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Research article

Filtration for improving surface water quality of a eutrophic lake

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A R T I C L E I N F O

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A B S T R A C T

Algal blooms and the presence of cyanotoxins in surface water restrict the public from accessing lakes and beaches for drinking and recreational activities. An effort was taken in this on-site study to improve the surface water quality of a eutrophic lake, which has been under a swimming advisory for many years. A floating filtration unit with non-woven geotextiles as a sole filter media was tested for removing algae, nutrients, and suspended solids from overlying water under different lake conditions. Three non-woven geotextiles of different pore sizes were examined in different combinations and lake water quality was monitored for different physico-chemical, biological parameters. A YSI-EXO2 multiparameter probe was used for continuous online water quality monitoring during filtration. Depending on the initial water quality, excellent removal efficiency was observed as follows: 85–98% turbidity, 98–100% total suspended solids (TSS), 57–88% total phosphorus (TP), 33–66% chemical oxygen demand (COD) and 80–96% chlorophyll *a* (Chl. *a*.). The filtered lake water quality satisfied the norm set for oligotrophic lakes for TP and Chl. *a*. Results from this on-site study are very promising, showing the potential applicability of geotextile filtration as an ecologically attractive technique to improve the surface water quality of small aquatic bodies.

1. Introduction

Lakes with excess nutrient concentrations, particularly phosphorus (P) and nitrogen (N), experience eutrophication-a state of increase in primary production, characterized by dense floating algal blooms and impaired surface water quality (Schindler et al., 2016; Smith et al., 1999). As a freshwater source for drinking and recreational activities, and habitat for both terrestrial and aquatic living beings, eutrophication in lakes can pose serious impacts to the environment, human health and economy (Hudnell, 2010; Le Moal et al., 2019).

In shallow lakes, nutrients are available throughout the water column due to relatively lower water column depth and smaller water volume (Søndergaard et al., 2003; Welch and Cooke, 2005). As phytoplankton grows, nutrients are taken up and removed from the water column and form algal blooms under favorable conditions. Microbial mineralization of a massive number of dead algae after each summer bloom results in the release of nutrients into overlaying water and surface sediment that serves as the sources for the bloom in the next spring. Thus, the blooms persist, which are very common in shallow lakes with existing eutrophication problems. Therefore, removal of algae must be encouraged not only to reduce nutrient concentrations but also to avoid the risk of release of cyanotoxins into the water column and thus to improve water quality.

Suspended solids (SS) such as fine sediments and organic matter (OM) are potential sources of particulate P, heavy metals and organic contaminants in the water column. SS can adversely affect lake water quality and pose risks to aquatic organisms due to their high contaminant load, poor settling (clay and colloids) and high residence time in the water column (Ran et al., 2000). Thus, their removal from the water column is as important as that of algae to control eutrophication and improve surface water quality.

Geotextiles consist of synthetic polymers and are available in two types: woven and non-woven. Non-woven geotextiles are better for particle separation over woven fabrics (Kutay and Aydilek, 2004). As an alternative filter media, non-woven geotextiles have recently been tested for improving stormwater and recreational water quality. Many studies have reviewed the use of non-woven geotextile filters alone or in combination with sand filters for stormwater filtration and have reported significant removal for total suspended solids (TSS), nutrients, and COD (chemical oxygen demand) (Alam et al., 2018a, b; Franks et al., 2015; Paul and Tota-Maharaj, 2015; Tota-Maharaj and Paul, 2015). However, limited studies have been done on the use of non-woven

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geotextiles as a sole filter media for surface water filtration although results from those studies are very promising. Mulligan et al. (2009) and Inoue et al. (2009) examined the use of non-woven geotextiles for treating surface water and reported significant removal for SS, turbidity, total phosphorus (TP), and COD.

Eutrophic lake water is very distinct in terms of high turbidity, TSS and presence of abundant algae in diverse sizes and shapes, which thus can affect treatment efficiency. In this on-site study, an effort was undertaken to evaluate the potential use of non-woven geotextiles to improve the surface water quality of a shallow eutrophic lake by removing algae and SS from overlaying water. A floating filtration unit containing non-woven geotextile filter media was used to evaluate specific in-situ applications in the future. Three non-woven geotextiles of different pore sizes, in different filter combinations, were tested for the filtration of lake water in real lake conditions, with and without the presence of the underlying layer of sediment which can release further nutrients. The main objective of this study is to assess the effectiveness of non-woven geotextiles as a filter media for surface water treatment and the subsequent improvements in surface water quality in terms of nutrient, turbidity and suspended particle removal.

2. Materials and methods

2.1. Site description and field sampling

Lake Caron (45,^{0}08′28″ N; 74,^{0}08′50″ W) is an artificial, shallow, eutrophic lake, located in the municipality of Sainte-Anne-des-Lacs, Quebec, Canada. The maximum and average depths are 2.6 and 1.4 m, respectively. The lake surface area covers 35,300 m^2 with an average water volume of 46,000 m^3 (Abvlacs org., 2020). Surface runoff from the neighbouring forest area, fertilizer runoff and release from the septic tanks in the past are believed to be the reasons for high sediment P content. In the past, the lake was enlarged by cutting down trees, which significantly increased organic matter in the lake sediment due to the remaining stumps and roots. The lake has exhibited floating algal biomass every summer since 2008, and a swimming advisory currently exists at the lake. Fig. 1a shows the map of Lake Caron showing sampling stations and the on-site study area. Water sampling was performed over two consecutive years (from June to October) at selected stations across the lake. The lake water was collected from the surface (0–10 cm depth) using clean, pre-rinsed, amber color HDPE water storage containers from a pedal boat. A Birge-Ekman grab sediment sampler was used to collect surface sediments from stations (St.) 4, 5, 6 and 8. Both water and sediment samples were taken to the laboratory in a cooler on ice and stored at 4 °C for different physico-chemical analyses.

2.2. On-site geotextile filtration test

A large rectangular plastic tank with a 540 L total capacity (35.6 cm height) was used for filtration tests. The filtration unit consists of two open cylindrical columns, made of plexiglass of the same diameter (20 cm) with a rectangular base at one end. The two columns were mounted together by attaching the square bases with removable screws. Non-woven geotextile filters were sandwiched between the two bases as shown in Fig. 1c and d.

A piece of styrofoam was used to float the filtration unit in the tank. A submersible fountain pump with flow rate (5–7 L/min) was used to pump the tank water into the filtration column. The pump was electronically controlled by a float level switch (located at an 18 cm height) to avoid overflow in the event of filter blockage.

