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RESEARCH ARTICLE

Stormwater treatment using an ultrafiltration membrane and pulsatile fluid flow

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ABSTRACT

A polymeric ultrafiltration (UF) membrane was used for stormwater treatment, with the focus on evaluating the increase in the membrane process productivity by adding pulsatile fluid flow to UF membrane treatment. Sedimentation and sieving were used as pre-treatment. The result showed that increasing the pulse frequency from 0 to 4 Hz increased productivity from −6.6 to 82 LMH. UF membrane removed suspended solids, oil and turbidity below detection limit. The UF membrane also separated total coliforms, *E. coli* and *P. aeruginosa* below detection limit. Total organic carbon (TOC) was reduced by between 81%, in average. In addition, the UF membrane was able to reduce BOD_7 and COD to below 7 mg/L in the permeate. According to the US EPA, WHO, and national regulations in Canada, Japan, and South Korea, treated stormwater can be used for flushing toilets and streets irrigation and agricultural use.

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KEYWORDS
PVP/PES; dead end filtration; pulse frequency; water reuse; fouling

1. Introduction

Stormwater treatment is important prior to the point of discharge due to the high concentration of various pollutants that can be washed off and enter water resources. From an environmental perspective, it is critical to prevent pollutants from entering receiving waters. The main contaminants that often need to be reduced in stormwater are the total and dissolved fractions of metals, e.g. Zn, Cu, Cd, Pb, Ni and Cr (Morquecho and Pitt 2012; Shi et al. 2019), nutrients (Madaeni 1999) sediment, microbiological content (Jeng et al. 2005) and organic pollutants (Cao et al. 2019). Efficient treatment is also important if the stormwater is to be reused. Treated stormwater can be a suitable resource for non-potable uses, such as flushing urban surfaces and roads (Hashem and Qi 2021), toilet flushing (Loganathan, Vigneswaran, and Kandasamy 2013), fire protection or irrigation (Sandoval et al. 2019).

Stormwater harvesting combined with efficient purification methods such as membrane processes, which have been successfully used in other applications in the water sector, could be a way to reduce the pressure on natural water resources, especially in areas with water scarcity. Membrane processes are widely used in various applications due to their high efficiency in reducing contaminants. For instance, it has been shown that pathogens (Li Bertram, and Wiley 1998), ammonium and colloids (Rodrigues et al. 2015), natural organic matter (NOM) and humic substances (Gorenflo, Velázquez-Padrón, and Frimmel 2003) can be almost completely removed by such methods. More specifically, UF membranes are efficient in separating colloidal and macro particles from various solutions. Investigations have shown that particles smaller than membrane pores can also be removed if they have the opposite surface charge of the membrane, as they can adhere to the surface and pores of the membrane (Madaeni 1999). UF membranes have also been shown to efficiently separate coliform as well as specifically fecal coliforms from waters (Pervov and Matveev 2014). The removal of viruses from the solution depends on the pore size and virus size (Madaeni, Fane, and Grohmann 1995). UF membranes can also remove dissolved contaminants from urban runoff to some extent (Lau, Ismail, and Firdaus 2013).

Various methods can be combined with membrane treatment systems to postpone fouling and improve membrane performance. A simple and therefore promising method used to postpone and partially eliminate, membrane clogging is pulsatile flow (Zhuang, Tan, and Yuan 2016; Cui et al. 2017; Eaton 2018). Pulsatile flow is explained as a flow with a steady component with time-dependent oscillation (Zhuang, Tan, and Yuan 2016) and increases the fluctuations in the flow, resulting in better mixing of the feed solution near the membrane surface. Thus, this method can be used to reduce boundary layer effects and increase mass transfer (Li, Bertram, and Wiley 1998; Pontrelli 1998; Rodrigues et al. 2015; Kastl et al. 2019). Furthermore, depending on the quality of the stormwater, a suitable pre-treatment strategy should be considered to improve the quality of imposing feed to the membrane. The use of physical mechanisms such as sedimentation as pre-treatment is a good way to remove coarse material that could destroy the membrane and helps to improve the quality of feed to the downstream membrane (Huang, Schwab, and Jacangelo 2009). Combining pre-treatment, pulsatile flow, a membrane process and regular membrane cleaning could potentially be a suitable treatment train for heavily polluted stormwater toward decreasing pollutant loads to natural waters.

Membrane applications have experienced significant growth in various industries, although not in stormwater treatment specifically and there are only a few previous studies that have investigated stormwater treatment using

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membrane technologies (Pervov and Matveev 2014; Prudencio and Null 2018; Shen et al. 2020). These studies focused on separation of one or several specific pollutants from stormwater and not on the final quality of stormwater and the possible reuse applications of the treated stormwater. Pulsatile flow has the potential to delay fouling and improve the productivity of membranes for stormwater treatment but has not been previously studied. More research is therefore needed to investigate the potential of efficiently treating stormwater using membrane processes, as well as investigating operational parameters in relation to the quality and volume of treated stormwater.

