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Hydraulic Performance of Advanced Treatment Media to Improve Quality of Stormwater from Airports Exposed to De-icing Chemicals

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Preface

This thesis is the result of the Master of Science degree in Civil and Environmental Engineering at the Norwegian University of Science and Technology (NTNU) and is conducted in the Department of Hydraulic and Environmental Engineering. The thesis was written in the autumn semester 2015/2016 as part of the project Klima 2050.

In the master thesis the hydraulic performance of different filter media for treatment of stormwater exposed to de-icing chemicals are tested in a laboratory column study. Filter media are provided by Weber Saint Gobain and sediments and de-icing chemicals are provided by Avinor.

I would like to thank my main supervisor, Tone M. Muthanna, Associate Professor at the Department of Hydraulic and Environmental Engineering, for support and feedback. Thank you to my supervisors at SINTEF Kamal Azrague and Gema Raspati. I am very grateful for discussions and help when needed. A special thanks to Gema for help through the laboratory experiments. In addition, I would like to thank Jaran Wood from Weber Saint Gobain for providing materials and valuable information, Anne Orderdalen Steen from Avinor for organising sampling of sediments and de-icing chemicals at Værnes Airport and Carlos Monrabal Martinez, PhD candidate at the Department of Hydraulic and Environmental Engineering, for letting me use his equipment for the laboratory experiments. Thank you to my fellow student, Hanna Haug Lindseth, for validation of results with results from her laboratory experiment and interesting discussions.

I would also like to thank my family and friends for support and feedback.

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Abstract

Winter-runoff from airports contains a high fraction of contaminated stormwater. Contaminants such as de-icing chemicals propylene glycol and potassium formate, heavy metals and PAHs are often present in stormwater runoff from airports and contribute to pollution of groundwater and surface water. Installing granular filters along the runway, can be seen as an alternative solution to remove contaminants by means of physical processes such as filtration, adsorption and by biodegradation.

As a part of the project Klima 2050, the hydraulic performance of five different filter media, consisting of fine, coarse and mixed Filtralite materials provided by Weber Saint-Gobain and activated carbon, was tested for treatment of stormwater. The synthetical stormwater used in the tests represented the first flush of winter-runoff from airports exposed to de-icing chemicals and contained sediments and de-icing chemicals from Værnes Airport in Trondheim, provided by Avinor. A column study consisting of four series of tests; with two different flows and two different concentrations of de-icing chemicals, was conducted to investigate the hydraulic performance of the different filter media in varying conditions and the removal of turbidity, suspended solids, de-icing chemicals and heavy metals.

The results showed that the hydraulic performance of the different filter media varied depending on the type of media used and the conditions tested. Whereas the experiments with high flow lasted only one day before the filters were clogged, the experiments with low flow lasted 5-7 days before clogging. All filter media provided good removal, between 93.8 % and 99.6 %, of particles by size exclusion, while adsorption (with removal of between approximately 10 % and 40 % of de-icing chemicals) only was observed in the filter media with an activated carbon layer. Biodegradation, causing removal up to 88 %, of de-icing chemicals was observed for the longer lasting tests, and started approximately after two days of operation. The hydraulic performance, treatment abilities and maintenance demands of the filter media were compared, and the recommended filter medium of the media tested was the fine material, Filtralite NC 0-2, with activated carbon layer.

Over all, the tested filter media showed acceptable hydraulic performance, both in terms of suspended solids removed and operation time before clogging. All filters, with two exeptions, removed more than 1.2 kg/m^2 suspended solids per surface area before clogging. Removal of

de-icing chemicals was good when biodegradation occurred in the test with low concentrations of de-icing chemicals, but toxicity seemed to prevent growth of biomass for high concentrations of de-icing chemicals.

Sammendrag

Vinteravrenning fra flyplasser inneholder en stor andel forurenset overvann. Forurensninger som av-isingskjemikaliene propylen glykol og kaliumformat, tungmetaller og PAH er ofte tilstede i overvannsavrenning fra flyplasser og bidrar til forurensning av grunnvann og overflatevann. Ved å installere grusfiltre langs rullebanen, kan forurensningene fjernes ved hjelp av fysiske prosesser som filtrering, adsorpsjon og biologisk nedbryting.

Som en del av prosjektet Klima 2050, ble de hydrauliske egenskapene til fem forskjellige filter media, bestående av fint, grovt og blandet Filtralite materiale fra Weber Saint-Gobain og aktivt kull, testet i forbindelse med rensing av overvann. Det syntetiske overvannet som ble benyttet i eksperimentene representerte «first flush» av vinteravrenning fra flyplasser forurenset av av-isingskjemikalier og inneholdt sedimenter og av-isingskjemikalier fra Værnes Flyplass i Trondheim, anskaffet av Avinor. Et kolonnestudie bestående av fire tester, med to ulike vannføringer og to ulike konsentrasjoner av av-isingskjemikalier, ble utført for å undersøke de hydrauliske egenskapene til de ulike filtermediene i varierende forhold og fjerning av turbiditet, partikler, av-isingskjemikalier, tungmetaller og PAH.

Resultatene viste at de hydrauliske egenskapene til de ulike filtermediene varierte i forhold til hverandre og ulike forhold. Mens eksperimentene med høy vannføring kun varte en dag før filtermediene klogget, varte eksperimentene med lav vannføring i 5-7 dager før klogging. Alle filtermediene viste god fjerning av partikler (mellom 93.8 % og 99.6 %) ved hjep av fysisk filtrering, mens adsorpsjon av av-isingskjemikalier, som fjernet ca. 10 % - 40 % av av-isingskjemikaliene, kun ble observert i filtermediene med lag av aktivt kull. Biologisk nedbrytning av av-isingskjemikalier ble observert i de testene som varte lengst, fjernet opp til 88 % av av-isingskjemikaliene, og startet etter ca. to dager. De hydrauliske egenskapene, rensingsegenskapene og vedlikeholdsbehovene til filtermediene ble sammenlignet, og det anbefalte filtermediet av mediene testet ble det fine materialet, Filtralite NC 0-2, med lag av aktivt kull.

Generelt sett viste filtermediene som ble testet, akseptable hydrauliske egenskaper, både med tanke på partikler fjernet og operasjonstid før klogging. Alle filtermediene, med to unntak, fjernet mer enn 1.2 kg/m^2 partikler pr. overflateareal før klogging. Fjerning av av-isingskjemikalier var god når biologisk nedbrytning for lave konsentrasjoner av av-

isingskjemikalier forekom, men giftige tilstander som følge av høy konsentrasjon av av-isingskjemikalier hindret vekst av biomasse.

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1 Introduction

1.1 Background

In airports, there are large areas covered by extensive roofed buildings, taxiways, runways and parking lots, which all are impervious areas contributing to stormwater loading. Stormwater from these areas often contains a large amount of pollutants, such as hydrocarbons, heavy metals and suspended solids. In addition, snow, ice and frost create problems at airports and for aircrafts in winter and cold climates. Airplanes are designed for predictable effects of airflow and clean wings. However, in cold temperatures the conditions are not always optimal. In order to make the airplanes appropriate for the conditions, ice, snow and frost need to be removed. The process used for this purpose is de-icing of airplanes and runways. Typically, the de-icing occurs at the gate areas or right before take-off. Aircraft De-icing Fluids (ADF), normally consisting of propylene glycol or formate acids and proprietary chemical additives such as surfactants and corrosion inhibitors and usually hot water under pressure, are added in the de-icing process. The quantities of ADFs depend on the weather conditions (Switzenbaum et al., 2001). During de-icing of airplanes and runways, the de-icing chemicals are usually mixed with the snow. When the snow melts, de-icing chemicals infiltrate the soil surface along the runways (French et al., 2001). In most cases, some of the ADFs are recovered and recycled or treated on-site, while an amount is collected in storm drains and treated in municipal treatment plants. In most cases however, significant amounts of the de-icing chemicals end up in the environment (Switzenbaum et al., 2001). Many airports, an example is Gardermoen Airport in Oslo, are built on large, unconfined aquifers. It is therefore important to assure that the de-icing chemicals do not contaminate the groundwater (French et al., 2001).

Figure 1: De-icing of aircrafts. Picture from (Allett, 2013)

Klima 2050 is a Centre for Research- based Innovation (SFI) aiming to reduce the societal risks associated with climate changes, increased precipitation and floodwater exposure to buildings, infrastructure and the environment. The project focuses on climate exposure and moisture protection of buildings, prevention of water trigged landslides, stormwater management and blue-green solutions. The part of Klima 2050 connected to stormwater management focuses on climate adaption and new technologies, in addition to risk connected to flooding of infrastructure and buildings. Knowledge on costs of flooding is included in this part. Research on blue-green solutions is an important part of the project. In order to create a functioning stormwater management system based on blue-green solutions, knowledge on how the solutions can be implemented and which solutions are the most functioning and suitable, is needed. The solutions needed for the future demand, need to be robust, innovative and climate adapted (Klima2050).

One such solution, are the granular filtration systems. The advantages with using granular filters in treatment of stormwarer are many, including that they treat the stormwater quality and quantity, are cost effective, incorporate natural processes such as infiltration and sedimentation, and they treat the stormwater on-site.

1.2 Objective

In this master thesis, the use of media filters at runways in airports for treatment of de-icing chemicals and other contaminants in stormwater will be investigated. Deliverables will be:

- Characterization of the hydraulic properties of various, selected filter media at two different starting flows and two de-icing chemicals
- Monitor and evaluate these filters for the achieved water quality treatment and compare the selected filter media tested
- Investigate the effect of different concentrations of de-icing chemicals
- Design, operation and maintenance recommendations using these filters and limitations for the system

1.3 Limitations and Approach

Laboratory experiments were performed at the Drinking Water Laboratory at Department of Hydraulic and Environmental Engineering at NTNU. A column study was conducted on five different filter media with Filtralite material supplied by Weber Saint-Gobain. Synthetic stormwater, containing sediments and de-icing chemicals propylene glycol and potassium formate from Værnes Airport, supplied by Avinor, was made in the laboratory.

Four tests were conducted on each of the five columns with variating flow conditions and concentrations of de-icing chemicals. Due to time restrictions, only two concentrations of de-icing chemicals were tested, and no repetitions were made.

The data from the laboratory was analysed in the Analytical Laboratory at SINTEF and Eurofins.

Validation of the results from the laboratory studies was performed by comparing results to the work by fellow student Hanna Haug Lindseth on the same column study.

1.4 Structure of the Thesis

Chapter 2 – Literature review on contaminants in stormwarer runoff from airports.

Chapter 3 – State of the art review on filter systems as method for stormwater treatment.

Chapter 4 - Description of the methods and materials of the laboratory experiments.

Chapter 5 – Presentation of the results from the laboratory experiments and flow modelling.

Chapter 6 – Discussion of the results from the laboratory experiments presented.

Chapter 7 – Conclusion of the study and suggestion for future work.

An analysis of de-icing chemicals in the stormwater at Værnes Airport 2013/2014, a linear approximation of porosity change, results from the same column study conducted by Hanna Haug Lindseth for validation, results from PAH and heavy metals analysis of the sediments used and results from heavy metals analysis for the treated stormwater are enclosed in the appendix at the end of the thesis.

2 Characterisation of Stormwater Pollution in Airports

In this chapter stormwater pollution from airports is described. The contaminants that usually occur in this stormwater and the impacts of stormwater pollution are presented.

2.1 Contaminants in Stormwater from Airports

2.1.1 Heavy Metals

Metals are often present in stormwater. Studies have shown that the most of the largest impacts on the environment today caused by heavy metals, are due to copper and zinc. The occurrence of heavy metals, even in small concentrations, in the environment can interrupt the balance of ecosystems. More severe consequences will appear from higher concentrations and in some cases it can lead to reduced growth, reproduction, survival in ecosystems and it can even be lethal (Erickson et al.).

Stormwater usually contains more pollutants in winter, during de-icing. Accumulation of pollutants in snow packs and snowmelt in addition to increased pollutant levels from increased heating, traffic and de-icing salts, lead to more contamination of stormwater and increased importance of stormwater treatment in winter (Blecken et al., 2010). In addition, the properties and characteristics of winter stormwater are different from summer stormwater.

2.1.2 Polycyclic Aromatic Hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbons (PAHs) form a group of complex hydrocarbons consisting of at least two benzene rings. The benzene rings consist of hydrogen and carbon and are connected with each other with one common side. For some PAHs, alkyl groups replace some of the hydrogen atoms. This results in many possible combinations, and therefore there are many different PAHs with different characteristics. In general, the PAHs have a low solubility and are in a high level adsorbed to soil particles in the unsaturated zone, and therefore immobile. They are often particle bound and present in stormwater. The solubility in water decreases as the molecule size increases. Therefore, some of the lightest PAHs will have a fair solubility and can be a possible pollutant of water. In addition, PAHs can be toxic to humans and animals, varying from a PAH compound to another. PAHs are made by incomplete combustion, such as from cars, fire and industry. They are also to be found in raw oil and paint (Brattli, 2009).

16 PAHs are selected as the 16 priority pollutant PAHs by the US EPA. They are selected based on toxicity, potential for human exposure, frequency of presence at hazardous waste sites and information available. Figure 2 shows characteristics of these PAHs (Khadhar et al., 2010).

Polycyclic aromatic hydrocarbons[a]	Structure (# of rings)	Molecular weight (g/mole)	Solubility (mg/L)	Vapor pressure (mm Hg)
Naphthalene	2	128.17	31	8.89E−02
Acenaphthene	3	154.21	3.8	3.75E−03
Acenaphthylene	3	152.20	16.1	2.90E−02
Anthracene	3	178.23	0.045	2.55E−05
Phenanthrene	3	178.23	1.1	6.80E−04
Fluorene	3	166.22	1.9	3.24E−03
Fluoranthene	4	202.26	0.26	8.13E−06
Benzo(a)anthracene	4	228.29	0.011	1.54E−07
Chrysene	4	228.29	0.0015	7.80E−09
Pyrene	4	202.26	0.132	4.25E−06
Benzo(a)pyrene	5	252.32	0.0038	4.89E−09
Benzo(b)fluoranthene	5	252.32	0.0015	8.06E−08
Benzo(k)fluoranthene	5	252.32	0.0008	9.59E−11
Dibenz(a,h)anthracene	6	278.35	0.0005	2.10E−11
Benzo(g,h,i)perylene	6	276.34	0.00026	1.00E−10
Indeno[1,2,3-cd]pyrene	6	276.34	0.062	1.40E−10

Figure 2: Characteristics of EPA's 16 priority pollutant PAHs (Khadhar et al., 2010)

2.1.3 De-icing Chemicals

Commonly used de-icing chemicals are glycol propylene and potassium formate. Glycol propylene is used for deicing of airplanes, while potassium formate is used for deicing of runways and taxiways. As glycol propylene is soluble in all proportions of water and potassium formate has a good solubility as high as 331 g/100 mL, the de-icing chemicals are transported easily in melt-water and groundwater. Clearing of snow spread the chemicals out. In Oslo Airport Gardermoen de-icing chemicals are found to be spread out up to 30 m from the runway (Wejden and Øvstedal, 2006). When snow is present on the ground, dispersion of de-icing chemicals makes the chemicals mix with the snow before entering the unsaturated zone. As a result, the chemicals infiltrate in a short period of time during snow melt (French et al., 2001).

Potassium is cationic and is naturally present in soils, and formate is the counter anion. Glycol propylene is easily degradable in soil. These properties make it suitable to use a sand-based system for treatment of water contaminated by these chemicals (French et al., 2001). In addition, glycol propylene is degradable by anaerobic and aerobic bacteria. However, it is still uncertain if it is possible to fully remove the contaminants from de-icing before the they reach the groundwater or surface water surrounding the airports (Bielefeldt et al., 2002).

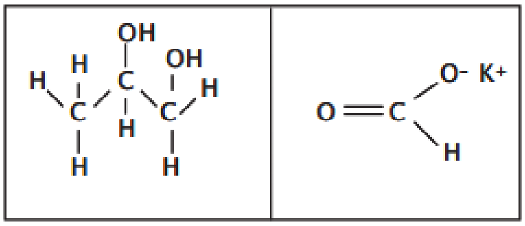

Figure 3: Chemical composition of propylene glycol and potassium formate (Wejden and Øvstedal, 2006)

De-icing chemicals propylene glycol and potassium formate can be removed by adsorption and biodegradation, presented in chapter 3.2.1 and 3.2.2. Biodegradation is significant for the removal of de-icing chemicals, but this process is strongly dependent on retention time (Wejden and Øvstedal, 2006).

The concentration of de-icing chemicals in water can be measured by measuring the concentration of total organic carbon (TOC). It is analysed by a TOC-analyser and the result is obtained rapidly. Because the water may contain particular organic substances, dissolved organic carbon (DOC) can be measured instead. DOC is the dissolved part of the organic substances. The concentration of de-icing chemicals, glycol propylene and potassium formate, can the measured based on the DOC in the water (Ødegaard and Norheim, 2014).

2.1.4 Suspended Solids and Turbidity

Turbidity is a parameter describing the cloudiness of the water. The unit for turbidity is nephelometric turbidity unit (NTU). The amount of suspended solids is a measure for the weight of particles present in the water and is measured in mg/L. By measuring the amount of suspended solids and turbidity for water, a linear relation can be found. This relation can be used to determine one of the parameters by measuring the other. This can be a good approach for measuring suspended solids, because measurements of turbidity are less time consuming (Ødegaard and Norheim, 2014).

2.2 Impacts of Stormwater Pollution

Water is everywhere on earth and can appear in solid form as ice, liquid form or gas form as water steam. Drinking water is essential for all life and water is used for daily purposes in agriculture, industry and household. Water goes in a hydrological cycle, where processes such as infiltration, evapotranspiration and precipitation play important roles. All of the water on earth, in the different forms, is part of the hydrologic cycle. Figure 4 shows how the different processes in the hydrologic cycle transform water between different forms and transport it between surface water, groundwater, runoff and the atmosphere. No water is lost, but continue to move around in the cycle. In the same way, no water is added to the cycle.

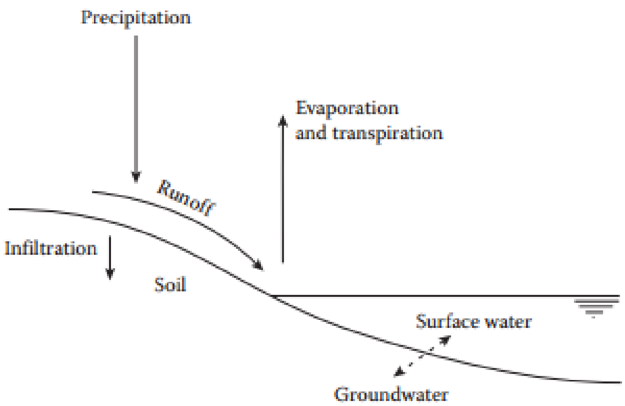

Figure 4: Hydrologic cycle (Davie, 2008)

In some parts of the cycle, water stays for long time periods, and in some parts water continues to the next part after a short stay. Groundwater is a crucial link in the hydrologic cycle because it is the source of a large amount of the water in rivers and lakes. Because groundwater is in slow, continual motion with a speed typically less than 1 m/day, residence time in the groundwater table varies from a couple of years to 1000 years or more (Dingman, 2008).

Both groundwater and surface water is used for the daily purposes in all life. When water is polluted, it has large consequences because the limited access to clean water is further reduced. As polluted stormwater from for instance airports is distributed to surface water or groundwater, it influences the environment in a negative way. Therefore, solutions for treatment of polluted water are important. By treating polluted stormwater from airports, the environment is protected from negative impacts and the water humans need for life and daily purposes is preserved.

3 Filter Systems for Stormwater Treatment

In this chapter, filters as method for stormwater treatment are described. After showing characteristics of filters, as well as possible problems and conditions affecting the performance of filters, design considerations and recommendations for maintenance and operation of filters are presented.

3.1 Filter Systems

Figure 5 shows the principle of infiltration systems. The stormwater flows through the filter vertically and either infiltrates to the ground or is collected and sent to receiving waters or a treatment plant. Surface sand filters utilize clean sand and gravel as filter media and provide both quantity control and water quality improvement of stormwater. Both the quantity control and quality performance of the filter depend on the grain size distribution and the medium's thickness (WEF, 2012).

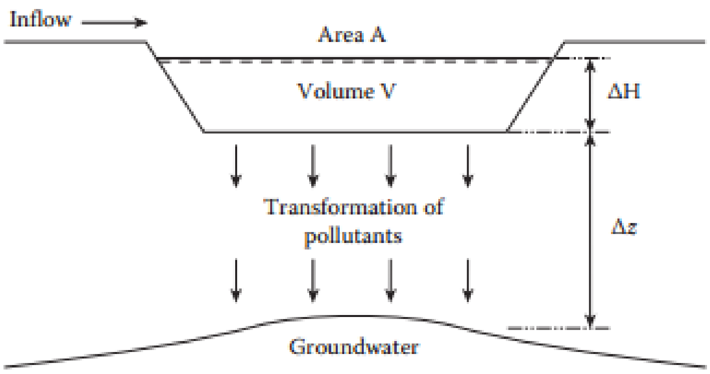

Figure 5: Principle of infiltration systems (Davie, 2008)

Filter systems are used for treatment of stormwater, wastewater and drinking water. Filters for stormwater treatment consist of a bed of specified porous filter medium, a storage and in some cases an underdrain and bypass or secondary spillway. The discharge from filters is lead to receiving water bodies, stormwater sewers or other treatment systems, or to shallow aquifers. Processes as physical size exclusion and adsorption are important mechanisms in the filter media because of the very high surface area of the grains in the media and the size of pore space. The filter media can in addition host attached microorganisms that can remove and consume organic pollutants and nutrients (WEF, 2012).

3.2 Processes in Filters

Physical processes are important for pollutant removal in filters. If microorganisms are attached to the filter medium, biological processes will work with the physical processes.

3.2.1 Physical Processes

Sedimentation is a physical process important in filters. In sedimentation, gravity separates particles by downward movement. Two types of sedimentation are significant in stormwater systems, discrete sedimentation and flocculent suspension. Coarser particles are separated by discrete sedimentation, which means that the particles do not attach when they are in contact with each other, but settle separately. Finer particles tend to attach to each other when in contact, which is flocculent suspension (WEF, 2012).

Size exclusion is physical filtration on and within the filter medium. Particles are removed by straining and sedimentation. When particles smaller than the openings of the medium reach the filter, the particles are retained or held against the medium by hydraulic force. Particles with size as small as 10 – 15 % of the nominal void diameter are retained by physical filtration (WEF, 2012).

Sorption is another physical process significant for filters. There are three different types of sorption, ion exchange, adsorption and absorption. Ion exchange substitutes ions with ions of greater interest, and the exchange can be either anionic or cationic. An example of ion exchange in stormwater treatment is removal of heavy metals by zeolite. Adsorption and absorption are mechanisms conducted by van der Waals forces and bindings between chemical complexes of the pollutants in stormwater on the surface of the filter. Absorption differs from adsorption in the degree of homogeneity. In absorption, the pollutant penetrates the medium on a molecular level, while the attachment in adsorption occurs on the surface of the media. The attachment occurs either on the external medium surface, or the internal medium surface within the porous grains. In stormwater filters, adsorption is the most important type of sorption. The substance that is adsorbed is called the adsorbate and the substance that the adsorbate concentrates on is called the adsorbent. Adsorption has the ability to desorb pollutants that are attached to the filter medium. During dry periods, the pollutants can be detached. For absorption, this is not possible. The ability to desorb pollutants when the chemistry of the water in the filter changes, can lead to release of pollutants (WEF, 2012).

3.2.2 Biological Processes

Biological filtration utilizes bacteria to form biofilm on the surface of the filter grains. Microorganisms in the biofilm remove the pollutants by biodegradation. Because biomass needs time to grow, biodegradation does not start right away. Biofilters therefore require sufficient operation time in order to let biodegradation start. It is important to maintain and control a healthy biomass on the filter surface and a constant source of substrates is required to obtain an effective and consistent operation. Substrates may be organic material or nutrients. Maintenance of the biomass attached to the surface of the filter is significant for the success of the biofilter (Chaudhary et al., 2003). The three main processes in the biofilter are attachment, growth and dispersal of microorganisms (Ødegaard and Norheim, 2014).

3.3 Problems in Filters

3.3.1 Clogging of Filter Media

Clogging of filter media by suspended solids or sediments is a typical problem for filter systems. Clogging develops when the permeability and porosity of the filter medium is reduced either by physical, chemical or biological processes. This phenomenon can appear when the sediment or suspended solid grain size is too coarse for the filter. However, often small particles contribute more to clogging due to pore constriction and are hypothesized as the main phenomenon leading to clogging. Clogging of filter media is an indication of poor hydraulic performance and depends essentially on the nature of filter media and characteristics of inflows, such as particle size of the filter medium, moisture conditions in the filter and influent flow rate (Blecken et al., 2010). Reduced hydraulic performance caused by clogging of filter media often leads to hydraulic failure, which will reduce the treatment efficiency significantly (Hatt et al., 2008). Increased overflows and long periods of ponding are consequences of clogging and may result in problems with health, hygiene, and reduced operational efficiency (Kandra et al., 2014).

The location of the clogging layer varies. Studies have shown that clogging can appear in the filter cake, in the upper layer of the filter, or it can appear throughout the entire filter. The properties of the filter media have a large impact on where the clogging develops (Hatt et al., 2008). The influence of the filter media on the hydraulic performance of filters is further described in chapter 3.5.

The effect of clogging is determined by the hydraulic performance of the filter. To describe the hydraulic performance of the filter, the hydraulic conductivity can be measured. Hydraulic conductivity describes how easily a fluid can flow between pores of a material. Hydraulic conductivity has the unit of velocity [m/s]. The hydraulic conductivity depends on the flow functions of the fluid and the porous material (Brattli, 2009). Viscosity of fluids is temperature dependant, therefore hydraulic conductivity will vary with different temperatures (Kandra et al., 2014). Darcy's law, equation 3.1, gives the hydraulic conductivity.

$$k = \frac{h \times Q}{A_s \times H} \tag{3.1}$$

Where k = hydraulic conductivity

Q = the volumetric flow rate [m^3/s]

A_s= the cross-section area of the column [m^2]

H = the total hydraulic head across the filter

h = the length of filter medium whose hydraulic conductivity is being tested

Because the hydraulic conductivity varies with temperature, a formula for adjustment to 20 °C can be used. In that way computed values of hydraulic conductivity in different temperatures can be comparable. The formula for adjustment from measured hydraulic conductivity to 20 °C is given by equation 3.2 (Monrabal-Martinez et al., 2015).

$$K_{20°C} = \frac{\mu_{measured} \times K_{measured}}{\mu_{20°C}} \tag{3.2}$$

Where $K_{20°C}$ = hydraulic conductivity at 20 °C

$K_{measured}$ = measured hydraulic conductivity

$\mu_{20°C}$ = water viscosity at 20 °C

$\mu_{measured}$ = measured water viscosity

3.3.2 Leaching of Pollutants

As mentioned in 3.1.2, pollutants from the filter media can be released when pollutants are desorbed due to changes in water chemistry of the stormwater. Changes in water chemistry of the stormwater can be related to pH, dissolved oxygen concentration, salinity or background concentration of the pollutant. In dry weather periods, there can be a significant change in the concentration of pollutants in the stormwater, causing a change in the stormwater composition and further leaching of pollutants. Leaching of pollutants can therefore be a problem for filters exposed to wetting and drying (WEF, 2012).

3.3.3 Compaction of Filter Media

Compaction of filter media is the reduction of the filter media's depth. By affecting the hydraulic conductivity, compaction of filter media reduces the ability to convey water (Hatt et al., 2008). The compaction of filter media can be measured by comparing the length of filter media before and after the experiment.

