Bioretention as a sustainable stormwater management option in cold climates

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Foreword

This thesis is based on research and findings that have been presented in five papers. For all five papers I have been the first author. For papers I, II, and V, I have conducted all the fieldwork, done all the analysis and written the paper in full with guidance and supervision from my advisors, who are also co-authors. Paper III includes a data set collected by the second author (Nina Gjesdahl), a master student at the time. The April portion of the data in this paper was collected as part of Nina Gjesdahl's MSc thesis, supervised by myself. For Paper IV the third author (Godecke Blecken), a PhD student working for Prof. Maria Viklander, at the Luleå University of Technology, also working with bioretention in cold climate helped in the planning of the experiment, and general discussions of the results. The experimental setup, execution, analysis and interpretation of the results were conducted by myself.

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First I would like to thank the Department of Hydraulic and Environmental Engineering and my advisor at NTNU, Sveinn Thorolfsson for giving me the opportunity to pursue a PhD at NTNU. The Risvollan Urban Hydrologic Research Station and the huge amount of data collected over 20 years gave me a great location for fieldwork. There is also one person more than anybody that made this thesis possible in the end, and that is my second advisor, Dr. Maria Viklander at the Luleå University of Technology, Luleå, Sweden. She is the most amazing person, she inspired me, gave me advice, helped me structure the work and pushed me to dig deeper into the scientific questions. She taught me so much about experimental research, and snow and meltwater quality. Thank you Maria, you are an amazing wonderful person!!

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Finally I would like to thank my family and friends around the world for giving me plenty of reasons for minibreaks and vacations. Thanks to my parents for always being there, and to my sister, Line, and Börje for lots of good times. It is always one of my favorite weekends when we see you guys, and little Hedda that came along and made me the worlds proudest aunt. Then there is only one person left, but he is the most important of them all, Chittiappa, my husband, thank you for making me feel like the worlds most special person every single day, that is truly special, and for reminding me of 'top of the world'!!

Abstract

Two pilot size bioretention boxes were constructed for field investigations at the Risvollan Urban Hydrological Research Station in Trondheim. The seasonal pollutant retention, hydraulic lag times, and rainfall runoff versus snowmelt chemo dynamics have been studied with respect to zinc, copper, and lead. The field investigations were divided into four parts; a long term continuous hydrologic performance, heavy metal retention of rainfall runoff during different seasons, and heavy metal retention from roadside snowmelt. The chemo dynamic pathways through the system were investigated for the warm versus the cold season, and rainfall runoff versus snowmelt. Overall the results showed consistent high retention of particles and total metals with respect to concentrations and mass removal, with more than 90% mass removal of total zinc and more than 85% mass retention of lead, while copper retention varied from 46% to 86% by mass. However increases in dissolved fractions through the system for all events in the case of copper and for the snowmelt events in the case of zinc could lead to an increase of bioavailable dissolved metals in the outflow which is not desirable. The top mulch layer was identified as the largest sink of metals and particles, which helped avoid clogging the soil due to high particle concentrations in the inflow. The plants did show some ability to retain and absorb metals in the roots and shoot, however this was less than 5% of the total metal retention. The plants had a more important function in improving root zone infiltration, and rejuvenating the system in the spring every year, making it a valuable green space in the urban landscape. Snow storage was also considered and it was found that snow storage, dependent on annual snow volume, quickly became a deciding design parameter with respect to sizing.

List of Papers

I.* **Building a bioretention area in a cold climate**
T. Nordberg, S.T. Thorolfsson
Proceedings of the 10th International Conference on Urban Drainage
ICUD 2005, Copenhagen, Denmark

II. **Seasonal climatic effects on the hydrology of a cold climate rain garden**
T.M. Muthanna, M. Viklander, S.T. Thorolfsson
In Review: Journal of Hydrological Processes

III. **Heavy metal removal in cold climate bioretention**
T.M. Muthanna, N. Gjesdahl, M. Viklander, S.T. Thorolfsson
In Review: Water, Air, and Soil Pollution

IV. **Snowmelt pollutant retention in bioretention areas**
T.M. Muthanna, G. Blecken, M. Viklander, S.T. Thorolfsson
In Review: Water Research

V. **An evaluation of applying existing bioretention sizing methods to cold climates with snow storage conditions**
T.M. Muthanna, M. Viklander, S.T. Thorolfsson
Proceedings of NOVATech 2007, Lyon, France

*Published under mainden name, Nordberg, before 2005.

List of Abbreviations

BMP - Best Management Practice

CEC - Cation exchange capacity

ET - Evapotransporation

HR ICP-MS - High Resolution Inductively Coupled Plasma-Mass Spectrometry

ICP-AES - Inductively Coupled Plasma-Atomic Emission Spectrometry

IMP - Integrated Management Practices

LID - Low Impact Development

Redox - Reduction oxidation

RUHRS - Risvollan Urban Hydrologic Research Station

TSS - Total Suspended Solids

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Chapter 1

Introduction

The management of urban stormwater has become a matter of great importance as our urban areas expand and grow. The problems associated with increasing runoff volumes and deteriorating water quality increases as a result of urbanization. Our management of urban water resources has to be climatically adapted to local conditions and be sustainable in nature. Bioretention, an infiltration medium made up of soil and mixed vegetation to infiltrate and treat stormwater, offers a great combination of local stormwater management, enhanced urban vegetation zones, increased aesthetical value, and functional pollutant retention. In this thesis, the use of bioretention areas in cold climates and how the special conditions of cold climates affect their performance and function are explored and investigated.

1.1 Structure of the thesis

Chapter 1 presents a general introduction to the topic and describes elements of urban hydrology and cold climate challenges building up the motivation and the objectives. Chapter 2 reviews the literature about bioretention facilities and the main soil and plant processes involved in water and metal retention in bioretention systems. Chapter 3 presents the field work setup, and experiments conducted. Then Chapter 4 summarizes the five scientific papers in the dissertation and gives the reader a guide to the motivation behind each papers and how the papers build on each other. In Chapter 5 the results from all the papers are compared and discussed in relation to the objectives of the thesis. Chapter 6 draws the main conclusions based upon the major findings in the work presented and discusses recommendations for future work. Then at the end in Appendix A, the five scientific papers are included in their original form.