In this study, a concept for treating stormwater with membrane technology was developed, using sedimentation as a pre-treatment followed by a hydrophilic polyether sulfone/polyvinyl-pyrrolidone (PES/PVP) UF membrane process in combination with a square wave pulsatile fluid flow. The pulsatile fluid flow was applied to increase the membrane's productivity and lifespan by removing the cake layer and postponing fouling. The aims of this study were to evaluate the efficiency of the membrane process in treating urban stormwater and assess the effect of different pulse frequencies on membrane productivity. Additionally, the potential to reuse the treated stormwater was discussed.

2. Material and methods

2.1. Experimental design

A membrane process was used to separate pollutants from melted snow after pre-treatment. To investigate the effect of different pulse frequencies on membrane filtration, a randomized single quantitative factor design was used (n = 3). The experimental order was randomized and one-way ANOVA was used to interpret the results. The frequency of pulsatile flow varied between 0 to 4 Hz at 6 levels (0, 0.8, 1.6, 2.4, 3.2 and 4 Hz). Each experiment was replicated three times, resulting in a total of 18 experiments.

2.2. Feed preparation and pre-treatment

Snow was collected from a roadside snow pile on a two-lane road with a traffic intensity of 20,000 vehicles per day in Luleå, Sweden (65°35′24.6″N 22°08′47.7″E) in March 2021. This sampling point was chosen since, in view of the location, it was expected to be rich in typical stormwater pollutants. After collection, the snow was mixed thoroughly before divided into batches and placed in plastic containers and thereafter stored in a freezer at a temperature of −10°C. Prior to each experimental run, one plastic container with about 20 L of snow was taken out of the freezer and left to melt for 36 h at room temperature. The melt water was then mixed thoroughly and left to settle for 60 min (sedimentation) as a pre-treatment. Then, the decanted melted snow was passed through a sieve to separate all particles larger than 315 µm, which was the recommended particle size limitation of this UF membrane and was recommended by the membrane manufacturer company.

Pretreated melted snow (feed) prior to each experimental run, and the permeate from the membrane process were sampled and analyzed with respect to total suspended solids (TSS), pH, turbidity, electrical conductivity, biological oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), oil index, total chlorine, chloride, particle size distribution, heterotrophic bacteria, *P. aeruginosa*, total coliforms, *E.coli* and cultivable microorganisms, and dissolved metals. (Table 1) In addition, the feed solution was analyzed on total metal concentration. The bacteria were selected based on the parameters regulated in various countries (Health Canada 2010; EPA 2012).

***Total concentrations are shown.*

Table 1. Characteristics of the feed water, i.e. melted snow batches after pre-treatment (n = 18).

Parameters	Unit	Concentration range (Average ± STDEV)
TSS	mg/L	210–490 (340 ± 56)
pH*	-	7.2–8.4 (7.7 ± 1.5)
Turbidity	NTU	157–361(253 ± 46)
Conductivity	mS/m	0.02–0.22 (0.04 ± 0.04)
BOD 7	mg/L	4.6–6.1 (5.4 ± 0.7)
COD	mg/L	83–108 (92 ± 14)
TOC	mg/L	1.1–20 (10.8 ± 5.7)
Oil index	µg/L	1130–3670 (2400 ± 750)
Cl^-	mg/L	4.05–54.2 (7.6 ± 11.6)
Chlorine, total	mg/L	0.04–0.07 (0.06 ± 0.03)
Heterotrophic bacteria	CFU/mL	>300
Pseudomonas aeruginosa	CFU/100mL	<1
Total Coliforms*	CFU/100mL	4–25 (13.6 ± 12.1)
E. Coli	CFU/100mL	<1
Cultivable microorganisms	CFU/mL	>3000
As**	µg/L	1.38–2.9 (2 ± 0.3)
Cd**	µg/L	0.055–0.245 (0.1 ± 0.04)
Cu**	µg/L	50–109 (77 ± 13)
Cr**	µg/L	11.2–26.2 (17.9 ± 3.4)
Ni**	µg/L	6.1–22.4 (10 ± 2.5)
P**	µg/L	0 (0.0±0.0)
Pb**	µg/L	5.09–11.4 (7.7 ± 1.4)
Zn**	µg/L	81.5–208 (137.5 ± 25.8)

**For pH and total coliform geometric mean and geometric standard deviation are shown(According to IUPAC recommendations)* (Currie' and Svehla2 1994).

