high-density polyethylene (HDPE) amber bottles (physical analysis). Both of them were stored at 4°C in the dark before any physical-chemical analysis and they were performed within 48h.

3.2.5 Water Quality Analysis

Water samples were analyzed for the following parameters: particle size analysis (PSA), total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), nitrate (NO_3^-), chemical oxygen demand (COD), pH, dissolved oxygen (DO), temperature (Temp.), oxidation-reduction potential (ORP), conductivity, turbidity, total dissolved solids (TDS), chlorophyll a (Chl.a) and blue-green algae-phycocyanin (BGA-PC).

Test kits from Hach Chemicals were used for accessing TP (Method 10209 - SM 4500-PE - Ascorbic Acid Method), TN (TNT 826, Method 10208, persulfate digestion), NO_3^- (TNT 835, Method 10206, dimethyl phenol method) and COD (TNT 820, Method 10221, reactor digestion method). In triplicate with a blank and two standards (within the lake water concentration) for each chemical analysis run to maintain results reproducibly. For those parameters analyses except for nitrate, which did not require heat digestion, water samples were first acid digested with its proper detailed method on a Hach DRB 200 heating block and after cooling down measured in a Hach DR 2800 UV–Vis spectrophotometer.

For measurements of pH, dissolved oxygen (DO), temperature (Temp.), oxidation-reduction potential (ORP), conductivity, turbidity, total dissolved solids (TDS), chlorophyll-a (Chl.a) and blue-green algae-phycocyanin (BGA-PC) during the whole experiment two YSI-EXO$_2^{\text{TM}}$ multiparameter probes were deployed in each contained area for hourly measurements. Probes were checked every week for data backup, battery life, and sensors performance and calibration. Equipment long-term monitoring ensured by automatic antifouling wiper activation 10 min before each hourly sampling.

To evaluate the concentration of the suspended particles in the lake water APHA 2540 D method was used. Additionally, the particle size analysis (PSA) was measured using a laser diffraction particle analyzer (LA-960 Horiba laser particle size analyzer) on lake water samples.

3.2.6 Data Analysis

All study variables were analyzed for descriptive statistics including means, medians, variances, maxima, minima, standard deviations, standard errors, and confidence intervals. After, to verify the existence of any outliers each variable was subsequently assessed. Data are represented as the means ± confidence interval in the text.

To corroborate if there were statistically significant differences between water quality variables with filter presence and absence in the lake enclosed areas, the parametric test Student's mean t-test ($p < 0.05$) was used for normally distributed variables and the equivalent paired nonparametric test: Wilcoxon matched-pairs signed-ranks test ($p < 0.05$) for not normally distributed variables. While the Student's t-test has the null hypothesis: water quality variable means with the presence and absence of the filter are statistically equal to the Wilcoxon matched-pairs signed-ranks test ($p < 0.05$). It has a null hypothesis if the water quality variables medians with the presence and absence of the filter are equal.

As requirements for the T-student parametric test were violated (normality by the Shapiro-Wilk test ($P < 0.05$) and homoscedasticity by Levene's test ($P < 0.05$)), for the following water quality variables PSA (i.e., D10, D50, D90), TP, TN, TSS, pH, DO, Temp., ORP, Conductivity, Turbidity, Chl. A, BGA-PC from day 0 until day 69 in the enclosure experiment, on those the equivalent paired nonparametric test, Wilcoxon matched-pairs signed-ranks test, were employed. In contrast, the T-student parametric test was applied for the variables nitrate and COD, which had normality and homoscedasticity.

Lastly, for the relationship verification between study variables, a correlation analysis was performed using Spearman's non-parametric test ($p < 0.05$). For this specific data representation, a heat map was used.

3.3 RESULTS AND DISCUSSION

3.3.1 Lake Water Quality

Lake Caron is a mesoeutrophic lake in the middle range (20-30 µg/L) in accordance with MELCC (2018) going towards the high range (i.e., eutrophic classification) in a possible near future. The phosphorus concentration in this lake is around 26 ± 1.6 µg/L with a maximum peak of 33 µg/L presented in the summer. Overall results are presented in Table 3-2.

With a light brownish colour and mud odour, the amount of dissolved carbon substances fluorescent organic matter (FDOM) and total dissolved solids (TDS) within this lake is an indication that some biological degradation is still occurring. It is possible that the tree roots remaining there as well as dead algae/cyanobacteria from past blooms are further contributing to its ageing. This is also significant for Chemical Oxygen Demand (COD) as is assumed to be mainly due to the dissolved organics present in this lake. In contrast, this water is well oxygenated throughout the summer-mid fall with a pH within the range for protecting aquatic life (USEPA, 2006) and positive ORP indicating an oxidizing environment.

Table 3.2: Lake Caron water quality during July-Sep., 2019

Parameters^a	2019
TP (µg/L)	26.0 ± 1.6
COD (mg/L)	23.6 ± 0.2
NO_3^- (mg/L)	0.20 ± 0.02
TN (mg/L)	0.81 ± 0.09
TSS (mg/L)	3.5 ± 0.5
D50 (µm)	63.74 ± 6.92
D90 (µm)	154.16 ± 12.45

YSI-EXO^{2}™ Probe data[b]	
Temp (°C)	19.7 ± 0.42
Conductivity (µS/cm)	23.0 ± 0.67
TDS (mg/L)	14.8 ± 0.43
DO (mg/L)	10.2 ± 0.04
pH	6.8 ± 0.02
Turbidity (FNU)	5.82 ± 3.37
ORP (mV)	+113.89 ± 13.17
FDOM (QSU or µg/L)	38.23 ± 1.35
Chlorophyll (µg/L)	7.32 ± 0.56
BGA – PC (µg/L)	0.49 ± 0.05

[a] Average of 7 samplings of 5 lake stations

[b] Average of 3 samplings of 5 lake stations

The turbidity presented in this lake, which is around 5.82 ± 3.37 FNU is composed of particles with sizes of 50% (D50) and 90% (D90) suspended solids (SS) under < 63.74 ± 6.92 µm ± and < 154.16 ± 12.45 µm. This TSS concentration is increasingly affecting the transparency of this lake and is composed mainly of very fine sediments with particulate nutrients, and some disperse algae/cyanobacteria in the water column, two contributions to phosphorus internal load. When related to algae/cyanobacteria they are dispersed and tend occasionally to concentrate in large colonies near the lakeshore due to wind action.

TN concentrations and nitrate are under Quebec guidelines (i.e., MDDEP, 2012) for protecting aquatic life, which are 1.0 mg/L and 2.9 mg/L, respectively. Concentrations of heavy metals in the lake water (dissolved) and surface sediments are below the norm set for the protection of freshwater aquatic organisms in Quebec and Canada.

3.3.2 Filtration In situ Experiment

The in-situ experiment in this project filtered lake water, approximately 2.61 m^3, continuously within the enclosed area for 69 days from August 14 to October 22 of 2019 shortly after the start of summer until the mid-fall season. The system ran smoothly without any interruption during the proposed timeframe even though the project is located inside a natural system.

The experimental system checks of this proposed method (i.e., on daily basis) show the adaptability and reactivity of the filtration process and geotextile membranes to filter lake water in long-term projects. This was achieved by acclimating to quick water quality changes preventing increase in primary productivity. In lakes, nutrients can be constantly replenished into the overlying water from bottom sediments by the concentration gradient and sediment resuspension (Palakkeel et al., 2021; Zhang et al., 2018a). Even with those mechanisms, the system was able to maintain its removal rate throughout the whole deployment. In the control-enclosed area, reported visible cyanobacteria colonies accumulation of possible *Woronichinia naegeliana sp*. occurred as can be seen in Figure 3-4, which was suppressed in the filtration area. Those are the cyanobacteria predominant species existing in this lake (Palakkeel et al., 2021).

Figure 3-4: Reported visible cyanobacteria colony accumulation in the control enclosed area

With approximately 7-8 days of filtering before changing the layers, the previously mentioned combination of 1-2 layers of the CM, 4-5 layers of TE-GMW35 with the addition of one TE-GTT170 when necessary were used. The entire deployment used 67 filter layers of TE-GMW35, 8 layers of TE- GTT 170 and 14 CM, totalling approximately 6.03 m^2, 0.72 m^2 and 1.26 m^2 for each AOS, respectively. The in-situ experimental cost related to only geotextile membranes (i.e., not including the CM) was $5.05 for treating 2.61 m^3 of lake water. Figure 3-5 presents one set of used geotextile filters after 1 week of lake water filtration throughout the experiments. Cake layer formation was observed on the geotextile top layer due to initial ripening that happened approximately 2 hours after changing the filters. The layer formed by particle accumulation decreases the AOS on those geotextiles, permitting the filtration mechanism to be employed not only by the straining filtration but also depth filtration.

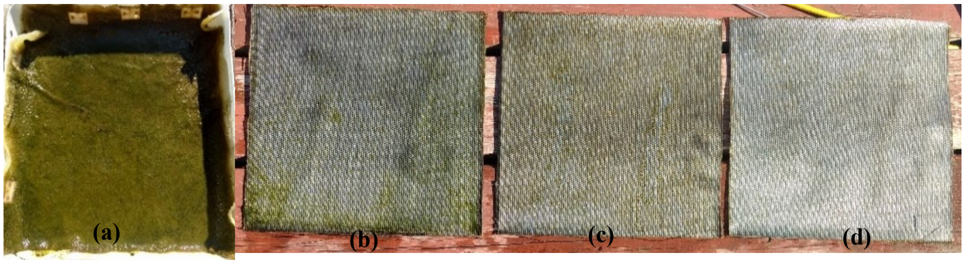

Figure 3-5:Woven geotextile after one week of filtration process for AOS order: (a) CM layer (b) TE-GMW35 first layer (c) TE-GMW35 second layer (d) TE-GMW35 third layer

3.3.3 Particle Removal and Size Reduction

By using this in-situ filtration experiment, it was hypothesized that the removal of suspended particles should be the first and most important, as it is the main application of any filtration system. This hypothesis was shown, by the efficiency and ability of this eco-remediation method for long-term project applications. In the deployment, there was a constant and representative removal of total suspended solids (SS) as the filter unit quickly adapted to changes in this natural system.

Statistically significant SS removal ($p < 0.01$) was observed in this project with an average value of 53%. After the fourth day of filtration, the removal trend was maintained in the experiment keeping the filter always below the control system as shown in Figure 3-6. By the end of the experiment, the control enclosed area has an average SS concentration of 3.7 ± 0.45 mg/L and the filter enclosed area had 1.7 ± 0.51 mg/L.

Even though the project only interrupts the SS content in the water column (i.e., using the silt curtain), within the natural system possible interaction of water and sediment as well as the curtain with the sediments have occurred, replenishing the SS into the overlying water from bottom sediments. In contrast, the floating filtration unit was able to quickly respond and maintain cleaning of the lake water. Additionally, by removing those SS particles present in the lake due to external or internal loads, there was the prevention of a possible future settling which can directly affect the nutrient and contaminates within the lake sediment.

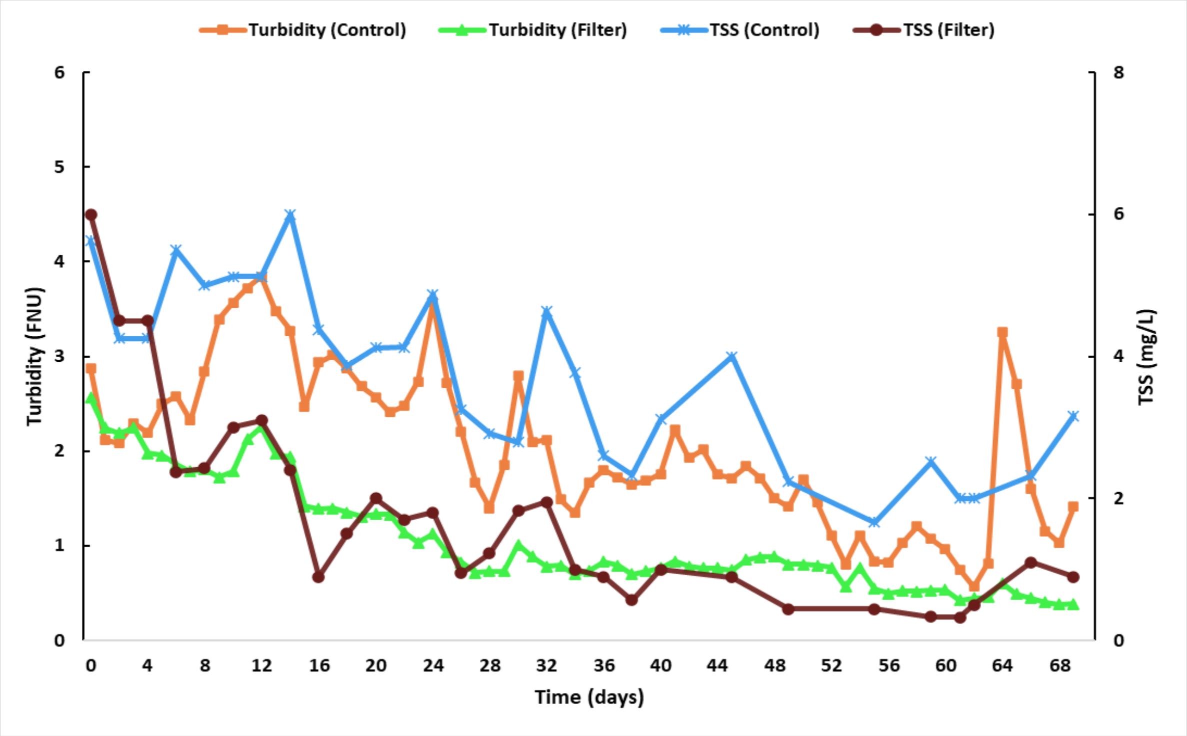

Figure 3-6: Turbidity (FNU) and suspended solids concentrations (mg/L) for the in-situ experiment

Following the SS removal in the filtration enclosed area; there was also turbidity reduction as presented in Figure 3-6. The floating filtration unit was able to maintain an average removal of 49%, statistically positive significant ($p< 0.01$) decreasing, even more, the low turbidity of the lake. There was also a strong correlation between those two variables ($R^2 = 0.833$, p-value < 0.01). Instead, in the control area, a tendency of constant increases in the SS concentration and turbidity was captured. This was possibly caused by the reported visible algae/cyanobacteria colony accumulation in this area, to which decrease when the water temperature starts to drop due to degradation and settling. However, in the filtration-enclosed area, values went below 1 FNU shortly after the middle of the experiment was reached. This has shown the geotextile membrane filtration effectiveness at this lake water. The average values present in each enclosed area were 2.02 ± 0.05 FNU in the control area and 1.04 ±0.03 FNU in the filter area.

With the SS and turbidity removal, a reduction in the particle size was also assessed in the filtration enclosed area as statistically significant (Figure 3-7). While in the filter enclosed area average values showed 50% (D50) and 90% (D90) of SS were < 28.40 ± 4.87 µm and < 77.94 ± 10.12 µm, the control area values were < 36.45 ± 4.71 µm and < 154.07 ± 9.33 µm respectively.

There was also a statistically significant positive correlation between D90 size reduction and turbidity on the filtration enclosed area ($R^2 = 0.8543$, p-value < 0.01). The reduction showed that particles between these D90 (i.e., 77.94 ± 10.12 μm > D90 >154.07 ± 9.33 μm) were the ones addressed by the geomembranes and possibly the ones with particulate contaminants and nutrients associated with them, as further evaluated. Particles below the D90 of the filter enclosed area (D90 < 77.94 ± 10.12 μm) were not removed by the geotextile combination chosen. For future applications of this eco-remediation in other water types, SS sizes and compositions present in the water (i.e., sizes of contaminated SS and sizes harmful algae/cyanobacteria) can be focused onto address custom-made geotextiles (defined by AOS) to use.

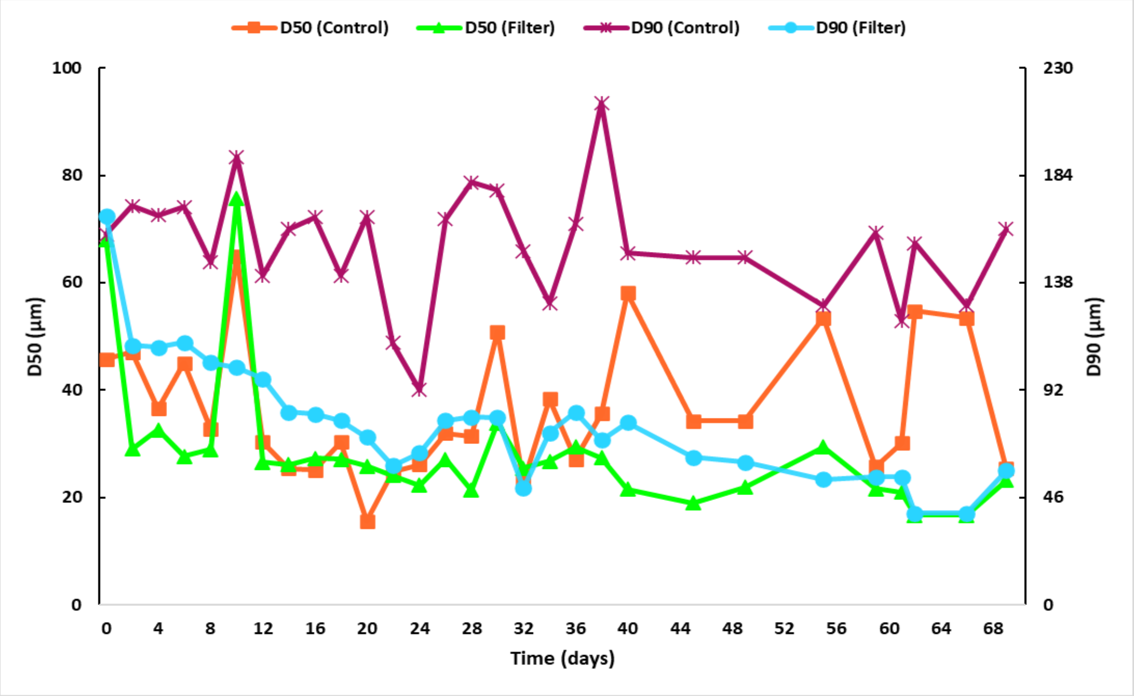

Figure 3-7: D50 (μm) and D90 (μm) for the in-situ experiment

3.3.4 Nutrient and Organic Matter Removal

The removal and size decrease of suspended particles affected the nutrients and organic matter (OM) concentration on the enclosed filtration area, which was the project hypothesis. Most precisely particulate phosphorus and some particulate COD removal on the system was continually achieved by recirculating water on the floating filtration unit through the summer and mid-fall. A good positive correlation between turbidity and total phosphorus removal was found ($R^2 = 0.6240$, p-value < 0.01) in the system as well as COD and turbidity ($R^2 = 0.6960$, p-value < 0.01).

