Carbon Filters for Drinking Water Treatment

- How Flow Rate and Empty Bed Contact Time Influence the Performance

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Abstract

Drinking water is an essential part of a sustainable society. In the future, the demand for drinking water will increase and contaminants in the water sources are also predicted to increase. Therefore, it is essential to ensure safe drinking water through functioning drinking water treatment plants (DWTPs). One important contaminant to treat is natural organic matter (NOM), which is harmless in itself but can produce harmful products. One technique to use for treating NOM is carbon filters (CFs).

The effect of increased flow rate and increased empty bed contact time (EBCT) on the CF efficiency was investigated at a DWTP. The investigated parameters were particles, ultraviolet absorbance at 254 nm, turbidity, conductivity, cultivable microorganisms, fluorescent dissolved organic matter, total organic carbon, chemical oxygen demand, and odour. Three CFs were studied at different flow rates; 190, 220, 250, and 280 L/s for 24 hours each. Additionally, two filters had increased EBCT of 60 and 76 %, while one filter continued with the regular flow rate of 190 L/s for six weeks. Outgoing water from the filters was analysed to see if the change had any effect on the DWTP.

This preliminary study did not find any significant effect on the CF treatment caused by increased flow rate or EBCT. This could be an indication that the CFs can handle a future increase in flow rate and thus be an essential part of a future expansion of the DWTP. The indications of CFs being affected by the increase in flow rates for some of the parameters could be explained by fluctuations in incoming water or differences between the separate filters.

In the future, a more thorough analysis of both incoming and outgoing water to the CFs should be done, where sampling occurs more frequently to better understand the fluctuations in incoming contaminant concentrations. The measurements should also be repeated to see how the treatment differs from day to day. How the CFs handle increased flow rates over longer time periods should also be investigated further.

Sammanfattning

Dricksvatten är en essentiell del av ett hållbart samhälle. Därför är det viktigt att säkerställa säkert dricksvatten genom fungerande vattenreningsverk. En viktig förorening att behandla är NOM, som i sig är ofarligt men som kan producera farliga föroreningar. En teknik som används för behandling av NOM är kolfiltrering.

Hur ökad flödeshastighet och ökad kontakttid påverkade kolfiltrens effektivitet undersöktes vid dricksvattenreningsverket Norrvatten. De undersökta parametrarna var partiklar, ultraviolett absorbans vid 254 nm, turbiditet, konduktivitet, fluorescent löst organiskt material, totalt organiskt kol, kemisk syreförbrukning, odlingsbara mikroorganismer och lukt. Tre kolfilter studerades vid olika flödeshastigheter; 190, 220, 250 och 280 L/s under ett dygn var. Samtidigt hade två filter ökad kontakttid på 60 och 76 % under sex veckor, medan ett filter fortsatte med den vanliga flödeshastigheten på 190 L/s. Utgående vatten från filtren analyserades för att se om dessa ändringar hade någon effekt på vattenreningen.

Denna preliminära studie fann ingen signifikant effekt på kolfiltreringens rening på grund av ökad flödeshastighet eller uppehållstid. Detta kan vara en indikation på att kolfiltreringen kan hantera en framtida flödesökning och därmed vara en väsentlig del av en framtida expansionen av vattenreningsverket. De tecken som visade på att kolfiltren påverkades av ökningen av flödeshastigheter kunde förklaras av fluktuationer i inkommande vatten och skillnader mellan de olika filtren.

I framtiden bör effekten av inkommande vatten studeras i detalj. En mer ingående analys av både inkommande och utgående vatten till kolfiltren bör utföras, där provtagning sker oftare för att bättre förstå fluktuationerna i inkommande föroreningskoncentrationer. Dessutom bör testerna upprepas för att se hur reningen skiljersig från dag till dag. Hur kolfiltren hanterar ökade flödeshastigheter över längre tidsperioder bör också undersökas vidare.

Populärvetenskaplig sammanfattning

Dricksvatten är en viktig del av ett hållbart samhälle då förorenat vatten kan vara en risk för människors hälsa. I takt med en växande befolkning och höjda krav på dricksvatten, ökar även behovet av en välfungerande dricksvattenanläggning. Dessutom ökar mängden föroreningar i vattenkällorna.

Norrvatten är Sveriges fjärde största dricksvattenreningsverk och förser 700,000 hushåll med dricksvatten. Verket tar sitt vatten från Mälaren för att sedan rena det i flera steg. Ett av dessa steg är att vattnet går genom ett kolfilter. Kolfilter renar vatten från föroreningar som naturligt material som kan ge vattnet färg samt lukt och smak.

Eftersom mer och smutsigare vatten kommer behöva renas i framtiden behöver kolfiltren klara av högre flöden. Därför undersöktes hur kolfiltren påverkades av ökade flödeshastigheter samt längre uppehållstid. Sex kolfilter undersöktes genom att testa hur olika flödeshastigheter påverkade vattenreningen. Resultatet visade att kolfiltren renade vattnet ungefär lika bra för lägre som högre flödeshastigheter och uppehållstid. Det fanns därmed inga tecken på att högre flödeshastigheter kommer leda till försämrat dricksvatten. Däremot kan resultatet ha påverkats av att det ingående vattnet var olika förorenat vid olika tillfällen. Påverkan av ingående vattenföroreningar bör undersökas för att säkerställa att detta inte påverkat resultatet.

Kolfiltren verkade kunna hantera ökade flödeshastigheter och antas därför kunna hantera framtida ökade krav på reningen och ett ökat behov av renat vatten. För att säkerställa resultatet bör dessa resultat dock kontrolleras genom att analysera effekten av ökad flödeshastighet under en längre period samt via upprepade försök för att säkerställa att resultatet är korrekt.

Acknowledgements

List of abbreviations

BAC	Biological Activated Carbon
CDOM	Coloured Dissolved Organic Matter
CF	Carbon Filter
COD	Chemical Oxygen Demand
DBPs	Disinfectant By-Products
DOC	Dissolved Organic Carbon
DOM	Dissolved Organic Matter
DWD	Drinking Water Directive
DWTP	Drinking Water Treatment Plant
EBCT	Empty Bed Contact Time
EU	European Union
fDOM	fluorescent Dissolved Organic Matter
FTU	Formazin Turbidity Units
GAC	Granular Activated Carbon
MW	Molecular Weight
NOM	Natural Organic Matter
PAC	Powdered Activated Carbon
PFAS	Per- and Polyfluoroalkyl Substances
SDGs	Sustinable Development Goals
SF	Sand Filter
SUVA	Specific Ultraviolet Absorbance
TOC	Total Organic Carbon
UN	United Nations
UV	Ultraviolet
UV254	Ultraviolet Absorbance at 254 nm
WHO	World Health Organisation

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Chapter 1

Introduction

Access to safe drinking water is an essential part of basic human rights and health for full enjoyment of life. Freshwater is a finite resource, and it is therefore essential to use the the source well and optimise the Drinking Water Treatment Plant (DWTP)s. [1]

1.1 Background

Görvälnverket is Sweden's fourth largest DWTP [2]. The plant has been active since 1929 and is constantly growing, both in treatment steps and in amount of treated water. The treatment plant is expected to meet future challenges regarding both quantity and quality of the drinking water. One important step to improve the treatment is to increase the Natural Organic Matter (NOM) removal, which can be done using Carbon Filter (CF)s. At Görvälnverket, there are full-scale CFs that were installed in 2004, which will need an increase in capacity. [3]

1.2 Aim and objectives

The primary aim of this project was to measure if and how the CFs capacity at Görvälnverket was affected by increased flow rates as well as how the capacity was affected by increased Empty Bed Contact Time (EBCT). The project also had a secondary aim, which was to investigate whether CFs should be included in a future DWTP.

The effect of increased flow rates was measured over three filters, one old which was installed in 2004, one new from 2011, and one which was recently regenerated in 2011. Flows of 190, 220, 250, and 280 L/s was tested over 24 hours for each filter. To measure how the filters were affected by the increased flow rates, various parameters were analysed, such as turbidity, particles, and Ultraviolet Absorbance at 254 nm (UV254). Similarly, two filters had increased EBCT of 60 and 76 % to measure this effect on the treatment process, while a third filter continued with the same flow rate of 190 L/s.

1.3   Methodology

First, a literature study was performed, to evaluate previous studies in the area. Various information sources were used such as academic, commercial, bibliographic databases, and other internet search engines. A table of key words was constructed to simplify the search for information. The main data for the project was given through measurements and analysis of water. This data was quantitative and both primary and secondary, given without control of background variables. Outliers were eliminated using Grubb's test for outliers before evaluating the data. The data was also tested for internal validity by repeating some of the measurements and testing for any significant difference.

1.4   Delimitations

It was assumed that all the filters had a biofilm growth that had deactivated the adsorption capacity of the CFs and instead the treatment was performed through bioactivity of the biofilm. Further, the measurements were performed durng both winter and spring time so it was assumed that the fluctuations of temperatures outside would have a negligible effect on the treatment.

1.5   Outline

Chapter 2 presents previous research regarding DWTPs in general and CFs specifically. It describes the function of adsorption in CFs using Granular Activated Carbon (GAC) and how biofilters affect the CF and makes it a Biological Activated Carbon (BAC)

and how various factors are affected by increased flow rates and EBCTs. Chapter 3 describes the methodology in detail and how the experiments were conducted as well as when and how analyses were made. Chapter 4 shows the results of all tested flow rates and EBCT and the parameters that were analysed while also discussing the results and reviewing the project in total. Chapter 5 concludes the results and discussion as well as puts forward suggestions for future work.

Chapter 2

Technical Background

The technical background gives information regarding CFs as well as the current DWTP at Norrvatten and which contaminants are treated using CFs and how these are measured.

2.1   Drinking water

Access to safe drinking water is an essential part of basic human rights and health for full enjoyment of life. Contamination of drinking water can cause diseases and be a high risk to human health, therefore, drinking quality regulations are important for ensuring consumer's access to sustainable and safe drinking water and can thus lead to benefits to human health [1].

The United Nations (UN) 2030 Agenda for sustainable development was made to have global Sustinable Development Goals (SDGs) aiming to protect the planet while striving for prosperity. Goal 6 in the SDGs aim at ensuring drinking water since a third of the world's population do not have access to safe drinking water today. Goal 6.1 focuses on achieving universal access to safe drinking water. [4]

To ensure drinking water is safe and has a high quality, the National Food Administration of Sweden sets rules and demands, which has to be followed by the DWTPs. The rules include parameters such as how the water should be prepared and quality demands, set in the form of limit values [5]. Within the European Union (EU) there are also regulations for drinking water, called the Drinking Water Directive (DWD), which aims to ensure clean and healthy drinking water. The DWD sets

minimum requirements for water to be wholesome and clean enough to be used for human consumption. Factors included in the DWD are, amongst others, colour, taste and odour, turbidity, and enumeration of cultivable microorganisms at 22 °C. [6]

World Health Organisation (WHO) also has guidelines for drinking water quality for the protection of public health, and include the recommendations from WHO for managing hazardous risks to ensure the safety of drinking water. [1]

2.2 Water treatment at Norrvatten

Norrvatten distributes drinking water to 700,000 people, Arlanda airport, and several large hospitals in the north of Stockholm with a capacity of 1,600 liters of drinking water per second and 50 million cubic metres of drinking water annually. It is Sweden's forth biggest drinking water distributor. The plant, Görvälnverket, is situated in the north of Stockholm, next to the river Mälaren. [2]

The treatment process at Norrvatten consists of several steps to ensure the water meets the set standards, including mechanical, chemical, and biological treatment. Water is taken from Görvälnfjärden in Mälaren from two different water depths, 22 or 4 m, depending on time of the year and water quality. The whole process is illustrated in Figure 2.2.1. [2]

1. Water intake   2. Sieve   3. Pump   4. Mixing   5. Flocculation   6. Sedimentation

7. Sand filter   8. Pump   9. Carbon filter   10. UV disinfection   11. pH + NH2Cl   12. Pump to tap
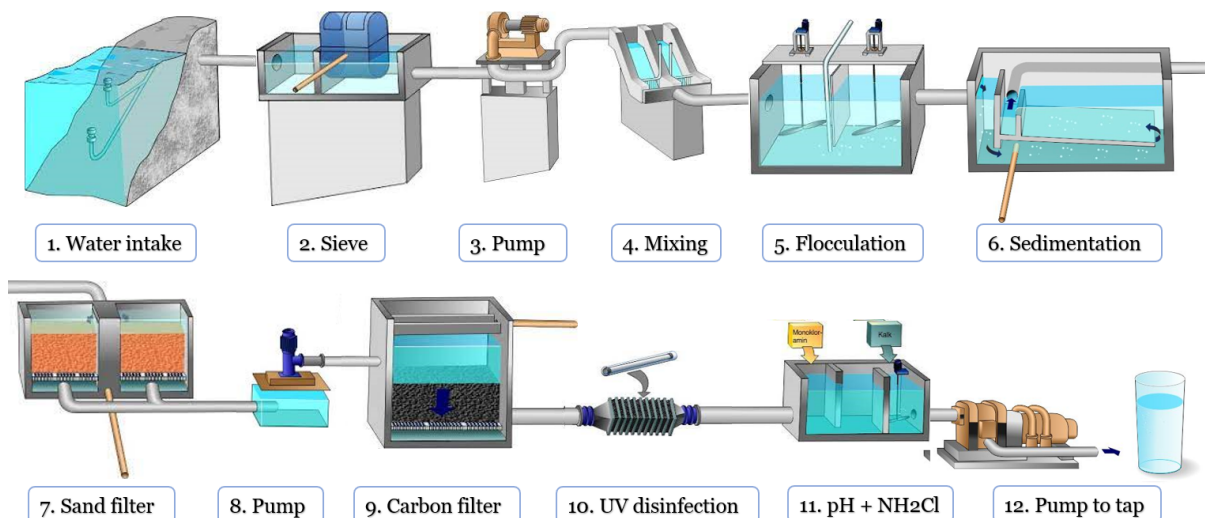
Figure 2.2.1: *Illustration of water treatment process at Norrvatten.*

First, the water is filtered from fish, algae, and other bigger particles using large micro-screens. This is followed by a pump station to ensure the correct amount of water

is pumped to the purification process. The water is then mixed in a mixing gutter where the chemical coagulant Al2(SO4)3 is added, followed by a flocculation chamber where the flocks bind to humic substances, mud, and microorganisms. This is done to separate suspended solids from the raw water. The auxiliary coagulant activated silica (NaSiO) is added to enlarge the flocks so that they can sediment in the following sedimentation step. The sediment from the sedimentation step goes to the sludge separation chamber, where polymers are added for thickening of the sludge. [7]

Next, the water passes through a Sand Filter (SF), which treats the water using sand and gravity to remove particles and other contaminants. This is followed by a CF with beds of GAC, which is described in detailed below. The water is then disinfected using Ultraviolet (UV) reactors where UV rays disinfect the water by inactivating germs. The pH is adjusted using lime to reduce the risk of corrosion in the pipes. Small amounts of monochloramine is also added to decrease bacteria growth. The purified water then goes to a reservoir. [7]

2.2.1 Carbon filters at Norrvatten

The treatment with CFs is done by adding water at the top of the filter. The water will then pass down, through the carbon particles which adsorbs contaminants from the water. The outgoing water will then leave in the bottom of the filters. This process is shown in Figure 2.2.2. [7]
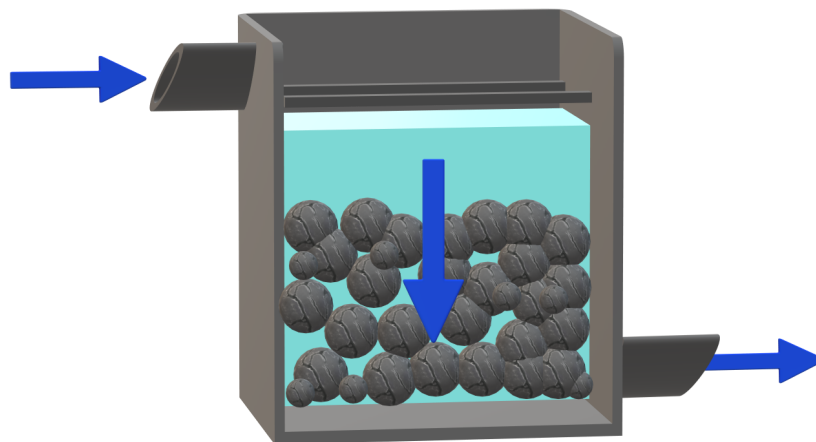
Figure 2.2.2: *Illustration of water treatment using CFs.*

The CFs uses GAC for the treatment of water, which improves odour and taste while also reducing the amount of organic substances and Per- and Polyfluoroalkyl

Substances (PFAS), and protecting the water from pollutants. The CFs at Norrvatten are backwashed with water every other week to reduce clogging to maintain a high filtration potential. [7]

There are ten CFs at Norrvatten and all of them have an area of 21.6 m² and a depth of 2.5 m. The carbon particles have a size of 0.9 mm. All filters are Norit GAC 830W and the carbon particles were activated through steam activation giving it a hardness which is suitable for thermal reactivation. The particles have a total surface area of 1,150 m³/g and a density of 485 kg/m³. The filter is suitable for water treatment for removal of NOM, colour, pesticides, chlorinated solvents, and taste and odour. The filters were installed in 2004 and in 2011, CF1 had the GAC exchanged to new carbon particles and CF2-9 were regenerated, while CF10 has never been regenerated. [8]

2.2.2 Future plans at Norrvatten

Since the 1960's, the capacity of Norrvatten has been relatively constant and there has been no need for capacity expansions. However, the past five years, the water consumption in the region has increased by 20 % and is expected to increase more the upcoming years. Further, there are regularly new demands on the quality of drinking water [9]. Lake Mälaren is expected to be affected by the climate changes as well as regional changes. The climate changes will affect the lake by more intense precipitation and increased temperatures. This will lead to an increase in NOM, microbial, and chemical loads such as PFAS and pesticides. Further, fluctuations in the concentration of contaminants will be more frequent. The regional changes will cause increased need of housing and infrastructure, including water [10]. Thus, the production capacity and treatment at Norrvatten has to be expanded to account for the future increased need and demands. To account for said expansion, both the existing plant and a new plant will be developed. [9]

2.3 Contaminants in drinking water

There are various contaminants in drinking water. The ones which are of relevance for CFs are described below.

2.3.1 Natural Organic Matter

NOM occurs in natural water sources and is produced through metabolic reactions and it exists in complex mixtures of organic compounds [11, 12]. Aquatic NOM can consist of various organic compounds with different sizes, structures, and functionality depending on the source [13]. Its main constituents are carbon, oxygen, hydrogen, and nitrogen [14]. Climate change has caused an increase in NOM concentrations. It has shown to cause several problems to drinking water such as taste and odour problems, colour of water, reduction of dissolved oxygen in water, and formation of Disinfectant By-Products (DBPs) [11]. Further, it has shown to impact the DWTP by fouling of membranes and reduction in CF effectiveness. [15]

NOM consists of humic and non-humic substances. The non-humic substances are the recognisable plant remains and organic compounds which are hydrophilic, for example carbohydrates, proteins, lignin, and amino acids. All other material of high Molecular Weight (MW), that are hydrophobic and brown to black colour are humic substances. The molecular structure and chemistry of humic substances are uncertain due to its heterogeneity and complexity [14]. Humic substances are therefore divided into three fractions depending on their solubility: fulvic acids, humic acids, and humin. Fulvic acids are soluble at any pH and have a yellow-brown colour in water. Humic acids are insoluble at pH values below 7, and have a higher MW than fulvic acids. Humin is insoluble in water and has a black colour [16].