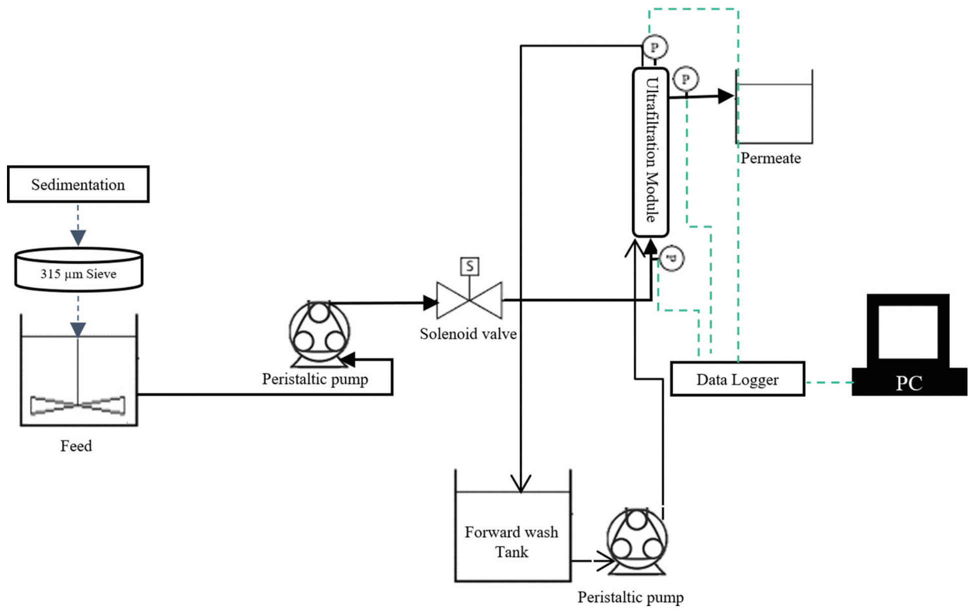

Figure 1. Schematic of the UF membrane experimental setup. P = pressure sensor.

2.3. Membrane filtration experiments

A bench-scale membrane module was used as a filter unit for the experiments (Figure 1) and was run in dead-end mode according to the recommendation of the membrane provider company. Using membranes in cross-flow mode provides higher shear stress on the membrane surface which can decrease fouling. However, dead-end mode is generally more energy efficient in comparison to cross-flow mode (Chew, Aroua, and Hussain 2018), and was considered applicable in the stormwater context since rain and snowmelt are non-continuous events. In addition, a benefit of using dead-end filtration is to produce a more concentrated solution of pollutants that could be removed from the urban environment, which might not be achieved with cross-flow mode.

A hollow fiber PES/PVP UF membrane with an active area of 0.07 m^2 and molecular weight cut off of 1 KDa was provided by Pentair, Sweden and installed in the module. To generate pulses, a solenoid valve (ASCO, Sweden) was installed on the tube, prior to the filter unit. The transmembrane pressure (TMP) was continuously measured using pressure sensors (EU Automation, Sweden), which were placed on the feed, retentate and permeate sides (Figure 1). The TMP was kept between 190 and 275 kPa. According to the manufacturer, the membrane should not be exposed to temperatures lower than 0 °C or higher than 60 °C. The temperature in the permeate and feed was measured manually every 5 minutes during the experimental runs, as was done for the permeate flux through the membrane. Prior to each of the 18 experimental runs, all containers were acid washed and the membrane surface was forward washed in cross flow mode with 3 L of permeate quality water for 75 min and the retentate from the forward wash was discharged. For each experimental run, the feed tank was filled with pre-treated snow melt and continuously stirred. A peristaltic pump at constant speed was used to pump the pretreated snowmelt from the feed tank through the filter unit. Each experimental run was stopped when a 40% flux decline was reached. The filtration productivity of the membrane over time was calculated according to equation (1):

$$P = \frac{Vp - Vf}{tp + tf} \quad (1)$$

where P is the productivity of the membrane, t is the time, V is the volume, and p and f indicate permeate and forward wash (James et al. 2007).

2.4. Water quality analyses

Particle size distribution was measured using a laser scattering particle size distribution analyzer HORIBA LA-960 (HORIBA, Japan). Total suspended solids (TSS) were measured using the standard method SS-EN 872:2005.

For the dissolved metal concentrations, the samples were passed through a 0.45 µm filter before analysis. Total and dissolved metal concentrations were analyzed with ICP-SFMS according to ISO 17,294–2:2016. The reporting limits (RL) for the total and dissolved metal concentrations were 0.5 and 0.05 µg/L for As; 0.05 and 0.002 µg/L for Cd; 1 and 0.1 µg/L for Cu; 0.9 and 0.01 µg/L for Cr; 0.6 and 0.05 µg/L for Ni; 0.5 and 0.01 µg/L for Pb; and 1 µg/L for P. The method AFS (ISO 17,852:2008) was used for Hg analysis, and RL for total and dissolved Hg concentrations was 0.02 and 0.002 µg/L, respectively.

