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Carlos Monrabal-Martinez

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Thesis for the Degree of
Philosophiae Doctor
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Department of Civil and Environmental
Engineering

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Abstract

Runoff from urban areas carries a wide range of pollutants both particle-bound and dissolved. Dissolved pollutants are generally more mobile and bioavailable as well as more difficult to remove by conventional infiltration based systems. Three adsorbent amended filters were studied for suitability in filtering swales for stormwater runoff management in cold climates, with special attention to the capture of dissolved metals. These alternative filters were composed of clean homogeneous sand and one adsorbent. The adsorbents used along the course of this thesis were granulated activated charcoal, granulated olivine Blueguard® G1-3, and pine bark *Pinus Sylvestris*. These adsorbents were selected in a previous multi-criteria study in which factors such as sorption capacity with respect to dissolved zinc (Zn), copper (Cu), nickel (Ni), and lead (Pb), cost, availability, end-of-life disposal, and others were considered.

The investigations were divided into the following 4 parts

1. An urban runoff sampling campaign over the course of 17 months in the city of Trondheim in order to characterize runoff and understand local patterns.
2. A column test to study the retention performance of these filters towards toxic metals detrimental for receiving water bodies.
3. A column test to study the infiltration response of these filters under cold climate conditions.
4. A full scale experimental study with two swales composed of selected filters and one swale composed of traditional soil for bioinfiltration in order to explore and compare their hydrological balance during runoff events.

The results from the characterization of urban runoff showed strong seasonal and spatial variations in all studied parameters. Metals associated to colloids were practically non-existent, and Cu was the only studied metal that exceeded Norwegian, European, and American water quality standards for fresh water bodies. Overall the metals were mostly particle-bound (> 99 % for Pb, > 96% for Ni, > 90 % for Cu, and > 91 % for Ni), and this trend was followed over the course of the year. Lack of cleaning and maintenance in low annual average daily traffic streets can yield pollutant concentration similar as transited roads. In addition, boundaries associated to cold climate such as use of studded tires, de-icing salts, and low temperatures were more likely reasons for the seasonal variations rather than long accumulation times on snow piles.

With regard to the retention performance of the filters, pine bark and olivine amended filter showed the best affinity to the target metals both under high inflow rates (> 97 % retention) and large inflow volumes (no exhaustion was reached in these filters), which helped to decide the candidate filters to test in full scale. In addition, all filters except the charcoal amended filter for Ni showed little leaching of metals (< 2.8 %) after the addition of sodium chloride (NaCl), being a common de-icing salt to avoid snow accumulation on roads. The pine bark amended filter showed the longest estimated service life, which will vary according to the target metal as well as the size of the tributary. For example, a filter composed of sand and pine bark receiving polluted runoff from a tributary 50 times larger (than the filter) is expected to last 9, 13 and 46 years for Zn, Cu and Ni, respectively.

With respect to infiltration capacity under cold climate conditions, snowmelt runoff will take more than 21 hours to be infiltrated through a partially frozen filter. This means that a ponding capacity is required if "shock" pollutant loads from snowmelt must be captured in the system. However, after the first 24 hours from the observation of the first discharge, infiltration rates will be higher than 1.27 cm/h, a value typically recommended for bioinfiltration. In addition, some of the studied adsorbents showed high unfrozen water content as well as being highly porous. These properties make the infiltration response to negative temperatures better due to positive impacts on the ratio ice content / porosity as well as on the heat exchange between incoming runoff and ice in the filter media.

In the swale setup, two swales composed of adsorbent amended filters (filtering swales) were compared with a traditional grass swale, and among each other. The experiments were performed under different boundary conditions that have been shown to influence the hydrological balance; type of media (olivine amended filter, pine bark amended filter, and soil traditionally used for bioinfiltration practices), inflow rate, swale slope, and degree of saturation of the media. Results showed that the infiltration performance of the filtering swales was considerably better and only dependent on the inflow rate for the studied range of slopes, up to 4 %. An equation that relates infiltration performance, storm intensity, and size of the drainage area is included to help planners to design filtering swales presented in this thesis. As an example, these swales can capture 90% of the runoff generated by a tributary 40 times larger (than the swale) during a storm event with a peak intensity of 12.2 mm/h.

All in all, the results of this thesis show that the environmental and hydrological benefits provided by the adsorbent amended filters are promising for further field implementation in cold climates. However, this thesis has not considered any economic feasibility aspects, which would be of interest for an overall assessment.

Preface

This doctoral thesis has been entirely performed at the Department of Civil and Environmental Engineering (NTNU) in Trondheim, with Associate Professor Tone M. Muthanna as main supervisor and Professor Jochen Aberle as co-supervisor.

This work is the result of a four-year PhD program, in which 75% was dedicated to research and 25% to duty work at the Department. This duty work included assisting in the Master´s courses TVM 4130 Urban Water Systems, VM8207 Environmental Field Course, and supervising students in their thesis and exchange programs. This work was mainly founded as a PhD position by the Department of Civil and Hydrological Engineering, NTNU. Statens Vegvesen (Norwegian Administration of Roads), through its program NORWAT, also contributed financially to the attainment of this thesis.

This thesis presents the work on adsorbent amended filters for stormwater runoff in cold climates that resulted in four scientific papers. For all four papers, I have been the first author with close guidance, advice and valuable inputs from my main supervisor, Tone M. Muthanna. For Paper I, I was responsible for the experimental design and field sampling. Laboratory analysis were performed with the assistance of the students Lensa Jotte and Andrea Bárcena Pasamontes. Associate Professor Thomas Meyn carried out the ultrafiltration of the samples. For Paper II, Aamir Ilyas, a post Doc funded by the NORWAT program, was closely involved during the design and performance of the experiments, and data analysis. For Paper III, I conducted the design and performance of the experiments in the lab. Elena Kuznetsova provided insight about the contact method, Mauro Orts helped during the contact method experimental work, and Sønke Maus generated and processed x-ray micro computed tomographic images. For Paper IV, I was responsible for the design of the experiments, carrying out the experiments, and analysing the results in close collaboration with Professor Jochen Aberle and Mauro Orts. For all four papers, interpretation and discussion of the results, and writing have been done together with the corresponding co-authors.

In accordance with the guidelines of the Faculty of Engineering Science and Technology, this thesis comprises an introduction to the research that has resulted in four scientific papers.

Acknowledgements

First I would like to thank the Norwegian University of Science and Technology (NTNU) and Statens Vegvesen (through NORWAT program) for funding this research. My supervisor Associate Professor Tone M. Muthanna believed in me for this PhD and she always provided with pleasure all resources I needed along these past years. I really appreciate your kindness, expertise, relaxed and smiley attitude and availability for meetings and discussions. Thank you so much, Tone, you helped a lot to make this happen! You are the best supervisor I could have ever imagined. My gratitude also goes to my co-supervisor Professor Jochen Aberle. Thank you, Joe, for transmitting rigor and aiming at excellence in research. Despite your brilliant CV and busy schedule, you are still close to students and willing for discussions, which, in my opinion, makes you even a greater Professor. Dr. Aamir Ilyas was crucial for a good starting in this project. It was so nice to have worked together with a colleague with your experience in my early phase of the PhD. I also want to show my gratitude to Dr. Elena Kuznetsova, Dr. Sønke Maus, Ass. Prof. Thomas Meyn, Dr. Kim H. Paus, and the students Mauro Orts, Lensa Jotte, Anine Drageset, Lucia and Andrea Bárcena, and Karlis Rieskts because all the valuable discussions, inputs, and help I received from you at different stages of my PhD.

It has been a real pleasure to have been a member of IVM. Phd fellows, Professors, and exchange students managed to create a really nice atmosphere during the past years, which made me feel appreciated, happy and motivated. Thank you, Arne, for the help with the lab setups, and thank you, Geir, for the wise technical advices. Trine, Varshita and Hege, your kindness and patience helped me a lot to feel welcome when I started in this department. Vladimir and Chunbo, my devoted friends during these years, you are special for me because of all the quality time we have spent together not only at the department and because of all the scientific talks at lunch time. You all are gold! I will miss to work in this department so much, honestly.

I don’t want to leave aside the leisure friends I have made during these 4 years; Violeta, Felix, Bernardi, Jose, Raul, Pablete, Vedat, Dioginho, Dani, Baptiste, Francesco, Robin, Kristin, Cristian, Elisse, Daniel, and Adrian. I feel so lucky to have met such good people like you. You are also part of my Norwegian experience!

A big “thank you” goes to my family. You are simply the best and a great example to follow. True support in any decision I have made, even when this meant to be thousands of km away. Dad and mom, thanks for the education and values you gave, give and will give us. I hope my future family can be as proud of me as I am of you. Vicky and Juan, it is so comforting to see that we would protect and care for each other at any price. Then Patricia comes; you are incredibly amazing. Funny, lovely, honest, and fair. You gave up so many good things for joining me in Trondheim and making things easier for me. Pure

definition of unconditional love. Thanks, Patri, what you did will stay with me forever. Love you so much, monito!

This achievement has to some degree been possible because of you. THANKS.

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List of Publications

Selected Papers

1. Carlos Monrabal-Martinez, Tone M. Muthanna and Thomas Meyn. "Characterization and seasonal variation of urban runoff in cold climate - design implications for SuDS." *In review: Urban Water Journal*

2. Carlos Monrabal-Martinez, Aamir Ilyas and Tone M. Muthanna (2017). "Pilot Scale Testing of Adsorbent Amended Filters under High Hydraulic Loads for Highway Runoff in Cold Climates." *Water*, 9(3), 230, DOI: 10.3390/w9030230 (Open Access).

3. Carlos Monrabal-Martinez, Sønke Maus, Elena Kuznetsova, and Tone M. Muthanna. "Infiltration response of adsorbent amended filters for stormwater management under freezing/thawing conditions." *In review: Journal of Cold Regions Science and Technology.*

4. Carlos Monrabal-Martinez, Jochen Aberle, Tone M. Muthanna, Mauro Orts-Zamorano. "Hydrological benefits of filtering swales for metal removal." *In Review: Hydrological Processes*

Secondary Papers

1. Carlos Monrabal-Martinez, Aamir Ilyas and Tone M. Muthanna. Study of infiltration performance of roadside filters with adsorbent media for catchment and filter sizing. In *12th Urban Environment Symposium*, Oslo, Norway, 2015.

2. Carlos Monrabal-Martinez, Tone M. Muthanna and Thomas Meyn. Seasonal variation in pollutant concentrations and particle size distribution in urban stormwater - design implications for BMPs. In *9th International Conference NOVATECH*, Lyon, France, 2016.

3. Carlos Monrabal-Martinez, Jochen Aberle, Tone M. Muthanna, Mauro Orts-Zamorano. Hydrological benefits of amended infiltration based swales for metal removal. In *14th International Conference of Urban Drainage*, Prague, Czech Republic 2017.

Chapter 1: Introduction

This chapter presents the background, the problem statement, and the aims and scope of the doctoral work. The research questions raised to accomplish the goal of the thesis and the thesis structure are introduced.

1.1 Background

Urban growth has direct consequences on the hydrology of an area as well as on the quality of its waters (Leopold, 1968). The introduction of relatively impervious surfaces, because of the urbanization process, will increase the volume of overland flows to the detriment of infiltration and groundwater recharge. These overland flows will occur earlier and shorter, generating higher discharges than predevelopment conditions. Apart from an increase in erosion, overflows and hydrology alteration, the water quality is also negatively impacted as runoff flows over urban surfaces (Kayhanian et al., 2012). This polluted water will end up directly into the environment or, in the best scenario, combine with sewage water in a waste water treatment plant. However, the latter option does not even guarantee a treatment for most of the pollutants in stormwater runoff (Y. Li and Helmreich, 2014).

Norway, as a European Free Trade Association (EFTA) country member, is via the European Economic Area, EEA, connected to the European Union and, consequently, it must accomplish certain legal obligations. Among these duties, it is included to achieve the goals set by the EU's Water Framework Directive (WFD), i.e., to reach good ecological and chemical water quality by 2021 (Kallis and Butler, 2001). Therefore, the Water Regulation (Norwegian regulation in relation to the WFD) entered into force in 2007. As the WFD, the Water Regulation proposed a list of priority toxic substances with negative effects such as accumulation in the ecosystem, intoxication of aquatic organisms, and detriment of habitats and biodiversity. Some metals in this list have been found in high concentrations in runoff from roads and tunnel wash water (Meland et al., 2010), which will eventually enter lakes, streams, and other recipients. Compared with many other countries, Norway's water resources are relatively unaffected by pollution from road traffic. However, as an example, the impact of polluted runoff from trafficked areas have been shown to alter the growth rate of living species in receiving water bodies (Mahrosh et al., 2014). Therefore, it is paramount for the Norwegian Public Roads Administration (NPRA) to implement the right measures to protect sensitive areas.

The 4-year research program Nordic Road Water (NORWAT) was created in 2011 by the NPRA in order to plan, build and operate the road network without harming the nearby water bodies. NORWAT focus on what chemical and biological effects polluted runoff water has on the aquatic environment, and what measures are most appropriate to reduce the risk of environmental harm.

The NPRA supports a sustainable development in order to cope with consequences derived from urban growth. It aims at developing new urban areas by paying attention to density, location of buildings, configuration of the infrastructure network, and implementation of Sustainable Urban Drainage Systems (SuDS). This will allow for preservation of natural vegetation, minimization of impervious areas, and maximization of infiltration and water quality treatment.

A treatment swale is a SuDS that suits well for dealing with road runoff because it replaces the conventional concrete solution, needed for collecting and conveying the runoff out of the infrastructure, by providing additional water quality and hydrological benefits. Water quality treatment might come through sedimentation, filtration, adsorption, biological uptake, and microbial breakdown. Associated hydrological benefits are groundwater recharge (if allowed), avoidance of erosive velocities, and volume and peak flow reduction.

1.2 Problem statement

Pollutants found in stormwater runoff will affect the quality of receiving water bodies. Pollutants commonly found in road runoff are heavy metals, polycyclic aromatic hydrocarbons (PAHs), pathogens and organic matter, and nutrients (Roy-Poirier et al., 2010b). These pollutants come from non-point sources such as traffic-related activities and emissions (Kayhanian et al., 2007; Sekabira et al., 2010), and atmospheric deposition (Amato et al., 2012). Therefore, urban runoff is expected to be strongly site dependent (Huber et al., 2016d). In regions with snow precipitation, runoff generation (Valtanen et al., 2014a) and pollution (Sansalone and Buchberger, 1996) will in addition be season and weather dependent. Pollutants will be present in different forms influenced by shifting boundary conditions such as pH, buffer capacity, temperature, and organic matter content (Blecken et al., 2011; Huber et al., 2016a). Within pollutants found in urban runoff, the dissolved fraction is more mobile and hence more bioavailable, and thus poses a higher risk for the recipients. However, particle-bound pollutants will deposit and contribute to sediment quality issues affecting benthic organisms, or will decomplexate due to changing conditions in the recipient. In addition, information with regard to metals associated to colloids, in which carcinogenic substances might be significantly present (Nielsen et al., 2015), is limited under cold climate conditions.

Treatment swales are designed for hydraulic roughness and residence times that will enhance the trapping efficiency of suspended solids and particle-bound pollution (Deletic and Fletcher, 2006; Muñoz-Carpena et al., 1999; Stagge et al., 2012). These swales are, in the best scenario, composed of soils such as loamy sands, loams, or sandy loams. Infiltration rates of these soils allow for reducing runoff volumes, good draining, and helping to recharge groundwater (Flanagan et al., 2017; García-Serrana et al., 2017).

In some cases, larger infiltration capacities are required to handle larger runoff events, cold climate constraints (Paus and Braskerud, 2014), or runoff from large tributaries by keeping a certain removal capacity to meet discharge regulations (Huber et al., 2016c). In addition, a good drainage capacity guarantees low moistures in the media, which have been shown to positively impact the volume retention (Lucke et al., 2014). These facts might justify the use of engineered filter media with large infiltration capacity (filtering practice). Therefore, filtering swales that can cope with cold climate constraints as well as offering an outstanding compromise between pollution retention and infiltration capacity seem an interesting option that worth to be investigated for successful further implementation.

1.3 Aims and scope

The overall goal of this thesis was to study the suitability of filtering swales for treating road runoff in cold climates, with special attention to the dissolved fraction of target metals for the NPRA, i.e., Zn, Ni, Pb, and Cu. The engineered filter media assessed in this thesis came up from a multi-criteria study carried out by Ilyas and Muthanna (2016), also within the NORWAT program. Both metal retention and infiltration performance were investigated in order to assess the performance of the candidate filters. Inherent cold climate conditions such as use of de-icers and low temperatures will affect their performance and, therefore, were considered during the experiments.

Field and laboratory studies were performed in order to accomplish the mentioned goal. A sampling campaign was performed to gain insight into the spatial and temporal variation of the runoff quality in the city of Trondheim, in which this thesis has been conducted. The removal of dissolved target metals and the infiltration performance of the candidate filter media were studied in column tests, in which the impact of NaCl and negative temperature could be investigated under controlled boundary conditions. The column test gave insight for choosing the two best media for further investigation of their hydrological performance in a full scale experimental study, and comparison to the performance of a traditional treatment swale. This latter study yielded a series of empirical equations for sizing filtering swales according to local rainfall patterns and volume capture requirements.

1.4 Research questions

In order to assess the suitability of the studied filter media for implementation in filtering swales in cold climates, the following research questions were raised:

Q1: What is the performance of the adsorbent amended filters media with regard to retention of target metals - both under high inflow rates and long inflow durations?

Q2: How is the retention of metals in the filter media affected by the use of NaCl for de-icing?

Q3: What is the infiltration response of these filters when the media is frozen and snow melts? Is there an optimal configuration of the media composing the filters?

Q4: What is the extent of the hydrological benefits of the filtering swales in comparison to a traditional green swale?

Q5: Runoff pollutant concentrations are site and seasonal dependent. Therefore, what is the quality of the runoff in the city of Trondheim? How the target metals are distributed site wise and season wise?

Q6: What is the expected service life of these media? Design guidelines for filtering swales for stormwater management?

1.5 Thesis structure

Chapter 1 has given an introduction to the topic addressed in this thesis. Chapter 2 reviews the main agents that need to be considered in the design of roadside drains in cold climates. Chapter 3 presents the research methodology and experiments performed to accomplish each paper. Chapter 4 summarizes the papers included in this thesis, and Chapter 5 discusses the results in order to answer the research questions. Chapter 6 draws the conclusions from this thesis and outlines some recommendations for future works. The selected papers of this work are given in Appendix A, while the bibliographies and abstracts of the secondary papers are given in Appendix B. Appendix C holds the co-author statements for publishing of this thesis.

Chapter 2: Background

An overview of the most significant actors involved in stormwater managed by swales is provided in this chapter. Cold climate constraints and concerning design guidelines are included.

2.1 Roadside storm drains

Since Roman times, engineers understood the importance of pavement drainage for a proper functioning of the infrastructure network (Dawson, 2008). Excess water on road surfaces due to poor drainage implies a series of consequences that will pose a risk for the users and for the infrastructure itself; road safety (aquaplaning and ice formation), erosion, reduction of the bearing capacity due to saturated subgrade layers (and potential permanent deformation), frost heave, reduction of the pavement life and increased operation costs, among others (Berntsen and Saarenketo, 2005).

Traditionally, grey solutions such as concrete ditches and curb-and-gutter systems have been adopted to cope with road runoff. They are designed for collection, conveyance, and disposal of the excess of rainfall. The down side of these solutions is that they will transport harmful contaminants into receiving water bodies as well as altering the hydrological balance of the site (Davis et al., 2012b). Swales play the same role as the latter solutions but, in addition, can offer aesthetical, hydrological, treatment and cost benefits (Barrett et al., 1998; Kaighn Jr and Yu, 1996), which is in line with SuDS' approach.