1.2 Background

1.2.1 Overview

The net growth of urban areas in Europe from 1990 to 2000 was 5.4%, which is a 0.6% annual increase (EEA, 2005). Though this might seem small, growth at this rate will lead to a doubling of urban areas in just over a century. If we do not change the way we urbanize and develop cities, we will dramatically increase impervious areas and suffer significant effects from increased urban runoff volume and water quality impairment.

The view of stormwater management in urban areas has changed over time. Early solutions combined sewer systems where large rainfall events resulted in overflows and toxic shock loads of pollutants to receiving waters, and fast conveyance of stormwater over impervious surfaces, further accelerated by deepening, straightening and lining of urban streams. This traditional approach has long be known not to be a sustainable way to manage urban stormwater (Marsalek et al., 1993). This lead to the use of separate storm sewers with the end-of-pipe approach to managing the water volumes, first with no treatment, just direct discharge to receiving water, later with the use of large detention basins and stormwater ponds built downstream collecting water from large areas became common practice. This created more erosion, and more flood in the downstream areas of the developments, and transport of large water volumes out of the watersheds creating shifts in the local water balance. Then, in the last decade the use of local and decentralized solutions and keeping the water in the watershed as long as possible emerged as a more viable and sustainable option for stormwater management. Over the last decade the potential water quality impairments from stormwater have also become an important issue in addition to flood risk. The need for better management of stormwater in urban areas as a result of increasing pressure on the combined sewer systems resulted in that the first national handbook for stormwater management was published in 2005 (Lindholm et al., 2005). The concept of sustainable stormwater management has also lead to the development of criteria and evaluation of separate stormwater management compared to combined sewers with respect to sustainability. Lindholm and Noreide (2000) found a natural based stormwater system to be 4-5% more sustainable than a conventional combined sewer system. The natural system scored better in metals in sludge, cost, operation, and landscape and recreational value.

Low Impact Development[1] emerged in the early 1990s as a new way of thinking about stormwater management, from a nuisance to a potential resource. The main goal of LID is to mimic the predevelopment hydrology to minimize the impact of development, especially impervious surfaces (PGC, 1999). Low Impact Development is a theory of urban development that encompasses more than conveyance and treatment of stormwater, through integrated management practices[2] that include five main groups; infiltration practices, conveyance, landscaping, conservation and minimization, and storage. Bioretention is a landscaping and infiltration practice and is maybe one of the most important IMPs because it is a multi functioning micro scale best management practice[3] that preserves all of the important hydrologic functions present in a natural setting (Figure 1.1). It provides canopy interception, evapotranspiration, water quality control, runoff volume and peak flow discharge control, and groundwater recharge if no impermeable textile or underdrain is present (Clar et al., 2004).

1.2.2 Urban hydrology

Urbanization alters the natural hydrology in an area both with respect to runoff volume, peak flow rates, and with respect to water quality. It changes the natural water paths through the watershed and imperviousness is the most critical factor in this process (Novotny and Harvey, 2003). In a natural forested watershed as much as 50% of rainfall becomes infiltration, and as little as 10% becomes surface runoff. While in a fully urbanized watershed this can shift to 10-15%

[1]In the following referred to as LID
[2]In the following abbreviated IMP
[3]In the following referred to as BMP

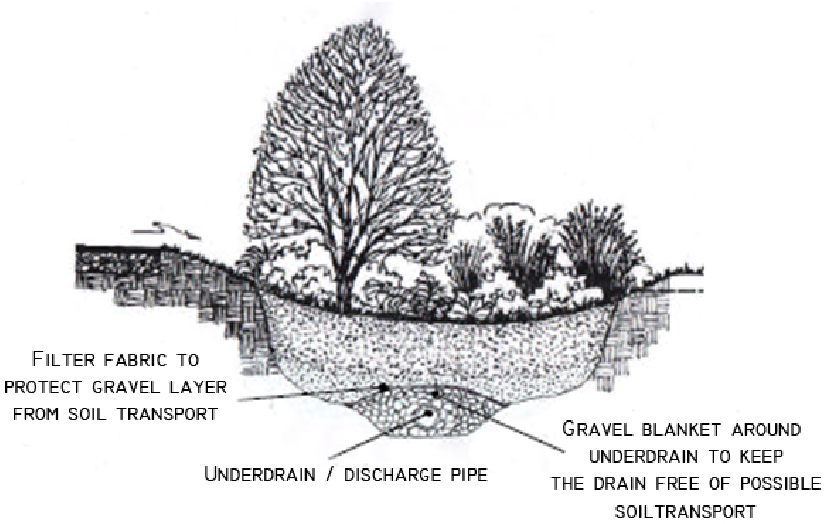

Figure 1.1: Typical design of a bioretention area with underdrain (PGC, 1993).

infiltration and as much as 55% surface runoff (FISRWG, 2001) (Figure 1.2). This contributes to increased peak and total volumes as well as water quality impairment. The increased runoff volumes leads to rapid increases in urban stream flows during rainfall events, while the reduced infiltration rates causes less water to slowly be released back into the stream. This reduces the dry weather flow in the stream, and in worst case changing a perennial stream to an intermittent stream (FISRWG, 2001). The evapotranspiration[4] has been traditionally thought to decrease in heavily urbanized areas as a result of less vegetation and less available water in the soil (Leopold, 1968), however the opposite have been shown to occur in some more recent studies. A study from an urban park reported ET values 3 times that neighboring residential areas, and 1.3 times higher than a close by agricultural land (Spronken-Smith et al., 2000). Claessens et al. (2006) showed through 60 years of data and long term modeling that landuse change did not have an effect on annual ET, however climate change was shown to affect annual ET rates. Ferguson and Suckling (1990) concluded that ET in urban areas can actually increase due to the increased sensible heat.