Total organic carbon (TOC) was analyzed according to DIN EN 1484(H3), while the oil index was analyzed according to CSN EN (ISO 9377–2). The fractions C10-C40 (RL 50 µg/L), C10-C12 (RL 5 µg/L), C12-C16 (RL 5 µg/L), (C16-C35 (RL 30 µg/L) and fraction C35-C40 (RL 10 µg/L) were analyzed with GC-FID (a gas chromatograph equipped with a flame ionization detector). Turbidity was measured using a turbidity meter 2100N (Hach, Loveland, Colorado), while pH was measured using a WTW pH 330 electrode (WTW, Weilheim, Germany) and conductivity using CDM210 conductivity meter. Chloride concentration was measured by ion chromatography according to the methods CSN EN ISO10304–1 and CSN EN 16,192 (RL 1 µg/L). The measurement of chlorine in samples was done by spectroscopy according to HACH method 8021. BOD7 was measured according to 5815–1:2019 and COD was analyzed according to the method ISO 15,705. Cultivable microorganisms and heterotrophic bacteria were determined according to SS-EN ISO 6222, ed 1, *E. coli* and coliforms according to SS-EN 1899–2 and *Pseudomonas aeruginosa* according to SS-EN ISI 16,266:2008.

Total and dissolved metal concentrations, TOC, BOD7, COD, oil index, microorganisms and bacteria, and chlorine and chloride content were analyzed by an accredited laboratory (ALS Scandinavia, SWEDAC accreditation number: 2030).

An integrity test on the membrane module was performed after the experiments. The membrane was submerged in water and the permeate side was pressurized with air (1 to 3 bar). With this methodology any leakage of the membrane is indicated by a bubble train from the compromised fiber.

2.5. Statistical analyses and data evaluation

To evaluate the effect of different pulse frequencies on the permeate volume and time of the filtration process, a one-way ANOVA was carried out. Tukey comparison was used to check if the results from various experiments were significantly different. All analyses were done with a significance level of 0.05 and MODDE software (Version 12.1) was used for the statistical evaluations.

3. Results and discussion

3.1. Pre-treatment

The sedimentation time of 60 min was sufficient to remove the coarse and large particles from the stormwater. The sedimentation step was combined with sieving to separate finer particles from melted snow samples to avoid any harm to the membrane and also fouling. The majority of the large particles were separated by sedimentation and only a small portion was separated using sieving, which may indicate that a simple pre-treatment method like sedimentation is enough prior to UF membrane for stormwater treatment. However, during some of the experimental runs, the feed had an elevated concentration of TSS which caused a decreased run time of the membrane (Figure 2). More types of stormwaters should be examined to confirm these results.

3.2. Effect of pulse frequency on membrane efficiency

When increasing the pulse frequency from 0 to 4 Hz, the maximum run time increased from 5 min to 70 min, reaching a flux decline of 40% (Figure 2). The difference was statistically significant when the 4 Hz pulsatile flow was used compared to the steady flow (one-way ANOVA, $p = 0.000$) and no statistically significant difference was observed between the effect of the 0.8, 1.6, 2.4 and 3.2 Hz frequencies. Increasing pulse frequency from 0 to 4 Hz, the average run time increased from 6.6 min to 55 min, and the permeate volume achieved during this time increased on average from 2.3 to 15.2 L. The average volume of treated stormwater for steady and pulsatile flow with various pulse frequencies is reported in Table 2, as well.

The permeate volumes of the frequencies of 0, 1.6 and 4 Hz were significantly different from each other, which was shown using a Tukey pairwise comparison ($p = 0.001$). This indicates the ability of the pulsatile flow to decrease boundary layer effects, postpone fouling and increase the run time of the membrane process. The difference in permeate volume was not significant for the frequencies 3.2, 2.4 and 0.8 Hz, possibly because of the short intervals between these pulse frequency values. However, an increasing trend was also observed in the permeate volume for these frequencies (Figure 2). Unexpectedly, the pulse frequency of 3.2 Hz resulted in a permeate volume of 3.6–5.4 L (4.6 ± 0.91) and run time of only 25–30 min (27 ± 2.9), see Figure 2. This can be explained