Among swales, different practices can be found (Burack et al., 2008) and can be grouped in 4 categories; (1) conveyance swales are specifically designed for conveying runoff at non-erosive velocities; (2) pre-treatment swales will in addition capture a limited amount of large sediment particles and associated pollutants; (3) treatment swales offer higher pollutant removal efficiencies than the others because they are designed for a minimum hydraulic residence time within the channel under design flow conditions, which will guarantee removal of pollution via sedimentation, adsorption, biological uptake, and microbial activity; (4) filtering swales differ from the above swales in that they are composed of an engineered filter media (Figure 1) instead of local soils. This fact will offer additional treatment and/or infiltration benefits at the expense of using a non-native soil.

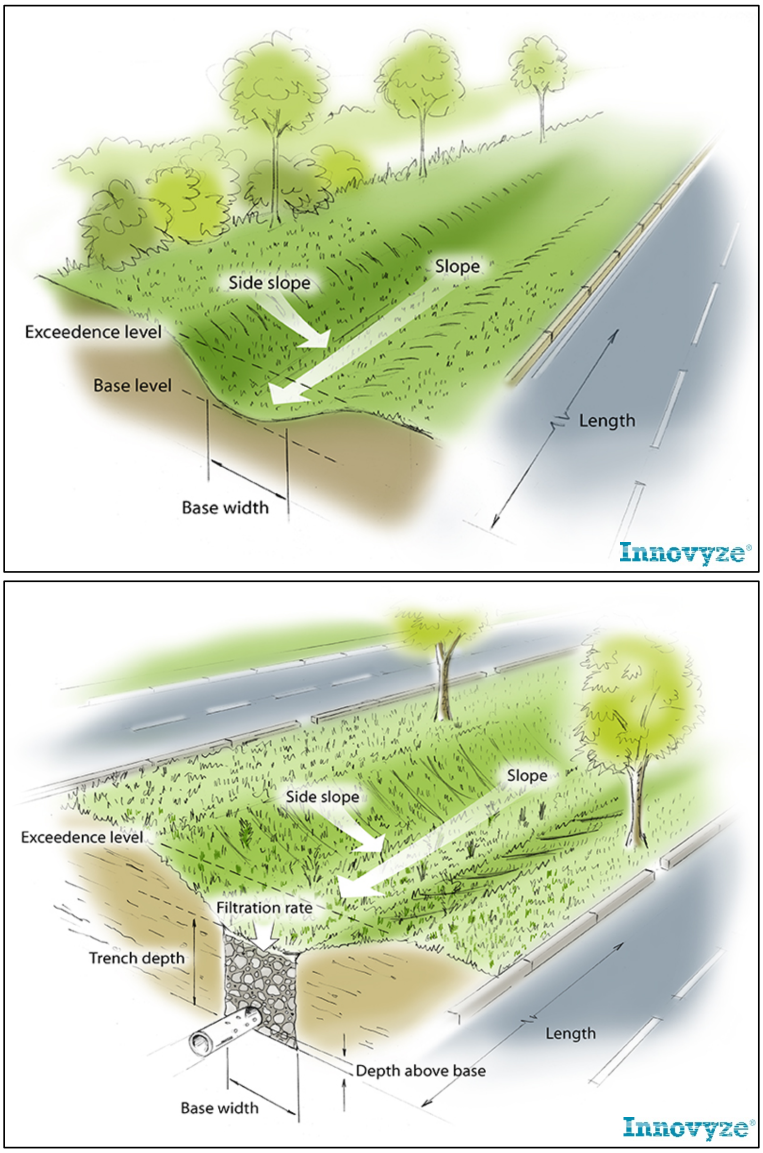

Figure 1. Schematic layout of two vegetated swales. In the top image, an infiltration based swale with local underground soil. In the bottom image, a filtering swale with engineered filter media designed with an underdrain to collect the treated water.

2.2 Runoff pollution

Water quality of stormwater is a concern in urban areas, both for human health aspects as well at receiving water body quality and ecological health (WFD-2000/60/EC, 2000). Sources of solids and pollution from urban surfaces originate from erosion of soil from surrounding land, airborne pollutants, wearing of pavements and vehicle parts, de-icing anti-skid agents, and emissions from vehicles (Gunawardana et al., 2011; Marsalek et al., 2003; Snilsberg et al., 2008). Additionally, the type of pavement will influence the subsequent wash-off and pollutant concentrations in runoff (Wicke et al., 2012).

Pollutants in stormwater runoff will be present in different forms influenced by shifting boundary conditions such as pH, buffer capacity, ionic strength, temperature, and organic matter content (Huber et al., 2016a; Lydersen et al., 2002). The fractionation of the pollution will affect the extent of the impact on the recipient as well as the eventual removal process. Dissolved and low molecular mass species (< 10 kDa) are more mobile and accessible to organisms hence will impact the biota more quickly (Meland et al., 2010). Colloids size varies from the smallest end of the particle size range to larger colloids in the range of clays and very fine silts (Tuccillo, 2006). Toxic metals and other priority pollutants such as polycyclic aromatic hydrocarbons (PAHs) can be found in this size (Nielsen et al., 2015). Particle-bound pollutants will eventually settle and contribute to long-term sediment quality issues affecting benthic organisms as well as being prone to decomplexate due to new conditions at the recipient.

Toxic metals concentrations and fractionations vary among studies due to diverse climates, seasons, and land uses (Huber et al., 2016d). Westerlund and Viklander (2006) found that total toxic metal concentrations were strongly correlated to total suspended solids concentrations during winter time. Helmreich et al. (2010) found variations in concentrations between different seasons but not in their fractionation, being the mean dissolved fractions below 30 % for Zn and Cu, and Pb practically associated to particles. However, Sansalone and Buchberger (1997) found Zn, Cd, and Cu mainly in dissolved form, which was attributed to low rainfall pH and the use of asphalt pavement. In addition, variations in pollutant concentrations are generally found within the runoff event itself, in which higher concentrations and toxicity occur in the initial fraction of the event, a.k.a., first flush (Kayhanian et al., 2012; Kayhanian et al., 2008).

However, most of the runoff characterization studies have been performed in warm or temperate climates, which makes runoff characterization and treatment practices less understood in cold climates.

2.3 Removal performance

The extent of the metal removal in swales depends on the metal fractionation and the design of the system. Pre-treatment and treatment swales are generally designed for a minimum length and a specific hydraulic residence time, respectively. For adequate treatment, runoff should flow over the full length of the swale and therefore it is recommended that the flow enters the upstream end of the swale, instead of the swale collecting runoff along its length (Burack et al., 2008). Treatment of suspended particles and metals associated with them will occur, mainly, through mechanical processes along the length of the swale such as sedimentation and filtration. The size distribution, the density, and the shape of the particles in runoff will affect their settling velocities and, subsequently, the trapping efficiency of the swale (Y. Li et al., 2006; Selbig et al., 2016; Zanders, 2005). On the other hand, the ratio between the particle diameter of the media and the infiltrating particle diameter will determine the dominant infiltration mechanism, i.e., surface straining (small ratios) or depth filtration and other mechanism of separation (large ratios) (H. Li and Davis, 2008). In addition, vegetation might offer a bonus metal removal by biomass accumulation. However, the extent of the plant metal uptake is generally low (Muthanna et al., 2007a) and affected by low temperatures (Blecken et al., 2010a). Hydraulic resistance (Samani and Kouwen, 2002), root growth (Le Coustumer et al., 2012), and activity of earthworms are processes associated to vegetation that are more beneficial performance-wise. Filtering swales can offer, if adequately designed, an enhanced filtration step to promote the removal of colloids and truly dissolved fractions of target metals via cation exchange, precipitation, specific adsorption, and complexation by the filter media (Genç-Fuhrman et al., 2007; Rieuwerts et al., 1998).

2.4 Hydrologic performance

Removal performance should go hand in hand with hydrological benefits, as reducing runoff volumes is an important part of reducing the annual pollutant load, i.e., the product of pollutant concentration and annual runoff volume (Hunt et al., 2011). Additionally, erosion reduction and recharge of groundwater (Cizek and Hunt, 2013) are also expected from a well-functioning swale.

The extent of the hydrological and environmental benefits is mainly influenced by design factors such as the ratio of the impervious area to the swale area, the size of the storm event, and the longitudinal slope determine the overland discharge and flow depth and hence the flow features. The overland flow in swales can be either super- or subcritical. Supercritical flows favour erosion, reduce volume and pollution retention and should therefore be avoided. Subcritical flows, which are less erosive compared to supercritical flows, can be obtained by constructing specific design elements increasing the hydraulic resistance. Such design elements are check dams (Davis et al., 2012a), stones (Narsimlu et al., 2004) and grass coverage (Mishra et al., 2006). The side-slopes of swales can provide a bonus for volume reduction which in turn is positively impacted by the infiltration capacity of the media, soil moisture deficit, and side-slope length (García-Serrana et al., 2017). For vegetated swales, the type of vegetation such as deep-rooting grass species and proliferation of root and earthworm channels improve infiltration (Abu-Zreig et al., 2004; Blanco-Canqui et al., 2004). Swales are recommended to be at least composed of soils such as loamy sands, loams, or sandy loams, to provide proper infiltration rates (Le Coustumer et al., 2009).

2.5 Stormwater design guidelines

Guidelines for sizing SuDS vary widely (Guo et al., 2013; Roy-Poirier et al., 2010a). For example, a water quality volume capture has been adopted in some countries as a design parameter in order to guarantee the removal of the majority of stormwater pollution on an average annual basis. This volume capture generally refers to the volume of runoff generated from a given percentile (normally, between 80th and 90th) of individual 24-hour rain events (Schueler and Claytor, 1996; Urbonas et al., 1989). Swales are flow-based treatment practices and, instead, the water quality flow associated with the water quality volume should be used for sizing (Burack et al., 2008). Hydraulic residence times that guarantee settling of target particle sizes, and flow depths smaller than vegetation height for increasing the roughness coefficient are additional criteria to bear in mind during the design process.

Stormwater is diffuse by nature, and at the time this thesis is being written, there are no applicable Norwegian water quality standards that regulate metal concentrations from non-point sources. SuDS like swales are considered non-point sources and hence do not currently have effluent concentrations standards in Norway. The sensitivity to toxic metals of the receiving water body will vary from one to the other, based on the fauna and flora, the influent pollutant loads, the volume of the water body, the capacity for dilution, etc. Good ecological quality of the water bodies as well as avoiding concentrations of priority pollutants that might pose acute or chronic toxicity to the fauna and flora (EU-EQS, 2007) can be set as a water quality guideline in order to meet the goals set by the EU's Water Framework Directive.

On the other hand, there are commonly local limitations with regard to stormwater that can be introduced into the sewer system. In Trondheim´s local regulations for the case of a typical-size urban catchments, the rational method (Kuichling, 1889) is used to calculate the runoff generated in the tributary, and a safety factor of 1.2 is considered for potential climate change impacts (Trondheim-V.A., 2015). In Oslo, the rational method is also used for dimensioning although the limitations are more restrictive, i.e., the supply of stormwater runoff to the public sewer system must be minimized (Oslo-V.A.V., 2011). For example, the maximum amount of runoff that a combined sewer system might accept from a tributary area of 0.5 ha is 12 and 6 l/s, in Trondheim and Oslo, respectively. If the sewer system is separate the maximum discharge is 25 and 9 l/s, in Trondheim and Oslo, respectively. Therefore, the rest of the stormwater runoff must be retained or infiltrated in the tributary by, preferably, SuDS.

2.6 Cold climate considerations

Climate is mainly determined by long-term records (at least 30 years) of air temperature and precipitation near the earth´s surface of an area. Cold or continental regions have at least one month averaging below 0 °C (32 °F) and at least one month averaging above 10 °C (50 °F) (Peel et al., 2007). Globally, 24.6 % of the earth´s surface can be classified as cold. In Europe, Asia and North America cold climate is the dominant type with 44.4, 43.8 %, and 54.5 %, respectively.

Unlike temperate climates, cold regions will introduce some limitations to the operation of SuDS. The hydrology and pollutant transport of the area will be impacted by periods with snow accumulation and, subsequently, melting during short warm days in winter or in the early spring. Snowmelt peaks are substantially less than those from warm periods with rainfall-runoff events, however the total event volume of a snowmelt can be substantially larger (Minnesota-SW.S.C., 2008). In addition, imperviousness and land use of the catchment will influence the occurrence of rainfall and snowmelt runoff events (Valtanen et al., 2014b). Snow piles might store up to 50% of the total suspended solids generated in the catchment (Sillanpää and Koivusalo, 2013). Consequently, during snow melting and rain-on-snow events, the number of particles will be considerably larger (Westerlund and Viklander, 2006), which will accelerate the clogging process of the upper layers in infiltration based filters, leading to inoperative systems.

Under negative temperatures, the soil will be a four-phase system composed of solid particles, unfrozen water, ice, and air (Stähli et al., 1996). The states at which media moisture will be present in the column are strongly believed to impact its infiltration response. Blockage of pores with ice is the main mechanism by which infiltration is restricted in frozen soils (Seyfried and Murdock, 1997). However, a fraction of the soil moisture will remain unfrozen (Watanabe and Wake, 2009), which will affect the thermal balance of the media by reducing ice formation. Therefore, materials with high unfrozen water content are beneficial with regard to the ice prevention and, consequently, volume attenuation during "shock" incoming loads of pollution.

Low temperatures will to some extent impact the removal of pollutants. A study by Blecken et al. (2010b) showed that phosphorus was removed by bio-filters at high percentages (> 90 %) because it is mainly bound to particles, and sedimentation-filtration processes are not affected by low temperatures. However, the removal of nitrogen, being a biological process and hence temperature dependent, was poor. With regard to metals, the performance is still effective at low temperatures because the removal processes, except plant uptake, are temperature independent (Blecken et al., 2010a; Muthanna et al., 2007b).

In urban areas, use of de-icers is a common practice for preventing snow accumulation (Caraco and Claytor, 1997). NaCl has a low cost and is readily available, which makes it commonly used. However, its application implies a series of environmental consequences; (1) impact on macroinvertebrate species; (2) creation of anoxic denser zones near the lake bottom due to incomplete mixing; (3) corrosion; (4) damage to nearby vegetation; (5) contamination of drinking water sources, etc. In infiltration based practices, the mobilization of already adsorbed metal cations due to ion exchange, competition of sodium with metal cations for sorption sites on the filter material, and complexation with chloride is of special concern (Huber et al., 2016b). In addition, the use of NaCl can negatively impact the soil structure and fertility due to migration of Ca, Mg, and organic matter (Amrhein et al., 1992).

2.7 Adsorbents

Adsorbents are porous materials that can enhance the retention of colloids and dissolved elements (adsorbate) from aqueous solutions on their surface. The main adsorption mechanisms are ion exchange and surface complexation, whose extent will vary according to boundary conditions such as charge density and structure of the adsorbent, and pH, concentration and type of competing ions in solution (Krall, 2012). The origin of adsorbents for metal retention differs widely (Babel, 2003; Huber et al., 2016a; Wium-Andersen et al., 2012); wastes from industrial operations such as fly/bottom ashes, sawdust, blast furnace slag, lignin, iron hydroxide, etc.; natural materials such as zeolites, shell-sands, clays, chitosan, etc.; low rank coal such as lignite; as well as processed products such as granular activated carbon, granular activated alumina, granular ferric hydroxide, etc. Generally, adsorbents are ranked according to their removal performance for target pollutants. However, in practices for filtering stormwater runoff, criteria such as initial costs, availability, environmental impact, end-of-life care, etc. should be also considered for a potential field implementation (Ilyas and Muthanna, 2016).

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Chapter 3: Research Methods

Three different research methods were applied in this work; a field sampling campaign, a laboratory column setup, and a laboratory swale setup. The combination of them allowed for a complete study considering the main actors in filtering swales for stormwater management in cold climates. A description of the methods is presented in this chapter following the sequence of the studies composing this thesis.

3.1 Field sampling campaign

The campaign was carried out over the course of 17 months in order to characterize the runoff in the city of Trondheim (warm-summer humid continental climate in the Köppen-Geiger classification) and to understand its fluctuations between seasons and among three different sites. The selection of the sites was based on the possibility of retrofitting SuDS along the roadside, the annual traffic loads, and the proximity to the research institute to facilitate the first fraction of the runoff as manual samples were taken.

Manual grab samples were adopted for this study to study actual road runoff. Therefore, mix with other water sources or previously deposited runoff as well as possible contamination and interferences associated to automatic samplers were avoided. Samples were taken right at manhole inlets (Figure 2). Hyetographs provided by nearby rain gages (approx. 500 meters from sampling locations) were used to estimate the runoff generated on the tributary road area by the rational method and, subsequently, the partial event mean concentration (PEMC) (Sansalone and Buchberger, 1997).

At site 1 samples were taken from the beginning of the runoff event, and at 5 min intervals in the first 30 min. The intervals were stretched as the runoff event progressed to collect a larger number of points in the early part of the runoff event. For the other sampling points and for events where it was not possible to collect the first flush, a single grab sample at a known time was collected.

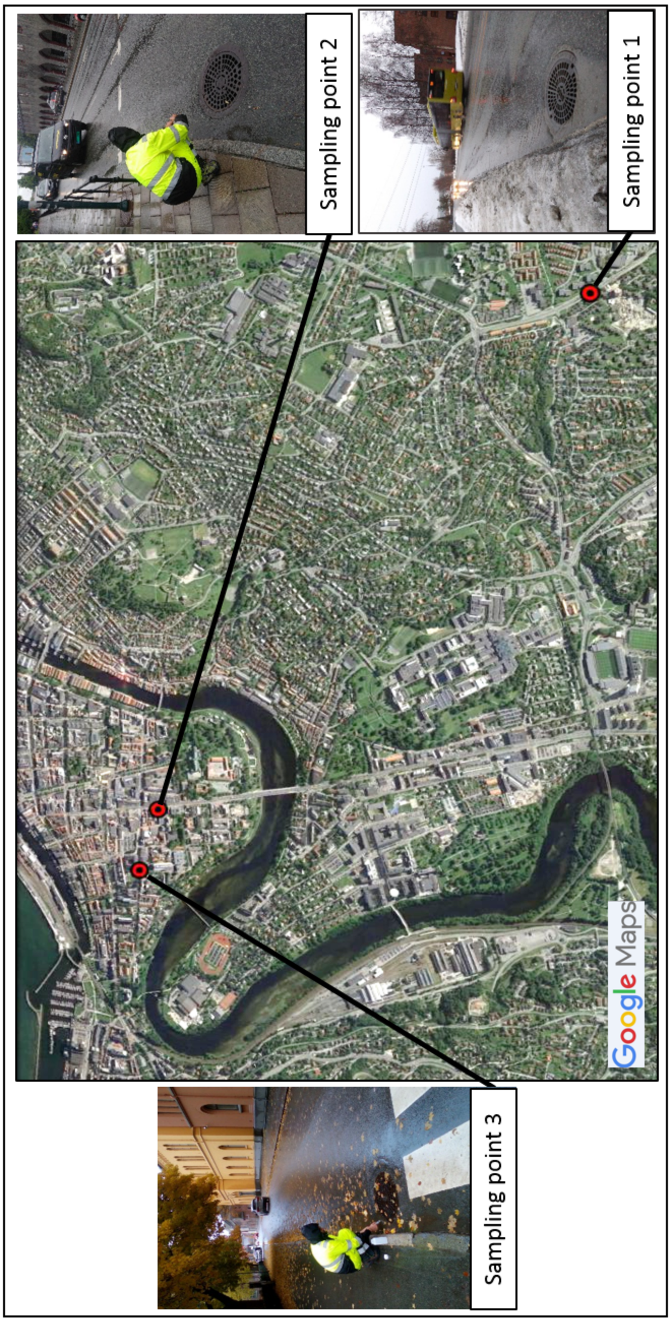


Figure 2. Sampling point 1 corresponded with an arterial road (Jonsvannsveg, Annual Average Daily Traffic (AADT) = 10500 vehicles), sampling point 2 corresponded with one of the streets with more traffic in Trondheim (Prinsens gate, AADT = 22140 vehicles), sampling point 3 took place in a residential street in downtown (Erling Skakkes gate, AADT = 2900 vehicles).