Dissolved Organic Matter (DOM) consists of organic matter which have heterogeneous structures and compositions and it is a common element in rivers and lakes. Dissolved NOM is DOM, which has a lower MW [17]. Dissolved Organic Carbon (DOC) is only the carbon in the DOM and is defined as the organic compounds that can pass through a filter of 0.45 μm. The Total Organic Carbon (TOC) is the total carbon concentration before filtration. The DOC is generally harmless but could cause problems in the treatment process. [18]

The biogeochemical cycles of the surrounding environment affects the NOM, which

makes it important to make the DWTP able to handle these fluctuations [19]. Both production and treatment of NOM is affected by seasonal variations such as temperature and precipitation. [20]

2.3.2 Particles

Carbon fines can be released from CFs using GAC, which will lead to traces of carbon particles in the drinking water [21]. There is no particular risk for humans to intake the carbon itself, however, the carbon particles can contain the adsorbed contaminants, which could be released upon digestion. [22]

2.3.3 Taste, odour, and colour

Taste and odour are of importance for treated water and can be derived from natural inorganic or organic chemical contaminants. Taste and odour can be an indicator of problems in the water treatment [1]. Two common sources for taste and odour of the water are geosmin and 2-methylisoborneol [23]. Neither of these compounds are toxic but both are unpleasant for users. [24]

Ideally, drinking water should not have any visible colour. The colour in drinking water usually origins from Coloured Dissolved Organic Matter (CDOM), which consists of humic and fulvic acids. [1]

2.3.4 Microorganisms

The concentration of microorganisms in the water has started to increase, which could cause an increase of water-born diseases. This risk will probably increase even more in the future due to climate change and precipitation. [25]

2.3.5 PFAS

PFASs are organic contaminants and have bioaccumulative, persisting, and toxic qualities. Drinking water has shown to be the main source for PFAS exposure to humans [26]. There are around 4,700 different kinds of PFAS substances, which are present everywhere in the environment since they are persistent and do not break down. PFAS does not occur naturally, but started being produced and used

in the 1940's and has since then polluted the environment. This has lead to PFASs contaminating the water sources. [27]

2.4 Carbon filters

Activated carbon is used either in fixed bed reactors using GAC or in a slurry using Powdered Activated Carbon (PAC). The PAC is used in a steady-state process and GAC in a nonsteady-state. The GAC can be used in a filter, called filter adsorber, or a reactor after the filter, called post-filter contactor. The latter being the most commonly used for groundwater treatment [28]. Using GAC adsorption is one of the most effective ways to reduce the amount of NOM in water. [29]

2.4.1 Contaminants treated with CFs

GAC is a treatment that is usually placed at the end of the treatment process to reduce taste and odour of the water. Another contaminant in drinking water that can be treated through CF is PFAS. The removal efficiency of PFAS using GAC has been shown to be 92-100 % for newer filters but 7-100 % for older filters [30]. NOM can also be treated using GAC [11]. Activated carbon also adsorbs DOM and can therefore control the formation of DBPs [28]. The adsorption using CFs treats contaminants such as DOC, organic micropollutants, DBPs, and taste and odour. [3]

Taste and odour can be treated by coagulation, sedimentation, and chlorination, but CFs can be used for additional treatment. For example hydrogen sulfide can be removed from the drinking water using carbon filters. [1]

2.4.2 Activation process

The activation process of carbon is done through carbonisation of the precursor material followed by activation of the material. The carbonisation is done anaerobically at 500 to 800 °C which thermally releases volatile organic matter and realigns the carbon atom to make it form a crystalline structure. The activation is then done thermally or physically using a temperature of 850 to 1 000 °C with an oxidising agent such as steam or carbon dioxide (CO_2). The activation increases the surface area and pore size of the carbon. Various materials can be used as sources for activated carbon;

for water treatment black coal, lignite coal, coconut shells, and wood are the most common sources. [28]

2.5 Adsorption process

The adsorption technique can be used to remove dissolved contaminants from water through a physical phase separation where the contaminants are accumulated on the surface of the adsorbent, inside the pores, while the water passes through the activated carbon [28]. This adsorption phenomena is shown in Figure 2.5.1.
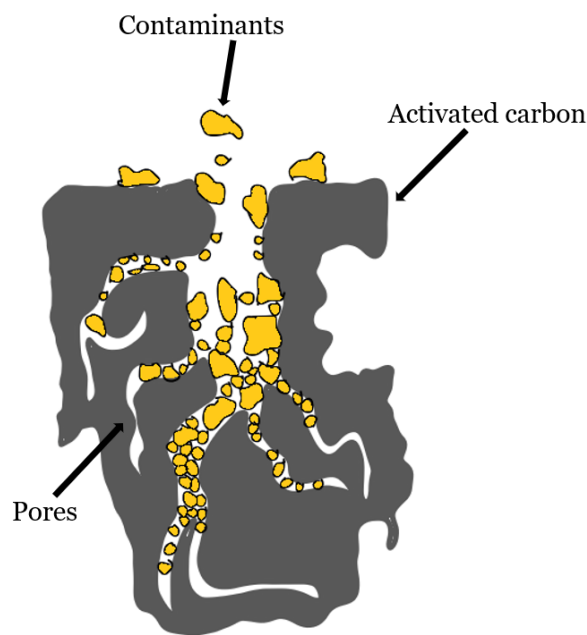
Figure 2.5.1: *Adsorption on activated carbon. [8]*

The adsorption is done through chemical or physical adsorption [31]. For the adsorption to reach a satisfactory performance, the CF must be replaced or regenerated once the adsorbate reaches the treatment objective. CFs has a high surface area, which makes it an economical adsorbent. Besides having a large surface area, it is of importance that the adsorbents have different target compounds. The adsorption capacity is highly influenced by the background matrix. [28]

The CF is saturated once all its adsorption sites are bonded to organic matter or microorganisms, at which point the CF is exhausted, which can cause organic matter to pass through the CF, causing bacteria to grow within the treatment system. This can lead to issues with water quality, cause corrosion, and lead to a risk of pathogenic diseases. [28]

Due to its high porosity and large surface area, CF is an efficient adsorbent. However, over time there will start to grow a biofilter on top of the filter, which will make the GAC filter saturated over time. This new biofilter will then be the main contributor to the treatment, through BAC [3]. Therefore, the CF needs to be regularly regenerated, meaning that contaminants are cleared from the carbon particles to make it activated once again. This is done through a similar process as the activation of carbon. Backwashing will only decrease clogging and not reactivate the active sites. If not regenerated, the treatment will only be done through the biofilm described below. [28]

2.6   Biofilm on CFs

Microorganisms can settle on the GAC, forming a biofilm which can further contribute to the removal of contaminants through biodegradation. The adsorptive capacity of GAC has been shown to be exhausted after six to seven months, at which point the GAC would turn into a BAC [24]. The biofilm can cause clogging, which leads to a need for frequent backwashing. After backwashing, the bacteria will grow back on the biofilm to then need backwashing again. Besides contributing to NOM removal and cause clogging, the biofilm can lead to anaerobic zones in the CF, and ruin the water quality as microorganisms detaches from the biofilm. [29]

Biofilms consists of microbial cells in a cluster, where the cells are stuck together on a surface. The cells are held in a dense cluster in an extracellular microbial organic polymer matrix. The microbial activity of the biofilm is increased when adsorbed onto the GAC [32]. In the BAC system, the carbon particles are used as a filtration for physical removal of pollutants. When the particles are exhausted, the biofilm will biodegrade contaminants instead. This process of using GAC and the biofilm simultaneously has environmental benefits such as decreased backwashing frequency, a lower demand of chlorine which leads to a more easily disinfected water, and no chlorination of by-products. [32]

The biofilm has been shown to be an important part of taste and odour removal from water but can negatively affect the removal of NOM as the removal efficiency of NOM is lower in BAC than in GAC. However, since the taste and odour effect is still active, the BAC can operate for several years without the need for regeneration or replacement. [24]

Several factors will influence the biofilm formation, such as water quality, hydraulic conditions, sort of activated carbon, backwashing system, and temperature. However, how these factors influence the biofilm formation has not yet been studied in detail. [29]

2.7 Influence of operating parameters

To achieve better performance, operating parameters such as flow rate, contact time, temperature, and backwashing regime has to be investigated. [33]

2.7.1 Backwashing of CF

Since both filtration and adsorption cause clogging to the GAC, backwashing is needed. This process is done by adding water or air up-flow through the GAC [29]. Backwashing has shown to have a significant effect on bacterial community and diversity. Previous studies have shown that backwashing can lead to a loss of 36 % of bacterial cells [34]. However, the bacterial cells have been shown to recover quickly. Thus, backwashing does not seem to have a negative effect on the removal efficiency of the CFs. [35]

2.7.2 Temperature influence on CF performance

There are several factors that can influence the performance of CFs, one of which is temperature. It has been shown that 2-methylisoborneol and geosmin has a lower removal rate in colder water. This temperature effect is kinetically driven and not thermodynamically. At higher temperatures of around 20 °C, 2-methylisoborneol removal can increase to up to 20-30 % compared to lower temperatures of 4-10 °C. [36]

2.7.3 Flow rate and EBCT influence on CF performance

The treatment using CFs has been shown to increase with lower flow rates. Reducing the flow rate with 10 L/s from 39 L/s has shown to give a higher removal efficiency of 6.5-14 % [30]. Hydraulic loading also affects the removal of both taste and odour [24].

CF usage rate has been shown to decrease with increased contact time when comparing

6 to 12 min [37]. Removal of contaminants such as estrone has been shown to increase with increased contact time of BAC [38]. Further, increased EBCT has shown to increase removal of NOM [11]. TOC removal has also been shown to increase with increasing contact time [39]. Other studies have shown that increased contact time influence GAC performance of taste and odour reduction but not BAC performance [40]. Studies have also indicated that there is a correlation between EBCT and temperature, where at low temperatures, an increase in EBCT can compensate for an eventual decrease in treatment efficiency. [41]

2.8 Analytical measurements

For analysis of the contaminants mentioned, various techniques can be used. The ones which are of relevance for this project are described here.

2.8.1 Natural Organic Matter

Organic matter can be measured as TOC, which measures both dissolved and particulate matter. It is usually measured by oxidising organic compounds to turn the compounds into quantifiable forms. The organic matter can also be measured using Chemical Oxygen Demand (COD), which is a measurement of the oxygen that is consumed when the water is oxidised under acidic conditions. COD and TOC can both be measured for comparative purposes. COD is the oxygen used for oxidising the organic matter in water. Fulvic and humic acids are oxidisable and is often a large portion of the COD present in the water. Usually, COD>TOC, if not it can be due to toxicity in the water. [42]

CDOM is organic matter which can absorb UV light. A fraction of CDOM is fluorescent and is therefore called fluorescent Dissolved Organic Matter (fDOM), a technique that can be used to track concentrations of organic matter in the water. Further, fDOM can be used as a measurement for TOC. [43]

2.8.2 Turbidity

Suspended and colloidal matter in water cause turbidity, which is an 'expression of the optical property that causes light to be scattered and absorbed'. It is caused by suspended matter or colloidal matter, for example clay, particles, organic or inorganic

matter, and microorganisms. Turbidity is a measurement of how much scattered light shines through the water. Increased turbidity gives a higher intensity of the scattered light. [44]

Turbidity measurement is a quick, cheap and continuous method for measurement of water quality. Turbidity is not a risk to public health itself, but can be an indication of pathogenic microorganisms. Turbidity can also be an indicator for filter performance, coagulation, and clarification. Further, a high turbidity can be visible, thus affecting the aesthetics of the water [45]. Turbidity can also be caused by disturbance of biofilms in the treatment system [1]. Turbidity should be below 0.5 Formazin Turbidity Units (FTU). [46]

2.8.3   UV-254

UV254 is a measurement of organic matter. It is a popular method for measurement of water quality since it does not need any pre-treatments or chemicals [47]. Using UV254 will make UV absorbing material absorb UV light proportional to the concentration of the material. The method is used at 253.7 nm, rounded to 254 nm [44]. UV254 is an indication for concentrations of organic matter [19]. The method has been shown to have a linear correlation to both turbidity and DOC [47]. The major interference to this method is from colloidal particles, inorganic material with UV absorbing qualities, ozone, chlorate, and others. However, most DWTPs have been shown to not have this interference due to the purity of the water. [44]

UV254 can also be used together with DOM to calculate carbon-normalised absorption, Specific Ultraviolet Absorbance (SUVA), which is calculated using Equation 2.1. SUVA can be used for characterisation of NOM, where values above 4 is considered to have high concentrations of humic substances and below 2 is considered to mainly contain non-humic substances. [19]

$$SUVA = \frac{UV_{254}\,[m^{-1}]}{DOC\,[\frac{mg}{L}]} \tag{2.1}$$

2.8.4   Other measurements

Microorganisms can be measured using various analysing technologies. One of these is cultivable microorganisms at 22 °C, which should be kept below 10 pcs/mL for disinfected drinking water. [46]

Conductivity is a measurement of the water's ability to carry an electric current, an ability that depends on several factors, such as concentration of ions, their mobility, and the temperature of the water [44]. Conductivity should be kept below 2,500 µS/cm. [46]

Particle analysis can be done through digital holographic imaging, which is an imaging technique. It can provide information on particle count, size, shape, and identification. Holography is the recording of inference patterns of diffracted light that occurs when particles are illuminated by a coherent light source. [48]

Carbon fines usually have a size of 0.45 µm and above [49]. Filtering the water through 0.45 µm is a method to measure the amount of suspended solids in water. [50]

Chapter 3

Method

The effect of increased flow rates over the CFs and increased EBCT was investigated. The flow rate variations and which analyses were made are described in detail in this chapter.

3.1 Flow rate variations

Three carbon filters that were installed in 2004 were studied for measurements of the effect of increased flow rate: one newer with an activated carbon age of 10 years (CF1), one which was regenerated 10 years ago (CF3), and one 20 year old filter (CF10). The three filters usually have a flow rate of 190 L/s and sometimes up to 230 L/s during the summer months. To measure how the filters were affected by increased flow rates, three other flow rates, besides 190 L/s, were analysed: 220, 250, and 280 L/s. The rates were tested for 24 hours, one day after backwashing.

While these CFs had an increase in hydraulic loading, other filters had to have a decrease in flow rate. A decrease in flow rate leads to increased EBCT just as increased flow rate leads to decreased EBCT. The effect of increased EBCT was studied for two filters, CF6 and CF7, which had an increase in EBCT of 60 % and 76 %. Further, one filter was not changed, but was studied to see if any results were related to fluctuations in the plant or the different EBCTs. All three filters were installed in 2004 and regenerated 10 years ago. The EBCT was calculated using Equation 3.1.

$$EBCT\,[min] = \frac{Volume\,[m^3]}{Flow\,rate\,[\frac{m^3}{min}]} \tag{3.1}$$

Table 3.1.1: *EBCT for the tested flow rates.*

Flow rate [L/s]	EBCT [min]
45	20.0
75	12.0
190	4.7
220	4.1
250	3.6
280	3.2

The tested EBCTs are shown in Table 3.1.1.

3.2 Analyses

The incoming water as well as the outgoing water from the CFs were tested to compare treatment efficiencies for the various flow rates.

UV254 was analysed using PerkinElmer UVVIS Lambda 365. This measurement was compared to the online measurements.

For the filtration of particles, samples were filtrated by taking 800 mL of the samples and filtering them through cellulose nitrate membrane filters of 0.45 μm with a diameter of 47 mm from GE Healthcare Life Sciences, Whatman.

Flow rates and conductivity were measured with an online sensor. An online particle analyser from Uponor was used for measuring particles in the water, where total particles, b-particles, c-particles, and f-particles were measured. The f-particles indicate fibre particles and c-particles indicate the amount of particles associated with waste and storm water. The b-particles indicate cluster-like particles that can be found in water due to disruption in water distribution, for example biofilm fragments or sediments.

Some analyses were made by the internal laboratory at Norrvatten. The tested factors were cultivable microorganisms at 22 °C over 3 days, TOC, COD, odour, and UV254. The TOC and UV254 was also used for calculation of SUVA.

Other measurements were made using an EXO sensor, with a magnetic stirring of 700 rpm. This tool measured fDOM and conductivity. The EXO sensor did not have any internal correction for temperature, this was therefore calculated manually, using

Equation 3.2.

$$fDOM_{tcorr} = fDOM_{QSU} + fDOM_{QSU} \cdot 0.012(T_{water} - 25) \tag{3.2}$$

The temperature corrected value was then corrected for absorbance due to coloured water using Equation 3.3.

$$fDOM_{abscorr+tcorr} = fDOM_{tcorr} + fDOM_{tcorr}\frac{0.2508 \cdot UV_{254}}{100} \tag{3.3}$$

3.3   Measurement frequency

The frequency of all analyses for acCFs with increased flow rates are shown in Table 3.3.1. The samples were taken right before (P0), one hour after (P1), three hours after (P3), and 24 hours after (P24) increased flow rate. For the samples marked with a *, incoming water was also measured.

Table 3.3.1: *Analysis methods used and frequency of analysis.*

Analysis	P0	P1	P3	P24
UV254	x*	x*	x*	x*
Particles	x*	x*	x*	x*
fDOM QSU	x	x	x	x
Turbidity	x*	x*	x*	x*
TDS	x	x	x	x
Conductivity	x	x	x	x
TOC				x
COD				x
Odour 20°C				x
Odour 50°C				x
Microorganisms - 3 days				x

The frequency of all analyses for carbon filters with increased EBCT are shown in Table 3.3.2, where "w" indicates the week.

Table 3.3.2: *Analysis methods used and frequency of analysis for carbon filters with reduced and constant flows.*

Analysis	w0	w1	w2	w3	w4	w5	w6
Turbidity	x*	x*	x*	x*	x*	x*	x*
UV254	x	x	x	x	x	x	x
Odour 20 °C	x	x	x	x	x	x	x
Odour 50 °C	x	x	x	x	x	x	x
TOC	x	x	x	x	x	x	x
COD	x	x	x	x	x	x	x

3.4 Statistical analysis

For ensuring the measurements were correct and had internal validity, F-tests were performed. This was done on the flow rate of 190 L/s for CF1 with 95 % confidence level. It was then assumed that the other filters would follow a similar pattern. To eliminate outliers, Grubb's test for outliers was used.

Chapter 4

Results and discussion

The results and discussions are presented in this chapter, which is divided into two parts; effect due to increased flow rates over the carbon filters and effect due to increased EBCT.