The TP removal was statistically representative ($p < 0.01$) with a 22% average removal shown in Figure 3-8. The water that was near to the limit of being considered eutrophic water (average concentration on the control enclosed area 29.0 ± 1.5 µg/L) was reduced to the limit of mesoeutrophic going towards the mesotrophic (filter enclosed area 22.7 ± 1.4 µg/L). By regulating primary production, the limiting nutrient for this lake was considered phosphorus, which was reduced by this geotextile membrane filtration. The maximum value reported in the control area was 37.0 ± 1.5 µg/L.

In contrast, throughout the experiments, no significant statistical change in the concentrations of TN and nitrate was observed, as they were mainly (>80%) in their dissolved forms. Lake water was already within the Quebec regulated guidelines for those parameters and the average value for both enclosed areas was kept below the values presented. For TN concentrations the values were 1.03 ± 0.06 and 1.08 ± 0.06 mg/L, in the control and filter enclosed area, respectively. In relation with nitrate, the average levels were of 0.236 ± 0.02 mg/L in the control area and 0.234 ± 0.02 mg/L in the filter area.

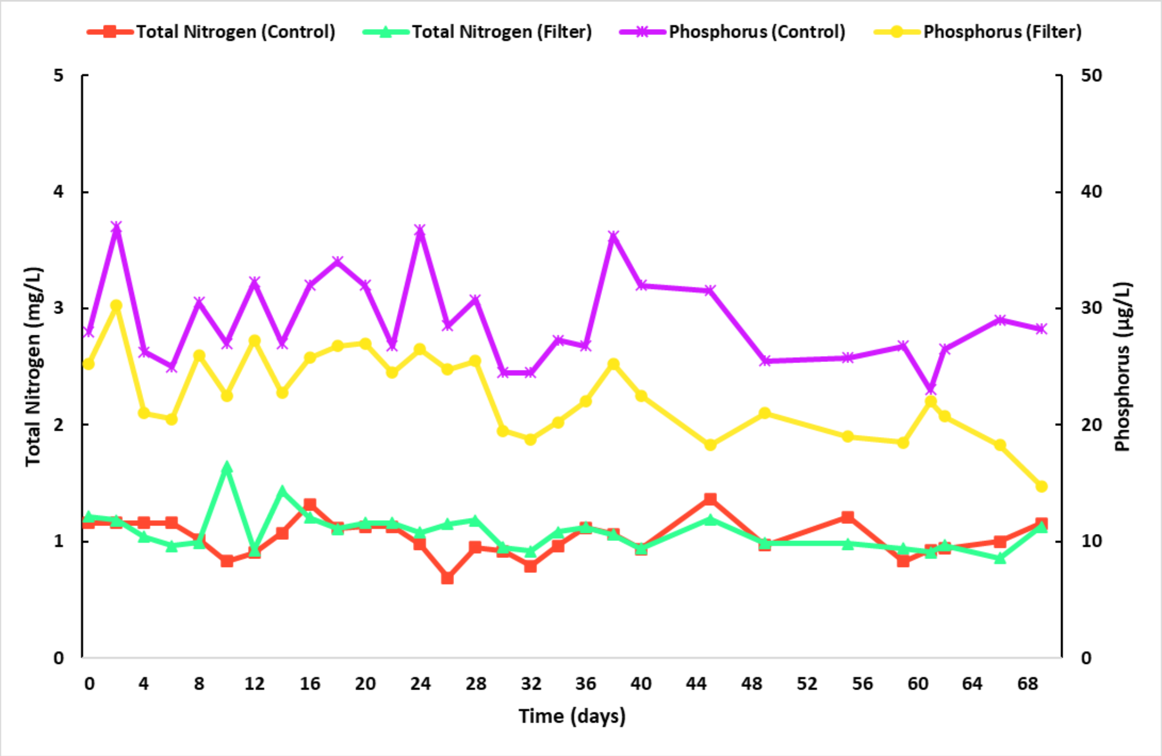

Figure 3-8: TP concentrations (µg/L) and TN concentrations (mg/L) for the in-situ experiment

For the removal of organic matter, it is necessary to explain the trends of other system parameters that can affect the concentration of organic matter being dissolved or particulate. Those variables that will be assessed are pH, conductivity, water temperature and DO.

Strong statistical positive correlated parameters, conductivity and water temperature presented similar behaviour ($R^2 = 0.997$, $p\text{-value} < 0.01$) denoted in Figure 3-9. On the whole deployment, there was no significant difference in those parameters between the two enclosed areas. The average values presented was 16.3 ± 0.27 °C and 21.24 ± 0.16 µS/cm. The maximum water temperature on the experiment was reached on the first days of the experiment when its value has reached 21.8 °C, which has stimulated primary productivity. After the middle of the experiment, the water temperature started to decrease, as the summer season was close to the end, and the trend on conductivity followed the same path, as the quantity of salts dissolved in the water decreased.

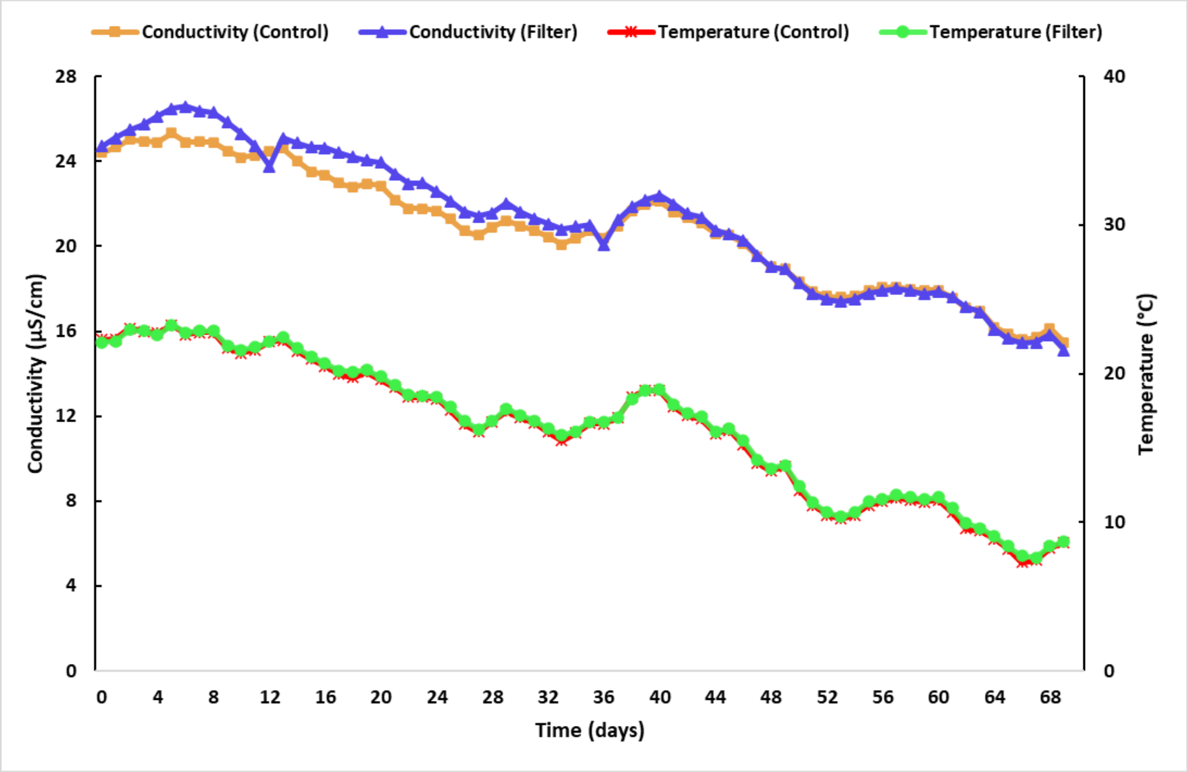

Figure 3-9: Conductivity concentrations (µS/cm) and water temperature (°C) for the in-situ experiment

The average pH in the enclosed areas was 6.73 ± 0.01 in the control and 6.51 ± 0.01 in the filter area, which is in recommended range (pH 6.5–9) as shown in Figure 3-10, for protecting aquatic organisms in surface water in Canada by CCME (2008). Slight modifications in the control area pH could be associated with cyanobacteria existence (Lürling et al., 2016) within this area. When related to dissolved oxygen, it was characterized by a short increase, after the water temperature drop, at the middle of the experiment. Temperature is inversely correlate with the dissolved oxygen (DO), in other words, when the temperature is lower a higher amount of oxygen can be dissolved in the water. Those variables were statistically negatively (R2 = -0.9755, p-value < 0.01) correlated. In addition, a trend of higher DO was observed in the enclosed filter area (10.53 ± 0.07 mg/L) compared to the control area (10.08 ± 0.06 mg/L). This was associated the continuous mixing by the pump intake and treated water return to the lake, which can input some oxygen in the water.

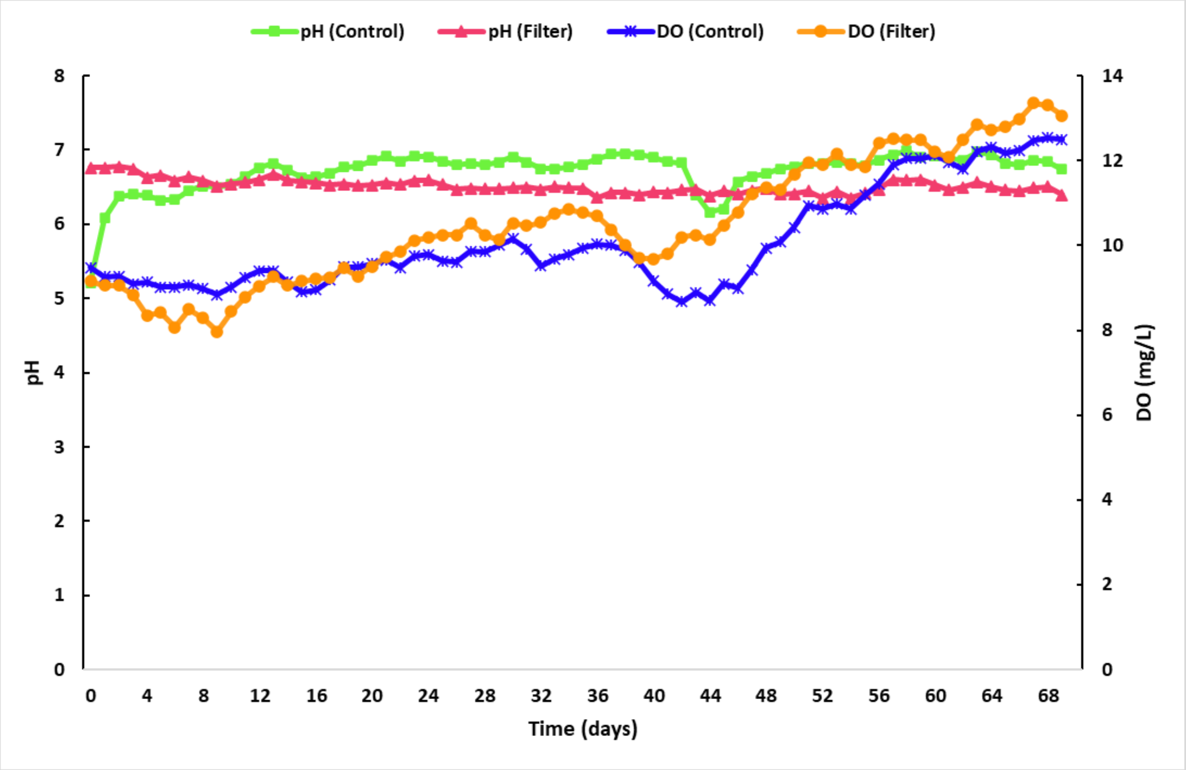

Figure 3-10: pH and dissolved oxygen concentrations (mg/L) for the in-situ experiment

Particle removal did not strongly affect the organic matter concentration in the system as previously explained; the majority of them is assumed to be mainly due to the dissolved organics present in this lake. For COD removal, some removal in this experiment could be associated with

COD particulate removal by the geotextile membranes or some dissolved COD removal by filter cake layer formed in about 2 hours after layer changes (i.e., filter ripening), and kept for at least 7 days before changes. Those mechanisms preserve the enclosed filter area below the control.

Sufficient oxygen was present in the system due to water mixing in the filter area unit. This has allowed continuous dissolved substance oxidation even though this did not allow any further increase in the lake's entire system as shown in Figure 3-11. Different behaviour was observed in the control unit area, which constantly increased, even after the experiment middle when the temperature dropped and DO increased. At that time cyanobacteria colonies started to perish, settling at the bottom and started decomposing (i.e., releasing dissolved organic matter and algae/cyanobacteria-sourced nutrients) in the water. As there was not any removal, this should explain the increase by the end of the experiment. This trend corroborates the nonexistence of algae/cyanobacteria in the filter-enclosed area. Average values on the experiment for FDOM and COD were 38.42 ±0.09 QSU (quinine sulphate units) and 24.24 ±0.59 mg/L for the filter and 43.93 ± 0.13 QSU and 26.10 ± 0.63 mg/L for the control, respectively.

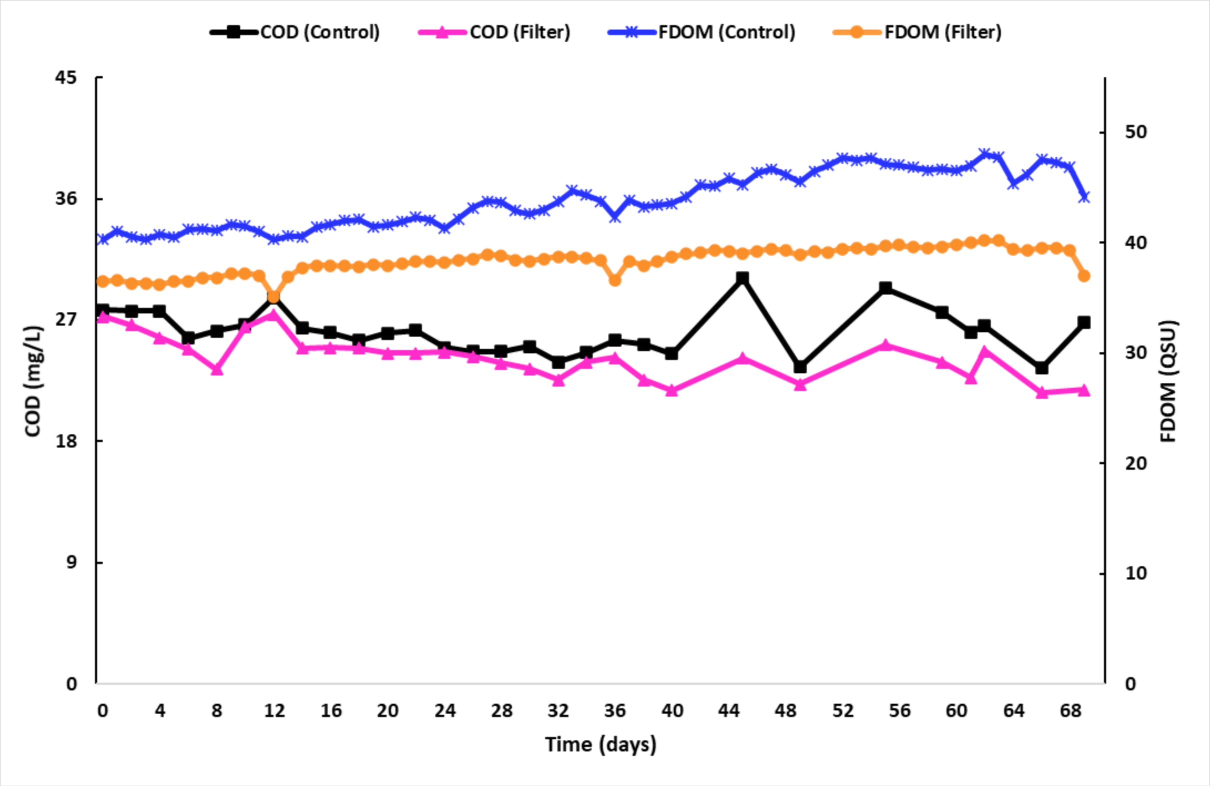

Figure 3-11: COD concentrations (mg/L) and FDOM concentrations (QSU) for the in-situ experiment

3.3.5 Algae/Cyanobacteria Removal

By removing particles, decreasing their size, addressing particulate nutrients prevent them to settle and possibly being available in the water column for easy uptake by harmful plankton the geotextiles were effective. The floating filtration in-situ unit was able to maintain a nutrient removal trend, even though it has been constantly replenished within the natural system. It suppressed any algae/cyanobacteria development, as presented in Figure 3-12. Some days after the middle of the experiment when the water temperature started to drop, an insurgence of chlorophyll-a followed by an increase in BGA in the control area could be observed. This could be explained that as the water temperature decreased some algae/cyanobacteria who were not acclimated with this condition have deceased and the ones that remained needed to adapt to the new conditions.

The average values for chlorophyll-a were 7.30 ± 0.09 μg/L for the control enclosed area and 3.13 ± 0.08 μg/L for the filter area, which represents a statistically significant removal of 57% ($p < 0.01$). As visible algae/cyanobacteria formation was not observed in the filter area, similar removal trends in the deployment for TSS, turbidity and particulate TP. All of them were found to be statistically correlated with chlorophyll-a and explained the absence of primary productivity. For BGA removal, which was 56% ($p < 0.01$) in the system, explained directly the cyanobacteria development, which was observed on the control but not in the filter area, as shown in Figure 3-12. The average values for BGA were 0.51 ± 0.01 μg/L for the control enclosed area and 0.23 ± 0.01 μg/L for the filter area. This is the final corroboration of this in-situ geotextile filtration as a flexible, potentially economically efficient, reactive and environmentally safe remediation in preventing algae/cyanobacteria formation for an entire season.