In order to study the seasonal impact on the water quality of the runoff, the data set was classified in two periods according to the salinity concentration, i.e., salting and rain season. During salting season, the presence of snow was practically inexistent in comparison to the size of the tributary area (Figure 3). Therefore, in rain-on-snow events, it was assumed that the snowmelt contribution to the runoff volume was negligible. This assumption allowed for computing the PEMC during the salting season with the data from the hyetographs. This implied that pollutant loads associated to the neglected snowmelt were disregarded in the calculations. However, this contribution was assumed irrelevant in comparison to the pollution generated on the much larger drainage area.

Figure 3. Runoff events during salting season at different sampling sites. The main tributary area was assumed clean from snow during sampling.

The characterization of runoff included the following parameters; pH, conductivity, salinity, turbidity, total suspended solids (TSS), total dissolved solids (TDS), volatile suspended solids (VSS), volatile dissolved solids (VDS), and particle size parameters such as D_{90} (which is the intercept for 90 % of the cumulative volume of the particle size distribution), D_{50} and D_{10}. Additionally, toxic metals (Lead, Nickle, Copper, and Zinc) were analysed regarding the total content, as well as abundance in the size fractions suspended matter (> 1.2 µm), colloids including fine clay-sized particles (< 1.2 µm and > 1 nm), and dissolved matter (< 1 nm). Analytical methods and standards followed during the analysis of the above parameters are referred in section 3.4.

3.2 Column tests

Colum tests were chosen to explain metal removal (Paper II) and infiltration (Paper III) processes under controlled and stable conditions and assess the performance of the candidate filters proposed by (Ilyas and Muthanna, 2016). Plexiglas columns (450 mm long and 100 mm diameter) were constructed and used in these studies (Figure 4). The ratio column diameter to media diameter was greater than 50, which is recommended for filtration studies (Lang et al., 1993). A plastic nozzle (6 mm inner diameter) was embedded in the middle of the bottom lid to convey infiltrated water out of the column. The filter media in the columns were volumetrically composed of 35 cm sand and 5 cm of adsorbent (pine bark, olivine or charcoal).

3.2.1 Dissolved metal retention

The filters were tested for removal of four concerning metals (Cu, Pb, Ni, and Zn) for the NPRA. Three columns were set up for each filter media including a control column that was packed only with sand. All columns were operated at room temperature (20 ± 2 °C) and the tap water used to produce the synthetic stormwater was at 8 ± 2 °C. Multichannel peristaltic pumps with variable flow were used for pumping the synthetic stormwater (Figure 4). The target metals were added in a quantity to achieve intended concentration of 1 mg/L for each metal in the 1 m3 influent tank of synthetic stormwater. The reason behind these high concentrations was to be able to detect concentrations at the effluent and to reach exhaustion of the adsorption capacity in a realistic period of time. Samples were collected from the effluent of every column and analysed for the target metals. After the collection, samples were filtered through cellulose-nitrate 0.45 µm pore size filters for analysing the dissolved fraction of the studied target metals, and preserved with 0.1 M HNO_3 acid.

The study was divided in two phases (Table 1). In the first phase flow rates, the objective was to verify the adsorption capacity of the filters under high hydraulic loads, in terms of inflow rates. After this step, one of the two duplicate columns for each media was taken aside to study the effect of road salt on the desorption of already immobilized metals. In the second phase, long-term operation was the objective, and the study continued in each of the remaining columns for 2.5 months (Table 1), in which high hydraulic loads in terms of volumes were used.

Table 1. Average volumes per column (AV) and hydraulic loading rate (HLR) used during the two phases of the study in Paper II. CRT stands for column running time.

Influent Type	Experiment Phase	AV (L)	HLR (cm/h)	CRT (Days)
Synthetic stormwater	1	50	47	0.6
Salt water	1	50	47	0.6
Synthetic stormwater	2	2500	18.8	73

Figure 4. Column setup during the toxic metal pump into the adsorbent amended filters.

The results from the second phase were used to estimate cumulative retention capacities of the different adsorbent amended filters for the target metals under the given conditions. The expected service life (year) was obtained dividing the expected cumulative pollutant retention at a required removal by the pollutant load expected to be treated by the filtration facility (Equation 1). The required removal was based on Norwegian quality guidelines for moderate contamination of the receiving surface waters (Andersen et al., 1997), which are more restrictive than values set by the European Water Framework for surface waters (EU-EQS, 2007).

$$service\ life\ (year) = \frac{\dfrac{RC\left(\dfrac{mg}{kg}\right)\cdot \mathrm{DH}(m)\cdot \mathrm{DS}\left(\dfrac{kg}{m^3}\right)}{\dfrac{I}{P}}}{\mathrm{IC}\left(\dfrac{mg}{m^3}\right)\cdot AP\,(m)\cdot \mathrm{C}\cdot \mathrm{VC}} \tag{1}$$

In the above equation, RC stands for retention capacity at required removal, DH for depth of the filter, DS for density of the media, I/P for ratio impervious area to pervious area, IC for input runoff concentration, AP for annual precipitation, C for empirical runoff coefficient, and VC for required capture of runoff volume.

3.2.2 Infiltration capacity

In this study, a constant head permeameter based on Smoltczyk (2003) was used to obtain the saturated hydraulic conductivity, K_{sat} (mm/s), of the filters, which was used to evaluate their infiltration capacity under temperate conditions (Figure 5). Different potential configurations were studied; pine bark was studied at the top and at the bottom of the sand layer, charcoal was studied in the three possible configurations (underlying the sand layer, overlying the sand layer, and homogeneously mixed with sand, and olivine in the homogeneously mixed and the underlying configuration.

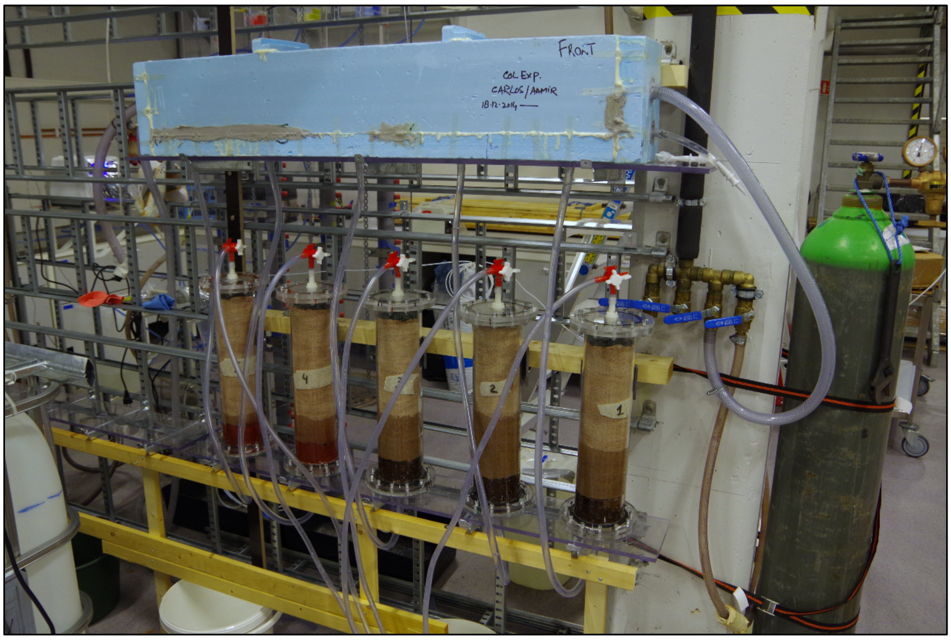


Figure 5. The blue reservoir applied a constant head pressure to the bottom of the columns. The height of the effluent (on the upper side of the columns) set the pressure on the media surface.

After the permeameter test, an additional column setup was conducted for evaluating the infiltration response of the filters under freezing/thawing conditions (Figure 6), which are typical of late winters and/or early springs in cold coastal regions. Under these conditions, soils might be partially frozen, and snowmelt intend to infiltrate through. The sequence followed to replicate this process in the laboratory was firstly to adjust the media moisture in the columns (saturated or drained for 24 hours), and insulate them laterally with Climcover Tube Alu2 (50 mm thickness and λ=0,036 W/m*K) and underneath with extruded polystyrene Styrofoam 400 SL-A-N (50 mm thickness and λ=0,001 W/m*K). Therefore, the freezing front will follow a downward direction similar to field conditions. Secondly, the columns were introduced into a cold chamber set at -5°C until the filter temperature was -2.5 ± 0.2 °C, which was monitored with thermocouples type T. The third step was to pour tap water at +2 ± 0.5 °C on the surface of the column. At this stage, the water level was kept constant at 5 cm and the room temperature at +2 °C throughout the duration of the infiltration test.

Two variables were adopted to evaluate the infiltration response under freezing/thawing conditions; one variable was the time passed from the beginning of the test until discharge from the partially frozen media was observed, i.e., breakthrough discharge time (BDT). The second variable was the decrease in infiltration rate (DIR) after the first 24 hours from the breakthrough.

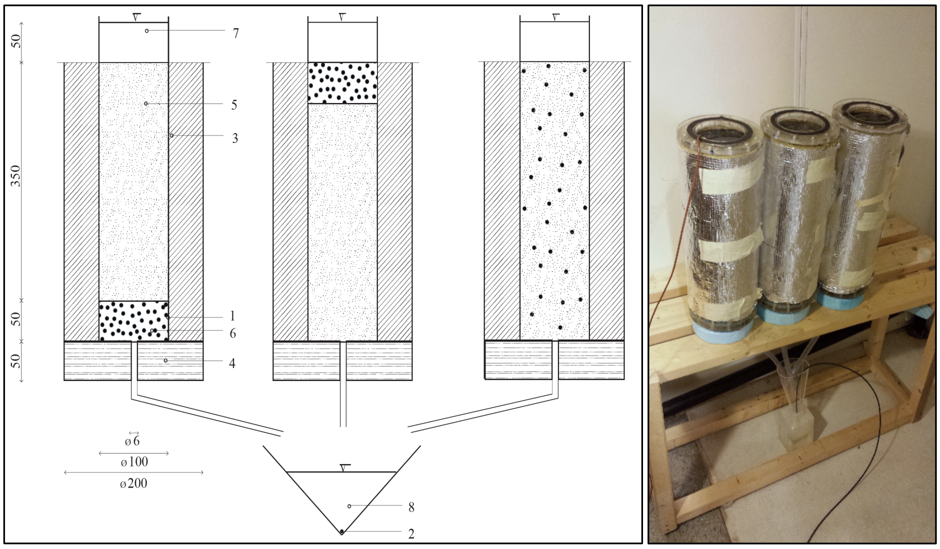


Figure 6. Layout of the column setup (left) used for simulating freezing-thawing conditions with three possible media configurations. 1 = thermocouple for controlling temperature in the media; 2 = actuator to detect infiltration from the column; 3 = lateral insulation; 4 = bottom insulation; 5 = sand; 6 = adsorbent; 7 = ponding water at +2 ± 0.5 °C; 8 = infiltrated water. Insulated columns inside the cold chamber (right). Units in mm.

The contact method for determining the unfrozen water content of the materials and x-ray micro computed tomographic imaging were used to support the results from the column test. These methods are presented in section 3.4, and more in depth in Paper III.

3.3 Swale setup

The results from Paper II and III were used to decide the filters composing the filtering swales in the full-scale setup. In addition, a third swale was composed of a sandy loam soil, typical for bioinfiltration practices (Figure 7). The dimensions of each tiltable swale were 500 cm long, 45 cm deep, and 80 cm wide. Pine bark and olivine amended filters were used in swale 1 and swale 2, respectively. Swales 1 and 2 were superficially protected with boulders (D_{50} = 70 mm; approx. 256 boulders/m2). In line with traditional treatment swales, swale 3 was vegetated with Festuca Rubra Rubra (Leik), a species tolerating cold climates and potential salty conditions.

Each swale was equipped with 6 profile probes PR2/4-SDI-12 from Delta-T Devices Ltd, and each profile had three moisture dielectric sensors distributed along the vertical, resulting in a total of 18 moisture sensors per swale. The moisture sensors allowed for delimiting the phases within each experiment, which made it possible to compare experiments with different boundary settings (Table 2). A 1 m3 tank filled with tap water provided the inflow discharge, which was controlled by a valve and measured with an electromagnetic flowmeter (Siemens Sitrans FM MAG 5000; accuracy ± 0.4 % of the flow rate). The other parameters needed for a water balance, i.e., run-out and infiltrated water were collected separately in two downstream tanks of 0.72 m3 (1.1 m wide, 1.1 m long, and 0.6 m height) and 0.21 m3 (0.5 m diameter and 1.1 m height), respectively. The water surface level in these tanks was measured with ultrasonic sensors (Microsonic mic+130/IU/TC; average resolution 0.4 mm and ± 1 % accuracy) with a sampling frequency of 1 Hz allowing for the determination of the accumulated water volume in the tanks as a function of time.

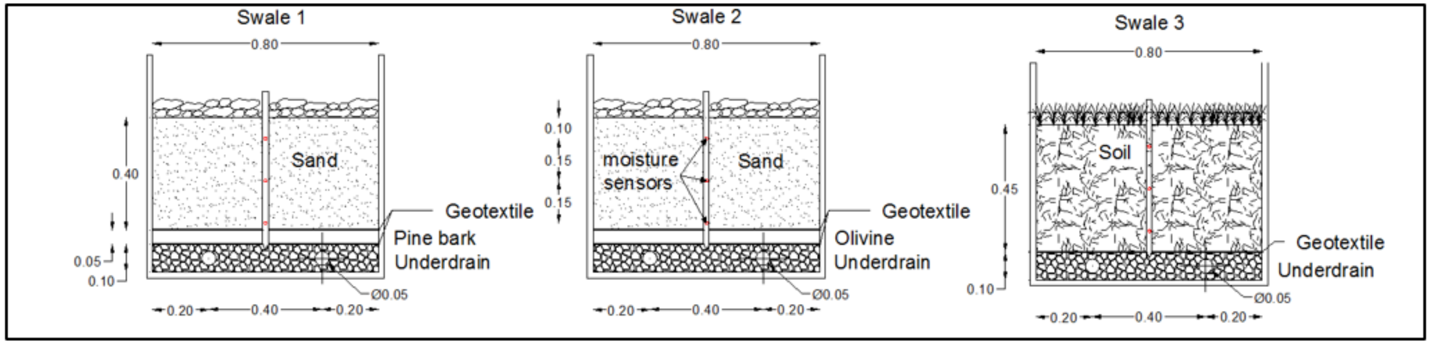
Table 2. Range of the experimental boundary conditions. S_{r0} stands for initial degree of saturation, $Q_{run\text{-}in}$ for inflow discharge, and S_{rmax} for the maximum degree of saturation reached during a simulation. K_{sat} was obtained with the MPD infiltrometer method.

Swale	**K_{sat} (m/s)**	**$Q_{run\text{-}in}$ (m^3/s)**	**Slope (%)**	**S_{ro}**	**S_{rmax}**
Swale 1	$(6.45 \pm 1.35) \cdot 10^{-4}$	0.2-1	2-4	0.51-0.67	0.67-0.91
Swale 2	$(5.59 \pm 1.14) \cdot 10^{-4}$	0.2-1	2-4	0.56-0.72	0.70-0.97
Swale 3	$(6.53 \pm 1.04) \cdot 10^{-5}$	0.2-0.7	2-4	0.71-0.91	0.95-1

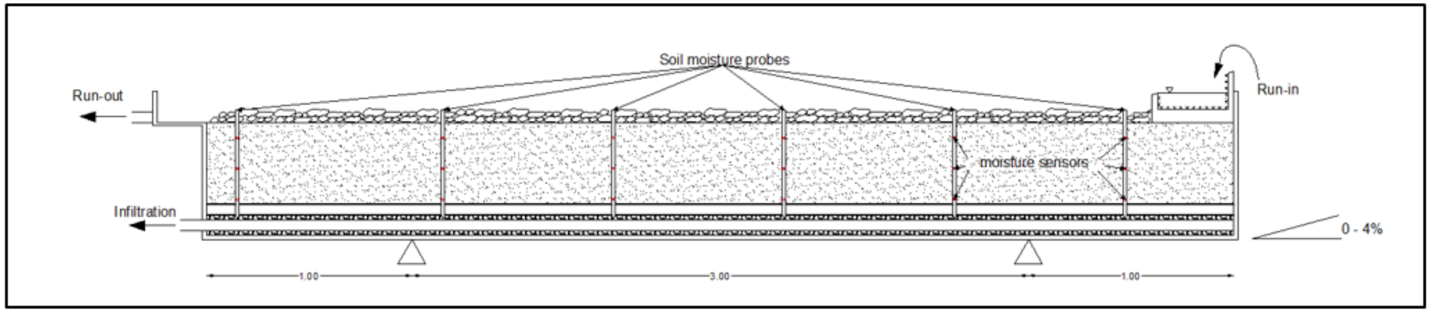
Dimensionless multiplicative models composed of factors that have been shown to influence the infiltration and drainage performance of swales were developed to explain infiltration and drainage performance in the swales. The infiltration performance (Q_{inf}) was modelled according to equation (2) as a function of the media type (K_{sat}), the longitudinal slope (J), and the inflow rate ($Q_{run\text{-}in}$). The decrease in media moisture in the first 20 minutes after stopping the inflow, ΔS_{r20} (%), was adopted as the parameter to assess the drainage capacity of the swale. The draining process was modelled according to equation (3) by the media type, the longitudinal slope, and the maximum degree of saturation reached during a simulation (S_{rmax}).

$$\frac{Q_{inf}}{g^{1/2}(wd)^{5/4}} = A\left(\frac{K_{sat}}{g^{1/2}(wd)^{1/4}}\right)^{\alpha} J^{\beta}\left(\frac{Q_{run-in}}{g^{1/2}(wd)^{5/4}}\right)^{\gamma} \tag{2}$$

$$\Delta S_{r20} = B\left(\frac{K_{sat}}{g^{1/2}\left(wd\right)^{1/4}}\right)^{\rho} J^{\sigma} S_{r_{max}}{}^{\tau} \qquad (3)$$


Swale 1
0.80
Sand
0.40
0.05
0.10
Geotextile
Pine bark
Underdrain
Ø0.05
0.20
0.40
0.20
Swale 2
0.80
0.10
0.15
0.15
moisture
sensors
Sand
Geotextile
Olivine
Underdrain
Ø0.05
0.20
0.40
0.20
Swale 3
0.80
Soil
0.45
0.10
Geotextile
Underdrain
Ø0.05
0.20
0.40
0.20

(a)


Soil moisture probes
Run-out
Run-in
moisture sensors
Infiltration
0 - 4%
1.00
3.00
1.00

(b)

(c)

Figure 7. Sketch of the setup of swales 1 to 3 (a). Lateral view of a swale composed of an adsorbent amended filter (b). Top view of the swale setup, from left to right, swale 1, swale 2, and swale 3 (c). All dimensions are given in meters.

In equations (2) and (3), A, α, β, γ, ρ, B, σ, and τ are dimensionless coefficients which were parameterized using the data acquired in the experiments

Finally, the rational method was combined with the infiltration model defined by equation (2) to estimate volume capture performances according to storm intensities and size of the drainage area.