4.1 Increased hydraulic loading

Various parameters were analysed for the measurements of the effect of increased flow rates. How these factors changed depending on flow rates are described in this chapter.

4.1.1 Effect on particle removal

The removal of total particles over the CFs is illustrated in Figure 4.1.1. This shows that incoming water had a higher concentration of total particles during the flow rates of 190 L/s and 280 L/s. However, the outgoing water at 190 L/s had a significantly lower outgoing particle concentration than that of 280 L/s, even though it had a higher incoming particle concentration. This indicates that the increased flow rate did have some effect on the particle removal, since the incoming particle concentration alone can not explain the difference in particle removal.

Both the flow rate of 220 and 250 L/s had a lower incoming particle concentration, which could be the reason for the lower removal efficiencies at these flow rates. This shows that the incoming particle concentration potentially could have an effect on the treatment efficiency. However, the background variables could not be controlled since

the measurements were performed in the plant which has natural fluctuations. This should be considered in future experimental designs to verify whether the effects are caused by the actual flow rates or the incoming particle concentrations.
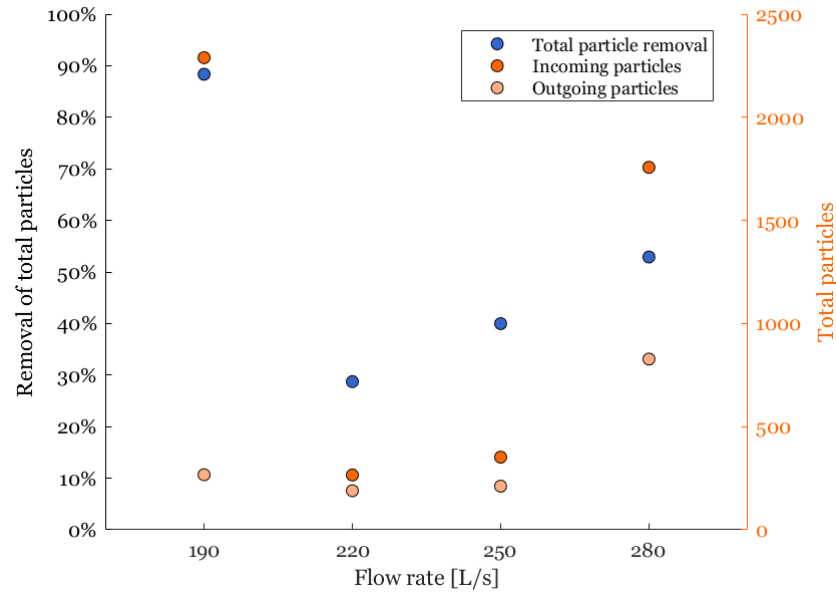
Figure 4.1.1: *Total particles*.

The removal efficiency of particles over all sampling points are shown in Figure 4.1.2, which indicate that the removal was highest at a flow rate of 190 L/s and 280 L/s. The highest fluctuations over the measured 24 hours were seen at 280 L/s.
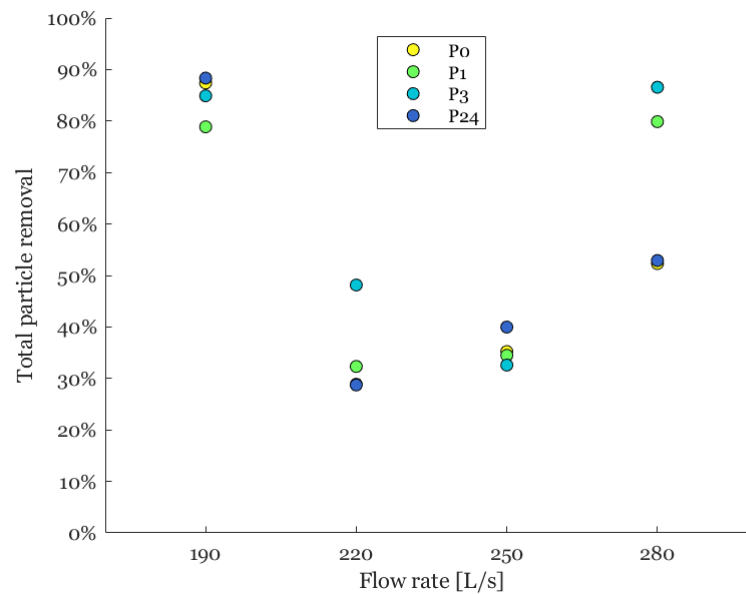
Figure 4.1.2: *Particle removal efficiency*.

The fluctuations in removal efficiency at 280 L/s could be explained by the fluctuations

in incoming particles, which is shown in Figure 4.1.3. No larger differences are shown in outgoing particle concentration over the observed 24 hours. However, incoming particle concentrations varied remarkably at 280 L/s, where sampling point 1 and 3 had much higher incoming particle concentrations.
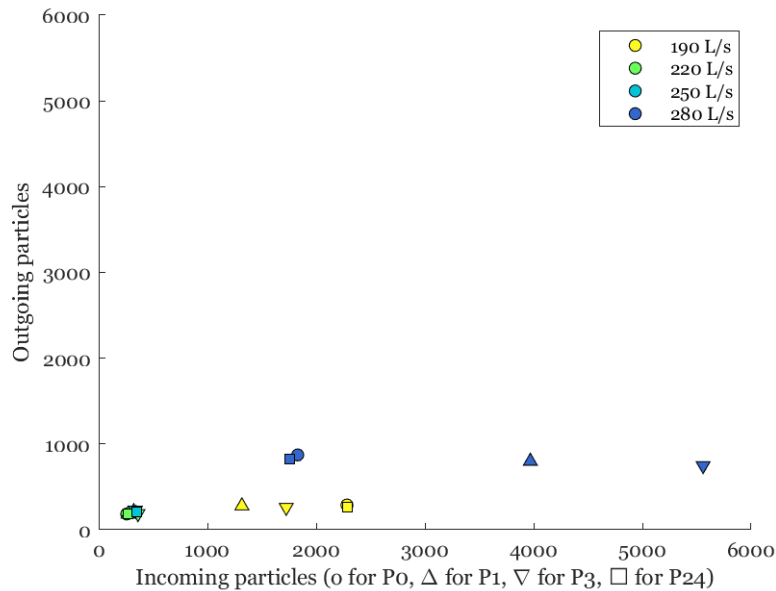
Figure 4.1.3: *Outgoing vs incoming total particles.*

The total outgoing particle concentration is shown in Figure 4.1.4 for all sampling points. The figures clearly show that for 280 L/s, the outgoing particles were much higher than that of the other flow rates. However, as mentioned above, the reason to the increase in outgoing particles could be explained by other factors than the increased low rate. The fluctuations over the observed 24 hours for each flow is negligible at most flow rates, but a bit higher for that of 280 L/s.

The differences in outgoing particles between CF1, CF3, and CF10 are shown in Figure 4.1.5, 4.1.6, and 4.1.7. These show no larger differences between the three filters, which validates the previous use of averages for the other figures. A slightly higher outgoing particle concentration is observed in CF1 at the flow rate of 280 L/s. The similarity between the three filters suggests that there is no significant effect from the age of the three filters. This could mean that the biofilm has become stable enough after time to make the difference between the filters negligible.

The removal of f-, c-, and b-particles are shown in Figure 4.1.10, 4.1.8, and 4.1.9 respectively. The removal of c-particles at 280 L/s was -354 %, which is why it is not shown in the graph. The figures show that the b-particle removal has a similar
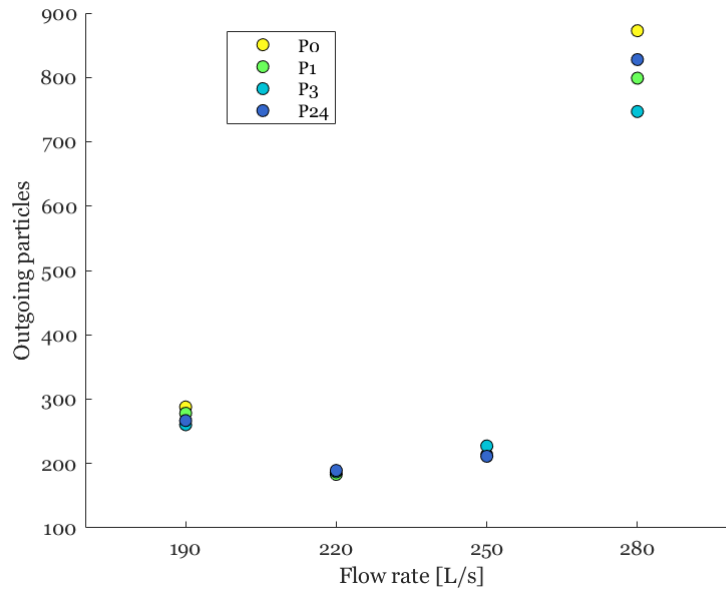
Figure 4.1.4: *Outgoing particles.*
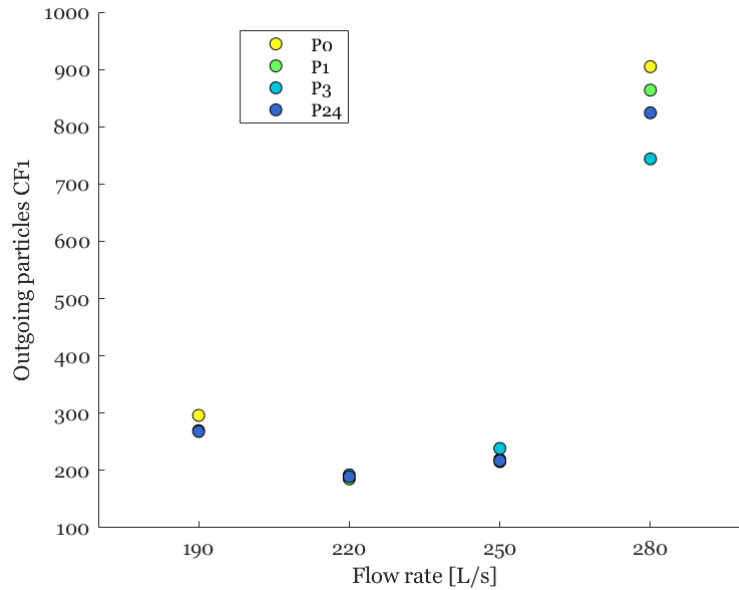
Figure 4.1.5: *Outgoing particles for CF1.*

pattern as that of total particles. The f-particles, however, have a lower removal efficiency at 190 L/s, and at P1 and P3, the f-particles increase over the filter instead of being reduced. The c-particles are not removed to the same extent as the other particles.

Figure 4.1.11 shows the outgoing f-, c-, and b-particle removal at all measured times. These show a similar pattern between c-, and b-particles, but a higher outgoing f-particle concentration at the flow of 190 L/s compared to the other flow rates. At the
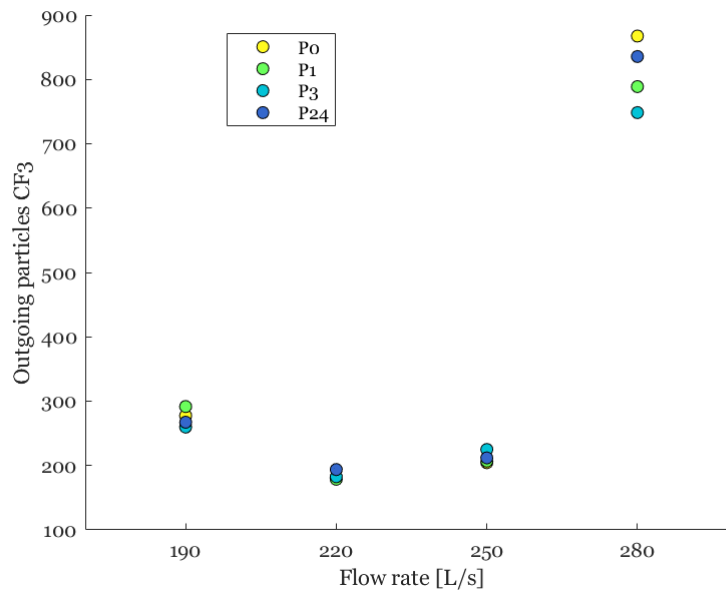
Figure 4.1.6: *Outgoing particles for CF3.*
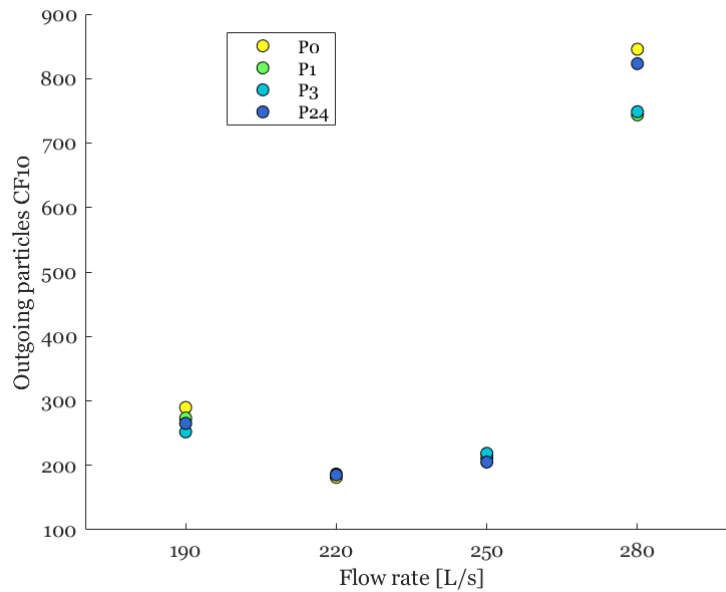
Figure 4.1.7: *Outgoing particles for CF10.*

higher flow of 280 L/s, the both c-, and b-particles have the highest measured outgoing concentration. However, the increase in outgoing particles does not seem to correlate to the increase in flow since the high outgoing particles were also measured before the increase in flow rate occurred.

Outgoing and incoming particles as well as particle removal after 24 hours for the various flow rates are shown in Figure 4.1.12. At 280 L/s, incoming f-particles had a concentration of 22.0 pcs/mL and incoming b-particles 21.9 pcs/mL. The figure shows
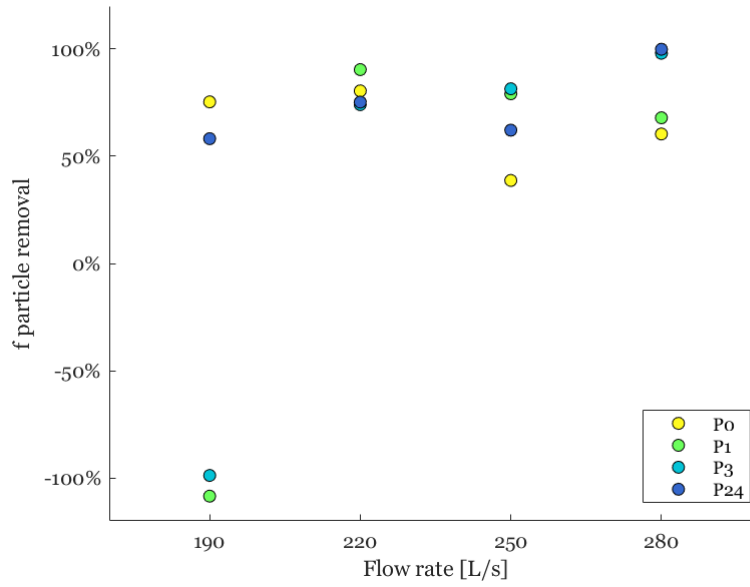
Figure 4.1.8: *Total f-particle removal.*
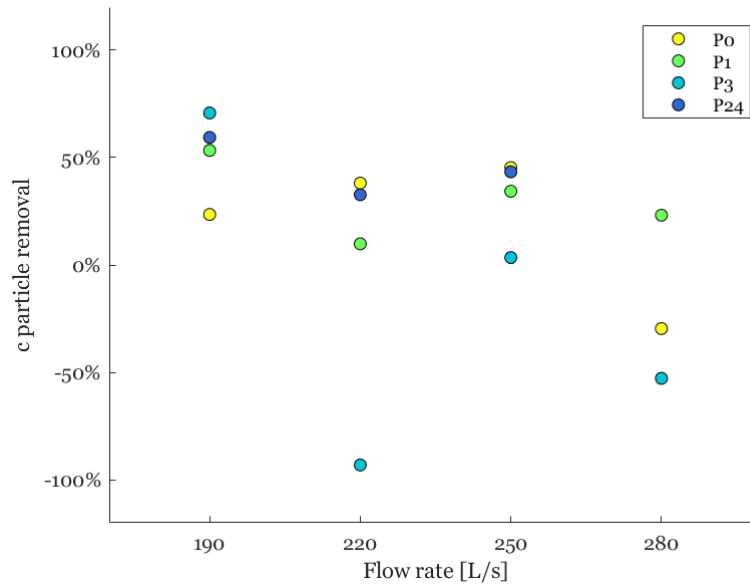
Figure 4.1.9: *Total c-particle removal.*