3.4 Conditions Affecting the Performance of Filters

3.4.1 Internal Conditions

The internal conditions in the filter media are of high importance for the performance of the filter. Properties, such as grain size, porosity, shape and smoothness of grains, of the filter will affect the hydraulic and treatment performance of the filter.

A study conducted by Kandra, McCarthy et al. (2014*)* investigated the influence of shape and smoothness on clogging of filters. The results showed that the shape and smoothness affected clogging in a limited way, but that grain size and porosity was more important (Kandra et al., 2014). The grain size of the filter media influences the performance of the filter in that fine particles behave differently than coarse particles. The pressure drop describes the resistance from the filter media to the fluid and the development of pressure drop describes how the resistance from the filter media will increase as the filter clogs. Low value of pressure drop is desired in filters. As large particles have a smaller specific surface area, the pressure drop in the filter during operation will be smaller than for smaller particles. This is shown in figure 6, which shows the development of pressure drop in an experimental study of clogging in filters with monodisperse PSL particles, conducted by Song, Park et al. (Song et al., 2006). In chapter 3.5 fine filter media and coarse filter media are further described.

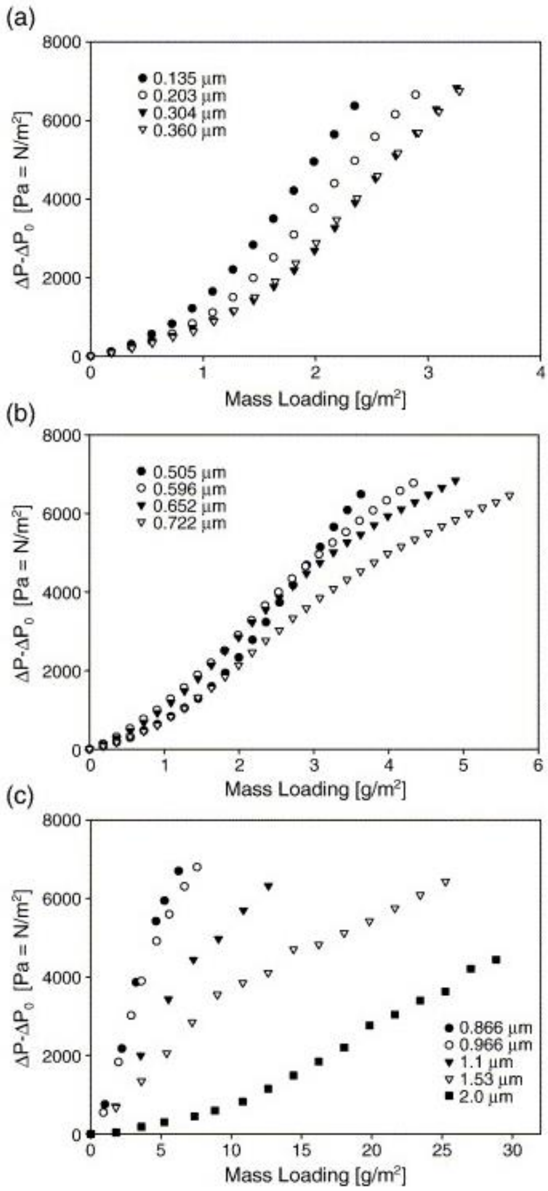

Figure 6: Development of pressure drop in filters with different particle size (Song et al., 2006)

The porosity of the grains in the filter media will have an impact on the hydraulic properties of the filter. As the filter clogs, the porosity of the grains will be reduced. Porosity in filters with flow through packed beds can be computed by Ergun's equation, equation 3.3.

$$\Delta P = 150\mu \frac{(1-\varepsilon)^2 L}{\varepsilon^3 {d_p}^2} v_s + 1{,}75 \frac{(1-\varepsilon)^2 L\rho}{d_p \varepsilon^3} {v_s}^2 \qquad (3.3)$$

Where ΔP = pressure drop in filter medium [Pa]

μ = viscosity of fluid [Pa s]

ρ = fluid density [kg m^{-3}]

ε = average bed porosity

v_s = superficial velocity of the fluid [m/s]

L = bed height [m]

d_p = particle diameter [m]

Ergun assumes decreasing pore size due to material accumulation. In the same instance, other phenomena can occur, such as cake development or pore plugging, and these phenomena are not taken into consideration in Ergun's equation. Ergun’s formula can be used for computation of porosity when constant pressure drop is assumed. In that way, the porosity change as the filter clogs can be investigated. The result will show the impact porosity has on hydraulic performance of filters. Ergun’s equation is originally developed for mono sized beds with spherical particles (Ribeiro et al., 2010).

3.4.2 External Conditions

The treatment efficiency may vary with temperature. When filters are exposed to cold temperatures, problems such as frozen filter media, clogging of filter media, high chloride loads and reduced biological activity may appear (Roseen et al., 2009). As plant and bacteria growth are dependent on temperature, the biochemical processes important to biological filtration are likely to be affected by low temperatures. Especially seasonal variations may affect the filters treatment efficiency as the varying conditions and temperatures may affect the performance of the filter (Blecken et al., 2011). As a result, the removal efficiency of suspended solids (SS), heavy metals and nutrients may be reduced.

Clogging of filter media was described in 3.3.1. Clogging can also occur in the filter due to frost. When filters are used in cold temperatures, concerns due to freezing of filter media are relevant (Roseen et al., 2009). Research presented by Roseen, Ballestro et al. (2009) evaluates treatment performance of six varied filtration systems based on Low Impact Development exposed to seasonal variations. Two of these systems were based on biofiltration. Frost penetration of the filtration systems was observed in the study, but it did not affect the hydraulic performance of the filter. The results of the study indicate that even if frost penetration appears in the filter media, the porosity, permeability and therefore the performance of the filter media can stay unaffected.

The chemical composition of the stormwater treated by the filter, is significant to the performance of the filter. The dominant processes in the medium affect the performance of the filter. As the dominant processes in the media depend on the contaminants and the grain size distribution of the stormwater, these factors affect the performance of the filter. As the contaminants and sediments are retained by the filter media, the infiltration rate of the filter is decreased. After a certain amount of time, the filter clogs. The concentration of pollutants and sediments will therefore increase the clogging rate. The first flush effect describes the phenomenon in which the first part of the runoff during a rainfall event contains a larger concentration of contaminants than the rest of the runoff (Hvitved-Jacobsen et al., 2010). As higher concentrations of contaminants increase the clogging rate, clogging may develop in association to the first flush.

When biodegradation occurs in a filter, problems with clogging due to retention of particles in the filter media can be reduced because the bacteria in the biofilm are fed by the particles causing clogging. However, extensive growth of biofilm can contribute to the clogging of filter media. A column study conducted by Bielefeldt, Illangasekare et al. (2002), investigated the biodegradation of propylene glycol using saturated sand filters. The results of the study showed that greater than 99 % of propylene glycol biodegradation was obtained. Problems with clogging were observed and the hydraulic conductivity was decreased by 2-2.5 orders of magnitude. The effect of intermittent loading was investigated and the results showed that propylene glycol biodegradation was rapid after periods without exposure of propylene glycol. Longer operational time will increase the growth of bacteria. As some of the processes in filter, for example adsorption, are time dependent, longer contact time gives better treatment. When column tests are conducted in order to test the performance of the filter and the occurrence of biodegradation, it is important to note the possibility of biodegradation in the tank or tubings before the stormwater reach the column, may be present. This was the situation in this study (Bielefeldt et al., 2002).

Other external conditions that may affect the performance of filters are ground conditions around the filter and wetting and drying of filter. It is important to investigate the ground conditions around the filter, because permeable soils are significant for the infiltration in filter systems.

3.4.3 Operational Conditions

How the filter is being operated will influence the performance of the filter. The preparation of the filter before the operation will be important for the performance. It is often required to wash and soak the filter medium before it is operated. Backwashing of the filter medium will in addition influence the performance of the filter. In the preparation of the filter medium, washing, soaking and backwashing of the filter medium removes pollutants (WEF, 2012).

The flow rate of stormwater flowing through the filter influences the treatment efficiency of the filter. Studies conducted on the effect of flow rate on treatment efficiency state that there is no statistical difference in volume of stormwater passed before clogging between experiments on restricted flow and unrestricted flow (Kandra et al., 2014). Nevertheless, some differences have been observed in experiments comparing these. The results show that flow restriction reduces the initial infiltration rate of filters, improves the volume of treated stormwater and efficiency of filter media. This indicates that increased flowrates will reduce the hydraulic performance and the treatment efficiency of the filter. Figure 7, from this study, shows how the treatment efficiency decreases as the infiltration rate increases, and how the infiltration rate decreases more rapidly for unrestricted flow than restricted flow.

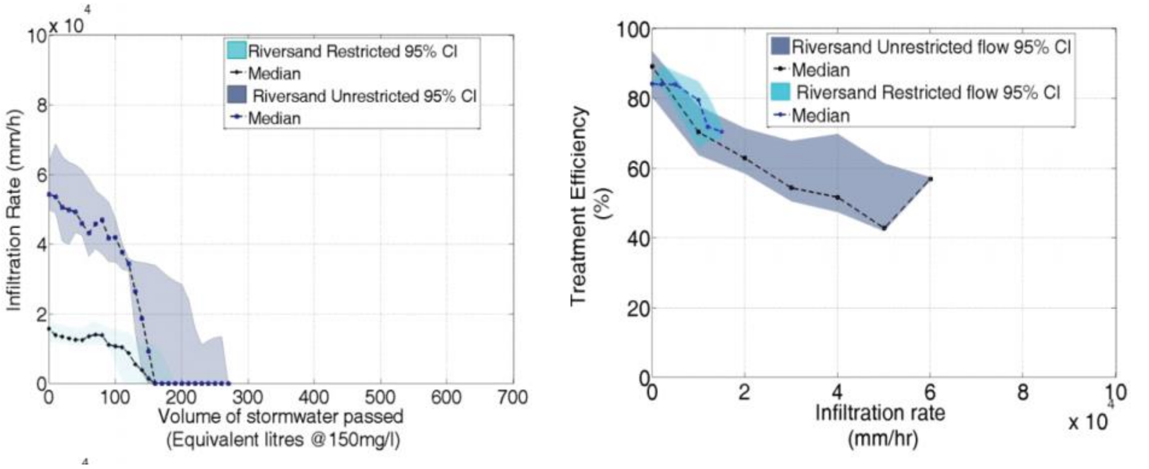

Figure 7: Development of infiltration rate by volume of stormwater passed and treatment efficiency in column study (Kandra et al., 2014)

Quality and frequency of the filter maintenance will affect the filter's performance and extend the lifetime. In addition, the design will have an influence on the filter performance (WEF, 2012). Maintenance and design of filters are further described in chapter 3.6 and 3.7.

3.5 Characterisation of Filter Media

As described in 3.4.1, the properties of the filter medium are significant for the treatment efficiency of filters. This chapter therefore focuses on the available research on different materials of the filter medium. There are many available materials for filter media. When choosing the material, there are several aspects to consider. The material should be consistent in composition, easily and commercially available, low in cost, environmentally benign, long lasting and nonbiodegradable, permeable, easy to handle during construction and effective for contaminant removal (Reddy et al., 2014). The problems that can occur in filters, described in 3.3, should be considered when choosing filter media material. The conditions and problems described in chapter 3.3 and 3.4 are considered when presenting the available knowledge and research on filter media in this chapter.

3.5.1 Coarse Filter Media

Coarse, granular filter media can be used as filter media for stormwater filters. There is shown effective removal for coarse sediments with this type of filter media. However, often problems due to clogging occur and removal of finer pollutants, especially dissolved pollutants. When clogging appear in filters with coarse filter media, the clogging layer usually develops at the bottom of the filter or is distributed throughout the entire filter medium, and this requires removal or replacement of the entire filter medium. An advantage using coarse filter media is that problems with compaction of filter media occur less rapidly (Hatt et al., 2008).

3.5.2 Fine Filter Media

When using finer materials as filter media, finer pollutants and dissolved material can be removed more easily. Several studies have shown the effectivity of fine filter media for stormwater treatment. Hatt, Fletcher et al. (2008) conducted a column experiment with six different filter media types consisting of fine sand or sandy loam. Hydraulic conductivity was measured in order to obtain knowledge on the compaction of the filter and to investigate the impacts on surface clogging on the filter. In addition, water quality samples were analysed for pollutants, such as SS, phosphorous and nitrogen compounds and heavy metals. The results showed that compaction of the soil-based materials reduced the hydraulic conductivity significantly. Compaction did not occur in the sand-based materials. Accumulation of sediments at, or close to the surface of the filter media was observed on almost all of the tests, causing clogging on the surface of the filters. The filter media effectively reduced the amount of SS and heavy metals. Leaching of nutrients such as nitrogen and phosphorous compounds was observed for the soil-based filter media, indicating that the medium is a source rather than a sink of nutrients (Hatt et al., 2008).

From this study it can be noted that problems such as compaction and leaching of pollutants can appear in fine media. Where coarse filter medium often have problems due to clogging of filter media, clogging is usually easier to manage for finer filter media than for coarse filter media. This is because the clogging layer usually develop on top of the filter, which makes it easier to remove the layer by scraping. In the column study by Hatt, Fletcher et al. (2008), it was indicated that the filter could be operated for 5-10 scrapings of the top layer. The fine filter media will in that way have an increased lifetime. An example of another advantage with fine filter media is that this kind of filter media can be used for vegetated filters in rain gardens and in biofiltration systems. Both techniques are increasing its growth in stormwater management. When fine filter media is used, adsorption will go faster than for coarser filter media. However, the faster the adsorption goes the faster the pressure and flow will drop (Ødegaard and Norheim, 2014).

3.5.3 Mixed Media Filter

Reddy, Xie et al. (2014) conducted a study where a mixed media filter consisting of crushed limestone, natural zeolite, white silica sand and iron fillings was used. The study showed efficient removal of multiple contaminants and no problems connected to clogging. However, the experiments were of short duration, which indicates that long term performance needs to be further investigated (Reddy et al., 2014).

Several studies have shown that, when using single filter media, the filter is not able to remove all contaminants. Often, different filter media have different properties, so that they remove different contaminants best. By using mixed media filter consisting of several single filter media, the properties of the different materials are combined. In that way contaminants are effectively removed. In addition, large scale laboratory testing has shown mixed media filter systems maintaining high flow rates without clogging issues (Reddy et al., 2014).

3.5.4 Filter Media with Activated Carbon as Adsorbent

Activated carbon can be made from almost all organic raw material, for example coconut shale, wood and coal. Because activated carbon obtains a large specific surface area when the carbon is activated, activated carbon is a significantly good adsorbent of organic substance. There are two types of activated carbon, powdered activated carbon (PAC) and granular activated carbon (GAC). For filters, GAC is the most relevant type of activated carbon. GAC is usually used as filter medium in sand filters where adsorption is wanted. For the choice of grain size of GAC, the same principle as for filter media applies. A high adsorption rate and low pressure drop is desired. Grainsizes between 0.5 mm and 2 mm are common for sand filters with GAC (Ødegaard and Norheim, 2014).

A study by Monrabal-Martinez et al. (2015) investigated the effect of placement of the activated carbon on hydraulic performance in filters for stormwater treatment. The studies showed that it is preferable to place the activated carbon on top of the filter media (Monrabal-Martinez et al., 2015).

3.6 Design Recommendations for Filters

Filters should be designed based both on hydraulic and chemical properties. It is desired that the resistance in the filter is as small as possible, and that the infiltration rate is as high as possible. In that way the optimum treatment capacity is obtained without causing clogging. Darcy’s equation, equation 3.4, is used for computing the surface area of the filter when designing the filter. In order to design the filter, the design flow specific for the area the filter is placed, is used. The filter should be designed for the volume of inflow to the filter for 24-48 hours.

$$A_{sf} = \frac{Vd}{K(h_{sf} \times d)t} \qquad 3.4$$

Where h_{sf} = maximum design depth of ponding

Vd = ponded volume

K = hydraulic conductivity

d = depth of filter

t = time of pounding

Filters are designed to meet the design flow for water quality. Commonly, the range of drainage of the design volume is 12-48 hours. This range should be sufficient to minimize the potential for the filter to be partially filled when a new storm arrives (Davie, 2008).

The most important part of the treatment processes occurs in the saturated zone, between the bottom of the filter and the ground water table. It is therefore important with sufficient space between the filter and the ground water table. For gravel filters, a depth of 0.3-0.5 m under the ground level is recommended and 1.5 m as the maximum depth. The properties of the underlying and surrounding soil influence the hydraulic performance of filters because the lower hydraulic conductivity controls the hydraulic load on the filter (Hatt et al., 2007).

3.7 Operation and Maintenance Recommendations for Filters

Maintenance of filters is of high significance. Clogging of filter media causes reduced hydraulic performance and results in the need of maintenance of filter media. Clogging occurs with the accumulation of approximately 1.2 to 5 kg/m^2 of sediments per filter media surface area. The frequency of maintenance of filters therefore depends on the characteristics of the contributing area. A higher frequency of maintenance will be required in sites with high sediment loads, such as sites exposed to agriculture and construction. In order to delay the degradation of filters due to clogging, pre-treatment is recommended. By adding vegetation to the filter, natural pre-treatment will be fulfilled and the impacts of clogging and compaction will be countered. In bioretention filters, the biological processes contribute to maintain the pore structure in the root zone (WEF, 2012).

Visual inspection of the media surface when the water is not pounded should be included in the periodic checks of the filters. In addition, observations of the time required draining time of the ponded water after rainfalls should be included in the periodic checks. The results of these checks should evaluate if the filter needs maintenance. If the filter system is not meeting the desired drain time criteria, the clogging sediments and debris should be cleaned from the filter medium. This is usually done by removing and replacing the top layer of the medium (WEF, 2012). After 5 to 10 scrapings, the filter should be replaced (Hatt et al., 2008).

3.8 Limitations for Filter Systems

The external conditions that affect the performance of filters, presented in chapter 3.4.2, introduces limitations to filter systems. Limiting factors for filter systems include maintenance, temperature, freezing of filter media and low permeability soil. It is important to have these factors in mind when planning and designing filter systems.

For stormwater treatment systems the hydraulic or the treatment performance can be the limiting factor for the life-span of the system. The lifetime of gravel filters is usually determined by the hydraulic performance, as gravel filter clogs (Hatt et al., 2007).

4 Laboratory Experiments

In this chapter the laboratory experiments performed are described. The preparations before the experiments, the parameters tested and the methods and materials for the laboratory study are described.

4.1 Performed Tests

The objective with the laboratory experiments was to investigate the performance of different commercial filter media with stormwater and flow conditions relevant for airports and representing the first flush, described in chapter 3.4.2. The stormwater therefore contained a high fraction of pollutants and suspended solids. By using five columns, five different filters were tested and compared with each other. The filters were tested with different concentrations of pollutants and with different flow conditions. In total, four tests were conducted for each column. For all tests, the following parameters were tested.

- Hydraulic Conductivity
- Turbidity
- Dissolved Organic Carbon (DOC)
- Suspended Solids (SS)
- Heavy Metals
- Porosity

Table 1: Experiment matrix

	Low flow (0.3 m/h)	**High flow** (1.5 m/h)
Low concentrations (Propylene glycol: 20 mg/L, Potassium formate: 19 mg/L)	Test 3	Test 1
High concentrations (Propylene glycol: 83 mg/L, Potassium formate: 109 mg/L)	Test 4	Test 2

4.2 Materials

4.2.1 Filter Media

Filtralite from Weber Saint-Gobain was used as filter media in the experiments. Filtralite is inert, ceramic particles and has a porous core surrounded by a dense shell. One of the advantages with Filtralite is that the grains have a large surface area, which is essential for good performance of filters. The density of Filtralite type NC, which is used in the laboratory studies, is 1100 g/m^3 (WebenSaintGobain, 2015). Weber Saint-Gobain provided all information about the materials given in this thesis.

Filtralite NC 0.8-1.6 consists of expanded clay granules. The grains are porous and sharp-edged. The material has low solubility in acids and strong resistance against mechanical abrasion. Figure 9 shows the sieving curve of the material, which gives a good picture of the grain size distribution of the material. The effective diameter, d_{10}, of this material is 0,96 mm.

Figure 8: Filtralite NC 0.8-1.6 from Weber Saint-Gobain. Photo: Hanna Haug Lindseth

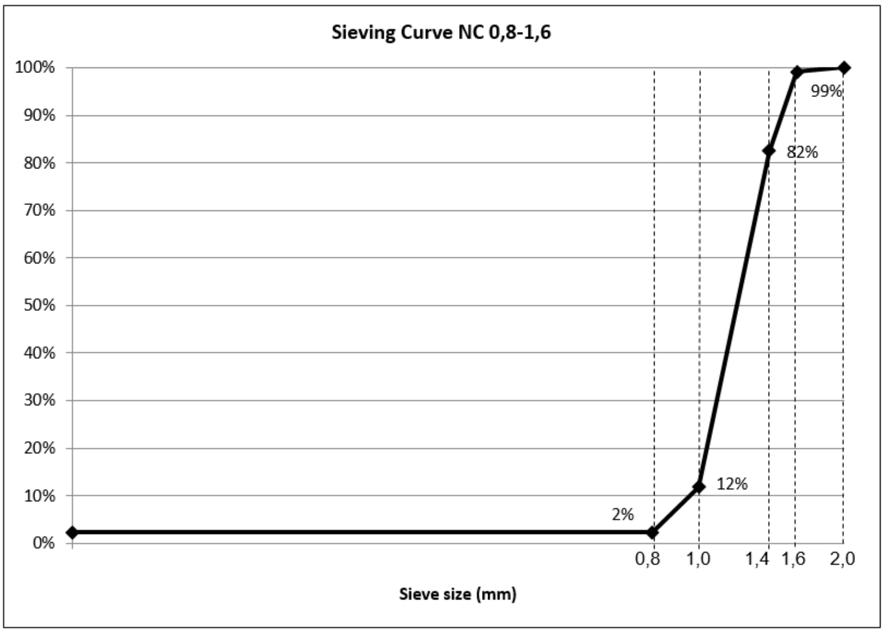

Figure 9: Sieving curve for NC 0.8-1.6

Filtralite NC 0-2 is not an yet a commercial product for Weber Saint-Gobain and is therefore not made in large quantities, but is made from under grain and rest products from other production. It is desirable to investigate the characteristics of this material in order to find an application for the material. This material consists of mostly fine particles. From figure 11, it can be seen that there are almost no particles larger than 1 mm and a high fraction, 17.5 wt %, has grain size lower than 0.125 mm. The effective diameter, d_{10}, of this material is 0.109 mm.

Figure 10: Filtralite NC 0-2 from Weber Saint-Gobain. Photo: Hanna Haug Lindseth

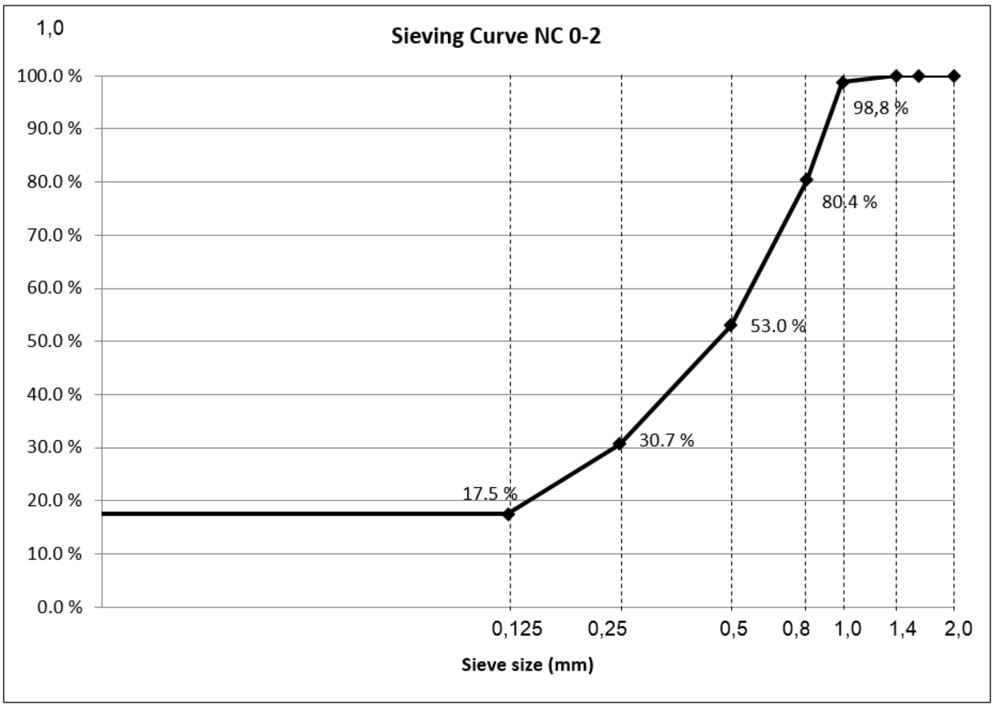

Figure 11: Sieving curve for NC 0.8-1.6

Figure 12 shows the type of GAC used and figure 13 shows the sieving curve for this material. The density of this material is 450 g/m^3 and the effective diameter, d_{10}, is 0.9 mm.

Figure 12: Granular Activated Carbon (GAC). Photo: Hanna Haug Lindseth

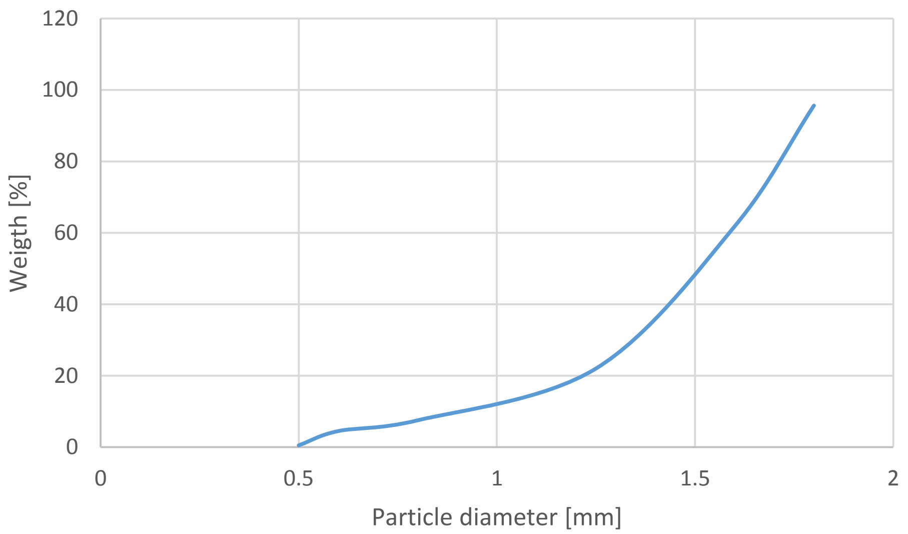

Figure 13: Sieving curve for GAC

4.2.2 Synthetic Stormwater

In the experiments, synthetic stormwater was made and used. Synthetic stormwater is artificial stormwater created in the laboratory, and used for laboratory experiments when natural stormwater is not available. By mixing tap water with sediments consisting of the pollutants relevant to the specific experiment, stormwater similar to the natural stormwater was obtained. The synthetic stormwater for this experiment was made by mixing tap water with sediment samples from Værnes Airport in Trondheim. In order to make the sediment sample representative for the airport, different parts of the sample were collected from different places of the airport. The first part of the sample was collected from the de-icing area at Værnes, and the two other parts were collected from two different places on the runway.