3.4 Laboratory methods

Samples from the runoff sampling campaign (Paper I) were preserved at 4 °C and analysed within 48 hours, except metals. Analysis procedures for the parameters characterizing the stormwater runoff were as follows; size distribution of the particles was measured with a Beckman Coulter LS230 Laser Diffraction Particle Size Analyzer; determination of suspended solids was carried by filtration through glass fibre filters (average nominal pore of 1.2 micrometres) according to NS-EN-872 (2005); the volatile fraction was obtained by ignition of the solids at 550 °C for one hour; conductivity and salinity were measured with a conductivity meter LF537 and a WTW Tetracon 96 probe, and temperature corrected for 20 °C; and turbidity was measured with a turbidity meter HACH 2100N. Sub-samples for analysis of target metals were preserved by adding five drops of ultrapure 0.1 M HNO_3, stored at 4 °C, and analysed externally by the Chemistry Department at NTNU in bulk batches throughout the sampling period. For analysis of total metal concentrations, the samples were previously digested with an acid mixture of 2 ml of HNO_3 and 1 ml H_2O_2, and processed in a microwave oven for 50 min at 160 °C. A high-resolution inductive coupled plasma HR-ICP-MS instrument from Thermo Fisher Scientific was used for analysis of metal concentrations in the different metal fractionations. Each individual sample was scanned 3 times and corrected for blank samples. The quantification detection limits for Ni, Zn, Cu and Pb were 0.015, 0.025, 0.03, and 0.002 µg/l, respectively. HR-ICP-MS was also used for determining metal concentrations in the column study (Paper II).

Mechanical and chemical properties of the sand and adsorbents (Paper II, III and IV), size distribution of the particles was obtained with a sieving machine according to ISO-17892-4 (2016). The particle density of the materials was obtained with the pycnometer test (ISO-17892-3, 2015). The proctor compaction test (ASTM-D698, 2002) was used to determine the maximum dry density of the sand. Specific surface area of the materials was externally analysed by the Chemistry Department at NTNU according to the Brunauer-Emmett-Teller test. Hygroscopic moisture was obtained by mass difference between air dried and oven dried samples in accordance to ISO-17892-1 (2014).

The contact method (Ershov et al., 1978) was used to determine unfrozen water content curves of the studied materials. This test was performed individually in every material as well as in two mixtures, i.e., mixture 1 composed of sand and charcoal (5 % in weight) and mixture 2 composed of sand and olivine (17% in weight). The test was conducted in triplicates at -2, -3, -5, and -11 °C (Figure 8).

X-ray micro computed tomographic images of the studied materials at -2.5 °C (as the temperature intended in the column test) were obtained to visualize the internal structure of the media in the columns, at the micron scale. This was performed with a XT H 225 ST micro computed tomographic system from Nikon Metrology NV. The freely available ImageJ software as well as GeoDict were used for further processing and pore space analysis. A typical procedure is illustrated in Figure 9 based on the horizontal slices for olivine.

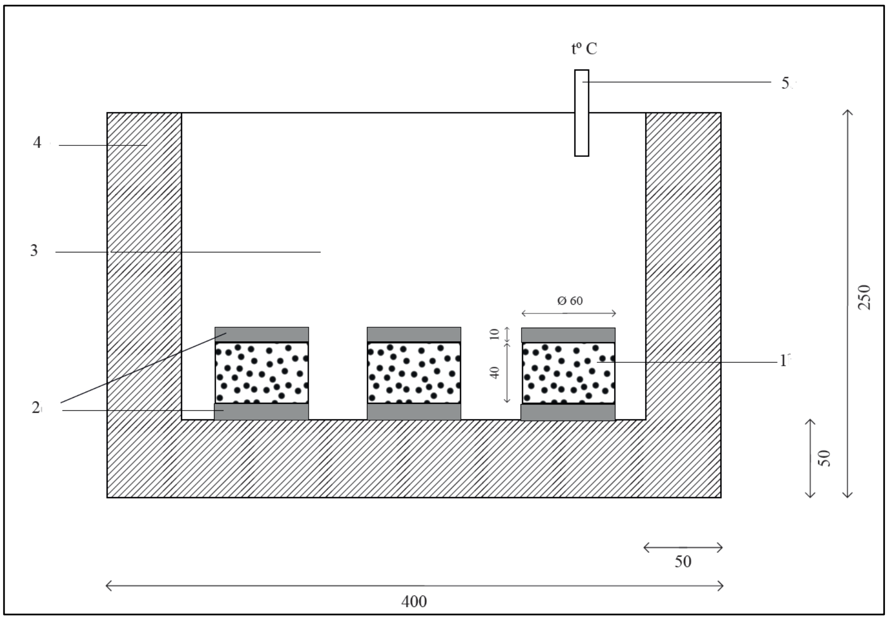
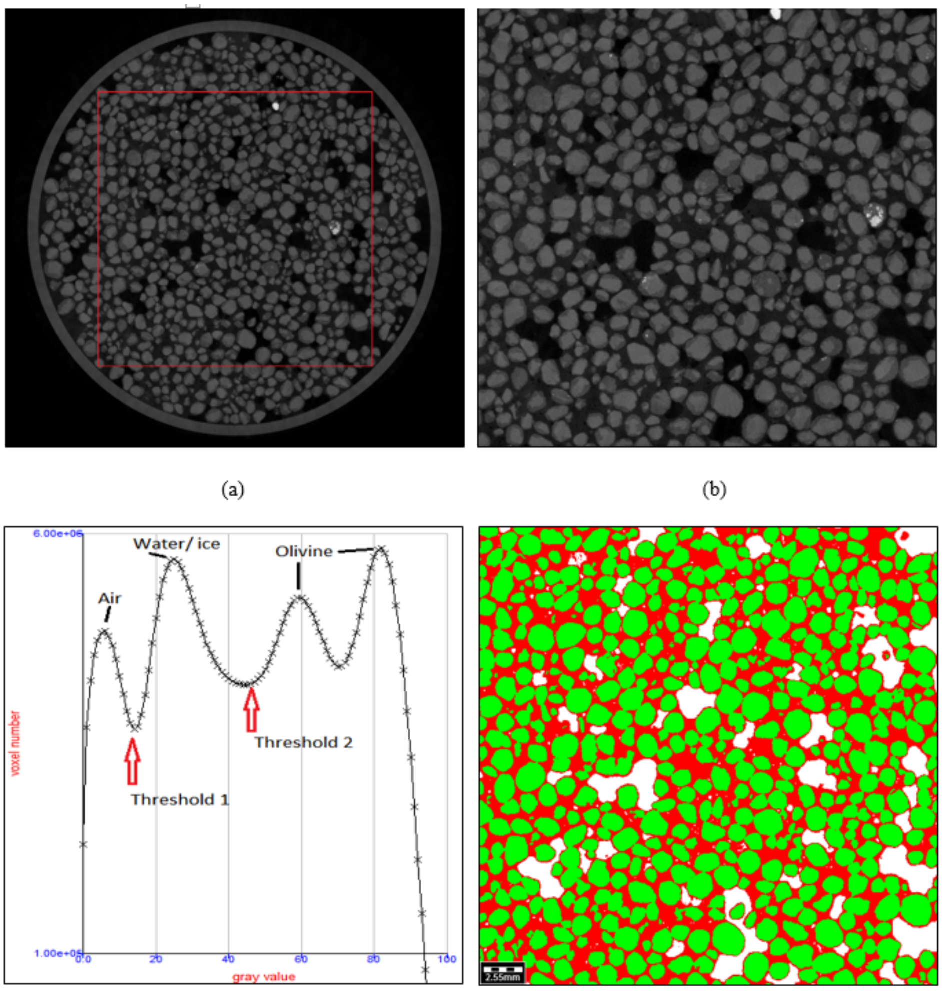


Figure 8. Layout of the contact method setup. 1 = dry sample; 2 = ice lens; 3 = cooling box; 4 = insulation; 5 = thermometer.
Units are in mm.



(a) (b)

(c) (d)

Figure 9. Schematic conversion sequence from raw image (a and b) to segmented image (d). The X-ray absorption histogram (c) is presented with the thresholds that split into individual elements. This allowed for representing the segmented image; water content is represented in red colour; particle content in green colour; air in white colour.

3.5 Statistical analysis

In Paper I, the amount of collected data allowed for analysis with statistical tests. Urban runoff parameters are, in most cases, not normally distributed due to the presence of outlying data points (Helmreich et al., 2010). Therefore, Kolmogorov-Smirnov test was performed in order to evaluate the normality of the studied parameters. Due to their non-normal distribution, correlations among parameters was studied by using the nonparametric Spearmen rank-order. Additionally, the Mann-Whitney test was used to study whether the seasonal differences in partial event mean concentrations (PEMC) were statistically significant. The Mann-Whitney test was chosen because the parametric assumption was not satisfied (non-normal distribution) and the samples were considered independents. The level of significance, α, was set at 5 %. In addition, Box-Whiskers were used for understanding distribution properties of the parameters used for characterizing the urban runoff.

In Paper IV, data collected from the experiments were considered normally distributed. The models were transformed into log-log-space to facilitate multiple linear regression analysis. The parametric ANOVA test was used to obtain statistically significant factors as well as the estimates of the associated coefficients in the empirical dimensionless models. A p-value < 5% allowed for rejecting the null hypothesis and, subsequently, the coefficient associated to the dimensionless factor was considered $\neq 0$.

In Paper II and III, the amount of data allowed for presenting the results by the mean (to measure the centre of the data set) and the standard deviation (to measure the data spread).

Chapter 4: Summary of the selected papers

This chapter presents the results from the field campaign, the column tests, and the swale test. Summaries of the four international scientific papers are presented, focusing on the motivations, relevant findings and connections to each other. The full version of the selected papers is provided in Appendix A.

4.1 Paper I

Characterization and seasonal variation of urban runoff in cold climate - design implications for SuDS

Stormwater runoff is known to be site and seasonal dependent, which motivated a sampling campaign in the city where the work has been performed. This paper characterizes the runoff in Trondheim (warm-summer humid continental climate in the Köppen-Geiger classification), and link seasonal and site fluctuations with the aim to improve design of SuDS in cold climates. The study differentiates between several particle fractions, including colloids. In addition, it contributes to enlarge the limited information in cold climate concerning runoff quality and, therefore help to interpret the impact of factors such as urbanization and altering urban traffic patterns.

This paper characterizes stormwater runoff with respect to metal fractionation, particle size distribution, and standard water quality parameters in Trondheim, Norway. Actual road runoff was sampled at the three different sites, and samples were divided in two seasons according to the salinity measured in the runoff, i.e., salting and rainfall season. Strong seasonal and spatial variations were found in all studied parameters (Figure 10). Suspended and dissolved solids showed four-fold and six-fold increase, respectively, during salting season. Metals associated to the colloidal fraction were extremely low compared with the suspended fraction (>1.2 µm), which was the most polluted fraction for all periods. It was noted that target metals were practically associated to suspended solids during all periods. However, dissolved fraction, being the most toxic, was found in higher quantities during rainfall season. Weak correlations between salinity and dissolved fraction of metals led to assume that higher metal loads in winter season can be explained by corrosion and abrasion rather than metal mobilization through chloride complexes. In general, roads with high traffic density yield larger concentrations of most parameters although residential streets might serve as a source of pollutants due to lack of regular cleaning and maintenance.

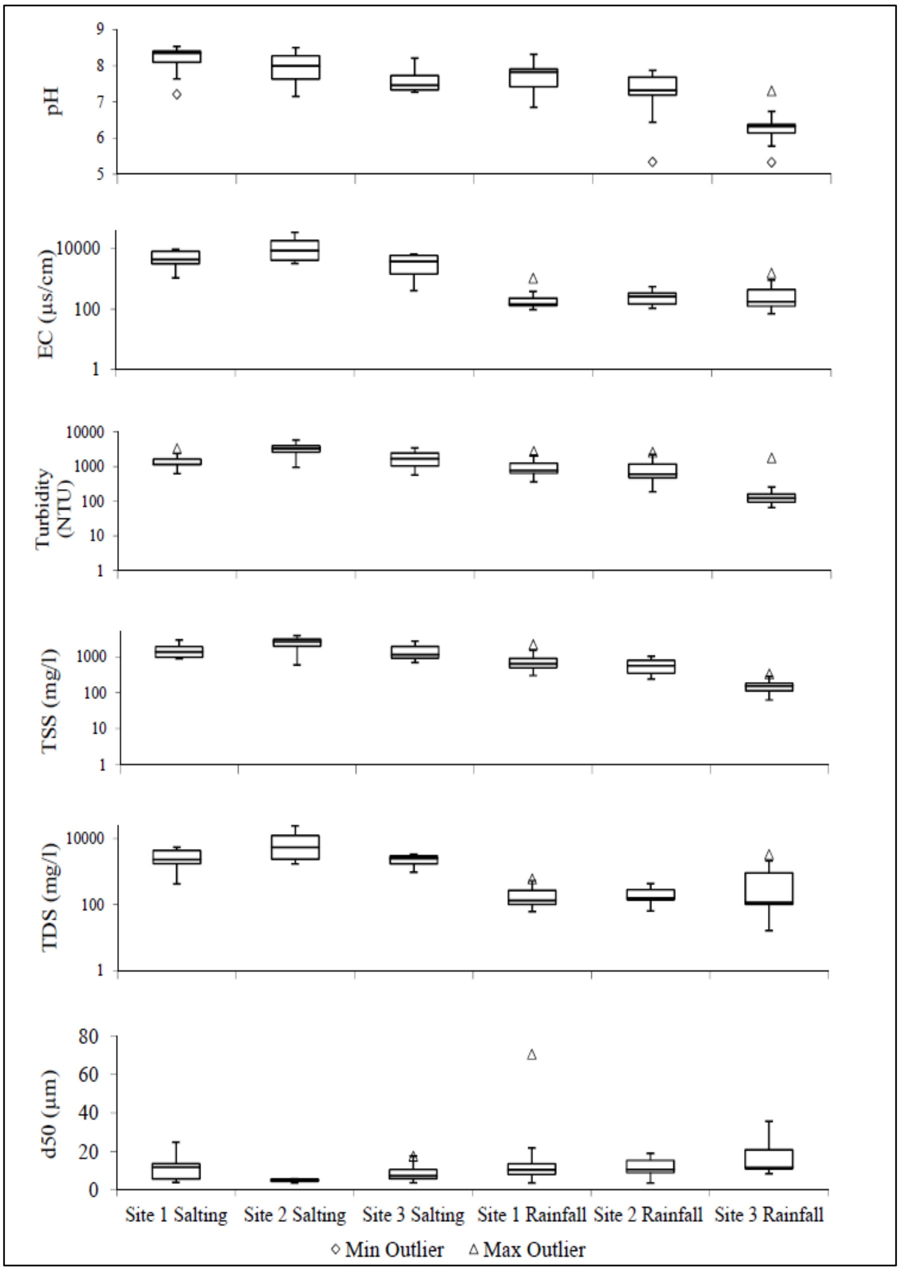


Figure 10. Box-and-Whisker plots for different runoff parameters. Upper and lower bounds of box refer to Q3 and Q1; 3rd and 1st quartile. Upper and lower bound of bars refer to max and min value within Q3+1.5·(Q3-Q1) and Q1-1.5·(Q3-Q1), respectively. Values off these boundaries are considered outliers. Note the logarithmic scale of the y-axis of TSS, TDS, turbidity and conductivity.

In average, dissolved metals were lower than quality standards except Cu, which was similar in concentrations as highly polluted tunnel runoff. Despite this, continuous untreated runoff into sensitive water bodies might justify the use of specific solutions such as adsorbent amended filters for treating the most bio-available metal fraction. In addition, Sustainable Urban Drainage Systems (SuDS) should be protected and adapted against excessive winter pollution loads, rather than oversizing or setting them offline. This will add robustness to the design, which is important for dependable functionality.

4.2 Paper II

Pilot Scale Testing of Adsorbent Amended Filters under High Hydraulic Loads for Highway Runoff in Cold Climates

The motivation behind this paper was to explore the use of adsorbent amended filters for handling dissolved toxic metals, which are commonly found in urban runoff and pose a threat to aquatic habitats. The proposed filters were tested in columns under high hydraulic loads in order to evaluate their response when large tributaries or infrequent storm events are expected to be managed with a certain pollution removal. Salt impact on the desorption of already mobilized metals was studied to evaluate the suitability of these filters in cold regions, where the use of de-icers is expected. Additionally, their life expectancy was estimated by considering cumulative sorption capacities at a required removal based on official discharge limitations and pollution loads obtained from the sampling campaign performed in Trondheim.

From previous theoretical and laboratory analysis granulated activated charcoal, pine bark, and granulated olivine were chosen as alternative adsorbent materials for this study. The objectives were to evaluate the effect of high hydraulic loads and the application of de-icing salts on the metal (copper, lead, nickel, and zinc) retention performance of these filters. High removal of input metals was achieved both under high inflow rates (during a short period of time) and long-term metal dose (more than 1500 pore volumes). Among the filters, the filters amended with olivine or pine bark provided the best performance both in short and long-term tests. In contrast, the filter amended with charcoal showed the lowest affinity with the target metals, and it was the only one that reached metal exhaustion (for Ni, and nearly for Zn). The addition of NaCl (1 g/L) did not show any adverse impact on the desorption of already adsorbed metals, except for Ni removal by the charcoal amended filter, which was negatively impacted by the salt addition.

In addition, this paper presents an estimation of the service life of these filters (Table 3). No official regulations with regard to discharge concentration from SuDS existed at the time the study was conducted. Therefore, this estimation was performed according to Norwegian water quality guidelines for moderate contamination of the receiving surface waters (Andersen et al., 1997). The service life of the filters was found to be limited by zinc and copper, due to high concentrations observed in local urban runoff, combined with moderate affinity with the adsorbents. It was concluded that both the olivine and the pine bark amended filter should be tested in full-scale conditions for better insight previous field implementation.

Table 3. Cumulative adsorption at the required removal and service life for different filters with respect to the target metals. I/P stands for impervious area to pervious area ratio and AF for amended filter.

I/P ratio	Target metal	Runoff Concentration (µg/l)	Required Removal (%)	Cumulative Adsorption (mg/kg) and Service Life (year) in brackets		
				Pine Bark AF	Charcoal AF	Olivine AF
50	Zn	18	31	9.1 (9)	2.3 (2.3)	2.5 (2.5)
	Cu	13.5	92	9.8 (13)	3.1 (4)	1.1 (1.5)
	Ni	2.32	35	6.1 (46)	0.6 (5)	2.4 (18)
20	Zn	18	31	9.1 (22)	2.3 (5.5)	2.5 (6)
	Cu	13.5	92	9.8 (32)	3.1 (10)	1.1 (3.8)
	Ni	2.32	35	6.1 (115)	0.6 (12)	2.4 (45)

4.3 Paper III

Infiltration response under freezing/thawing conditions of adsorbent amended filters for stormwater management

This paper complements Paper II with regard to evaluate the suitability of the three-proposed adsorbent amended filters for treatment of urban runoff in cold climates. The motivation behind this paper was to study the infiltration response of the proposed filters and, in particular, towards snowmelt runoff, which can be highly polluted. Infiltration performance is as important as pollution removal because the second would not exist without the first. In this study snowmelt infiltration into frozen filters is replicated by using a column test, and supported by x-ray tomographic images and unfrozen water content of the different materials composing the filters. Time needed to collect water at the bottom of the column, defined as breakthrough discharge time (BDT), and decrease in infiltration rates after 24 hours from BDT were used to assess the infiltration performance under freezing temperatures.

Infiltration capacity of adsorbent amended filters was studied in columns under freezing temperatures. The experimental design included two initial media water contents prior to freezing, and different media placements in the column. BDT was larger than 21 hours in all columns (Table 4 and 5). In average, BDT arrived ten hours later if the filter was saturated prior to freezing than if the filter had been drained prior to freezing, which highlights the importance of a good drainage to avoid water retention and subsequent ice formation.

Charcoal and pine bark, due to their high micro porosity, showed relatively large unfrozen water contents at negative temperatures, i.e., 21.7 and 6.7 % at -2.5 °C, respectively.