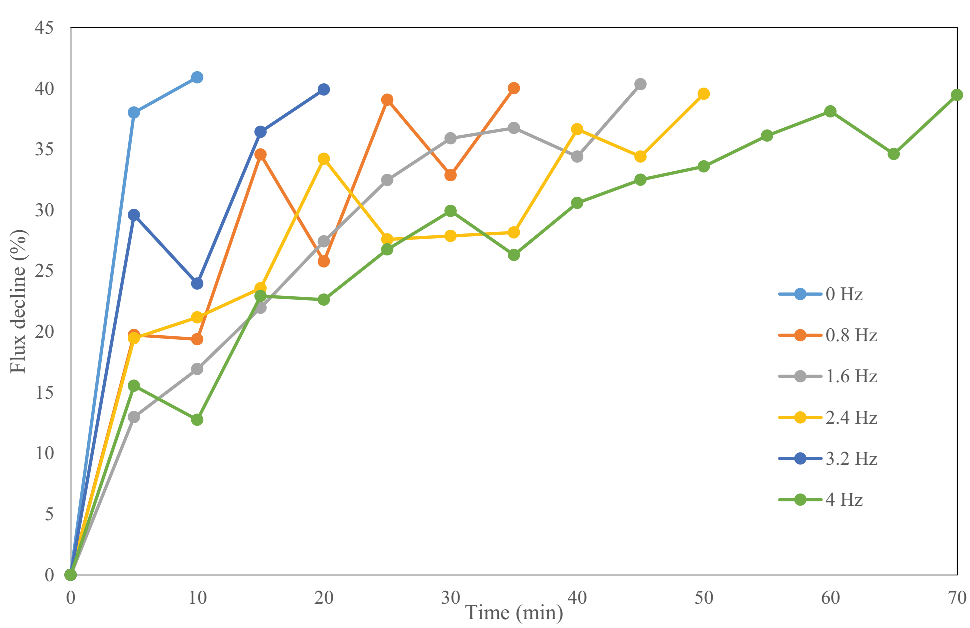

Figure 2. Average flux decline variation over time for different pulse frequencies (n = 3).

Table 2. Treated stormwater volume (permeate) achieved until 40% flux decline and productivity for various pulse frequencies. Means of three replicates are shown.

	Frequency of pulsatile flow (Hz)					
	0	0.8	1.6	2.4	3.2	4
Permeate volume (L) Min-Max (mean ± STDEV)	1.8–2.9 (2.3±0.56)	6–9.45 (8±1.8)	7–14 (10.7±3.7)	7.5–11.2 (9.6±1.9)	3.6–5.4 (4.6±0.9)	14.2–17 (15.2±1.5)
Productivity (LMH)	−6.6	38	54	45	13	82

by the quality of the melted snow (feed) used for the experimental runs at 3.2 Hz, which had a higher TSS and turbidity (411 ± 108.7 mg/L and 302 ± 80.5 NTU, respectively) than the melted snow used for the other experimental runs (TSS 327.3 ± 63 mg/L and turbidity 243 ± 50.3 NTU), although the snow pile was thoroughly mixed before moved to the plastic containers in the freezer.

According to the quality of stormwater, longer sedimentation times might be needed to further assist membrane process or consider more pre-treatment steps. This is especially important when treating stormwater, as the TSS in stormwater can vary greatly during a precipitation event and also from one event to another (Westerlund, Viklander, and Bäckström 2003; Westerlund and Viklander 2014). A pre-treatment must be designed to cope with these variations.

In the present experiment, the fouling rate decreased when increasing the pulse frequency from 0 to 4 Hz. According to integrity test no leakage was observed which showed that using pulsatile flow in dead-end filtration did not damage the membrane. Kastl et al. (2019) have shown that Womersley numbers in the range of 0 to 7 and transient inertial forces, can overcome viscous effects existing in the boundary layer of the membrane, which prevents cake layer formation on the membrane surface and leads to a longer experimental run time and more permeate volume. In this study, using a pulsatile flow with pulse frequencies between 0.8–4 Hz, the Womersley number varied between 0.7 and 1.5, which is in the quasi steady and then for frequencies of 3.2 and 4 Hz in intermediate region (Özahi and Çarpınlıoğlu 2015). This therefore helped to prevent fouling. However, using a pulsatile flow could not completely prevent cake layer formation and concentration polarization in the system as the initial flux of the clean membrane in the beginning of experiments was 461.2 LMH, which decreased to 206.5 LMH in the last experiment (Figure 3), demonstrating the importance of membrane cleaning optimization. Application of pulsatile flow to the membrane process may increase the energy demand in comparison to using steady flow, which needs to be addressed in further assessments to find the balance between the energy demand, costs and the productivity of the process.

The experiments were started exactly after 36 hr of melting time to ensure similar temperatures in the feed solution. The feed temperature was between 13–16°C for all the experiments. Higher temperatures have been shown to result in higher flux (Puri, Singh, and O'mahony 2020). However, increasing the temperature of stormwater would use significant amount of energy, especially in areas with cold climate and would not be recommended for practical applications.

Due to fouling, the permeate flux decreased during the course of the experiment (Figure 3), showing that the membrane cleaning was not efficient enough. To clean the membrane, both a backwash and forward wash were attempted, but the backwash was not successful, thus the membrane was mainly forward washed. The poor flux recovery was probably the reason for the one-way ANOVA not revealing any significant effect of the pulse frequencies on the average flux ($p =$ 0.157).