This filtration study was performed over two consecutive summers. In the first summer, different combinations of four non-woven

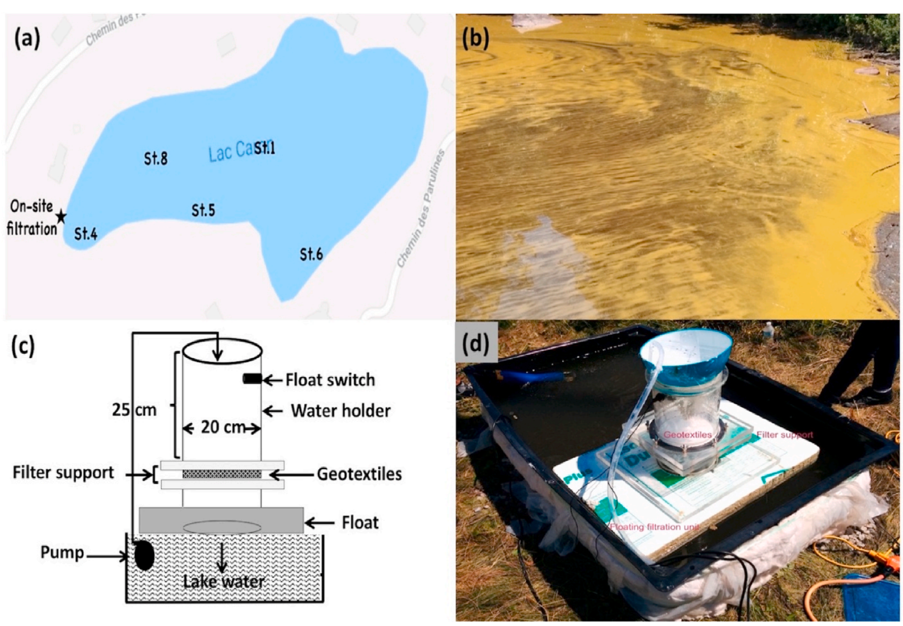


Fig. 1. (a) Lake Caron map showing sampling stations (source: google map), (b) algal bloom at St. 4 in Lake Caron, (c) schematic and (d) photo of on-site filtration set up.

geotextiles with pore sizes ranging from 75 to 110 μm were tested for different water qualities, by adjusting lake water turbidity and TSS with fine sediments, to select a suitable filter combination for better nutrient and TSS removals (Sarma, 2016). In the second stage, additional filtration tests were conducted to validate the results with selected filter combinations from the previous stage. A site, close to St. 4 was used in the second phase as this station was often found with massive algal blooms, due to currents and wind. Two kinds of tests were performed in this stage: (i) filtration of lake water alone, and (ii) filtration of lake water with sediment at the bottom of the tank.

For tests with lake water alone, about 300 L of lake water were filtered in each batch, without adjusting turbidity or TSS, through a set of selected non-woven filters for 4 days continuously. The filtered water quality was monitored for different physico-chemical parameters. During filtration, the entire tank water was mixed well to filter out all SS in the tank using a mixing pump and three other submersible pumps. The rising water head and flow rate through the filter were measured regularly and clogged filters were removed accordingly. For filtration tests with an underlying sediment layer to simulate more closely actual lake conditions, the calculated quantity of surface sediment (3.56 kg dry weight) from St. 4 was gently added with the lake water (300 L), resulting in a final solid content of 1.15% (w/v). As sediment addition resulted in a very high initial turbidity in the tank water, 3–4 days of settling were allowed before filtration. Mixing pumps at very low speed, near the surface, were used.

2.3. Non-woven geotextiles as filter media

Custom-made non-woven geotextiles obtained from Titan Environmental Containment Ltd. Manitoba, Canada, were used as filter media for this study to capture the SS and algae in the lake water. The selection of geotextiles for the filtration was primarily based on their apparent opening sizes (AOS). Table 1 summarizes the physical properties of geotextiles used for the filtration tests. The TE-GTN and TE-GTX series geotextiles were made using needle punched staple fibers and continuous filaments, respectively.

2.4. Physical, chemical, and biological analysis

Hach Chemicals test kits were used to analyze TP (Method 10,209, ascorbic acid), total nitrogen (TN) (Method 10208, persulfate digestion), nitrate (NO_3^-) (Method 10206, dimethyl phenol) and COD (Method 10221, reactor digestion) in water samples (Hach, 2020). For analyzing the total P, N, and COD, water samples were first acid digested on a Hach DRB 200 heating block and then measured in a UV–Vis spectrophotometer (Hach DR 2800). Total dissolved phosphorus (TDP), total dissolved nitrogen (TDN) and dissolved COD (DCOD) were also measured using the test kits after filtering water samples through a 0.45 μm syringe filter. Chemical analysis was verified by running blanks and two standards for every batch and triplicates were run for each parameter. The particle size of SS in water samples was determined with the help of a laser scattering particle size analyzer (LA-950V2 Horiba particle size analyzer). The method APHA 2540 D was used for TSS measurements (APHA, 1998). A YSI-EXO2 multiparameter probe from Hoskin Inc. was used to monitor real-time water quality during sampling and experiments. The probe was equipped with multiple sensors and capable of measuring pH, dissolved oxygen (DO), temperature (Temp.), oxidation-reduction potential, conductivity, turbidity, total dissolved solids (TDS), chlorophyll *a* (Chl. *a*) and blue-green algae-phycocyanin (BGA-PC) in the water. The probe was provided with an automatic antifouling wiper for cleaning the sensors and thus made its application for both spot and continuous, long term, monitoring. For the filtration test, the probe was deployed with a 1-h logging interval to read water quality. In addition to using a YSI probe, turbidity was monitored using an Oakton turbidity meter and the results were compared from both methods. Phytoplankton analysis of lake water was performed at University of Quebec at Montreal after fixing the samples immediately with Lugol's solution (Iodine solution, 0.2–0.4 mL/100 mL sample). Surface images of raw and clogged filters were taken by a scanning electron microscope (SEM) (Hitachi S-3400 N variable pressure mode) after coating the filter surface with a thin layer of gold by a gold sputter (QuorumQ150 R ES).

Table 1
Technical data sheet of geotextiles used in this study (Source: Titan Environmental Containment Ltd.).

Filters	AOS (μm)	Flow rate (L/m^2/min)	Mass/unit area (g/m^2)	Material[a]	Permittivity (sec^{-1})
TE-GTX 300	110	3900	300	PET	1.62
TE-GTN 300	90	3300	300	PP	0.75
TE-GTN 350 A	75	2700	350	PP	0.56

[a] PET: Polyester; PP: Polypropylene.

Analysis of heavy metals and phosphorus in sediment samples was done by using ICP-MS (Inductively Coupled Plasma Mass Spectrometer, Agilent 7700 Series), after performing a partial nitric acid-hydrogen peroxide digestion (HNO_3–H_2O_2) of powdered sediment sample using a Digi prep acid digester (Digi prep, SCP Science) (U.S.EPA, 1996). Certified reference material (Enviro Mat II, obtained from SCP Science, Canada) was used for quality control for acid digestion and analysis. Water samples were filtered through a 0.45 μm size PTFE syringe filter and acidified with 1% HNO_3 and 0.5% HCl for measuring dissolved metals.