These materials perform best under not fully saturated conditions, because they can adsorb a great fraction of the media moisture in these pores, and thereby reduce the water content prone to freezing in larger pores. However, they are not recommended in layers prone to continuous saturation and with limited contact with heat sources due to their high storage capacity of gravitational water in larger pores, which is easily prone to freeze. Olivine showed lower unfrozen water contents (3.1 %), and those in sand were low (0.25 %) and, subsequently, promotes the ice formation. Mixing the adsorbent homogeneously with the sand was shown to provide the lowest BDT, because of an even distribution of the benefits of using adsorbents, i.e., higher unfrozen water contents and void sizes along the media depth.

Lower BDT implies that overall less heat has been transferred to the media, and the pathway that ponding water might have followed is narrow and limited. The latter was reflected in larger decrease in infiltration rates. Despite of the infiltration detriment due to frozen media, adsorbent amended filters proposed in this study meet international recommendations for stormwater management in cold regions with regard to infiltration rates. This study confirms that, if placed optimally, filters amended with adsorbents can perform satisfactorily in cold climates infiltration-wise, being of critical importance for the environmental impact.

Table 4. Infiltration parameters obtained during the column tests with saturated media. $K_{20°C}$ stands for the corrected saturated hydraulic conductivity at 20 °C, BDT for breakthrough discharge time, IR for infiltration rate after 24 hours after breakthrough, and DIR for decrease in infiltration rate regarding $K_{20°C}$.

Filter media	Adsorbent placement	$K_{20°C}$ (mm/s)	BDT (h)	IR (mm/s)	DIR (%)	Number of columns
Charcoal and Sand	Overlying	0.17±0.09	44.9±5.5	0.018±0.02	89.5±2.5	3
Charcoal and Sand	Mixed	0.19±0.01	35±5.2	0.016±0.01	91.6±0.1	2
Charcoal and Sand	Underlying	0.25±0.18	51.8±2	0.022±0.01	91.1±4.5	2
Olivine and Sand	Mixed	0.24±0.01	34.1±2.7	0.03±0.02	87.7±9.0	2
Olivine and Sand	Underlying	0.34±0.09	46±5.3	0.048±0.03	86±6.7	3
Pine bark and Sand	Overlying	0.22±0.05	46.2±3.9	0.022±0.01	87.7±0.8	3
Pine bark and Sand	Underlying	0.17±0.01	55.8±2.2	0.022±0.01	87.0±1.1	2
Sand	-	0.28	50.2	0.039	86	1

Table 5. Infiltration parameters obtained during the column tests with drained media. See Table 3 for abbreviation explanations.

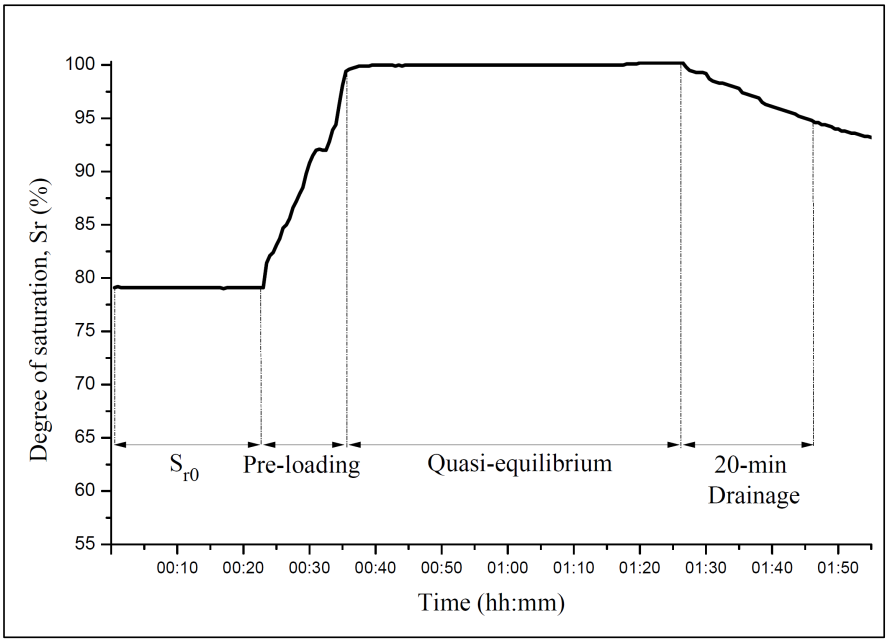
Filter media	Adsorbent placement	$K_{20°C}$ (mm/s)	BDT (h)	IR (mm/s)	DIR (%)	Number of columns
Charcoal and Sand	Overlying	0.21±0.04	33.2±1.2	0.014±0.008	93.4±2.5	2
Charcoal and Sand	Mixed	0.21±0.07	21.6±2.9	0.008±0.002	96.1±2.5	3
Charcoal and Sand	Underlying	0.24±0.08	39.9±3.0	0.017±0.005	92.8 ±0.5	3
Olivine and Sand	Mixed	0.21±0.07	30.9±4.5	0.007±0.001	96.7±1.9	2
Olivine and Sand	Underlying	0.26±0.03	33.1±0.7	0.009±0.001	96.6±1.0	2
Pine bark and Sand	Overlying	0.24±0.12	37.3±3.3	0.015±0.002	93.6±4.7	3
Pine bark and Sand	Underlying	0.26±0.08	49.7±7.8	0.027±0.012	89.1±1.9	2
Sand	-	0.26±0.01	41.1±5.8	0.021±0.005	91.9±1.7	2

4.4 Paper IV

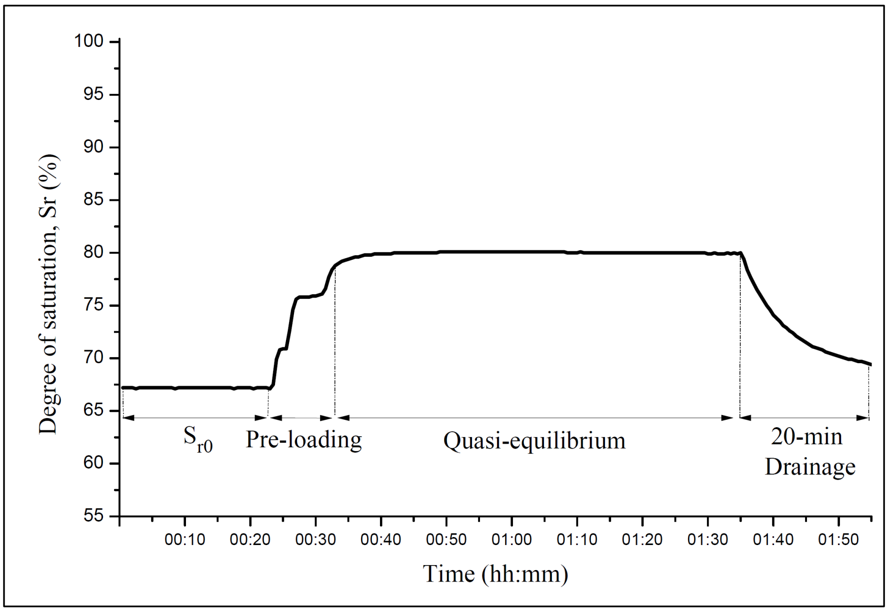
Results from Paper II and III were used to upscale the most suitable filters for stormwater management in cold climates. The motivation of this study was to study in a full-scale swale setup the hydrological balance of the selected filters, and compare it to a media composed of a sandy loam soil; a soil recommended for bioinfiltration. In this paper, dimensionless empirical models were developed to study the hydrological response of swales by varying boundary conditions. Subsequently, these models were used to estimate storm events that could be handled at a given runoff volume capture by this infiltration based swales.

Two filtering swales were composed of pine bark (swale 1) and olivine (swale 2) amended filters with verified capacity for toxic metal retention and infiltration under negative temperatures, and the third swale was composed of traditional soil used in bioinfiltration practices. The experiments were carried out with different boundary conditions by varying, besides the aforementioned media (swales 1-3), the initial degree of saturation, the swale slope, and the inflow rate ($Q_{run\text{-}in}$). Figure 11 shows that the hydrological response of the swale 1 (filtering swale) differed to a great extent from swale 3 (sandy loam soil) for similar boundary conditions. Swale 1 showed a considerably quicker drainage response than swale 3. This is associated with the high infiltration capacity of the filter, which allows for emptying quickly the water stored in the media. In addition, unlike swale 3, which reached full saturation during the quasi-equilibrium phase, swale 1 only reached a degree of saturation of 80 % for the same experimental conditions. This fact suggests that swale 3 will generate overland flow at the downstream end of the swale, and this water will escape any potential treatment in the media.

The statistically significant factors in the empirical models showed that the swales behaved differently. The longitudinal slope was found non-statistically significant in the hydrological performance of the swales 1 and 2. Furthermore, the fitting of the models was individually very good for the adsorbent amended filters but very poor for the traditional media. It was observed that run-in discharges used during the experiments exceeded by far the infiltration capacity of swale 3, which was approx. 10 times lower than the alternative filters. Therefore, infiltration collected from swale 3 was somewhat constant regardless the run-in flow, and only affected by the slope. The traditional soil filter was able to handle considerably smaller run-in events than the other two filters, which was assessed by the ratio of run-in to infiltrated water. As an example, for a 100 % volume capture and a design storm event of 5 mm/h, an adsorbent amended swale will handle the runoff from a catchment 40 times larger. If the capture requirement is set at 90 %, a 12.2 mm/h storm event could be handle by the system for the same I/P ratio. The latter storm intensity is slightly larger than a 2-year 1-hour rainfall for the city of Trondheim.



(a)



(b)

Figure 11. Degree of saturation as a function of time in swale 3 (a) during test with 0.3x10^{-3} m^3/s run-in rate and 2% longitudinal slope (a), and in swale 1 (b) during experiment with same slope and run-in rate.

Chapter 5: Discussion

This chapter presents the results obtained along the studies performed in this thesis in a way that the research questions (Q) presented in Section 1.4. are discussed. In addition, the limitations of the work are addressed to give a critical guidance for future use of the results.

5.1 Metal retention (Q1 and Q2)

Adsorbents tested in this thesis showed very high removal rates (> 95 %) even under considerable high hydraulic loads (0.13 mm/s), equivalent to infrequent storm events in Trondheim (Paper II). Unlike Pb, Cu and Zn, the removal of Ni did not follow the same pattern in the case of the filter amended with charcoal, and only 60 % of the input concentration (1 mg/l) could be retained in the short-term phase. This result agrees with the release of already retained Ni (9–15%) from this filter after a saline solution (1 g/l NaCl) was pumped in. This behaviour might be because charcoal has been found to have quite low affinity for Ni, which allows Na to replace it easily through ion exchange. In the rest of cases, a relative low release (< 2.8 %) after pumping the saline solution indicates that the adsorption was stable, and salts would not have a major influence on the metal release rates.

For the long-term phase, a total of 2500 litre were passed through the filters along the course of 73 days. In Trondheim (with an average annual precipitation depth of 895 mm), this volume would be equivalent to the runoff generated over the course of almost 8 years for an impervious drainage area 50 times larger than the filter system. The removal performance varied from filter to filter depending on the metal in question. In general, the charcoal amended filter showed the lowest affinity for the target metals, which is in line with results from the early stage. In addition, the combination of Ni and filter amended with charcoal was the only one in which full exhaustion was detected, closely followed by Zn. In contrast, the olivine amended filter was still achieving 50% removal for all four metals at the end of the 73 days. In the pine bark amended filters, Pb and Cu showed a high removal percentage, 83% and 77% respectively, at the end of the long-term experiment. However, Ni adsorption was close to exhaustion which would control the operational life even though it still has very high affinity for uptake of Pb and Cu. Therefore, pine bark or olivine amended filters showed the best performance from a metal retention perspective.

The retention performance of adsorbent amended filters will be influenced by chemical and physical factors associated with the influent solution such as pH, ionic strength, concentration of the solute in the solution, and temperature. In the metal retention test (Paper II), the temperature and pH were intended as in the field. However, elevated concentrations (1 g/l) were used in the artificial influent stormwater. The reason behind was to be able to obtain detectable concentrations in the outflow and early breakthroughs because high adsorption was expected in the filter based on prior batch tests. This fact might introduce some uncertainties when it comes to estimate the sorption performance in the field based on results obtained in the columns. As an example, Kalmykova et al. (2008) found that there might be some processes such as competition between metals and complex formations inhibiting sorption under field concentrations. Therefore, high concentrations of metals can favour the sorption performance and overestimate the capacity with regard to real solutions. However, the largest concentrations measured in the sampling campaign were adopted in the estimations of the annual input loads for the service life in Paper II. This fact might counterbalance the mentioned performance overestimation.

5.2 Infiltration capacity (Q3 and Q4)

Infiltration performance is a vital feature in filtering practices because reducing runoff volume is an important part of reducing the annual pollutant load. The adsorbent amended filters proposed in this study are composed of highly permeable materials, allowing simultaneously for adequate infiltration and good metal retention. In Table 6 the adsorbent amended filters yielded a saturated hydraulic conductivity near twice as large as the most restrictive European guideline (ONORM-B2506-1, 2000), found in the literature for these practices. Initially, K_{sat} was concluded to vary significantly among different media and even among different adsorbent placement within same media (secondary Paper I). However, further K_{sat} tests (Paper III) as well as observations by Moghadas et al. (2016) suggested that packing/compaction of the media in the column might explain to a greater extent the variations in measured $K_{sat.}$

Table 6. Recommended minimum design infiltration rate for infiltration facilities, and K_{sat} measured in the constant head permeameter.

Reference	Infiltration rate (mm/s)
Caraco and Claytor (1997)	0.02
Paus and Braskerud (2014)	0.03
ONORM-B2506-1 (2000)	0.1
ARC (2003)	0.00347
PGC (2007)	0.00705
Filters in this project	0.17-0.34

On the other hand, MPD tests (Paper IV) carried out in swale 1 and 2 yielded values much higher (around 0.59 mm/s) than measured with the constant head permeameter (Paper III). It is possible that complete full saturation of the media was not reached in the swale, which was reflected in values higher than the actual saturated hydraulic conductivity. In columns, saturation of the media is certainly reached because the experimental setup allows for more controlled boundary conditions. Additionally, Ahmed et al. (2015) observed that values measured by the MPD test were roughly 2.8 times greater than reported for the same type of soil in laboratory permeability tests. Therefore, discrepancies found in this study are within a reasonable range.

In Paper IV, the filtering swales (swale 1 and swale 2) registered collection of overland flows from run-in discharges of $0.7 \cdot 10^{-3}$ m^3/s. In contrast, swale 3 composed of a sandy loam soil, typically recommended for bioinfiltration systems, collected overland discharge from run-in discharges of $0.2 \cdot 10^{-3}$ m^3/s. The low infiltration performance of swale 3, in comparison with the filtering swales, was confirmed by the K_{sat} measured with the MPD test, i.e., approx. 0.06 mm/s.

The use of the adsorbent amended filters presented in this thesis is principally meant for adverse scenarios such as proximity to sensitive water bodies and/or cold climate regions. In Paper III, the detriment of the infiltration performance during snowmelt periods was studied. It was shown that a minimum of 24 hours will be needed to observe some discharge out of a filter with a depth of 40 cm. This emphasizes that, during this period, practically no infiltration will occur, and additional measures for handling the runoff should be taken such as ponding allowance or to discharge the excess runoff safely through controlled spillways. However, the latter option might pose a risk to the recipient because of the "shock" pollutant loads commonly found during winter times (salting season in Paper I). The use of adsorbents with high unfrozen water content and large pore contents enhances the infiltration response at negative temperatures under given conditions; on one hand, materials with high unfrozen water content can adsorb a great fraction of the media moisture in micro pores, and thereby reduce the water content prone to freezing in larger pores; on the other hand, materials with a large content of pores prone to hold gravitational water (large pores) can enhance the thermal exchange into underlying frozen layers. However, the latter can bring unwanted results if good drainage is not allowed, because large gravitational water contents prior freezing might lead to concrete frost in this layer. It must be highlighted that after 24 hours from the beginning of the discharge the infiltration rate became larger than recommended values for bioinfiltration, which implies that runoff can be managed.

Field conditions differ considerably from laboratory controlled conditions, which will introduce uncertainties in conclusions yielded from lab results. However, it is needed to constrain the experimental boundary conditions in order to explain research hypotheses and understand processes involved in them. Field tests can represent faithfully real conditions but the extent of the influence from external factors is unknown and unpredictable, which might introduce even larger uncertainties in the conclusions. As an example, in the case of the freezing test, the temperature was constant over the duration of the infiltration process, which differs from the reality. However, introducing oscillations in the temperature of the freezing room in order to replicate day-night cycles would have probably led to freeze of the ponding water, which might not have been the case in the field due to the scale factor.

5.3 Design implications (Q5 and Q6)

The results from the long-term experiment in Paper II allowed for obtaining cumulative adsorption capacities at specific removal percentages which will fulfil Norwegian quality guidelines for moderate contamination of the receiving surface waters (Andersen et al., 1997), which are more restrictive than EU-EQS (2007) and USEPA (2007). These concentrations are 12.5, 1.1, 0.85, and 1.5 µg/l for zinc, copper, lead, and nickel, respectively. On the other hand, results from Paper I gave insight about metals loads entering these systems. The average event mean concentrations measured during the rainfall season, in which dissolved fraction was more unfavourable, were used to calculate the total metal loads in the incoming runoff. The dissolved concentrations (< 0.45 µm) were 18, 13.5, 0.13, and 2.32 µg/l for zinc, copper, lead, and nickel, respectively. These concentrations were adopted based on the data available at the time Paper II was being written. Therefore, a removal of 31, 92, 0, and 35 % is needed for zinc, copper, lead, and nickel, respectively. As it can be observed, the concentrations of lead were below the water quality standards, which can mostly be linked to leaded gasoline phase-out regulation (Kayhanian et al., 2012). As a consequence, this element will not pose a risk for the receiving water body, regardless of the removal acquired in the filter. On the other hand, in Paper II Ni was shown the element with the lowest affinity for the filters. However, results from Paper I showed that other elements are present in larger amount in urban runoff, i.e., zinc and copper, and could determine the service life of the filter despite of having better retention and affinity with the filters. This was confirmed by the estimation of service life carried out in Paper II; zinc will generally determine the service life of the filters amended with pine bark or charcoal due to high concentrations detected in urban runoff as well as the moderate affinity with the adsorbents. On the other hand, copper was found to determine the service life of the olivine amended filter due to the low cumulative adsorption observed at the required removal combined with relatively high runoff concentration. Nickel showed low affinity with all the adsorbents although the removal requirement was more relaxed, which allows these filters to stand during longer periods. This latter highlights the importance of combining a retention performance study (Paper II) with a characterization study (Paper I) for a proper estimation of the service life of the candidate filters for field implementation.

In real conditions, the main function of the filters studied in this project will be to retain the dissolved fraction of hazardous metals (copper, lead, nickel and zinc) for the biota. Results from Paper I show that the dissolved fraction of metals found in urban runoff was, in average, not alarming high regarding European (EU-EQS, 2007) or American (USEPA, 2007) water quality standards, except for Cu. However, it is still important to know about the metal associated to the solid fraction because the environmental conditions are continuously shifting both in time and in distance, and might, in the worst case, change the distribution of the solid-bound metals into a more soluble and toxic state. The bulk of the metal distribution (> 99 % for Pb, > 96% for Ni, > 90 % for Cu, and > 91 % for Ni) was observed to be particle-bound (> 1.2 µm), and this trend was followed over the course of the year. This metal characterization suggests that metals detected in urban runoff would not mean a problem if a sedimentation step is integrated and the receiving water body is large enough to dilute incoming untreated dissolved fractions down to non-hazardous concentrations for the biota living in that water body. However, small water bodies with limited dilution capacity or especially sensitive areas might justify the use of filters to retain dissolved metals before discharge.