In addition to altered hydrology, urbanization also causes significant water quality impairments that also tend to be elevated with increased water volumes. After several decades targeting point source pollution at the end of the 20^{th} century

[4] In the following referred to as ET

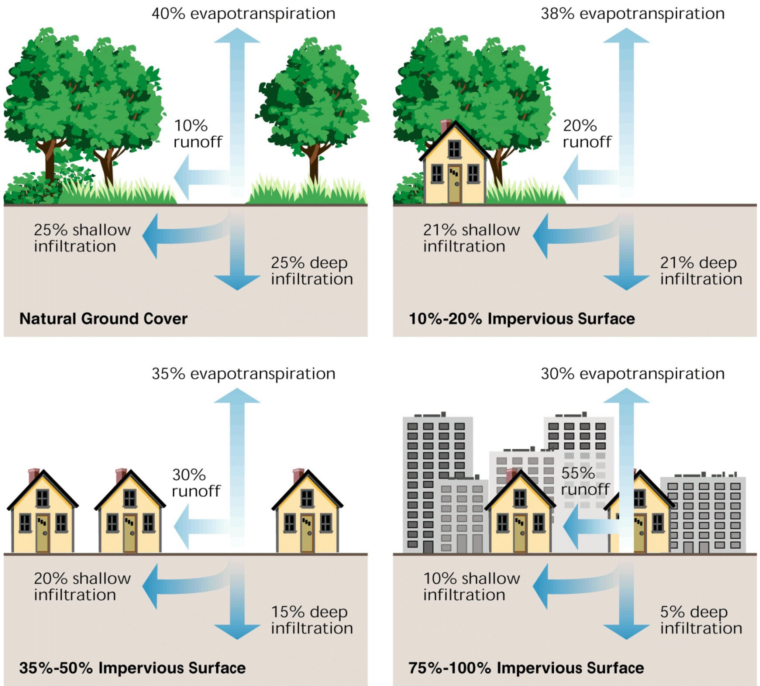

Figure 1.2: Change in hydrology from a natural to a fully urbanized watershed adapted from (FISRWG, 2001).

non point source pollution is now responsible for 50% of all stream, river and lake impairments in the United States and it is estimated that urban non point source pollution contributes as much as 25% of all non point source pollution (USEPA, 2002, 1990). The same trend has been reported in Europe, as pollution from point sources have been heavily regulated and organic matter concentrations fell at 50% of the measurement stations in Europe during the 1990's (EEA, 2005). The diffuse pollution from agriculture, urban activities, residential, and highway landuse are now significant contributors to the overall pollution levels in receiving waters.

1.2.3 Urban runoff quality

The sources of urban runoff can be divided into several categories based on the landuse such as roads, buildings, parks, and parkinglots. Urban roads are one of the main sources of pollutants in the urban landscape. Marsalek et al. (1999) identified characterization of stormwater discharges, identification of their effects on receiving waters, and remediation of these effects as the three aspects of interest with respect to highway runoff. In character, the main sources of pollutants in road runoff include copper, zinc, lead, cadmium, sediments, PAHs, and deicing salts (Makepeace et al., 1995; Barett et al., 1998). Several studies have also found a link between pollutant concentrations and traffic density, with highest pollutant loads from highways and highway bridges (Storhaug, 1996; Marsalek et al., 1999). This indicates an increased effect on receiving waters for increased traffic density. A laboratory and field sampling study investigated the copper, cadmium, zinc, and lead specific source loadings in the urban environment. The results revealed that building sidings were important sources for all four metals, vehicle brake emissions were a high source of copper, and tire wear was a significant source of zinc. In addition atmospheric deposition was found to be important for lead, cadmium, and copper (Davis et al., 2001a). The sources of metal in road runoff can be divided into pavement wear (40-50% of particulate mass), tire wear (20-30% of particulate mass) and the remaining 15% comes from engine and brake parts and 3% from urban atmospheric deposition not related to road activities (Kobriger and Geinopoles, 1984). Analyzing particle size fractions and metal conentrations has shown that heavy metals are attached to the smallest particles, less than 10μ (Boller et al., 2004; Westerlund and Viklander, 2006). Tuccillo (2006) also found that zinc and copper tended to be either associated with particles less than 5μm or smaller than 10 kilo Daltons (A dalton is a unit used to measure the mass of atoms and molecules, one dalton equals the atomic weight of a hydrogen atom), which is considered dissolved phase.

The partitioning coefficient for metals is important in determining the toxicity of the metal concentrations, which is more toxic in dissolved than in particulate form. The precipitation pH and alkalinity of the impervious surface have been found to affect the partitioning coefficient (Sansalone and Buchberger, 1997). Marsalek et al. (1999) compared highway runoff to general urban landuse and found that large multilane highways with more than 100 000 cars/day had a higher frequency of severe toxicity that general urban landuse. Further subdividing the multilane highway data into summer and winter also revealed a higher toxicity frequency in the winter months.

In addition to highway runoff, tunnelwash water is another significant source of pollutants in Norway, with more than 700 km of tunnels. The cleaning of these tunnels can produce shock loads of pollutants to the receiving waters. In addition to the high levels of heavy metals and particles in the wash water, the tensides in the soap cause acute toxic effects on aquatic organisms (Roseth et al., 2003).

1.2.4 Cold Climates

Cold climate by the classification by Köppen (McKnight and Hess, 2005) includes areas with three months with temperatures above 10 ° C and where the coldest month has a average below -3 ° C . Another definition of cold climate areas are defined as areas where the mean monthly temperature for at least one month of the year is less than 1 ° C (Smith, 1996). This is a significant number which emphases the need for research on sustainable solutions for cold climate urban hydrology. Most of Norway, except the southwest coast falls into these two definitions, with an exception of some areas of the southwest coast which typically experience and warmer wetter winter. Cold climate adds additional and different challenges to urban stormwater management both with respect to water volume and water quality. The hydrologic cycle becomes more complex in cold climates by adding a snow phase to the cycle (Marsalek, 1991). This affects the pools of water where water is stored in the snowpack and it affects the waterborne pollutant transport. Four main added challenges are attributed with cold climate, cold temperatures, deep frost lines, short growing seasons, and significant snowfall (Caraco and Claytor, 1997). In a survey by US practitioners, government officials and experts more than 40% reported that frozen pipes, slower infiltration, vegetation establishment, and spring melt were always a concern when designing stormwater systems (Caraco and Claytor, 1997). Traditional stormwater system with inlets and pipes are especially susceptible to cold temperatures. Frozen inlets and frozen pipes can cause flooding during winter rain events. In Trondheim, 7 out of 12 major floods between 1978 and 2000 were found to occur in the winter (Nilsen and Bjørgum, 2001). Frost-heaves caused by frost lines can be several meters deep, causing difficulties in laying of pipe, and possible frozen pipes. Large volumes of snowfall adds a snow storage problem and a subsequent snowmelt problem to cold climate urban stormwater management. Research has also shown that falling snowflakes can scavenge atmospheric particulate and aerosol pollutants (Colbeck, 1981). Accumulation of pollutants, heavy metals in particular increases as the snow is stored along the roadside. This accumulation can result in metal concentrations up to ten times higher than that of snow fallen on urban grass surfaces (Malmqvist, 1978). A short growing season for vegetation in stormwater treatment affects the treatment efficiency during the cold periods though this is seldom accounted for in the design of the systems (Novotny et al., 1999). Each of these areas can be additionally elaborated, however only frozen soils and soil infiltration, short growing seasons, and snowmelt will be further discussed as these are important factors for bioretention performance in cold climates. Frozen pipes could be an issue if the bioretention facility has an underdrain and the frost line is deeper than the underdrain. However adequate slope on the underdrain can avoid standing water in the pipe and hence avoid freezing even if the pipe is above frost free levels.