3. Results and discussion

3.1. Water and sediment quality

Lake Caron water quality over the two year period is given in Table 2. The lake water pH varied between 6.7 and 7.1, which is within the range recommended (pH 6.5–9) for protecting aquatic organisms in surface water in Canada by CCME (Canadian Council of Ministers of the Environment) (CCME, 2008).

Table 2
Lake Caron water quality.

Water quality parameters	Year 1[a]	Year 2[b]
TP (μg/L)	49.6[c]	36.5 ± 7.8
COD (mg/L)	24.4 ± 4.5	28.6 ± 7
TN (mg/L)	1 ± 0.11	0.99 ± 0.1
NO_3^--N (mg/L)	0.2 ± 0.04	0.25 ± 0.1
TSS (mg/L)	4.4 ± 1.1	4.95 ± 3.7
Turbidity (NTU)[d]	NA	17.1 ± 7.6
YSI-EXO2 Probe data		
Temp. (°C)	21.7 ± 0.7	24.3 ± 2.3
Conductivity (μS/cm)	24	24 ± 2
TDS (mg/L)	NA	16 ± 1
DO (mg/L)	7.4 ± 0.3	8 ± 0.9
pH	7 ± 0.3	6.7 ± 0.4
ORP (mV)	176 ± 21	338 ± 14
Turbidity (NTU)	2.5 ± 1.7	19.8 ± 6.6
Chlorophyll (μg/L)	NA	6.5 ± 2.3
BGA-PC (μg/L)	NA	0.6 ± 0.1

[a] No. of samples analyzed:12; YSI-EXO2 data based on single deployment (June).
[b] No. of samples analyzed: 7; YSI-EXO2 data from three deployments (August).
[c] Average of two readings.
[d] Turbidity by Oakton turbidity meter; NA: Not available.

The lake water had poor transparency due to algal suspension. According to the data from MDDELCC (Ministère du Développement Durable de l'Environnement et de la Lutte contre les Changements Climatiques), Quebec, Lake Caron water transparency was reduced to its lowest value of 0.6 m in year 2. Particle size analysis of water samples showed 50% (d_{50}) and 90% (d_{90}) of SS were under <22–30 μm and <80–116 μm. TP concentration in the lake water exceeded the lower range (30–100 μg/L) set for eutrophic lakes in Quebec by MDDELCC and its concentration varied from 36.5 to 49.6 μg/L. TP concentration should be controlled below 30 μg/L, as a preventive measure to avoid eutrophication in freshwater systems. The average Chl. *a* concentration was 6.5 ± 2.3 μg/L with a maximum value of 8.1 μg/L. The recommended concentration range of Chl. *a* for eutrophic lakes is 8–25 μg/L.

The COD concentration in Lake Caron water samples varied between 24 and 29 mg/L. TDS concentration was about 16 mg/L, which is assumed to be mainly due to the dissolved organics as DCOD values were close to the TDS concentration. Due to a massive algal bloom in year 2, the lake water turbidity reached up to 32.4 NTU.

The concentrations of heavy metals in the lake water (dissolved) and surface sediments were below the norm set for the protection of freshwater aquatic organisms in Quebec and Canada (MDDELCC, 2020; CCME, 2020). The sediment P concentration varied between 866 and 1298 mg/kg, and relatively high P concentrations were found in sediments from St. 4 and St. 8 (Table S1, supplementary data).

3.2. Geotextile filtration

3.2.1. Preliminary filtration tests

A total of 14 filtration experiments were conducted using the following filter combinations: TE-GTX 300 (110 μm) alone, TE-GTX 300 & TE-GTN 300 (90 μm), and TE-GTX 300 & TE-GTN 350 A (75 μm). Each combination consisted of four to five layers of filters of the same or different type, arranged in descending order of their opening sizes. The tests were done at different initial turbidity values, between 4 and 19 NTU. The best removal rate for TP, TSS, and turbidity was obtained with the filter combination of TE-GTX 300& TE-GTN 350 A and thus this combination was selected for further tests in the second phase (Sarma, 2016).