Particle-bound metals are intrinsically removed in infiltration based systems by sedimentation and filtration processes. The sand layer composing the studied filters will filter out the particulate fraction of the metals entering the system, apart from allowing a quick and effective infiltration and drainage response. From an operational approach, it seems more convenient to place the adsorbent beneath the sand because this will protect it from weathering, clogging, and erosion, which will optimize and enlarge the service life of the media. This configuration gains even more relevance in the case of a pine bark amended filter because this adsorbent is expected to decay over time. In this context, Hollesen and Matthiesen (2015) investigated the impact of soil temperature, water contents and oxygen contents on the decay of soil organic carbon. It was shown that variations in soil organic carbon loss are principally driven by changes in soil temperature, and the reactivity of the soil is lowest either when is dry or when is nearly saturated or saturated. This suggests that the best disposition of pine bark is at the bottom of the filter; it allows for being protected from temperature variations along the year as well as tending to a saturated status, which hinders oxic decay. Therefore, other limitations such as clogging due to particle loading from runoff or pollutant breakthrough will to a greater extent determine the service life of a pine bark amended filter.

According to Paper III, the position of the adsorbent within the media (overlying the sand layer, underlying the sand layer, or mixed homogeneously with the sand) will not suppose an important impact on the infiltration performance under normal conditions (rain season). However, adsorbent underlying the sand was shown as the worst configuration when the media is frozen and snowmelt infiltration is desired (salting season), which conflicts with the metal retention and operational criteria (in which the bottom configuration is best). During rain-on-snow events (salting season), runoff is likely to face with frozen media, and the dissolved fraction was shown lower than during pure rain events (rain season). This will tip the decision regarding adsorbent placement towards the most convenient for the rain season as the filter is expected to work over more hours and expose to larger dissolved input loads. Still, a study is needed to evaluate the snowmelt contribution to the annual runoff volume depth as pollutant load is the product of pollutant concentration and runoff volume. This will allow for assessing which season is the most critical in terms of environmental impact, and hence implement the right measures.

Conductivity showed on average nearly 10-fold increase in salting season, which is explained by the intense use of de-icers in urban areas. In salting season, the suspended and dissolved solids concentrations were four and eight times higher than in rain season respectively. However, size of particles carried along the runoff was larger in rain season because of higher intensity events with more transport energy. Ion exchange units coupled to SuDS might be an option to enhance the service life and performance of systems linked to roads with high salt loads. In addition, a pre-sedimentation basin or grass filter strips is highly recommended to reduce clogging that hinder further filtering processes. In this case, the rain season, as the most unfavourable in terms of particle size, will determine the length needed to provide enough residence time to trap the target suspended particle size. The considerably higher concentrations of suspended solids during winter will clog the media faster and, eventually, decrease the overall performance. This can either be rectified by keeping the SuDS offline during winter, or by covering the SuDS with a geotextile prior snow piling. The latter option can allow SuDS to act as passive sinks because they will collect built-up sediments on top of the textile and allow dissolved fractions for infiltration through the textile and into the systems for treatment.

The rational method can be used for estimating runoff discharges in small drainage areas such as roads or urban catchments. The time of concentration of the drainage area and the recurrence interval of the target storm event will determine the peak storm intensity, SI (m/s), which multiply by the drainage area, DA (m^2), and the empirical runoff coefficient, C (dimensionless), will yield the peak discharge rate entering the filtering swale. A safety factor, SF (dimensionless), can be adopted in order to consider potential climate change impacts. The empirical formulation obtained in Paper IV will help to size filtering swales according to volume capture (infiltration) requirements

$$\frac{Q_{\text{inf}}}{g^{1/2}(wd)^{5/4}} = e^{-1.22}\left(\frac{SI \cdot C \cdot DA \cdot SF}{g^{1/2}(wd)^{5/4}}\right)^{0.85} \qquad (1)$$

As a practical example, in Trondheim, a highly impervious (C = 0.9) drainage area of 400 m^2 with a time of concentration of 10 min and a storm with a design recurrence interval of 2 years ($SI = 1 \cdot 10^{-5}$ m/s) will generate a peak runoff discharge of 0.0043 m^3/s (adopting 1.2 as a safety factor). In Oslo, for the same boundary conditions the peak runoff discharge would be 0.006 m^3/s, being larger due to more intense rainfall patterns. Using equation (1), a filtering swale with 0.8 m width and 0.45 m depth will be able to infiltrate 0.0028 and 0.0037 m^3/s, in Trondheim and in Oslo, respectively. This makes 0.0015 and 0.0023 m^3/s of excess runoff flow, in Trondheim and in Oslo, respectively. According to local regulations, 0.003 and 0.002 m^3/s stormwater runoff discharges can be introduced into a combined (most unfavourable) sewer system, in Trondheim and in Oslo, respectively. Therefore, the filtering swale will be able to handle completely the storm event in Trondheim, and nearly completely in Oslo. Apart from reducing runoff volumes entering the sewer network, the effluent of the filtering swale will meet water quality guidelines in terms of metal concentrations and, therefore, can be discharge into water bodies with no need to enter the sewer for further treatment.

Empirical models in Paper IV were calibrated and validated for given boundary lab conditions with regard to slope, media type, initial media moisture, coverage, and inflow rates. Field conditions will introduce additional actors that might affect the performance of the models. This will add uncertainties in the design of field filtering swales. Therefore, in Paper III some considerations are given when using results yielded in this study.

Chapter 6: Conclusions and recommendations

This chapter concludes the thesis and answers the research questions set out in Section 1.4. In addition, this thesis opens the way for future research in the filtering swale field, and hence some suggestions are given.

6.1 Conclusions

The characterization study of the urban runoff in the city of Trondheim revealed strong seasonal and spatial variations in all measured parameters. The seasonal variations were explained by the increase of abrasion, corrosion, and emissions from elements involve in road traffic rather than accumulation of snow piles. On the other hand, AADT might not always serve as the only key estimator of pollution transported in urban runoff because residential streets with low AADT might be as polluted as transited roads due to lack of cleaning and maintenance. Salting season was shown as the most unfavourable in terms of solid loads (8 times higher concentrations than rain season), however higher dissolved metal concentrations were measured in rain season.

In order to protect sensitive water bodies from dissolved metals, adsorbent amended filters were studied as an option to implement in filtering swales. The retention performance was excellent at infrequent inflow rates, and only Ni could exhaust the charcoal amended filters after having passed 2500 litres of polluted influent. In addition, no significant remobilization of adsorbed metals was observed due to NaCl addition, which could have otherwise been an issue for implementation in cold climates. In terms of allowable effluent concentration, a filter composed of sand and pine bark receiving polluted runoff from a drainage area 50 times larger (than the filter) is expected to last 9, 13 and 46 years for Zn, Cu and Ni, respectively. These values vary according to the type of filter as well as the size of the drainage area.

The infiltration response under frozen condition was tested to have better insight for assessing the suitability of these filters in cold climates, and the results were promising. Mixing the adsorbent homogeneously with the sand was shown to provide the lowest breakthrough discharge time (BDT). Where mixing is not a practical option, adsorbents with high porosity are recommended to be placed on top of the sand layer to enlarge the potential heat exchange from the incoming runoff. Under not fully saturated conditions, materials with high micro porosity performed best because a large fraction of the media moisture can be adsorbed in these pores, and thereby reduce the water content prone to freezing in larger pores. However, more than 21 hours were needed to start observing some infiltration at the bottom of the frozen filters. This fact would not pose an important issue because the dissolved concentrations during winter time were low and the critical period for the dissolved fractions is, in the case of Trondheim, the season with pure rain events, in which the filters function properly infiltration-wise. However, a significant annual snow melt runoff volume will imply that an important annual pollutant load might be missed and, therefore, to retain these snowmelt volumes is important and a ponding capacity or a safe overflow discharge should be included. Regarding non-freezing temperatures, the infiltration response is considerably higher than international guidelines, which in turn implies that these filters might handle runoff from larger areas or from infrequent events.

Olivine and pine bark amended filters were selected for further study in a full-scale swale setup, in which their hydrological balance was compared to each other and to a traditional green swale composed of a sandy loam soil. The infiltration response of the filtering swales was substantially better than the traditional swale, which was assessed by the ratio inflow water to infiltrated water. Empirical dimensionless formulations for explaining infiltration and draining processes worked poorly in the treatment swale due to the incapacity of handling the inflow discharge rates used during the experiments. In contrast, the modelled values fitted well the observed values in the filtering swales. Additionally, the longitudinal slope of the filtering swales was shown non-statistically significant neither in the infiltration nor in the drainage phase.

A formula based on the experimental results was presented to help planners to design filtering swales presented in this thesis. The equation relates practical design parameters such as infiltration performance, storm intensity, and size of the drainage area. The equation was used to evaluate the suitability of filtering swales for handling stormwater runoff in two Norwegian cities with different rainfall patterns, i.e., Oslo and Trondheim. The results showed that filtering swales are an optimal option for infiltrating stormwater runoff from 2-year return period storm events and, subsequently, treating the pollution on the spot and avoid loading the sewer systems.

6.2 Recommendations for Future Work

There is room for further research in filtering swales for stormwater management. The following research topics could be interesting for complement this thesis:

1. Compare the sediment trapping efficiency of a boulder coverage and a grass coverage.

2. Investigate the field validity of the empirical formulations proposed in Paper IV as well as the estimated service life.
3. Investigate the use of vegetation covering the filtering swales.

Sediments are an important part of the pollutants in stormwater runoff. However, they were not used during the laboratory tests. The scope of this thesis was the dissolved fraction of metals as well as cold climate implications on the performance of filtering practices. However, the importance of implementing prevention measures towards this constraining phenomenon was mentioned in several occasions in the presented papers. In this context, experiments about the hydrological balance of the swales was conducted with bare tap water. The first suggestion is to add sediments in the influent tank and test the trapping efficiency of the different coverages (boulders and grass). The target size of the sediments should be that of the particles that bind more target pollution. This will give insight about the removal of particle-bound pollution, and complement the information yield in this study about the dissolved metal retention.

The second recommendation involves the implementation of the studied filtering swales in the field. The empirical formulas were developed under controlled laboratory conditions that widely differ from real conditions. Therefore, field validation with real storm events as well as external constraints such as negative temperatures in winter time or lead litter in fall time will give valuable and complementary information for field calibration.

The third recommendation is about the coverage of the swale. In this thesis, boulders protected the filtering swales. No grass was planted in the filtering swales because the clean sand lacked organic matter for establishing the grass. The use of any kind of compost or similar source of organic matter on the surface would have changed the media composition. Therefore, the results from the column studies would have been more difficult to associate with the following results from the swale setup. However, it is highly encouraged to study these filters with a grass coverage, which will passively protect the media against clogging from sediment deposition.

Last but not least, a cost analysis is recommended for a complete assessment of the suitability of the presented filters. Cost and availability of materials, transport, carbon footprint and construction labor as well as considerations such as environmental impact and cost of the land might incline the final decision towards alternative engineered filter media. This will most likely also be influenced by geographical location and availability of raw materials.

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Appendix A: Selected Papers

The full versions of the selected papers presented in this thesis are presented in the following. The original formatting is preserved and does not conform to the general formatting of the thesis.

Paper 1

Characterization and seasonal variation of urban runoff in cold climate - design implications for SuDS.

Carlos Monrabal-Martinez, Tone M. Muthanna and Thomas Meyn.

In review: Urban Water Journal.

Is not included due to copyright

Paper 2

Pilot Scale Testing of Adsorbent Amended Filters under High Hydraulic Loads for Highway Runoff in Cold Climates.

Carlos Monrabal-Martinez, Aamir Ilyas and Tone M. Muthanna (2017).

Water, 9(3), 230, DOI: 10.3390/w9030230 (Open Access).

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Article

Pilot Scale Testing of Adsorbent Amended Filters under High Hydraulic Loads for Highway Runoff in Cold Climates

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Abstract: This paper presents an estimation of the service life of three filters composed of sand and three alternative adsorbents for stormwater treatment according to Norwegian water quality standards for receiving surface waters. The study conducted pilot scale column tests on three adsorbent amended filters for treatment of highway runoff in cold climates under high hydraulic loads. The objectives were to evaluate the effect of high hydraulic loads and the application of deicing salts on the performance of these filters. From previous theoretical and laboratory analysis granulated activated charcoal, pine bark, and granulated olivine were chosen as alternative adsorbent materials for the present test. Adsorption performance of the filters was evaluated vis-à-vis four commonly found hazardous metals (Cu, Pb, Ni and Zn) in stormwater. The results showed that the filters were able to pass water at high inflow rates while achieving high removal. Among the filters, the filters amended with olivine or pine bark provided the best performance both in short and long-term tests. The addition of NaCl (1 g/L) did not show any adverse impact on the desorption of already adsorbed metals, except for Ni removal by the charcoal amended filter, which was negatively impacted by the salt addition. The service life of the filters was found to be limited by zinc and copper, due to high concentrations observed in local urban runoff, combined with moderate affinity with the adsorbents. It was concluded that both the olivine and the pine bark amended filter should be tested in full-scale conditions.

Keywords: stormwater runoff; alternative adsorbents; pilot scale; hydraulic loading; adsorption; service life; toxic metal removal

1. Introduction

Infiltration based solutions have been shown to be an efficient method for treating hazardous substances from stormwater in urban areas [1–4]. These solutions include different forms and functions, depending on the area of application, such as rain gardens, bioretention swales, and infiltration trenches, etc. Infiltration based stormwater options aim to restore/mimic pre-development conditions [5] by reducing runoff volumes, trapping sediments, and mitigating peak flow rates. In some cases, infiltration based systems are also designed to remove dissolved contaminants by adding a specific adsorbent layer [6], or relying on combined effects of plants and soils—bioretention [7]. Heavy metals are found in urban runoff from multiple nonpoint sources such as vehicle components wear, exhaust emissions, lubricants, and galvanized elements along roads, among others [8]. The presence of these metals vary in both spatial and temporal resolution, as well as phase (particulate and dissolved forms). It is the latter form that is the most bioavailable and hazardous for biota [1,9].

A wide range of materials have been identified and tested for their performance for removal of heavy metals [10], nutrients [11], and organic contaminants [12], among others. These adsorbents materials include secondary wastes, minerals, and biological materials. Generally, adsorption processes are dependent on the specific surface area of the material, which increases with decreasing particle size. However, a decrease in the particle size leads to a lower hydraulic conductivity of the filters. In stormwater solutions that are designed for a certain allowable ponding, such as bioretention areas, wetlands, and detention ponds, a lower hydraulic conductivity and larger surface area can be adequate given the pooling capacity of such facilities. On the other hand, in areas close to road surfaces or systems with no ponding capacity, the runoff must be infiltrated as quick as possible for safety issues. Therefore, high hydraulic conductivity is an important design feature to allow for a high hydraulic loading. This favors adsorbents with a larger particle size.

For the end user, the service life of the infiltration based facility is also highly relevant, because it is an important factor in the selection decision. The service life of an adsorbent/filter is mainly determined by a combination of pollutant concentration in the effluent, pollutant accumulation in the filter, and loss of infiltration potential due to clogging [13]. Several studies have been undertaken to quantify the service life of the filters from the pollution perspective [13–16]. Batch studies might be used to preselect potential adsorbents based on adsorption criteria. Generally, isotherm models are adopted to fit experimental batch data. However, these models are meant for gas adsorption on solid surfaces, which differs from solution-solid conditions occurring in infiltration based systems. Additionally, assumptions made by isotherm models will introduce uncertainties when determining adsorption capacities of adsorbents. In contrast, column studies, which are also laboratory based tests, can best reproduce field conditions of varying inflows, increasing liquid to solid ratios over time, and inducing dynamic conditions. Breakthrough curves obtained from column studies can help determine the volume of water treated before the filter no longer can meet a certain pollutant removal in the effluent. On the other hand, high intensity inflows, freezing-thawing cycles, and application of deicing salts are generally ignored during the evaluation of the performance of these filters, which can affect the adsorbent performance. Consequently, this poses an obstacle for an appropriate design of infiltration based facilities.

This study evaluated three filters composed of sand and three alternative adsorbents (pine bark, olivine, and charcoal) in a pilot scale column study under high hydraulic loads. The adsorbents were identified in a previous study, which used multicriteria analysis and batch tests to evaluate the upscaling potential of eight adsorbent materials [17]. In the first phase of the study, the influence of high hydraulic loads as well as deicing salts over the pollutant retention was evaluated. In the second phase, the long-term performance was studied in order to obtain data for estimating the service life of the materials.

2. Materials and Methods

2.1. Adsorbent Materials

All the adsorbent materials and the sand (Table 1) were obtained by commercial suppliers locally. The granulated activated charcoal (extracted from anthracite coal) was a Sigma Aldrich AS product (Oslo, Norway), the sand was manufactured by Rådasand AB (Lidköping, Sweden), the pine bark *Pinus Sylvestris* was provided by Nittedal Torvindrustrie AS (Bjørkåsen, Norway), and the olivine was supplied by Sibelco Nordic AS (Rud, Norway) and belongs to the Blueguard® series. Charcoal and olivine were used without any chemical processing or modification. While, pine bark was sieved <4 mm particle size prior to use in order to favor water retention. The adsorbents were placed in pilot scale columns with clean quartz sand, which was selected for its uniform particle size and little or no background contamination. Therefore, the influence of the sand on the hydraulic conductivity and removal performance was assumed homogeneous throughout the study.

Table 1. Material properties of the sand and adsorbents used in the study. UC stands for uniformity coefficient.

Parameter	Sand	Olivine	Charcoal	Pine Bark
Particle Density $^{\alpha}$ (g/cm^3)	2.66	3.12	1.91	-
Max Dry Density $^{\beta}$ (g/cm^3)	1.77	-	-	-
Bulk density (g/cm^3)	1.48	1.62	0.44	0.24
$D_{90}{}^{\gamma}$ (mm)	0.65	1.93	1.83	-
$D_{60}{}^{\gamma}$ (mm)	0.403	1.53	1.33	-
$D_{10}{}^{\gamma}$ (mm)	0.183	0.903	0.73	-
UC (D_{60}/D_{10})	2.22	1.66	1.85	-
BET Surface Area $^{\delta}$ (m^2/g)	0.564	4.264	881.964	0.444

Notes: $^{\alpha}$ Data from the present study obtained with pycnometer test; $^{\beta}$ Data from the present study obtained with proctor compaction test; $^{\gamma}$ Data from the present study obtained from particle size distribution curves; $^{\delta}$ Data from the present study obtained with Brunauer-Emmett-Teller (BET) test.

2.2. Column Tests

The adsorbents were tested for removal of four dissolved metals (Cu, Pb, Ni, and Zn) commonly found in urban and highway runoff and of environmental concern for official authorities due to their toxicity towards the biota in the receiving water bodies. For the column tests, synthetic stormwater was prepared in a large tank (1 m^3) by mixing tap water with a stock solution containing the metals. Metal chloride salts were used for preparing the stock solution, and were chosen for the additional benefit of simulating salts in stormwater. On the other hand, tap water contains other major ions (Na^+, Ca^{2+}, etc.), which makes it a realistic surrogate for actual stormwater (Table 2). The target metals were added in a quantity to achieve intended concentration of 1 mg/L for each metal in the 1 m^3 influent tank. The reason behind this high concentrations was to be able to obtain detectable concentrations in the outflow and early breakthroughs because high adsorption was expected in the filter based on prior batch tests [17]. The pH of the synthetic stormwater was approx. 7.5, which is similar to values observed in local urban runoff.

Table 2. Major constituents in the tap water.

Parameter	Concentration (mg/L)
Calcium	21.7
Sodium	4.45
Magnesium	0.89
Potassium	0.45
Chloride	7.46
Sulphate	2.5

Plexiglas columns with 45 cm length and 10 cm diameter were constructed and used in the study. The columns were filled with 35 cm sand overlying 5 cm of adsorbent (see Figure 1). Adsorbent placement at the bottom will protect the material from eventual frost and erosion. In addition, bottom placement for pine bark means less oxidation problems as lower zones will remain wetter with lower O_2 availability. The length (40 cm) represents minimum recommended depth for bioretention facilities in Norwegian climate [18], where these filters might potentially be used.