1.2.5 Urban snowmelt

In climates with significant snowfall over the cold season the storage of snow and the subsequent snowmelt season are two added challenges to stormwater management. First is the problem of snow storage, as large volumes of snowfall require adequate and suitable storage areas. Secondly, pollutant accumulation in snow can be substantial and the sources of pollution can differ from the warm season. This includes the use of studded winter tires on vehicles which increases asphalt abrasion, less optimal combustion in engines as a result of cold temperatures, more heating of houses which leads to increased particle deposition (Malmqvist, 1978; Viklander, 1997). In addition to the changes in snow pollutant accumulation, the residence time in the snow can be up to several months long, compared to a residence time of hours or days for rainfall runoff, which can significantly increase the pollutant loads in the snowpack. The snowmelt period can be divided into three stages, the pavement melt stage, where de-icing chemicals and solar radiation will melt the impervious areas where snow clearing also takes place. This process generally produces low runoff volumes and occurs several times during the winter. The second stage involves the roadside melt of snow piles accumulating around the roads and parking lots. This stage produces moderate flow volumes, but high pollutant loads and can occur over some time. This is the snowmelt which generally carries the heaviest pollutant loads. And last, the third stage melts snow on pervious areas, such as parks, grass, and other pervious surfaces in the urban landscape. This last stage can often produce the highest runoff volumes depending on the soil infiltration rates (Oberts, 1994). The change in pollutant accumulation also affects the snowmelt water quality. Novotny et al. (1999) claimed that snowmelt generally has lower suspended solids concentrations, but much higher dissolved solids concentrations. This can be said to be true as the large masses of particles are left along the roadside after snowmelt and will either be cleaned by the first heavy rainfall or by street sweeping but not in the initial melt water. However if the snow is transported to a storage/treatment area the particles will be left as a gray cover of dirt and grit after the melt period has ended.

Several studies investigating the composition and pathways of snowmelt pollutants have concluded that there is an enrichment ratio of dissolved pollutants early in the snowmelt, and as much as 80% of the dissolved pollutants can be transported with the first 20% of melt water volume (Viklander and Malmqvist, 1993; Ecker et al., 1990). During several freezing and thawing cycles of the snowpack over the winter, the dissolved components are flushed from the snow pack and accumulate at the toe of the snowpack, which will melt first. This process is also called "acid flushing", "preferential evolution" or "freezing exclusion" (Oberts, 1990). A study from northern Sweden comparing melt water runoff and rain runoff concluded that the concentration of sediments were significantly higher in the melt period, and a stronger correlation between total suspended solids[5], particle sizes and metal (Cd, Cu, Ni, Pb, and ZN) concentrations (Westerlund and Viklander, 2006). Snow handling and management will also greatly affect snow quality and pollutant pathways, and with snow, unlike rain, this pathway can more easily be selected based on management strategy (Reinosdotter and Viklander, 2005).

[5]In the following referred to as TSS

1.2.6 Motivation and objectives

Bioretention as a method for stormwater treatment focuses on water retention, peak flow reduction, and water quality improvement with respect to nutrient, organic pollutants, heavy metals and sediments. However, in colder climates the performance of bioretention areas is to a large extent unknown. The most problematic issues in winter conditions are the many interchanged snow and rainfall events, creating rain-on-snow events, resulting in ice formation, then melting and refreezing as mentioned in the previous sections. The underlying idea of the thesis was that bioretention can offer a great possibility for use both as a snow deposit and retention of pollutants from the melt water.

The interchanging winter conditions and the challenges of urban snow melt with respect to water quality inspired this study. The goal was to further increase the knowledge of the hydrologic function and the mechanisms for pollution retention in bioretention systems in cold climates. The main objectives of this thesis were:

- Investigate the hydrologic function of bioretention as a stormwater treatment option in cold climate with respect to seasonal infiltration rates, storm lag times, and effect of ice and snow cover during the cold months.
- Investigate the seasonal metal retention in the system, and if type of precipitation event, rainfall or snowmelt, or temperature affects the metal retention in the system.
- Study the pollutant pathways through the bioretention for snowmelt, and investigate if the enrichment factor found in snowmelt events is also found in snowmelt through the bioretention media.
- As a final objective, use the observed data to evaluate the design and sizing criteria for bioretention facilities and their applicability for cold climate areas where snow storage is required.

Chapter 2

Bioretention function and processes

2.1 Bioretention overview

Bioretention as a stormwater practice was developed in the early 1990's in Maryland, USA by Prince George's County, a suburb to Washington DC. In 1993, they wrote the first bioretention manual (PGC, 1993). Bioretention areas are often also referred to as rain gardens and have some similarities to other BMPs, such as vegetated buffers, grass swales, and infiltration trenches. However, there are some features according to the original design by Prince George's County that distinguishes bioretention from other BMPs. These include the use of a mixed vegetation cover with some perennials, shrubs, and evergreens, as opposed to the mono culture in grass swales or infiltration trenches which may not have any vegetation. Bioretention areas also have a 5-10cm thick mulch layer composed of shredded bark and or compost litter that functions as a highly absorbent layer high in organic matter content. Some design may not include this feature but in this thesis the definition of bioretention used by Prince George's County is used, where it includes a top mulch layer. The soil in a bioretention facility is also clearly defined in terms of infiltration rate and texture, compared to buffer strips and grass swales, which are designed more for conveyance than infiltration. To create a clear frame around bioretention in this thesis the following definition will serves as working definition:

A bioretention is an engineered system to manage stormwater runoff and consist of a soil with a clearly defined texture as a sandy loam with mixed in organic matter or other soil amendments. The soil is covered with mulch layer rich in organic matter, and a mixed vegetation cover consisting of drought and water tolerant terrestrial plants. The system can be with or without a drainage pipe at the bottom, functioning as a groundwater recharge system or as a pure stormwater treatment system with drainage at the bottom.