all three particle types. Incoming f-, and b-particles at the flow of 280 L/s was much higher than that of all other flow rates. This increased concentration could have some effect on the removal efficiency. The f-particle seems to not be significantly affected by the increase in incoming f-particles. Thus, fibre-like particles does not seem to be affected by the increased flow rate. The b-particles have a linear relationship between increase in flow rate and increase in outgoing particle concentration. At 190 L/s, the incoming particle concentration is higher than that of 220 and 250 L/s, hence, the
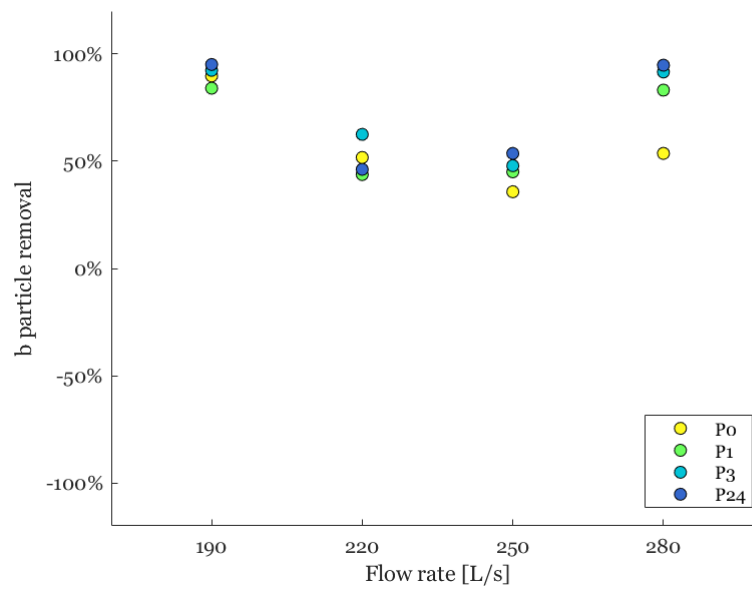
Figure 4.1.10:   *Total b-particle removal.*
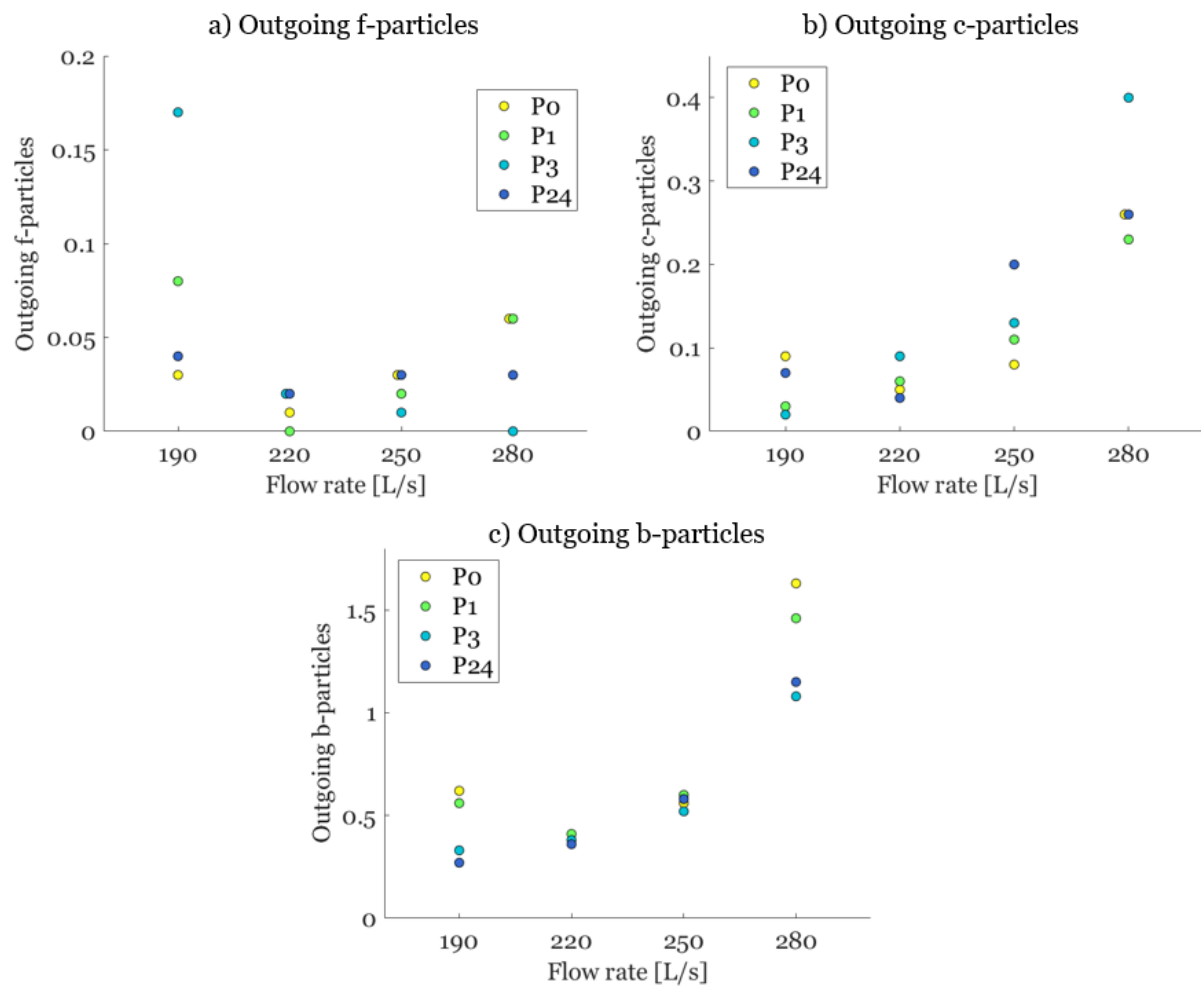
Figure 4.1.11:   *Outgoing a) f-particles, b) c-particles, and c) b-particles.*

relationship seen could also be caused by the increased flow rate. This could be an indication of biofilm fragments getting released at higher flow rates. Further, at 280 L/s, the outgoing c-particle concentration is higher than the incoming.
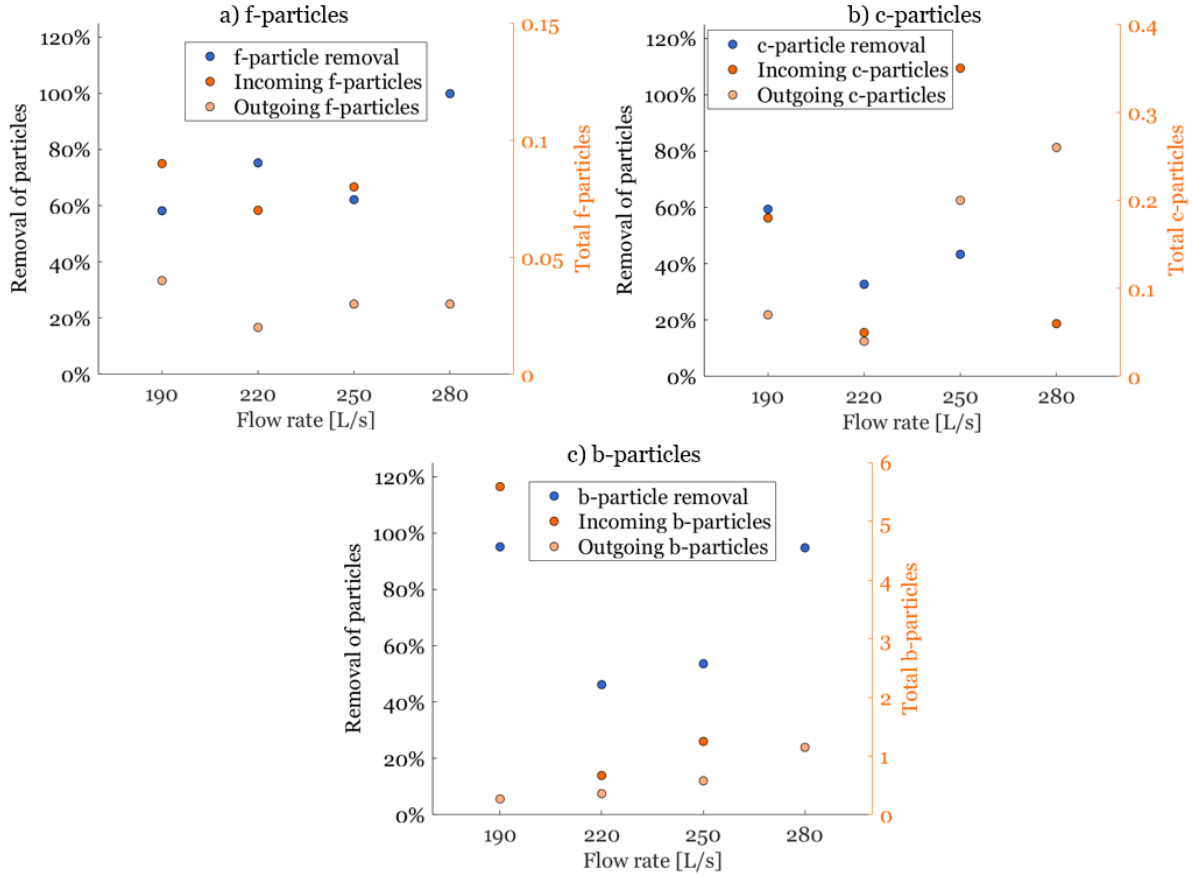
Figure 4.1.12: *Outgoing, incoming and total removal of a) f-particles, b) c-particles, and c) b-particles.*

All values for particles can be seen in Appendix A.

4.1.2 Effect on UV254 removal

Figure 4.1.13 shows the removal efficiency as well as the incoming and outgoing UV254 over the CFs. The figure shows a small difference in UV254 removal, with a variation of between 1 % to 4 %. All values for UV254 can be seen in Appendix B. In Figure 4.1.14 the removal efficiencies at all sampling times can be seen. This show that over the measured 24 hours, the difference in removal efficiency is low, thus, no larger effect is seen over the measured time. Since P0 has a similar removal efficiency as the other times for each flow rate, the removal efficiency does not seem to correlate to the flow rate, but rather other factors. Further, no significant effect can be seen between the flow rates.
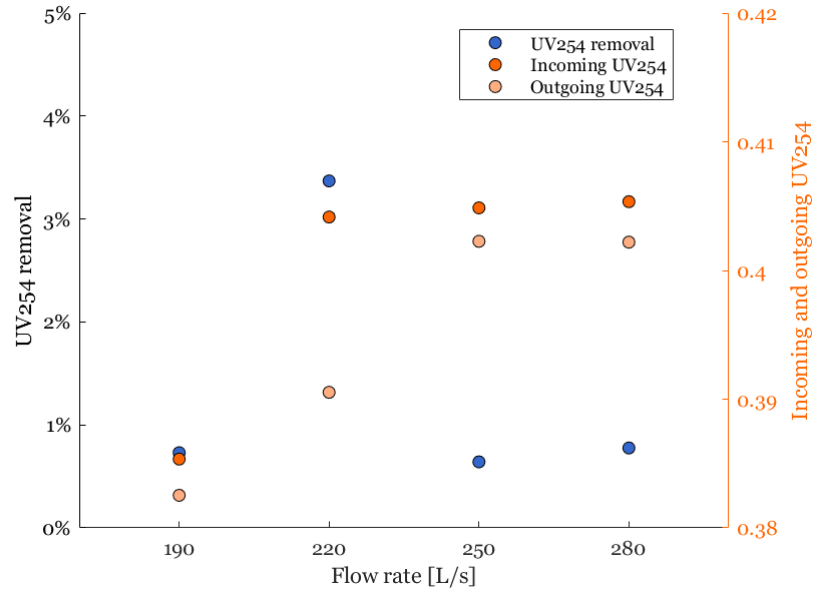
Figure 4.1.13: *Outgoing, incoming and total removal of UV254.*
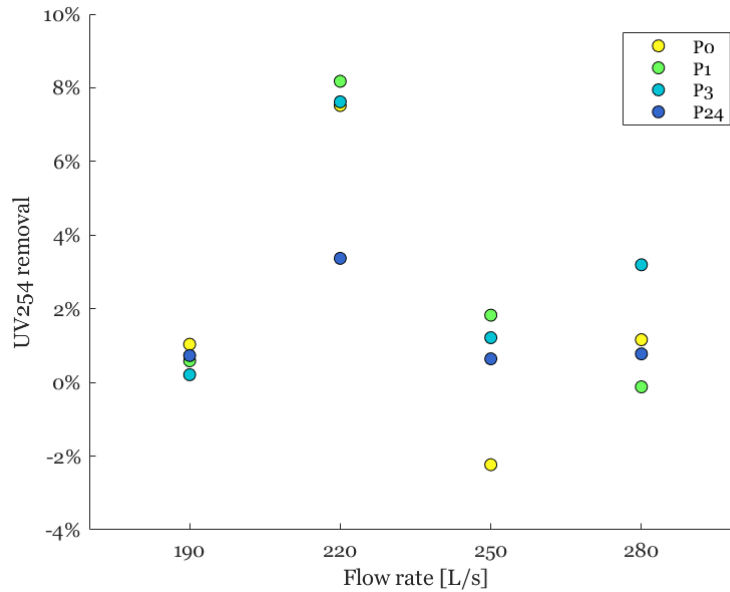
Figure 4.1.14: *UV254 removal efficiency.*

The outgoing UV254 is shown in Figure 4.1.15. Here, a larger variation between the measurements are shown. The highest value is shown at 250 L/s, 1 hour after increased flow rate. In general over the 24 hours, the UV254 is highest for the flow rates of 250 and 280 L/s. However, the outgoing UV254 was as high before increased flow rate as after. This indicates that the change in UV254 concentration is not due to the flow rate, but rather the fluctuations in incoming UV254.
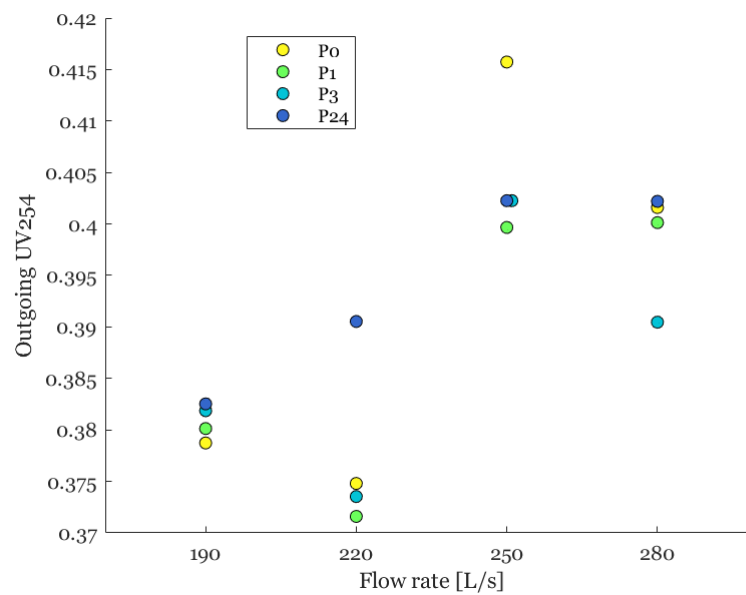
Figure 4.1.15: *Outgoing UV254.*

4.1.3 Effect on turbidity

The turbidity removal over the 24 hours where the flow was increased is shown in Figure 4.1.16. The figure shows that by the last ten hours, the highest flow rate of 280 L/s had the lowest removal efficiency, while 190 L/s had the highest. This indicates that the higher flow has a negative effect on the removal of turbidity.
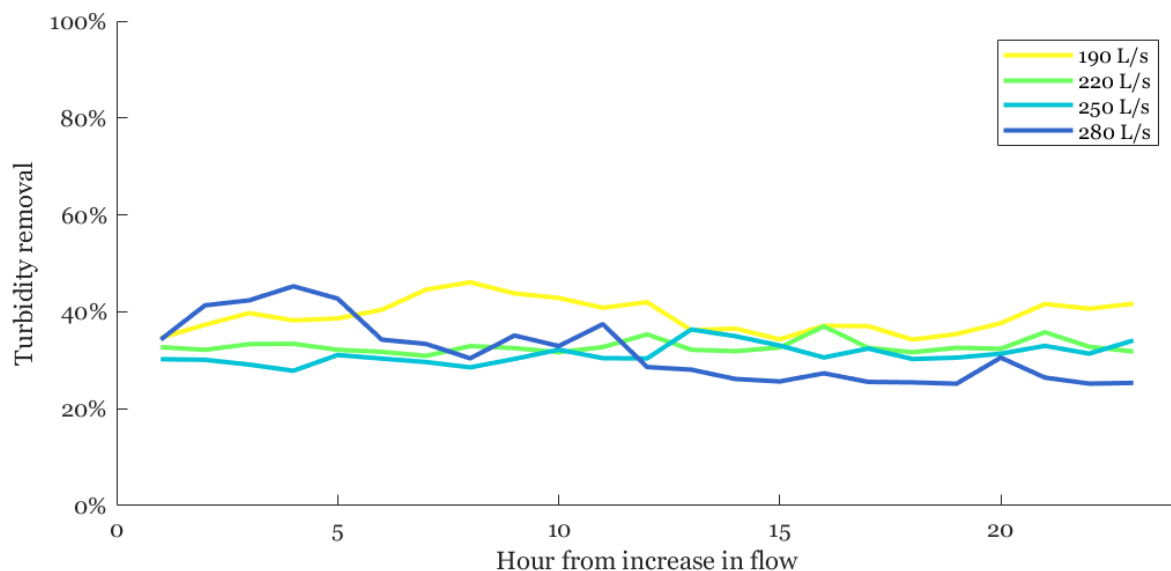
Figure 4.1.16: *Turbidity over different flow rates.*

The flow rates with the greatest difference, 190 and 280 L/s are presented in more detail, with incoming and outgoing turbidity concentrations shown together with

turbidity removal in Figure 4.1.17 and 4.1.18. These figures show that incoming turbidity is higher for that of the higher flow. However, the incoming turbidity decreases while the outgoing increases over time. This could be an indication of higher flow rate having some effect on turbidity. For the lower flow, the fluctuations in incoming turbidity does not seem to have any effect on the outgoing turbidity, which is stable at this flow rate.
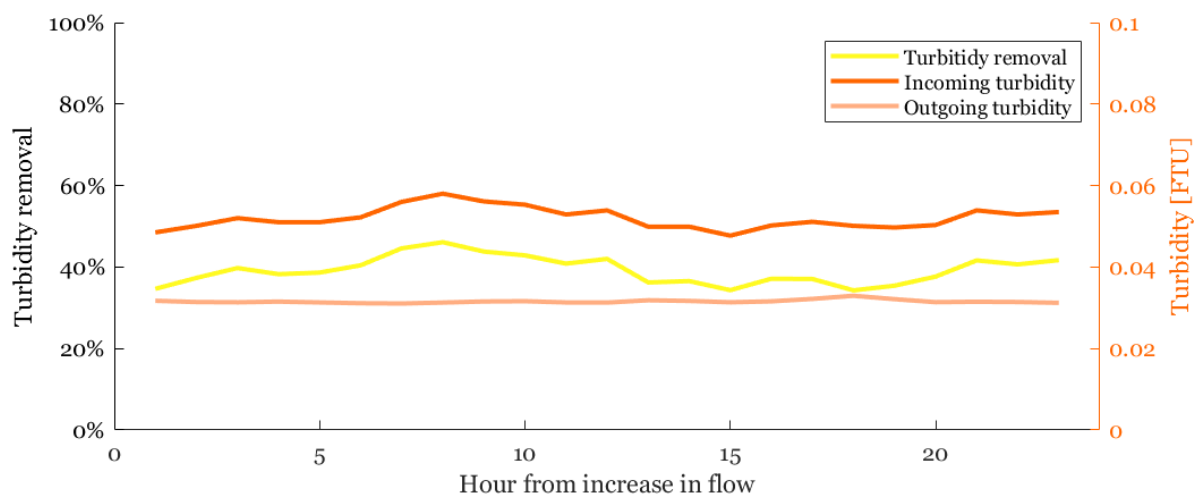
Figure 4.1.17: *Turbidity for reference flow of 190 L/s.*
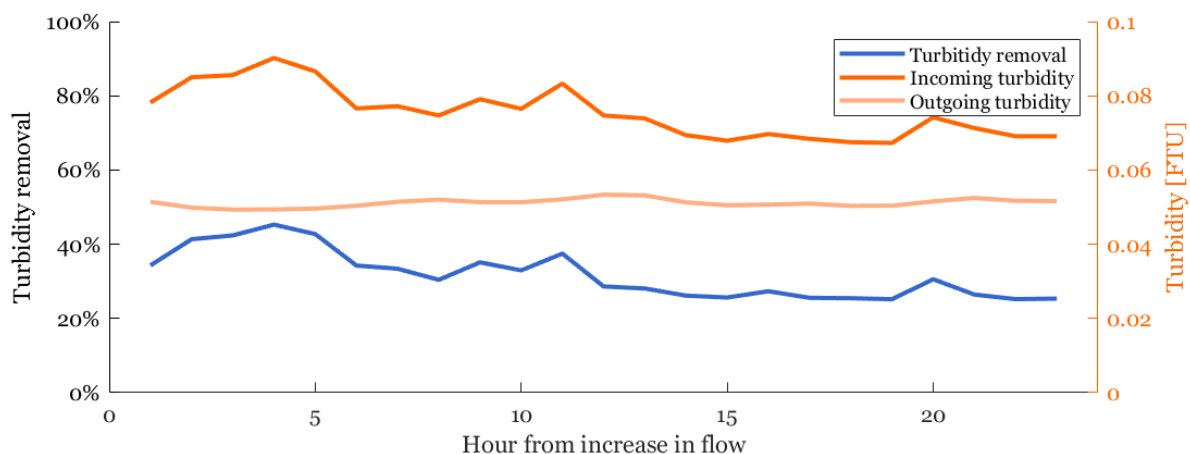
Figure 4.1.18: *Turbidity at flow of 280 L/s.*