The average productivity of the membrane (calculated using equation (1)) for the various pulse frequencies was lowest in steady flow and increased when pulsatile flow was used (Table 2). Across the different levels of pulse frequency, the productivity was lowest at a pulse frequency of 3.2 Hz (due to the high TSS load, explained above) and highest at a frequency of 4 Hz. Higher productivity shows a higher net permeate flow

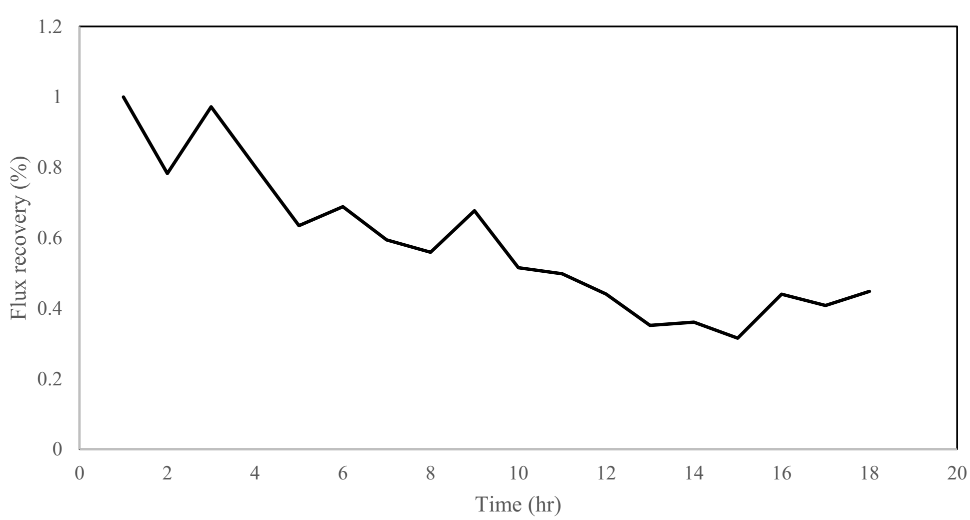

Figure 3. Initial flux recovery decline after membrane cleaning using forward wash over time.

rate and while investigating pulse frequencies higher than 4 Hz may be useful, it was not possible with the laboratory set-up used here because the maximum TMP was limited to 300 kPa. Kastl et al. (2019) investigated pulse frequencies as high as 11.57 Hz when filtrating silica in water as a colloidal solution and reported that the formation of a fouling layer was totally prevented. However, using such high pulse frequencies also increases the energy demand of the process and might not be energy efficient in stormwater treatment, considering the large size of the volumes to be treated. Since in the current experiment the membrane was used in dead-end mode, using such a high frequency might result in choking or damaging the membrane.

3.3. Permeate quality

The TSS and turbidity in the permeate were below the detection limit throughout the experiment, indicating that the UF almost completely removed particles from melted snow. In addition, using a laser scattering particle size distribution analyzer, it was shown that following the membrane process, the permeate was free from particles. The melted snow had a high concentration of oil (Table 1) originating from traffic pollution and oil fraction concentrations were decreased below detection limits in the permeate as well. The chloride content in the feed samples has the potential to affect membrane functionality; investigations have shown that a high chloride content will decrease a membrane's lifespan (Minnesota Rural Water Association 2001). Therefore, the chloride content of melted snow samples was measured. The concentrations in the feed and permeate were determined as 7.6 ± 11.7 mg/L and 7.8 ± 11.1 mg/L, respectively (Table 1). These concentrations are high compared to what has been recommended (Minnesota Rural Water Association 2001), which is that chloride concentrations be lower than 0.5 mg/L to avoid damage to the membrane. This needs to be further considered if UF applications will be considered for snowmelt/stormwater treatment along roads, maintained with road salt in wintertime.

The TOC removal varied between 70 and 91%, indicating that a part of the TOC was not removed, this part being probably dissolved organic carbon and also organic particles which were smaller than the pore size of the membrane. The TOC removal was not affected by pulse frequency (one-way ANOVA). Surprisingly, the heterotrophic bacteria concentration was reported to be more than 300 CFU/mL in both feed and permeate (Table 3). The influent and effluent tanks were totally separated and according to membrane integrity testing, there was no leaking in the membrane. *Pseudomonas aeruginosa* was

Table 3. Concentrations of stormwater pollutants in the feed and permeate and their average removal efficiency (calculated using averages) after ultrafiltration. All metal concentrations refer to the dissolved fraction.