Early research on bioretention focused on pollutant retention and the water quality control function. Davis et al. (2001b) conducted a series of laboratory studies of the metal retention in bioretention using a smaller shallow box, 61cm deep, and a larger deeper box, 91cm deep. The media in the boxes was classified as sandy loam with mulch on top and Creeping Juniper (J. horizontalis) as vegetation. The results from the study indicated excellent metal removal, exceeding 90% removal for both boxes, however no additional metal removal was seen for the deeper box, indicating that removal rates are independent of depth beyond a certain depth. The mulch layer was also identified as a very important to metal retention, 20, 10, 34% of the copper, lead and zinc respectively were retained in the mulch. A continuation study by Davis et al. (2003) investigated the effect of pH and inflow concentrations, and flowrate on the same two bioretention boxes. The flowrate, hydraulic loading were found to have an effect on metal removal in the upper ports (the boxes had an upper, middle, and lower outflow ports), however the effects were not seen in the lower ports. The same was true for increasing or decreasing the pH from 7 in the standard to 6 and 8, with the exception of the upper port copper concentration, which was significantly lower at pH 6. Halving or doubling the metal concentrations in the inflow had only marginal effect on outflow copper concentrations, somewhat reducing the percentage reduction but not changing the outflow concentration significantly. As a conclusion the bioretention system seemed resistant to change in inflow characteristics or flowrates. Field performance tests of two already installed bioretention areas receiving runoff from parking lots were also conducted (Davis et al., 2003). The two sites had somewhat different construction and quality of vegetation. Three different hydraulic loading rates, 2.0, 4.1, and 8.1 cm/h flow were used. The metal retention was shown to be independent of hydraulic loading rate, but did differ for the two sites. The site with poor vegetation and less fine fractions in the soil had a lower allover metal retention, especially for copper (Davis et al., 2003).

Limited studies of the hydraulic function of bioretention systems have been studied in laboratory column tests, event based field tests and one long term monitoring project. Hsieh and Davis (2005b) studied the flowrate in a laboratory column setup over 12 weeks. The columns had a 5cm top mulch layer, a 15cm middle porous soil layer, and a 75 cm bottom sand layer. The runoff rates remained constant throughout the 12 week study period. Most of the TSS was filtered out in the mulch layer, reducing the clogging risk of the underlying soil layer. Dietz (2005) conducted a long term, 56 weeks monitoring study of two rain gardens with underdrains in Haddam Connecticut, receiving roof runoff from residential houses. The hydrologic function of the rain gardens showed that 98.8% of the flow was infiltrated and left the system as subsurface flow, with only a few recoded overflow events (Dietz, 2005). Increased lag times and reduced peak flow rates were observed in the rain gardens compared to the roof runoff inflow (Dietz and Clausen, 2005).

Bioretention systems ability to treat nitrogen and phosphorus pollution have been investigated in some studies (Hsieh and Davis, 2005b,a; Kim et al., 2003; Davis et al., 2006; Dietz and Clausen, 2006). However, these studies will not be discussed in detail here as the mechanisms and conditions for nutrient removal processes are different from those of heavy metals, which are the primarily pollutants of concern in this study.

2.2 Bioretention processes

In order to better understand the physical, chemical, and biological processes responsible for water and pollutant retention in a bioretention system, it is necessary to include some discussion on hydrologic and physiochemical soil properties, soil biological activity, and plant metal uptake.

2.2.1 Soil infiltration

The use of in situ infiltration practices has been recommended as treatment for urban snowmelt with high concentrations of soluble pollutants. Infiltration uses the ion-exchange capacity in the soil, or engineered infiltration media, to adsorb soluble pollutants (Oberts, 2003). For successful infiltration of melt water adequate infiltration rates are very important, 1.3 cm/hr as a minimum rate and clay contents less than 30% has been reported in the literature (Caraco and Claytor, 1997). Frozen soil infiltration is a key parameter to ensure adequate infiltration and hydraulic performance of the system all year long. Many studies have been conducted concerning infiltration into frozen soil and, a few concerning snowmelt infiltration and infiltration into seasonally frozen soils (Brun, 1990; Kane, 1980; Granger et al., 1984; Kok and McCool, 1990). The common findings from these studies were the importance of pre-freezing soil moisture content, and drainage capacity of the soil. The soil moisture content during freezing has been shown to create three types of soil frost; porous frost, granular frost, and concrete frost. Concrete frost occurs when saturated soil freezes, ice lenses and crystals throughout the soil blocked movement of water and air. Granular frost occurs in unsaturated soils with very low moisture. The infiltration rates in granular frost can exceed that of unfrozen soil, while infiltration in concrete frost can be much lower than the unfrozen soil infiltration rate (Stoecker and Weitzman, 1960). Xiuqing and Flerchinger (2001) found the infiltration curve for frozen and unfrozen soil to be similar, indicating that infiltration in frozen soil followed the same curve as unfrozen soils. This indicates that infiltration should be maintained during the cold season in a well drained soil where concrete frost is avoided. Reported infiltration rates for sandy loams, recommended for use in bioretention areas, range from 5-10 cm /hr (Beven, 2001). A study from Sweden using two sandy soils also showed that the rate at which infiltrated water refreezes in the soil can greatly affect the infiltration rate, especially in the upper 50 cm of the soil (Stähli et al., 1999). The frost penetration in the soil is influenced by the snow cover. The thermal regime of the upper soil layers will be influenced by the snow cover, as will the water movement under the frost penetration zone (Iwata and Hirota, 2005).

2.2.2 Soil and heavy metals interaction

Heavy metals in soils are a whole part of soil science in itself. Heavy metal interactions with soils and plants, remediation of contaminated soils, and molecular interactions between soil colloids and heavy metals are some of the topics in this field. In this section the important aspects for bioretention are discussed, however this is not intended to be a complete review of soil metal interactions. There are many factors and processes in the soil that affect the chemical processes in the soil, such as reduction-oxidation[1] potential, pH, organic matter content. All these factors will interact and determine the total metal retention in a system (Dietz, 2005). Chang et al. (1984) reported soil copper and zinc forms in a sandy loam, typically used in bioretention, of 1/3 organically bound, 1/3 as carbonate/iron oxides, and 1/3 as residual form and 1-2% in exchangeable format. Lead had 85% as carbonate/iron oxides and 12% residual with only minor amounts as exchangeable and organically bound. The most important chemical processes in the soil media with respect to metals, are the processes responsible for metal adsorption from the liquid phase to the solid phase. These can be grouped in four groups; cation-exchange (non-specific adsorption)[2], specific adsorption, co-precipitation, and organic complexation. These processes control the metal complexes present in the soil solution, which controls the plant uptake of metals. The overall extent of adsorption can be measured, but it can be difficult to identify the individual processes responsible for the particular retention (Alloway, 1995).