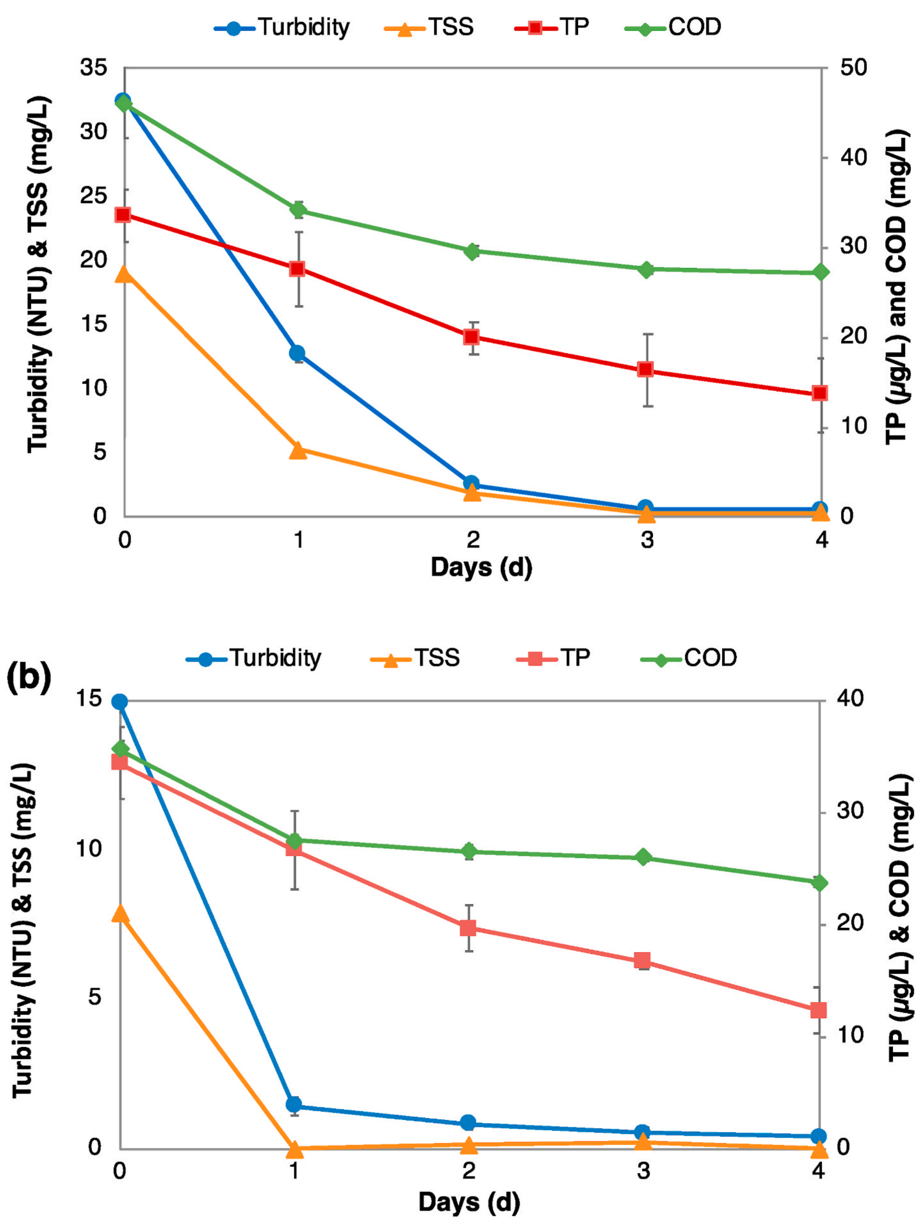


Fig. 2. Turbidity, TSS, COD, and TP removals during filtration (a) test 1 and (b) test 2.

3.2.2. Extended filtration tests with selected geotextiles

(i) Filtration of lake water alone

A total of five batch filtration experiments were conducted in the second phase. The lake water quality for each test was different, which is common and expected in natural systems like lakes, especially in the summer when primary production is high. A combination of three TE-GTX 300 (110 μm) and one TE-GTN 350 A (75 μm) at three different turbidity values: 32.4 (test-1), 14.9 (test-2), and 10.4 (test-3) NTU were tested. During the test, clogged filters (when the water head reached 16 cm or above) were replaced with clean ones. A total of 15 and 11 filters were used in 4 days of operation for tests 1 and 2, respectively.

In most cases, the top filter clogged rapidly and had to be removed in the first few hours of filtration as more TSS and turbidity (50–60%) removal occurred in this period. During filtration, the algae forms a biomass layer on the filter surface by interlacing with the filamentous fibers on the non-woven fabric. This reduces the filter pore size and leads to a complete clogging of the filter in a short time with rising water head, especially for cases with high turbidity. The SEM images of unused and clogged TE-GTX 300 filters are given in the supplementary data of Fig. S1. While large algae are mainly retained on the surface of the top filter, fine sediment particles and microscopic algae were trapped on/into the inner filter layers. The TE-GTX filter was thicker than TE-GTN and had a good solid retention capacity. Using multiple layers of filters may enhance capturing particles in each layer, but on the other hand a significant reduction in filter permittivity and flow throughput can be expected. The initial flow rate and permittivity for test 2 were 86.4 m^3/m^2/day and 5×10^{-2} sec^{-1}, respectively. The permittivity was reduced by half in the first 2 h of test 2.

The changes in water quality for turbidity, TSS, COD, and TP, during tests 1 and 2 are given in Fig. 2. As seen in Fig. 2a, high turbidity (from 32.4 to 0.6 NTU) and TSS (from 19 to 0.4 mg/L) removal was observed during filtration, yielding an overall 98% removal at the end for test 1.

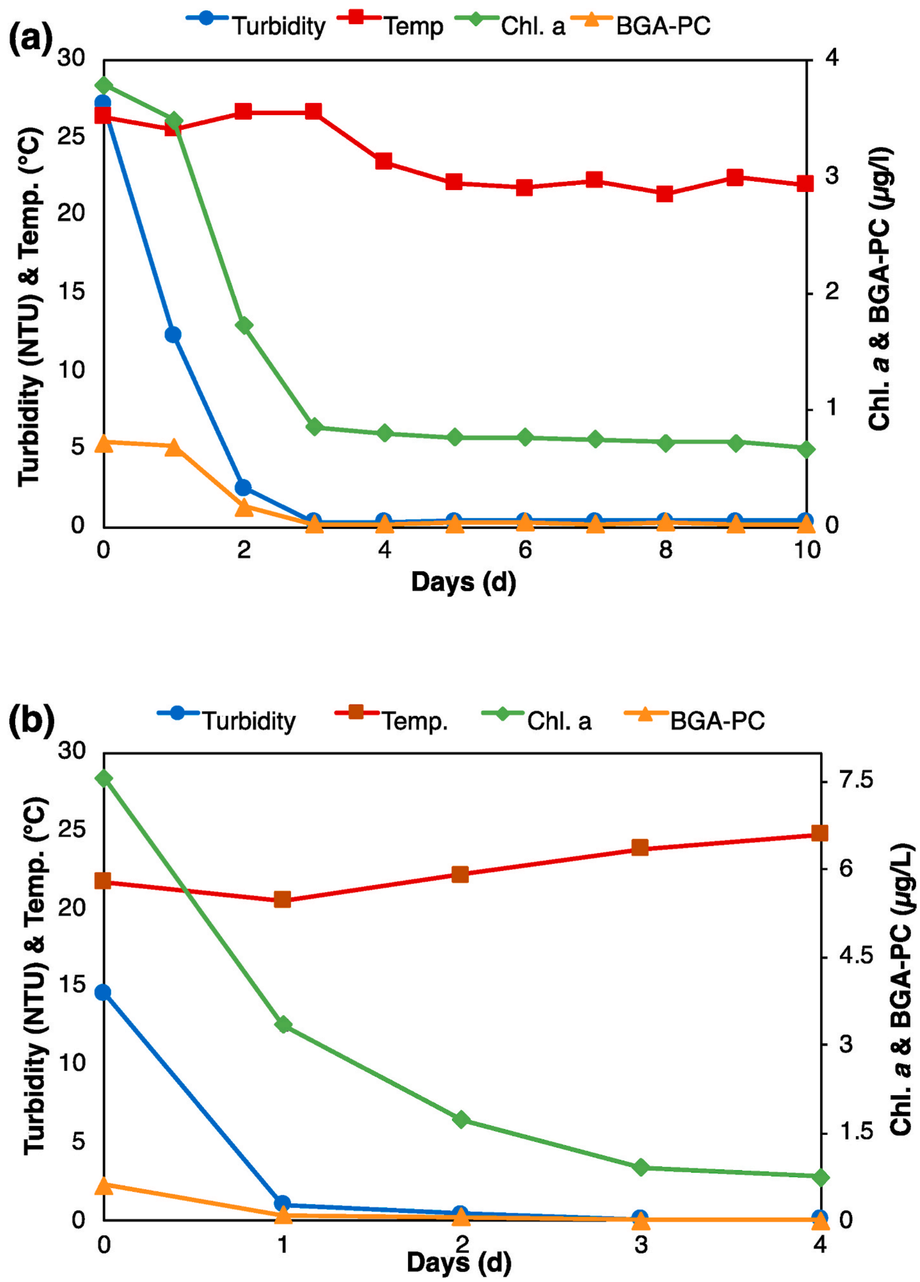


Fig. 3. YSI-EXO2 probe data for turbidity, temperature, Chl. a and BGA-PC for (a) test 1 and (b) test 2.