Parameter	Unit	Pretreated feed min-max (average ± STDEV)	Permeate min-max (average ± STDEV)	Removal efficiency (%)
TSS	mg/L	210–490 (340 ± 56)	Below detection limit	≈100
pH**	-	7.2–8.4 (7.7 ± 1.5)	7.2–8.4 (7.7 ± 1.5)	-
Turbidity	NTU	157–361(253 ± 46)	Below detection limit	≈100
Conductivity	mS/m	0.02–0.22 (0.04 ± 0.04)	0.03–0.06 (0.03 ± 0.008)	-
BOD 7	mg/L	4.6–6.1 (5.4 ± 0.7)	2.8–4.4 (3.67 ± 0.8)	33%
COD	mg/L	83–108 (92 ± 14)	<5–7.1	92%
TOC	mg/L	1.1–20 (10.8 ± 5.7)	0.55–2.4 (1.8 ± 0.6)	70 to 91%
Oil index	µg/L	1130–3670 (2400 ± 750)	Below detection limit	≈100
Cl-	mg/L	4.05–54.2 (7.6 ± 11.6)	4.05–50.7 (11 ± 7.8)	-
Chlorine, total	mg/L	0.04–0.07 (0.06 ± 0.03)	Below detection limit	≈100
Heterotrophic bacteria	CFU/mL	>300	>300	-
Pseudomonas aeruginosa	CFU/100mL	<1	<1	-
Total Coliforms**	CFU/100mL	4–25 (13.6 ± 12.1)	<1	≈100
E. Coli	CFU/100mL	<1	<1	-
Cultivable microorganisms**	CFU/mL	>3000	860–1690 (1270 ± 422)	>57
Al	µg/L	19–41 (26 ± 5)	5.8–27 (12±5)	57
As	µg/L	0.05–0.09 (0.07 ± 0.02)	<0.024–0.078 (<0.05±0.02)	>16
Ba	µg/L	3.9–9.5 (5.2 ±1.2)	3.6–10 (5 ±1.3)	6.6
Ca	mg/L	1.8–3 (2.2 ±0.4)	1.8–3 (2.2 ±0.4)	0
Cd	µg/L	0.002–0.02 (0.007±0.007)	0.001–0.02 (0.004±0.004)	13
Co	µg/L	1.9–3.6 (2.4±0.4)	1.8–3.8 (2.4±0.45)	1.7
Cr	µg/L	0.07–0.1 (0.17 ± 0.01)	<0.01–0.1 (<0.08 ± 0.03)	>24
Cu	µg/L	1.6–3.9 (2.1 ±0.5)	0.8–3.5 (1.9±0.6)	12
Fe	mg/L	0.005–0.08 (0.012±0.01)	0.0004–0.004 (0.001±0.001)	74
Hg	µg/L	0	0	0
K	mg/L	0.4–0.6 (0.5±0.2)	0.4–0.6 (0.5 ±0.3)	0
Mg	mg/L	0.2–0.3 (0.2±0.02)	0.2–0.3 (0.2±0.03)	0
Mn	µg/L	10–16 (12±1)	11–18 (14±1)	-*
Mo	µg/L	0.3–0.7 (0.4±0.1)	0.3–0.5 (0.4±0.07)	0
Na	mg/L	2.5–41 (5.3±9)	2.5–41 (5.5±9)	0
Ni	µg/L	0.2–0.5 (0.4±0.07)	0.2–0.4 (0.3±0.07)	21
P	µg/L	2–12 (5.2±3.3)	0.1–3.3 (1.2 ±0.9)	73
Pb	µg/L	0.01–0.05(0.03±0.001)	<0.01–0.015 (0.01 ±0.00)	44
Si	mg/L	0.17–0.26 (0.2±0.02)	0.17–0.23 (0.2±0.01)	6
Sr	µg/L	4–6.5 (5±0.7)	4–7 (5±0.8)	-*
V	µg/L	0.3–0.5 (0.4±0.05)	0.3–0.5 (0.4±0.05)	1.4
Zn	µg/L	3–7.5 (5±1)	0.37–11 (6.7±1.4)	-*

**The pre-tests showed that Mn, Sr and Zn leakage existed in the setup and therefore the removal efficiency for these metals was not calculated.*

*** for pH, cultivable microorganisms and total coliforms geometric means and standard deviations are shown..*

reported to be less than 1 CFU/100 ml both in feed and permeate. Total coliforms were decreased to below 1 CFU/100 ml in the permeate. The concentration of cultivable microorganisms in the permeate was 860–1960 CFU/mL. The concentrations of free, total and bound chlorine were measured in both feed and permeate and were decreased in the permeate to below 0.03 mg/L.