Figure 4.1.19 show the outgoing turbidity for the different flow rates. This indicate a correlation between outgoing turbidity and flow rate. However, the incoming turbidity varied between the flow rates, as was seen in Figure 4.1.17 and Figure 4.1.18. The values for the turbidity can be seen in Appendix C. At the flow rate of 280 L/s, the turbidity is the highest, however, this is still well below the limit value of 0.5 FTU.
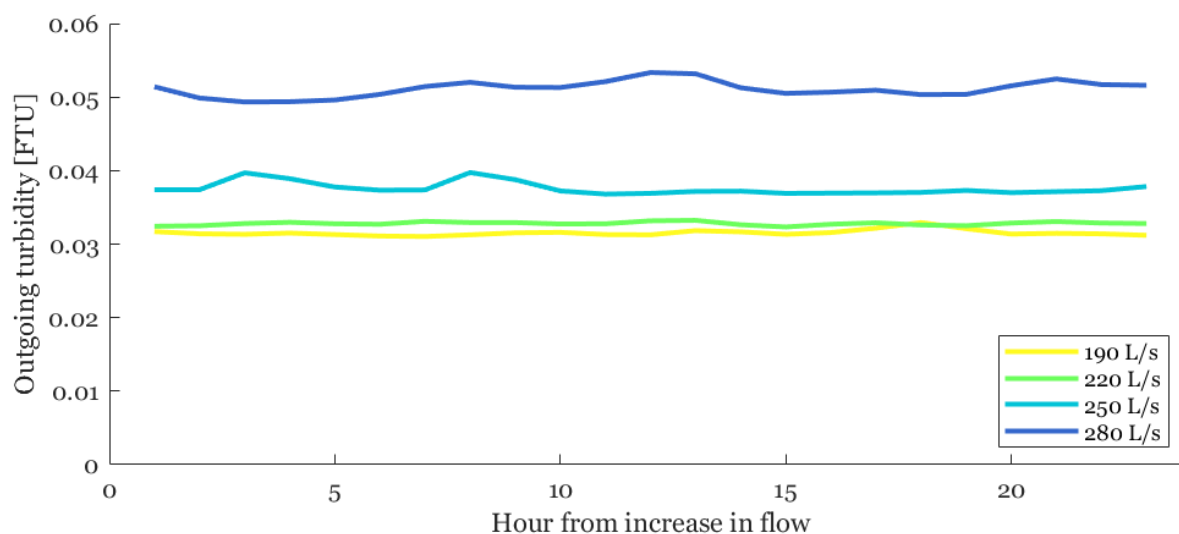
Figure 4.1.19: *Turbidity at flow of 280 L/s.*

4.1.4   Effect on conductivity

The outgoing conductivity is shown in Figure 4.1.20 and the values in Appendix D. The figure shows a difference in outgoing conductivity at the measured times. However, the measured conductivity was as high for the samples taken before the increase in flow rate as after. Thus, the increased conductivity is probably not due to the increased flow rate, but rather other factors in the DWTP. Further, the level of conductivity never reaches the limit value for outgoing conductivity, which is 2,500 µS/cm. The exact numbers for outgoing conductivity can be seen in Appendix D.
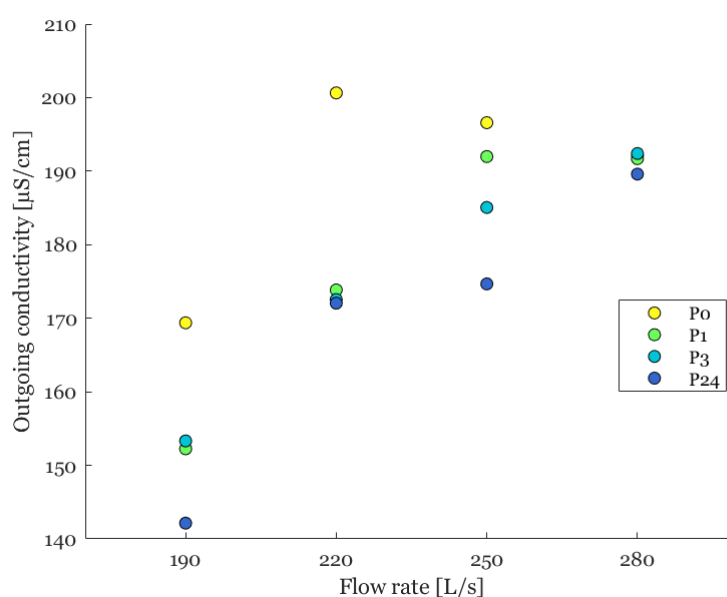
Figure 4.1.20: *Outgoing conductivity.*

4.1.5   Effect on fDOM

The outgoing fDOM is shown in Figure 4.1.21 and the values in Appendix D. The fDOM shows a similar pattern to that of conductivity, where the increase in flow rate shows a higher outgoing fDOM, but as with conductivity, the sample taken before the increase in flow rate has almost as high fDOM as the samples takena after the increase in flow rate. However, a slight difference in fDOM can be seen between the sampling points. However, this difference is not seen at the highest flow rate, 280 L/s. Thus, the difference between the sampling points is probably not due to the increase in flow rate.

The accuracy of fDOM is not that high, however, since large fluctuations of ±2 were observed during measurements. This difference is almost as large as the differences at the flow rates. Thus, no conclusions can be taken from this measurement alone.
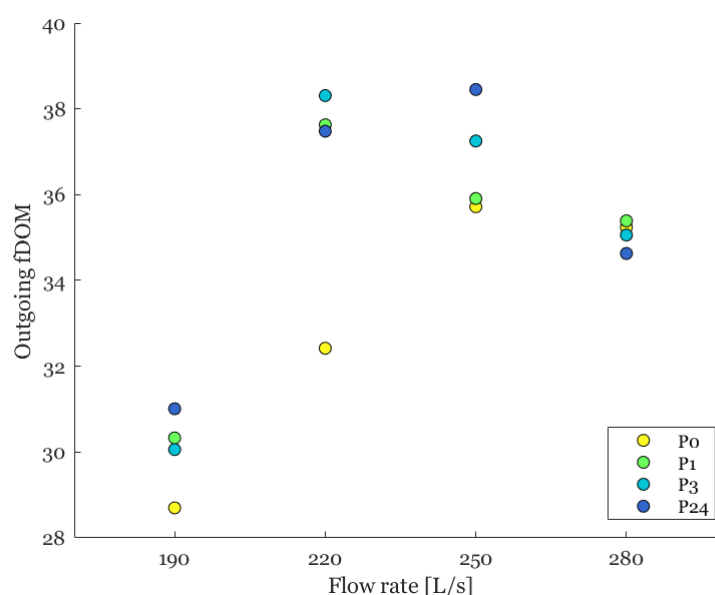
Figure 4.1.21: *Outgoing fDOM.*

4.1.6   Effect on TOC and SUVA

The outgoing TOC measured 24 hours after increase in flow rate is shown in figure 4.1.22 and the values can be seen in Appendix E. The highest TOC was measured at 220 L/s. However, the TOC at both 250 and 280 L/s was almost as low as that of 190 L/s, implying that the increase in flow did not have any effect on the outgoing TOC concentration. No larger differences between the three filters were observed.
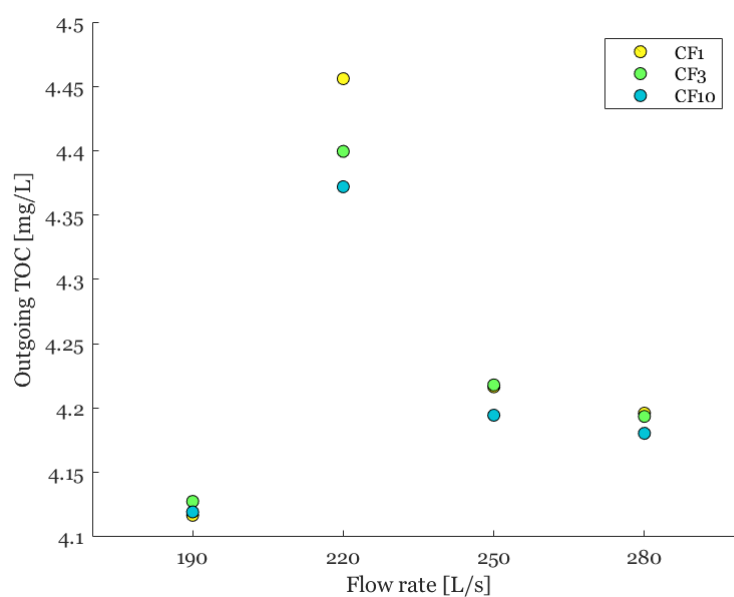
Figure 4.1.22: *Outgoing TOC.*

The SUVA was calculated using Equation 2.1 and the values for UV254, but per m and not per 5 cm, and TOC are presented in Appendix E and are shown in Figure 4.1.23. This shows a small increase in SUVA as the flow rate increased. This could be an indication of increase of humic substances with the increased flow rates. However, the SUVA is still below 2, which shows that it is still mainly non-humic substances present.
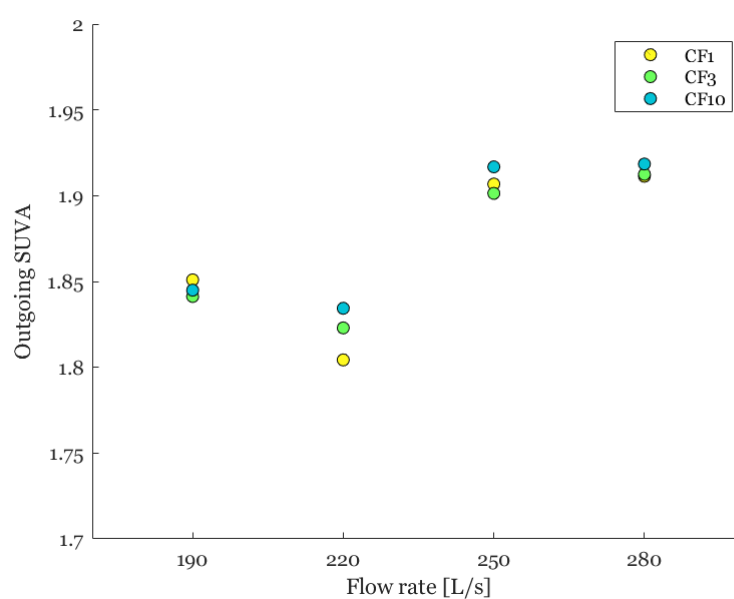
Figure 4.1.23: *Outgoing SUVA.*

4.1.7 Effect on COD

The COD measured 24 hours after increase in flow rate is shown in Figure 4.1.24 and the values in Appendix E. The only larger difference between filters was observed at 220 L/s where CF1 had a higher COD concentration. Besides this, no effect from flow rates or differences in filters was observed. Similar to TOC, the highest outgoing COD was measured at 220 L/s, but still not with a significant difference in concentration.
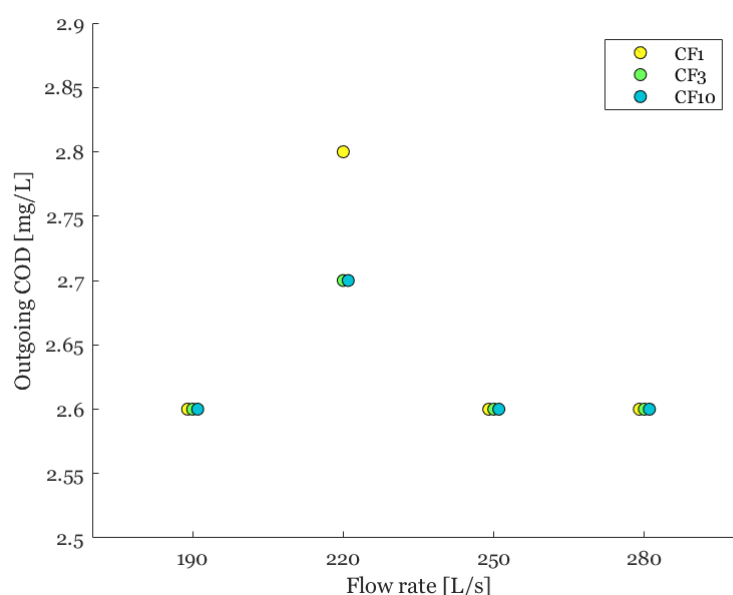
Figure 4.1.24: *Outgoing COD.*

4.1.8 Effect on cultivable microorganisms

The outgoing cultivable microorganisms at 22 °C over 3 days are shown in Figure 4.1.25 and the values in Appendix E. This shows an increase in outgoing microorganisms correlated to the increase in flow rate. However, the incoming concentration was not measured for microorganisms at the same time, which makes it unclear whether this effect was due to increase in flow rate or increase in incoming concentrations of microorganisms. Measurements of incoming microorganisms was made a few days prior and after the sampling for outgoing. These showed an increase in incoming microorganisms around the time of the increase in flow rate. However, no definite conclusion can be drawn from the cultivable microorganisms. At 280 L/s, the microorganisms are of a level higher than the limit value of 10/mL. The next step in the treatment process should still treat the water enough so that this is not an issue.
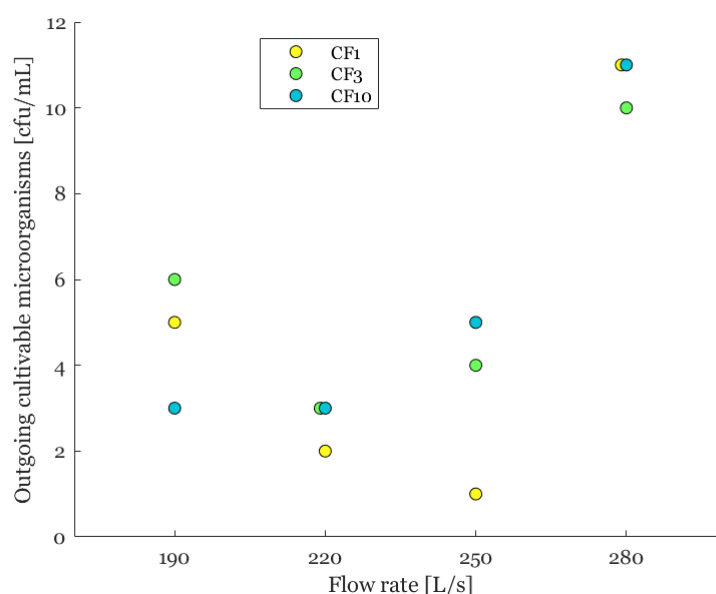
Figure 4.1.25: *Outgoing cultivable microorganisms.*

4.1.9 Effect on odour

The outgoing odour can be seen in Appendix F, which shows that with a flow rate of 250 L/s, CF10 had a weak odour at 50 °C, which was an undetermined odour. Besides this measurement, all others showed no odour at all. Thus, the increased flow rate did not seem to have any significant effect on the CF treatment.

4.1.10 Filtration

The filtrations that were done through 0.45 µm filters, show no significant difference between the flow rates and sampling points. Further, there seems to be no visible contaminants that are separated from the water using the filters. For this reason, the assumption that TOC could be used instead of DOC for the calculation of SUVA was assumed to be a reasonable assumption. Pictures of the filtrations can be seen in Appendix G.

4.2 Increased EBCT

For the increase of EBCT, the results are presented below.