Most of the turbidity and TSS removals occurred within a day and a statistically significant correlation ($R^2 = 0.9835$, p-value < 0.001) was observed between them, indicating the lake water turbidity was mainly due to the suspended particles, with the least influence from color. Excellent TSS (100%) and turbidity (90%) removal were attained for test 2 (Fig. 2b) in a day, compared to test 1. This can be related to less filter clogging due to relatively low TSS and turbidity in the lake water. The higher the TSS and turbidity, the sooner the filter blocks.

SS are sources of particulate P and COD in the water column and their removal by filtration was accompanied with the removal of TP and COD. As filtration proceeds, the TP concentration in the filtered water was gradually reduced and yielded 59% and 64% removal for tests 1 and 2, respectively. Final TP concentration in the treated water was varied between 12 and 14 μg/L (Fig. 2). Initial TDP concentration in the lake water was between 10 and 14 μg/L, which was later reduced to 3–12 μg/L (not given). This means just removing the particulate form of P could bring the TP concentration in the lake water within the norm set for an oligotrophic or mesotrophic lake. Unlike turbidity and TSS, removal efficiency for TP was a little low, which is expected as 30–40% of initial TP was in its dissolved form. Low removal of dissolved organics and nutrients may be possible by adsorption on the solids that are captured on the filter surface. However, for better removal, an adsorbent may need to be incorporated with the filter media. COD removal was associated with the removal of algae and suspended organic matter. Unlike TP, overall COD removal rate was very low as 60–70% of the COD was in its dissolved state which is less likely to be removed by filtration.

TN associated with the algae and OM was removed (24–50%) by filtration. However, no removal was observed for NO_3^- (not given) as it was mostly in the dissolved form. Instead a small increase in its concentration was observed over time. This could be due to microbial oxidation (nitrification) of reduced nitrogen species (NO_2^- and NH_4^+) in the water (Kozak et al., 2017). The strong and continuous mixing of tank water might have provided favorable conditions, like high DO, for nitrifying bacteria for the oxidation of reduced nitrogen species in the water. In the ecosystem, nitrogen is present in its gaseous (N_2), dissolved (NO_3^-, NO_2^-, NH_4^+) and particulate forms and cycles through different phases by microbial activities. Thus, its removal from the lake ecosystem is not as feasible as for the limiting nutrient P.

The YSI-EXO2 probe data for temperature, turbidity, Chl. *a* and BGA-PC during filtration is given in Fig. 3. As seen in Fig. 3, Chl. *a* and BGA-PC removal were accompanied by turbidity removal.

About 79–90% Chl. *a* and 96% BGA-PC removal were obtained during filtration and their final concentration in the filtered water was 0.8 and 0.02 μg/L, respectively. During test 1, filtration was stopped at day 4 as scheduled and the system was idled for an extra week to see any algal growth in the filtered water. Both Chl. *a* and BGA-PC concentrations remained the same after the filtration stopped, and no algal growth was observed even with a day time surface water temperature of 22–25 °C (Fig. 3a). This could be due to insufficient nutrient concentrations in the filtered water for algae to grow. However, it must be noted that in real lake conditions, nutrients can be replenished into the overlying water from bottom sediments by diffusion and sediment resuspension which is not the situation in the tank.

In test 3 (turbidity 10.4 NTU and TSS 7.8 mg/L), the filtration was continued with partially clogged filters with a water head of 16.5 cm (final permittivity was 1.7×10^{-2} sec^{-1}). The pump was in an on/off mode depending on the height of water to the float switch. A good removal was observed for TP (50.5%), TSS (99%), Chl. *a* (88%), BGA-PC (97%) and turbidity (96%), although the filtration performed with a partially blocked filter (results are not given).

(ii) Filtration of lake water with sediment

Lake water quality before adding the sediment was as follows: TSS (9.5 mg/L), TP (32 μg/L), COD (38.5 mg/L), turbidity (12.4 NTU) and TN (0.76 mg/L). Sediment addition resulted in a very high initial turbidity (202 NTU) and Chl. *a* concentration (19.9 μg/L) in the water. Thus, the whole system was idled for 3–4 days to allow for natural settling before the test began. Approximately 76% of the turbidity and 85% of the Chl. *a* were removed, according to YSI data, from the water column by settling. The resultant water had TSS (32.5 mg/L), TP (229 μg/L), COD (60.1 mg/L), turbidity (44.4 NTU), TN (2.3 mg/L), Chl. *a* (2.9 μg/L) and BGA-PC (0.2 μg/L) and used for filtration (exp. 1). The experiment started with the same filter combination that was used for lake water alone and continued for 17 days. Because of the high turbidity and TSS, the filters rapidly clogged initially and were replaced by new sets. A total of 16 filters were used in the first 3 days of filtration and thereafter the experiment ran without any filter replacement.

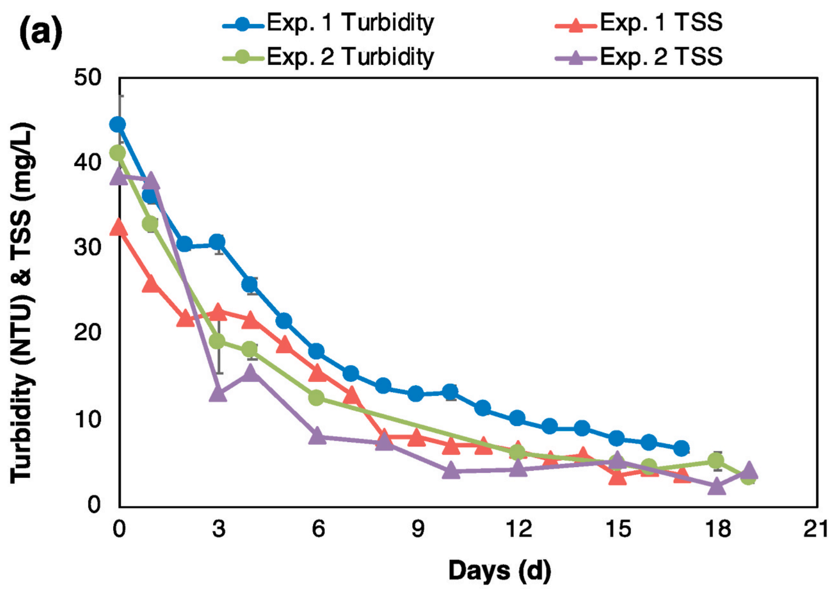
The filtration test with the sediment (exp. 2) was repeated using the same procedure as discussed above, except for the filter combination used. For exp. 2, the following filter combinations were tried: two TE-GTX 300 (110 μm) & three TE-GTN 350 A (75 μm) and two TE-GTX 300 & three TE-GTN 300 (90 μm). Initial water quality used for exp.2 was TSS (39 mg/L), TP (197 μg/L), COD (64 mg/L), turbidity (46 NTU), TN (2.7 mg/L), Chl. *a* (6.2 μg/L) and BGA-PC (0.4 μg/L). A total of 18 filters were used over the 19 day long test. The TSS and turbidity level used in both filtration experiments was extremely high and such conditions are very rare in Lake Caron.