Three columns were set up for each filter media including a control column that was packed only with sand. All columns were operated at room temperature (20 ± 2 °C) and the tap water used to produce the synthetic stormwater was at 8 ± 2 °C. Multichannel peristaltic pumps with variable flow were used for pumping the synthetic stormwater. The flow rates were based on the saturated hydraulic conductivity (K_{sat}) of each filter, which has been investigated separately [19]. Therefore, full infiltration at the largest possible inflow rate was intended with no visible ponding water.

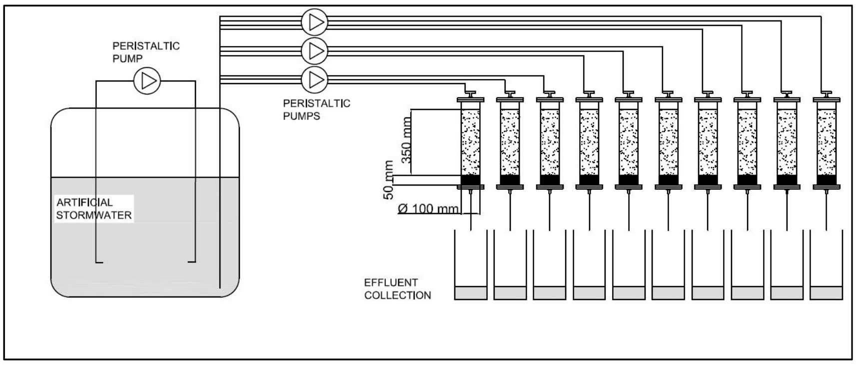


Figure 1. Schematic overview of the column setup with adsorbents placed at the bottom.

The study was divided in two phases. In the first phase flow rates, supplied by the peristaltic pumps, were controlled and set at the K_{sat} of each filter. The objective was to verify the adsorption capacity of the filters under high hydraulic loads, specifically under the largest inflow rate that is expected to not generate water ponding. The experimental columns were continuously run for approx. 14 h, and each column received a water volume of approx. 50 L (liquid to solid ratio LS = 11). After passing this volume of water, one of the two duplicate columns for each media was taken aside to study the effect of road salt on the desorption of already immobilized metals. For the salt experiment, the columns were initially fed with approx. 50 L (LS = 11) of plain tap water, and then with the same amount of a solution composed of tap water with 1 g/L NaCl. The concentration of NaCl was based on common concentrations found in highway stormwater in Norway, similar to the value adopted by previous studies [20]. In the second phase, long-term operation was the objective, and the study continued in each of the remaining columns for 2.5 months (Table 3). Samples were collected biweekly from the effluents of every column and analyzed for the target metals. After the collection, pH and electroconductivity of the samples were measured, then samples were filtered through 0.45 μm pore membrane filters for analyzing dissolved fraction of the studied target metals, and preserved with 0.1 M HNO_3 acid. Samples were stored at 4 °C until the analysis with a high resolution inductive coupled plasma HR-ICP-MS instrument from Thermo Fisher Scientific AS (Oslo, Norway). Each individual sample was scanned three times and the results were corrected for blank samples. The quantification detection limits for Ni, Zn, Cu and Pb was 0.015, 0.025, 0.03, and 0.002 μg/L, respectively.

Table 3. Average volume per column (AV) and hydraulic loading rate (HLR) used during the two phases of the study. CRT stands for column running time.

Influent Type	Experiment Phase	AV (L)	HLR (cm/h)	CRT (Days)
Synthetic stormwater	1	50	47	0.6
Salt water	1	50	47	0.6
Synthetic stormwater	2	2500	18.8	73

Similar column studies of metal adsorption and nutrient removal are found in the literature (Table 4). In this study, long-term data was needed to explore the exhaustion capacity of the studied filters because input concentrations were low in comparison to the other studies. On the other hand, high hydraulic rates were used to study the removal capacity of these filters under intense inflow rates with expected lower contact times with the filter.

Table 4. Experimental characteristics of similar column studies. AV stands for average volume per column, HLR for hydraulic loading rate, CRT for column running time, IC stands for input concentration, MD for media depth, CD for column diameter, and TP for target pollutants.

AV (L)	HLR (cm/h)	CRT (Days)	IC (mg/L)	MD (cm)	CD (cm)	TP	Reference
120	70.8	27	5–16	23	1.8	MTBE, Naphthalene, Zn	[15]
480	10	90	1	20	5.08	Cd, Cu, Pb, Zn	[13]
300	-	70	0.004–0.28	800	37.7	Cd, Cu, Pb, Zn	[21]
158	124	30	2.5–5	40	2	Cu, Ni, Zn	[22]
300	4.1	183	0.048–0.6	31	31	Zn, Cu, Pb, Cd	[23]
9	1.06	2	0.08–0.6	3.5	1.9	Zn, Pb, Zn	[14]
2550	18.8	133	1	40	10	Zn, Pb, Ni, Cu	This study

2.3. Hydrological Perspective

In order to relate the simulated flows back to the dimension of the storm events, the following hydraulic approach is presented. This approach is connected to the first phase of the adsorption study, in which the influent rate was adjusted to match the K_{sat} of each of the media.

In the laboratory setup (Figure 1), the column acts as an infiltration based system (P) and the pumped water from the tank represents the urban runoff from impervious surfaces (I). The ratio between impervious to pervious area (I/P) is often used to size such filters [24,25]. In areas with a high percentage of impervious surfaces such as roads, sidewalks, roofs, etc., an empirical runoff coefficient (C) close to 1 can be assumed.

Equation (1), which is based on the rational method, allows for calculating the ideal storm intensity (SI) in (mm/h) that will generate the HLR in (mm/h) applied on the columns through the peristaltic pump. For a certain hydraulic load, the intensity of the storm event is indirectly linked to the size of the fictitious catchment feeding the columns (I).

$$\mathrm{SI} = \frac{\mathrm{HLR}}{\mathrm{C \cdot I/P}} \tag{1}$$

2.4. Expected Service Life

The results from the second phase were used to estimate cumulative adsorption capacities of the different adsorbent amended filters for the target metals under the given conditions. The cumulative adsorption for each metal, q (mg/kg), was obtained from Equation (2).

$$\mathrm{q} = \frac{\int_0^{\mathrm{Vd}} (\mathrm{Ci} - \mathrm{Ce}) \cdot \mathrm{dV}}{\mathrm{M}} \tag{2}$$

where Ci is the influent concentration (mg/L), Ce is the effluent concentration (mg/L), Vd is the cumulative volume passed until a certain % removal (L), and M is the amount of material in the filter (kg).

Expected cumulative pollutant retention (mg) was obtained as the product of the area of the filter, density, filter depth, and q at the required removal. Expected pollutant input load (mg/year) was obtained as the product of the average dissolved pollutant concentration measured at local streets, annual precipitation depth, area of the tributary catchment, and a volume capture factor of 0.9, based on international design guidelines. The expected service life (years) was obtained, dividing the expected cumulative pollutant retention at a required removal by the pollutant load expected to be treated by the filtration facility.

3. Results and Discussion

3.1. Control of Flowrate, First Phase

In this phase, flow rate was controlled and frequent sampling performed to collect enough data to evaluate the performance in the short term of the different filters under high hydraulic loads.

3.1.1. Metal Removal by Adsorbent Amended Filters

Figure 2 presents the percentage removal of the four target metals, by three adsorbent amended filters for stormwater, as a function of pore volume of synthetic stormwater passed through the filter. In this study, one pore volume equaled to 1600 cm^3 approx. and corresponded to the volume occupied by voids in a certain column. It varied from column to column because of different materials, bulk densities and different porosities. From the curves in Figure 2, it is clear that all of the adsorbent amended filters had a very high removal rates (>99% in case of Pb) even under considerable high hydraulic loads. There are some fluctuations and variations in the adsorption behavior of Cu and Zn both on the pine bark and the olivine amended filter, which could be due to variable flow patterns inside the gravity based filter. The gentle increasing trend for removal of these two metals on pine bark and olivine points to time dependency of adsorption reactions. However, in contrast to Pb, Cu and Zn, the removal of Ni did not follow the same pattern in the case of the filter amended with charcoal. The decrease of Ni removal with increasing water passed indicates that Ni has a relatively low affinity for the charcoal, and with increasing volume of passed water the competition for the sites may also have increased. Nevertheless, with the exception of charcoal vis-à-vis Ni, the fluctuations in removal of metals (±1%–2%) on the rest of the adsorbents were small, which demonstrates that the presented filters would perform robustly in the actual conditions.

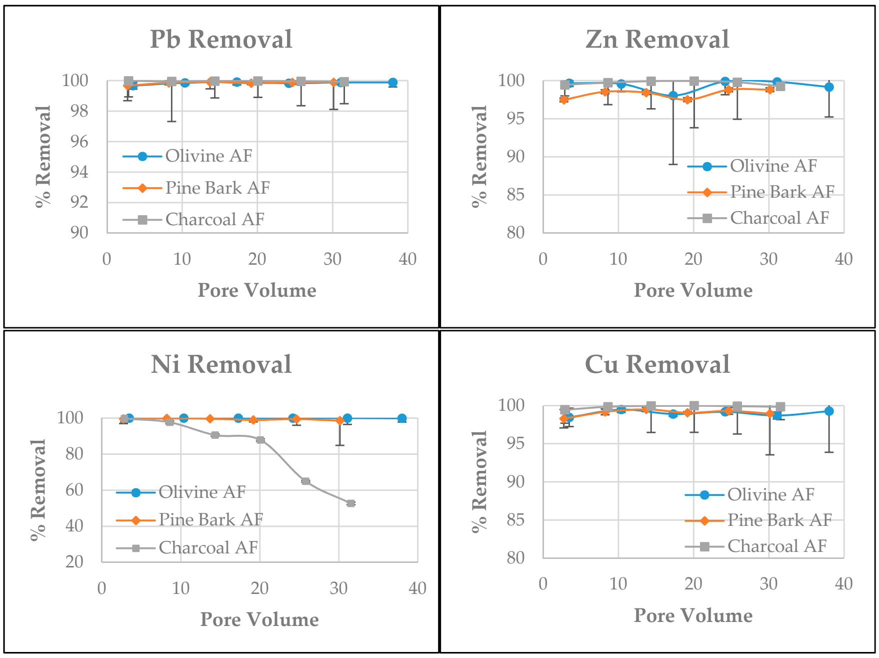


Figure 2. Percentage removal of the four toxic metals as a function of pore volume. Note that the Y-axis is different in each case. AF stands for amended filter.

3.1.2. Desorption of Metals Due to Salts

The columns were fed with synthetic stormwater continuously for approx. 14 h (time to reach a liquid to solid ratio of 11), then one of the two replicate columns was taken apart to study the influence of salt application on desorption of already adsorbed metals. Table 5 shows the results of metal release (in percentage) from the columns as a function of pore volume. The results show that the saline solution had variable effects on the three adsorbent amended filters and the four metals. A small release of metals (<3%) was observed in most of the filters. This relative low release indicates that the adsorption was stable and salts would not have a major influence on the metal release rates. This finding is in agreement with [26], which have shown that NaCl has the lowest impact on the desorption of already mobilized metals compared with other studied deicers. Additionally, [20,27] reported that metals adsorbed on soils designed for bioretention were scarcely leached due to NaCl applications and, therefore, retention under cold climate conditions is likely to be effective for the studied purpose. However, [28] detected a significant impact of salt addition on the removal of dissolved Pb and Cu, which might be due to the fact that the salt favors dissolution of organic matter which has a strong affinity of these metals. In the present study, a high release of Ni (9%–15%) from the charcoal amended filter was detected. This behavior might be due to the fact that charcoal has been found to have quite low affinity for the Ni, which allows Na to replace it easily through ion exchange. Furthermore, binding forces of adsorbed cations are also dependent on hydrated radius of the divalent ions as well as relative concentrations, which means that sodium, due to smaller hydrated radius and larger concentrations, will face optimal conditions for replacing adsorbed Ni.

The release behavior with regards to the same metal differs from adsorbent to adsorbent. As an example, Ni, which shows an increasing trend both in the case of the charcoal and the olivine amended filter, is decreasing with increasing pore volume in the case of the filter amended with pine bark. However, common aspects among adsorbents are observed, for example, extremely low release of Pb. This might indicate that Pb is difficult to exchange because of having smaller hydrated radius and hence being more strongly adsorbed to the site of the negative charge. Moreover, Pb might form inner sphere complexes with the charge sites, which further reduces the chances of Pb adsorption reversing itself. Similarly, Ni, Zn, and Cu mobilization from the olivine and the charcoal amended filter follow a gentle increasing trend with pore volume. This shows that their desorption is dependent on the exchange process with Na. Nonetheless, with the exception of Ni, the release of metals from all presented filters is below 3%, which is an encouraging aspect as this indicates that a minimal environmental impact can be expected in full scale systems.

Table 5. Percentage desorption of four metals as a function of pore volume from three alternative filters. Note that the pore volumes are different in each case. NA stands for not available and AF for amended filter.

Pore Volume	Charcoal AF				Pore Volume	Olivine AF				Pore Volume	Pine Bark AF			
	Pb (%)	Ni (%)	Cu (%)	Zn (%)		Pb (%)	Ni (%)	Cu (%)	Zn (%)		Pb (%)	Ni (%)	Cu (%)	Zn (%)
2.8	<0.01	9.37	0.04	0.17	**3.4**	<0.01	0.06	0.41	0.20	**2.7**	0.02	2.15	0.23	2.78
8.6	<0.01	7.72	0.12	0.53	**10.3**	<0.01	0.07	0.27	0.21	**8.2**	0.03	2.62	0.35	2.72
14.3	0.01	5.57	0.09	0.32	**17.3**	0.01	0.23	0.49	1.89	**13.7**	0.04	1.73	0.34	1.39
20	0.01	15.26	0.11	0.49	**24.2**	0.02	0.26	1.13	2.02	**19.2**	0.02	1.19	0.24	1.43
25.8	0.03	9.65	0.11	0.36	**31**	0.01	0.34	1.06	2.09	**24.6**	0.04	2.06	0.31	1.65
31.5	0.01	11.64	0.14	0.41	**38**	NA	NA	NA	NA	**30.1**	0.02	1.91	0.41	1.28

3.1.3. Simulating Storm Events

Table 6 shows that, in the case of the charcoal amended filter, the hydraulic rate applied to the columns corresponds with the runoff generated by a storm event with an intensity of 12 mm/h. This storm intensity is slightly higher than a two year return period and one hour duration storm event in the city of Trondheim (10.7 mm/h). In other words, if this event fell in an impervious catchment

50 times bigger than the facility (I/P = 50), it could be handled by this filter without ponding. On the other hand, the filter composed with pine bark and sand would only be able to manage completely a storm intensity of 8.5 mm/h for the same tributary catchment. The clogging process, which will have a negative impact on the actual infiltration capacity in a field application, was not considered in the calculations. However, K_{sat} values, which were used to dimension these systems, may counterbalance the clogging risk because these values represent a conservative estimate of the potential infiltration rate [29].

Table 6. Hydrological approach using formula 1 during the first phase of the adsorption test. PS stands for pump speed, HLR for hydraulic loading rate, I/P for impervious to pervious ratio, SI for storm intensity, and AF for amended filter. C is the empirical runoff coefficient.

Filter	PS (mL/min)	HLR (cm/h)	I/P	SI (mm/h) if C = 0.9
Charcoal AF	72.2	55	50	12
Olivine AF	58.7	45	50	9.9
Pine bark AF	51.1	39	50	8.5

3.2. Control of Volumes. Second Phase

In this phase, high loading was simulated by passing large volumes (approx. 2500 L per column) to study the long-term performance of the adsorbents.

Metal Removal by Adsorbent Amended Filters

In Figures 3–5, the results regarding removal of the target metals over increasing pore volume are shown. Looking at the results, complete exhaustion was only observed in the filter amended with charcoal for Ni. The filter composed of charcoal and sand showed the lowest affinity for the target metals, which is in agreement with results from a similar study [26]. In contrast, the olivine amended filter was still achieving 50% removal for all four metals.

Figure 3 shows that, in the case of the filter amended with olivine, the removal curves of all target metals follow a non-linear decreasing trend. The removal of Pb, Ni, and Zn shows a sharp decrease after 1200 pore volumes. This might indicate that spherical shape allows the influent to bypass the olivine surfaces. Furthermore, spherical shapes limit the exposed surface, which as it becomes covered with metals starts to release some into the solution. Additionally, adsorption and desorption might have operated simultaneously due to the length of the experiment as well as fluctuations in the flow rate. The use of olivine as adsorbent for dissolved metals is relatively new, and the nature of its charge sites/surface functional groups, and removal mechanisms under different experimental conditions have not been fully evaluated yet. Therefore, to elucidate main metal removal mechanisms of olivine and their variability in response to operational factors would require further detailed investigation.

In the case of pine bark (Figure 4), the shapes of the curves for Pb/Cu and Ni/Zn are different. Pb and Cu showed a high removal percentage, 83% and 77% respectively, after more than 1500 pore volumes. However, Ni adsorption was close to exhaustion (Figure 4b), which would control the operational life even though it still has very high affinity for uptake of Pb and Cu. A similar adsorption sequence for pine bark and the studied heavy metals have been previously reported in a batch study [30].

Unlike the other adsorbents, pine bark has lower surface area but achieved a high removal of metals. This can be attributed to different adsorption mechanism on pine bark, which has been attributed to compounds such as pectin, lignin, and tannin [31] that provide carboxylic, phenolic, and hydroxyl groups for the adsorption of metals. On the other hand, pine bark is prone to leaching of some of these organic compounds and dissolved organic carbon (DOC), which can interfere with the adsorption process due to complexation of dissolved metals such as Cu with DOC [22]. Several treatments have been reported in the literature to prevent the release of soluble organics, which can color and contaminate the effluent [32]. However, additional treatments can also reduce the attractiveness of pine bark amended filters due to increased costs associated with pre-treatment and/or post-treatment disposal of chemicals.

For the charcoal amended filter (Figure 5), the removal of metals, with the exception of Cu and Pb, decreased sharply within the first 200 pore volumes. For reduced adsorption of Zn and Ni as compared to the other two metals, variable binding mechanisms, competition from other cations and dissolved organic carbon in tap water, could be the probable cause. A previous study [33] reported that Pb and Cu formed covalent or strong bonds with biosorbents. However, Ni and Zn generally adsorb on weak electrostatic binding sites. This kind of binding behavior can result in reduced adsorption for certain metals if there is a competition from other ions (i.e., Ca^{2+}). However, the concentration of Ca^{2+} in our synthetic stormwater was substantially low to have caused any substantial interference in the adsorption of metals on charcoal.