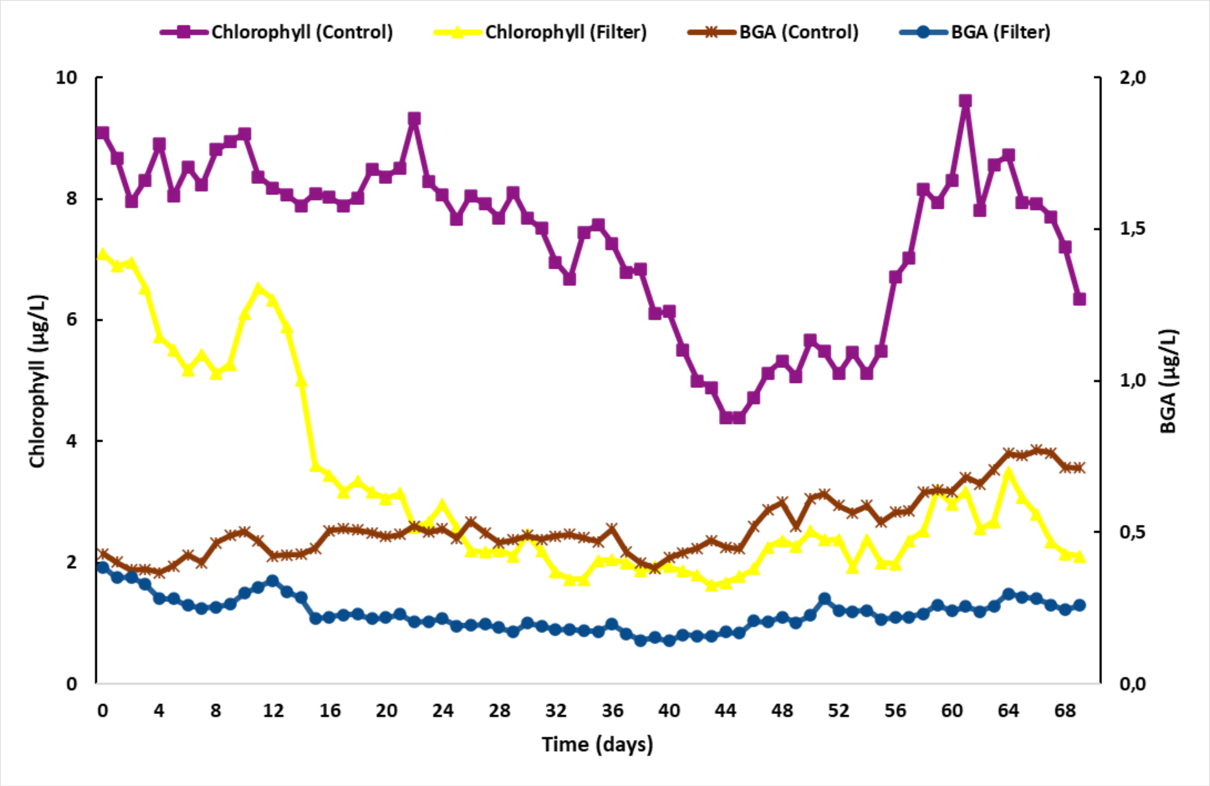

Figure 3-12: Chlorophyll-a (µg/L) and BGA-PC concentrations (µg/L) for the in-situ experiment

3.3.6 Spearman Correlations on the Experiment

The correlation analysis using Spearman's non-parametric test ($p < 0.05$) was chosen in a way to represent any monotonic relationship between two variables in the treatment proposed. In other words, the matrix presented variables that change with the same compartment but not necessarily at a constant linear rate. This relationship was used to assess how the filter enclosed area variables affect each other in this work. Spearman variables correlation matrix was represented with a heat map, in Figure 3-13, where not statistically significant correlations ($p < 0.01$) are crossed out.

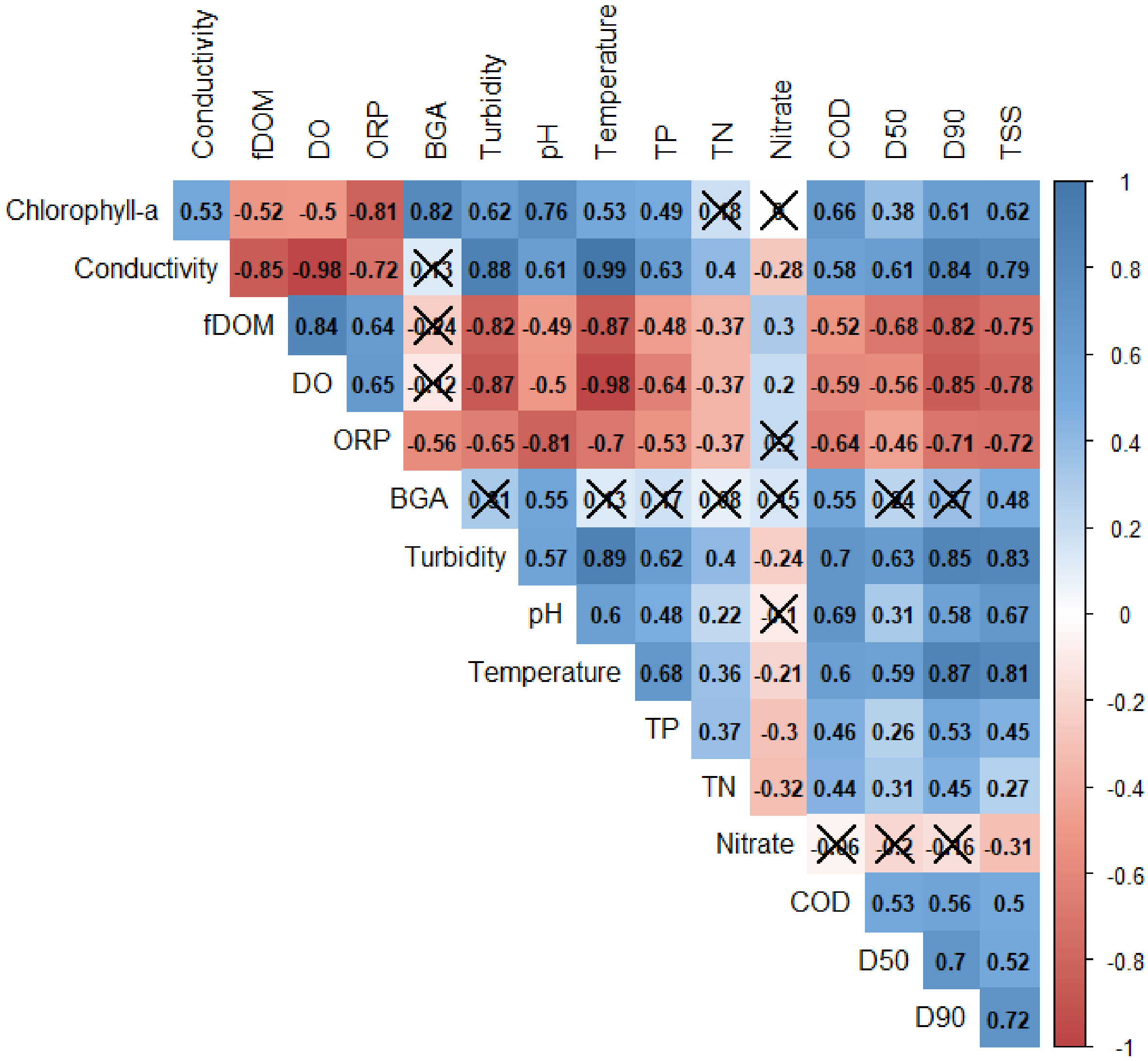

Figure 3-13: Heat map representation of the Spearman correlation matrix on all variables, not statically significantly correlation ($p > 0.01$) is crossed out.

Turbidity and TSS present excellent positive correlations with important variables of the filtration process intended to represent particle removal: D90, D50, TP, COD and Chlorophyll-a. In other words, all variables that could characterize particles in some way present a good and excellent correlation between them. This validates the in-situ geotextile process applied in which the removal of particles is responsible for the absence of algae/cyanobacteria, reduction of phosphorus levels and decrease of particle sizes.

Well known correlations in lake water were also presented in this study being conductivity and DO, conductivity and temperature, temperature and DO. Also, the water temperature was strongly correlated with SS and turbidity behaviour in this process. This could be explained as particles absorb more heat if there is an increase in this variable due to lake mixing or other mechanisms water temperature will rise, which will cause a reduction on the DO concentration.

Negative relations were also presented in the system; one of the most representative was DO and Turbidity and TSS and DO. To better explain, as there are more particles in the water DO has decreased, as the dissolved oxygen was used in others processes in the natural system. The inverse was also true in this process when the removal of these particles, the main objective of the applied process, was to increase the dissolved oxygen content.

3.3.7 Possibly Applications and Challenges

By this effective, environmentally safe and economic in-situ eco-remediation method other water types can be easily remediated with few steps. With the previous assessment of particle size, nutrient spatial distribution and nutrient concentration within them, turbidity curtains can separate highly contaminated areas, most of the cases are located near to shore were due to the wind action. Geotextile filtration as presented that can remove and prevent any health, and recreational advisories for the specific confined areas throughout entire seasons where primary productivity is higher.

Not only shallow lakes (average depth < 2m) can be focused on but also ponds, river sections, coastal regions and bays that have similar issues. As the filtration unit is easy to operate and maintain, the deployed system did not need a highly technician-trained person, which is a plus. Also, possible pre-filtration (with higher pore sizes) for any large debris removal is recommended before application of the water in the geotextiles, to prevent rapid clogging.

Operational costs of this method are associated with electricity for continuous pumping, which is about 68% of the total value. It is recommended for any future applications the use alternative energy sources as renewable ones (i.e., solar or wind energy), depending on the installed location.

Further investigations and development possibly addressed in near future will be the following: increased the enclosed area for the proposed treatment, application of other geotextile AOS sizes, geotextile layers reuse after high-pressure washing and natural drying, and uptake of dissolved organic matter by microorganisms using ceramsite (i.e., porous clay particles produced with by pelletizing and sintering) as support media combined with filtration. Lastly, related to the captured sediment, in-situ dewatering of the SS captured by evaporation followed by assessment for direct application or final disposal.

3.4 CONCLUSIONS

The in-situ experiment showed that geotextile filtration is an effective, environmentally safe and economic method for which SS and particulate nutrients can be reduced and algae and cyanobacteria development suppressed in an entire recreational season in lake water. The geotextile filter combination used allowed TP, TSS, turbidity and reduced particle sizes directly affecting the chlorophyll-a and BGA concentrations (i.e., primary productivity) on the system. Even though with constant nutrient replenishment into the overlying water, removal trends were maintained showing the adaptability of the applied methodology. Preventing particles from settling which could be possibly include harmful plankton, is strongly statistically positively correlated with TSS and turbidity, variables that represent particles in the system (total phosphorus (TP), turbidity, chlorophyll-a). The lake water was decreased to the limit of mesoeutrophic going towards the mesotrophic state with this filtration process. For future work, attention will be made to the clogged geotextile filter reuse by simple washing, dissolved COD uptake in the lake water and captured sediment dewatering and final disposal. Possible larger in-situ filtration pilot experiments will be assessed in this project.

AUTHOR CONTRIBUTION

Antonio Cavalcante Pereira: Conceptualization, Methodology, Investigation, Writing – original draft, Dileep Palakkeel Veetil: Methodology, Investigation, Catherine Mulligan: Supervision, Methodology, Writing -Reviewing and Editing, Funding acquisition, Sam Bhat: Provision, Methodology

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CHAPTER 4. IN-SITU WOVEN POLYPROPYLENE GEOTEXTILE FILTRATION FOR ECO-REMEDIATION OF EUTROPHIC LAKE WATER: FOLLOW UP STUDY AT LAKE CARON, QUEBEC

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Abstract:

Human interactions synergically associated with climate change scenarios within inland waters are dated to augment eutrophication cases worldwide. Eutrophication is going to be amplified not only by warming scenarios but also anthropogenic changes in the environment. Warmer climates will cause water to increase its temperature, affecting stratification and water mixing which will modify biological and chemical process within it. Those circumstances when associated with human-made actions within inland waters will cause irreversible consequences. In order to attenuate this situation, ways to improve water systems need to be proposed. Diverse remediation methods are used for nutrient removal, in most cases, phosphorus input. Common approaches applied currently are highly technical, material and energy demanding, expensive and harmful for lake organisms. In this way, proper environmental remediation methods are being proposed, sustainable methods relaying on minimal invasive techniques helping waterbody own restoration process. With this consideration, the in-situ method established in the previous study with the use of a turbidity curtain, floating filtration unit and geotextiles as filtration layer has been employed in a follow-up application at the same eutrophic study lake (Lake Caron) with few changes on enclosed area and pump intake height. In this second year deployment of 76-days, the in-situ geotextile filtration experiment results were compared with first year study when possible. Turbidity, total suspended solids (TSS), total phosphorus (TP), blue-green-algae-phycocyanin (BGA-PC) and chlorophyll-a statistically significant average removal efficiencies were of 17%, 36%, 18%, 34% and 32% respectively less than the first-year results. Nonetheless need to be considered larger water volume being treated with larger pore sizes geotextiles in the same filtration unit. The experiment has sustained the hypotheses, suspended particle removal reduces particulate nutrients in the water column and suppresses primary productivity, offering the key components for the lake system to initiate its own remediation. Further studies will focus on extending the lake remediation study applying larger filtration unit, flow rate and enclosed area.

Keywords: Eutrophication; Total Phosphorus Algae; Cyanobacteria; Suspended solids; Woven geotextile; Lake Water; Remediation; Surface Water

4.1 INTRODUCTION

Due to human interactions within inland waters synergically associated with climate changes scenarios, eutrophication cases are dated to increase, worldwide (Cavicchioli et al., 2019; Glibert, 2020; Zhang et al., 2020). Being a natural response of increased nutrient enrichment, a contemporary water issue, eutrophication is caused where higher nutrient input is found in the water column. Nutrient enrichment those inputted in lakes from point and nonpoint sources of pollution. When increased, this nutrient enrichment will produce physicochemical and biological modifications leading to the proliferation of excessive algal blooms and macrophytes, anoxic conditions as a consequence of bacterial respiration causing breakdown of dead aquatic biota (Dubey & Dutta, 2019). In this way, the raised temperatures presented by climate change circumstances affect the thermal stratification, and as consequence, nutrient fluctuations on the water system, are favoring cyanobacterial taxa to regulate buoyancy in the water column (Bartosiewicz et al., 2019; Monchamp et al., 2017).

The main nutrients present in the water column which can favor those situations are the presence of nitrogen (N) and phosphorus (P). Nitrogen is not readily absorbed by soil particles as phosphorous does, it exists in the atmosphere and may be removed through the process of denitrification (Chapra 1997) in the water. Phosphorus and phosphorus-based compounds, on other hand, are usually solids at the typical temperature and pressure range and are usually not soluble in water. This phosphorous strongly absorbs soil particles which makes dry deposition and erosion one of the chief sources of phosphorous in water (Dubey & Dutta, 2019). In other words, phosphorus is being strongly inputted in waters due to watershed interaction, and when present on it can be recycled from the sediment and dead aquatic biota decomposition. Two specific phosphorus forms are presented, dissolved and particulate, being the first one easily available for uptake by plankton.

As phosphorus is considered the limiting nutrient in primary productivity (Correll, 1999; Pant, 2020), diverse remediation technologies applied nowadays focus on its abstraction of the lake system. Being the most used methodologies sediment dredging hypolimnetic withdrawal, sediment capping, phosphorus inactivation in water and bottom sediments, and artificial aeration (Dunalska, 2021). Those remediation techniques are highly technical, material and energy demanding, expensive, and harmful for lake organisms. Additionally, in most cases, only the effects observed in the first few years after the intervention are described, and therefore little is known about the long-term perspective (Søndergaard et al., 2007).

In order to answer the raised issue by common remediation techniques, in-lake methods based on sustainable remediation are proposed. Those methodologies are based on presenting conditions for the waterbody's own restoration due to changes made in itself (Dunalska et al., 2021; Rosińska et al., 2018). By minimal invasive techniques, nutrients are removed, or lake biota is reconstructed in order to provide a healthier lake system. In this way, gradual reconstruction of the aquatic communities' composition, from phytoplankton and zooplankton to benthic macroinvertebrates and macrophytes could be observed after the application of those processes (Gołdyn et al., 2014).

With this understanding, geotextiles have been employed as filter membranes for inland water remediation, more precisely lake water filtration on-site and in-situ. By this process, particulate nutrient and suspended solids removal, by this minimally invasive technique, has been achieved suppressing primary productivity (Palakkeel et al., 2021; Pereira et al., 2020; Mulligan et al., 2009). Demonstrating the geotextile filtration as robust, effective, and reactive methodology which is also environmentally safe and economic remediation that can be deployed on shallow lakes and other water types.

The in-situ method being used in this paper is established on a turbidity curtain, floating filtration unit, and geotextiles as filtration layer, the same method used in the first-year application with few changes (i.e., related to pump water intake weight and enclosed area size). The technique cited and applied in this follow-up study has been proofed as a possible method for suspended solids and particulate phosphorus removal of enclosed areas on the eutrophic study lake, Lake Caron, located in *Sainte-Anne des-Lacs* municipality, Québec. Removal which in conjunction with reduced turbidity and particle sizes could provide suppression of primary productivity in the enclosed area.

As in any project or plan applied directly in the environment, proper follow-up needs to be done. The second-year study, the follow-up of 76 days, had closed a larger lake area and attempt to remediate it using a similar filtration unit and water flow rate in conjunction with only woven geotextiles of larger apparent opening sizes (i.e., 700 and 425 microns). Therefore, the objective of this paper is to assess the experiment deployment of in-situ geotextile filtration, in its second year of application of 76-days. Presenting variables correlations for the process understanding and providing future insights on this method for inland water sustainable eco-remediation.

4.2 MATERIALS AND METHODS

4.2.1 Project Study Area for Follow-up Study

Lake Caron (45°50'28″N; 74°08'50"W), a shallow eutrophic lake, in the *Sainte-Anne des-Lacs* municipality, Québec (75km north from downtown Montreal). An artificial lake and closed water body, shown in Figure 4-1, with the main sources of water replenishment being precipitation, surface runoff and snow.

This study lake has average, maximum, and minimum depths of 1.4 m, 2.6 m, and 0.5 m, respectively and approximate water volume and surface area of 48,400 m^3 and 35,300 m^2 (ABVLacs Org. 2018), represented in Figure 4-1 with sampling stations and households. Located in the *Lac Ouimet* watershed, mainly composed of wild vegetation and a few residents (Coutore et al., 2013. Additionally, its renewal time is 0.86 years and exiting to a large lake, *Lac Ouimet*, which has been possibly degrading by this eutrophic water.

Figure 4-1: Lake Caron map with sampling stations

Phosphorus loadings on the lake is linked to possible septic tank discharges and plants decomposition in the water, when related to external loads. Additionally, past lake enlarging with incomplete tree cutting (i.e., decomposing remains still within), phosphorus sediment release and algal deceasing/decomposition. This is the possible recurring reason causing bouncing algal/cyanobacteria biomass, every summer since 2008, which has placed this lake on a swimming advisory. Together with the MELCC 2019 report, under the Quebec *Réseau de surveillance* *volontaire des lacs* (RSVL) recommends adoption of measures to limit nutrient inputs for avoiding further degradation of and loss of uses.