Fig. 4(a and b) shows the filtration results of exp. 1 and 2 for different water quality parameters. As seen in Fig. 4a, both turbidity, and TSS were reduced gradually over time and showed similar removal patterns for both exp. 1 and 2. Both turbidity and TSS removal were low in the first few days due to filter blockage. Initially, slightly better TSS and turbidity removal were observed for exp. 2 than exp. 1, possibly because of using more layers of the filter with a small pore size. A significant correlation was found between TSS and turbidity ($R^2 = 0.9170$ and p-value < 0.005). A total of 89% TSS removal obtained for both experiments. The turbidity removal varied between 86 and 92%.

Fine suspended sediments such as colloids, clay, silt, and particulate OM are a potential source of contaminants, like heavy metals, nutrients, and organic compounds, in surface water. As contaminated suspended sediments can adversely affect the surface water quality, their removal is very important in the context of remediation of surface water and sediments (Mulligan et al., 2009). TSS removal not only reduces inorganic and organic pollutants in surface water but also could improve the bacteriological quality of water by removing pathogenic bacteria. Many studies reported a direct correlation between the presence of total coliform and fine SS in surface water (Hipsey et al., 2006; Przybyla-Kelly et al., 2013). In an in-situ study, Lowe (2008) reported 93% total coliform and 73% fecal coliform reduction in recreational water by removing TSS with the help of a floating non-woven turbidity curtain (150 μm pore size).

Fig. 4b shows the changes in TP and TDP concentrations in the lake water during filtration. The lake water had a relatively high TP (230 and 197 μg/L, for exp. 1 & 2, respectively), attributed to the presence of P bearing sediment fines in the water. Lake Caron sediments contained a high level of P (1298 ± 88 mg/kg in St.4 sediments) and removing P bearing fine sediment particles, other than floating algae, can significantly reduce TP concentration in the overlying water. A statistically significant correlation was found between TP and TSS in this study ($R^2 = 0.9134$ and p-value < 0.001) (Fig. 5b). A slight increase in the concentration of TDP in the water was observed and this could be due to the release of P from sediment by microbial degradation of dead algae at the bottom. A close look at the conductivity and TDS profile (not given) during the experiment showed a slight increment in their values with decreasing temperature, and this could probably be due to the release of nutrients and dissolved organics. Considering the initial and final concentrations, the average TP removal was about 82%. TP and TDP concentrations in the final filtered water were 35 & 42 μg/L and 12 &18 μg/L, respectively for exp. 1 and 2 (Fig. 4b).

Fig. 5a shows the filtration removal of both COD and DCOD. Sediment resuspension led to high COD (60–64 mg/kg) in the overlaying



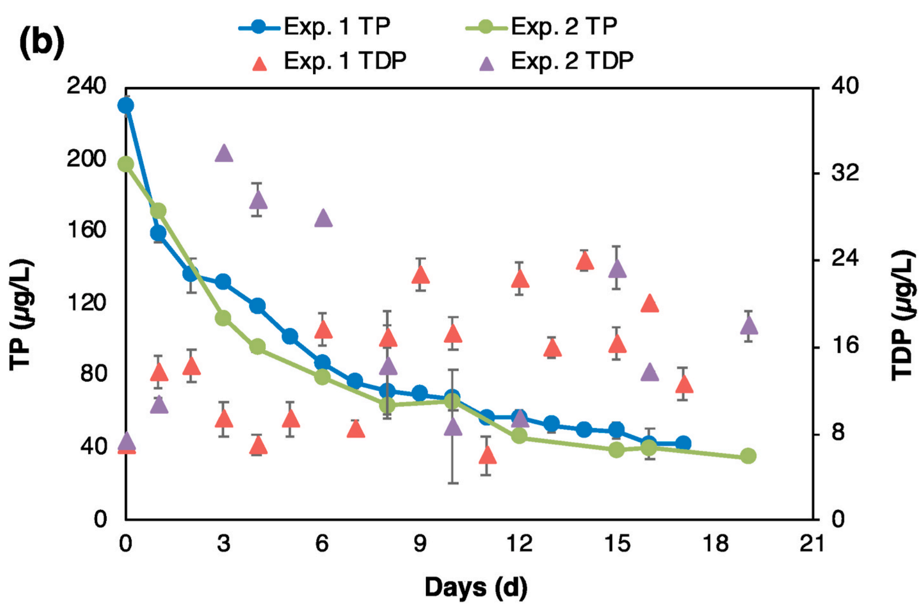


Fig. 4. (a) Turbidity &TSS and (b) TP&TDP changes during filtration tests.

water due to the resuspension of sedimentary OM. Organic pollutants and oils are known to be associated with OM due to its hydrophobic nature. Besides, heavy metals have a strong binding affinity and form stable complexes (e.g., copper) with OM (Fukue et al., 2012; Ran et al., 2000). Thus, removal of heavy metals and organic contaminants can also be accompanied by the removal of OM from the surface water, which in turn is associated with the removal of TSS. The filtration results from both experiments showed 63–66% removal for COD, whereas the DCOD concentration did not change much during the tests and yielded 14–18% removal. A statistically good correlation was found between TSS and COD ($R^2 = 0.9089$, p-value < 0.001) (Fig. 5b).

No significant removal was observed for TN and NO_3^- during filtration as they were mainly (>80%) in their dissolved forms. The concentration of NO_3^- was found to slightly increase during the test and this could be possibly due to the oxidation of reduced forms of nitrogen (NH_4^+, NO_2^-) by nitrifying bacteria in the lake water and sediment (Fig. S2, supplementary data).

The YSI probe data for Chl. *a* and BGA-PC is given in Fig. 6. Due to some technical issues the probe was used only for 12 days for exp. 1. Both Chl. *a* and BGA-PC concentrations were found to decrease with the removal of turbidity and TSS. Overall, removal of Chl. *a* was 56% for exp. 1 and 85% for exp. 2, and BGA-PC removal was 61 and 69%, respectively. The turbidity readings from both the YSI probe and Oakton turbidity meter were well matched. In the tank, due to the low water column depth, nutrient removal by particle settling could also be suspected, in addition to filtration. According to the probe data, about 70% of the turbidity by sediment resuspension was removed in the first 2 days of settling and no significant removal was observed thereafter by settling, indicating that the water column contained mainly fine sediment clays and silts with poor settling. Thus, the treatment removal reported here for different water quality parameters was exclusively by filtration.