The turbidity for CF 6, 7, and 9 are shown in Figure 4.2.1 and Figure 4.2.2. The red marker shows where the increase in EBCT occurred, where the flow rate decreased for

CF6 to 75 L/s and for CF7 to 45 L/s. Before the decrease in flow rate, CF9 already had a higher turbidity than the other two filters. There are no larger effect by the difference in EBCT, not for outgoing turbidity nor turbidity removal. The difference between the filters seem to be due to difference in the filters and not the EBCTs.
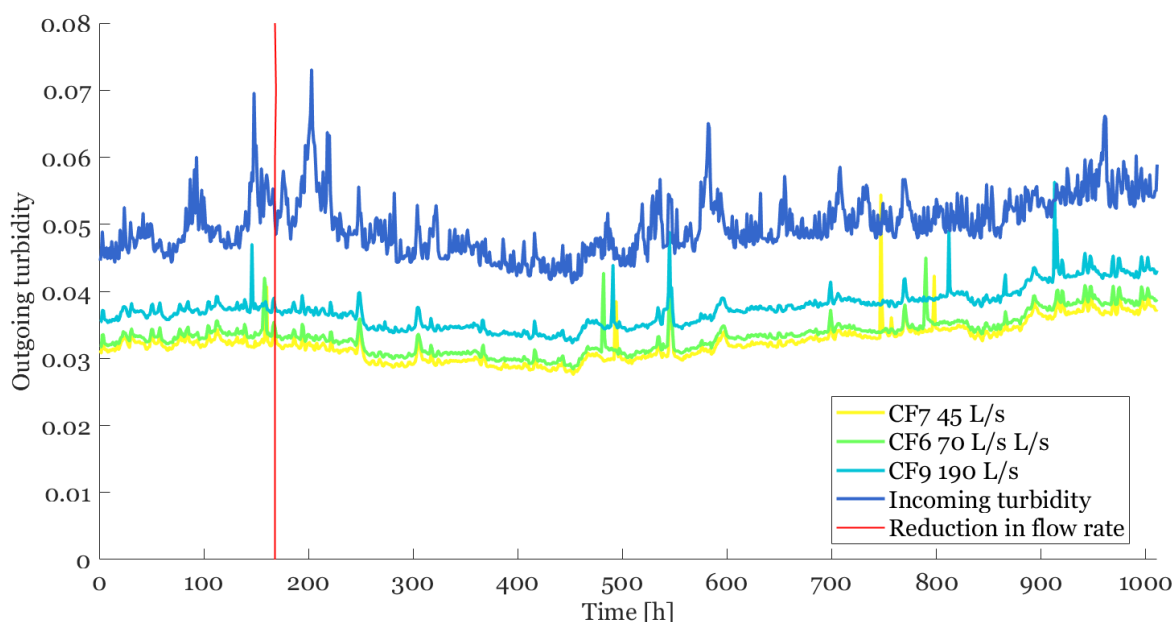
Figure 4.2.1: *Outgoing and incoming turbidity.*
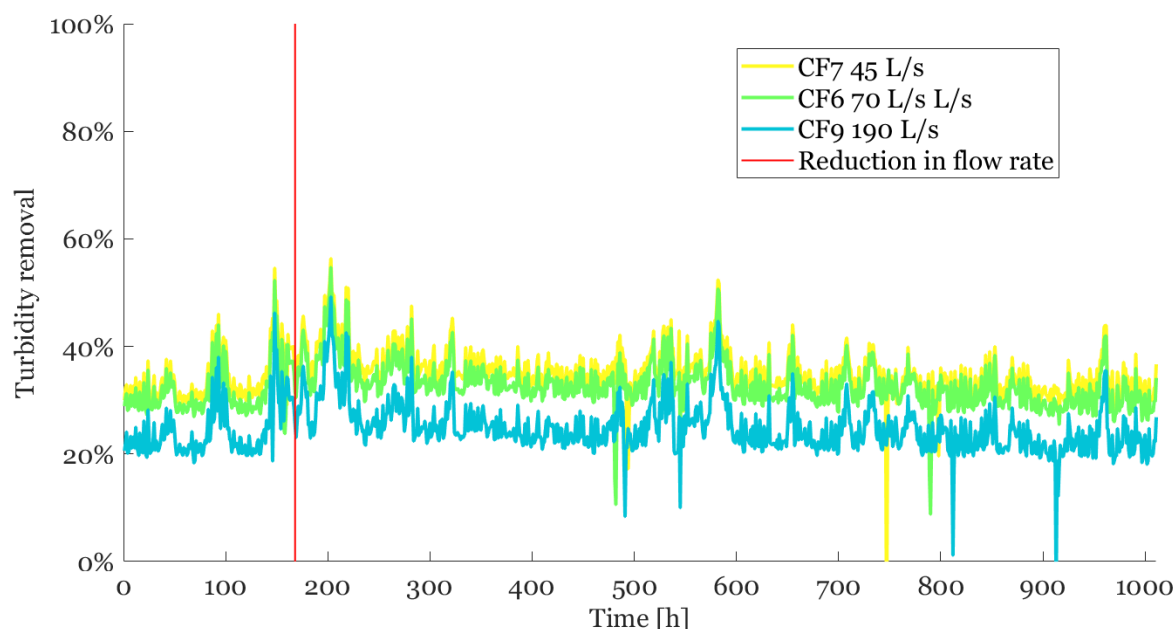
Figure 4.2.2: *Turbidity removal for carbon filters.*

Outgoing TOC from filters with increased EBCT did not show any difference that could be connected to the EBCT. This can be seen in Figure 4.2.3 and the values in Appendix H.
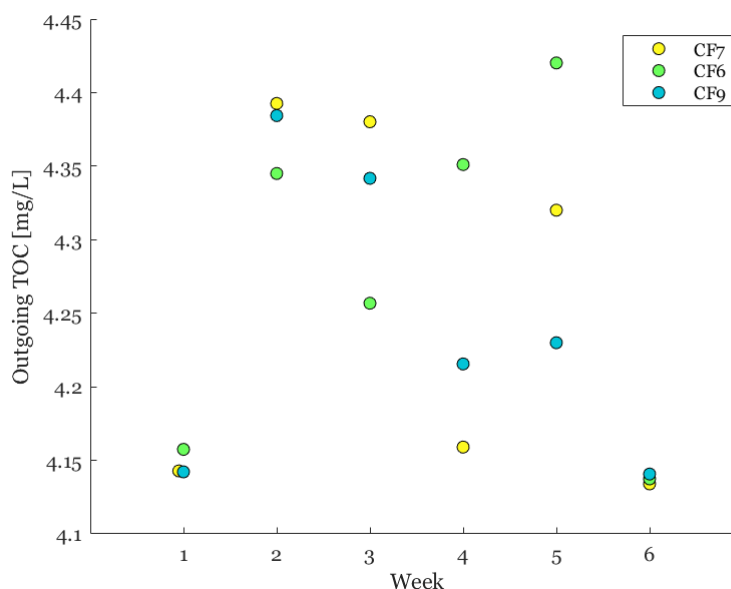
Figure 4.2.3: *Outgoing TOC for filters with increased EBCT.*

Similar to TOC, outgoing COD did not indicate any effect due to increase in EBCT, as can be seen in Figure 4.2.4 and Appendix H. For all analyses of the CFs with increased EBCTs, the effect seems to be due to differences between the filters and not due to the EBCTs.

The SUVA was calculated using the values for UV254 and TOC presented in Appendix H and are shown in Figure 4.2.5. This shows an increase in SUVA after six weeks has passed with increased EBCT, however, this effect is visible for CF9 as well, which did not have an increase in EBCT. Thus, no correlation between SUVA and increased EBCT can be seen here either.

No odour was detected at either temperature (20 and 50 °C) at any of the measured times. No increase in odour could therefore be seen, but since there was no odour before the increase in EBCT, it could have been a small increase or decrease in odour removal, but not any that was possible to measure since it was already low to begin with.
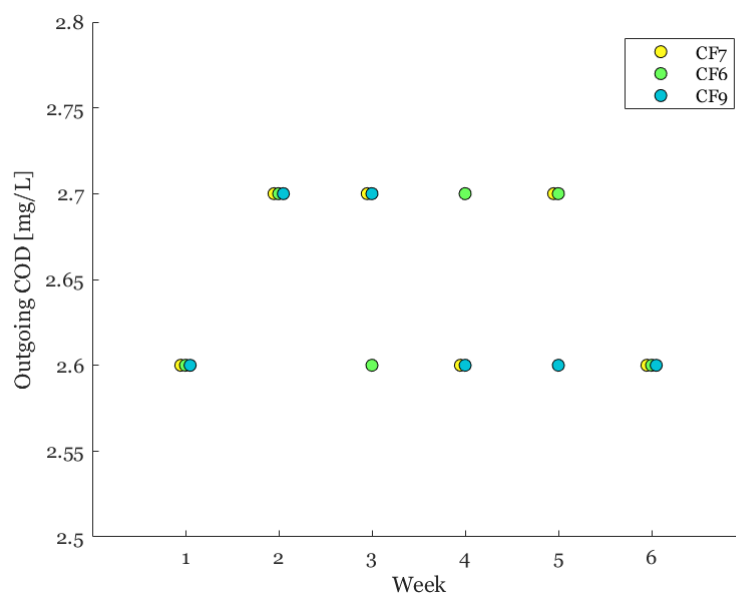
Figure 4.2.4: *Outgoing COD for filters with increased EBCT.*
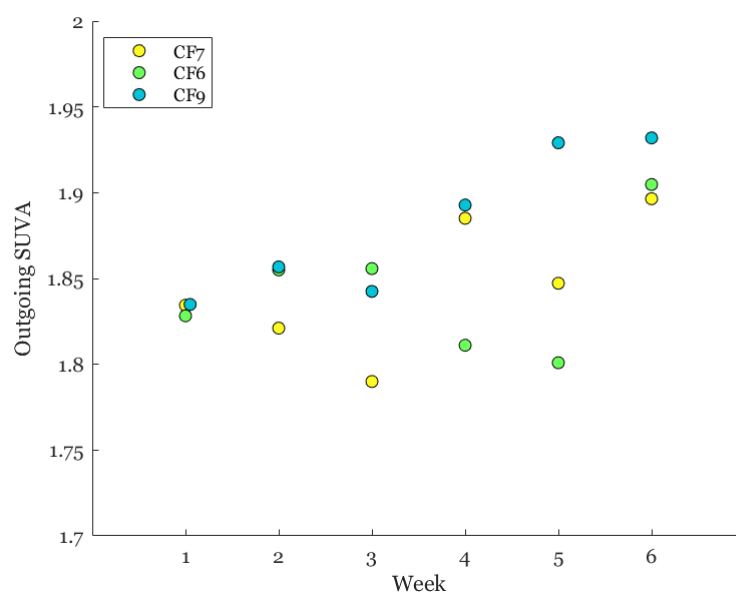
Figure 4.2.5: *Outgoing SUVA for filters with increased EBCT.*

4.3 Experimental uncertainties and future studies

The filters with increased flow rates were studied for 24 hours for each flow rate. There could be an increase of contaminants in this period due to the backwashing effect that could occur. The effect of the increased flow rate could be different if the flow rate is increased over a longer period. Perhaps the filter will stabilise after some time and

find a new balance for the treatment. The filters could also be negatively affected by an increase over longer time periods than over shorter times. This would need to be further investigated to find out how the filters react to the higher flow rates over a longer period.

The fluctuations in pH and temperatures were assumed to be negligible. However, temperature does influence how well the biofilters treat the water, as described earlier. Therefore, the temperature and pH could in fact have some effect. The temperature in Sweden also varies over the year, thus it would be beneficial to study the filters over a whole year to see how the filters are affected by the shifts in temperature. Some analyses, such as fDOM, had formulas for the difference in temperature, however, such formulas were not available for all measurements. Thus, for samples that were not analysed immediately after they were sampled, the results can be depending on the small increase in temperature that occurres after sampling rather than the effect of increased hydraulic loading.

Since there were no control of background variables, the incoming water had fluctuations in most parameters, but mainly the particle measurement had a large variation over the different sampling points. This is assumed to have affected the result of how well the treatment works. The effect of differences in incoming contaminant concentrations has to be further evaluated in future experiments.

The measurements were tested for internal validity, which is shown in Appendix I. This showed that turbidity as well as f-, c-, and b-particles did not have any significant difference in the measurements and were assumed to have internal validity. However, the total particles, conductivity and fDOM measurements did have a significant difference between the measurements. Therefore, future studies should be conducted multiple times to ensure the measurements and the conclusions drawn are correct and have internal validity. These differences can be due to differences in incoming water described earlier, something that needs to be studied in detail.

Chapter 5

Conclusions

Three CFs were studied at different flow rates; 190 L/s, 220 L/s, 250 L/s, and 280 L/s during 24 hours each. Simultaneously, two filters had increased EBCT for six weeks, while one filter continued with the regular flow rate of 190 L/s. Outgoing water from the filters was analysed to see if the increase in flow rates and EBCTs had any effect on the DWTP.

This preliminary study did not find any significant effect on the CF treatment due to increased flow rate. This could be an indication that the CFs can handle a future increase in flow rate and can thus be an essential part of a future expansion of the DWTP. The results were scattered, but some seemed to indicate an effect of increased flow rate over the CFs. However, most of these effects can be traced to differences in incoming contaminant concentrations and not due to the increase in flow rates. To verify the effects, further research is needed. Some of the measurements had a significant difference between measurements, while some did not. Some of the measurements were therefore not completely validated and should be repeated in future research to find the reason to the differences.

No larger differences were seen between the three filters with increased flow rate, indicating that after time the biofilter on the CFs is as efficient without regeneration as it is with.

For all analyses of the CFs with increased EBCT, the effect seems to be due to differences between the filters or the incoming water and not due to the actual change in EBCT. This implies that the effect of increased EBCT is negligible and will not have any significant effect on the treatment efficiency.

5.1   Future Work

This project can be seen as the ground work for the larger goal, which is to evaluate how the CFs will function with increased flow rates. Future work should include evaluations of how the filters are affected by this increased loading over longer times. Additionally, the effect on fluctuations in incoming pollutants should be identified to separate this effect from the effect of increased flow rate. Further, the effect of the increased flow rates should be evaluated frequently, with analyses on both incoming and outgoing waters to and from the CFs. The difference between the various carbon filters should also be established for future reference. Further, the same experiments should be repeated to ensure internal validity and that temperature changes does not affect the result.

Bibliography

[1] WHO. *Guidelines for drinking-water quality, 4th edition, incorporating the 1st addendum.* 2017, p. 26. ISBN: 978-92-4-154995-0.

[2] Norrvatten. *Om Norrvatten.* URL: `https : / / www . norrvatten . se / om - norrvatten/`.

[3] Lavonen, E et al. *Dricksvattenberedning med nya reningstekniker – en pilotstudie.* Svenskt Vatten, 2018. URL: `https : / / www . svensktvatten . se / contentassets/5d03d31c9b3a4d9591e27636f6c2c949/svur_2018-07a.pdf`.

[4] UN. *Goal 6: Ensure access to water and sanitation for all.* URL: `https://www. un.org/sustainabledevelopment/water-and-sanitation/`.

[5] Livsmedelsverket. *Livsmedelsverkets föreskrifter om ändring i Livsmedelsverkets föreskrifter (SLVFS 2001:30) om dricksvatten;* 2017. DOI: `https://www.livsmedelsverket.se/globalassets/om-oss/lagstiftning/ dricksvatten---naturl-mineralv---kallv/livsfs-2017-2_web.pdf`.

[6] EU. *Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption.* 1998. DOI: `http://data.europa.eu/eli/ dir/1998/83/oj`.

[7] Norrvatten. *Reningsprocessen.* URL: `https : / / www . norrvatten . se / dricksvatten/dricksvattenproduktion/reningsprocessen/`.

[8] Norrvatten. *Processövervakning - Kol och UV.* -.

[9] Norrvatten. *Budget 2021 med verksamhetsplan 2022-2023.* 2020. URL: `https://www.norrvatten.se/globalassets/3.-om-norrvatten/ekonomi/ norrvattens-budget-for-2021-med-verksamhetsplan-for-2022-2023.pdf`.

[10] Ejhed, H. *Mälarens framtida vattenkvalitet*. 2020. URL: `https : / / www . norrvatten . se/contentassets/39ef7aefe9cc4e1ba0c526e609b3c910/2020-02-malarens-framtida-vattenkvalitet.pdf`.

[11] Bhatnagar, A and Sillanpää, M. "Removal of natural organic matter (NOM) and its constituents from water by adsorption – A review". In: *Chemosphere* 166 (2017), pp. 497–510. DOI: `10.1016/j.chemosphere.2016.09.098`.

[12] Al-Naseri, S K and Abbas, T R. "Predicting NOM Removal by Fixed-Bed GAC Adsorbers". In: *Jordan Journal of Civil Engineering* 3.2 (2009), pp. 172–183. URL: `https : / / www . researchgate . net / profile / Saadi _ Al - Naseri / publication / 280562196 _ Predicting _ NOM _ removal _ by _ fixed - bed _ GAC _ adsorbers/links/55b9cf4608aed621de087c0b/Predicting-NOM-removal-by-fixed-bed-GAC-adsorbers.pdf`.

[13] Hua, G, Reckhow, D A, and Abusallout, I. "Correlation between SUVA and DBP formation during chlorination and chloramination of NOM fractions from different sources". In: *Chemosphere* 130 (2015), pp. 82–89. DOI: `10.1016/j.chemosphere.2015.03.039`.

[14] Fanun, M. *The Role of Colloidal Systems in Environmental Protection*. 2014. ISBN: 978-0-444-63283-8. DOI: `10.1016/C2011-0-05681-8`.

[15] Keucken, A, Wang, Y, Tng, K H, Leslie, G, Spanjer, T, and Köhler, S J. "Optimizing Hollow Fibre Nanofiltration for Organic Matter Rich Lake Water". In: *Water* 8.10 (2016), p. 430. DOI: `10.3390/w8100430`.

[16] Machenbach, I. "Drinking Water Production by Coagulation and Membrane Filtration". In: *Norwegian University of Science and Technology* (2007).

[17] Wershaw, R L. "THE STUDY OF HUMIC SUBSTANCES—IN SEARCH OF A PARADIGM". In: *Soils and Water* (2000), pp. 1–7. DOI: `10 . 1016 / B978 - 1 - 85573-807-2.50005-9`.

[18] Kida, M, Fujitake, N, Suchewaboripont, V, Poungparn, S, Tomotsune, M, Kondo, M, Yosjitake, S, Iimura, Y, Kinjo, K, Maknual, C, and Ohtsuka, T. "Contribution of humic substances to dissolved organic matter optical properties and iron mobilization". In: *Aquatic Sciences* 80 (2018), p. 26. DOI: `10 . 1007 / s00027-018-0578-z`.

[19] Lin, P, Zhang, X, Wang, J, Liu, S, and Chen, C. "Comparison of different combined treatment processes to address the source water with high concentration of natural organic matter during snowmelt period". In: *Journal of Environmental Sciences* 27 (2015), pp. 51–58. DOI: `10.1016/j.jes.2014.04.013`.

[20] Krzeminski, P, Vogelsang, C, Meyn, T, Köhler, S J, Poutanen, H, Wit, H A de, and Uhl, W. "Natural organic matter fractions and their removal in full-scale drinking water treatment under cold climate conditions in Nordic capitals". In: *Water* 241 (2019), pp. 427–438. DOI: `10.1016/j.jenvman.2019.02.024`.

[21] Sharma, S and Bhattacharya, A. "Drinking water contamination and treatment techniques". In: *Applied Water Sciences* 7 (2017), pp. 1043–1068. DOI: `10.1007/s13201-016-0455-7`.

[22] National Research Council (US) and Safe Drinking Water Committee. *Drinking water and health: Volume 2.* 1980. URL: `https://www.ncbi.nlm.nih.gov/books/NBK234593/`.

[23] Scott, S R et al. "Granular activated carbon adsorption of MIB in the presence of dissolved organic matter". In: *Water Research* 47.10 (2013), pp. 3507–3513. URL: `http://www.sciencedirect.com/science/article/pii/S0043135413002789`.

[24] Doederer, K, Vera, G A De, Espino, M P, Pype, M-L, Gale, D, and Keller, J. "MIB and geosmin removal during adsorption and biodegradation phases of GAC filtration". In: *Water Supply* 18.4 (2018), pp. 1449–1455. DOI: `10.2166/ws.2017.213`.

[25] Svenskt vatten. *Dricksvattenförsörjning i förändrat klimat: Underlagsrapport till Klimat- och sårbarhetsutredningen.* 2007.

[26] Gobeluis, L, Persson, C, Wiberg, K, and Ahrens, L. "Calibration and application of passive sampling for per- and polyfluoroalkyl substances in a drinking water treatment plant". In: *Journal of Hazardous Materials* 362 (2019), pp. 230–237. DOI: `10.1016/j.jhazmat.2018.09.005`.

[27] Livsmedelsverket. *PFAS - Poly- och perfluorerade alkylsubstanser.* 2021. URL: `https://www.livsmedelsverket.se/livsmedel-och-innehall/oonskade-amnen/miljogifter/pfas-poly-och-perfluorerade-alkylsubstanser`.

[28]   Chowdhury, Z et al. "Activated Carbon - Solutions for Improving Water Quality".
         In: *American Water Works Association* 182 (2011). URL: `https://app.knovel.`
         `com/hotlink/toc/id:kpACSIWQ0E/activated-carbon-solutions/activated-`
         `carbon-solutions`.