Figure 14: Collection of samples on runway in Værnes Airport

After sampling, the sample was sieved in order to remove rocks and grass. First a grain size distribution of the sediments was made after removing grass and large rocks. One grain size distribution was made for the coarse fraction of the sediments by sieving the sediments and one for the fine sediments with grain size smaller than 63 µm using LS32. The sediments were sieved so that only fine sediments were used in the stormwater because larger particles would be readily settleable and sieved on the upper soil layer, before reaching the filter. A new grain size distribution was made for the fraction of the sediments actually used in the stormwater. In addition, an analysis of the pollutants in the sediments was obtained. The results from the grain size distributions are given in chapter 4.2.3 and the results from the analysis are given in Appendix D.

The sediments were then added to tap water in a tank, and deicing chemicals were added. The tank was filled up with new synthetic stormwater for all four tests. To determine the concentration of sediments in the synthetic stormwater, the turbidity was measured. The goal was to have a turbidity that equaled 150 mg/L suspended solids (SS). In order to find the turbidity that matches this concentration of SS, a graph showing the relation between turbidity and SS was used. The turbidity measured in the stormwater varied from 56.3 NTU in Test 1 to 61.7 NTU in Test 4, these turbidity values equaled approximately 200 mg/L. The deicing chemicals were collected at Værnes Airport. At Værnes Airport, propylene glycol is used for de-icing of airplanes and potassium formate is used for de-icing of runways. The concentration of de-icing chemicals was based on an analysis made of concentration of deicing chemicals found in stormwater at Værnes Airport the winter 2013/2014, provided by Avinor. A report from the analysis is given in Appendix D. Different concentrations of de-icing chemicals were used in the different tests. Two tests were conducted using the average value of concentration of de-icing chemicals from the analysis, and two tests were conducted using the highest concentrations observed the winter 2013/2014. The properties of the stormwater used for the different tests are given in chapter 4.4.

Figure 15: Tap water

Figure 16: Synthetic stormwater (from test 1)

Figure 15 and 16 show the difference in colour between tap water and the synthetic stormwater.

4.2.3 Particle Size Distribution of Sediments

Figure 17 and 18 show the particle size distribution of the sediments collected from Værnes. Figure 17 shows the distribution of the sediments coarser than 63 µm, while figure 18 shows the distribution of the sediments finer than 63 µm.

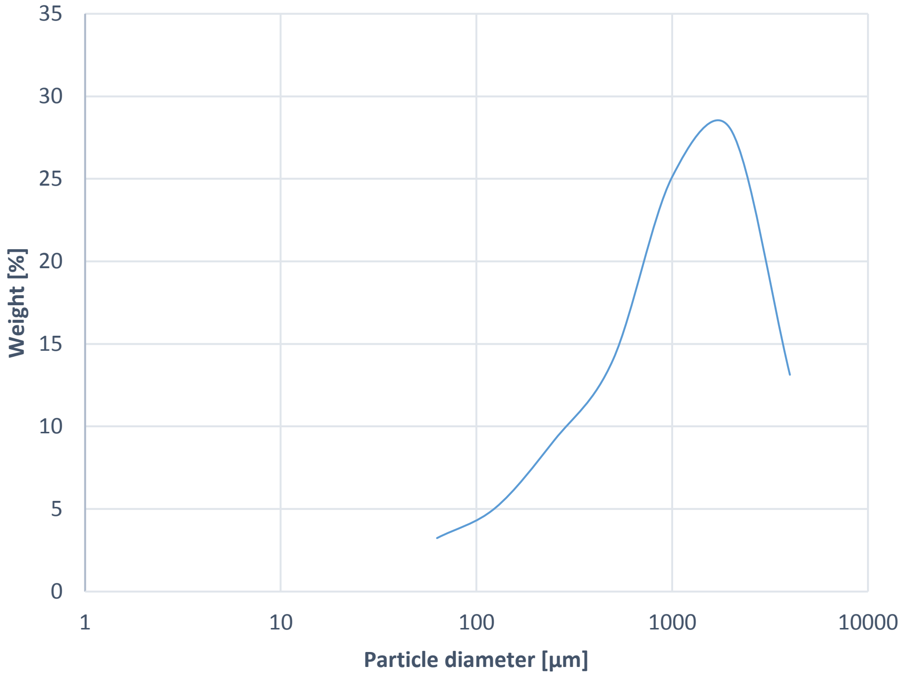

Figure 17: Particle size distribution of sediment sample from Værnes, coarse fraction

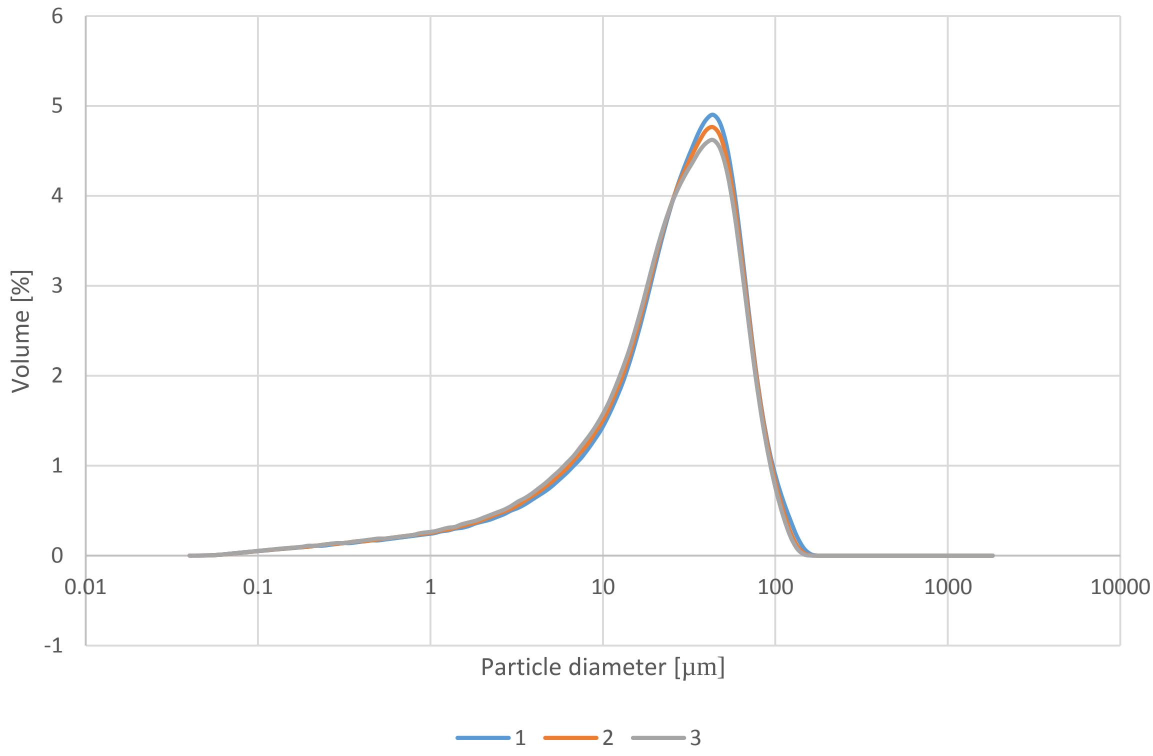

Figure 18: Particle size distribution of sediment sample from Værnes, fine fraction

The sediments contained a high fraction of coarse sediments. Because a high fraction of coarse sediments in the stormwater most likely will lead to sedimentation of a large part of the sediments, the coarsest particles were left out when the stormwater was made in order to obtain the desired turbidity of the stormwater. Therefore, a new grain size distribution was made for the raw water tank using the LS32. Figure 19 shows this grain size distribution for Test 1.

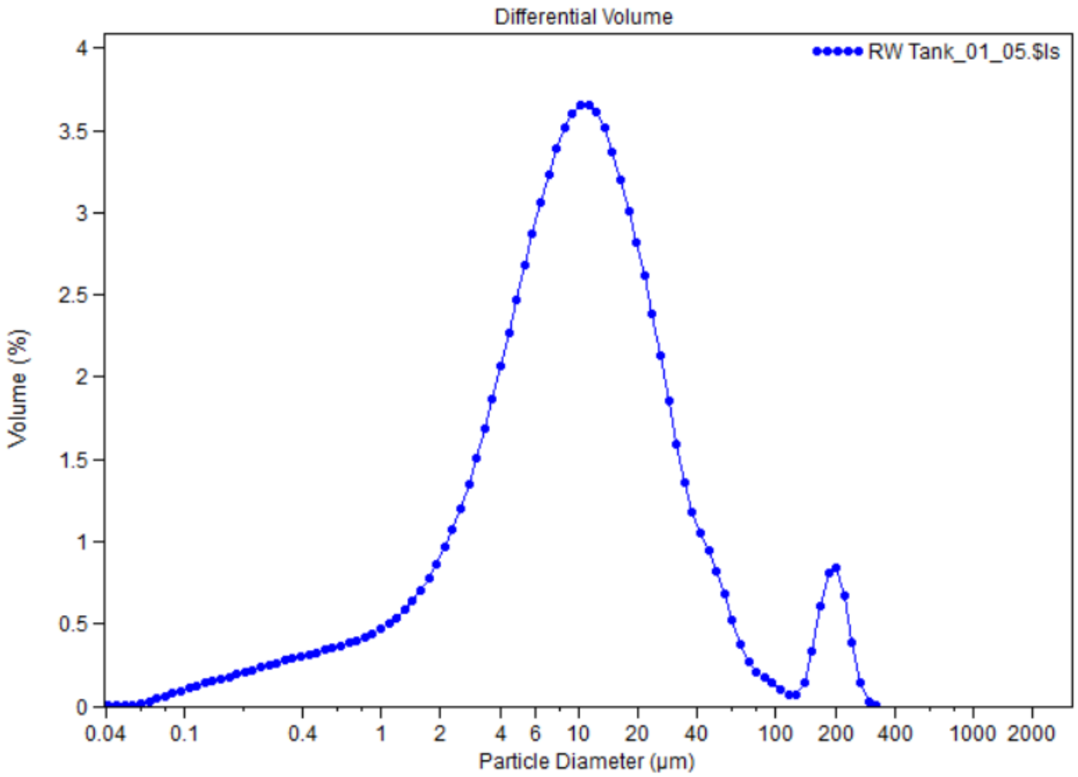

Figure 19: Particle size distribution of sediments from Test 1

4.2.4 Analysis of Sediments

The results of the analysis of the sediments from Værnes Airport, performed by Eurofins, are given in Appendix D. The concentration of PAHs is low for all of the 16 PAHs the sediments were tested for, but a significant concentration of heavy metals was observed. Table 2 shows the concentration of heavy metals and table 3 shows the concentration of the 16 priority PAHs present in the sediments from Værnes.

Table 2: Concentration of heavy metals present in sediments from Værnes. Results from soil analysis

Heavy Metal	Concentration [mg/kg TS]	Measured Uncertainty [%]
Arsenic (As)	3.5	30
Lead (Pb)	6.1	40
Cadmium (Cd)	0.15	25
Copper (Cu)	82	30
Chromium (Cr)	20	30
Mercury (Hg)	0.002	20
Nickel (Ni)	17	30
Zinc (Zn)	44	25

Table 3. Concentration of PAHs in sediments from Værnes. Results from soil analysis

PAH	Concentration [mg/kg TS]	Measured Uncertainty [%]
Naphthalene	< 0.010	
Acenaphthylene	< 0.010	
Acenaphthalene	< 0.010	
Fluorene	< 0.010	
Phenanthrene	< 0.010	
Anthracene	< 0.010	
Fluoranthene	0.019	40
Pyrene	0.055	25
Benzo(a)anthracene	0.013	40
Chrysene	0.17	35
Benzo(b)fluoranthene	0.085	25
Benzo(k)fluoranthene	0.019	40
Benzo(a)pyrene	0.050	35
Indeno(1,2,3-cd)pyrene	0.031	40
Dibenzo(a,h)anthracene	0.020	40
Benzo(ghi)perylene	0.059	40

4.3 Preparations of Filters

4.3.1 Washing of Filter Media

Before the experiment started, the filter media were soaked for at least three weeks. This is the procedure recommended by Weber Saint-Gobain for the material.

4.3.2 Set-up of Columns

The five columns were filled up with the materials NC 0-2, NC 0.8-1.6 and granular activated carbon (GAC).The columns had a height of 40 cm and a diameter of 10 cm. After soaking, the filter media were put in the columns. A layer of geotextile was placed at the bottom of the filter. Figure 20 shows the five columns filled with materials. The columns were fed with stormwater from the holding tank over the columns, which were supplied with stormwater from a tank by a pump.

Figure 20: Set-up of experiment. Column 1 to 5 from the right to the left. Photo by Hanna Haug Lindseth

The columns were filled with the material as following:

- Column 1: NC 0.8-1.6
- Column 2: NC 0-2 + GAC
- Column 3: NC 0-2 + NC 0.8-1.6
- Column 4: NC 0.8-1.6 + GAC
- Column 5: NC 0-2

The column numbering above is consistently used throughout the thesis.

4.3.3 Flow Conditions in Experiments

As chapter 3.4.2 explains, the flow conditions have a large impact on the occurrence of clogging in the filter media. In this experiment restricted flow conditions were chosen, because it requires less synthetic stormwater and gives better treatment efficiency and slower clogging of filter media for coarse materials. Natural flow conditions relevant for airports were obtained by testing the filters for flow scenario representing normal precipitation.

Similar column experiments were studied to find the fitting flow rates. Studies conducted by Kandra, McCarthy et al. (2014) used restricted infiltration rate 1,5- 3 m/hr in similar experiments, where assessment of clogging was one of the main topics (Kandra et al., 2014). The same infiltration rate was used for the high flow rate of this study. To investigate the filters behaviour in both high and low flow, a flow rate five times lower was chosen for the low flow rate testing. The two flow rates chosen was 200 mL/min and 40 mL/min.

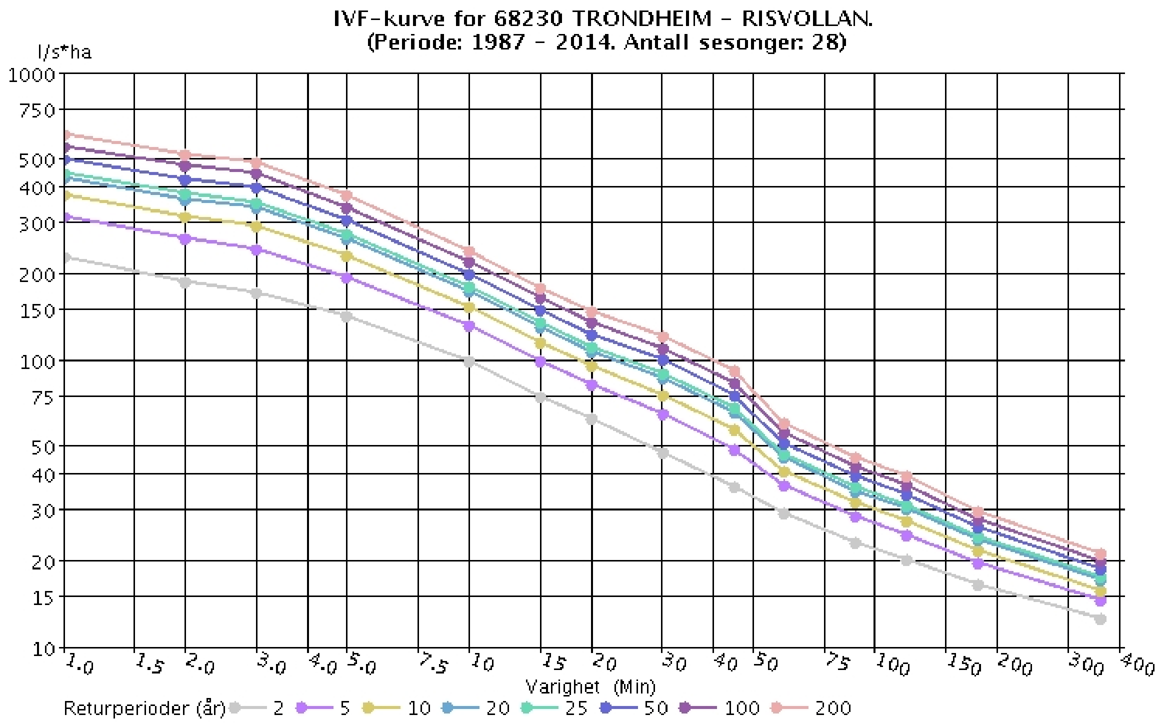

Figure 21: IDF curve for Risvollan in Trondheim (eKlima, 2016)

Figure 21 shows the IDF for Risvollan Station for precipitation measurements in Trondheim. From the curve, it can be seen that the flows representing 1.5 m/hr and 0.3 m/hr are higher than the rainfall with 200-year return period. Both these flows will therefore represent extreme rainfalls. Flows that high are chosen to represent the first flush.

4.4 Testing Parameters

The following parameters were tested for all tests.

4.4.1 Hydraulic Conductivity

To test clogging of the filter media, the hydraulic conductivity was measured before and after the tests. The measurements were conducted three times and the average value was used in the calculations. To determine the hydraulic conductivity, Darcy's law, explained in chapter 3.3.1, was applied. The hydraulic head, surface area and length of filter were measured and the flow was determined by measuring the volume of effluent from the column in 60 seconds.

4.4.2 Measurements and Modelling of Flow

The flow was determined every hour of the first hours of each experiment, and twice every day for the rest of the experiment. To investigate the physical properties of clogging, the porosity change as the filter clogged was computed. In order to compute the porosity, Ergun's equation, equation 3.3, was used. The change of porosity was used to model the flow in order to make the flow measurements more accurate. By computing the slope and intersection of the porosity curve for each of the filters in all tests and relating these properties to the flow through the filter, an approximation to the flow through the filter was obtained.

4.4.3 Water Quality Analysis

The relation between the amount of suspended solids (SS) and turbidity was measured by calculating suspended solids and turbidity of seven samples of stormwater with different concentrations of SS. By plotting the values, an equation was determined. This relation was used when measuring the amount of SS during the testing. By measuring the turbidity, the amount of SS was determined.

The analysis of SS was done in the analytical laboratory for seven samples to see the relation between SS and turbidity and for the samples of the synthetic stormwater, collected before every test. Figure 22 shows the realtion between turbidity and suspended solids.

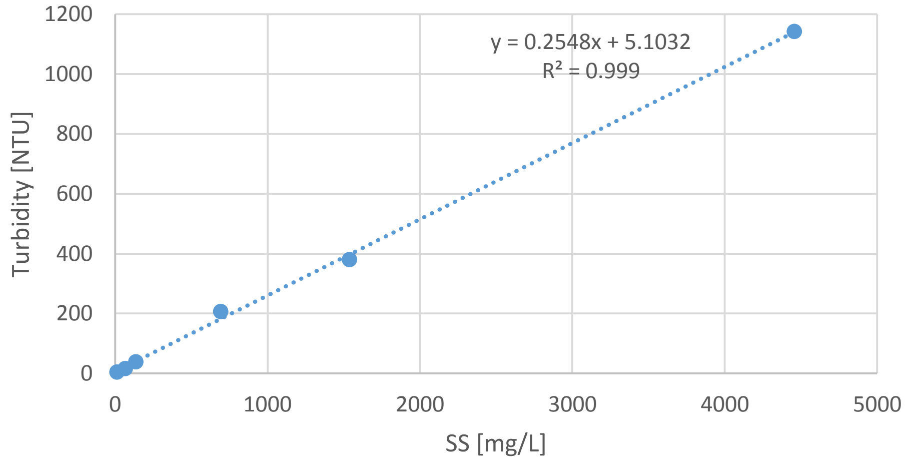

Figure 22: Relation between turbidity and suspended solids (SS)

Samples for turbidity testing were taken every hour the first day of the experiment, and twice a day for the rest of the experiments. The turbidity was measured in the analytical laboratory, using a turbidmeter. Figure 23 shows the turbidmeter used.

Figure 23: Turbidity measurements by Turbidmeter

Table 4 shows the initial value for turbidity in the raw water measured for each of the four tests. Two measurements were conducted for the two first tests and three for the two last tests. The standard deviation is the deviation between the measurements.

Table 4: Initial raw water values for turbidity in NTU for the laboratory Test 1-4

Test	**1**	**2**	**3**	**4**
Turbidity in Raw water [NTU]	56.3	56.4	57.0	61.7
Standard deviation	±0.05	±0.3	±5.8	±1.25

Samples for DOC were taken twice a day and analysed in the analytical laboratory. Table 5 shows the DOC value measured for the raw water for the laboratory tests. The standard deviation for the measurements is given in the same table. Because the measured value of DOC in the raw water in the third sample had a low value after several measurements, errors in the sampling due to biodegradation was assumed. Therefore, the raw water value was extrapolated from the rest of the values measured in Test 3. This value is given in table 5, and the standard deviation is chosen to be 0.05 as a standard error.

Table 5: Initial raw water values of DOC in mg/L for the laboratory Test 1-4

Test	**1**	**2**	**3**	**4**
DOC in Raw water [mg/L]	7.191	29.458	11.501	33.457
Standard deviation	±0.065	±1.222	±0.05	±0.379

Samples were collected from the raw water tank and all columns when clogging was observed in at least one of them. In total 24 samples were send in for analysis of heavy metals.

4.5 Testing Procedure

Four tests were conducted. Test 1 and Test 2 had a high flow rate and Test 3 and Test 4 had a low flow rate. In Test 1 and Test 3, the average value of propylene glycol and potassium formate found in the stormwater at Værnes Airport, from the analysis in appendix A, was used. This concentration was set to 20 mg/L potassium formate and 19 mg/L propylene glycol. For the Test 2 and Test 4, the largest amount of de-icing chemicals observed in the stormwater that year (2013/2014) was used. This concentration was set to 83 mg/L propylene glycol and 109 mg/L potassium formate. Properties of the four different tests are given in table 6.

Table 6: Description of tests conducted on the columns

	Test 1	**Test 2**	**Test 3**	**Test 4**
Flow rate [mL/min]	200	200	40	40
Potassium formate concentration [mg/L]	19	109	19	109
Propylene glycol concentration [mg/L]	20	83	20	83
Turbidity [NTU]	56.3	56.4	57.0	61.7
Suspended solids [mg/L]	201	201	204	222

4.6 Basic Assumptions

For the porosity computation and flow modelling, Ergun's equation, equation 3.3, was used. Because the filter media in this laboratory study were not mono sized or had spherical particles, the effective particle diameter was used as the particle diameter in the calculations of porosity. The effective particle diameter was the d_{10}, which is the particle diameter larger than 10 weight % of the particles of the size distribution of that respective media. Other assumptions for these calculations were constant pressure drop and temperature throughout the whole experiment.

5 Results

In this chapter, the results from the laboratory experiments are presented and discussed. The results of tests connected to hydraulic performance, the hydraulic performance related to the treatment of stormwater and the causes of the reduction in hydraulic performance are presented in this chapter.

5.1 Hydraulic Performance of Filters

The hydraulic performance of the filters were tested by measuring the hydraulic conductivity and the flow development. The results of these measurements are given in this section.

5.1.1 Hydraulic Conductivity Tests

Table 7: Hydraulic conductivity measured for Column 1-5 for test 1-4

Column		**1**	**2**	**3**	**4**	**5**
Test	**Hydraulic Conductivity [m/s]**	**NC 0.8-1.6** $[\times \mathbf{10^{-4}}]$	**NC 0-2 + GAC** $[\times \mathbf{10^{-4}}]$	**NC 0-2 + NC 0.8-1.6** $[\times \mathbf{10^{-4}}]$	**NC 0.8-1.6 + GAC** $[\times \mathbf{10^{-4}}]$	**NC 0-2** $[\times \mathbf{10^{-4}}]$
1	Initial	51.66	6.445	14.93	37.30	10.09
	After test	0.1632	0.2336	0.5177	0.06944	0.9109
2	Initial	36.68	4.415	7.784	33.41	10.09
	After test	0.2330	0.4864	0.5343	0.4074	0.04109
3	Initial	44.90	11.15	14.20	48.19	5.888
	After test	2.330	0.8481	1.427	32.62	0.4920
4	Initial	22.09	5.796	4.896	42.49	3.824
	After test	10.44	3.342	0.7930	21.61	0.7968

Table 7 shows the measured hydraulic conductivity before and after the tests for all filter media in all four tests. For the tests with high flow rate, Test 1 and Test 2, the reduction in hydraulic conductivity was similar for all filter media, except NC 0.8-1.6 + GAC, which had a large decrease in Test 1. For the low flow tests, Test 3 and Test 4, the fine filter media and the mixed filter media had more or less the same reduction as in the first tests. The coarse materials behaved differently in the low flow tests than in the high flow tests. In the low flow tests, the course materials had a much lower reduction in hydraulic conductivity than in the high flow tests.

The initial hydraulic conductivity of the fine filter media NC 0-2, especially the media without activated carbon layer, varied between the different tests. Preparations of these filters were necessary before the tests. Because the material contained pollutants, flushing of all columns was necessary before tests. However, the initial hydraulic conductivity was significantly reduced when filter media NC 0-2 was flushed too long due to compaction of filter media. The solution for this problem was shaking of columns or backflushing. Due to suction of the fine fraction of the material when backflushing, this solution was unsuccessful. In addition, air bubbles were created when the columns with NC 0-2 and NC 0-2 + GAC were left over night without being fed with water. The formation of air bubbles in the columns created problems for the hydraulic performance of the filters in that the hydraulic conductivity was reduced significantly.

As the hydraulic conductivity measurements, as well as the laboratory column study, were conducted manually, uncertainties due to approximations and human errors appear. In addition, uncertainties due to different values for initial hydraulic conductivity measured, and When evaluating the results, it is important to have these uncertainties in mind. Air bubbles and compaction were also observed in the fine media columns. This was one of the contributing factors making the hydraulic conductivity different for the same media in different tests. This may have affected the results.

5.1.2 Analysis of Flow Measurements

The results from the flow analysis are presented in the following. With varying concentrations of de-icing chemicals, the filters behave differently. The flow through the columns with the filter media is plotted against the bed volume, which is the volume of stormwater treated divided by the volume of the columns, as presented in equation 5.1.

$$Bed\ volume\ = \frac{V_{treated\ stormwater}}{V_{column}} \tag{5.1}$$

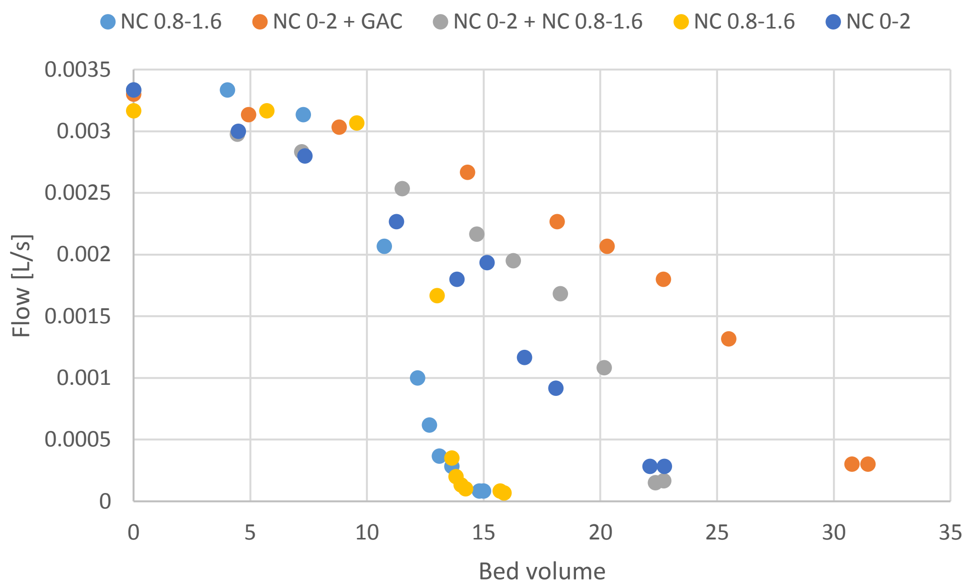

Figure 24: Test 1, Column 1-5. Monitored outlet flow versus bed volumes

In Test 1, where the stormwater contained a low concentration of de-icing chemicals and a high flow was used, the coarse filter media clogged first. The finer filter media and the mixed filter media lasted longer without clogging. For the filters where a GAC layer was added, clogging occurred later than for the filter media using the same material, but no GAC layer.