Cation exchange describes the process in which metals are exchanged on the surface of negatively charged soil particles with positively charged cations. With a few exceptions metals exists in the soil as cations, and all the heavy metals discussed in this thesis are cations. The CEC depends on the relative amount of

[1] In the following referred to as redox
[2] In the following referred to as CEC

different colloids and the CEC of each of these colloids (Alloway, 1995). Sandy soils tend to have a lower CEC than clay soils rich in clay and humus minerals. The CEC has a non pH dependent part, the isomorphous substitution, and a pH dependent charge on the surface of clay minerals and humus polymers, that tend to be at the highest around pH 7 to slightly alkaline (Brady and Weil, 1996). The cation exchange process is reversible and controlled by diffusion (Alloway, 1995).

Specific adsorption creates a stronger adsorption than CEC and forms lattice ion structures of heavy metal cations adsorbed onto ligand surfaces by covalent bonds (Fairbridge and Finkl, 1979). Literature has shown much higher specific adsorption rates than CEC, however this process is very pH dependent and increases with decreasing dissociation constant (pK) values (Alloway, 1995). Co-precipitation is the process in which metals precipitate in conjunction with other elements, typically forming hydrous Fe, and Mn oxides and calcites where isomorphous substitution then can occur. Copper co-precipitates with Fe, Pb with Mn, and Zn can co-precipitate with both Fe and Mn (Table 2.1). This process can also take place with calcium carbonates co-precipitating Cd. Replacement of (Ca^{2+}) with (Cd^{2+}) can also occur if calcite is present and in contact with Cd in solution (Alloway, 1995).

Table 2.1: Trace metals normally found to co-precipitate with secondary minerals in soils (Sposito, 1983).

Mineral	Co-precipitated trace metals
Fe oxides	V, Mn, Ni, Cu, Zn, Mo
Mn oxides	Fe, Co, Ni, Zn, Pb
Ca carbonates	V, Mn, Fe, Co, Cd
Clay minerals	V, Ni, Co, Cr, Zn, Cu, Pb, Ti, Mn, Fe

The last process, organic complexation, is the process in which humic acids adsorb metals forming chelate complexes with varying degree of solubility, with Cu most soluble and Zn least soluble (Alloway, 1995). McBride et al. (1997) showed that the soluble zinc and lead contents were more correlated with total metal content and pH in the soil than soluble copper, and did not tend to complex strongly with soluble organic matter like copper. Furthermore a stronger correlation was found between free metal copper (Cu^{2+}) and organic matter than with total soluble copper and organic matter. This suggests that it is the free metal activity that is directly controlled by sorption. Total soluble copper is influences by soluble organic matter, inorganic ligand concentrations and reactivity as well as dispersed colloidal particles that have not been removed by filtration. This make it complex to identify the specific factors responsible for the total soluble copper content.

No specific research on heavy metals in soils in cold climates could be found, but as discussed in the following sections deicing salts will impact soil metal forms and pathways.

2.2.3 Plants and metal interactions

The plant processes in a bioretention system include; uptake of nutrients,water consumption through evapotranspiration, phytoremediation (plant uptake of heavy metals), and improved infiltration by root zone development. Phytoextraction of metal contaminated soils have been studied in several studies including (Kumar et al., 1995; Dimitriou et al., 2005; Kholodova et al., 2005; Kamal et al., 2004), however these studies tend to focus on already contaminated sites, or aquatic plants, or uptake in terrestrial plants placed in metal polluted water directly, not from soil uptake of infiltrated stormwater. Only a few cited references could be found studying the metal uptake in typical stormwater plants. Fritioff and Greger (2003) performed a screening test of terrestrial and aquatic plant species with potential to remove heavy metals. The highest removal rates were seen in free floating aquatic plants and some plants with high surface area contact with the contaminated water, however metal uptake was also seen in the terrestrial plants. As a continuation of this study, the sensitivity of submersed plants to temperature and salinity changes with respect to metal uptake was further investigates (Fritioff et al., 2005). Further species specific studies were also carried out with respect to uptake and distribution of metals (Fritioff and Greger, 2006), however this only involved an aquatic plant species.

Vegetation in cold climates has less time to establish roots and above ground biomass in a short growing season to survive a long and harsh winter. Alternative planting techniques and specially adapted species can still create successful use of vegetation for stormwater treatment in cold climates (Caraco and Claytor, 1997). Road salt applications can also affect vegetation, as many plant species, and especially trees are very sensitive to salt pollution (Caraco and Claytor, 1997). Chloride negatively impacts the soil fertility by affecting the soil structure and the transport of water through the soil column (Marsalek, 2003). The decreased fertility can have a negative impact on plant in bioretention system, however Oberts (1994) reported that incorporating mulch into the soil can help alleviate the salt problem. Leaching of chloride and sodium to groundwater, or cation exchange between (Na^{+}) and (Ca^{2+}) or (Mg^{2+}) resulting in calcium or magnesium leaching is another problem (Marsalek et al., 2003). Several studies have also shown an increases metal leachability from urban roadside soils receiving high concentrations of deicing salts, with some variability within the metals (Amrhein et al., 1992; Bäckström et al., 2004). Zinc and cadmium were more easily leached in the presence of deicing salts, indicating a ion exchange or chloride complexation. Copper and lead did not show the same effect, indicating that these metals were coagulated or sorbed to organic matter ion combination with colloidal dispersion (Bäckström et al., 2004).

Chapter 3

Field Setup and Methodology

3.1 Field Investigations and Methods

The main portion of this thesis involved field investigations of two pilot sized bioretention boxes at the Risvollan Urban Hydrologic Research Station (www.ivt.ntnu.no/ivm/risvollan)[1] in Trondheim, Norway. The station measures meteorological and hydrological parameters from a 20ha suburban residential watershed, with townhouses and about 1500 residents. The station has been in operation since 1986, collecting high resolution urban hydrological data (Thorolfsson et al., 2003), including air temperature, solar radiation, wind speed, relative humidity, and precipitation which were used in the field work. The construction of the bioretention box and the instrumentation of the setup are described in detail in Paper I, and II. A schematic of the setup and some pictures from the operation can be found in Figures 3.1 and 3.2. The two bioretention boxes were constructed in 2004 and 2005 and the first field investigations involve only the first box, while the later ones involves both. This is stated clearly for each part [2].