[29]   Gibert, O. "Characterising biofilm development on granular activated carbon
         used for drinking water production". In: *Water Research* 47.3 (2013), pp. 1101–
         1110. URL: `https://www-sciencedirect-com.focus.lib.kth.se/science/`
         `article/pii/S004313541200838X`.

[30]   Belkouteb, N et al. "Removal of per- and polyfluoroalkyl substances (PFASs) in
         a full-scale drinking water treatment plant: Long-term performance of granular
         activated carbon (GAC) and influence of flow-rate". In: *Water research* (2020),
         pp. 115913–115913. URL: `https://www-sciencedirect-com.focus.lib.kth.`
         `se/science/article/pii/S0043135420304504`.

[31]   Lavonen, E. *Norrvattens Framtida Dricksvattenproduktion, delprojekt PILOT
         – Försök 1A: ozon + GAC*. Norrvatten, 2020.

[32]   Simpson, D R. "Biofilm processes in biologically active carbon wa-
         ter purification". In: *Water Research* 42.12 (2008), pp. 2839–2848.
         DOI: `https : / / www . sciencedirect . com / science / article /`
         `pii / S0043135408001000 ? casa _ token = mvinIb1SYRsAAAAA :`
         `IXRXFYR9eDtSfkBIr2uUgW6XtlJNO3V4jc2ZhimIuiRJ2YFeoeG50IJIvLLa847VhPLHEHGh3Os`.

[33]   Santos, P R and Daniel, L A. "A review: organic matter and ammonia removal
         by biological activated carbon filtration for water and wastewater treatment".
         In: *International Journal of Environmental Science and Technology* 17 (2020),
         pp. 591–606. DOI: `10.1007/s13762-019-02567-1`.

[34]   Kasuga, I, Shimazaki, D, and Kunikane, S. "Influence of backwashing on the
         microbial community in a biofilm developed on biological activated carbon used
         in a drinking water treatment plant". In: *Water science and technology* 55.8–9
         (2007), pp. 173–180. URL: `https://iwaponline-com.focus.lib.kth.se/wst/`
         `article/55/8-9/173/13219/Influence-of-backwashing-on-the-microbial`.

[35]   Liao,   X,   Chen,   C,   Zhang,   J,
         Dai, Y, Zhang, X, and Xie, S. "Operational performance, biomass and microbial
         community structure: impacts of backwashing on drinking water biofilter". In:

Environmental Science and Pollution Research 22 (2015), pp. 546–554. DOI: `10.1007/s11356-014-3393-7`.

[36] Yuan, J et al. "The effect of water temperature on the removal of 2-methylisoborneol and geosmin by preloaded granular activated carbon". In: *Water research* 183 (2020), pp. 116065–116065. DOI: `https : / / www - sciencedirect - com . focus . lib . kth . se / science / article / pii / S0043135420306023`.

[37] Shih, T C, Wangpaichitr, M, and Suffet, M. "Evaluation of granular activated carbon technology for the removal of methyl tertiary butyl ether (MTBE) from drinking water". In: 37.2 (), pp. 375–385. DOI: `10 . 1016 / S0043 – 1354(02 ) 00271-3`.

[38] Li, Z, Dvorak, B, and Li, X. "Removing 17β-estradiol from drinking water in a biologically active carbon (BAC) reactor modified from a granular activated carbon (GAC) reactor". In: *Water Research* 46.9 (2012), pp. 2828–2836. DOI: `10.1016/j.watres.2012.03.033`.

[39] Kaarela, O E, Härkki, H A, Palmroth, M R T, and Tuhkanen, T A. "Bacterial diversity and active biomass in full-scale granular activated carbon filters operated at low water temperatures". In: *Environmental Technology* 36.6 (2014), pp. 681–692. DOI: `10.1080/09593330.2014.958542`.

[40] Faruqi, A, Henderson, M, Henderson, R K, Stuetz, R, Gladman, B, McDowall, B, and Zamyadi, A. "Removal of algal taste and odour compounds by granular and biological activated carbon in full-scale water treatment plants". In: *Water Science and Technology* 18.5 (2018), pp. 1531–1544. DOI: `10 . 2166 / ws . 2018 . 001`.

[41] Wu, H and Xie, Y F. "Effects of EBCT and Water Temperature on HAA Removal using BAC". In: *American Water Works Association* 97.11 (2005), pp. 94–101. DOI: `https://www.jstor.org/stable/41313633`.

[42] Chapman, D. *Environmental Monitoring - Second Edition*. 1992. ISBN: 0419215905.

[43] YSI. *CDOM-fDOM*. 2021. URL: `https://www.ysi.com/parameters/cdom-fdom`.

[44] Rice, E W, Baird, R B, and Eaton, A D. *Standard Methods for the Examination of Water and Wastewater*. 2017.

[45] WHO. *Water quality and health - review of turbidity: information for regulators and water suppliers*. 2017. URL: `https://apps.who.int/iris/handle/10665/254631`.

[46] Livsmedelsverket. *SLVFS 2001:30 Livsmedelsverkets föreskrifter om dricksvatten*. 2001.

[47] Shi, Z, Chow, C W K, Fabris, R, Zheng, T, Liu, J, and Jin, B. *Evaluation of the impact of suspended particles on the UV absorbance at 254 nm (UV254) measurements using a submersible UV-Vis spectrophotometer*. Vol. 28. 2021, pp. 12576–12586. DOI: `10.1007/s11356-020-11178-0`.

[48] Nayak, A R, Malkiel, E, McFarland, M N, Twardowski, M S, and Sullivan, J M. "A Review of Holography in the Aquatic Sciences: In situ Characterization of Particles, Plankton, and Small Scale Biophysical Interactions". In: *Frontiers in Marine Science* 7 (2021). DOI: `10.3389/fmars.2020.572147`.

[49] Leilei, W, Wei, C, and Tao, L. "Particle size distribution and property of bacteria attached to carbon fines in drinking water treatment". In: *Water Science and Engineering* 1.2 (2008). DOI: `10.3882/j.issn.1674-2370.2008.02.010`.

[50] Sterlitech. *Glass Fiber Filters*. -. URL: `https://www.sterlitech.com/glass-fiber-filter.html`.

Appendix - Contents

Appendix A

Particle values

In Table A.0.1 outgoing, incoming, and removal of particles are shown. In Table A.0.3 and A.0.2, incoming and outgoing and removal efficiency of f-, c-, and b-particles are shown. Each value is an average of ten and Grubb's test for outliers was used.

Table A.0.1: *Outgoing, incoming, and removal of particles.*

Sample	Flow rate	Outgoing particles	Incoming particles	Removal of particles
P0	190	310	2283	84%
P1	190	279	1317	77%
P3	190	279	1725	84%
P24	190	267	2289	88%
P0	220	184	258	29%
P1	220	184	271	32%
P3	220	188	362	47%
P24	220	190	267	29%
P0	250	213	329	35%
P1	250	211	324	35%
P3	250	228	339	33%
P24	250	211	352	40%
P0	280	873	1830	50%
P1	280	799	3970	79%
P3	280	749	5558	86%
P24	280	831	1757	49%

Table A.0.2: *Outgoing and incoming f-, c-, and b-particles.*

Sample	Flow rate	f out	c out	b out	f in	c in	b in
P0	190	0.032	0.089	0.618	0.128	0.116	6.022
P1	190	0.082	0.031	0.557	0.039	0.066	3.486
P3	190	0.167	0.022	0.335	0.084	0.076	4.389
P24	190	0.037	0.072	0.274	0.088	0.176	5.585
P0	220	0.009	0.048	0.376	0.044	0.077	0.779
P1	220	0.004	0.058	0.412	0.045	0.064	0.732
P3	220	0.018	0.093	0.384	0.069	0.048	1.024
P24	220	0.018	0.036	0.362	0.073	0.053	0.672
P0	250	0.032	0.084	0.562	0.052	0.153	0.874
P1	250	0.019	0.106	0.596	0.089	0.161	1.085
P3	250	0.009	0.131	0.520	0.047	0.136	0.999
P24	250	0.031	0.197	0.581	0.081	0.348	1.254
P0	280	0.059	0.263	1.632	0.150	0.203	3.522
P1	280	0.061	0.232	1.461	0.189	0.302	8.661
P3	280	0.005	0.403	1.076	0.233	0.264	12.779
P24	280	0.032	0.257	1.149	22.011	0.057	21.912

Table A.0.3: *Removal of f-, c-, and b-particles.*

Sample	Flow rate	Removal of f	Removal of c	Removal of b
P0	190	75%	23%	90%
P1	190	-108%	53%	84%
P3	190	-99%	71%	92%
P24	190	58%	59%	95%
P0	220	80%	38%	52%
P1	220	90%	10%	44%
P3	220	74%	-93%	63%
P24	220	75%	33%	46%
P0	250	39%	45%	36%
P1	250	79%	34%	45%
P3	250	81%	3%	48%
P24	250	62%	43%	54%
P0	280	60%	-30%	54%
P1	280	68%	23%	83%
P3	280	98%	-53%	92%
P24	280	100%	-354%	95%

Appendix B

UV254 values

In Table B.0.1 UV254 measured for outgoing water from each filters are shown. Each sampling point had 5 measurements for internal validity. The values shown are for 5 cm.

Table B.0.1: *Outgoing UV254 from CF1, CF3, and CF10.*

190 L/s	CF1	CF3	CF10	220 L/s	CF1	CF3	CF10
P0	0.378	0.378	0.376	P0	0.371	0.376	0.376
	0.378	0.379	0.378		0.372	0.376	0.376
	0.379	0.379	0.378		0.372	0.377	0.376
	0.379	0.380	0.380		0.372	0.376	0.376
	0.379	0.380	0.380		0.373	0.377	0.376
P1	0.382	0.373	0.380	P1	0.373	0.369	0.372
	0.383	0.374	0.381		0.373	0.369	0.372
	0.385	0.375	0.382		0.373	0.370	0.372
	0.385	0.375	0.382		0.373	0.370	0.371
	0.385	0.376	0.384		0.374	0.370	0.373
P3	0.378	0.383	0.381	P3	0.379	0.374	0.368
	0.380	0.384	0.381		0.379	0.373	0.368
	0.381	0.385	0.381		0.380	0.373	0.367
	0.381	0.385	0.381		0.380	0.373	0.368
	0.382	0.385	0.380		0.380	0.373	0.368
P24	0.381	0.384	0.382	P24	0.383	0.395	0.393
	0.381	0.384	0.383		0.383	0.396	0.392
	0.381	0.384	0.383		0.382	0.396	0.392
	0.381	0.385	0.382		0.383	0.396	0.394

250 L/s	CF1	CF3	CF10	280 L/s	CF1	CF3	CF10
P0	0.414	0.416	0.414	P0	0.403	0.398	0.403
	0.414	0.417	0.415		0.403	0.398	0.403
	0.415	0.417	0.416		0.402	0.398	0.404
	0.416	0.418	0.415		0.403	0.398	0.405
	0.416	0.418	0.415		0.403	0.398	0.405
P1	0.400	0.398	0.400	P1	0.400	0.400	0.400
	0.400	0.398	0.401		0.400	0.401	0.400
	0.400	0.397	0.401		0.402	0.400	0.399
	0.401	0.398	0.401		0.400	0.399	0.400
	0.401	0.398	0.401		0.402	0.400	0.399
P3	0.402	0.400	0.403	P3	0.39	0.389	0.391
	0.404	0.400	0.402		0.391	0.389	0.391
	0.403	0.401	0.403		0.391	0.388	0.392
	0.404	0.401	0.403		0.392	0.389	0.391
	0.404	0.400	0.404		0.392	0.389	0.392
P24	0.405	0.398	0.404	P24	0.401	0.406	0.400
	0.404	0.398	0.403		0.400	0.405	0.401
	0.405	0.398	0.404		0.400	0.405	0.401
	0.404	0.398	0.405		0.400	0.405	0.401
	0.405	0.398	0.405		0.401	0.406	0.401

The incoming UV245 was measured using an online sensor and manually. The difference between the values was calculated to be 0.025, with online values being lower than the manually measured. This value was therefore added to the online measurements when compared to outgoing values. The incoming values for UV254 is shown in Table B.0.2.

Table B.0.2: *Incoming UV254.*

Sample	Flow rate	Incoming UV254
P0	190	0.3827
P1	190	0.3824
P3	190	0.3827
P24	190	0.3853
P0	220	0.4053
P1	220	0.4047
P3	220	0.4043
P24	220	0.4042
P0	250	0.4067
P1	250	0.4071
P3	250	0.4072
P24	250	0.4049
P0	280	0.4063
P1	280	0.3997
P3	280	0.4034
P24	280	0.4053

Appendix C

Turbidity measurements

Table C.0.1 and Table C.0.2 shows incoming and outgoing turbidity with the unit FTU, respectively hourly from increase in flow rate.

Table C.0.1: *Incoming turbidity.*

Hour from increase	190 L/s	220 L/s	250 L/s	280 L/s
1	0.0485	0.0482	0.0536	0.0782
2	0.0501	0.0479	0.0535	0.0850
3	0.0520	0.0492	0.0560	0.0856
4	0.0510	0.0495	0.0539	0.0902
5	0.0510	0.0483	0.0548	0.0866
6	0.0522	0.0479	0.0536	0.0766
7	0.0560	0.0479	0.0531	0.0772
8	0.0580	0.0491	0.0556	0.0747
9	0.0561	0.0488	0.0556	0.0791
10	0.0553	0.0479	0.0549	0.0765
11	0.0529	0.0487	0.0529	0.0833
12	0.0539	0.0513	0.0530	0.0747
13	0.0499	0.0490	0.0584	0.0739
14	0.0499	0.0479	0.0572	0.0694
15	0.0477	0.0480	0.0551	0.0679
16	0.0502	0.0519	0.0532	0.0697
17	0.0511	0.0488	0.0547	0.0684
18	0.0501	0.0477	0.0531	0.0675
19	0.0497	0.0482	0.0537	0.0673
20	0.0503	0.0486	0.0539	0.0742
21	0.0539	0.0515	0.0554	0.0713
22	0.0529	0.0489	0.0543	0.0691
23	0.0535	0.0481	0.0574	0.0691

Table C.0.2: *Outgoing turbidity.*

Hour from increase	190 L/s	220 L/s	250 L/s	280 L/s
1	0.0317	0.0325	0.0374	0.0514
2	0.0314	0.0325	0.0374	0.0498
3	0.0314	0.0328	0.0397	0.0493
4	0.0315	0.0330	0.0389	0.0494
5	0.0313	0.0327	0.0377	0.0496
6	0.0311	0.0327	0.0374	0.0504
7	0.0311	0.0331	0.0374	0.0515
8	0.0313	0.0329	0.0397	0.0520
9	0.0316	0.0329	0.0388	0.0513
10	0.0316	0.0327	0.0372	0.0513
11	0.0313	0.0328	0.0368	0.0521
12	0.0313	0.0332	0.0369	0.0533
13	0.0318	0.0333	0.0372	0.0532
14	0.0316	0.0326	0.0372	0.0512
15	0.0314	0.0323	0.0369	0.0505
16	0.0316	0.0327	0.0370	0.0507
17	0.0322	0.0329	0.0370	0.0509
18	0.0329	0.0326	0.0370	0.0503
19	0.0321	0.0325	0.0373	0.0504
20	0.0314	0.0329	0.0370	0.0515
21	0.0315	0.0331	0.0371	0.0525
22	0.0314	0.0329	0.0373	0.0517
23	0.0312	0.0328	0.0378	0.0516

Appendix D

Measurements using EXO

The result from the measurements done using an EXO sensor is shown in Table D.0.1, which shows the average outgoing particles from CF1, CF3, and CF10 for all sampling times.

Table D.0.1: *Average outgoing values measured with the EXO sensor.*

	Conductivity	fDOM QSU	TDS	Turbidity	Temperature
	[μS/cm]		[mg/L]	[FNU]	[°C]
190 L/s					
P0	165.16	29.62	159	1.13	8.0
P1	149.20	30.54	159	0.47	4.5
P3	144.97	30.55	157	0.45	4.1
P24	139.51	31.18	155	0.55	3.3
220 L/s					
P0	195.75	34.77	186	1.62	8.4
P1	175.28	37.81	186	0.25	4.8
P3	168.79	38.82	187	0.18	3.4
P24	168.57	38.18	185	0.17	3.7
250 L/s					
P0	193.86	34.75	184	0.53	8.4
P1	192.42	35.04	187	4.48	7.7
P3	182.10	38.04	186	0.29	5.9
P24	173.04	38.62	187	0.21	4.2
250 L/s					
P0	188.75	35.73	183	0.23	7.7
P1	187.68	36.16	183	0.31	7.5
P3	187.26	35.42	183	0.28	7.4
P24	189.29	34.43	183	0.57	7.9

The fDOM values were temperature and colour corrected, and the values for this is shown in Table D.0.2

Table D.0.2: *Temperature and colour corrected fDOM.*

Sample	Flow rate	fDOM QSU	T	UV254	T corr fDOM	Colour corr fDOM
P0	190	29.62	8.0	0.3787	23.58	23.60
P1	190	30.54	4.5	0.3801	23.03	23.05
P3	190	30.55	4.1	0.3819	22.89	22.91
P24	190	31.18	3.3	0.3825	23.06	23.08
P0	220	34.77	8.4	0.3748	27.84	27.87
P1	220	37.81	4.8	0.3716	28.64	28.67
P3	220	38.82	3.4	0.3735	28.76	28.78
P24	220	38.18	3.7	0.3905	28.42	28.45
P0	250	34.75	8.4	0.4157	27.83	27.86
P1	250	35.04	7.7	0.3997	27.77	27.79
P3	250	38.04	5.9	0.4023	29.32	29.35
P24	250	38.62	4.2	0.4023	28.98	29.01
P0	280	35.73	7.7	0.4016	28.31	28.34
P1	280	36.16	7.5	0.4016	28.57	28.60
P3	280	35.42	7.4	0.3905	27.94	27.97
P24	280	34.43	7.9	0.4022	27.36	27.39

Appendix E

Laboratory values

In Table E.0.1 the values measured by Norrvatten's own lab are shown for turbidity, UV254, TOC, and COD.

Table E.0.1: *Outgoing UV254.*

Sample	Flow rate	Turbidity [FNU]	UV254	TOC [mg/L]	COD [mg/L]
CF1	190	0.06	0.381	4.117	2.6
CF3	190	0.06	0.380	4.128	2.6
CF10	190	0.06	0.389	4.119	2.6
CF1	220	0.06	0.402	4.456	2.8
CF3	220	0.06	0.401	4.400	2.7
CF10	220	0.07	0.401	4.372	2.7
CF1	250	0.1	0.402	4.217	2.6
CF3	250	0.07	0.401	4.218	2.6
CF10	250	0.06	0.402	4.195	2.6
CF1	280	0.08	0.401	4.196	2.6
CF3	280	0.07	0.401	4.194	2.6
CF10	280	0.07	0.401	4.180	2.6

In Table E.0.2 the values measured by Norrvatten's own lab are shown for cultivable microorganisms over three days. The incoming values are measured a few days prior to the outgoing measurements and are therefore not fully comparable.