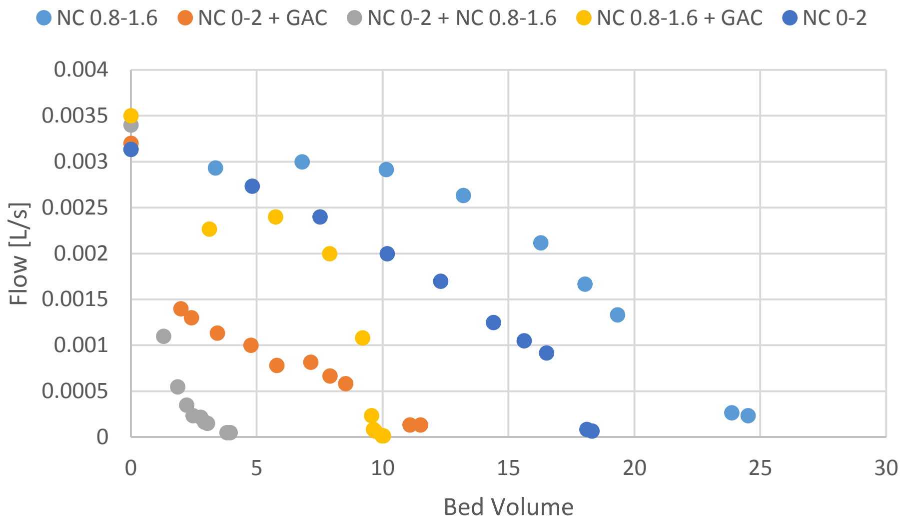

Figure 25: Test 2, Column 1-5. Monitored outlet flow versus bed volumes

Different results were observed in Test 2. This test had the same flow as Test 1, but the stormwater had a high concentration of de-icing chemicals. It was observed that clogging of the filters where a GAC layer was added occurred before the filter media with the same material without GAC layer clogged. As Test 1, where the stormwater had a low concentration of de-icing chemicals, showed opposite results on this, it indicates that the GAC layer has adsorbed de-icing chemicals. This corresponds well to the properties of the adsorbent GAC, presented in 3.5.4.

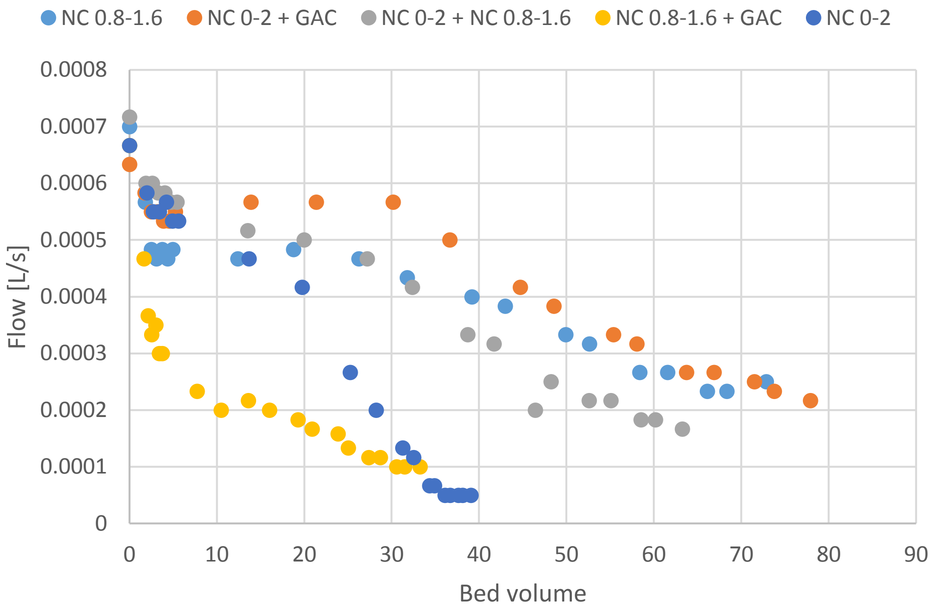

Figure 26: Test 3, Column 1-5. Monitored outlet flow versus bed volumes

In Test 3, a low flow rate was used and the stormwater contained the same low concentration of de-icing chemicals as in Test 1. The results show some of the same things as Test 1, but the filter media NC 0.8-1.6 + GAC clogs much earlier than the rest of the filters, and before the same material without the GAC layer. In Test 1, the filter medium consisting of the fine material and the mixed filter medium showed significantly better hydraulic performance than the coarse material. The same was observed in this test. When the test was stopped, after 7 days, the fine and mixed filter media were partly, but not fully clogged. Both coarse media were then clogged fully. Because a low flow rate was used, the duration before clogging was significantly longer than for Test 1 and Test 2.

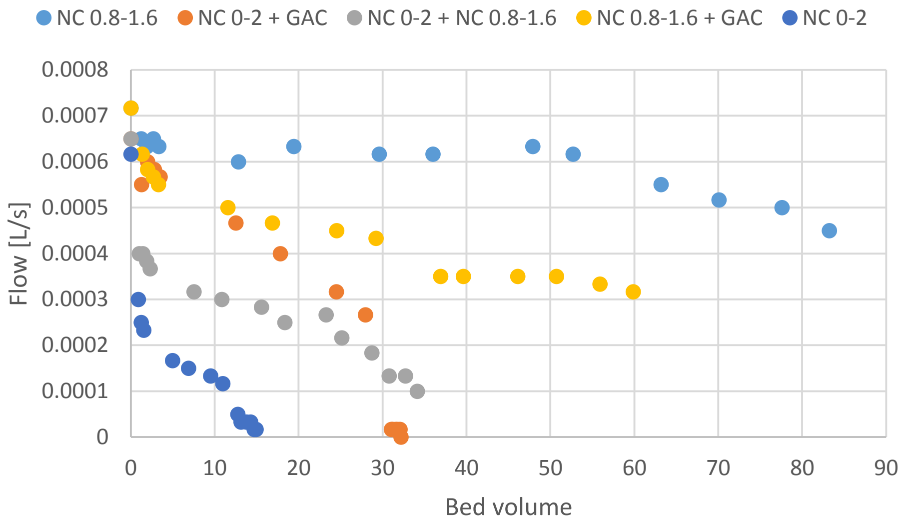

Figure 27: Test 4, column 1-5. Monitored outlet flow versus bed volumes

Figure 27 shows the flow measurement from Test 4, were high flow and high concentrations of de-icing chemicals were used. The figure shows that the course materials (NC 0.8-1.6 and NC 0.8-1.6 + GAC) only clogged partly during the test, while the fine and mixed material clogged at an early stage. During this test, the pump stopped over night after approximately 4000 min and the test had to be started again after the columns had been drained for several hours. By this time, Column 5 with NC 0-2 was already almost completely clogged. For NC 0-2 + GAC however, the new start-up of the test had a significant influence on the hydraulic performance of the filter. A very large decrease in flow rate of this filter can be seen in figure 27. This indicates that the filter most likely would have been operating longer without clogging completely if the pump had not stopped in the middle of the test.

Over all the results from the flow testing varied between the different tests. When the stormwater contained low concentrations of de-icing chemicals, the fine filter medium NC 0-2 and the mixed filter medium showed good hydraulic performance and had less problems with clogging than the coarse material NC 0.8-1.6. However, for high concentration of de-icing chemicals the opposite was observed. The coarse material had better hydraulic performance with less problems with clogging in the tests with high concentration of de-icing chemicals. Addition of an activated carbon layer gave better hydraulic performance for the low concentrations, but reduced performance for the high concentrations. The exception was NC 0.8-1.6 + GAC in Test 3.

Flow measurements were performed manually and this brings the possibility for human errors and inaccuracies. In Test 4 the pump stopped and drained the columns, which affected the results.

5.2 Hydraulic and Treatment Performance of Filters

5.2.1 Flow and Turbidity Tests

The development of turbidity in samples of the stormwater effluent from the columns and the flow is presented in this chapter. The trend shows that the turbidity increases in the first period of the test, and then it decreases as the contact time between the media and the pollutants is increased. This indicates that the performance of the filter media is dependent on contact time between the particles and the filter media. It is important to note that all the columns where filled with tap water at the start of the test. This means that there is a dilution of stormwater in the columns in the beginning of the tests. The reason why the turbidity increase the in the beginning, is because the filter needs time to function before the actual removal takes place. This phenomenon is called the ripening period. As the operation time of the filter increases, the flow decreases in all of the columns. Because the filter starts clogging as particles are retained, the development of the flow will follow the development of turbidity in the samples.

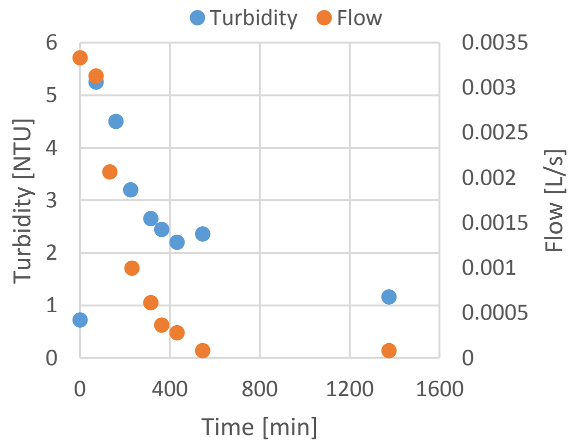

Figure 28: Test 1, NC 0.8-1.6. Turbidity and flow

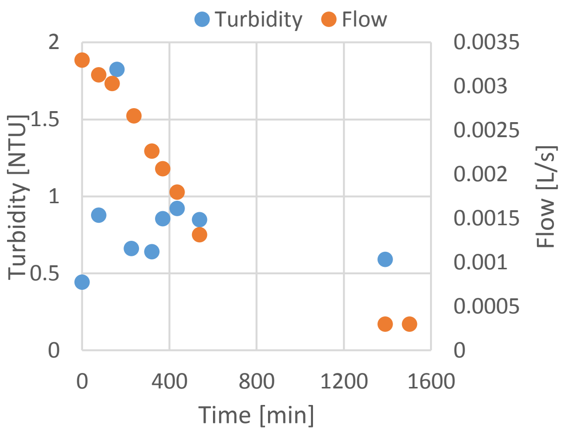

Figure 29: Test 1, NC 0-2 + GAC. Turbidity and flow

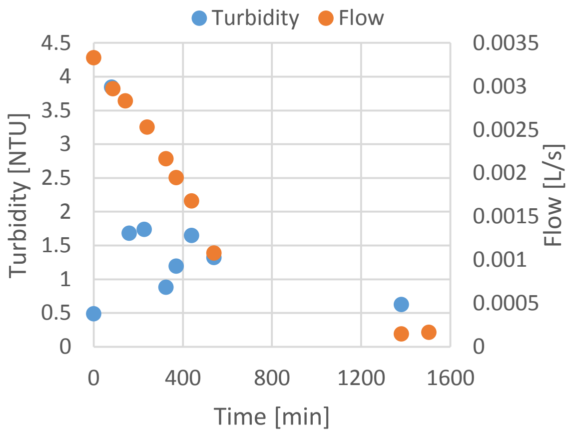

Figure 30: Test 1, NC 0-2 + NC 0.8-1.6. Turbidity and flow

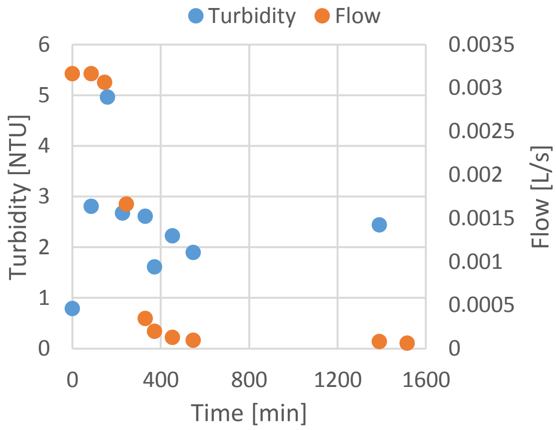

Figure 31: Test 1, NC 0.8-1.6 + GAC. Turbidity and flow

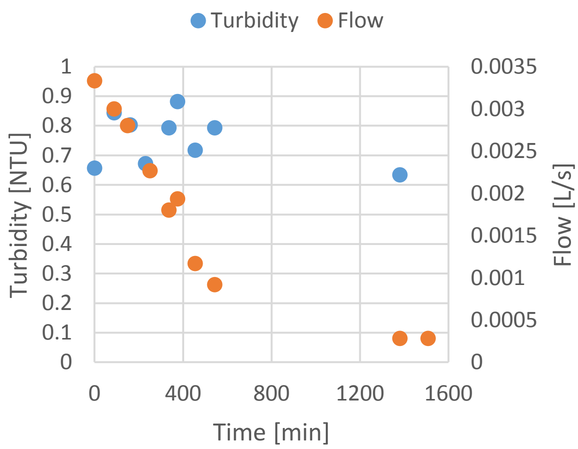

Figure 32: Test 1, NC 0-2. Turbidity and flow

Figure 28 – 32 show the results from the turbidity and flow measurements from the first laboratory test. The trend described in the introduction to this chapter fits for all columns, except for Column 5 with filter media NC 0-2. In all the other columns, the flow decreases with the same rate as the turbidity, and when the filter is clogged the development of the removal of turbidity is decreased. For Column 5, the removal of turbidity is more or less consistent throughout the entire test. Over all, the largest removal of turbidity is for Column 2 and 5 (the columns with filter media NC 0-2 + GAC and NC 0-2) consisting of the material with the finest grain sizes, NC 0-2. This indicates, as expected and described in 3.5.2, that fine filter media remove particles more rapidly than coarse filter media. Column 3 (with the mixed filter media of NC 0-2 and NC 0.8-1.6) shows better removal of turbidity than Column 1 and 4, consisting of the coarser material NC 0.8-1.6 and NC 0.8-1.6 + GAC.

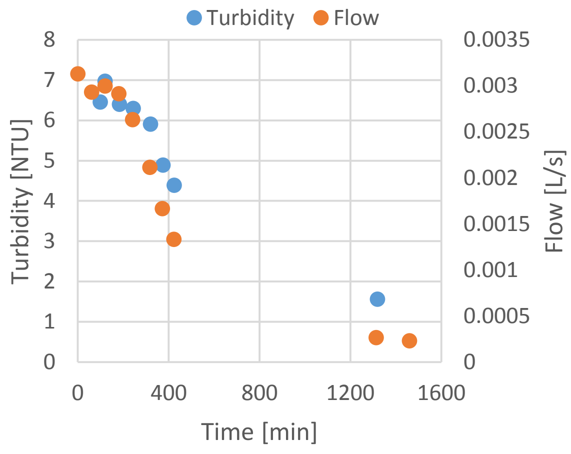

Figure 33: Test 2, NC 0.8-1.6. Turbidity and flow

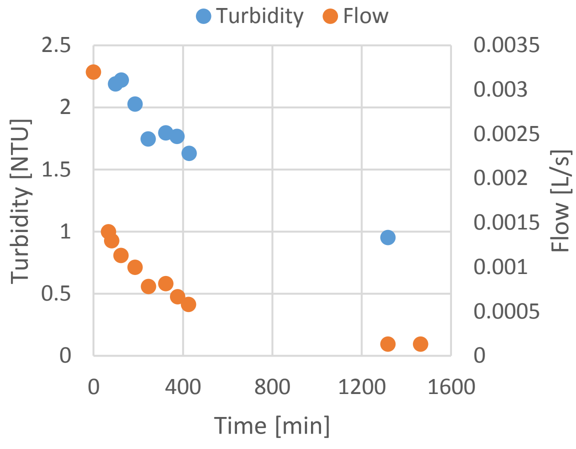

Figure 34: Test 2, NC 0-2 + GAC. Turbidity and flow

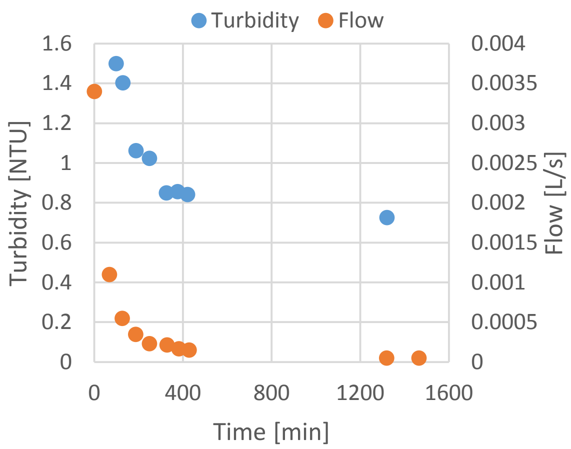

Figure 35: Test 2, NC 0-2 + NC 0.8-1.6. Turbidity and flow

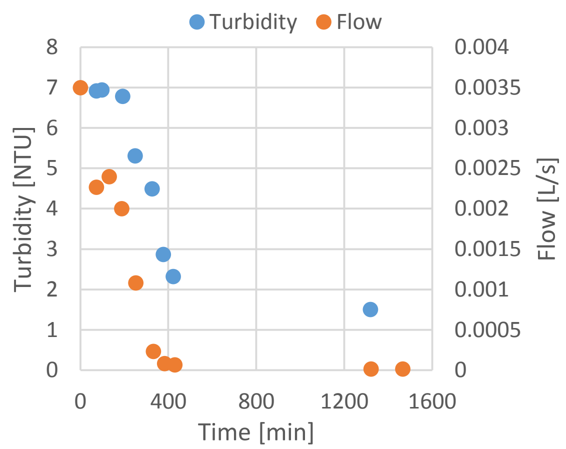

Figure 36: Test 2, NC 0.8-1.6 + GAC. Turbidity and flow

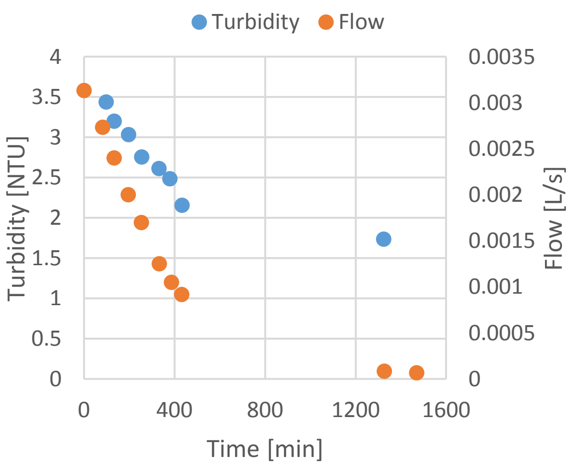

Figure 37: Test 2, NC 0-2. Turbidity and flow

Figure 33-37 show the turbidity and flow development for Column 1-5 for Test 2. The trend explained in the introduction of this chapter fits all five columns for this test. There was no increase in turbidity in the beginning of the test. One explanation of this is that the first measurement was conducted one hour after the start of the test. As the ripening period might be over, the turbidity value might have reached the maximum before the first measurement. The development of flow follows the removal rate of turbidity. Column 3 (the mixed filter medium consisting of NC 0-2 and NC 0-8-1.6) was the column with best turbidity removal and Column 2 (with NC 0-2 + GAC) showed the next best removal. These were the filters that clogged first. The values of turbidity in the samples from Test 2 were higher than for Test 1.

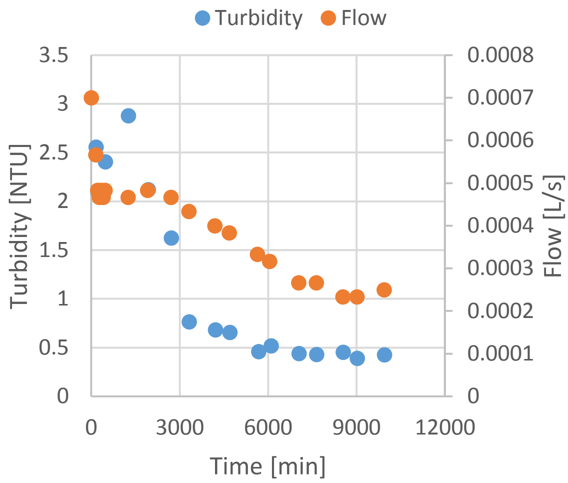

Figure 38: Test 3, NC 0.8-1.6. Turbidity and flow

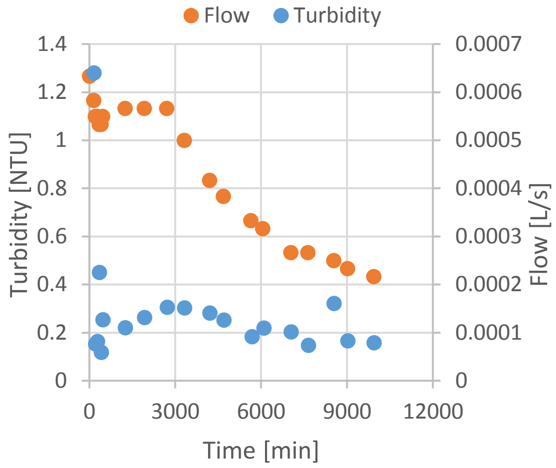

Figure 39: Test 3, NC 0-2 + GAC. Turbidity and flow

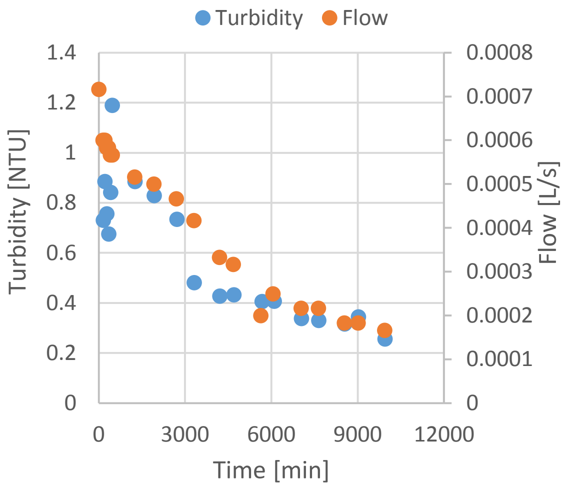

Figure 40: Test 3, NC 0-2 + NC 0.8-1.6. Turbidity and flow

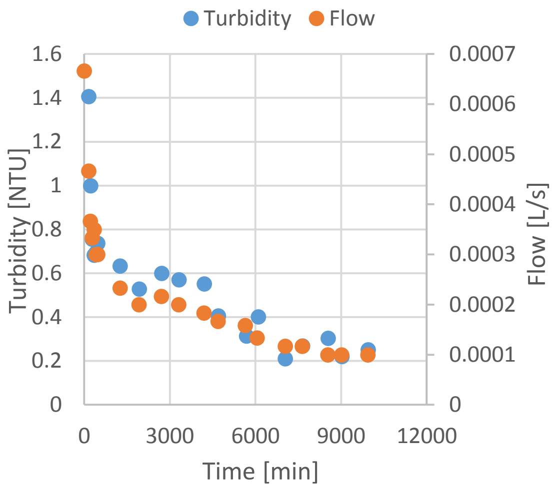

Figure 41: Test 3, NC 0.8-1.6 + GAC. Turbidity and flow

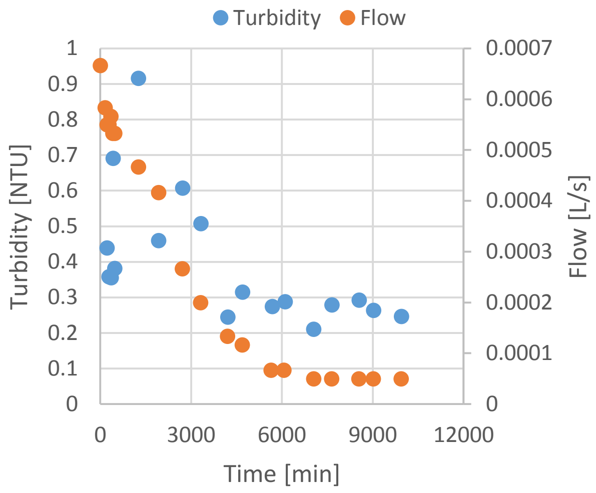

Figure 42: Test 3, NC 0-2. Turbidity and flow

Figure 38-42 show the development of turbidity and flow over time for Column 1-5 of Test 3. For this test, a lower flow rate was chosen. As a result, the turbidity removal in all columns was better. Another consequence of lower flow rate is that the flow reduction was lower, it took more time before clogging was observed in any of the filters. All columns, except Column 2, followed the trend expected for the development of turbidity and flow. Column 2 (consisting of NC 0-2+ GAC) had consistent, good removal of turbidity. This filter medium showed the best removal of turbidity in this test. Column 5 (consisting of NC 0-2) gave good removal, while Column 1 and 3 showed fair removal in the beginning and good removal as the filter clogged. This indicates that this filter clogs when a large amount of particles is retained.

The filters consisting of the finer material removed more particles than the coarse material before they clogged. The same indication was found in Test 1, where the same concentration of de-icing chemicals in the stormwater was used. For higher concentrations of de-icing chemicals, the fine filter media clogged at an earlier stage. One explaination of this can be that the fine filter media retained de-icing chemicals, and that this is what caused the clogging of the filter.