The filtration efficiency on removing algae was further confirmed by performing phytoplankton analysis of water samples collected on days 0, 4 and 17 (final) during the filtration exp. 1. The water samples were counted for different phytoplankton species and expressed for their

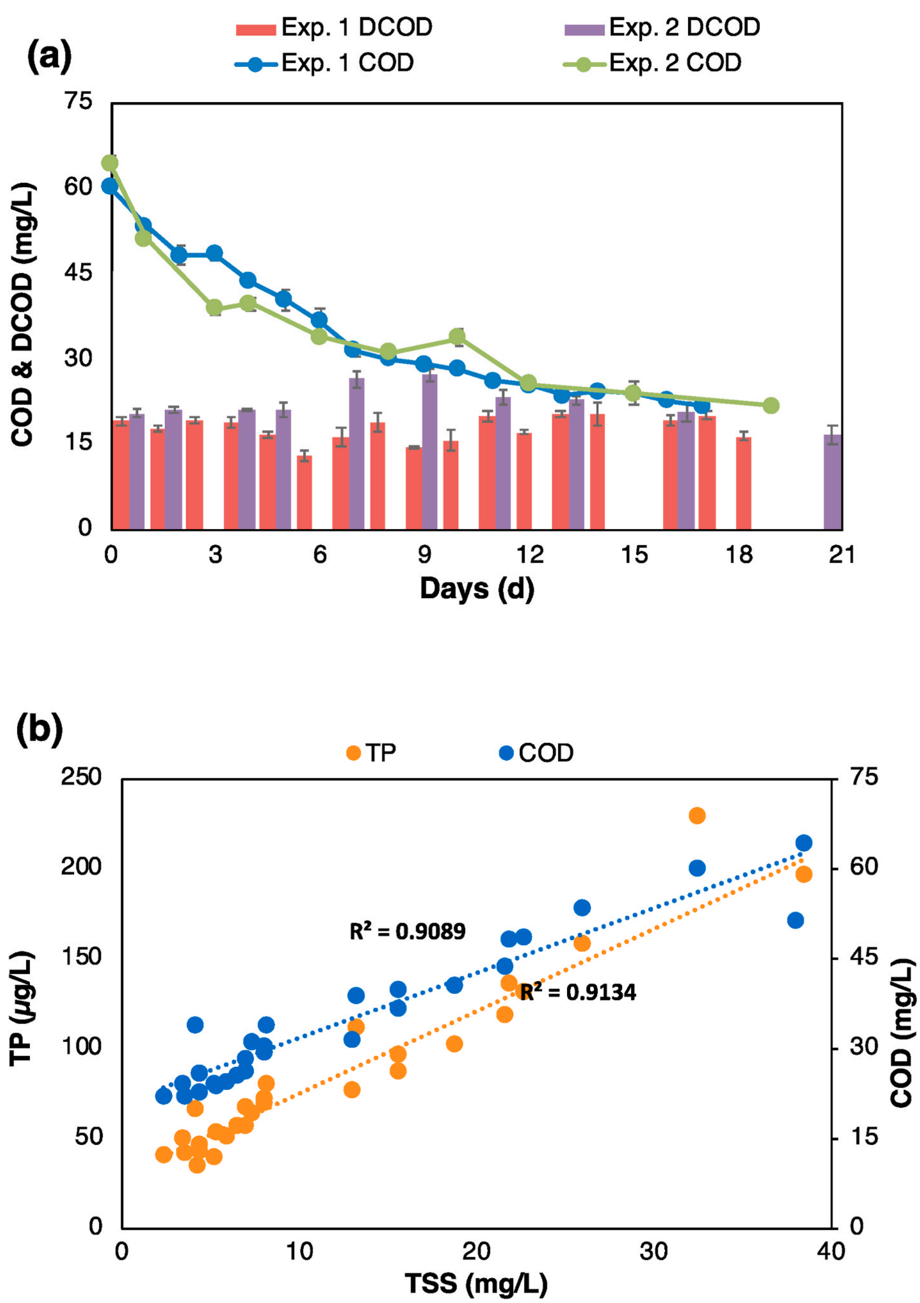


Fig. 5. (a) COD and DCOD changes during filtration and (b) relation between TSS, TP, and COD.

abundance as cells/L. The lake water sample before sediment addition had a total of 48 species (sp.) from 17 groups (classes) with a total abundance of 3.5×10^8 cells/L. The major groups according to their abundance were *Cyanophyceae* (89.6%, 5 sp.), *Chrysophyecae* (2.3%, 7 sp.), *Cryptophyceae* (0.28%, 7 sp.), and *Chlorophyceae* (0.1%, 7 sp.). The remaining groups were smaller in species number and population (21 sp. from 13 classes) and categorized as "miscellaneous", which accounted for 7.8% of the total phytoplankton. Among the five species identified in the class *Cyanophyceae*, *Woronichinia naegeliana* sp. (91% of the total Cyanophyta) was the most abundant sp., followed by *Aphanothece clathrata brevis sp.* (6.5%) *Microcystis aeruginosa* sp. (1.1%), *Aphanocapsa parasitica* sp. (0.74%) and *Coelosphaerium kuetzingianum* sp. (0.6%).

The sample collected on day 0 had a relatively smaller phytoplankton diversity, comprising only 26 species from 14 groups, with a total abundance of 7.12×10^8 cells/L, twice the population before the sediment resuspension. Abundance and removal of phytoplankton on different days of filtration test are shown in Fig. 7(a and b).

Cyanophyceae was the major phytoplankton group in every sample that was analyzed. Most of the phytoplankton were removed in the first four days and their removal was 88% *Cyanophyecae,* 69% *Chrysophyecae,* 100% *Cryptophycae* and 70% others.

The abundance of phytoplankton before and after filtration were 7.12×10^8 and 1.02×10^7 cells/L, respectively, yielding an overall algal removal of 97%. During geotextile filtration various types of phytoplankton will be captured and removed and no selective separation of a specific phytoplankton group is possible by this method. However, as there are still significant amounts of phytoplankton remaining, there will not be an overall negative impact on the lake ecosystem.

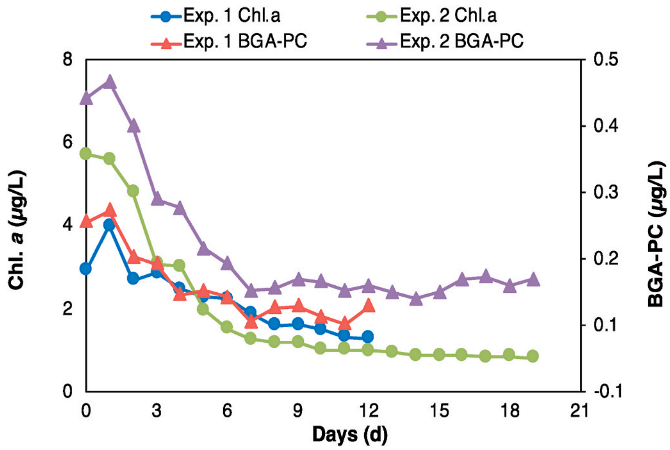


Fig. 6. Chl. a and BGA-PC changes during filtration.