Table E.0.2: *Outgoing and incoming cultivable microorganisms.*

Sample	Flow rate	Incoming [cfu/mL]	Outgoing [cfu/mL
CF1	190	3	5
CF3	190	3	6
CF10	190	3	3
CF1	220	5	2
CF3	220	5	3
CF10	220	5	3
CF1	250	7	1
CF3	250	7	4
CF10	250	7	5
CF1	280	36	11
CF3	280	36	10
CF10	280	36	11

Appendix F

Odour measurements

The outgoing odour from the CFs can be seen in Table F.0.1

Table F.0.1: *Outgoing odour from CF1, CF3, and CF10.*

Filter	Flow [L/s]	Strength 20 °C	Type	Strength 50 °C	Type
CF1	190	none	-	none	-
CF3	190	none	-	none	-
CF10	190	none	-	none	-
CF1	220	none	-	none	-
CF3	220	none	-	none	-
CF10	220	none	-	none	-
CF1	250	none	-	none	-
CF3	250	none	-	none	-
CF10	250	none	-	weak	undetermined
CF1	280	none	-	none	-
CF3	280	none	-	none	-
CF10	280	none	-	none	-

Appendix G

Filtration pictures

All samples were filtrated using 0.45 µm filters. These are shown in Figure G.0.1, G.0.2, G.0.3, and G.0.4.
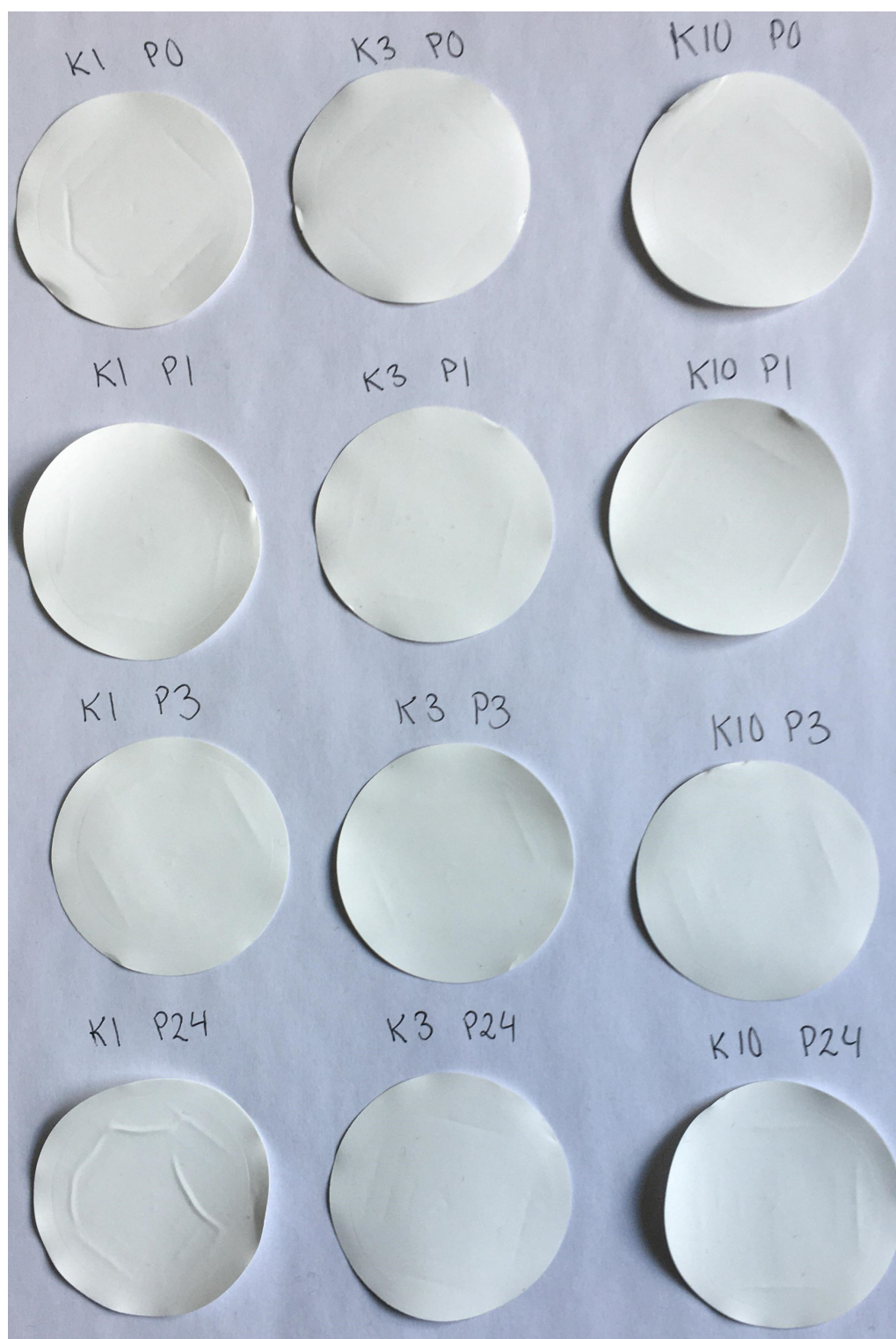
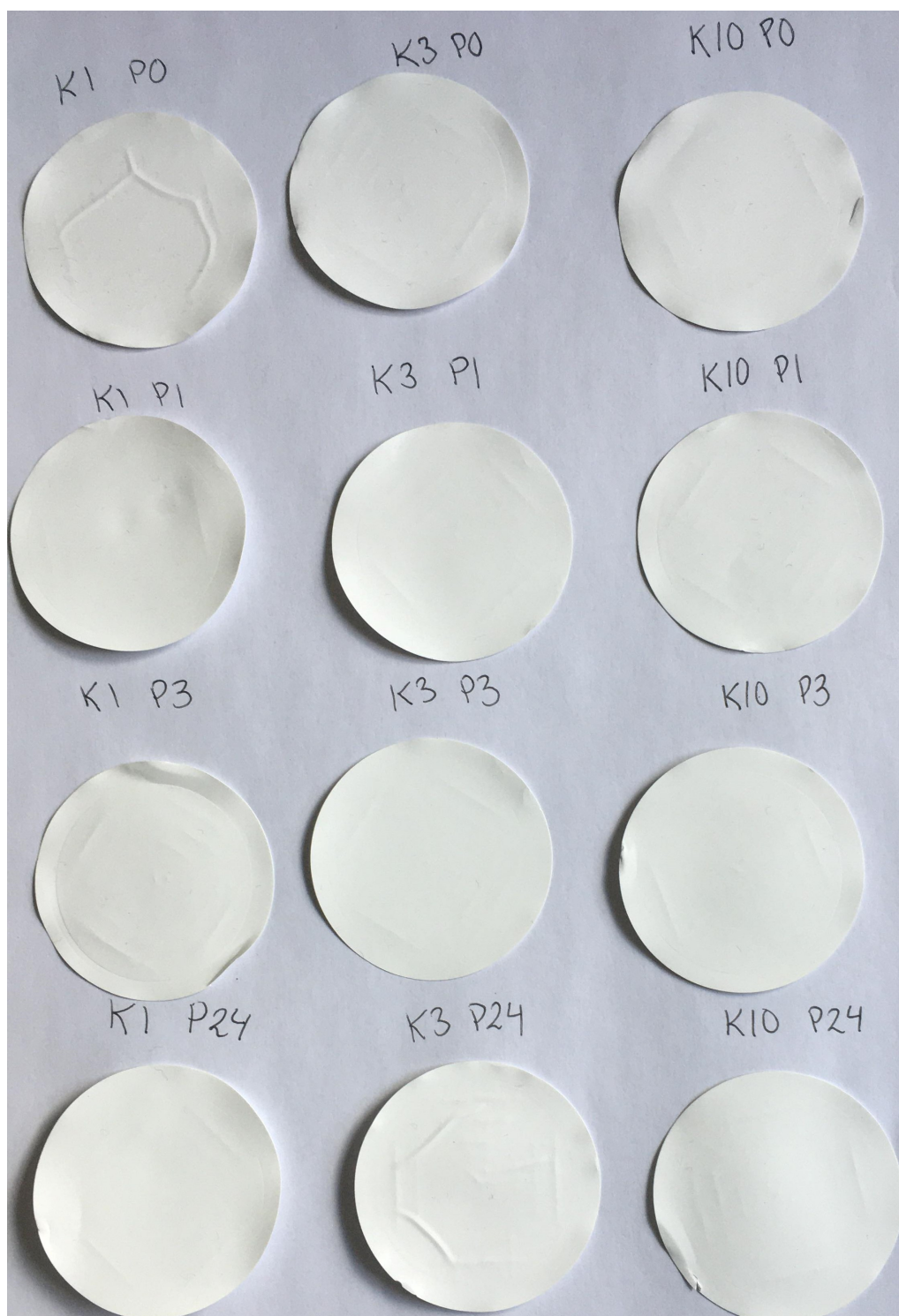Figure G.0.1: *Picture of filtration with flow rate 190 L/s.*

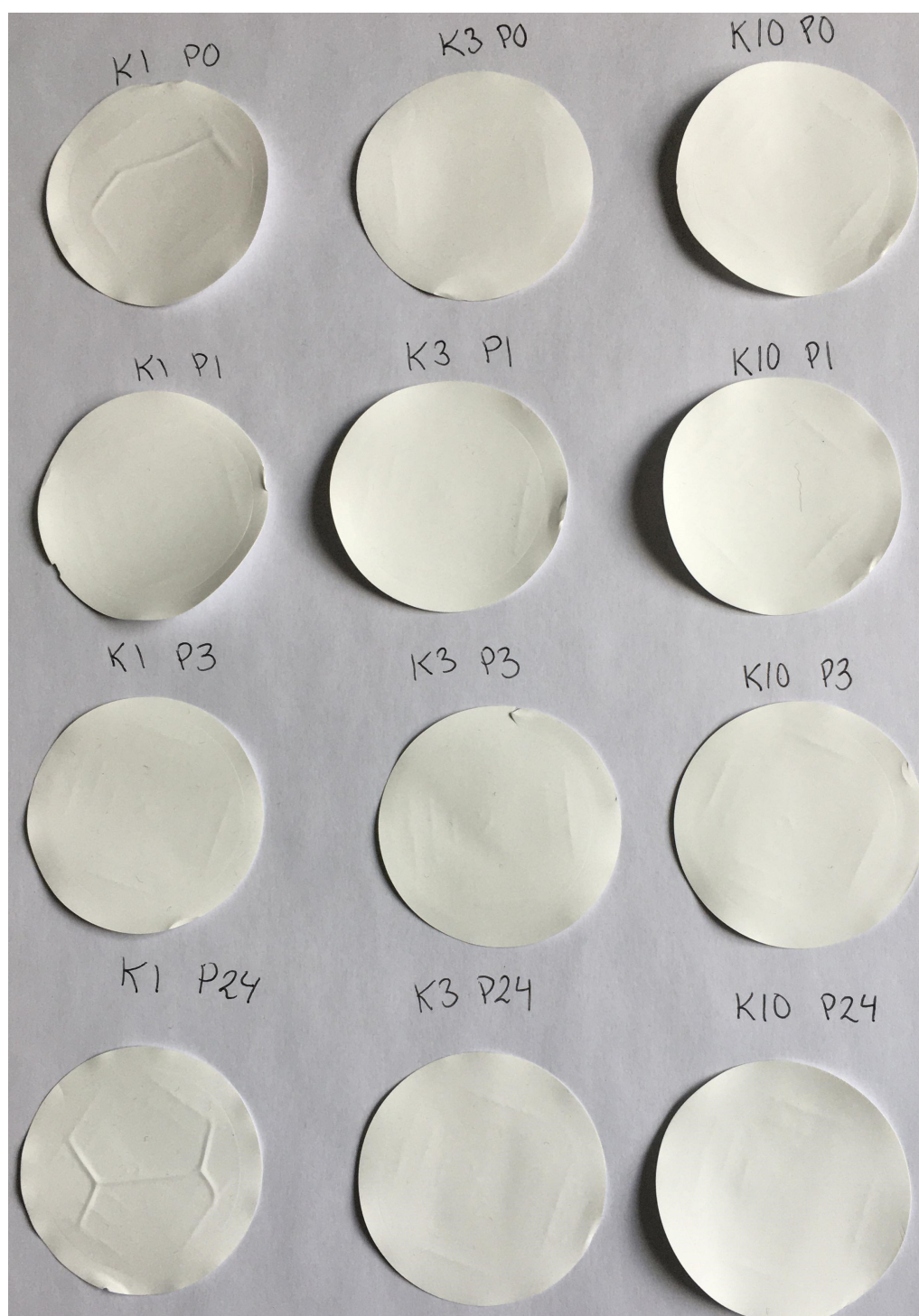Figure G.0.2: *Picture of filtration with flow rate 220 L/s.*

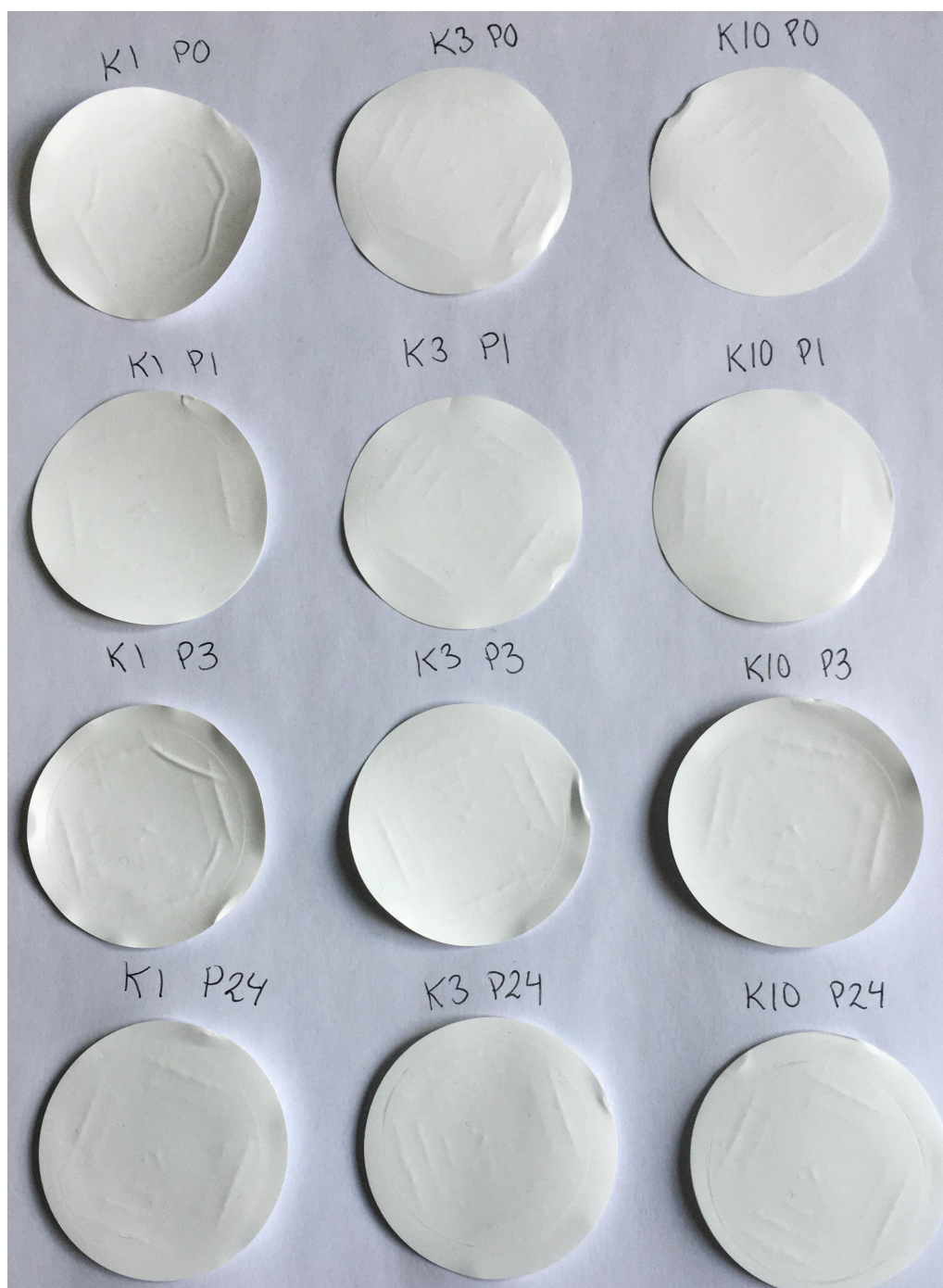Figure G.0.3: *Picture of filtration with flow rate 250 L/s.*

Figure G.0.4: *Picture of filtration flow rate 280 L/s.*

Appendix H

Values for CFs with increased EBCT

The values from the lab at Norrvatten is shown in Table H.0.1.

Table H.0.1: *Lab values for CFs with increased EBCT.*

Filter	UV254	TOC [mg/L]	COD [mg/L]
CF6	0.380	4.157	2.6
CF7	0.380	4.143	2.6
CF9	0.380	4.142	2.6
CF6	0.403	4.345	2.7
CF7	0.400	4.393	2.7
CF9	0.407	4.384	2.7
CF6	0.395	4.257	2.6
CF7	0.392	4.380	2.7
CF9	0.400	4.342	2.7
CF6	0.394	4.351	2.7
CF7	0.392	4.159	2.6
CF9	0.399	4.216	2.6
CF6	0.398	4.420	2.7
CF7	0.399	4.320	2.7
CF9	0.408	4.230	2.6
CF6	0.394	4.137	2.6
CF7	0.392	4.134	2.6
CF9	0.400	4.141	2.6

Appendix I

Statistical analysis

F-tests were calculated using Equation I.1.

$$F = \frac{S_1^2}{S_2^2} \tag{I.1}$$

The F-test for turbidity was measured at 190 L/s for CF1, two sample periods were used. The critical value for F at 95 % confidence level was 2.0495 and the calculated value for standard deviations of 0.000433 and 0.000415 was 1.0896. Since the calculated value was below the critical value, the difference in turbidity was not significant and the turbidity measurement was assumed to have internal validity.

The same was done for the particle measurements. For all kinds of particles, a critical value of 3.44 was used for the 9 values from each set, the calculated values can be seen in Table I.0.1. These show that the total particles had a significant difference in the measurements. The other test did not.

Table I.0.1: *Values of particles for F-test.*

	Tot particles	f-particles	c-particles	b-particles
Average 1	296.193	0.029	0.000	0.184
Standard deviation 1	39.334	0.087	0.000	0.127
Average 2	603.547	0.117	0.868	0.072
Standard deviation 2	15.396	0.078	0.364	0.094
F-value	6.527	1.221	0.000	1.819

For conductivity and fDOM, the critical value used was 3.18 since 10 measurements points from each set was used. The measured F-values were 12.3 for conductivity and 15.5 for fDOM, meaning that both measurements had a significant difference between the data sets.