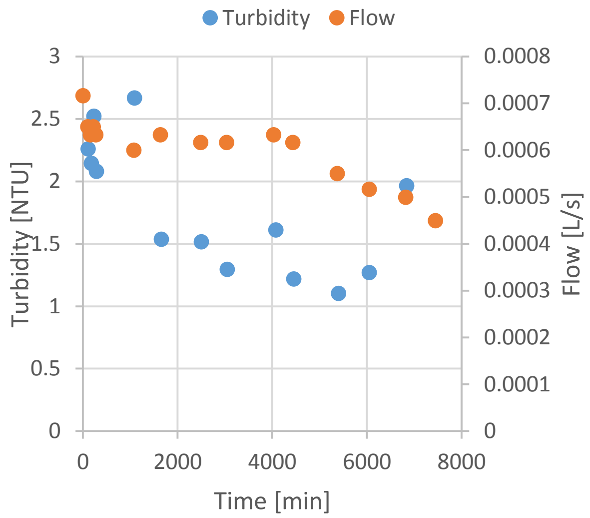

Figure 43: Test 4, NC 0.8-1.6. Turbidity and flow

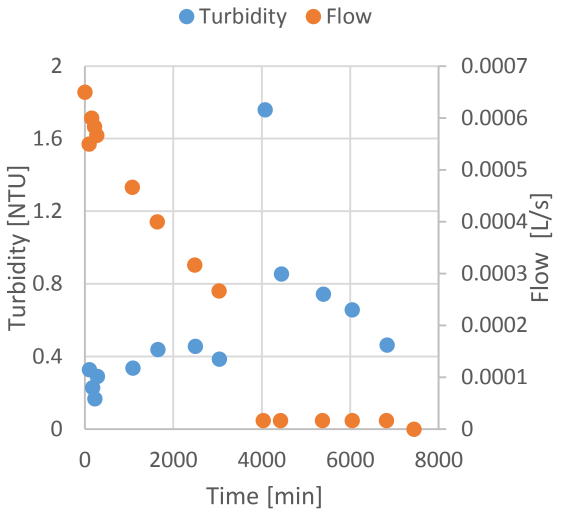

Figure 44: Test 4, NC 0-2 + GAC. Turbidity and flow

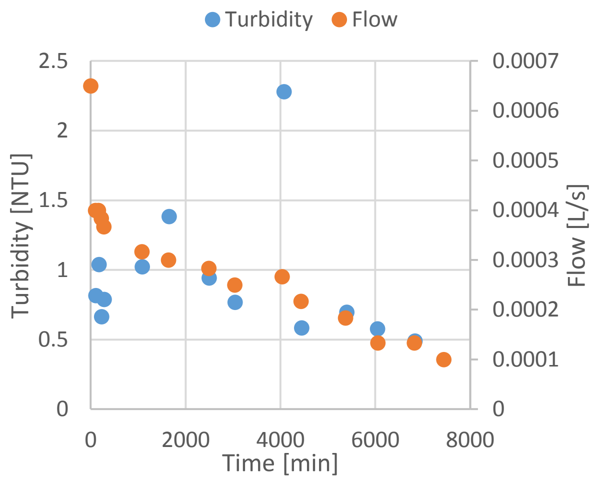

Figure 45: Test 4, NC 0.8-1.6 + NC 0-2. Turbidity and flow

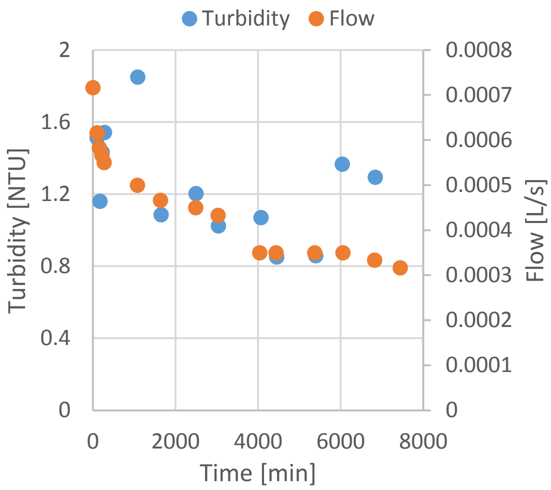

Figure 46: Test 4, NC 0.8-1.6 + GAC. Turbidity and flow

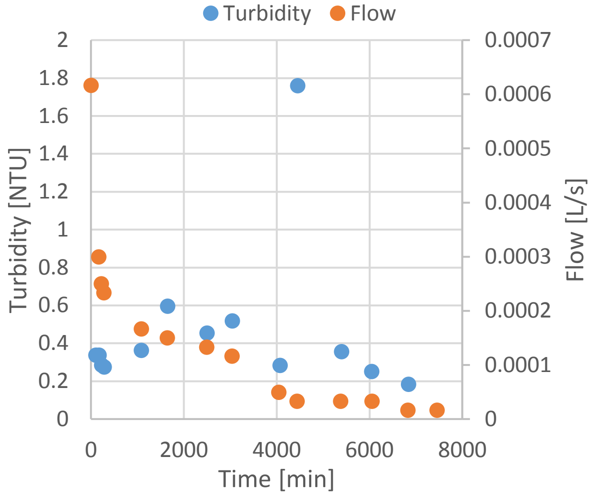

Figure 47: Test 4, NC 0-2. Turbidity and flow

Figure 43-47 show the turbidity removal and the flow development for all columns for Test 4. The turbidity increased significantly when the test was started again because the pump stopped. Column 2 (with filter media NC 0-2 + GAC) clogged immediately after the test was started up again. The results showed in figure 44 therefore differ from the trend that most of the other tests have shown. One possible reason why the impact of the new start-up of the test on NC 0-2 was larger than for NC 0.8-1.6, is that it easily develops air voids in the this media and the hydraulic performance is influenced by this. This is also in the previous tests and analysis shown to be a weakness with the material NC 0-2. In hydraulic conductivity tests the same problems with this material was observed, as the material needs shaking or backwashing in order to obtain good hydraulic performance.

For the filter medium with NC 0.8-1.6 the turbidity and flow graphs followed the trend until the last part of the test. For both NC 0.8-1.6 and NC 0.8-1.6 + GAC an increase in turbidity in the last part of the test was observed. This may indicate collapse of the filter. These filters were only partly clogged when the test ended. Of the filters in the Test 4, the filter medium NC 0.8-1.6 had the least problems with clogging. The filter medium NC 0-2 clogged before the pump started and was therefore not affected by the stop of the test. This filter, together with NC 0-2 + GAC before the stop of the test, showed the best removal of turbidity in Test 4. For the mixed media filter, partly clogging was observed shortly after the test started, but this filter was not entirely clogged when the test ended and there was a good removal of turbidity.

The turbidity measurements were performed manually and uncertainties connected to these measurements need to be taken into account. Sedimentation in the tank and tubes before the stormwater reached the columns may have affected the results. It is likely that a lower fraction of particles actually reached the filter than the amount of particles added to the tank.

5.3 Investigation of Clogging

5.3.1 Computation of Porosity and Modelling of Flow

Figure 48 and 49 show the procedure of modelling the flow from Column 1, NC 0.8-1.6, for Test 1. The porosity was computed based on the measured values for flow throughout the test in the laboratory. Linear regression was used to compute the slope and interception for the modelled porosity. As figure 48 shows, the porosity in the filter is not linear and the modelled porosity is therefore not accurate for the entire porosity change measured during the test. Because the most interesting part of the flow is at the point where the filter clogs, the linear approximation to the porosity curve is made to fit this part of the curve. As a result, the modelled flow fits the measured values in the part where the filter clogs, but differs from the measured values before and after the occurrence of clogging. The graphs showing the porosity change in the filter media and the linear approximation are given in Appendix B.

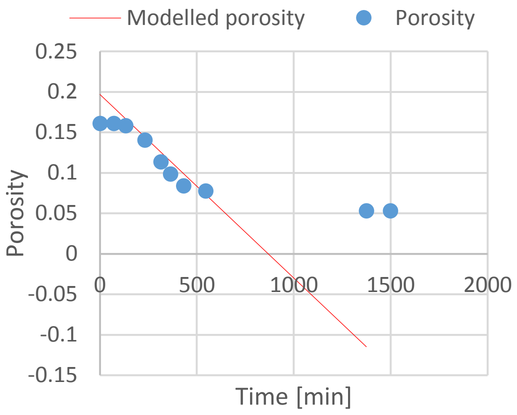

Figure 48: Computed porosity with modelled porosity

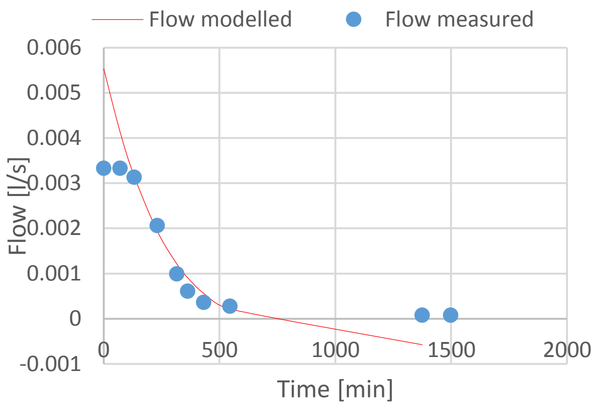

Figure 49: Flow measured with modelled flow

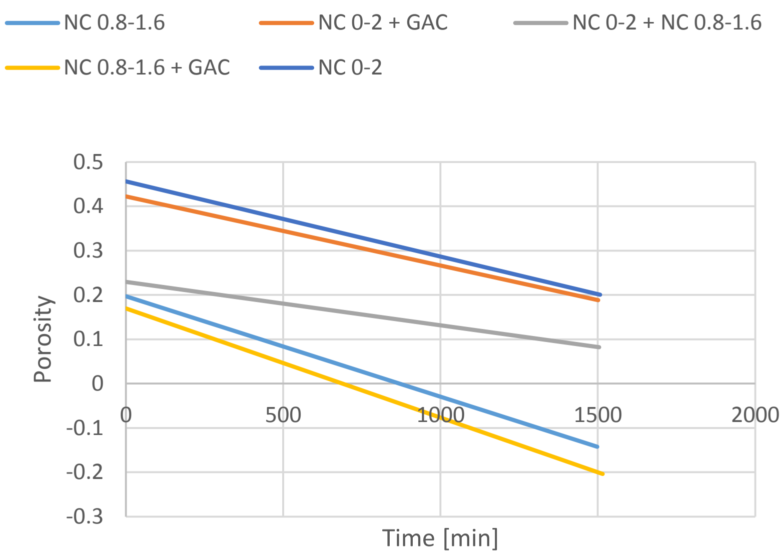

Figure 50: Test 1, Column 1-5. Linear approximation of porosity change

Figure 50 shows the plot of the porosity approximations for Column 1-5 for Test 1 made with the method described above.

Table 8: Linear approximated functions for porosity for Column 1-5 for Test 1-4

Column	**1**	**2**	**3**	**4**	**5**
Test					
1	$P = 0.146 - 1.83 \times 10^{-3}t$	$P = 0.422 - 1.56 \times 10^{-3}t$	$P = 0.229 - 9.78 \times 10^{-5}t$	$P = 0.169 - 2{,}46 \times 10^{-3}t$	$P = 0.146 - 1.70 \times 10^{-3}t$
2	$P = 0.161 - 1.49 \times 10^{-3}t$	$P = 0.392 - 2.71 \times 10^{-3}t$	$P = 0.209 - 1.98 \times 10^{-3}t$	$P = 0.160 - 2.32 \times 10^{-3}t$	$P = 0.413 - 2.16 \times 10^{-3}t$
3	$P = 0.093 - 2.01 \times 10^{-6}t$	$P = 0.133 - 8.53 \times 10^{-6}t$	$P = 0.133 - 4.96 \times 10^{-6}t$	$P = 0.094 - 7.45 \times 10^{-6}t$	$P = 0.294 - 2.15 \times 10^{-5}t$
4	$P = 0.096 - 9.12 \times 10^{-7}t$	$P = 0.268 - 3.04 \times 10^{-5}t$	$P = 0.132 - 7.15 \times 10^{-6}t$	$P = 0.095 - 3.92 \times 10^{-6}t$	$P = 0.287 - 2.36 \times 10^{-5}t$

Table 8 shows that the decrease in porosity is significantly lower for Test 1 and Test 2 (with high flow) than for Test 3 and Test 4 (with low flow). In addition, the decrease in porosity shows that the filter media that have the most rapid decrease in hydraulic performance are the media with the most rapidly decreasing porosity. Examples are Column 4 (NC 0.8-1.6 + GAC) in Test 1 and Column 5 (NC 0-2) in Test 4. That the slope of porosity decrease corresponds well with the measured flow decrease, increase the credibility of the linear approximation of the porosity and therefore the modelled flow.

The models of the flows for the filter media in Column 1-5 for all four tests are made with the same method and given in figure 51-70.

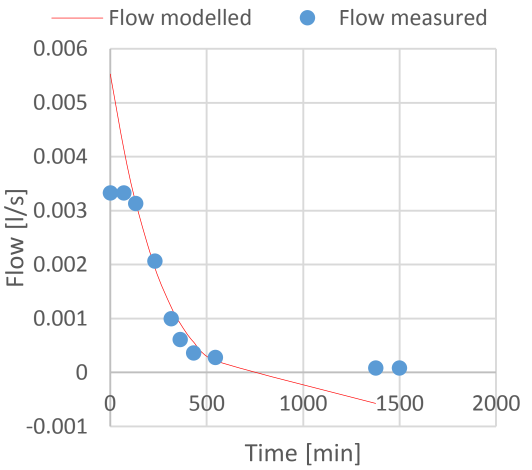

Figure 51: Test 1, NC 0.8-1.6. Model of flow

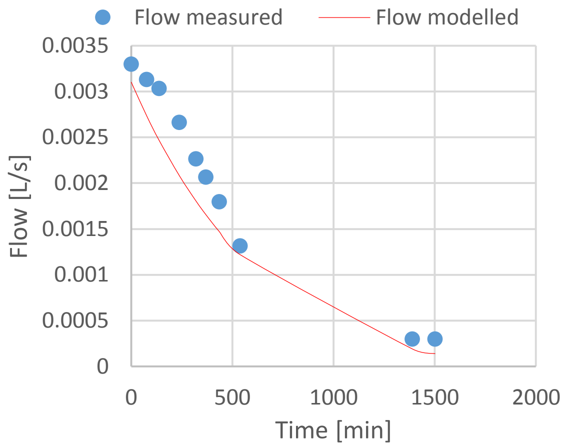

Figure 52: Test 1, NC 0-2 + GAC. Model of flow

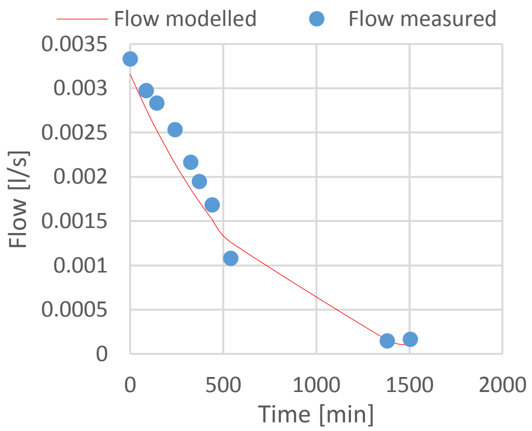

Figure 53: Test 1, NC 0-2 + NC 0.8-1.6. Model of flow

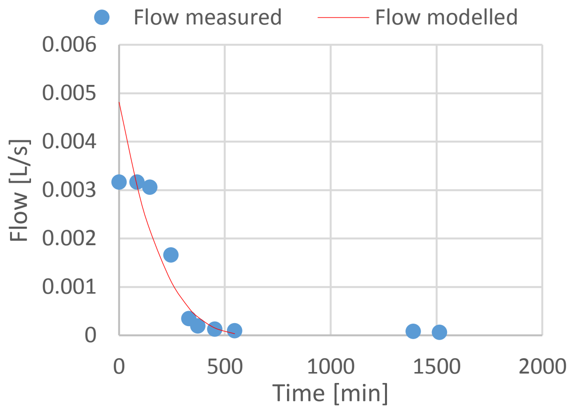

Figure 54: Test 1, NC 0.8-1.6 + GAC. Model of flow

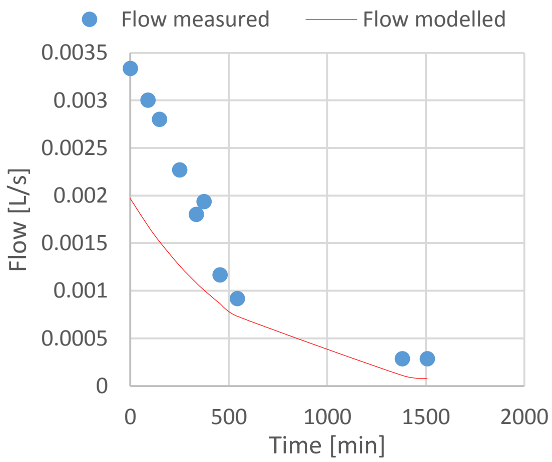

Figure 55: Test 1, NC 0-2. Model of flow

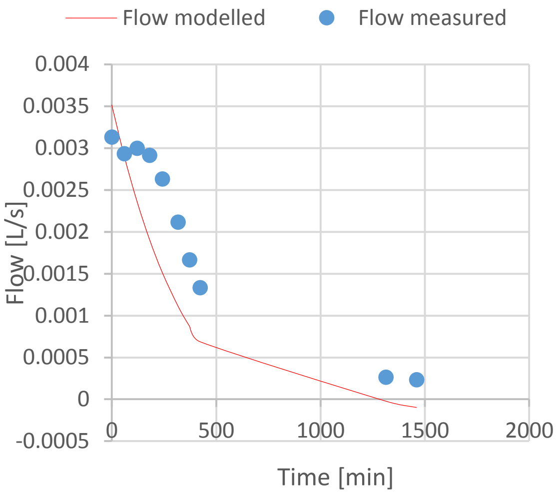

Figure 56: Test 2, NC 0.8-1.6. Model of flow

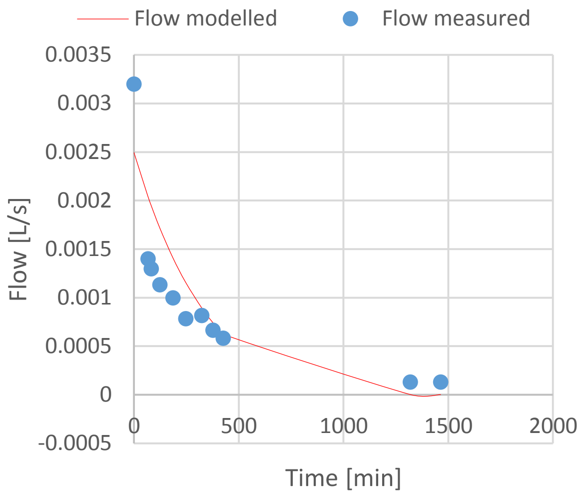

Figure 57: Test 2, NC 0-2 + GAC. Model of flow

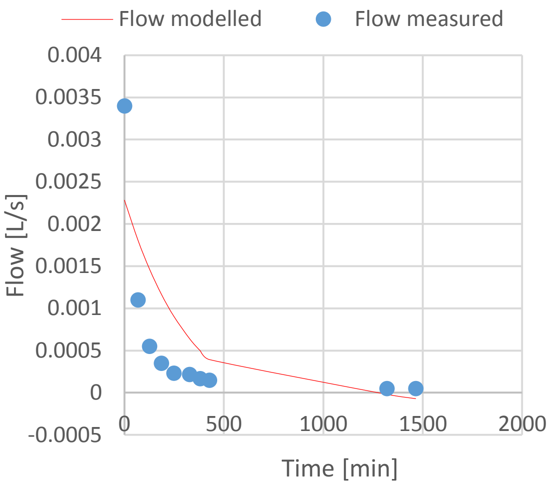

Figure 58: Test 2, NC 0-2 + NC 0.8-1.6. Model of flow

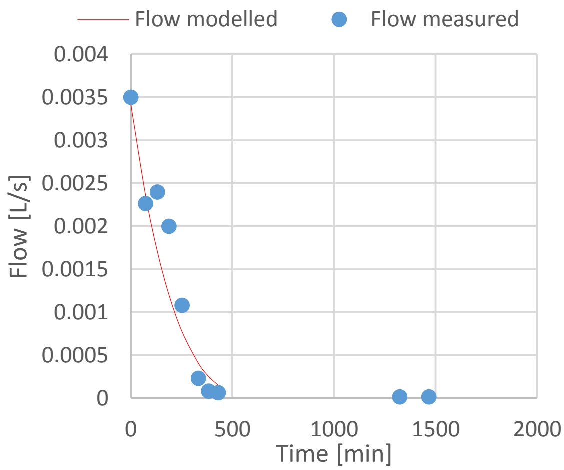

Figure 59: Test 2, NC 0.8-1.6 + GAC. Model of flow

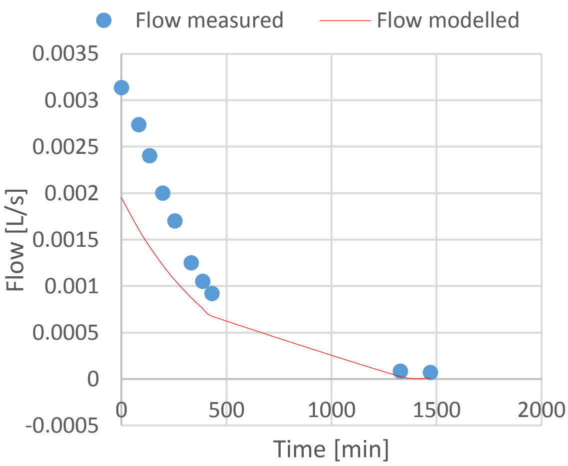

Figure 60: Test 2, NC 0-2. Model of flow

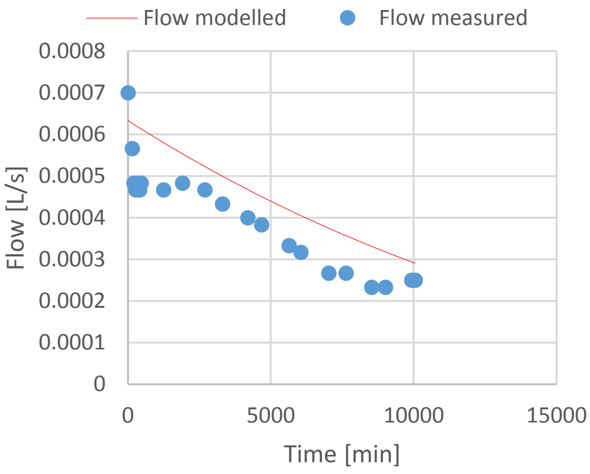

Figure 61: Test 3, NC 0.8-1.6. Model of flow

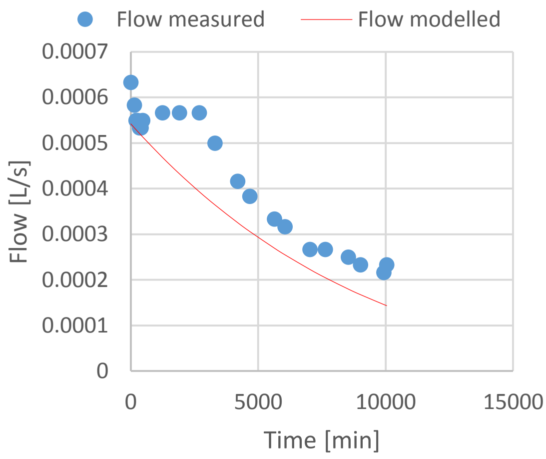

Figure 62: Test 3, NC 0-2 + GAC. Model of flow

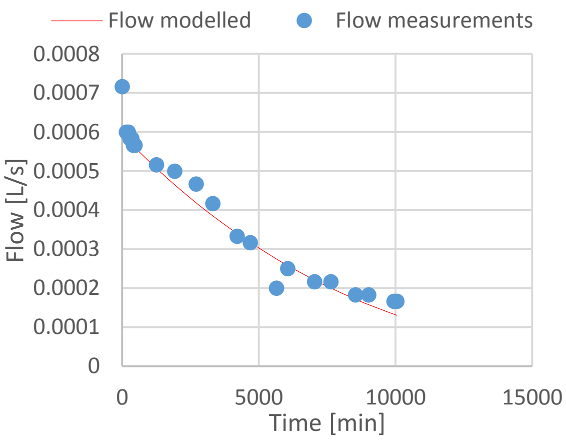

Figure 63: Test 3, NC 0-2 + NC 0.8-1.6. Model of flow

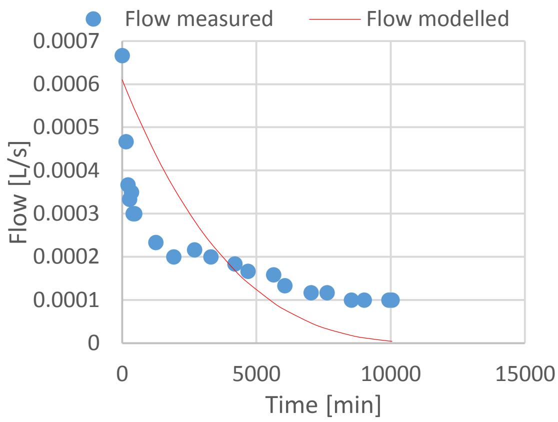

Figure 64: Test 3, NC 0.8-1.6 + GAC. Model of flow

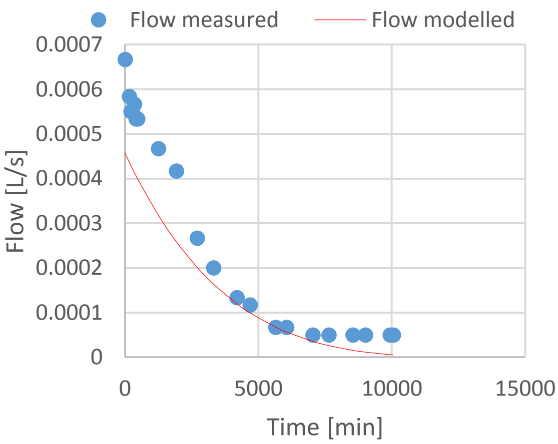

Figure 65: Test 3, NC 0-2. Model of flow

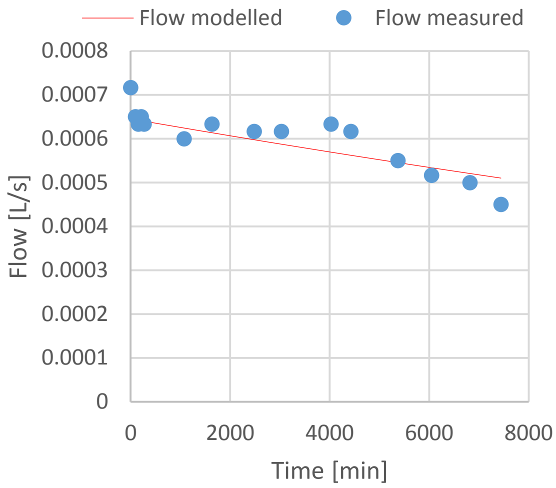

Figure 66: Test 4, NC 0.8-1.6. Model of flow

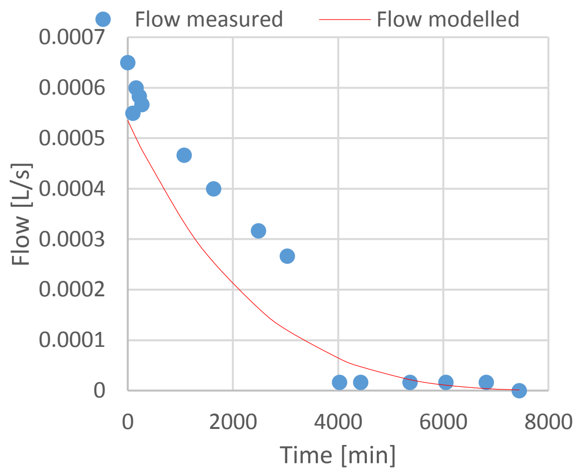

Figure 67: Test 4, NC 0-2 + GAC. Model of flow

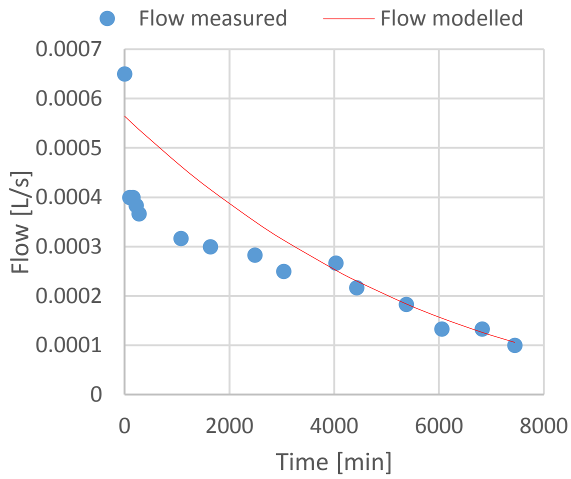

Figure 68: Test 4, NC 0-2 + NC 0.8-1.6. Model of flow

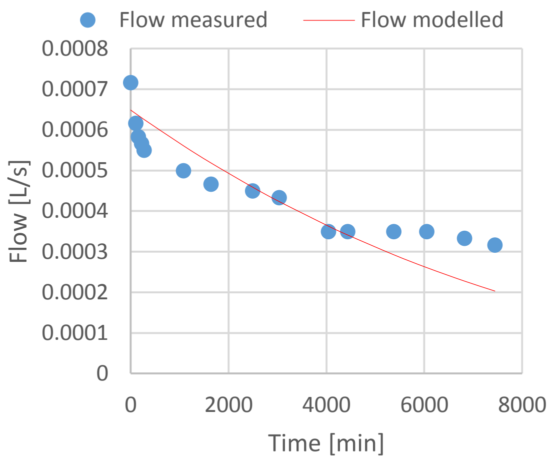

Figure 69: Test 4, NC 0.8-1.6 + GAC. Model of flow

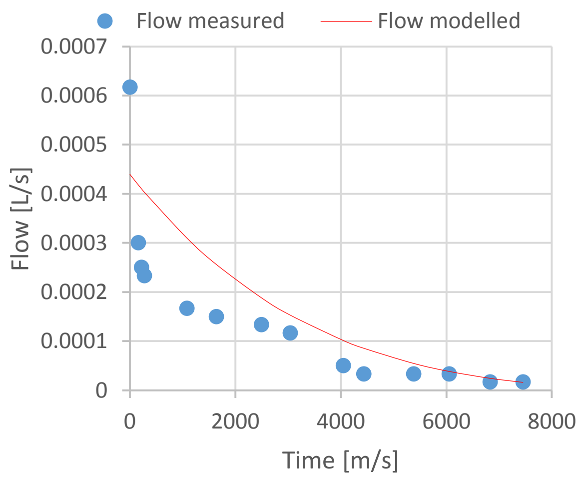

Figure 70: Test 4, NC 0-2. Model of flow

Assumptions made when modelling the flow, lead to uncertainties in the model. For many of the models, there was a clear discrepancy between the model and the measured values. This is due to approximations and assumptions made in the computation of porosity. The assumptions made are presented in 4.6.