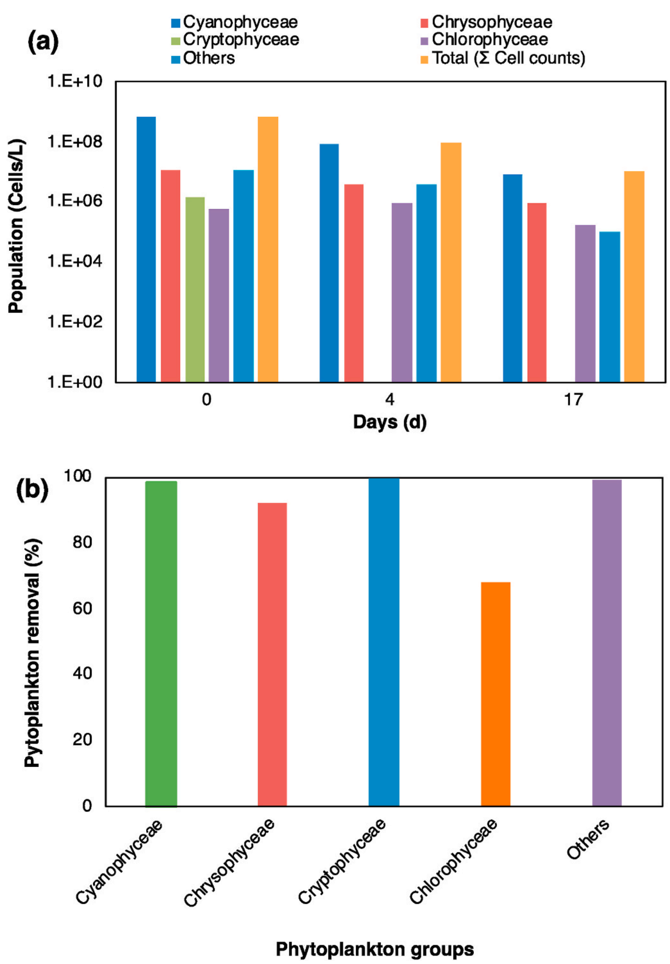


Fig. 7. (a) The abundance of phytoplankton and (b) removal of phytoplankton during filtration (exp. 1).

3.3. Scope, potential applicability and challenges of geotextile filtration for surface water treatment

In this research study, the filtration of lake water with a wide range of turbidity (10.4–32.4 NTU) and TSS (7.8–19 mg/L) was successfully treated. The results obtained show the potential applicability of geotextile-based filtration system for treating surface water quality in ponds or small, shallow lakes (with average depth <2 m) where a lack of space for treatment is also an issue. The simple design and flexibility make this unit ideal for localized application in which a specific area of the water body with massive algal blooms can be treated by containing those areas using a floating turbidity curtain. Once the water quality is improved, the unit can be removed. For example, in the case of Lake Caron massive algal blooms were often found at St. 4 (Fig. 1b) and surrounding areas. Therefore, isolating and treating those areas with multiple units would be more economic and efficient instead of filtering the whole lake. As non-woven geotextiles show excellent liquid/solid separation, this filtration approach could be used at ports and harbors for both sediment and surface water treatment where removal of contaminated fine sediments and OM from liquid phase are subjects of interest.

The main problem associated with the filtration of eutrophic water is the rapid clogging of geotextiles by algae which forms a passive algal layer on the filter and thus reduces the treatment throughput. Thus, adequate removal or clean-up of the clogged filter is required to increase filtration performance. As mostly the top layer clogs rapidly, removal of this layer, which is simple to perform, could improve the filtration rate and avoid any kind of leaching from the biomass that is retained on the filter. However, clogging of the filter is a potential issue in the long run as it makes the treatment more costly. Therefore, reuse of filters must be studied which is a future subject of this work. Inorganic solids can likely to be dislodged from the filter fabric by applying a high-pressure jet wash. However, removing the algal biomass that is cross-linked with the filamentous fibers of non-woven fabric could be difficult and needs to be assessed.

Considering the filtration conditions and number of filters used, the approximate operational cost (cost of electricity and geotextiles) associated with the treatment of 300 L lake water for test 1 (32.5 NTU) and test 3 (10.4 NTU) were $0.58 and $0.47 CAD, respectively. Among the total operational costs, 68% of the cost was associated with the electricity used and a part of this amount can be offset by running the system on solar energy. In the next phase of this project, an in-situ pilot test of this work running on solar energy will be considered. A larger scale pilot in-situ study will be able to more accurately determine the treatment cost, efficiency and potential application challenges.

The yearly changes in lake water quality in terms of algal size and shape are challenging for proper selection of geotextiles for filtration as algal morphology can significantly affect filter clogging and efficiency. Thus, selection of geotextiles of appropriate pore size is very important for the filtration efficiency. Based on the experimental observation from this on-site study, it is recommended to (i) use single or multiple layers of a non-woven geotextile of larger pore size (>110 μm) on the top of the fine filter, like a prefilter, and (ii) then use decreasing pore size filters in subsequent layers (like 4 or 5 in this study) in a set.

4. Conclusions

In this on-site study, a floating filtration unit containing non-woven geotextiles as filter media was successfully tested to improve the surface water quality of a eutrophic lake, Lake Caron. The filamentous fiber strands on the non-woven filters were very effective in capturing sediment fines and algae and thus yielded significant TSS (98–100%), turbidity (85–98%), Chl. *a* (80–96%), and TP (57–88%) removal from the water column in a short period of run. With a four day long filtration, Lake Caron water quality was improved from a eutrophic to a meso-oligotrophic state or better for both TP and Chl. *a* concentrations.

Although results from this study are very promising, improvements are needed which include (i) selection of geotextiles of appropriate pore size for removing algae of various sizes and shapes and (ii) reuse of clogged filters. The simple design and floating concept make this treatment approach ideal for both in-situ and on-site applications for remediating small, shallow enclosed water bodies without disturbing the aquatic life. Since the filtration is simply a particle separation technique with no chemical use, this type of treatment system can be easily set up and run at different locations of the lake with the participation of local community and lake associations as done in this study.

Author contribution

Dileep Palakeel Veetil: Conceptualization, Methodology, Investigation, Writing – original draft, Esteban Castillo Arriagada: Methodology, Investigation, Catherine Mulligan: Supervision, 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.111766.

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