4.2.2 In situ floating Geotextile Filtration Setup

The floating filtration equipment used in this experiment was made of Plexiglas. Material and type of unit has been selected to offer easy follow up of geotextile clogging rate and filter media modifications. The open square filtration unit had the following dimensions of 30.5 x 30.5 x 20 cm (W x L x H) coupled with a base galvanized copper grid to support the filters; Figure 4-2 shows the unit. Additionally, a Plexiglass wall of 20cm height fixed by clamps was introduced for avoiding filters layer movement when the experiment is being deployed.

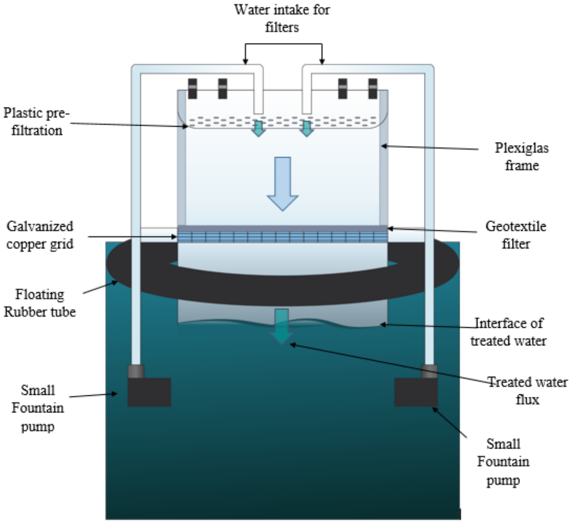

Figure 4-2: Floating filtration unit with specifications

The whole unit was tied up and floated with the support of an inflated synthetic rubber tube, Figure 4-3 represents the in-situ deployment. Also, for water recirculation on the filters, two submersible water pumps (DC 12V, 4.8 W) with flow rates of 240 L/h were used for pumping. The nearest outlet present provided the electrical supply. Additionally, a plastic prefilter was used to guarantee a prefiltration for removing larger debris, if presented in the water as well as to guarantee that the pumped water was uniformly distributed in the geotextile. All treated water was returned to the enclosed area and the filtration unit was able to move freely inside the contained water.

In-situ pilot filtration was based on the first-year study, with just a few modifications. Two turbidity curtains were used to contain suspended solids including the algae/cyanobacteria and fine sediment particles in a circular enclosed area inside the lake. By using enclosing areas, the second-year project objective was accessing how the absence/presence of a floating filtration unit modifying water quality parameters in this natural system.

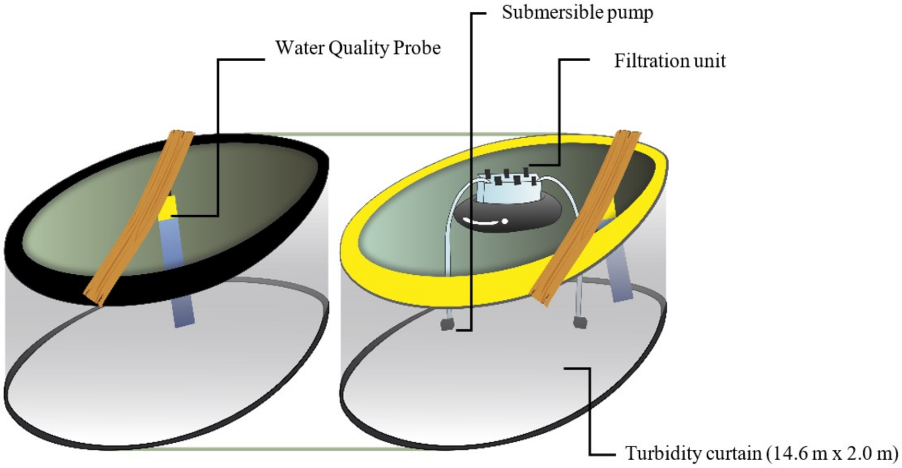

Figure 4-3: Schematic 3D view of the experiment enclosed areas

The two enclosed circular areas inside the lake, contained with floating turbidity curtains (14.6 m x 1.2 m) (L x W), had approximately diameter of 2.60 m each. (Figure 4-3) with 7.43 m^3 approximately of volume, when compared with last year it was more 4.82 m^3. As in the previous year, one enclosed area was used to deploy the filtration unit and the other function as a control. The location inside the lake was similar, in order to have comparable results (represented by St. D in Figure 4-1). As shown in Figure 4-4, the location was chosen due to bouncing cyanobacteria colonies accumulation possible from *Woronichinia naegeliana sp.* in this area and easy access for sampling and maintenance.

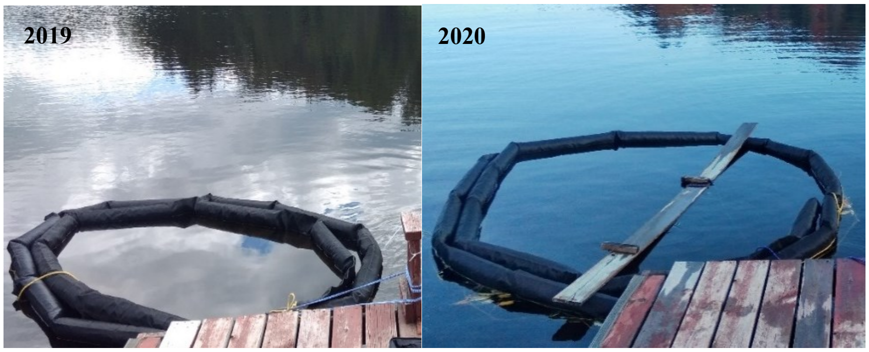

Figure 4-4: Larger deployment in-situ for the follow-up studies showing the control enclosed area

4.2.3 Filter Media

In this filtration follow-up experiment, only custom-made woven geotextiles were used instead of the combination of non-woven and woven geotextiles used in the previous year. As the first year, they were developed and received from Titan Environmental Containment Ltd., MB. In Table 4-1 are presented, geotextile physical characteristics (based on the datasheets obtained from the company are presented with details). While the TE-GMW70 is a black woven geotextile, a multifilament, high tenacity polypropylene fabrics with UV resistance and apparent opening size (AOS) 658 µm, the TE-GMW35 is a gray woven geotextile from the same material with AOS of 425 µm. Geotextiles, highly flexible material were used as a filtration membrane.

Table 4.1: Woven geotextile characteristics used in this study

Filters	Material	Apparent Opening Size (AOS) (µm)	Flow rate (L/m^2/min)	Permittivity (sec^{-1})	Mass per unit area (g/m^2)
TE-GMW70	[a]PP	658 µm	2973	0.98	180
TE-GMW35	[a]PP	425 µm	2039	0.70	

[a]PP: Polypropylene

Precut 30cm square layers were combined for experiments and placed on the floating filtration unit. The defined combination were always 1-3 layers of the TE-GMW70, 5-6 layers of TE-GMW35, and the number of layers was defined based on the first-year study results and following the particle size in the enclosed filtration area. Also, the TE-GMW70 were used in the plastic tray as prefiltration layer. Clogged layers were entirely changed every week or when clogged, whichever occurred first. Also, these filter combinations from 6 to 9 layers were used throughout the entire experiment. Figure 4-5 presents the woven geotextiles before the filtration process.

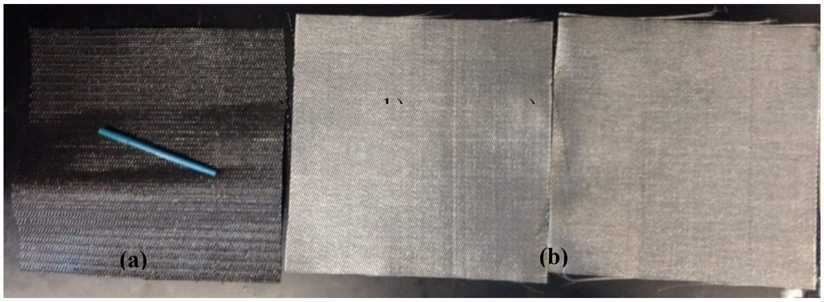

Figure 4-5: Woven geotextiles used in the deployment: (a) TE-GMW70 – AOS: 700 µm and (b) TE-GMW35 – AOS: 425µm before the filtration process

4.2.4 Field Sampling and Experiment Sampling

Water samples were collected using 1L high-density polyethylene (HDPE) amber bottles (physical analysis) and 50 ml sterilized polypropylene test tubes (chemical analysis), stored at 4°C in the dark with analyses completed within 48h. In order to perceive water quality parameters modifications on the in-situ deployment, every 2-3 days, water samples were retrieved from both enclosed areas. Also, to access the general water quality in the entire shallow eutrophic lake, field sampling was done over the 2020 summer/fall seasons at selected stations, presented on Figure 4-1 (i.e., St. S, St. 1, St. 4, St.7, St.8 and St.9).

4.2.5 Water Quality Analysis

Samples were assessed for the following water quality parameters: pH, dissolved oxygen (DO), temperature (Temp.), oxidation-reduction potential (ORP), conductivity, turbidity, chlorophyll a (Chl. a) and blue-green algae-phycocyanin (BGA-PC), particle size analysis (PSA), total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), nitrate (NO_3-), chemical oxygen demand (COD) and Fluorescent Dissolved Organic Matter (FDOM).

Two YSI-EXO_2™ multiparameter probes were employed for water quality measurements installed in each enclosed area (filtration and control areas), during the entire test for hourly samples. The water quality parameters measured for its probes were: pH, dissolved oxygen (DO), temperature (Temp.), oxidation-reduction potential (ORP), conductivity, turbidity, total dissolved solids (TDS), chlorophyll-a (Chl. a) and blue-green algae-phycocyanin (BGA-PC). In order to ensure accuracy of the results, every week data backup was performed in combination with sensor performance, sensor fouling cleaning (additionally to automatic wiper) and system battery check.

Lake water suspended particles concentration were measured using APHA 2540 D method and particle sizes analyse (PSA) using laser diffraction particle analyzer in a LA-960 Horiba laser particle size analyzer. Test kits from Hach chemicals were used for evaluating TP (Method 10209 - SM 4500-PE - Ascorbic Acid Method), TN (TNT 826, Method 10208, persulfate digestion), NO_3^- (TNT 835, Method 10206, dimethyl phenol method) and COD (TNT 820, Method 10221, reactor digestion method).

For chemical analysis, duplicates with blank and two standards within the lake water concentration were used. Except for nitrate (which did not require digestion), water samples were first acid digested on a Hach DRB 200 heating block and after cooling down were measured in a Hach DR 2800 UV–Vis spectrophotometer follow specific method.

4.2.6 Data Analysis

Descriptive statistics were used to summarize the dataset analyzed including measures of central tendency (i.e., means, medians, maxima, and minima) and measures of dispersion (i.e., variances, standard deviations, standard errors, and confidence interval) with verification and removal of any outliers (0.05). Data denoted in text as the means ± confidence interval.

Statistically significant changes concerning water quality variables with filter presence and absence in the lake enclosed areas were evaluated using a parametric test Student's mean t-test ($p < 0.05$) for normally distributed variables and the paired nonparametric test: Wilcoxon matched-pairs (equivalent T-student) signed-ranks test ($p < 0.05$) for not normally distributed variables. The Student's t-test has the null hypothesis that water quality variable means of filter presence and absence are statistically equal. Instead, Wilcoxon matched-pairs signed-ranks test ($p < 0.05$), has null hypothesis which water quality variables medians mean with filter presence and absence are equal.

The T-student parametric test requirements were violated (normality by the Shapiro-Wilk test ($P < 0.05$) and homoscedasticity by Levene's test ($P < 0.05$), for all the following water quality variables in the enclosure experiment, expect from .... In the remaining variables, (i.e., D10, D50, D90, TP, TN, TSS, pH, DO, Temp., ORP, conductivity, turbidity, Chl. a, BGA-PC), equivalent paired nonparametric test, Wilcoxon matched-pairs signed-ranks test, were employed. Spearman's non-parametric test ($p < 0.05$) were used to corroborate relationships (i.e., correlation analysis) concerning study water quality variables, a heat map was used for data representation.

4.3 RESULTS AND DISCUSSION

4.3.1 Lake Water Quality Second Year

At the study lake, related to nutrients, there was not a significant change on those parameters when comparing the second-year study with previous one, as presented on Table 4-2. Phosphorus concentration on the lake stayed on an average of 28.8 ± 2.2 μg/L with a maximum peak of 33 μg/L in the summer. In accordance with the Quebec lake classification the lake has remained on the mesoeutrophic range. When associated with nitrogen, it is understood that the parameter is not a limiting at this lake system, as the value remained equal to first year in the range of Quebec guidelines (i.e., MDDEP, 2012) for protecting aquatic life, which are 1.0 mg/L. Nitrate, which is a component represented in the total nitrogen concentration, its value remained lower than the Quebec regulation of 2.9 mg/L.

Table 4.2: Lake Caron water quality during July-Sep, 2019 and July-Sep 2020

Parameters	2019[a]	2020[b]
TP (μg/L)	26.0 ± 1.6	28.8 ± 2.2
COD (mg/L)	23.6 ± 0.2	24.0 ± 5.5
NO_3^- (mg/L)	0.20 ± 0.02	0.30 ± 0.05
TN (mg/L)	0.81 ± 0.09	1.0 ± 0.05
TSS (mg/L)	3.5 ± 0.5	3.2 ± 1.4
D50 (μm)	63.74 ± 6.92	54.67 ± 8.63
D90 (μm)	154.16 ± 12.45	160.08 ± 18.00
YSI-EXO$_2$ Probe data	2019[c]	2020[d]
Temp (°C)	19.7 ± 0.42	18.2 ± 0.20
Conductivity (μS/cm)	23.0 ± 0.67	20.3 ± 0.11
TDS (mg/L)	14.8 ± 0.43	13.1 ± 0.04
DO (mg/L)	10.2 ± 0.04	8.37 ± 0.03
pH	6.8 ± 0.02	6.5 ± 0.01
Turbidity (FNU)	5.82 ± 3.37	3.24 ± 1.35
ORP (mV)	+113.89 ± 13.17	+498.38 ± 3.86
FDOM (QSU or μg/L)	38.23 ± 1.35	41.12 ± 0.79
Chlorophyll (μg/L)	7.32 ± 0.56	5.82 ± 0.86

BGA – PC (μg/L)	0.49 ± 0.05	0.50 ± 0.04

[a] Average of 7 samplings of 5 lake stations; [b] Average of 3 samplings of 5 lake stations

Related to particles, turbidity decreased when compared with the first year, even though particles sizes remained similar to the ones found previously. Higher variance in the confidence intervals were found for TSS concentration, which can explain the reduced cloudiness in the water. Still related to particles, chlorophyll-a reduced in comparison to the first year. Dissolved oxygen was still available throughout and ORP indicates an aerobic environment. pH remained in the same range as well and thus did not affect any chemical reaction that could occur inside the lake.

Related to organic matter, chemical oxygen demand (COD) of this lake, was mainly assumed to be in its dissolved form, and did not present any significant variation on the lacustrine system in the second year. There is a constant replenishment of organic matter from decomposition processes which occur in the lake, this value has remained without alteration. Regarding the water colour (i.e., which was a light tea-like color) it was noticed in the lake water, as mentioned on the first year remained unchanged, despite previous algae blooms and some plants/trees that was not properly removed when the lake was created/enlarged.

4.3.2 Second Year Filtration In Situ Experiment

In-situ experiment was deployed from June 23, 2020 to October 07 of 2020 for a total of 76 days, despite the COVID-19 pandemic. This experiment had one more week than the first-year study, but still was between summer and fall seasons. The system operated without any major concern, continuously removing suspended particles and its associated particulate phosphorus. Deployment followed by daily operation, of the proposed Eco remediation, has shown the system possibility to maintain continuous removal rate for a second-year long-term project, in a larger enclosed area of 2.60 m when compared with the 1.54 m diameter of the first year. A constant removal rate was observed.

Using only woven geotextiles membranes with larger AOS, the filter run has maintained 7 days before requiring geomembranes combination change. The combination of layers sandwiched has consumed approximately 50 square filter layers of TE-GMW70 and 132 filter layers of TE-GMW35. If the 30cm square area is considered as, approximately 3.96 m^2 and 11.88 m^2 for each AO, this results a cost of $29.70 when related only for TE-GMW35 to remediate approximately

7.4 m^3 of lake water. A floating filtration system was able to support a good particle and its associated parameter removal rate, during the whole experiment in this second-year study. Cake superficial development, on the geotextile, is shown on Figure 4-6, after one-week filtration. This filter ripening ensured AOS reduction by not only filtering the water from particle sizes (i.e., straining) but by forming a filter cake (i.e., depth filtration).

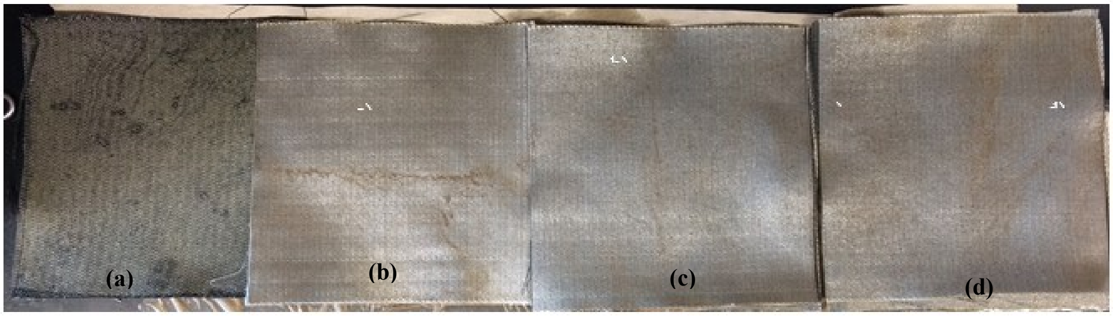

Figure 4-6: Woven geotextiles after the filtration process: (a) TE-GMW70 - AOS: 700 µm, (b) TE-GMW35 second layer – AOS: 425µm, (c) TE-GMW35 third layer – AOS: 425µm and (d) TE-GMW35 fourth layer – AOS: 425µm

Visible bouncy regulated cyanobacteria formation was observed possible cyanotoxin producing strains of *Woronichinia naegeliana sp.*, that accumulated at the shore due to wind action as presented in the Figure 4-7. Those organisms have gas vesicles, providing mechanisms to move up and down in the water column, which increases access to nutrients and other growth factors. No visible cyanobacteria formation was observed in both enclosed areas.