5.3.2 Removal of Suspended Solids (SS)

By computing the amount of turbidity removed from the raw water and relating the total amount of turbidity removed to the relation between turbidity and SS, using figure 22, the amount of SS removed per liter stormwater through the filter was found. This number was multiplied with the volume raw water through the filter. Table 9-12 show the total amount removed per surface area and the removal efficiency of suspended solids in all tests for all filters tested. The surface area of the columns was 0.00785398 m^2. The removal efficiency was computed by equation 5.1.

$$Removal\ efficiency = \frac{SS_{total} - SS_{through\ filter}}{SS_{total}} \tag{5.1}$$

Table 9: Test 1, Column 1-5. Removal of suspended solids

Column	Filter media	SS removed [g]	SS removed/ Surface area [kg/m^2]	Removal efficiency [%]
1	NC 0.8-1.6	11.14	1.418	95.9
2	NC 0-2 + GAC	26.22	3.338	98.6
3	NC 0-2 + NC 0.8-1.6	22.97	2.925	97.7
4	NC 0.8-1.6 + GAC	11.34	1.444	95.9
5	NC 0-2	21.92	2.791	98.7

Table 9 shows that the removal efficiency of all filters was good in the Test 1. The fine filter media (NC 0-2 and NC 0-2 + GAC) had the best removal efficiency. It is important to note that a significant part of the removal may have been due to sedimentation in the tank before the stormwater reached the filter media.

Table 10: Test 2, Column 1-5. Removal of suspended solids

Column	Filter media	SS removed [g]	SS removed/ Surface area [kg/m^2]	Removal efficiency [%]
1	NC 0.8-1.6	22.17	2.823	93.8
2	NC 0-2 + GAC	10.31	1.313	97.6
3	NC 0-2 + NC 0.8-1.6	4.853	0.6179	98.6
4	NC 0.8-1.6 + GAC	8.515	1.084	95.4
5	NC 0-2	16.48	2.098	96.4

Table 10 shows that the removal efficiency in Test 2 was best in the mixed media filter. In this test, all filters obtained a good removal efficiency.

Table 11: Test 3, Column 1-5. Removal of suspended solids

Column	Filter media	SS removed [g]	SS removed/ Surface area [kg/m^2]	Removal efficiency [%]
1	NC 0.8-1.6	47.80	6.086	98.2
2	NC 0-2 + GAC	51.94	6.613	99.6
3	NC 0-2 + NC 0.8-1.6	45.60	5.551	99.1
4	NC 0.8-1.6 + GAC	22.94	2.921	99.2
5	NC 0-2	24.97	3179	99.3

In Test 3, the removal efficiency was best for NC 0-2 + GAC. As for the previous tests, the removal efficiency was good for all filter media.

Table 12: Test 4, Column 1-5. Removal of suspended solids.

Column	Filter media	SS removed [g]	SS removed/ Surface area [kg/m^2]	Removal efficiency [%]
1	NC 0.8-1.6	57.50	7.321	97.5
2	NC 0-2 + GAC	21.12	2.689	99.0
3	NC 0-2 + NC 0.8-1.6	24.51	3.120	98.4
4	NC 0.8-1.6 + GAC	40.66	5.177	98.1
5	NC 0-2	9.833	1.252	99.2

Table 12 shows the removal of suspended solids in Test 4. Filter medium NC 0.8-1.6 gave the largest amount of suspended solids removed before clogging, while NC 0-2 had the best removal efficiency. However, NC 0-2 clogged at an early stage and therefore removed significantly less suspended solids before clogging than the rest of the filters.

In section 3.7 the amount of suspended solids removed before clogging in a typical filter for stormwater treatment was set to 1.2-5 kg/m^2 per filter medium surface area. Table 9-12 show that all filters, except NC 0.8-1.6 + GAC and NC 0-2 + NC 0.8-1.6 in Test 2 have removed an amount of suspended solids in this range or more.

After the tests were finished, it was observed that the fine media were dirtier than the coarse media. This indicates that a higher fraction of suspended solids was collected in the fine media, and that sieving was a more dominating mechanism for the fine media than for the coarse media. However, the fine material contained a fraction of particles with smaller grain sizes than 0.125 mm and this may be one reason why the fine media looked dirtier than the coarse media. It was certain that clogging occurred in the top layer for the fine material and throughout the whole medium for the coarse material.

Uncertainties due to tubidity and flow measurements and calculation and approximations of the removal efficiency and amount of SS removed per surface area are important for the results from these calculations. In addition,there are uncertainties with the approximation made for the relation between SS and turbidity.

5.3.3 Removal of Dissolved Organic Carbon (DOC)

The results from the DOC analysis are presented in figure 71 to 74. By analysing the DOC removal of the filters, the adsorption and biodegradation of de-icing chemicals can be investigated.

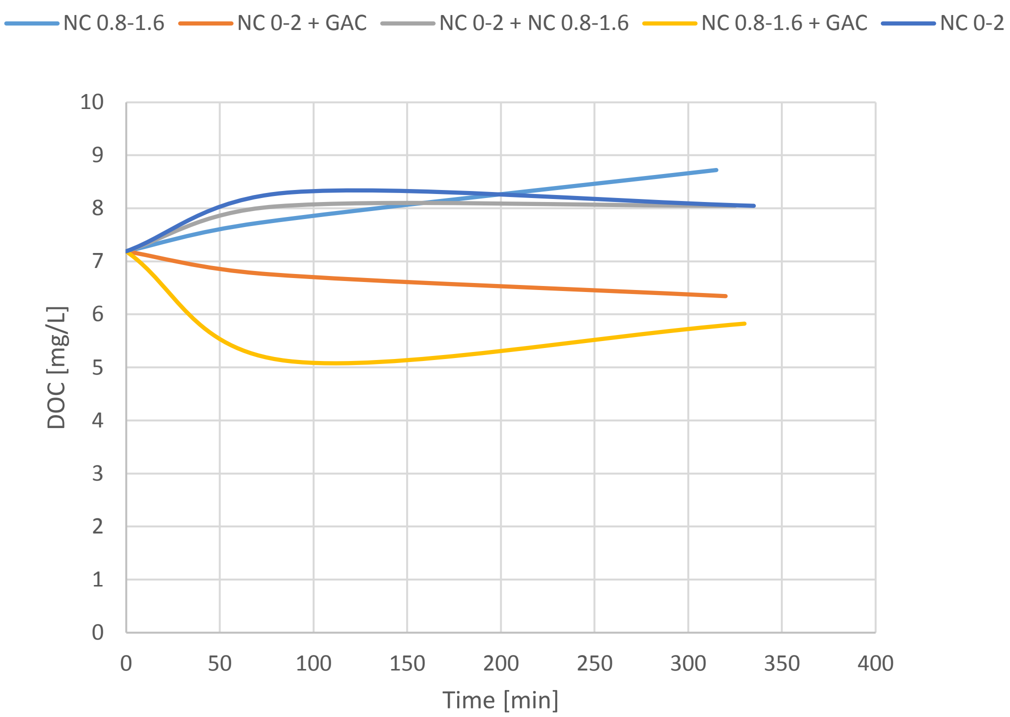

Figure 71: Test 1. DOC for Column 1-5

Figure 71 shows the DOC removal for all columns for Test 1. Column 2 and 4, the filter media with activated carbon layer, had a small removal of DOC the first 100 minutes of the test. After approximately 100 min, the removal in Column 4, NC 0.8-1.6 + GAC, was reduced. This indicates that the activated carbon layer was saturated and therefore collapsed, which means that the adsorption in the layer was reduced. For the three filters without activated carbon layer, there was no removal. This indicates no adsorption in the Filtralite material, only in the activated carbon, and no biodegradation. Test 1 only lasted one day and was then stopped due to clogging. Most likely, the reason why there was no biodegradation in the filters, was because the tests were stopped before biomass had started growing in the filters.

The DOC value for the raw water was low and figure 71 shows an increase in DOC compared with the raw water. The DOC value for the raw water is most likely higher than the measured value. Biodegradation of de-icing chemicals in the bottles after sampling and before analysis may be an explanation, because the samples were kept in plastic bottles before they were filtered and acidified before analysis. The same effect was observed in the column study conducted by Bielefeldt, Illangasekare et al. (2002), described in chapter 3.4.2 (Bielefeldt et al., 2002).

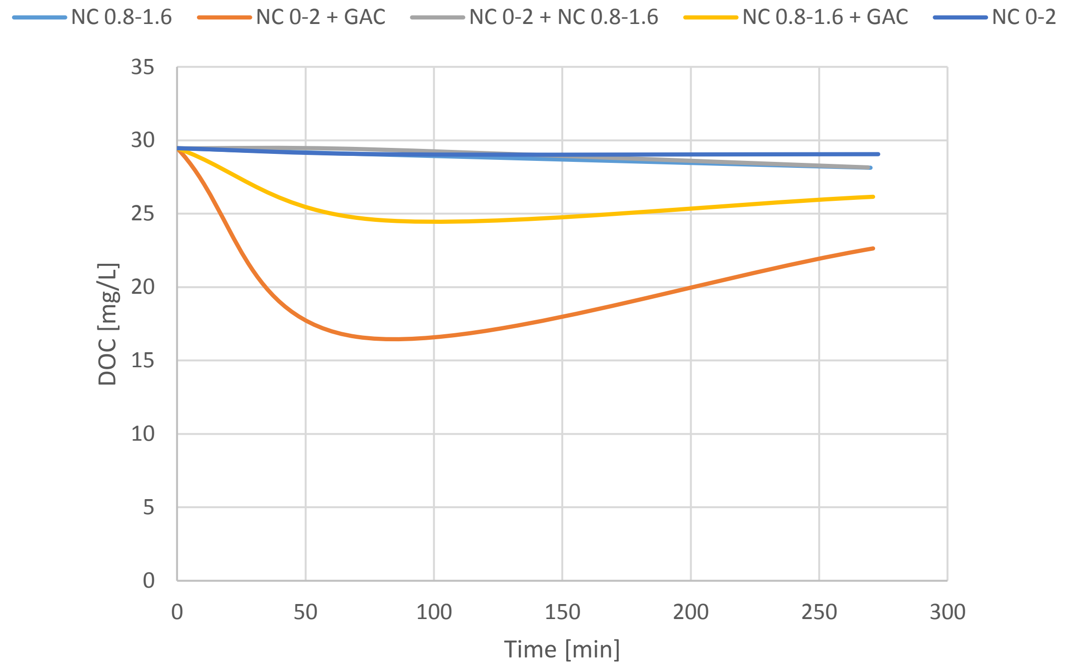

Figure 72: Test 2. DOC for Column 1-5

Figure 72 shows the DOC removal for all columns in Test 2. The results for this test are similar to the results for the Test 1, with lower concentration of de-icing chemicals and the same flow. There was a larger removal of de-icing chemicals for the filters with activated carbon layer. Due to saturation of activated carbon layer, there was a decrease of DOC removal in Test 2 after approximately 100 min, as for Test1. As for Test 1, there was no removal of DOC in the three filters without activated carbon layer. This indicates that there was no adsorption or biodegradation in this test either. Because the same flow was used, the duration of Test 1 and 2 was approximately the same.

After Test 2 was finished, the filter medium was left in the columns for two weeks, as the next test was prepared. When the filter media was emptied after two weeks, biomass was observed in Column 1 with NC 0.8-1.6. This indicates that biodegradation of pollutants is possible if the filter can be in operation for a sufficient amount of time so that biomass can grow.

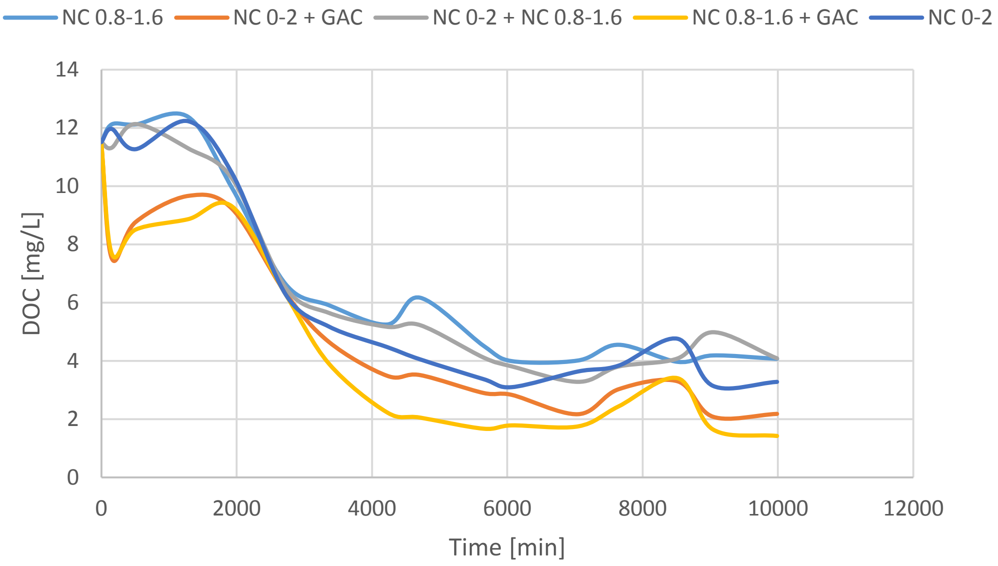

Figure 73: Test 3. DOC for Csolumn 1-5

Test 3 lasted for seven days, had low concentration of de-icing chemicals and had a much lower flow than Test 1 and Test 2. Figure 73 shows the DOC removal of Test 3 for all filters. In the first 2000 min, which equals between 1 and 2 days, the same trend as for the first two tests was observed. For the two filters with activated carbon layer there was first a decrease in DOC due to adsorption, then the DOC value increased as the activated carbon layer saturated. For the three columns without an activated carbon layer, there was no removal of DOC the first approximately 2000 minutes. Then, there was a high removal rate of DOC until the removal stabilized at a constant rate for all filters. This indicates that there was growth of biomass and that biodegradation of the de-icing chemicals occurred.

The DOC value measured for the raw water was sampled from the tank during the test. Due to biodegradation in the tank, the value was significantly smaller than what would be expected. Therefore, a new DOC value for the raw water was computed by extrapolating the curves and finding a fitting, more realistic value. This value is plotted in figure 73 as the raw water value.

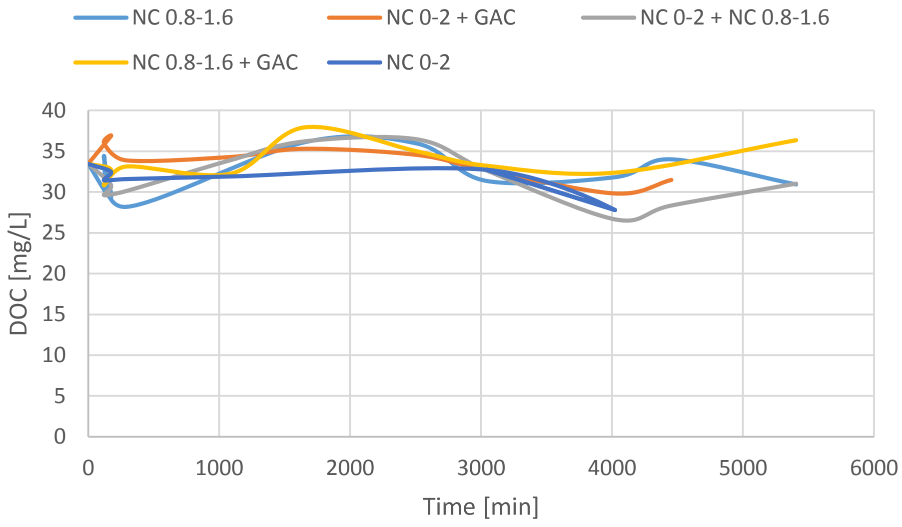

Figure 74: Test 4. DOC for Column 1-5

Figure 74 shows the DOC measured for all columns in Test 4. The results show that there was almost no removal of DOC in the test. For all columns the values were more or less the same in the entire test. There was a decrease in DOC for all filters after approximately 2000 minutes. However, after the test had to be restarted after approximately 4000 minutes, the DOC increased for all filters. This indicates that biomass started to grow and biodegradation of de-icing chemicals started, but because the test had to start up again, the biodegradation stopped. In the study conducted by Bielefeldt, Illangasekare et al. (2002), presented in chapter 3.4.2, the effect of intermittent loading was investigated and it was found that biodegradation of propylene glycol was rapid after periods with no exposure (Bielefeldt et al., 2002). However, the conditions around the stop of the pump were not ideal and can not be compared to the observed results of the study. However, even before the pump had stopped the removal of DOC was significantly lower than for Test 3. One explanation can be that the high concentration of de-icing chemicals created conditions too toxic for the biomass to grow.

In the filters with activated carbon layer, a reduction in the starting period of the test similar to the one observed in Test 1, 2 and 3 would be expected. However, this was not observed. Instead, the filters with activated carbon had the same removal as the filters without activated carbon. Inaccuracies can be one explanation to the difference between these tests. In addition, the raw value of de-icing chemicals is the highest in this test, which can make it more difficult to see the decrease in DOC than for the first tests.

Uncertainties due to manually measurements of DOC need to be taken into account. Because the DOC samples were diluted before analysis, the uncertainties regarding the analysing of the samples increases. The samples from Test 1 was diluted five times, while Test 2 was diluted ten times. For Test 3, there were originally no dilution, but due to high values, all values larger than 10 mg/L was diluted two times. The samples in Test 4 was diluted ten times. The uncertainty increase with the amount of times diluted. In addition, uncertainties due to lower values because of biodegradation in tank, samples and tubes appear. It is likely that biodegradation occurred in the tank, tubes and bottles, which may have given lower values of DOC in the samples. This was especially a problem for the raw water samples.

5.3.4 Removal of Heavy Metals

The results from the heavy metal analysis for Test 1-4 for Column 1-5 are given in Appendix E. Table 13-16 show the removal efficiency for the heavy metals analysed, computed by equation 5.2. The results show that the removal efficiency for the different heavy metals varied. In general, the filter media with the fine material (NC 0-2 and NC 0-2 + GAC) showed the best removal, which corresponds to the results from the analysis of the removal of suspended solids. The removal of mercury was not calculated, as the concentration of mercury in the stormwater in the tank was measured as <0.001 µg/L for Test 1-4.

$$Removal\ efficiency = \frac{C_{in} - C_{out}}{C_{in}} \tag{5.2}$$

Table 13: Heavy metal removal in Column 1-5, Test 1

Heavy Metal	**Removal efficiency [%]**					
	Column	**1**	**2**	**3**	**4**	**5**
	Filter media	**NC 0.8-1.6**	**NC 0-2 + GAC**	**NC 0-2 + NC 0.8-1.6**	**NC 0.8-1.6 + GAC**	**NC 0-2**
Arsenic (As)		0	0	0		0
Lead (Pb)		98.6	99.9	98.9		99.1
Cadmium (Cd)		89.8	93.8	95.4		93.3
Copper (Cu)		60	94.7	68.6		80
Chromium (Cr)		76	86.2	78		80
Mercury (Hg)		-	-	-		-
Nickel (Ni)		22	93.6	83.3		91
Zinc (Zn)		89	88.6	94.7		98.2

The values for removal of heavy metals for Column 4 in Test 1 was missing in the analysis from Eurofins, in Appendix E, and is therefore not part of the results presented in table 13.

Table 14: Heavy metal removal for Column 1-5. Test 2

Heavy Metal	**Removal efficiency [%]**					
	Column	**1**	**2**	**3**	**4**	**5**
	Filter media	**NC 0.8-1.6**	**NC 0-2 + GAC**	**NC 0-2 + NC 0.8-1.6**	**NC 0.8-1.6 + GAC**	**NC 0-2**
Arsenic (As)		0	0	0	0	0
Lead (Pb)		72.6	94.1	96.4	67.1	80.8
Cadmium (Cd)		66.2	94.6	93.9	85.1	85.1
Copper (Cu)		58.3	86.7	74.4	73.9	77.8
Chromium (Cr)		11.8	70.6	11.8	23.5	17.6
Mercury (Hg)		-	-	-	-	-
Nickel (Ni)		8.2	95.1	84.9	26.2	75.4
Zinc (Zn)		64	93	96.4	79	88.5

Table 15: Heavy metal removal for Column 1-5. Test 3

Heavy Metal	**Removal efficiency [%]**					
	Column	**1**	**2**	**3**	**4**	**5**
	Filter media	**NC 0.8-1.6**	**NC 0-2 + GAC**	**NC 0-2 + NC 0.8-1.6**	**NC 0.8-1.6 + GAC**	**NC 0-2**
Arsenic (As)		0	0	0	0	0
Lead (Pb)		99.1	99.7	98.7	99.3	99.7
Cadmium (Cd)		92.1	93.0	91.4	93.0	93.0
Copper (Cu)		82.6	87.7	89.7	93.7	92.6
Chromium (Cr)		82.8	85	82.8	74.1	79.3
Mercury (Hg)						
Nickel (Ni)		0	82	35	63	67
Zinc (Zn)		92.9	98.4	64.3	87.1	99.0

Table 16: Heavy metal removal for Column 1-5. Test 4

Heavy Metal	**Removal efficiency [%]**					
	Column	**1**	**2**	**3**	**4**	**5**
	Filter media	**NC 0.8-1.6**	**NC 0-2 + GAC**	**NC 0-2 + NC 0.8-1.6**	**NC 0.8-1.6 + GAC**	**NC 0-2**
Arsenic (As)		0	0	0	0	0
Lead (Pb)		87.1	95.1	92.4	78.9	94.9
Cadmium (Cd)		47.1	76.5	76.5	64.1	76.5
Copper (Cu)		22.7	87.3	71.8	63.6	70
Chromium (Cr)		14.3	14.3	21.4	44.3	0
Mercury (Hg)		-	-	-	-	-
Nickel (Ni)		0	56.7	18.3	62.5	64.2
Zinc (Zn)		0	0	70.9	54.7	76.7

The results were analysed by Eurofins and uncertainties with the analysis occur. The uncertainy due to the analysis are given in Appendix E.

5.4 Validation of Results

Due to uncertainties in the results among other reasons, discussed in chapter 5, because of manually performed tests and plotting, the results obtained are validated. To validate the results, the results of Test 4 were compared with the results of a study by Hanna Haug Lindseth, master student at the department of Hydraulic and Environmental Engineering at NTNU, who performed a test with the same column and filter set-up and the same properties of the synthetical stormwater as in Test 4. The results of this test are given in Appendix C.

The results of the flow measurements of Hanna Haug Lindseth show similar trends as the results of Test 4 in this study. While the filter media with the fine material, NC 0-2 and NC 0-2 + GAC, clogged quite rapidly, the coarse material filter media and mixed media, NC 0.8-1.6, NC 0.8-1.6 + GAC and NC 0-2 + NC 0.8-1.6, obtained a higher flow after the test was stopped. However, it is important to note that also for this test the pump stopped during the test. This affected especially NC 0-2 + GAC, which clogged after the test started up again. The same observation was seen in Test 4 in this study.

The turbidity measurements from the validation study differed from the results of Test 4 in this study for the coarse material. As for Test 4, the fine filter media gave the best removal of turbidity and followed the trend seen in the other tests. The turbidity removal of NC 0-2 + GAC was reduced when the pump stopped and the same was seen in Test 4. However, the most significant difference of the two studies was that all filters in the validation study had an increase of turbidity in the last part of the test. A brown layer was observed coming from the tubes out of the columns after the test was stopped. This was not seen in Test 4 of this study, and explains why the turbidity values are higher at the end of the experiment for this test.

In general, the results from the tests by Hanna Haug Lindseth showed the same results as the results from Test 4 conducted in this study. There were some differences, but they are explained by conditions affecting the results that were not present in this study. This increase the accuracy of the results obtained in this study.

6 Discussion

In this chapter the results from chapter 5 are further discussed.

6.1 Investigation of Reduction in Hydraulic Performance of the Filters Tested

The hydraulic performance of filters was investigated in this study. In this chapter the causes of clogging are discussed, as well as the variations of hydraulic performance caused by different conditions of the tests. In addition, the modelling of the flow performed and the physical properties of clogging are discussed.

6.1.1 Dominant Processes in Filters

The processes that are causing reduced hydraulic performance of the filters were tested in this study. The results showed that the most important processes for the material Filtralite by Weber Saint-Gobain were size exclusion and biodegradation.

Size exclusion was explained in chapter 3.2.1 and is the physical retention of particles by the filter media. The results from the tests in this study showed that a large amount of particles were retained by the filter, which indicates that size exclusion was a dominant process in these filters. Adsorption, on the other hand, was only observed for the GAC, and in Test 4 (with high concentration of de-icing chemicals and low flow) almost no adsorption of GAC was observed. Toxicity because of high concentrations of de-icing chemicals was mentioned as a possible explanation for this observation.

Biodegradation, described in 3.2.2, was the dominant process for removal of the de-icing chemicals for the filters in this study. In addition, GAC adsorbed some de-icing chemicals. Biodegradation of de-icing chemicals was only significant in Test 3, because there was not enough time for growth of biomass in Test 1 and Test 2 and because of toxicity in Test 4. Removal of de-icing chemicals by using these filters is therefore most efficient when both biodegradation and adsorption occur.

6.1.2 Conditions Affecting the Hydraulic Performance of Filters

The results show that external, internal and operational conditions described in chapter 3.4 affect the hydraulic performance of filters. It was observed that the different materials behaved differently when it comes to clogging with varying composition of the stormwater. Comparison of the hydraulic behaviour of the materials is further discussed in 6.3. In general, high concentrations of de-icing chemicals made the filter media clog at an earlier stage than low concentrations. In addition, high concentrations prevented biodegradation because of toxicity, causing reduced removal efficiency of de-icing chemicals.

Internal factors like physical properties, such as compaction and the presence of air within the media, showed to have a large impact on the hydraulic performance of the filters. As for the stormwater composition, the grade of impact on the performance varied between the different materials. Only the fine filter media had problems with compaction, but reduced hydraulic performance due to air within the media was observed in all filter media tested. The different behaviour of NC 0-2 and NC 0.8-1.6 showed that the grain size distribution of the materials used in the media had an effect on the hydraulic performance of the filters.