By treating the stormwater with the UF module, the BOD_7 decreased by 33% on average (permeate concentrations 2.8–4.4 mg/L (3.67 ± 0.8 mg/L)). COD was removed by more than 92% (permeate concentrations<5–7.1 mg/L). Stormwater is known to contain environmentally harmful metals such as Zn, Cu, Cd, Pb, Ni and Cr (Esfandiar, Suri, and McKenzie 2022). In stormwater treatment, it is of particular interest to remove the dissolved and colloidal forms of these metals. The metal ions are normally smaller than the UF membrane pore size and the separation of metal fractions may therefore be due to difference in the surface charge of particles and membrane. In addition, it is possible that some of the metal ions were trapped in the fouling layer on the membrane surface or that the metal ions aggregated with other particles in the solution and formed larger particles that could not pass through the membrane. The removal efficiency for different metals in dissolved form (<0.45 µm) is shown in Table 3. The concentration of total and dissolved Cd and Hg were below detection limit in both pretreated feed and permeate (Tables 1 and 3). However, the results showed that the UF process reduced dissolved As, Cd, Cu, Cr and Ni (16, 13, 12, 24, 21%), and also efficiently separated P and Pb concentrations (73 and 44%) (Table 3). In this study, the quality of the stormwater was analyzed with respect to typical stormwater pollutants as well as the parameters specified in the regulations. However, depending on the sampling location of stormwater and planned usage of the permeate, the permeate may need to be analyzed for additional parameters.

3.4. Reuse of UF treated stormwater

According to international guidelines, treated stormwater can be used for various purposes, e.g. urban usage, irrigation, etc. urban usage includes washing streets, car parks, irrigation of plantations and trees, etc.). The pH of the permeate water varied between 7.2 and 8.3. This is within the permitted water pH for urban reuse, which is 6.5–8.4, according to the US EPA. The US EPA guidelines for water reuse in 2012 states that the permeate water from UF module is suitable for urban reuse. However, the permeate needs to be chlorinated beforehand (EPA 2010; 2012), since the residual chlorine in the permeate water in this study was less than 1 mg/L. Treated melted snow could be used for irrigation as it complies with regulations for reuse for different applications in different countries. According to regulations of the WHO, in Canada (Health Canada 2010), Italy (Fountoulakis et al. 2016), and China (Dou 2019), the permeate can be used for toiletor urinal flushing (Herschy 2012), for agriculture (Kramer, Post, and Reseach 2003), the maintenance of wetlands (Baresel and Dalameh 2014), Sandoval et al. (2019) showed that UF can remove fecal coliforms and coliforms by more than 90%, which is approved by this study, as well which showed the effectivity of UF membrane treatment in separation of pollutants from highly polluted stormwaters which is of importance for reuse for agricultural purposes. However, to safely reuse the produced permeate for irrigation purposes, it would need to undergo disinfection to remove microorganisms in order to comply with the EU water reuse directive (EPA 2012). In the present study, the dissolved metal concentrations in both the feed and permeate were lower than the permitted limits for potable water reuse as stipulated in Swedish drinking water regulations (Livsmedelsverket 2005) and WHO guidelines. In addition, the permeate had low concentrations of TSS and turbidity. According to European regulations for drinking water, the permitted limit of chloride is 52 mg/L (world health organization 1984) and the concentration in the permeate from this experiment was between 4.05 and 50.4 mg/L. According to the US EPA, the TOC value should be less than 2 mg/L in drinking water before disinfection (EPA 2010). The TOC measured in the permeate was in the range of 0.55–2.4 mg/L (1.78 ± 0.59) and was therefore mainly below this limit.

4. Conclusions

The membrane performance was defined in accordance with the terms, produced permeate water volume per time unit (productivity) and the quality of the produced (permeate) water. The tested UF process successfully removed total suspended solids, total coliforms, particulate bound metals (>0.45 µm), oil fractions and turbidity from the stormwater to below the detection limit. Dissolved As, Cd, Cu, Cr, Ni, Pb and P (defined as having a size smaller than 0.45 µm) were reduced by 16, 13, 12, 22, 21, 44 and 73%, respectively. The TOC removal varied between 70 and 91%.

The quality of treated stormwater was assessed according to various regulations for water reuse. Permeate water could be a good option for urban reuse, irrigation purposes, maintenance of wetlands and flushing toilets. According to the US EPA, the treated stormwater would need to be disinfected to be reused.

The pulsatile flow was shown to positively affect the productivity of UF membranes. Increasing the pulse frequency from 0 (steady flow) to 4 Hz resulted in a significant improvement in the efficiency of the membrane process, which was assessed in terms of run-time (increasing from 6.6 min to 55 min on average) and permeate volume (increasing from 2.3 to 15.2 L). This resulted in an increase in productivity from −6.6 to 82 LMH.

To conclude, the proposed concept for stormwater treatment – using sedimentation as a simple pre-treatment followed by a UF process in dead-end mode in combination with a square wave pulsatile fluid flow – can be a promising method for treatment of urban stormwater but future research should address optimization of membrane productivity, including operational issues such as membrane cleaning which can extend the lifetime of the membranes. Membrane cleaning methods need to be investigated further, including studying the fouling layer on the membrane surfaces to better understand the fouling process and to choose an appropriate cleaning method. In addition, it might be interesting to compare the efficiency of different types of membranes with different pore sizes when used for stormwater treatment.

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