Figure 4-7: Bouncy regulated cyanobacteria that Lake Caron presented in the second year study

4.3.3 Total Suspended Solids and Turbidity Removal

Following the first-year testing of this proposed remediation technology for eco long-term project applications; this second-year study maintained the hypothesis for suspended particle removal, which includes the reduction of parameters. A larger enclosed area was used with a similar flow rate, filtration unit and geotextile area. Additionally, larger AOS woven geotextiles membranes were employed. Statistically significant TSS removal, shown in Figure 4-8. An average of 37% ($p < 0.01$) was obtained which was less than the 53% ($p < 0.01$) in the previous study. This has enabled water TSS concentration to be below 3.0 ± mg/L after the tenth day until the end of the test. In the filtration enclosed area, has the same behaviour as entire lake. By the end of the experiment, the control enclosed area has an TSS concentration average value of 4.23 ± 0.32 mg/L and the filter enclosed area had 2.67 ± 0.37 mg/L.

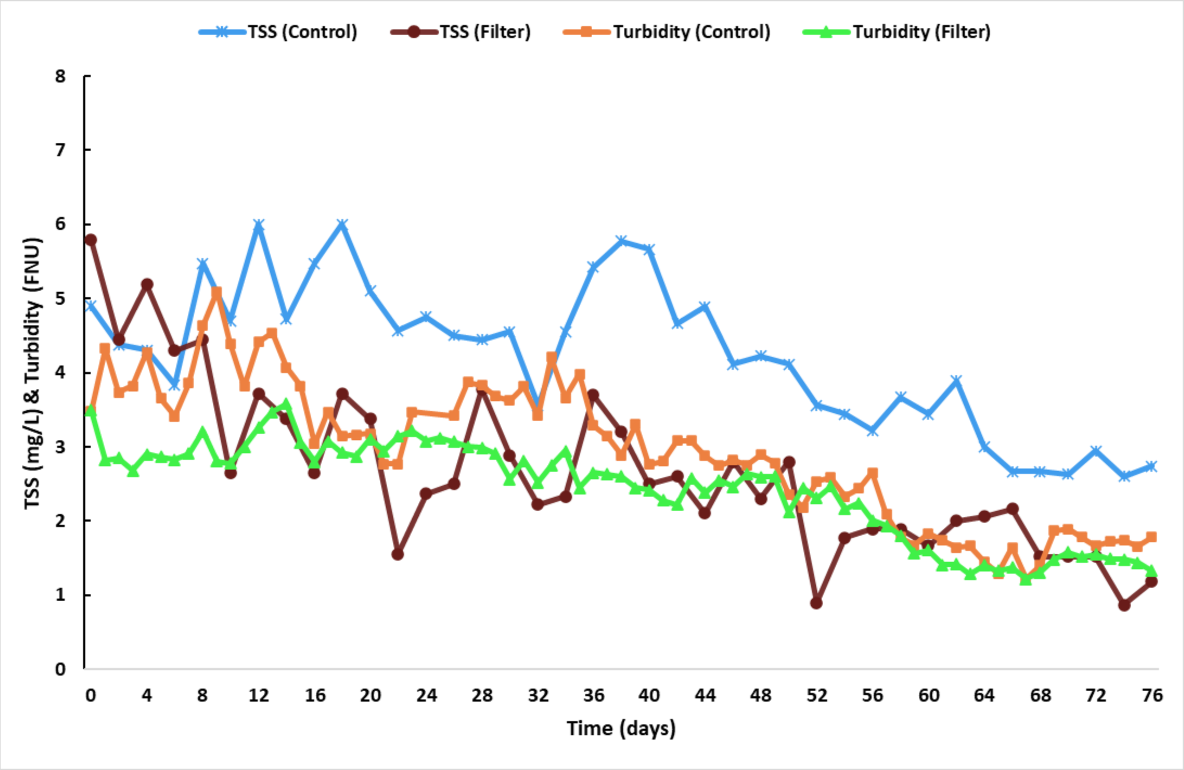

Figure 4-8: Turbidity (FNU) and total suspended solids concentrations (mg/L) for the second year in situ experiment

Removing particles, reduced the water cloudiness. Average turbidity removal in the filter enclosed area was of 17%, as presented in Figure 4-8, which was statistically significant ($p< 0.01$). An average of 2.92 ± 0.05 FNU was obtained in the control area and 2.42 ± 0.03 FNU in the filtration-enclosed area. This removal percentage was lower than in the previous study (34%). However, there was an observed trend, as the control area was always higher than the removal in the filtration enclosed area. Also, this has shown that the floating system used was able to quickly respond and remediate the water despite suspended solids and nutrient replacement from due to sediment resuspension, and watershed runoff.

The control enclosed area particle size average showed 50% (D50) and 90% (D90) of SS as presented in Figure 4-9. They were < 52.85 ± 7.47 µm and < 158.60 ± 6.64 µm and < 54.57 ± 6.26 µm and < 142.36 ± 9.25 µm, in the control and filter areas, respectively. This can be explained as the SS removal percentage presented being not a representative removal as in the previous study, which removed all particles between 154.07 ± 9.33 µm and 77.94 ± 10.12 µm. Those particles as shown in the results of the first-year project are associated with particulate nutrients. In this year only, particles between 158.60 ± 6.64 µm and 142.36 ± 9.25 µm were addressed, leading to a lower in particulate nutrient. There was a statistically significant positive correlation between D90 size reduction and turbidity on the filtration enclosed area ($R^2 = 0.56$, p-value < 0.01) and D90 and BGA ($R^2 = 0.64$, p-value < 0.01). Explanation of this correlation can be that those particles were in the majority of cases, photosynthetic organisms like cyanobacteria, which were captured by the filter's layers.

Figure 4-9: D50 (µm) and D90 (µm) for the second year in situ experiment

4.3.4 Nutrient and Algae/Cyanobacteria Removal

Removal of suspended particles and associated particulate nutrient, prevents them from settling and enabling growth of harmful plankton. Associated particulate nutrient such as total phosphorus in the filter-enclosed area were reduced. In the previous study, the lake water that was at a eutrophic level (average concentration of 29.0 ± 1.5 µg/L) but was reduced to the limit of mesoeutrophic going towards the mesotrophic (filter-enclosed area 22.7 ± 1.4 µg/L) which has been represented a statically representative average removal of 22% presented on Figure 4-10.

In this, follow-up study, lake water TP removal has the same behaviour as the first-year study. Even this parameter presented a higher average amount in the control enclosed area of 34.1 ± 1.2 µg/L, which is at the higher limit of the mesoeutrophic trophic level. However, in the filter area, where particulate nutrient was removed the average was 27.8 ± 0.6 µg/L, as shown on Figure 4-10. The TP removal on this study, was statistically representative ($p < 0.01$) with a 19% average removal. No correlation between turbidity and TP removal as well as TSS and TP was found. This could be explained as not a significant number of particles were reduced and removed in the system for TP reduction.

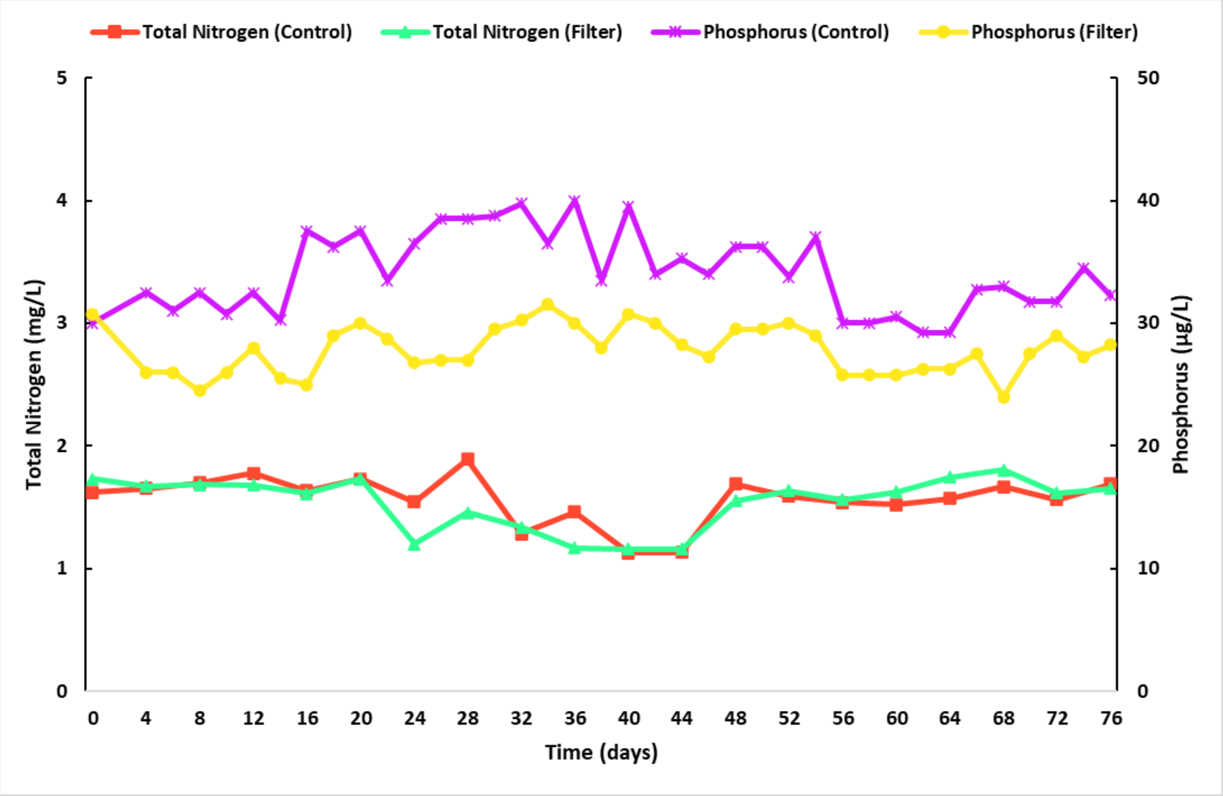

Figure 4-10: TP concentrations (µg/L) and TN concentrations (mg/L) for the second year in situ experiment

As TN and nitrate were mainly denoted (> 80%) in their dissolved forms in this lake water previously, this remained unchanged on the second year. The average values of 1.57 ± 0.09 mg/L and 0.21 ± 0.01 mg/L for TN and nitrate in the control area and 1.54 ± 0.10 mg/L and 0.21 ± 0.01 mg/L in the filter area. Both parameters were still under the Quebec regulation guidelines and were not affected by the experiment.

The Chlorophyll-a parameter in the filter area was always lower than the control area with average values for Chlorophyll-a of 5.66 ± 0.06 µg/L and 3.85 ± 0.05 µg/L for the filter area, which represents a statistically significant removal of 32 % ($p < 0.01$) (Figure 4-11). This was less than the first-year study that showed 57% chlorophyll-a removal. Any organism photosynthetic that grew in the system were constantly dying in the control area throughout the summer/mid-fall (i.e., returning to the bottom surface sediments to decompose) and the filtration system were able to suppress primary productivity at some level in the experiment. Total suspended solids (TSS) ($R^2 = 0.61$, p-value < 0.01) and turbidity ($R^2 = 0.55$, p-value < 0.01) were found to be statistically correlated with chlorophyll-a meaning that the suspended solids is mainly photosynthetic matter such as algae, etc.

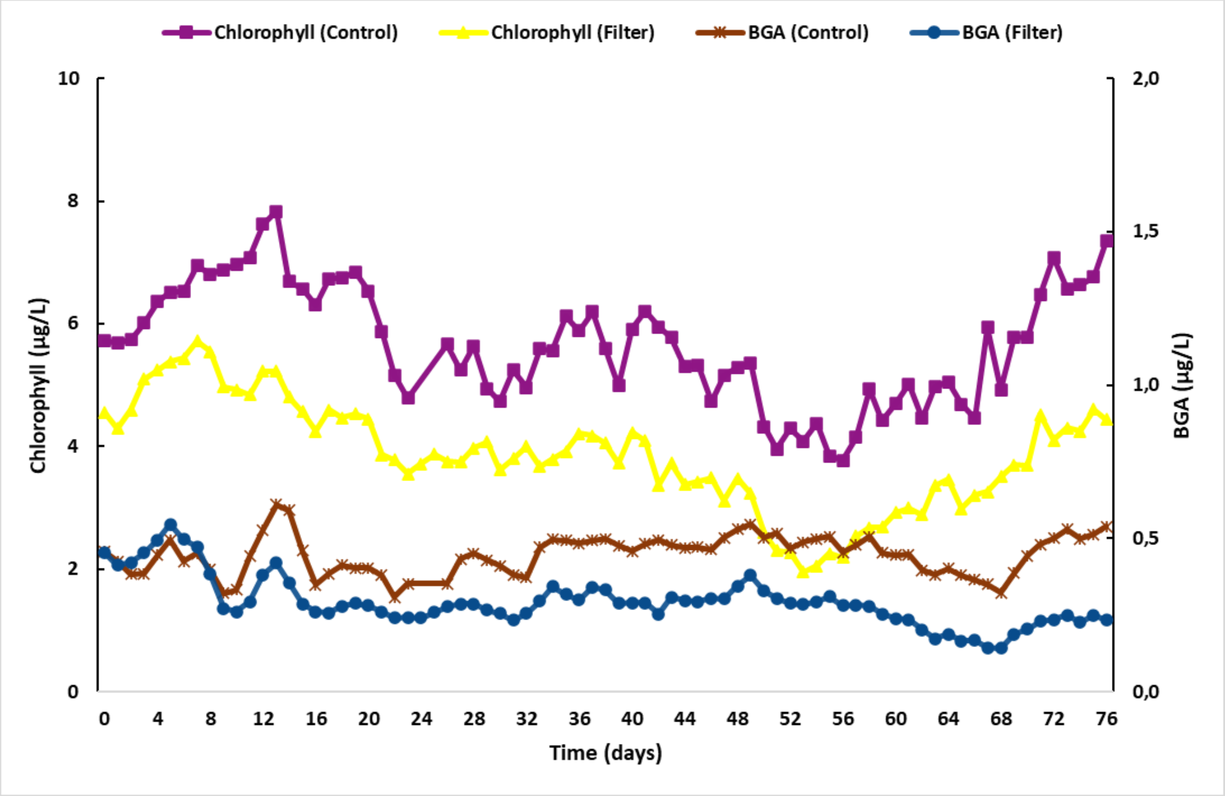

Figure 4-11: Chlorophyll-a (µg/L) and BGA-PC concentrations (µg/L) for the second year in situ experiment

The BGA parameter in filter area was always below the control area as well. As commented, bouncy regulated cyanobacteria formation was observed in this lake water but at low densities. This has shown as the average values for BGA, which were 0.45± 0.004 µg/L for the control-enclosed area and 0.29 ± 0.004 µg/L for the filter area, which represents a statistically significant removal of 35 % ($p < 0.01$) which was less than the first-year study (57%). This could be considered as an indication of this floating filtration unit as a potentially environmentally harmless, flexible, and efficient remediation in removing algae/cyanobacteria development for an entire season.

4.3.5 Organic Matter Removal

Removing suspended solids on lake water, following the first-year study behaviour, the follow-up study results has shown organic matter removal as well (i.e., dissolved and particulate), but in a discreet way. Some parameters (such as DO, pH, conductivity and water temperature) are related to this removal and insights on them will be given first.

Water temperature was the same for both enclosed areas. Average values of water temperature presented was 19.2 ± 0.20 °C for the control area and 19.5 ± 0.20 °C in the filter area, with a maximum water temperature reaching 27 °C in the summer Figure 4-12. Temperature was strongly correlated with DO concentration ($R^2 = -0.86$, p-value < 0.01), Conductivity ($R^2 = -0.98$, p-value < 0.01), and pH ($R^2 = 0.86$, p-value < 0.01), which can indicate that changes in water temperature can affect substances dissolution, in the case of H^+ and salts, or concentration reduction, in the oxygen case. With the trends as water temperature, conductivity has followed a constant decrease throughout the experiment. This can be explained as the temperature decrease the dissolved salts quantity in water is affected. Average conductivity values were 19.9 ± 0.11 µS/cm in the control area and 20.3 ± 0.11 µS/cm in the filter area.

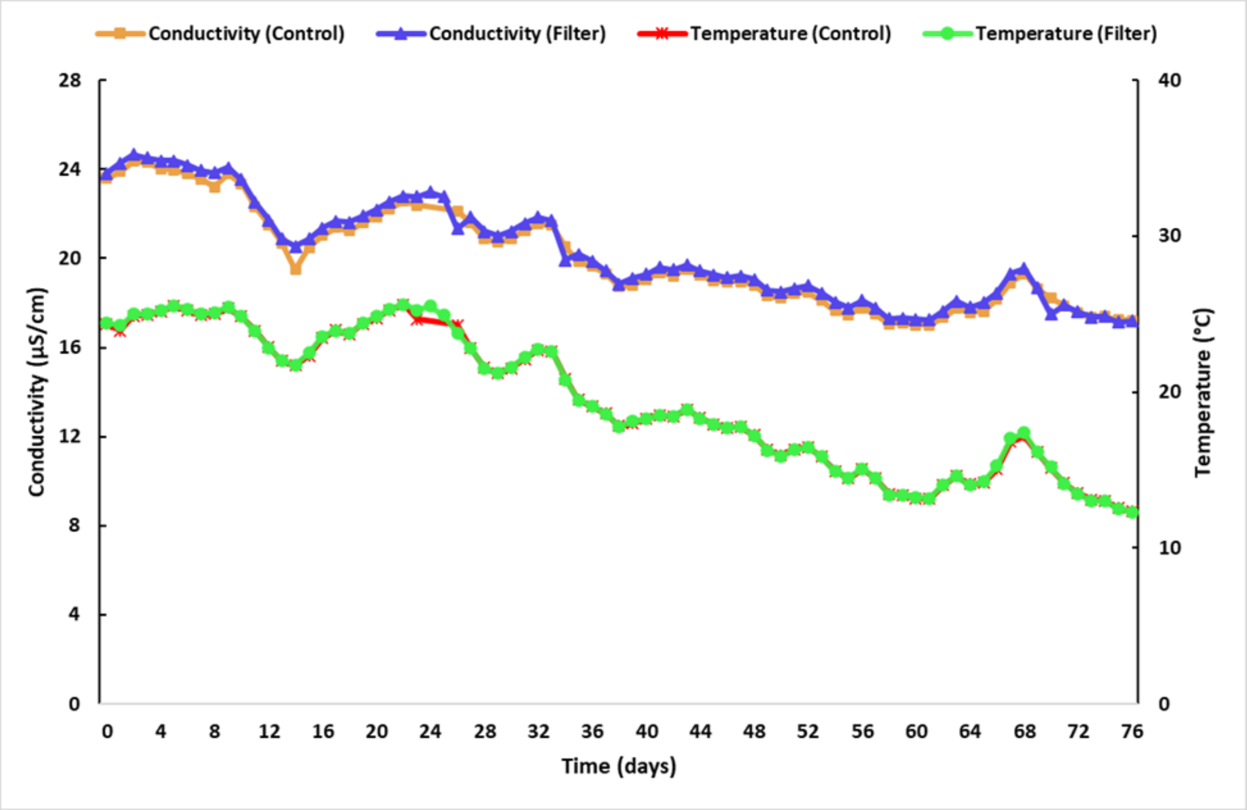

Figure 4-12: Conductivity concentrations (µS/cm) and water temperature (°C) for the second year in situ experiment

On this study, DO concentration in epilimnion water was on average 8.47 ± 0.03 mg/L in the control area and 8.24 ± 0.03 mg/L in the filter area (Figure 4-13). Related to pH, it remained between the recommended guidelines for protecting aquatic organisms in surface water (pH 6.5–9) in Canada by Canadian Council of Ministers of the Environment (CCME, 2008) with not significant difference between enclosed areas. Average pH values were 6.61 ± 0.01 in the control area and 6.51 ± 0.01 in the filter area.