The bioretention boxes were instrumented for continuous monitoring of inflow, outflow, soil temperature, soil moisture content, and for bioretention box 1 the total weight of the system was also measured using S-shaped strain gagues. The

[1]In the following abbreviated RUHRS

[2]The first bioretention box constructed in 2004 will be referred to as box 1, and the second bioretnetion box, constructed in 2005 will be referred to as box 2

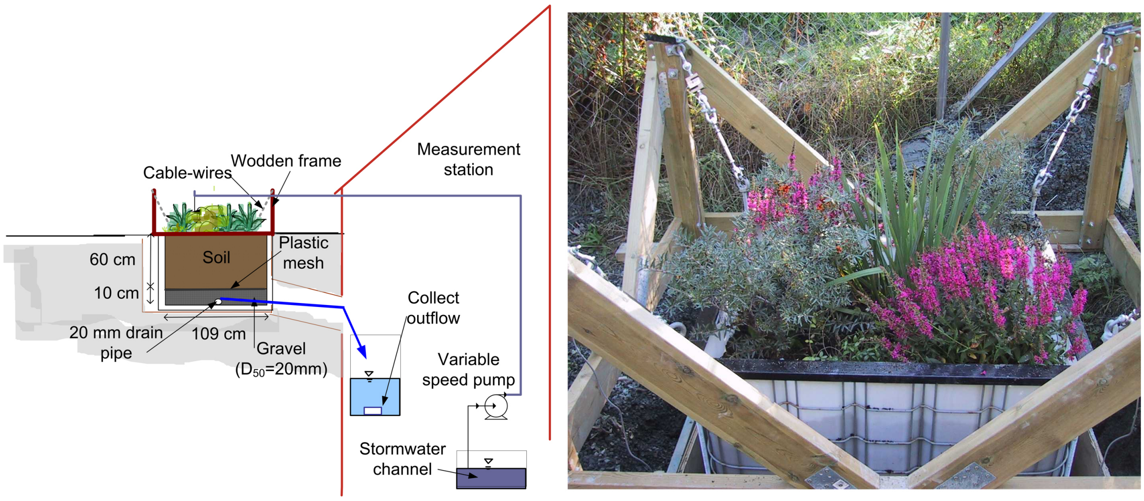

Figure 3.1: Field setup of the bioretention box. Water can enter the box either from the stormwater channel, or from another inflow source using the variable speed pump.

field data together with the meteorological and hydrological data at the station were collected at 2 minute time resolution. The first bioretention box was constructed in the summer of 2004 and in operation from September 2004. Then in August 2005 it was decided to build a second box, identical to the first one, to use as a control and for parallel studies. The soil medium was mixed to be identical, yet as can be seen from Table 3.1 some minor differences existed between them, especially the CEC capacity was much higher in the first box. The reason for this could be that at the time of sampling, September 2005, the bioretention box 1 had already been in operation for 12 months, while the box 2 had just been constructed. It was also decided not to use strain-gages for box 2 (to weigh the box), as this instrumentation was considered redundant with the good performance of the inflow and outflow pressure transducers.

The field investigations were divided into four parts, the first part was construction of bioretention box 1 and initial verification of the system with respect to water balance and reliability of the instrumentation and data collection procedure (Paper I). Then from March 2005 until June 2006 bioretention box 1 was continuously tested for hydraulic retention, lag time, and peak flow reduction (Paper II). And in this period bioretention box 2 was constructed and used as a control, supplying additional data, however only receiving precipitation and no stormwater runoff due to only one set of pumps. Two Bredel hose pumps were connected in

Figure 3.2: Field pictures from bioretention box 1 over the 22 months of data collection.

series to cover needed pumping rates. Stormwater from the stormwater channel at RUHRS was pumped into bioretention box 1 using two variable speed pumps that were controlled by the watershed hydrograph, measured in the stormwater channel at the station and a scaling factor to adapt to the design drainage area for the bioretention box, $20m^2$. The third part of the experiment investigated the pollution retention from road runoff using bioretention box 1, looking at the three heavy metals; copper, zinc, lead, and particles in April and August (Figure (3.3 and Figure 3.4). April represented typical early spring conditions with low above ground biological activity right after snowmelt season with partly frozen soils. August represented full summer season with maximum biological activity and above ground biomass (Paper III). The fourth part investigated the retention

Table 3.1: Physical and chemical properties of the bioretention boxes.

	Bioretention box 1	Bioretention box 2
Clay (%)	2.6	2.9
Sand (%)	92.7	88.3
Silt (%)	4.7	8.8
Organic matter (%)	8.7	10.7
Bulk density (kg/m3)	0.79	0.84
Solid particle density (kg/m3)	1.05	1.18
pH soil	6.88	6.79
pH mulch	5.5	5.6
CEC (cmolc/kg)	45	22
Infiltration rate (cm/hr)	12	10.5

of metals, and particles during snowmelt. For this part snow from three different roads; a residential, an urban collector road, and an urban highway, was collected during the winter and stored in large freezers until the snowmelt season arrived in mid April of 2006. The snow from each road type was divided equally between bioretention box 1 and 2 and left to melt and infiltrate through the bioretention boxes (Paper IV) (Figure 3.5 and Figure 3.6). For both the rainfall runoff event studies in Paper III and the snowmelt study in Paper IV an easily detachable plastic roof was built for the bioretention boxes to prevent precipitation contamination of the event studies. The covers were placed on the boxes a few days prior to the start of the studies to allow for complete draining of the boxes and removed afterwards.