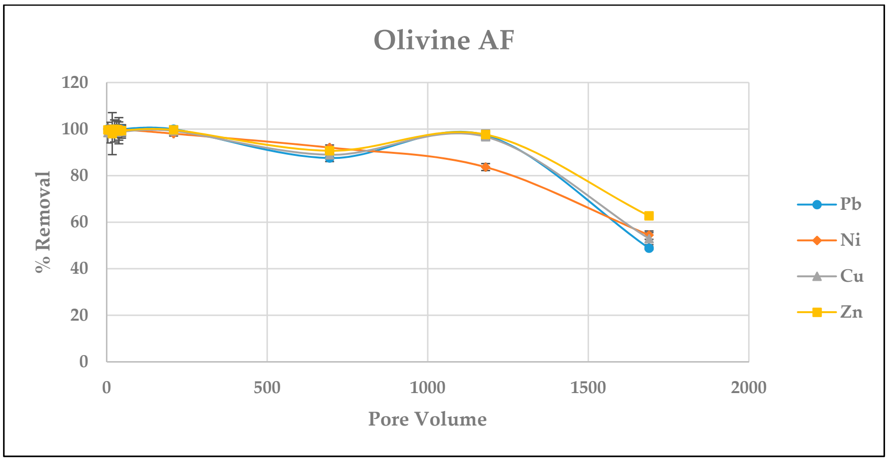
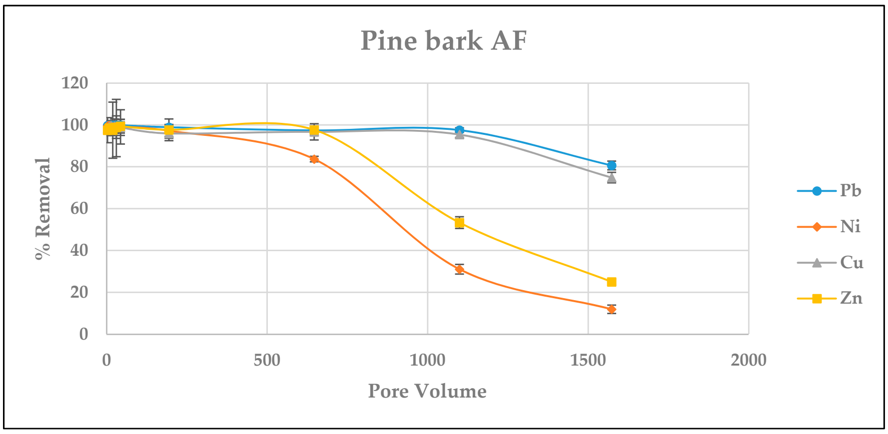
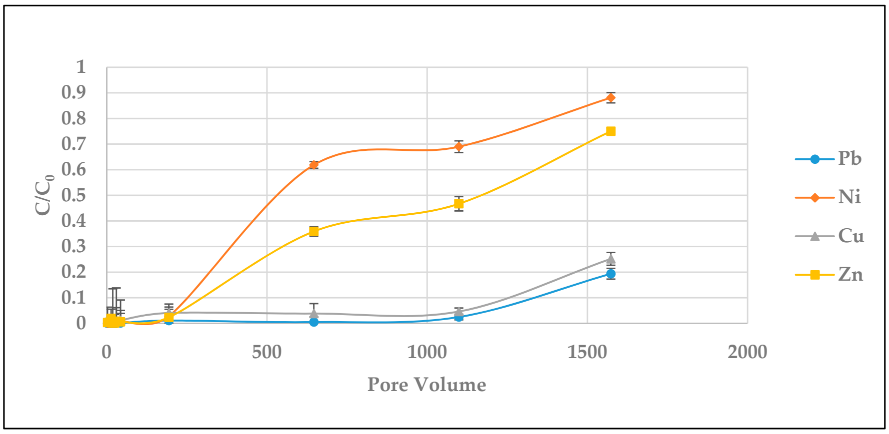


Figure 3. Percentage removal of the four metals by olivine amended filters as a function of pore volume. AF stands for amended filter.



(**a**)

Figure 4. *Cont.*



(**b**)

Figure 4. Percentage removal (**a**) and breakthrough curve (**b**) of the four metals by pine bark amended filters as a function of pore volume. AF stands for amended filter. C and C_0 are the effluent and influent metal concentrations, respectively.

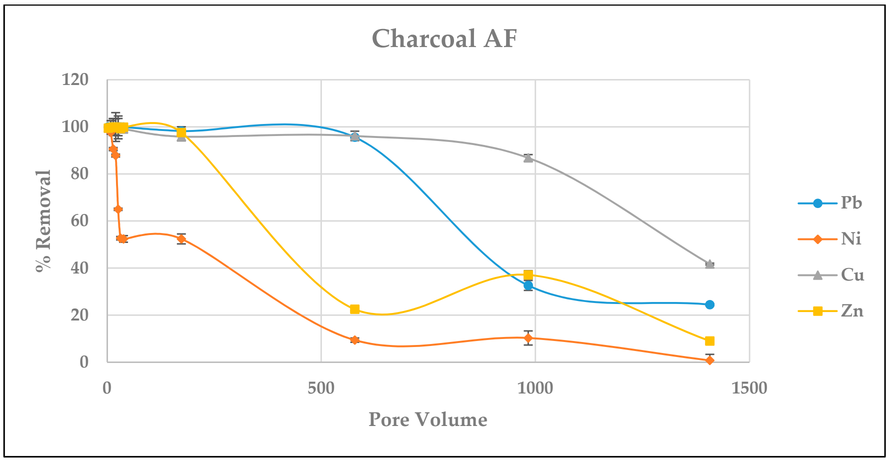


Figure 5. Percentage removal of the four metals by charcoal amended filters as a function of pore volume. AF stands for amended filter.

The low removal of Ni by charcoal could also be due to the pH of the inflow solution, at 7.5, while optimal Ni adsorption occurs at pH 6 [34]. However, coal based adsorbent, as in this case, has point of zero charge at pH 7.2 [35], which is close to the pH of the influent. Therefore, the pH conditions are favorable for cationic metal adsorption. Another reasonable explanation for low Ni adsorption could also be due to the nature of the adsorbent, which is derived from a metamorphic source—anthracite charcoal. Fourier transform infrared spectroscopy (FTIR) data from [36] showed that anthracite based carbons contain low oxygen surface functional groups, which can affect adsorption of metals such as Ni. Additionally, adsorption of Ni has been reported to be several orders of magnitude lower than other metals such as Cu at pH < 8 [37]. Zn and Pb showed initially high affinity but it declined over time, which indicates saturation of adsorption capacities of these two metals or increased competition for limited binding sites. This emphasizes the metamorphic nature of charcoal as suitable for removal of Cu, Pb, and Zn but not for Ni. The life span of the charcoal amended filter will be controlled by Ni because it showed the earliest breakthrough, which is in agreement with a previous study using charcoal for metal removal [26].

3.3. Estimating Service Life

Estimated service life of the studied filters with respect to the target metals are presented in Table 7. For the calculations, a density of 1.600 kg/m^3, a filter depth of 40 cm, an average total precipitation depth of 895 mm/year for Trondheim area, and a 90% runoff capture were considered. Additionally, allowable release concentrations from the filters were adopted based on Norwegian quality standards for moderate contamination of the receiving surface waters. The input dissolved concentrations were based on average runoff concentrations detected in the streets of Trondheim [38].

Table 7. Cumulative adsorption at the required removal and service life in (years) for different filters with respect to the target metals. I/P stands for impervious area to pervious area ratio and AF for amended filter.

I/P Ratio	Target Metal	Runoff Concentration (µg/L)	Required Removal (%)	Cumulative Adsorption (mg/kg) and Service Life in Brackets		
				Pine Bark AF	Charcoal AF	Olivine AF
50	**Zn**	18	31	9.1 (9)	2.3 (2.3)	2.5 (2.5)
	Cu	13.5	92	9.8 (13)	3.1 (4)	1.1 (1.5)
	Ni	2.32	35	6.1 (46)	0.6 (5)	2.4 (18)
20	**Zn**	18	31	9.1 (22)	2.3 (5.5)	2.5 (6)
	Cu	13.5	92	9.8 (32)	3.1 (10)	1.1 (3.8)
	Ni	2.32	35	6.1 (115)	0.6 (12)	2.4 (45)

From the values in Table 7, it can be seen that zinc generally will determine the service life of the filters amended with pine bark or charcoal due to high concentrations detected in urban runoff as well as the moderate affinity with the adsorbents (Figures 3–5). On the other hand, copper was found to determine the service life of the olivine amended filter due to the low cumulative adsorption observed at the required removal combined with relatively high runoff concentration. Nickel showed low affinity with all the adsorbents although the removal requirement was more relaxed, which allows these filters to stand during longer periods. Lead was not considered in the calculations because the observed concentrations in local runoff was lower than Norwegian standards for receiving surface waters, indicating that no treatment would be required. Therefore, this element will not pose a risk for the receiving water body, regardless of the removal acquired in the filter. On the other hand, I/P ratios set by the planners will influence the service life of the filters because it will modify the relation between the pollutant input load and the mass of the filter. A higher ratio means a larger tributary providing pollution into the facility, which will cause the filter to reach the removal requirement earlier and, subsequently, its service life.

4. Conclusions

The results presented in this study demonstrate the potential of the studied adsorbents for use in treatment filters for urban and highway runoff, both from a removal and a volume mitigation point of view. In terms of removal performance, the pine bark and the olivine amended filters showed the best affinity with the target metals. To mitigate the poor performance of pine bark with respect to Ni and Zn removal and the higher cost of olivine, it appears attractive to explore the combined use of these two adsorbents. Charcoal showed the lowest affinity for the target metals among all the adsorbents. However, the final choice of adsorbent should also consider infiltration performance, initial costs, need for maintenance, material stability, potential leaching of other pollutants, etc., and not just the removal performance criterion. The hydraulic loading rates used were considerably high in comparison with other similar studies. Despite higher rates, satisfactory pollution removal was achieved, which highlights the outstanding metal removal under infrequent storm events such as two years return period one hour duration events for the city of Trondheim. In terms of environmental impact, all the filters showed very little release of metals in response to addition of NaCl as deicer. However, Ni was to a greater extent leached from charcoal due to low affinity with this adsorbent as well as competition with sodium. From the point of view of the effluent discharge, Zn was shown to determine the service life of filters amended with charcoal or pine bark, and Cu did the same for the service life of olivine. Furthermore, the filter composed of pine bark and sand showed the largest values ranging from nine years to more than 100 depending on the target element as well as the size of the tributary. It must be highlighted that laboratory conditions differ from real field conditions; hence, it is recommended that these values be used as a general indication of their potential service life. Nonetheless, these results can be a useful tool to discard materials for subsequent experiments, as well as providing a general understanding of the factors influencing the service life of the studied filters. Additionally, it is recommended to couple these filters with a pre-sedimentation basin in order to reduce high input loads of sediments that might clog top layers and hinder further adsorption processes. Finally, these filters should be tested in field scale experiments to further study hydraulics and removal performance for practical design guidelines.

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Author Contributions: Carlos Monrabal-Martinez, Aamir Ilyas, and Tone M. Muthanna conceived and designed the experiments. Carlos Monrabal-Martinez and Aamir Ilyas performed the experiments and analyzed the data. Carlos Monrabal-Martinez, Aamir Ilyas, and Tone M. Muthanna wrote the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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Paper 3

Infiltration response of adsorbent amended filters for stormwater management under freezing/thawing conditions.

Carlos Monrabal-Martinez, Sønke Maus, Elena Kuznetsova, and Tone M. Muthanna.

In review: Journal of Cold Regions Science and Technology.

Is not included due to copyright

Paper 4

Hydrological benefits of filtering swales for metal removal.

Carlos Monrabal-Martinez, Jochen Aberle, Tone M. Muthanna, Mauro Orts-Zamorano.

In Review: Hydrological Processes

Is not included due to copyright

Appendix B: Secondary Papers

This appendix presents three presented conference papers on which some of the selected papers were built. The full bibliographies and abstracts are presented.

SP1 Carlos Monrabal-Martinez, Aamir Ilyas and Tone M. Muthanna (2015). “Study of Infiltration Performance of Roadside Filters with Adsorbent Media for catchment and filter sizing.” 1*2th Urban Environment Symposium,* Oslo*,* Norway*,* 1 - 3 June 2015.

Abstract: Infiltration based solutions have been shown to reduce peak flow and efficiently treat runoff pollutants by processes such as filtration, and adsorption, and plant uptake in case of rain gardens. In this paper, we evaluate infiltration-based swales with using low-cost sorbents (e.g. activated charcoal, olivine, pine bark, and bottom ash + iron oxide) for use in roadside storm water treatment. The objective was to evaluate the infiltration capacity and use this information to find optimal adsorbent placement, delineate the catchment area and dimension the filter. The saturated hydraulic conductivities (K_{sat}) were obtained by a constant head and upwards flow permeameter. The results show that placement of the adsorbent material within the filter media does make a difference concerning infiltration performance. The catchment size was dependent on K_{sat} and rainfall characteristics of different regions. For practical applications, a selection table relating rainfall characteristics, K_{sat} and catchment areas is presented.

SP2 Carlos Monrabal-Martinez, Tone M. Muthanna and Thomas Meyn (2016). “Seasonal variation in pollutant concentrations and particle size distribution in urban stormwater - design implications for BMPs” *9th International Conference NOVATECH,* Lyon, France, 28 June - 1 July 2016.

Abstract: Understanding the particle size distribution and metal distribution within the particle size fractions are essential to design the correct treatment alternatives. Seasonal variation and cold climate creates additional variance in storm water characterization that has an important design implication. The objective of the study was to investigate the seasonal variation in pollutant concentrations and particle size distribution in the city of Trondheim, and how this might affect design parameters of storm water treatment systems, like bio retention areas and swales with respect to treatment efficiency and clogging problems. Total solids found in urban runoff during the wintertime showed around 8 times higher concentrations than in rainfall season. Toxic metal concentrations exceeded international water quality criteria, and agreed with other studies in similar climate. In cold climate countries, a pre-sedimentation basin or filter strip could be an option to capture the bulk of the considerably higher particle concentration of melting and rain-on-snow events.

SP3 Carlos Monrabal-Martinez, Jochen Aberle, Tone M. Muthanna, Mauro Orts-Zamorano (2017). “Hydrological benefits of amended infiltration based swales for metal removal.” *14th International Conference of Urban Drainage,* Prague*,* Czech Republic, 10 – 15 September *2017.*

Abstract: Laboratory experiments were carried out to evaluate the impact of controlled variables such as slope, filter media, antecedent water content, and event size on the hydrological performance of swales for stormwater management. Two filters were composed of highly permeable material with verified capacity for toxic metal retention, and the third was composed of traditional soil used in raingardens. The longitudinal slope was found non-statistically significant in the hydrological performance of the swales. The traditional soil filter could handle considerably smaller run-in events than the other two filters, which was assessed by the ratio of run-in to infiltrated water. On the other hand, the other two filters can handle medium to large events depending on the size of the tributary.

Appendix C: Co-Author Statements

This appendix holds the statements from the co-author confirming co-authorship and the contributions made by the PhD candidate.

NTNU

Encl. to application for assessment of PhD thesis

STATEMENT FROM CO-AUTHOR

(cf. section 10.1 in the PhD regulations)

Carlos Monrabal-Martinez applies to have the following thesis assessed:
Name of candidate

Hydrologic and metal removal potential of filtering swales for stormwater control in cold climates
title

*) The statement is to describe the work process and the sharing of work and approve that the article may be used in the thesis.

*)
Statement from co-author on article: Monrabal-Martinez, C., Muthanna, T.M., Meyn, T.

Characterization and seasonal variation of urban runoff in cold climate - design implications for SuDS. Urban Water journal (in review).

I hereby declare that I am aware that the article mentioned above, of which I am co-author, will form part of the PhD Thesis by the PhD Candidate Carlos Monrabal-Martinez who made a major contribution to the work in the experiment, data analysis and writing phase.

Trondheim, 22.08.17 T. Meyn

Place, date Signature co-author

*)
Statement from co-author on article: Monrabal-Martinez, C., Muthanna, T.M., Meyn, T.

Characterization and seasonal variation of urban runoff in cold climate - design implications for SuDS. Urban Water journal (in review).

I hereby declare that I am aware that the article mentioned above, of which I am co-author, will form part of the PhD Thesis by the PhD Candidate Carlos Monrabal-Martinez who made a major contribution to the work in the experiment, data analysis and writing phase.

Trondheim, 31.08.17

Place, date Signature co-author

Encl. to application for assessment of PhD thesis

STATEMENT FROM CO-AUTHOR

(cf. section 10.1 in the PhD regulations)

Carlos Monrabal-Martinez applies to have the following thesis assessed:

Hydrologic and metal removal potential of filtering swales for stormwater control in cold climates
title

*) The statement is to describe the work process and the sharing of work and approve that the article may be used in the thesis.

*)
Statement from co-author on article: Monrabal-Martinez, C., Ilyas, A., Muthanna, T.M.

Pilot Scale Testing of Adsorbent Amended Filters under High Hydraulic Loads for Highway Runoff in Cold Climates.
Water, 9(3), 230, DOI: 10.3390/w9030230.

I hereby declare that I am aware that the article mentioned above, of which I am co-author, will form part of the PhD Thesis by the PhD Candidate Carlos Monrabal-Martinez who made a major contribution to the work in the experiment, data analysis and writing phase.

TRONDHEIM, 28.08.17
Place, date

Signature co-author

*)
Statement from co-author on article: Monrabal-Martinez, C., Ilyas, A., Muthanna, T.M.

Pilot Scale Testing of Adsorbent Amended Filters under High Hydraulic Loads for Highway Runoff in Cold Climates.
Water, 9(3), 230, DOI: 10.3390/w9030230.

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Trondheim, 31.08.17
Place, date

Signature co-author

NTNU

**Encl. to app-
lication for
assessment of
PhD thesis**

STATEMENT FROM CO-AUTHOR

(cf. section 10.1 in the PhD regulations)

Carlos Monrabal-Martinez applies to have the following thesis assessed:

Hydrologic and metal removal potential of filtering swales for stormwater control in cold climates
title

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*)
Statement from co-author on article: Monrabal-Martinez, C., Maus, S., Kuznetsova, E., Muthanna, T.M.,

Infiltration response of adsorbent amended filters for stormwater management under freezing/thawing conditions. Journal of Cold Regions Science and Technology (in review).

I hereby declare that I am aware that the article mentioned above, of which I am co-author, will form part of the PhD Thesis by the PhD Candidate Carlos Monrabal-Martinez who made a major contribution to the work in the experiment, data analysis and writing phase.

Trondheim, 01.09.2017
Place, date

Kuznetsova Elena
Signature co-author

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*)
Statement from co-author on article: Monrabal-Martinez, C., Maus, S., Kuznetsova, E., Muthanna, T.M.,

Infiltration response of adsorbent amended filters for stormwater management under freezing/thawing conditions. Journal of Cold Regions Science and Technology (in review).

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Trondheim, 01.09.2017
Place, date

Signature co-author

*)

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Trondheim 04.09.17
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NTNU

Encl. to application for assessment of PhD thesis

STATEMENT FROM CO-AUTHOR

(cf. section 10.1 in the PhD regulations)

Carlos Monrabal-Martinez applies to have the following thesis assessed:

Filtering swales for stormwater management in cold climates

*) The statement is to describe the work process and the sharing of work and approve that the article may be used in the thesis.

*)

Statement from co-author on article: Monrabal-Martinez, C., Aberle, J., Muthanna, T.M., Orts-Zamorano, M.

Hydrological benefits of filtering swales for metal removal.
Hydrological Processes (in review).

I hereby declare that I am aware that the article mentioned above, of which I am co-author, will form part of the PhD Thesis by the PhD Candidate Carlos Monrabal-Martinez who made a major contribution to the work in the experiment, data analysis and writing phase.

VALENCIA, 22/08/2017
Place, date

Signature co-author

*)

Statement from co-author on article: Monrabal-Martinez, C., Aberle, J., Muthanna, T.M., Orts-Zamorano, M.

Hydrological benefits of filtering swales for metal removal.
Hydrological Processes (in review).

I hereby declare that I am aware that the article mentioned above, of which I am co-author, will form part of the PhD Thesis by the PhD Candidate Carlos Monrabal-Martinez who made a major contribution to the work in the experiment, data analysis and writing phase.

Trondheim, 25/08/2017
Place, date

Signature co-author

*)
Statement from co-author on article: Monrabal-Martinez, C., Aberle, J., Muthanna, T.M., Orts-Zamorano, M.

Hydrological benefits of filtering swales for metal removal.
Hydrological Processes (in review).

I hereby declare that I am aware that the article mentioned above, of which I am co-author, will form part of the PhD Thesis by the PhD Candidate Carlos Monrabal-Martinez who made a major contribution to the work in the experiment, data analysis and writing phase.

Trondheim, 31.08.17 ……………………………………
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