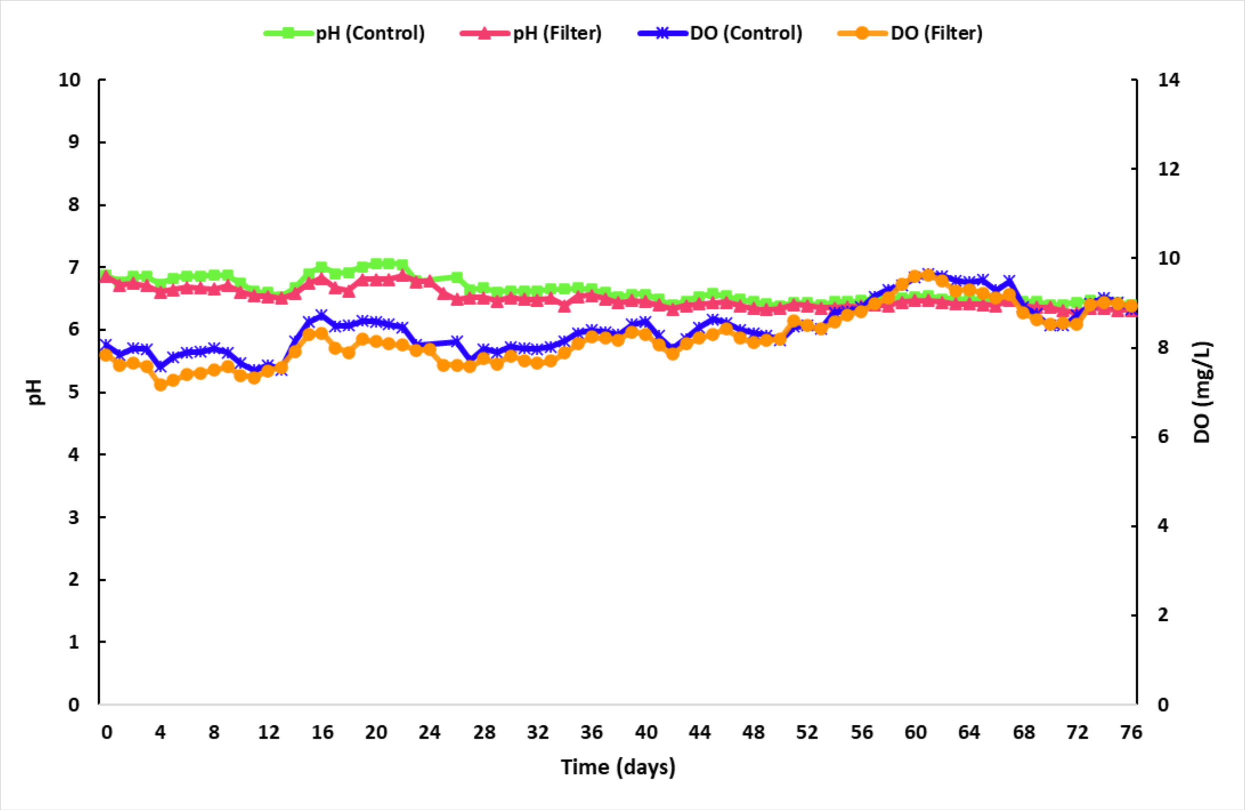

Figure 4-13: pH and dissolved oxygen concentrations (mg/L) for the second year in situ experiment

Fluorescent dissolved organic (FDOM) components on the water, as previously explained denoted for FDOM presented unusual behaviour, the filter enclosed area was always higher than the control. Average values of FDOM concentrations were 40.9 ± 0.09 QSU (quinine sulphate units) in the filter area and 36.6 ± 0.05 QSU in the control area (Figure 4-14). The behaviour was the opposite in the first-year study. This could be explained as the pump water intake height (i.e., deeper in the lake than first-year study) allowed oxygen introduction near to surface sediments brought dissolved organic matter to release.

By a constant oxygen input in the water due to water mixing and pumping, dissolved substances presented on the enclosed area were constantly released, but not mineralized. FDOM behavior was not entire captured by COD removal, presented in Figure 4-14, average COD concentration values were 24.7 ± 0.37 mg/L and 23.9 ± 0.56 mg/L in the control and filter area, respectively.

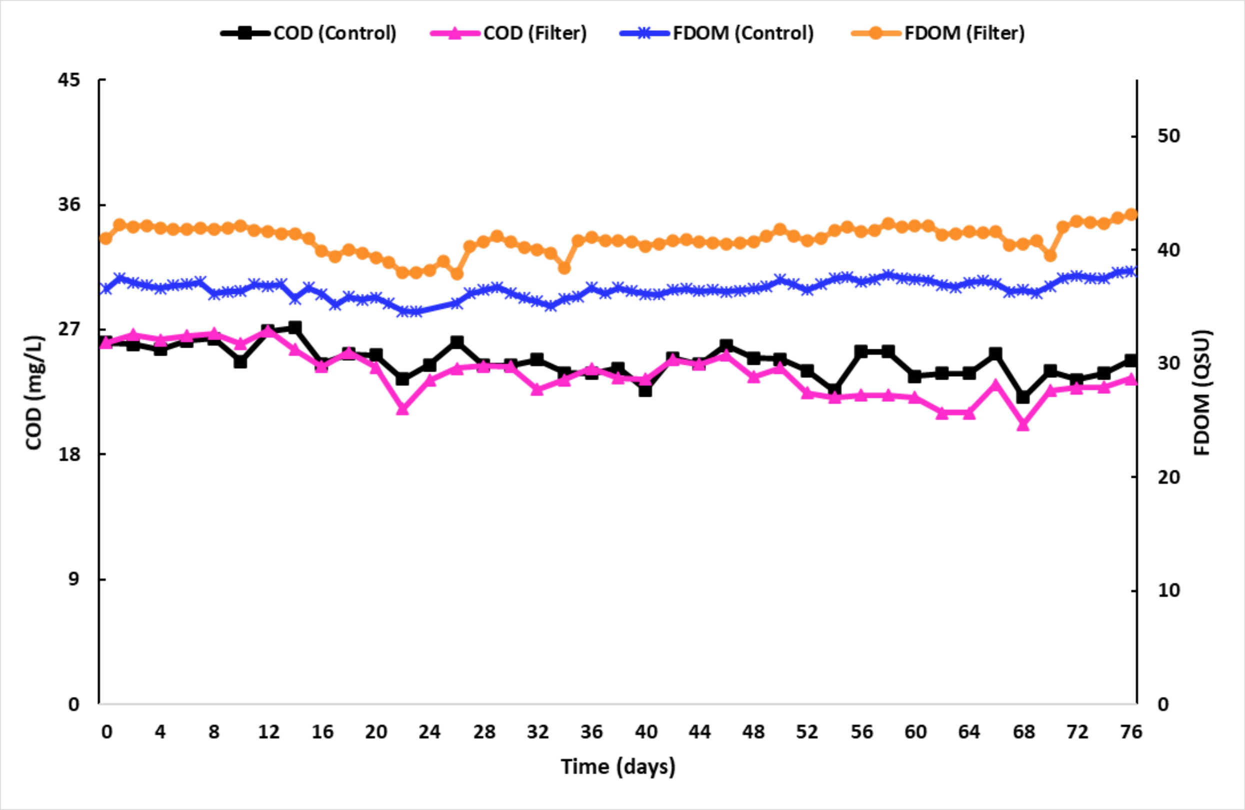

Figure 4-14: COD concentrations (mg/L) and FDOM concentrations (QSU) for the second year in situ experiment

Particle removal did not strongly affect the organic matter concentration in the system as previously explained. The highest proportion is assumed to be mainly due to the dissolved organics present in this lake. For COD removal in this experiment is associated with COD particulate removal by the geotextile membranes and/or dissolved COD removal by filter cake uptake (i.e., filter ripening). Those mechanisms allowed the COD in the filter area to be somewhat below the control.

4.3.6 Experiment Correlations

Correlation analysis using Spearman's non-parametric test ($p < 0.05$) was chosen in a way to represent any monotonic relationship between two variables in the treatment proposed. In other words, the analysis results will present variables that show the same behaviour but not necessarily at a constant linear rate. This relationship was used to assess how the filter enclosed area variables affect each other in this work. The Spearman variable correlation matrix was represented with a heat map, in Figure 4-15. Not statistically significant correlations ($p < 0.01$) are crossed out

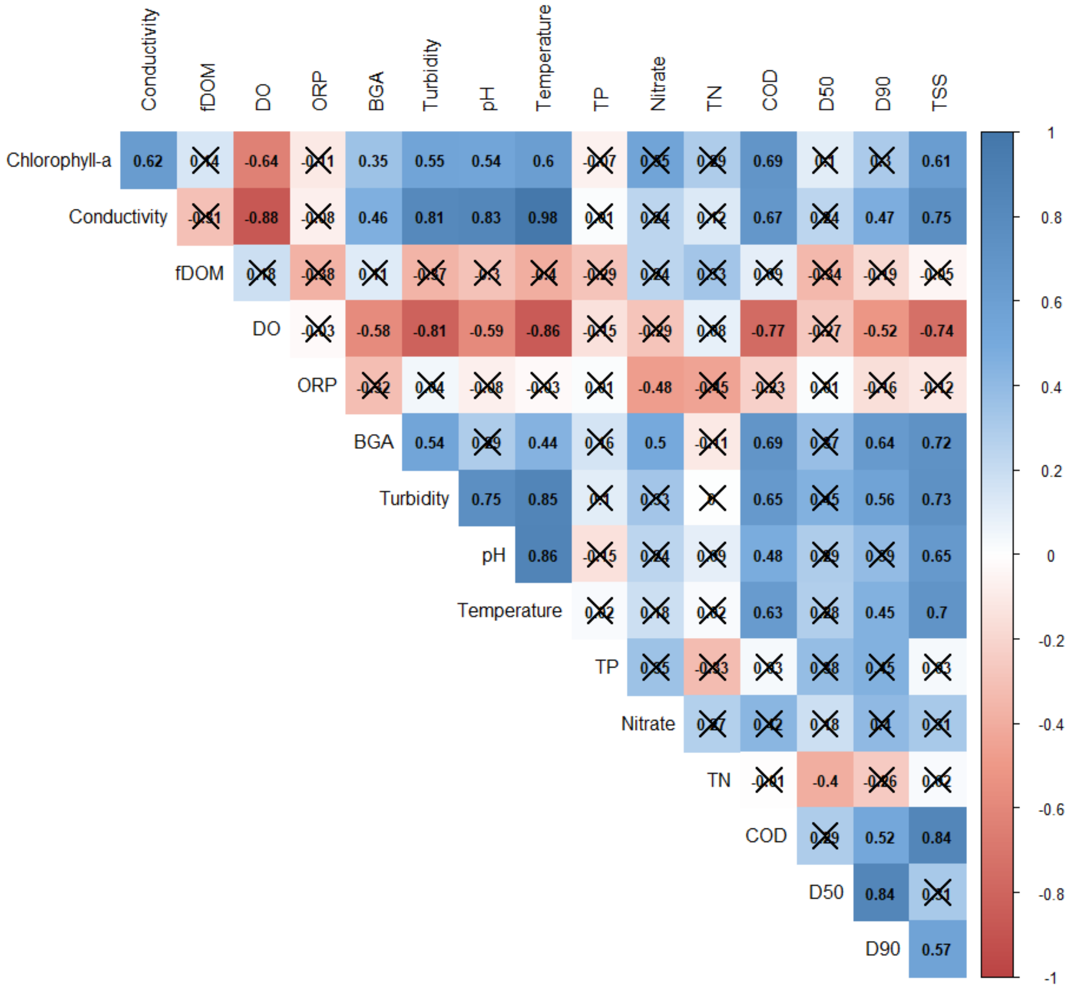

Figure 4-15: Heat map representation of the Spearman correlation matrix on all variables for the second year in situ experiment

This follow-up study has the same performance as the previous one, where variables that can characterize particles presented excellent correlation with turbidity and TSS removal, as they have presented with themselves. Variables like D90, BGA, COD and Chlorophyll-a. This validates, even more, this in-situ geotextile process can be applied in a large, enclosed area for a long-time project to Eco-remediate lake water.

Strong negative correlations were found with DO and variables like turbidity, water temperature, COD, TSS and conductivity. This can be explained by the quantity of DO dissolving in the water is affected by the water temperature. Also DO can affect the number of suspended solids in the water changing its cloudiness.

4.3.7 Future Applications

By this second year study, it was perceived that even increasing filtration area but using the same flow rate and the same geotextiles membranes floating unit with just woven layers, the project showed good removal. Possibly continuously remediating the lake water in the enclosed filter area, average removal was reduced when compared with the first-year study. As there is less water to be filtered in the first year and the commercial mesh (CM) membrane (i.e., used as pre-filtration on this project) presents fibre-like comportment in capturing algae/cyanobacteria, which has improved the filtration removal of suspended solids by employing the depth filtration mechanism.

In this second-year study, some lessons were learned, related to pump intake height, which could affect the release/oxidation of some substances in the lake water. A large, enclosed area will require the scale-up on the filtration unit, which will have a higher contact area for the membranes as well as will support for a higher flow rate pump. This requirement would be used to produce a further methodology for the potential the full-scale implementation of this remediation technique.

For further studies attention still need to be given to an increased enclosed area, application of other geotextile AOS sizes, and dissolved COD removal that should be done by continuing this investigation. Additionally, consideration will be given to the lake water dissolved organic matter characterization, understanding internal release mechanics within the lake water, geotextile layers reuse and solid captured assessment for direct application or final disposal.

4.4 CONCLUSIONS

In-situ experiment follow-up supported the hypothesis risen for suspended particle removal. Regardless a lower percentage was removed compared with the first-year study parameters by this continuous filtration. The filter combination used on this second-year study has allowed removal of particles, represented by TSS and turbidity that affected the chlorophyll-a and BGA concentrations in the system in addition to some particulate phosphorus. Strong correlation was found with parameters that characterize particles like turbidity and TSS removal and variables like D90, BGA, COD and chlorophyll-a. The lake water in the filter enclosed area was altered from the limit of mesoeutrophic to the limit of mesotrophic state with only this floating filtration methodology. For further studies, attention still needs to be the scale up of experiment as well as; lake water microplastics assessment and waste management routes.

AUTHOR CONTRIBUTION

Antonio Cavalcante Pereira: Conceptualization, Methodology, Investigation, Writing – original draft, Dileep Palakkeel Veetil: Investigation Catherine Mulligan: Supervision, Methodology, Writing - Reviewing and Editing, Funding acquisition, Sam Bhat: Provision, Methodology

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CHAPTER 5. EXPERIMENTAL INVESTIGATION TOWARDS A CIRCULAR ECONOMY APPROACH FOR WASTES PRODUCED BY EUTROPHIC/MESOTROPHIC LAKE WATER GEOTEXTILE FILTRATION

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Abstract:

Eutrophication on aquatic systems is predicted to increase due to anthropogenic actions and climate change scenarios. These increased nutrients caused by point and diffuse releases will increase the internal and external loads mainly on inland waters. To reduce this natural ecological response to excessive nutrient enrichment, a method for phosphorus removal, the limiting nutrient, by a novel in-lake and on-site non-invasive sustainable remediation methodology is being investigated based on floating filtration using geotextiles as filter media. These processes will generate wastes, being the clogged geotextile membranes with captured suspended solids. In order to bring this treatment towards sustainability, using circular economy principles, waste management routes for those materials, more precisely reuse, are being proposed. This initial study aims to investigate potential reuse strategies for wastes generated by proposing a methodology, by washing clogged membranes in combination with dewatering captured suspended solids. The washing method was pressurized tap water inside with a gardening pump sprayer with no chemical additives. For the dewatering, natural and artificial evaporation were tested. Results have shown efficiency of the washing method, for removing visible membrane (woven or non-woven) clogging, with permeate flow rates reaching a value close to the initial process values. No geotextile fibre disruption was shown, enabling its possible reuse. Related to dilute liquid waste a high concentration of some heavy metals (manganese, zinc) and phosphorus were found. Further studies are going to be done to indicate if reuse is possible. No liquid waste concentration or mixing between the two types generated in this project (i.e., the liquid wastes generated by washing woven and non-woven geotextiles) is recommended as they could increase contamination and decrease possible waste management routes. Captured suspended solids presented a greater concentration than in liquid wastes, as expected. Some heavy metal concentrations (manganese < zinc < copper) and phosphorus, located in the solids were found to be above regulations. At the moment, the possible solid waste generated in this process needs to be further assessed for the inclusion of others waste routes in its lifecycle.

Keywords: Circular Economy; Nonwoven geotextiles; Woven geotextiles; Reuse; Membrane Fouling; Waste Management; Effluent; Suspended Solids

5.1 INTRODUCTION

Eutrophication of inland and marine waters is a rising concern around the world (Le Molal et al., 2019; Jilbert et al., 2020) and will possibly increase in the following years due to climate change and anthropogenic actions (Glibert, 2020). By nature, this is an ecological response to excessive nutrient enrichment (Bonsdorff, 2021; Kadiri et al., 2021), mainly phosphorous and nitrogen for internal and external loads (i.e., point and diffuse releases) that threatens water resources.

Those eutrophication scenarios produce various issues on water, including reduction of transparency, harmful algal/cyanobacteria blooms, hypoxic "dead zones", fish deaths, increased organic matter degradation, water safety issues, aquatic food supplies disruption, cultural and social value degradation (Wurtsbaugh et al., 2019; Bhagowati et al., 2020; Chislock et al., 2013). In many cases, phosphorus the limiting nutrient for primary productivity, is present in those systems, and needs to be reduced. Therefore, its management is a more practical way to respond to this increased concern.