Different operational conditions had an impact on the filters. Operational time influenced the hydraulic performance by increased clogging with time. The treatment of both turbidity and suspended solids and de-icing chemicals was affected by operational time, because increased contact time increase removal and starts biodegradation. No effect on clogging caused by the presence of biomass in the filter media was observed, neither increased clogging nor decreased clogging due to removal of particles within the filter by biomass. However, most likely longer operation time will reveal more observations of the biodegradation and presence of biomass in the filter media.

The treatment performance influenced the hydraulic performance in that increased removal of turbidity and DOC gave development of clogging in the filter. This can clearly be seen from the turbidity and flow graphs.

6.1.3 Modelling of Flow through Filters

The modelling of the flow showed the change of porosity in the filters as clogging occurred and this gave a physical understanding of the clogging development. By comparing the change in porosity for the different filter media, the properties of the filter media can be compared. The change in porosity showed mostly the same results as the flow measurements, which proves that the porosity decreases as the filter clogs. There were some exceptions, which can be explained as inaccuracies with the approximation made.

When making the model, a linear approximation of the porosity change was made even if the porosity change not always is linear. As a result, there is a discrepancy between the model and the measured value. No statistical test was performed in order to evaluate the accuracy of the model.

6.2 Design Recommendations for the Filters Tested

In chapter 4.3.3, the flow used in the tests was described. As mentioned in this chapter both flows represent a flow with longer return period than 200 years, meaning that the flows the filters were tested for in the experiments of this study were higher than the largest part of the flows the filters will actually be operated in in reality. The stormwater contained a high concentration of suspended solids and therefore, the fact that the filters clogged after one day for the highest flow and five to seven days for the lower flow is acceptable.

The amount of suspended solids typically removed before clogging develops was set to 1.2-5 kg/m^2 in chapter 3.7. The results showed that all filters in all tests, with the exception of NC 0.8-1.6 + GAC in Test 2 with high flow and high concentrations of de-icing chemicals, removed more than 1.2 kg/m^2 suspended solids in the operational time of the experiments. This indicates that the amount of suspended solids the filters are able to remove before they need maintenance is acceptable (WEF, 2012). Whereas the fine filter media clogged mainly on the top layer, clogging occurred throughout the whole filter medium for the coarse media. For the fine media filters, scraping of the top layer is therefore recommended every time the hydraulic performance is reduced significantly due to clogging and replacement of the whole filter after 5-10 scrapings. Replacement of the whole filter is recommended for the coarse media filter and the mixed media filter every time the hydraulic performance is reduced significantly due to clogging, because scraping of the top layer will not be enough when the whole filter is clogged. Maintenance will therefore be easier for fine media filters than for the coarse media filters, and the life time of the fine media filters will most likely be longer than for the coarse and mixed media filters.

The results from the column study show that clogging is the limiting factor of the performance of the filters tested. When the filters started clogging, removal of SS remained constant. This indicates that a stormwater system using these filters will require maintenance or replacement due to reduced hydraulic performance rather than reduced treatment performance due to pollutant breakthrough. As a result, pre-treatment is suggested for filter systems using these filters.

If the filter is placed on the airport with underlying soils with the same grain size distribution as the filter and no underdrain is installed, the pollutants that are not retained by the filter will most likely contribute to contamination of groundwater. As this is an undesired situation, installing an underdrain in the filter system is recommended.

6.3 Evaluation of the Filters Tested

In the laboratory experiments, the filters were tested for hydraulic conductivity, flow, porosity, turbidity removal, DOC removal, PAH removal and heavy metal removal. The results varied between the different tests, which indicates that the performance of the filters varies with different conditions and behave differently in different conditions.

The fine filter media, NC 0-2 and NC 0-2 + GAC had overall the best treatment efficiency of turbidity and suspended solids. The effluent from these filters contained less particles than the effluent from the coarse media filters. This is because the finer grains of the filter media retain more particles than the coarse grains. However, all filters had good treatment of particles and the difference in turbidity in the effluent from the filters was not significant.

There was no removal of DOC for any of the filter media without GAC layer for the tests with high flow. This shows that there was no indication of adsorption of de-icing chemicals by the materials Filtralite NC 0-2 and Filtralite NC 0.8-1.6. The filter with GAC did adsorb de-icing chemicals in these tests. However, after the GAC layer was saturated the removal of DOC was reduced to the initial value. To improve this, a larger layer of GAC could be added to the filter media, so that the time before saturation of GAC would increase. The decrease of the biodegradation was significantly higher than from the adsorption from the GAC. However, even after biodegradation started, the filters with GAC had the best removal of DOV, which indicates that these are the filters giving best DOC removal.

The hydraulic performance of the five filter media varied when the flow and concentration of de-icing chemicals was changed. For low concentrations of de-icing chemicals, NC 0-2 + GAC had the best hydraulic performance and was the last medium to clog. NC 0.8-1.6, on the other hand, clogged before the fine media in the low concentration tests, but lasted longer in the high concentration tests. In Test 4, this material was only partly clogged when the test ended. The effect of GAC to reduce clogging of filter media varied between the different tests. When low concentration of de-icing chemicals was present in the tank, the materials with GAC clogged later than the materials without GAC, but for high concentrations, the opposite was observed. The mixed media behaved similar to the fine media, but clogged at an earlier stage. From the hydraulic conductivity tests it is indicated that the hydraulic conductivity decreases more for the media with NC 0-2 than the media with NC 0.8-1.6. This means that the coarse material reobtains the hydraulic performance better after clogging. By flushing the filter, the hydraulic performance can be reobtained better than for the fine media. In addition, NC 0-2 showed weakness due to reduced performance when compaction due to water pressure or air bubbles appeared in the filter. Air bubbles were also observed in the coarse media, but these media seemed less affected by this.

It was clear that choosing the best material for treatment of stormwater from airports exposed to de-icing chemicals is difficult because the performance of the materials tested in this study varied when the conditions varied. NC 0-2 + GAC showed the best performance for low concentrations and NC 0.8-1.6 showed the best result for high concentrations. However, it is important to note that NC 0-2 needs to be backwashed carefully before operation and that it is important to prevent compaction. NC 0-2 + GAC is the recommended filter medium of the filter media tested in this study, because this medium remove more suspended solids and de-icing chemicals than NC 0.8-1.6 and is easier to maintain.

7 Conclusions and Further Work

7.1 Conclusions

By conducting a column study, the hydraulic performance of five different filter media with Filtralite NC 0-2, Filtralite NC 0.8-1.6 and granular activated carbon (GAC) was tested in the laboratory. The columns were fed with synthetic stormwater with de-icing chemicals and sediments from the runway and de-icing platform at Værnes Airport containing SS, heavy metals and PAHs. The hydraulic performance of the filter media was tested by investigating the development and causes of clogging. Flow measurements, turbidity and SS analysis and DOC, PAH and heavy metals analysis was performed for the effluent from the five columns.

Four tests, with high and low flow of stormwater to the columns and with high and low concentrations of de-icing chemicals in the stormwater, were performed for the five filter media. The results showed that the development of clogging in the different media varies with the flow and concentration of de-icing chemicals. The filter media clogged after one day in the high flow tests, and after 3-7 days in the low flow tests. Clogging developed first in the coarse filter medium NC 0.8-1.6 in stormwater with low concentration of de-icing chemicals, and the fine filter medium NC 0-2 clogged first in the stormwater with high concentration of de-icing chemicals. The DOC tests indicated no adsorption of de-icing chemicals from the Filtralite material, only by the GAC. Biodegradation was observed in the tests with low flow that lasted for more than two days.

The flows that the filter media were tested for were both flows with a return period longer than 200 years and therefore, the clogging development after 1 day for the highest flow and 5-7 days for the low flow is acceptable. Over all, the filter media in the study performed well in terms of particles removed before clogging. The rate of maintenance and replacement expected for these filters seems to be acceptable. Even though there is no removal of de-icing chemicals by the Filtralite itself, biodegradation of de-icing chemicals was observed in all filters after 2 days of operation. However, variations of results between the tests due to interruptions of one of the tests indicate that further investigation of biodegradation in the filter media is needed.

7.2 Further Work

This study marks the beginning of investigation of properties of Filtralite material from Weber Saint-Gobain for treatment of stormwater from airports exposed to de-icing chemicals. More testing of these filters should be conducted. The following focus is recommended for further laboratory experiments:

- Performing a statistical test for determining the accuracy of the flow model
- Investigation of biodegradation in the filter media
- Testing the effect of wetting and drying on the hydraulic performance of the filters
- Testing the effect of temperature and frost on the performance of the filters
- Testing of the effect of backwashing of filter media
- Further investigation of the processes occurring in the filters

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Appendix A

Water quality analysis of stormwater in Værnes Airport

Vedlegg 5. Resultater overvann til resipienter 2013/2014
6131649 Miljøovervåking Trondheim lufthavn Værnes 2013/2014

Gamle elveleie nord

		Feltmålinger overvann				Analyseresultater overvann					
Stasjon	Dato	Oksygen [mg/l]	Temperatur [°C]	pH	Ledn.evne [µS/cm]	PG [mg/l]	Formiat [mg/l]	KOF [mg/l]	TOC [mg/l]	Fe [µg/l]	Mn [µg/l]
GEN	10.10.2013	7,7	7,3	7,7	2610	<0,2	<0,5	200	-		
GEN	10.12.2013	9	1,6	7,26	795	0,37	<0,5	29	-		
GEN	07.01.2014	7,7	5	7,15	3130	<0,2	<0,5	420	-		
GEN	04.02.2014	8,7	4	7,99	3530	<0,2	<0,5	250	1,6		
GEN	04.03.2014	9,8	6,6	7,32	3710	<0,2	<0,5	340	3,1		
SRGE	07.01.2014	7,2	6,5	8,3	313	<0,2	<0,5	11	2,8	610	230
SRGE	05.02.2014	6,8	5,7	7,58	326	<0,2	<0,5	<30	3,8	640	240
SRGE	04.03.2014	7,7	5,2	8,65	353	<0,2	<0,5	<10	3,7	600	270
LGE	07.01.2014	6,4	5,2	8,79	317	<0,2	<0,5	13	3,3	610	210
LGE	05.02.2014	6,1	7,34	7,34	328	<0,2	<0,5	<30	4	530	240
LGE	04.03.2014	8,1	4,1	9,42	509	<0,2	<0,5	<10	3,8	540	270
OV1 og OV2	07.01.2014	7,1	5,6	9,48	462	<0,2	<0,5	16	i.a.	1600	250

Stjørdalselva

		Feltmålinger				Analyseresultater					
Stasjon	Dato	Oksygen [mg/l]	Temperatur [°C]	pH	Ledn.evne [µS/cm]	PG [mg/l]	Formiat [mg/l]	KOF [mg/l]	TOC [mg/l]	Fe [µg/l]	Mn [µg/l]
SE2	27.11.2013	8,2	4,1	8,07	229	3,1	<0,5	22	i.a.	340	7,4

Stasjon	Dato	Benzen	Toluen	Etylbenzen	m,p-xylen	o-xylen	C5-C8 [µg/l]	C8-C10 [µg/l]	C10-C12 [µg/l]	C12-C16 [µg/l]	C16-C35 [µg/l]	SUM C5-C35 [µg/l]
SE2	27.11.2013	<0,1	<0,1	<0,1	<0,2	0,63	<5	<5	6,3	<5	34	40

		Feltmålinger vann i kum				Analyseresultater automatisk prøvetaker					
Stasjon	Dato	Oksygen [mg/l]	Temperatur [°C]	pH	Ledn.evne [µS/cm]	PG [mg/l]	Formiat [mg/l]	KOF [mg/l]	TOC [mg/l]	Fe [µg/l]	Mn [µg/l]
SE	10.10.2013	-	10,3	7,28	59	<0,2	<0,5	1000	-	270	5,8
SE	01.11.2013					14	<0,5	66	-	190	23
SE	14.11.2013					<0,2	2,64	30	-	54	8,5
SE	27.11.2013	9,4	4,8	8,10	116	23	3,44	74	-	1300	28
SE	10.12.2013	9,5	2,2	8,50	199	57	4,22	130	-	1500	34
SE	19.12.2013	7,8	3,8	7,77	489	83	109	170	-	330	41
SE	07.01.2014	4,0	5,8	7,20	741	78	94,9	240	-	350	27
SE	21.01.2014	2,8	13,4	8,13	62	<0,2	3,91	81	-	2800	57
SE	04.02.2014	-	-	-	-	-	-	-	-	-	-
SE	18.02.2014	2,2	10,9	7,91	449	<0,2	7,57	72	17	530	25
SE	04.03.2014	3,8	6,1	8,79	356	2,7	16,4	38	15	120	9,3
SE	19.03.2014	7,6	0,5	7,76	102	28	<0,5	56	16	470	14
SE	01.04.2014	4,8	11,8	7,97	215	7,9	34,2	35	16	110	4,7
SE	10.04.2014	6,5	6,1	8,24	199	1,9	<0,5	17	6,4	100	4,1
SE	24.04.2014	7	12,1	8,1	78	<0,2	<0,5	10	2,3	160	3,7
SE	08.05.2014	6,8	7,4	7,7	80	0,23	<0,5	29	13	150	3,4

SE = de-icing platform

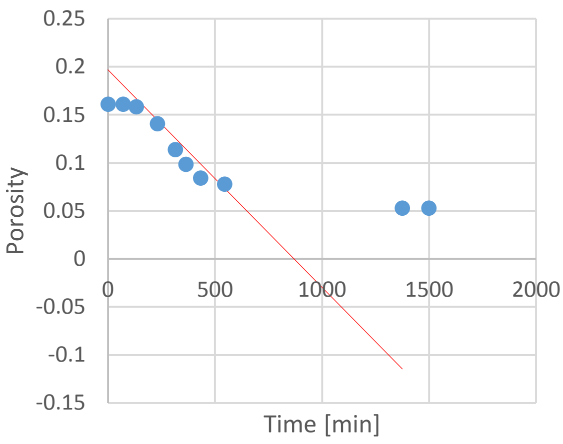
GEN/SPRGE = rivers nearby

De-icing chemicals in stormwater from de-icing platform, Værnes Lufthavn

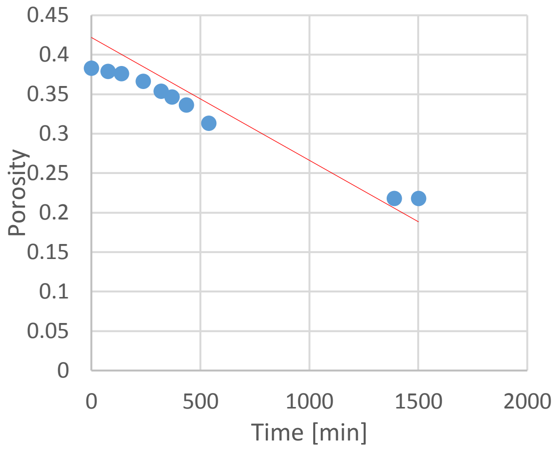
	Date	PG [mg/L]	Formiat [mg/L]
	10.10.2013	0.2	0.5
	1.11.2013	14	0.5
	14.11.2013	0.2	2.64
	27.11.2013	23	3.44
	10.12.2013	57	4.22
	19.12.2013	83	109
	07.01.2014	78	94.9
	21.01.2014	0.2	3.91
	18.02.2014	0.2	7.57
	04.03.2014	2.7	16.4
	19.03.2014	28	0.5
	01.04.2014	7.9	34.2
	10.04.2014	1.9	0.5
	24.04.2014	0.2	0.5
	08.05.2014	0.23	0.5
TOTAL	**15**	**296.73**	**279.28**
Average		**19.782**	**18.61866667**
Highest		**83**	**109**

Appendix B

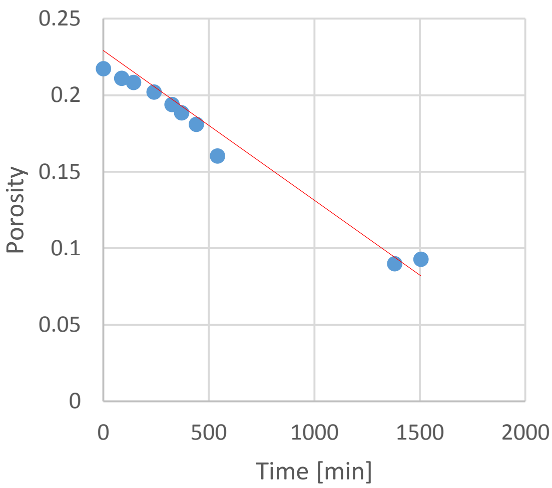
Linear approximation of porosity change in filter media



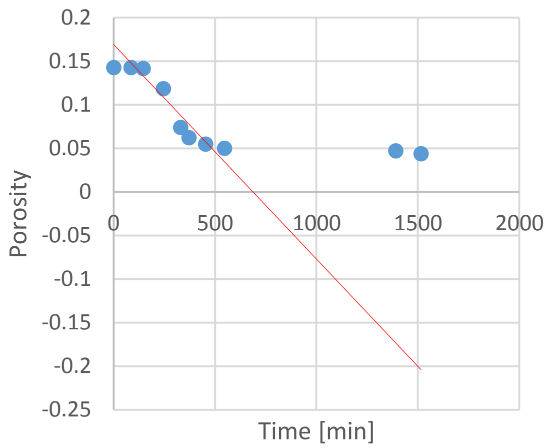
Test 1, NC 0.8-1.6. Linear approximation of porosity



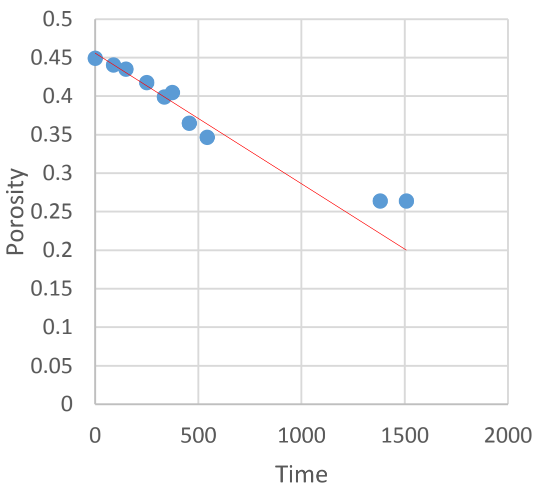
Test 1, NC 0-2 + GAC. Linear approximation of porosity



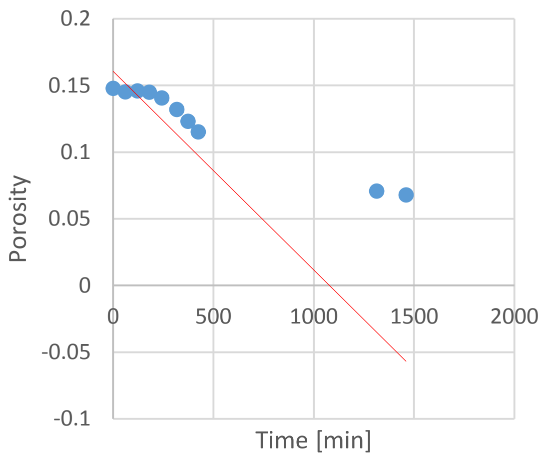
Test 1, NC 0-2 + NC 0.8-1.6. Linear approximation of porosity



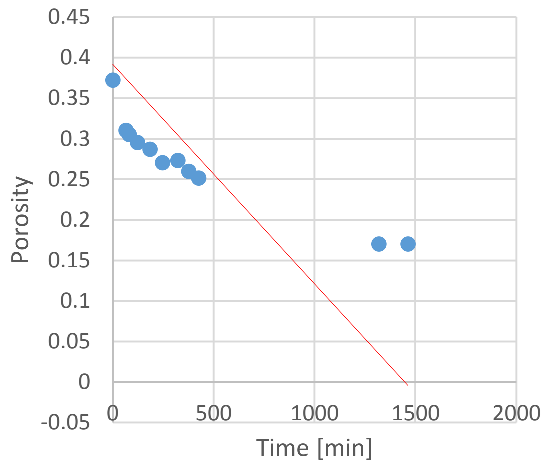
Test 1, NC 0.8-1.6 + GAC. Linear approximation of porosity



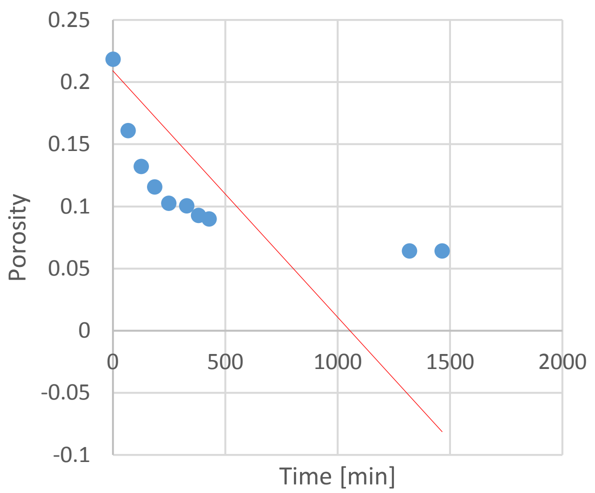
Test 1, NC 0-2. Linear approximation of porosity



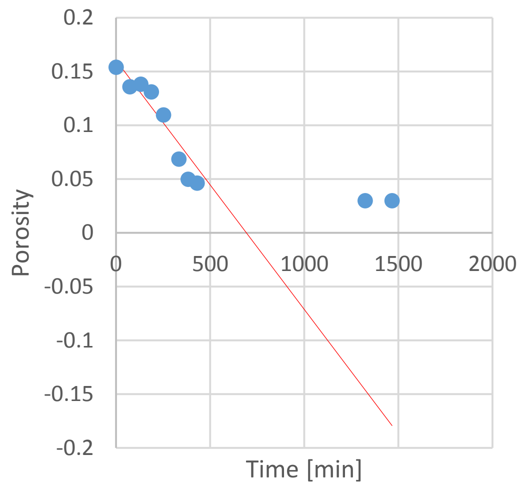
Test 2, NC 0.8-1.6. Linear approximation of porosity



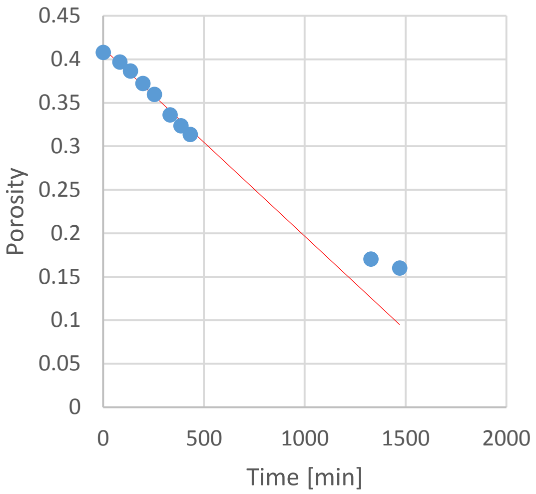
Test 2, NC 0-2 + GAC. Linear approximation of porosity



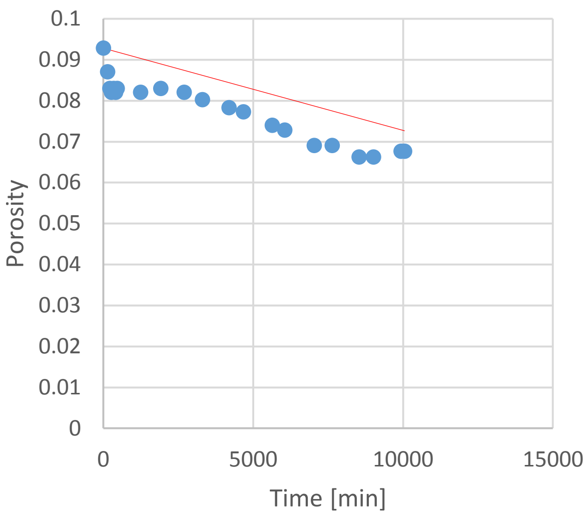
Test 2, NC 0-2 + NC 0.8-1.6. Linear approximation of porosity



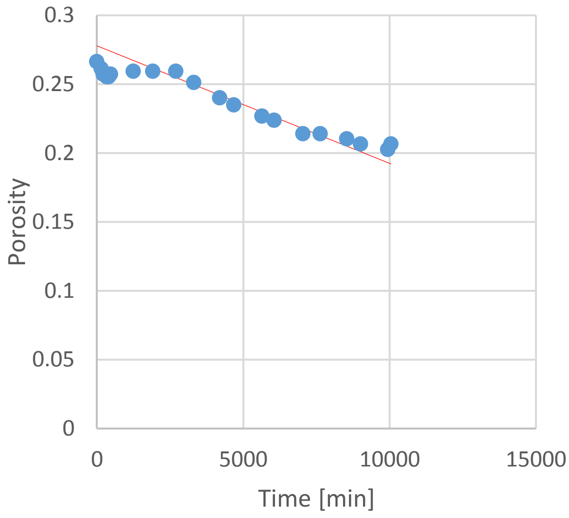
Test 2, NC 0.8-1.6 + GAC. Linear approximation of porosity



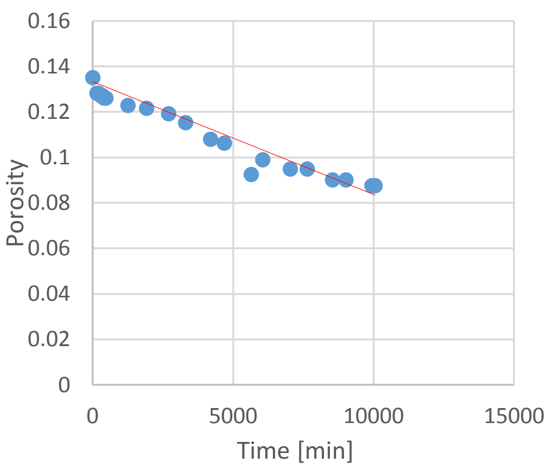
Test 2, NC 0-2. Linear approximation of porosity



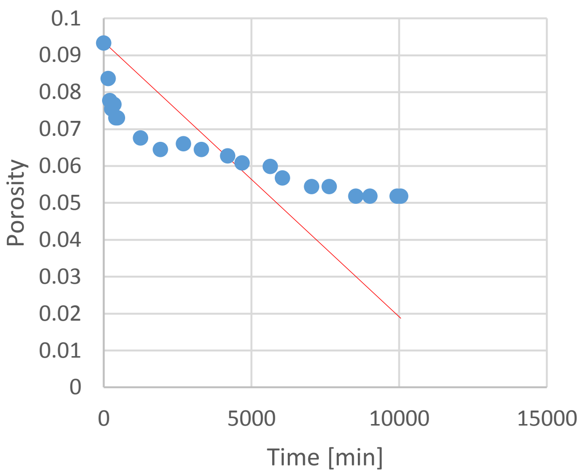
Test 3, NC 0.8-1.6. Linear approximation of porosity



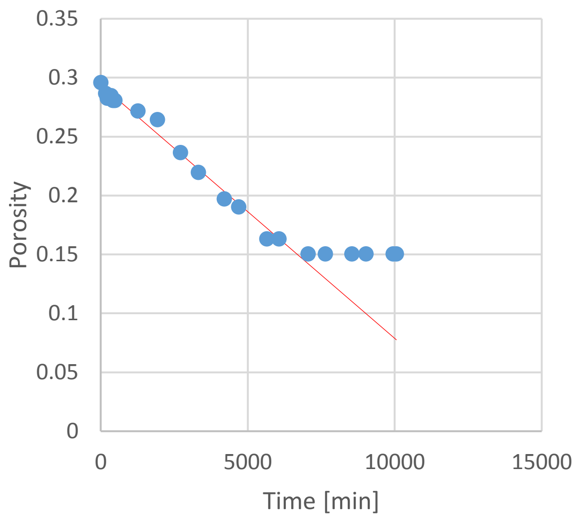
Test 3, NC 0-2 + GAC- Linear approximation of porosity