A novel in-lake and on-site non-invasive sustainable remediation methodology is being studied for removal of this increased nutrient in shallow lakes, that uses geotextile floating filtration. This method has been used for removing suspended solids and their associated particulate nutrients (Palakkeel et al., 2021; Pereira et al., 2020; Mulligan et al., 2009). It shows high potential as an economic, efficient, and flexible technique for environmental remediation. However, like any other activities, waste production needs to be dealt with. The main wastes produced from this treatment are clogged geotextile membranes and captured suspended solids. To increase sustainability for this treatment, those wastes should be addressed for further development.

The filter media used in this methodology, geotextiles, are permeable geosynthetics comprised solely of textiles (Wiewel & Lamoree, 2016) composed of thermoplastic polymers, such as polypropylene (PP), polyethylene terephthalate (PET) or polyester (Prambauer et al., 2019). A flat product that is dimensionally stable, and highly flexible which as been presented as an exceptional fabric material for use as a filtration membrane. On the other hand, suspended solids in the lake, are comprised in the majority of times of small particles and organic matter that tend to bind heavy metals (Kamzati et al., 2020), particulate phosphorus, algae and/or cyanobacteria.

Following the current economic linear model, business and industry are after, a linear model that is built on the premise of "take-make-consume and dispose of" (EU, 2014) assuming resources are abundant, available, and cheap to dispose of (Camilleri, 2019). The most convenient way of discarding these wastes would be incineration for volume reduction, with or without energy recovery, followed by final disposal, of used geotextile layers and dried captured solids, to landfills as inert material and hazardous material, respectively. Disposal of, even as an inert material is wasteful, environmentally damaging and costly (Landaburu-Aguirre et al., 2016) with the main impact caused by land occupation and transportation.

In contrast, there is another economic model following sustainability principles, the circular economy, based on minimizing waste and the use of resources. This model keeps these wastes in a closed-loop by maximizing the consumption and minimizing waste production (Moradi et al., 2019; Landaburu-Aguirre et al., 2016; Yusuf et al., 2020). The application of this principle brings different potential routes to these wastes, where the selected one should be the most environmentally safe with less energy and materials use. Potential routes are based on the 4R's-D, which are waste reduction (i.e., prevention), reuse, recycle, recovery and lastly final disposal. As waste generation from this project, will continue as the process is applied for lake water eco-remediation. Alternative ways for waste reuse need to be studied based on the circular economy and thus will be the focus of this study.

To prepare materials for re-use checking, cleaning, repairing or recovery should be employed (European Parliament Directive, 2008). Also, to allow this reuse, proper waste management principles, based on detailed characterization of the material are the initial and critical step to be applied (Lawler et al., 2012). This will determine if the potential waste management strategy proposed can be employed. Based on this premise, the aim of this initial study is therefore to investigate potential reuse strategies for waste generated after lake water geotextile filtration based on a proposing methodology for clogged membrane washing as well as dewatering the captured suspended solids. The main outcome of this will be a viability assessment. It will determine if this route is to be followed, what modifications to this process should be made or if any other route needs to be further assessed.

5.2 MATERIALS AND METHODS

5.2.1 Study Materials

Used filter layers were obtained from on-site and in-situ lake water filtration, from mesotrophic lake and eutrophic lake, respectively for two consecutive summers. The layers are composed of woven geotextiles for the in-situ project and nonwoven for the on-site experiment. The clogged geotextile layers were of different apparent opening size (AOS) sizes with captured suspended solids during the approximately 7-day filter run.

The woven membrane combinations used in the experiments were not the same over the two years of the project, the combination for the in-situ project was 1 layer of the commercial mesh (CM) in the first year and 1-2 layers of TE-GMW70 in the second year, 4-5 layers of TE-GMW35 with the addition of one TE-GTT170 was needed. In contrast, the non-woven geotextile filtration was composed of five membranes of different apparent opening size (AOS) (110 µm, 100 µm, 90 µm, 70 µm, and 65 µm). The combination of 7-5 layers of both projects was washed using the method proposed. After washing, only the top and bottom layers of each combination were further characterized in this project. Figure 5-1 presents the non-woven geotextiles before washing.

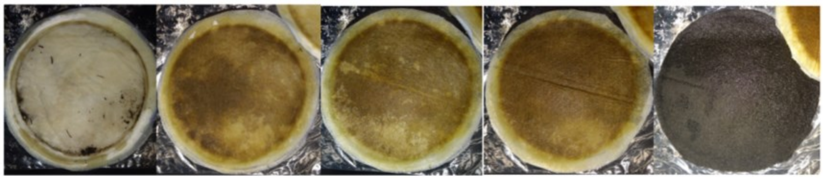

Figure 5-1: Non-woven geotextile before washing process for AOS order: (a) 110 µm (b) 100 µm (c) 90 µm (d) 70 µm and 65 µm

Raw geotextiles' physical and hydraulic characteristics (based on the datasheets obtained from Titan Environmental Containment Ltd.) are defined in detail in Table 5-1.

Table 5.1: Non-woven and woven geotextiles characteristics used in this study

Filters	Material	Apparent Opening Size (AOS) (µm)	Flow rate (L/min/m^2)	Permittivity (sec^{-1})	Mass per unit area (g/m^2)
TE-GMW70	PP	700	2730	0.85	-
TE-GMW35	[a]PP	425	2039	0.70	-

TE- GTX300	[b]PET	110	3900	1.62	350
TE-GTN350B	PP	65	2700	0.56	350

[a]PP: Polypropylene [b]PET: Polyester

5.2.2 Geotextile Washing Proposed Method

The treatment proposed in this work was done with only pressurized tap water inside a gardening pump sprayer. As a quick treatment will be required in-situ when the experiment is deployed, it was by using the described method consider the most coherent, environmentally safe and easily applicable. No cleaning agents were used or planned to be used to remove the fouling on the geotextile, as this could cause further contamination of the liquid waste.

By using a 4L hand pump sprayer, which has a pressure of 45 psi, the tank was filled with 2L of tap water and pressurized by mechanical energy, shown in Figure 5-2. Any electrical energy input for creating a pressurized system not required for this equipment, reducing its environmental footprint. After the necessary pressure was reached, each geomembrane set was washed on both sides following a line pattern. About 200-300 mL were used to wash each geomembrane. The generated leachates were captured completely on a plastic tray. Washed membranes were left to dry at room temperature for 24 hours.

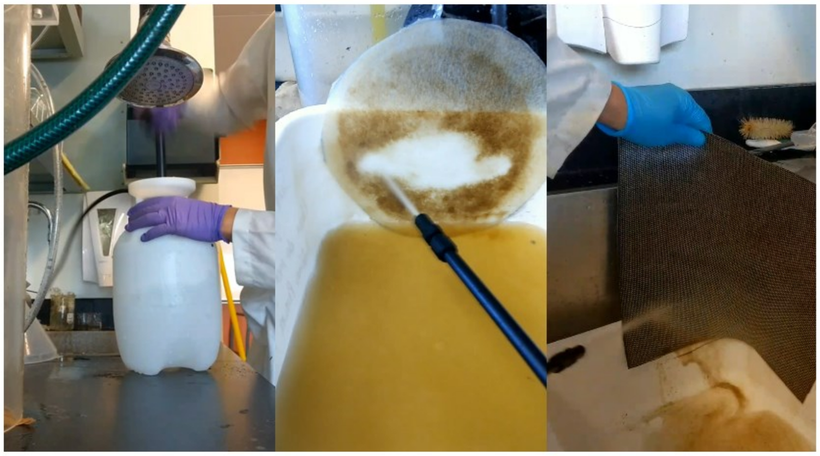

Figure 5-2: Proposed washing method on non-woven and woven geotextiles

5.2.3 Suspended Solid Dewatering

To reduce the liquid waste volume generated, the water content was evaporated at room temperature (i.e., 22 °C) in a plastic tray, during 7-10 days from 2 L to approximately about 300-200 mL. This methodology was chosen because it can be easily applied using sunlight evaporation when the project is being applied on-site/in-situ and does not need any technical training. Concentrated liquid waste was then preserved at 4 °C in a sealed container for further analysis. Water content removal was also evaluated using a drying oven for 48 hours at 60 °C. With this method, it was possible to evaporate 2 L of liquid waste generated to approximately 1.0 g of solid. The temperature was used to avoid losses of components, which are volatile at temperatures above 50 - 60 °C (Förstner, 2004).

5.2.4 Geotextile Assessment after Washing

After drying the washed geotextiles, they were separated by AOS size and stored in tight plastic bags to be prepared or sent for further analysis. Hydraulic geotextile assessments were performed at Geotextile Testing Lab SGI Testing Services, LLC. according to procedures prescribed by ASTM: method for determination of geotextiles AOS (ASTM D 4751), method for determination of permittivity and flow rate (ASTM D 4491).

Unused, clogged and washed filter surfaces (top and bottom) images were taken by a scanning electron microscope (SEM) on a Hitachi S-3400 N using variable pressure mode after coating the geotextile surface with a layer of gold by a gold sputter (QuorumQ150 RES).

5.2.5 Leachate and Solids Analysis

Non-concentrated, concentrated liquid waste and reclaimed suspended solids were analyzed for heavy metal and phosphorus concentrations. Also, for the liquid waste, Chemical Oxygen Demand (COD) and nitrate concentration were determined. Captured solid waste phosphorus and heavy metals content was determined by elemental analysis done by inductively coupled plasma mass spectrometry (ICP-MS) with a quadruple mass analyzer after partial acid-peroxide digestion (HNO_3-H_2O_2) of liquid samples (USEPA 3050B). Liquid wastes were evaluated for dissolved metals and phosphorus content, for this samples were filtered through a 0.45 μm size (Polytetrafluoroethylene) PTFE syringe filter and acidified with 1% HNO_3 and 0.5% HCl before injection on the ICP-MS.

For nitrate (TNT 835, Method 10206, dimethyl phenol method) and COD (TNT 820, Method 10221, reactor digestion method), test kits from Hach Chemicals were used. While the COD parameter requires heat digestion on a Hach DRB 200 heating block and after cooling down, be measured by Hach DR 2800 UV–Vis spectrophotometer, the nitrate was measured in the same spectrophotometer after the required reaction time.

5.2.6 Data Analysis

All variables of the study were analyzed for descriptive statistics including means, medians, variances, maxima, minima, standard deviations, standard errors, and confidence interval when possible. Data are represented as the means ± confidence intervals in the text.

Metal concentrations in liquid waste were compared according to chapter Q-2, r. 19 of the Environmental Quebec Quality Act (2005), Regulation respecting the landfilling and incineration of residual material guidelines and also with the Canadian Water Quality Guidelines for the Protection of Agricultural Water Uses from 1997 to classify its possible reuse (CCME, 2020). Suspended reclaimed solids were compared with the *Politique de protection des sols et de réhabilitation des terrains contaminés* in MDDEPQ (1999).

5.3 RESULTS AND DISCUSSION

5.3.1 Proposed Washing and Drying Solids Method

Using the methodology proposed, a non-conventional washing technique with the use of hand pressurized water without additional chemical and/or additional energy input was used for cake removal. The membranes were washed in packs, with 2L of tap water. More precisely each membrane used 200-300mL of water. The method was efficient for removing visible fouling on the geomembranes, whether woven or non-woven. The process easily detached particles from the membrane surface with the water jet. Used wet geomembranes, the ones removed directly from the filtration unit, presented more efficiency for cleaning other than if they were dried before washing. Figure 5-3 presents one filtration set, before use, after use and washing.

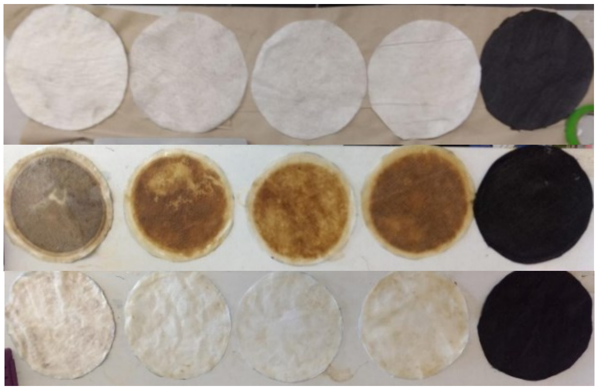

Figure 5-3: Unused, used and washed geotextiles layers (top – bottom) in the following AOS order from left to right (110 µm, 100 µm, 90 µm, 70 µm, and 65 µm)

For the drying method, to reduce waste volume, the applicability of natural evaporation was also proven. Even though there is timeframe constraint, it was observed by letting a low water column (i.e., approximately 8 cm of water column) in a large black plastic container, it has facilitated the reduction. This could be explained as this colour absorbs more heat, evaporation was faster. In future with sunlight use, this method could be further assessed and upgraded. Possible environmental footprint was reduced with this treatment which should lower even more the already minimal cost of the geotextile floating filtration in this project bringing a more sustainable approach. Also, this method could be easily operated by a non-technical person on site.

5.3.2 Washed Geotextile Assessment

Following waste management principles, the first and foremost step for reuse of the washed membranes is to demonstrate if they are comparable with the new materials. If comparable this should enable its reuse, instead of using new layers. In other words, a critical step in this reuse process is validation of the cleaned membrane's integrity and permeability before the membranes can be successfully reused (Lawler et al., 2012).

5.3.3 Hydraulic Testing

Hydraulic testing was performed on the washed geotextile for definition if the process alone was satisfactory for removing the existing foulants on the geotextile membranes. The cleaning process will be effective when the membrane flux is recovered, in other words, when the permeate flow rate reaches a value close to the initial (Coutinho de Paula & Amaral, 2017). Non-woven and woven geotextiles, corresponding to the top and bottom layers of each filter set were analyzed, as shown in Table 5-2. Overall, all geotextiles reached values close to the unused geotextiles, which could enable their reuse.

Table 5.2: Non-woven and woven geotextiles unused and washed characteristics used in this study

	Unused			**Washed**		
	AOS mm	Flow rate l/min/m^2	Permitivity (1/s)	AOS mm	Flow rate l/min/m^2	Permitivity (1/s)
TE GTX300	0.11	3900	1.62	0.141 ± 0.01	4208.25 ± 247.36	1.38 ± 0.08
TE-GTN350B	0.065	2700	0.56	0.078 ± 0.01	1387.25 ± 300.48	0.455 ± 0.10

TE-GMW35	0.425	2039	0.7	0.399 ± 0.01	1565.33 ± 157.92	0.513 ± 0.05
TE-GMW70	0.658	2973	0.98	0.657± 0.12	3042.00 ± 497.22	0.998 ± 0.16

The nonwoven GTX300 presented an increase of 28% of the AOS which could be explained due to the force of the water flow and the energy of the waterhead. This was followed by a slight increase of 8 % of the flow rate that permeates in the membrane, that was within the confidence interval. On the other hand, there was a reduction in the permittivity of 15% of the material. which could be explained as this material was previously used and fully clogged. The reduction of the geotextile's permeability (hydraulic conductivity) is not reversible. The TE-GTN350B has a similar behavior with a slight increase of 20% of the geotextile pore size, followed by a decrease of 51% in the geotextile flow rate which resulted in a permittivity loss of 19%.

For the woven TE-GMW70, the flow rate and permittivity were similar to the unused geotextile, due to that higher pore size which allow easy cleaning by the water jet. On other hand, TE-GMW35 was affected by the filtration order, being after the TE-GMW70, this allowed more solids to pass. This layer was affected by more pressure by the filtration clogging resulting in a reduction in the pore size of 6%, in the water volume filtered by 23% and the permittivity by 27%.

5.3.4 SEM Surface Pictures

To assess the clogged geotextile membrane reuse, the physical status of this generated waste was the second validation of the proposed methodology for cleaning. Also, visual autopsy of the material structure was used to determine if the water jet will affect the filtration media. These results are demonstrated with SEM pictures according to the: non-woven and woven ones.

Non-woven geotextiles presented excellent removal when washed, represented in Figure 5.4. Fibres were about 20 microns in size and were not disrupted by the pressurized jet and its structure remained intact after the process. The first layer (i.e., TE GTX300) of the used combination, showed excellent filtration performance as the fabric had retained high suspended solids loads on the surface as presented in Figure 5.4 (b). In contrast, the TE-GTN350B layer analyzed, which has been protected by the previous layers with larger pore sizes, did not clog on the surface, showed only a small detritus within its depth (Figure 5.4 (h)), which was also removed with the proposed washing. The cleaning method also removed particles that were retained within the geotextile and its bottom side (pictures not presented).

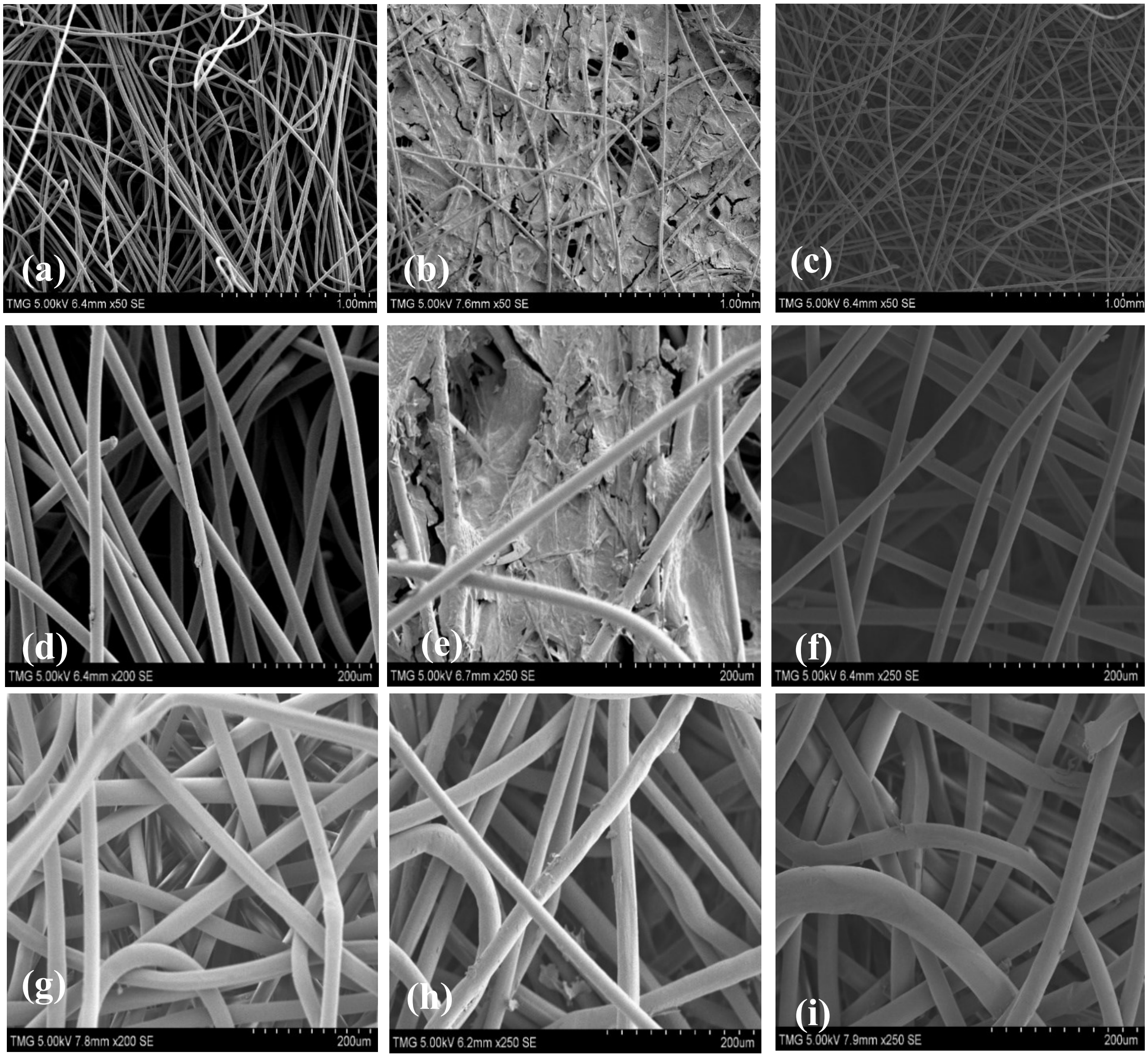

Figure 5-4: Unused, used and washed non-woven geotextiles: (a) Unused TE GTX300 (b) Used TE GTX300 (c) Washed TE GTX300 (d) Unused TE GTX300 (e) Used TE GTX300 (f) Washed TE GTX300 (g) Unused TE-GTN350B (h) Used TE-GTN350B (i) Washed TE-GTN350B

Woven geotextiles which also were used for filtration process presented good recovery after washing. Both woven geotextiles analyzed presented particle accumulation on the top surface, Figure 5-5 (b) and 5-5 (e), possibly reducing AOS and increasing smaller suspended solid capture. As the fibres on those geotextiles are placed like braids, a small relaxing of those was observed after washing. Figure 5-5 (c) and (f), showed the changed structure and increased pore size when compared with 5 (a) and (d), due to particles that were forced throughout it by the water jet. The bottom layer of the geotextile showed few modifications. The top layer was the most affected side as they were in direct contact with the water pressure.

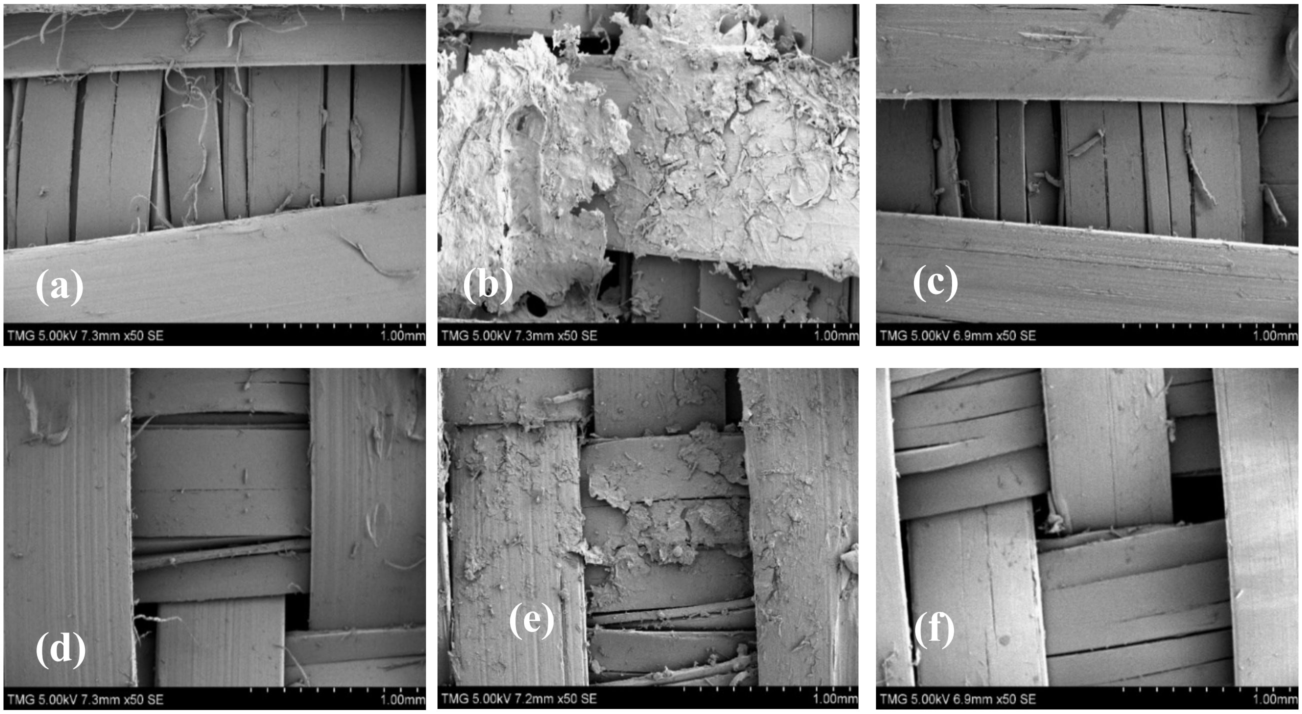

Figure 5-5: Non-woven geotextiles unused, used and washed: (a) Unused TE-GMW70 (b) Used TE-GMW70 (c) Washed TE-GMW70 (d) Unused TE-GMW35 (e) Used TE-GMW35 (f) Washed TE-GMW35

5.3.5 Liquid Waste Assessment

The liquid waste generated in this process was about 2L for each washed set being this woven or non-woven geotextile set. This effluent presented a high concentration of some heavy metals, and in all cases increased concentrations occurred after water evaporation as expected.

As there no specific regulations in Quebec for this waste type and the Q-2, r. 32 - Regulation respecting hazardous materials from the Environment Quality Act of the *Ministère de l'Environnement du Québec*, does not have a complete guideline for leachable materials regarding metal concentrations in this liquid waste. They were compared according to chapter Q-2, r. 19 Regulation respecting the landfilling and incineration of residual materials from the Environment Quality Act (2005) as the quality guidelines for water or leachate released into the environment. Also, for a reuse point of view, the Water Quality Guidelines for the Protection of Agriculture concentrations on Environment were used as a comparison as well (CCME, 2020).

For the diluted liquid waste generated, high concentrations of manganese, copper, zinc and phosphorus were observed, as presented in Table 5-3. Even though they were high, for these specific heavy metals, the values were below the guidelines for Protection of Agriculture which can be used to classify its reuse for irrigation. It is worth commenting, that the following parameters should be taken into consideration, including the amounts of COD and nitrate present in the effluent if reuse is going to be proposed.

Table 5.3: Liquid waste characterization

Contaminants	Woven leachate diluted	Woven Leachate concentrated	Non-woven leachate diluted	Non-woven leachate concentrated	Règlement sur l'enfouissement et l'incinération de matières résiduelles	Water Quality Guidelines for the Protection of Agriculture
Chromium (µg/L)	0.49	0.53	0.68	1.76	50.00	-
Manganese (µg/L)	112.72	500.85	0.33	28.76	50.00	200.00
Cobalt (µg/L)	0.09	6.19	0.10	4.91	-	50.00
Nickel (µg/L)	1.13	3.05	0.34	7.04	20.00	200
Copper (µg/L)	16.66	69.68	20.57	18.12	-	Variable[a]
Zinc (µg/L)	88.12	369.71	29.15	59.28	500	Variable[b]
Arsenic (µg/L)	1.07	5.13	0.13	3.99	-	100
Selenium (µg/L)	0.89	1.16	0.95	1.84	-	Variable[c]
Cadmium (µg/L)	0.03	0.03	0.00	0.01	5.00	5.10
Antimony (µg/L)	0.13	0.57	0.33	0.497	-	-
Lead (µg/L)	0.11	0.19	0.04	0.517	10	200
Phosphorus (µg/L)	120.18	304.74	73.38	139.15	-	-
Nitrate (mg/L)	5.49	16.5	4.47	11.2	10	-
COD (mg/L)	669	4363	844	3430	-	-

[a] 200 µg/L for cereals = 1000 µg/L for tolerant crops; [b] 1000 µg/L when soil pH < 6.5 and 5000 µg/L when soil pH > 6.5; [c] 20 µg/L for continuous use on all soils = 50 µg/L for intermittent use on all soils

Concentrated liquid waste showed particularly increase on concentrations for manganese, zinc and phosphorus in the woven leachate, which were higher than guidelines for water reuse and leachate to be released onto the environment. However, this behaviour was not observed on the non-woven leachate, even though concentrations were higher than diluted waste values, they were not higher than both guidelines. This could indicate that the liquid concentrated wastes should not be mixed for disposal as one of the liquid wastes has its quality is better than the other one when regarding to heavy metals as showed in Table 5-3.

5.3.6 Solid Waste Assessment

The reclaimed solids, obtained after the proposed washing geotextile and dewatering method using evaporation, presented a higher concentration than the liquid waste, as expected. These captured solids have a higher concentration of some metals, even above the Québec regulatory limits for commercial and industrial site use (criteria C) (MDDEPQ 1999) for manganese < zinc < copper as presented in Table 5.4. In other words, these solids cannot be reused even for application as a soil layer for those sites.

Table 5.4: Reclaimed solid characterization after dewatering

Contaminants	Captured Solid Waste	Lake sediment near the filtration experiment	Lake sediment away from filtration experiment	RL		
				A	B	C
Chromium (mg/kg)	38.39 ± 11.39	5.85 ± 0.78	9.77 ± 0.25	100	250	800
Manganese (mg/kg)	3017.82 ±1000.03	84.00 ± 4,08	208.19 ± 1.72	1000	1000	2200
Cobalt (mg/kg)	8.09 ± 2.95	4.55 ± 0.23	6.04 ± 0.23	25	50	300
Nickel (mg/kg)	16.31 ±1.03	5.15 ± 1.94	6.13 ± 0.31	50	100	500
Copper (mg/kg)	619.36 ± 189.16	2.81 ± 0.42	8.59 ± 0.28	50	100	500
Zinc (mg/kg)	1834.41 ± 74.60	42.24 ± 1.45	54.93 ± 2.65	140	500	1500
Arsenic (mg/kg)	13.30 ± 5.71	0.94 ± 0.31	1.79 ± 0.01	6	30	50
Selenium (mg/kg)	2.33 ± 0.37	2.00 ±0.14	3.88 ± 0.42	1	3	10
Cadmium (mg/kg)	0.30 ±0.02	0.07 ± 0.04	0.25 ± 0.01	1.5	5	20
Lead (mg/kg)	45.44 ± 21.15	3.64 ± 0.30	17.65 ± 0,48	50	500	1500
Antimony (mg/kg)	0.82 ±1.07	0.02 ± 0.01	0.06 ± 0.01	-	-	-
Phosphorus (mg/kg)	2123.05 ± 950.37	1240.10 ± 91.65	1826.29 ± 249.12	-	-	-

The higher concentration of the cited metals (manganese < zinc < copper) is explained as follows. Zinc in aquatic environments readily sorbs to sediments or suspended solids, including hydrous iron and manganese oxides, clay minerals, and organic matter (Małecki et al., 2016), resulting in the formation of metallo-organic complexes (Diatta & Kocialkowski, 1998). Copper on the other hand has a strong affinity for particulate matter (Rader et al., 2019) due to sorption to mineral surfaces. Cu^{2+} sorbs strongly to mineral surfaces over a wide range of pH values (Weiner, 2008) and also in organic matter. As explained, they were found in the removed suspended solids which were filter from the water column.

Manganese and phosphorus concentrations in the solids are related. Manganese dynamics have been linked to the mobility of sediment P in many eutrophic freshwaters and marine systems (Pearce et al., 2013). Mn oxides are thought to contribute to sediment reactive phosphorus sorption and release where Mn oxide minerals become reduced and dissolved, potentially important in phosphorus cycling (Lovley, 1991). As particulate phosphorus is removed by this project, this nutrient could be associated with the higher manganese as indicated on the suspended solids captured.

When this reclaimed suspended solid is compared with the heavy metal concentration from the study lake, different behavior is noted for sediment samples near the filtration experiment and far away from it. As the process of dewatering can be considered a concentration process (i.e., after 7 days of suspended solids being concentrated on the geomembranes they were washed with water and evaporated until there were just the reclaimed solids remaining), increasing the heavy metal concentration in this waste. As can be perceived in Table 5.4, some heavy metals presented similar concentrations or only a small increase. This behavior was not observed for the heavy metals that are easily sorbed on the surface of suspended sediments and organic matter (i.e., manganese, zinc, and copper as previously mentioned), which are the particles removed by this geotextile filtration.

For those heavy metals, an increase of a magnitude order of the lake sediment 14 times the original value, 72 times the original value, and 33 times the original value, respectively for manganese, zinc, and copper was obtained. It is worth commenting that the phosphorus concentration on the reclaimed sediment is approximately 2 times the one found in the lake sediment. Heavy metal concentrations in the reclaimed suspended solids are higher than found in the lake sediment for the reasons presented (i.e., filtration and dewatering as a concentration process), and they are not comparable. More precisely, this could be explained as follows: the washing for 1 set of geotextiles, which was used in the experiment for approximately 7 days (i.e., composed of 5-7 geomembranes) with approximately 2 L of water being evaporated naturally or using an external heat source has only generated 1 g of reclaimed sediment to be disposed of.

5.3.7 Possibly Waste Routes and Challenges

As assessed in the methodology proposed, geotextiles can be possibly reused by washing them with pressurized water. This did not affect its physical integrity, permeability and flow rate and possibly indicate that these layers could be successfully reused. The liquid waste generated when diluted can be further reused, only if there is a COD removal technique in place for this effluent. Effluent concentration by evaporation is not recommended as this liquid waste presented a higher heavy metal concentration, which can be difficult to properly treat and dispose of.

Washing liquid waste from woven and nonwoven geotextiles should not be mixed in any way for disposal, and they should be dealt with separately, which was not done in this paper. The concentration of washing liquid waste is only determined for removing the entire water content, for reducing the volume of the reclaimed solids, for final disposal to a specified landfill for hazardous material. Evaporation at room temperature was able to reduce the majority of the water content. It is recommended for applications on site to not use any external heat source and possibly sunlight could be enough for this drying.

5.4 CONCLUSIONS

Towards a circular economy for minimizing waste and the resource use, the potential routes for geomembrane reuse were demonstrated. Using the proposed washing methodology with only a pressurized water jet, fibres were not disrupted on the woven and non-woven geotextile proven by a visual physical structure autopsy. It was shown that the recovered geotextiles exhibited hydraulic proprieties as the flow rate and permittivity to a value close to the unused membranes. When applied on site, this will increase its life span, delaying final disposal. Related to liquid waste, possible reuse could take place, only if further explored for possible methods for reducing concentrations of metals and organic matter. Reclaimed solids after drying cannot be reused as a soil layer in industrial and commercial sites at this moment. Final disposal at a specified landfill for hazardous material would be the proper method. This could be justified as the amount of solid waste produced is low. For future work, it is necessary to analyze if the washed geotextiles when applied onsite/in-situ will introduce any leaching to the surface water. The number of times that the geotextile can be reused without losing its initial characteristics should be demonstrated. Additional sustainable waste management processes should be further assessed and used to avoid final disposal. Related to the remaining wastes (liquid waste and reclaimed captured solids) further assessment needs to be done to propose possible reuse methods or sustainable treatment methods.

AUTHOR CONTRIBUTIONS

Antonio Cavalcante Pereira: Conceptualization, Methodology, Investigation, and Writing – original draft, Dileep Palakkeel Veetil: Investigation, Catherine Mulligan: Supervision, Writing - Reviewing and Editing, Funding acquisition, Sam Bhat: Provision

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CHAPTER 6. CONCLUSIONS

The novel in-situ remediation method based on geotextile filtration proposed by this thesis has demonstrated the hypothesis for lake remediation, that after two consecutive years of removing suspended solids, particulate phosphorus was reduced. The study lake water trophic level, in this study has been decreased to the limit of mesoeutrophic towards the mesotrophic state with just this filtration process without any chemical addition in the first and second year of study. Also, the presented thesis, has proposed a sustainable methodology of lake water remediation. The SDG 6 were as addressed for providing clean water, and possibly restoring the enclosed ecosystem which it was applied (target 6.6) and creating an enabling environment (targets 6.a and 6.b) without signs of eutrophication.

Using this effective economic in-situ eco-remediation method, it is understood that other water types can be remediated with few steps such as: particle size evaluation, nutrient assessment and sediment analysis. Not only shallow lakes (average depth < 2m), as the study lake, can be remediated but also ponds, river sections, coastal regions, and bays that have similar issues. Additionally, as the spatial distribution internal or external loads of nutrients and contaminated sediment, are not homogeneous in the entire water source, the methodology proposed is not intended at the moment for filtering an entire water system. Instead, in the case of this thesis, with a minimally invasive technique for suspended solids removal, highly contaminated areas can be previously assessed and enclosed with turbidity curtains and remediated separately with this filtration technique. By application of this sustainable restoration at the beginning of deterioration can possibly reduce ecosystem degradation and improve the water quality.

Thinking after the eutrophic remediation method, towards a circular economy for minimizing waste and resources, potential routes for membrane reuse as well as for liquid waste were demonstrated. The cleaning process of geomembranes without any chemical additives, using just tap water with a gardener spray, was show sufficient for used geotextile recovery. These ones exhibited hydraulic proprieties values close to the unused membranes (i.e., for the flow rate and permittivity). Liquid waste generated, by the preliminary analysis has shown possible potential for reuse. If the concentration of the liquid waste is required, total dewatering is advised generating a suspended solids waste captured with less volume to be disposed of in a landfill. Out of the 17 goals by the UN, sustainable consumption and production (SDG 12) and the conservation and sustainable use of the oceans, seas, and marine resources (SDG 14) were the most relevant when applying the circular economy and waste management to this project.

Further investigations and development in this project will be possibly done by addressing the following future studies in this remediation method: an increased enclosed area for in-lake remediation, scale-up of filtration unit, application of other geotextile AOS sizes and types, and removal of dissolved COD. Additionally, consideration will be given to the lake water dissolved organic matter characterization, internal release mechanics for understanding on this lake water, and cyanobacteria/cyanotoxin assessment. Related to geomembranes and waste generated in the process, further studies will be done on leaching tests for used geotextiles, geotextile layers reuse in-situ, possible waste routes for used geotextiles after the end of lifecycle, and washing liquid waste reuse applications. Related to the remaining waste (reclaimed suspended solid), further assessment needs to be done to propose possible reuse methods or sustainable treatment for it. As sustainable tracks were suggested, all future work will be intended to close the sustainability loop and strengthen this idea.

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