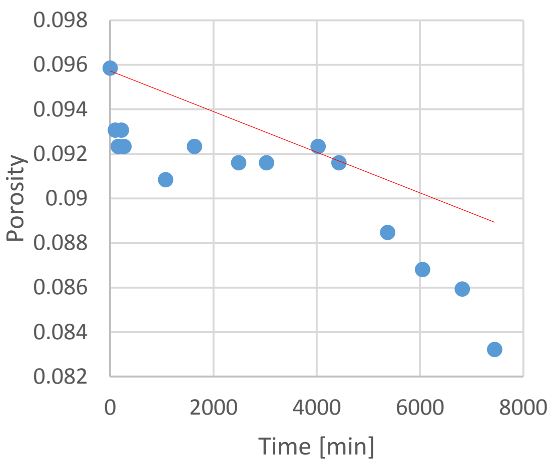
Test 3, NC 0-2 + NC 0.8-1.6. Linear approximation of porosity



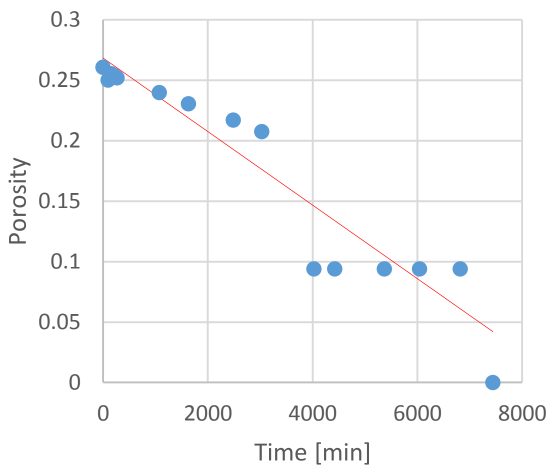
Test 3, NC 0.8-1.6 + GAC. Linear approximation of porosity



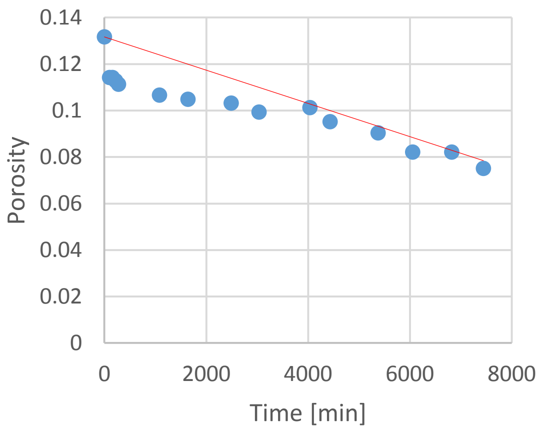
Test 4, NC 0-2. Linear approximation of porosity



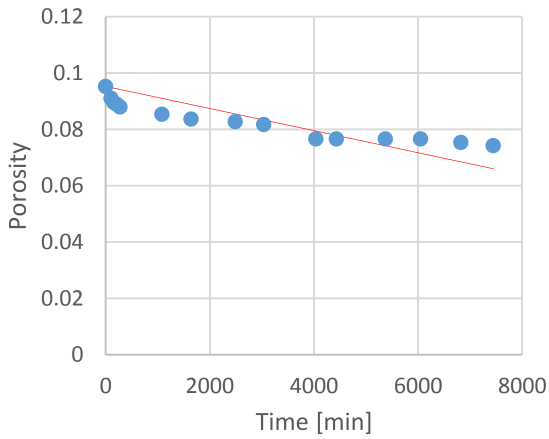
Test 4, NC 0.8-1.6. Linear approximation of porosity



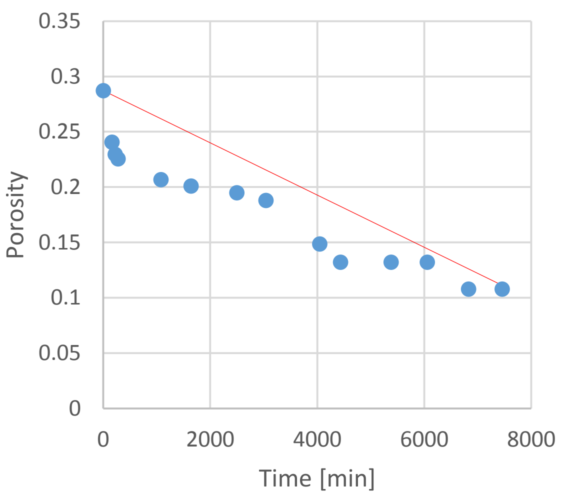
Test 4, NC 0-2 + GAC. Linear approximation of porosity



Test 4, NC 0-2 + NC 0.8-1.6. Linear approximation of porosity



Test 4, NC 0.8-1.6 + GAC. Linear approximation of porosity

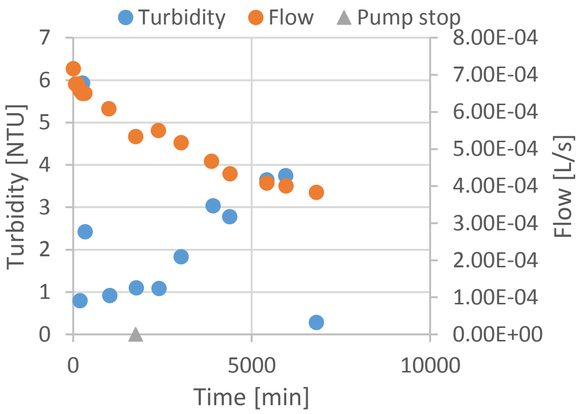


Test 4, NC 0-2, Linear approximation of porosity

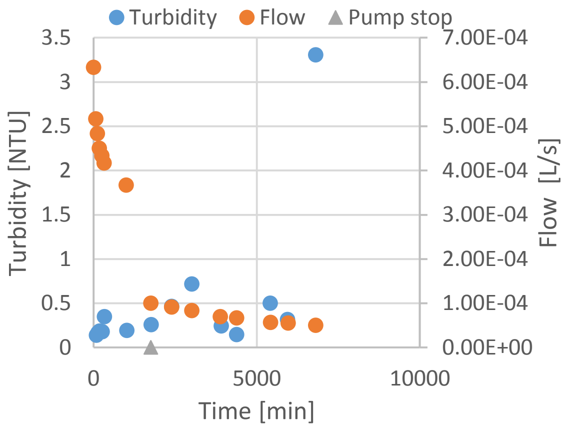
Appendix C

Results from Column Experiment by Hanna Haug Lindseth

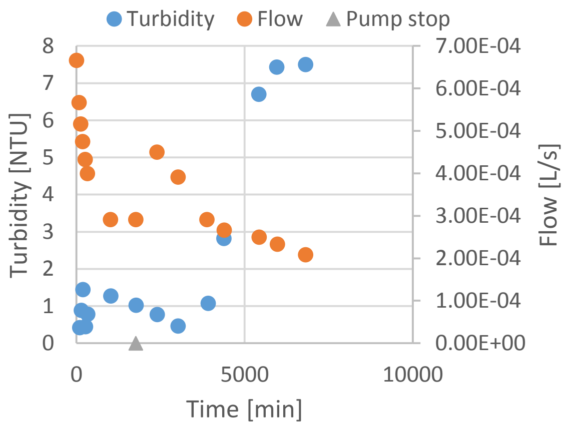
Results from Flow and Turbidity Measurements by Hanna Haug Lindseth



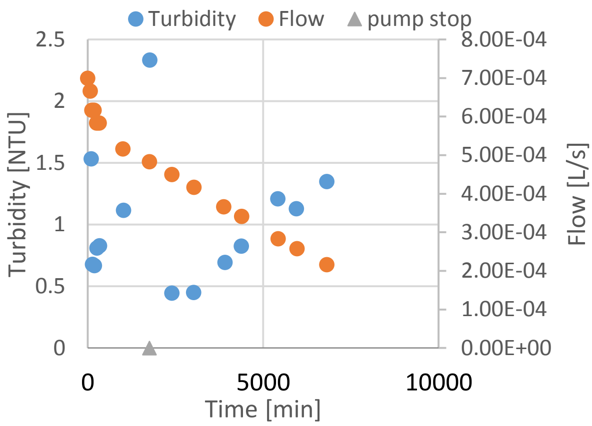
Test 4, NC 0.8-1.6. Turbidity and flow measurements by Hanna Haug Lindseth



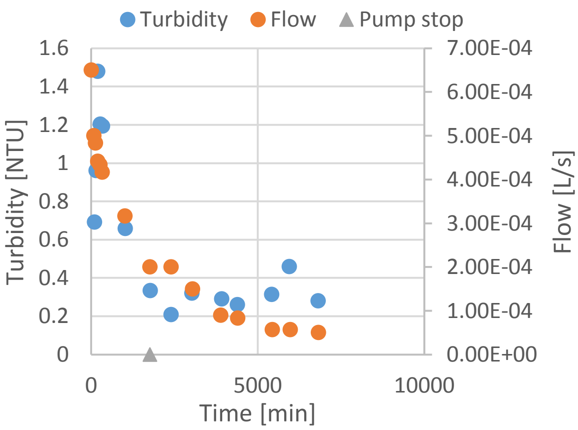
Test 4, NC 0-2 + GAC. Turbidity and flow measurements by Hanna Haug Lindseth



Test 4, NC 0-2 + NC 0.8-1.6. Turbidity and flow measurements by Hanna Haug Lindseth



Test 4, NC 0.8-1.6 + GAC. Turbidity and flow measurements by Hanna Haug Lindseth



Test 4, NC 0-2. Turbidity and flow measurements by Hanna Haug Lindseth

Appendix D

Analysis of Sediments from Værnes Airport in Trondheim from Eurofins

Eurofins Environment Testing Norway AS (Moss)
F. reg. 965 141 618 MVA
Møllebakken 50
NO-1538 Moss

Tlf: +47 69 00 52 00
Fax: +47 69 27 23 40

SINTEF UTVIKLING AS
Klæbuvn 153
7465 Trondheim
Attn: Gema Sakti Raspati

AR-15-MM-021589-01

EUNOMO-00129397

Prøvemottak: 30.11.2015
Temperatur:
Analyseperiode: 30.11.2015-07.12.2015
Referanse: KLIMA2050

ANALYSERAPPORT

Tegnforklaring:
* Ikke omfattet av akkrediteringen LOQ: Kvantifiseringsgrense MU: Måleusikkerhet
<: Mindre enn >: Større enn nd: Ikke påvist

Opplysninger om måleusikkerhet fås ved henvendelse til laboratoriet.
Rapporten må ikke gjengis, unntatt i sin helhet, uten laboratoriets skriftlige godkjennelse. Resultatene gjelder kun for de(n) undersøkte prøven(e).

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Prøvenr.:	**439-2015-11300030**	Prøvetakingsdato:	20.11.2015
Prøvetype:	Jord	Prøvetaker:	Oppdragsgiver
Prøvemerking:	1 - Soil Værnes	Analysestartdato:	30.11.2015

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As)	3.5	mg/kg TS	0.5	30%	NS EN ISO 17294-2
a)	Bly (Pb)	6.1	mg/kg TS	0.5	40%	NS EN ISO 17294-2
a)	Kadmium (Cd)	0.15	mg/kg TS	0.01	25%	NS EN ISO 17294-2
a)	Kobber (Cu)	82	mg/kg TS	0.5	30%	NS EN ISO 11885
a)	Krom (Cr)	20	mg/kg TS	0.3	30%	NS EN ISO 11885
a)	Kvikksølv (Hg)	0.002	mg/kg TS	0.001	20%	NS-EN ISO 12846
a)	Nikkel (Ni)	17	mg/kg TS	0.5	30%	NS EN ISO 11885
a)	Sink (Zn)	44	mg/kg TS	2	25%	NS EN ISO 11885
a)	Tørrstoff	89.0	%	0.1	5%	EN 12880
a)	**Totale hydrocarboner (THC)**					
a)	THC >C5-C8	<5.0	mg/kg TS	5		ISO/DIS 16703-Mod
a)	THC >C8-C10	<5.0	mg/kg TS	5		ISO/DIS 16703-Mod
a)	THC >C10-C12	<5.0	mg/kg TS	5		ISO/DIS 16703-Mod
a)	THC >C12-C16	<5.0	mg/kg TS	5		ISO/DIS 16703-Mod
a)	THC >C16-C35	340	mg/kg TS	20	25%	ISO/DIS 16703-Mod
a)	Sum THC (>C5-C35)	340	mg/kg TS		25%	ISO/DIS 16703-Mod
a)	**PAH 16 EPA**					
a)	Naftalen	<0.010	mg/kg TS	0.01		ISO/DIS 16703-Mod
a)	Acenaftylen	<0.010	mg/kg TS	0.01		ISO/DIS 16703-Mod
a)	Acenaften	<0.010	mg/kg TS	0.01		ISO/DIS 16703-Mod
a)	Fluoren	<0.010	mg/kg TS	0.01		ISO/DIS 16703-Mod
a)	Fenantren	<0.010	mg/kg TS	0.01		ISO/DIS 16703-Mod
a)	Antracen	<0.010	mg/kg TS	0.01		ISO/DIS 16703-Mod
a)	Fluoranten	0.019	mg/kg TS	0.01	40%	ISO/DIS 16703-Mod
a)	Pyren	0.055	mg/kg TS	0.01	25%	ISO/DIS 16703-Mod
a)	Benzo[a]antracen	0.013	mg/kg TS	0.01	40%	ISO/DIS 16703-Mod
a)	Krysen/Trifenylen	0.17	mg/kg TS	0.01	35%	ISO/DIS 16703-Mod
a)	Benzo[b]fluoranten	0.085	mg/kg TS	0.01	25%	ISO/DIS 16703-Mod
a)	Benzo[k]fluoranten	0.019	mg/kg TS	0.01	40%	ISO/DIS 16703-Mod
a)	Benzo[a]pyren	0.050	mg/kg TS	0.01	35%	ISO/DIS 16703-Mod
a)	Indeno[1,2,3-cd]pyren	0.031	mg/kg TS	0.01	40%	ISO/DIS 16703-Mod
a)	Dibenzo[a,h]antracen	0.020	mg/kg TS	0.01	40%	ISO/DIS 16703-Mod
a)	Benzo[ghi]perylen	0.059	mg/kg TS	0.01	40%	ISO/DIS 16703-Mod
a)	Sum PAH(16) EPA	0.52	mg/kg TS		30%	ISO/DIS 16703-Mod

Utførende laboratorium/ Underleverandør:
a) ISO/IEC 17025 SWEDAC 1125, Eurofins Environment Sweden AB (Lidköping), Box 887, Sjöhagsg. 3, SE-53119, Lidköping

Kopi til:
Kamal Azrague (Kamal.Azrague@sintef.no)

Tegnforklaring:
* Ikke omfattet av akkrediteringen LOQ: Kvantifiseringsgrense MU: Måleusikkerhet
<: Mindre enn >: Større enn nd: Ikke påvist

Opplysninger om måleusikkerhet fås ved henvendelse til laboratoriet.
Rapporten må ikke gjengis, unntatt i sin helhet, uten laboratoriets skriftlige godkjennelse. Resultatene gjelder kun for de(n) undersøkte prøven(e).

eurofins

Moss 07.12.2015

Kjetil Sjaastad

Kjetil Sjaastad
Laboratorie Tekniker

Appendix E

Analysis of Heavy Metals from Treated Stormwater, from Eurofins

Eurofins Environment Testing Norway AS (Moss)
F. reg. 965 141 618 MVA
Møllebakken 50
NO-1538 Moss

Tlf: +47 69 00 52 00
Fax: +47 69 27 23 40

SINTEF UTVIKLING AS
Klæbuvn 153
7465 Trondheim
Attn: Gema Sakti Raspati

PR-16-MM-000069-01

EUNOMO-00132764

Prøvemottak: 02.02.2016
Temperatur:
Analyseperiode: 02.02.2016-05.02.2016
Referanse: 700281 Gema S. Raspati

Midlertidig rapport

(Resultatene på rapporten er validerte. Endelig analyserapport oversendes når alle validerte resultater foreligger)

ANALYSERAPPORT

Merknader prøveserie:

Endelig rapport sendes så fort alle resultatene er klare.
Prøven merket "3. Stormwater effluent from column 4" var tom ved ankomst.
Ikke nok prøvemengde til PAH.

Prøvenr.: **439-2016-02020085** Prøvetakingsdato: 25.01.2016
Prøvetype: Urent vann Prøvetaker: Kamal Azrague
Prøvemerking: 1. Stormwater from tank Analysestartdato: 02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	0.36	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	35	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	0.087	µg/l	0.004	15%	NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	70	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.50	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	9.0	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	36	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	<0.001	µg/l	0.001		NS-EN ISO 12846

Prøvenr.: **439-2016-02020086** Prøvetakingsdato: 25.01.2016
Prøvetype: Urent vann Prøvetaker: Kamal Azrague
Prøvemerking: 2. Stormwater effluent from column 1 Analysestartdato: 02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	0.56	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	0.50	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	0.0089	µg/l	0.004	25%	NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	28	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.12	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	7.0	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	3.9	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	0.013	µg/l	0.001	15%	NS-EN ISO 12846

Tegnforklaring:
* Ikke omfattet av akkrediteringen LOQ: Kvantifiseringsgrense MU: Måleusikkerhet
<: Mindre enn >: Større enn nd: Ikke påvist

Opplysninger om måleusikkerhet fås ved henvendelse til laboratoriet.
Rapporten må ikke gjengis, unntatt i sin helhet, uten laboratoriets skriftlige godkjennelse. Resultatene gjelder kun for de(n) undersøkte prøven(e).

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Prøvenr.:	**439-2016-02020087**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	4. Stormwater effluent from column 2	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	2.5	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	0.039	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	0.0054	µg/l	0.004	25%	NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	3.7	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.069	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	0.58	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	4.1	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	0.003	µg/l	0.001	40%	NS-EN ISO 12846

Prøvenr.:	**439-2016-02020088**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	5. Stormwater effluent from column 3	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	0.89	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	0.42	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	< 0.0040	µg/l	0.004		NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	22	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.11	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	1.5	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	1.9	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	0.002	µg/l	0.001	40%	NS-EN ISO 12846

Prøvenr.:	**439-2016-02020089**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	6. Stormwater effluent from column 5	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	1.8	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	0.30	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	0.0058	µg/l	0.004	25%	NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	14	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.10	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	0.81	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	0.66	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	0.001	µg/l	0.001	40%	NS-EN ISO 12846

Tegnforklaring:
* Ikke omfattet av akkrediteringen LOQ: Kvantifiseringsgrense MU: Måleusikkerhet
<: Mindre enn >: Større enn nd: Ikke påvist

Opplysninger om måleusikkerhet fås ved henvendelse til laboratoriet.
Rapporten må ikke gjengis, unntatt i sin helhet, uten laboratoriets skriftlige godkjennelse. Resultatene gjelder kun for de(n) undersøkte prøven(e).

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Prøvenr.:	**439-2016-02020090**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	7. Stomwater from tank	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	0.39	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	7.3	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	0.074	µg/l	0.004	15%	NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	36	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.17	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	6.1	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	20	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	<0.001	µg/l	0.001		NS-EN ISO 12846

Prøvenr.:	**439-2016-02020091**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	8. Stormwater effluent from column 1	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	0.68	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	2.0	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	0.025	µg/l	0.004	25%	NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	15	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.15	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	5.6	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	7.2	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	<0.001	µg/l	0.001		NS-EN ISO 12846

Prøvenr.:	**439-2016-02020092**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	9. Stormwater effluent from column 2	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	3.4	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	0.43	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	< 0.0040	µg/l	0.004		NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	4.8	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	< 0.050	µg/l	0.05		NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	0.30	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	1.4	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	<0.001	µg/l	0.001		NS-EN ISO 12846

Tegnforklaring:
* Ikke omfattet av akkrediteringen LOQ: Kvantifiseringsgrense MU: Måleusikkerhet
<: Mindre enn >: Større enn nd: Ikke påvist

Opplysninger om måleusikkerhet fås ved henvendelse til laboratoriet.
Rapporten må ikke gjengis, unntatt i sin helhet, uten laboratoriets skriftlige godkjennelse. Resultatene gjelder kun for de(n) undersøkte prøven(e).

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Prøvenr.:	**439-2016-02020093**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	10. Stormwater effluent from column 3	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	3.6	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	0.26	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	0.0045	µg/l	0.004	25%	NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	9.2	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.15	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	0.92	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	0.73	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	0.002	µg/l	0.001	40%	NS-EN ISO 12846

Prøvenr.:	**439-2016-02020094**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	11. Stormwater effluent from column 4	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	1.5	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	2.4	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	0.011	µg/l	0.004	25%	NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	9.4	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.13	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	4.5	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	4.2	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	<0.001	µg/l	0.001		NS-EN ISO 12846

Prøvenr.:	**439-2016-02020095**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	12. Stormwater effluent from column 5	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	1.9	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	1.4	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	0.011	µg/l	0.004	25%	NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	8.0	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.14	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	1.5	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	2.3	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	<0.001	µg/l	0.001		NS-EN ISO 12846

eurofins

Prøvenr.:	**439-2016-02020096**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	13. Stormwater effluent from column 1	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	0.95	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	0.029	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	0.0045	µg/l	0.004	25%	NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	6.1	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.10	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	4.3	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	1.5	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	<0.001	µg/l	0.001		NS-EN ISO 12846

Prøvenr.:	**439-2016-02020097**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	14. Stormwater effluent from column 2	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	2.1	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	< 0.010	µg/l	0.01		NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	< 0.0040	µg/l	0.004		NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	4.3	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.087	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	0.36	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	0.33	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	<0.001	µg/l	0.001		NS-EN ISO 12846

Prøvenr.:	**439-2016-02020098**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	15. Stormwater effluent from column 3	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	2.1	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	0.041	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	0.0049	µg/l	0.004	25%	NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	3.6	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.100	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	1.3	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	7.5	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	0.001	µg/l	0.001	40%	NS-EN ISO 12846

Tegnforklaring:
* Ikke omfattet av akkrediteringen   LOQ: Kvantifiseringsgrense MU: Måleusikkerhet
<: Mindre enn   >: Større enn   nd: Ikke påvist

Opplysninger om måleusikkerhet fås ved henvendelse til laboratoriet.
Rapporten må ikke gjengis, unntatt i sin helhet, uten laboratoriets skriftlige godkjennelse. Resultatene gjelder kun for de(n) undersøkte prøven(e).

Prøvenr.:	**439-2016-02020099**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	16. Stormwater effluent from column 4	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	1.3	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	0.022	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	< 0.0040	µg/l	0.004		NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	2.2	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.15	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	0.74	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	2.7	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	<0.001	µg/l	0.001		NS-EN ISO 12846

Prøvenr.:	**439-2016-02020100**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	17. Stormwater effluent from column 5	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	3.5	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	0.010	µg/l	0.01	50%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	< 0.0040	µg/l	0.004		NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	2.6	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.12	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	0.66	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	< 0.20	µg/l	0.2		NS EN ISO 17294-2
	Kvikksølv (Hg)	<0.001	µg/l	0.001		NS-EN ISO 12846

Prøvenr.:	**439-2016-02020101**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	18. Stormwater from tank	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	0.48	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	3.1	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	0.057	µg/l	0.004	15%	NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	35	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.58	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	2.0	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	21	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	<0.001	µg/l	0.001		NS-EN ISO 12846

Prøvenr.:	**439-2016-02020102**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	19. Stormwater effluent from column 1	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	0.89	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	0.058	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	0.0090	µg/l	0.004	25%	NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	8.5	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.12	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	3.0	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	13	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	<0.001	µg/l	0.001		NS-EN ISO 12846

Prøvenr.:	**439-2016-02020103**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	20. Stormwater effluent from column 2	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	3.0	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	0.022	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	< 0.0040	µg/l	0.004		NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	1.4	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.12	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	0.52	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	55	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	0.001	µg/l	0.001	40%	NS-EN ISO 12846

Prøvenr.:	**439-2016-02020104**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	21. Stormwater effluent from column 3	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	2.6	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	0.034	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	< 0.0040	µg/l	0.004		NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	3.1	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.11	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	0.98	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	2.5	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	0.003	µg/l	0.001	40%	NS-EN ISO 12846

Tegnforklaring:
* Ikke omfattet av akkrediteringen LOQ: Kvantifiseringsgrense MU: Måleusikkerhet
<: Mindre enn >: Større enn nd: Ikke påvist

Opplysninger om måleusikkerhet fås ved henvendelse til laboratoriet.
Rapporten må ikke gjengis, unntatt i sin helhet, uten laboratoriets skriftlige godkjennelse. Resultatene gjelder kun for de(n) undersøkte prøven(e).

Prøvenr.:	**439-2016-02020105**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	22. Stormwater effluent from column 4	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	0.74	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	0.095	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	0.0061	µg/l	0.004	25%	NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	4.0	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.078	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	0.45	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	3.9	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	0.008	µg/l	0.001	40%	NS-EN ISO 12846

Prøvenr.:	**439-2016-02020106**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	23. Stormwater effluent from column 5	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	8.6	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	0.023	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	< 0.0040	µg/l	0.004		NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	3.3	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.27	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	0.43	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	2.0	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	0.016	µg/l	0.001	15%	NS-EN ISO 12846

Prøvenr.:	**439-2016-02020107**	Prøvetakingsdato:	25.01.2016
Prøvetype:	Urent vann	Prøvetaker:	Kamal Azrague
Prøvemerking:	24. Stormwater from tank	Analysestartdato:	02.02.2016

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Arsen (As) ICP-MS	0.29	µg/l	0.02	15%	NS EN ISO 17294-2
a)	Bly (Pb) ICP-MS	0.45	µg/l	0.01	20%	NS EN ISO 17294-2
a)	Kadmium (Cd) ICP-MS	0.017	µg/l	0.004	25%	NS EN ISO 17294-2
a)	Kobber (Cu) ICP-MS	11	µg/l	0.05	25%	NS EN ISO 17294-2
a)	Krom (Cr) ICP-MS	0.14	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Nikkel (Ni) ICP-MS	1.2	µg/l	0.05	15%	NS EN ISO 17294-2
a)	Sink (Zn) ICP-MS	8.6	µg/l	0.2	25%	NS EN ISO 17294-2
	Kvikksølv (Hg)	<0.001	µg/l	0.001		NS-EN ISO 12846

Utførende laboratorium/ Underleverandør:
a) ISO/IEC 17025 SWEDAC 1125, Eurofins Environment Sweden AB (Lidköping), Box 887, Sjöhagsg. 3, SE-53119, Lidköping

Kopi til:
Kamal Azrague (Kamal.Azrague@sintef.no)

Tegnforklaring:
* Ikke omfattet av akkrediteringen LOQ: Kvantifiseringsgrense MU: Måleusikkerhet
<: Mindre enn >: Større enn nd: Ikke påvist

Opplysninger om måleusikkerhet fås ved henvendelse til laboratoriet.
Rapporten må ikke gjengis, unntatt i sin helhet, uten laboratoriets skriftlige godkjennelse. Resultatene gjelder kun for de(n) undersøkte prøven(e).

Moss 05.02.2016

Stig Tjomsland

Stig Tjomsland

ASM/Bachelor Kjemi