3.2 Plant and soil sampling

Plant and soil samples were collected three times from the bioretention boxes, first at the time of construction representing natural and background levels. Then samples were taken after 20 and 7 months of operation of bioretention box 1 and 2 respectively, which was after all the rainfall runoff studies had been conducted and before the pure snowmelt experiments were initiated. The last samples were taken at the end of the study period, 22 and 9 months of

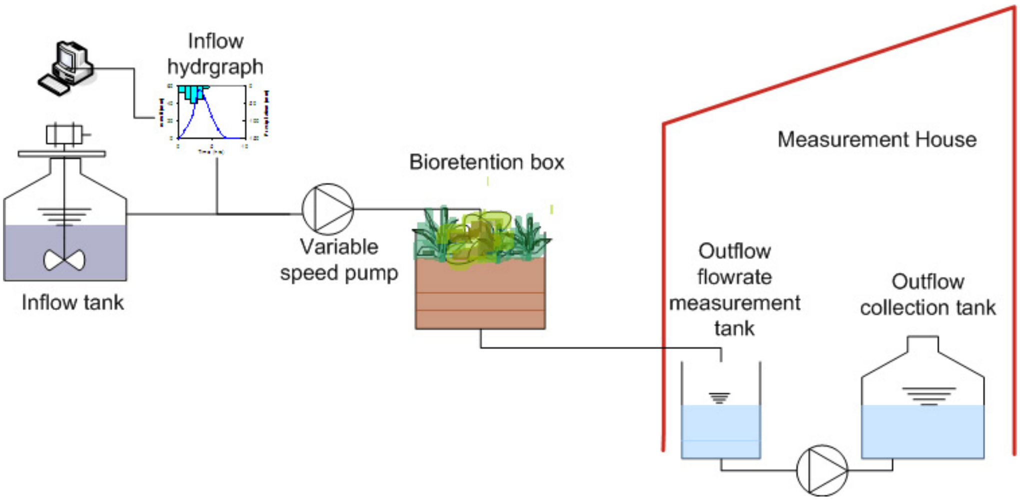

Figure 3.3: Schematic of the setup for the seasonal road runoff pollution retention studies in April and August 2005.

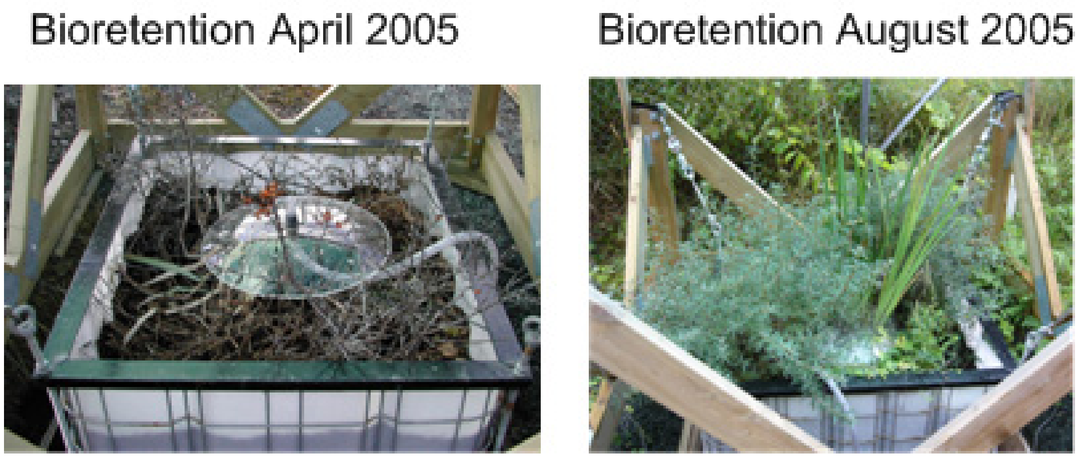

Figure 3.4: Field pictures from the seasonal road runoff pollution retention studies in April and August 2005.

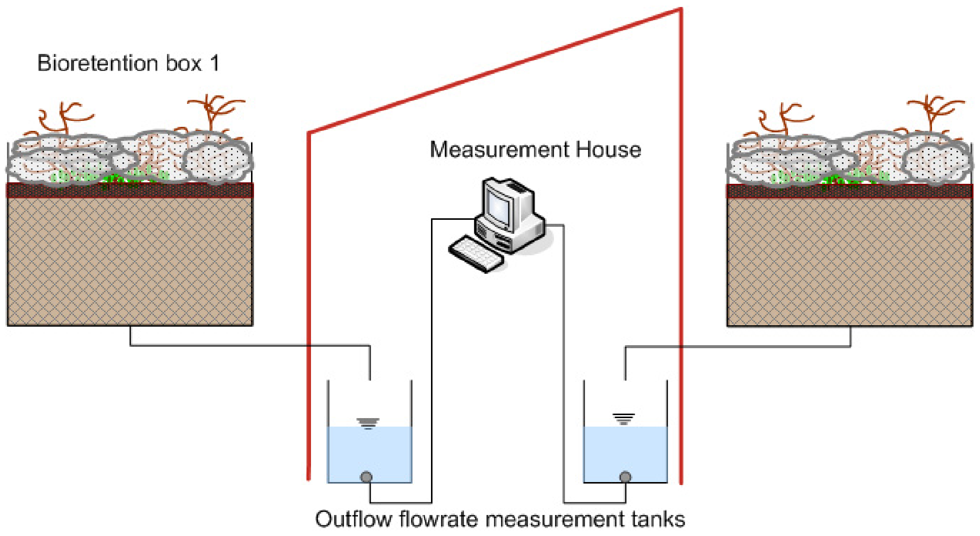

Figure 3.5: Schematic of field setup for the snowmelt study in April 2006.

operations for box 1 and 2 respectively. At the intermediate sample time only above ground biomass, mulch, and the top soil layer were sampled, because core samples of the frozen soils would interfere with infiltration for the upcoming snowmelt study, and complete root samples could only be conducted after study completion to avoid premature killing of the plants.

The soil samples at the end of the study period were collected using a soil auger, taking three core samples from each box. The samples were then divided into 10-15cm depths and the three samples from each box in the same depth was mixed together as one composite sample. This resulted in 3 layers in bioretention box 1 and five layers in bioretention box 2, in addition to the top mulch layer which was sampled separately for both boxes. Both bioretention boxes started with a soil depth of 60 cm, however over the two years of operation the soil bioretention box 1 had compressed to only 50 cm of soil, while bioretention box 2 still had 58cm thick soil core. The plant samples consisted of 15 cuttings from each plant for each part; leaves and roots, then the same species plant samples were combined into one composite sample for leaves and one composite for roots for each bioretention box.

Figure 3.6: Field pictures from the snowmelt study in April 2006. The two top pictures were taken just after snow was applied to the bioretention boxes. The middle row of pictures shows the grey layer of sediments and pollutants on top of the mulch layer after the experiments. The bottom pictures show the bioretention boxes 2 months later with vegetation fully recovered.

3.3 Laboratory analysis methods

The temperature, conductivity, and pH were measured for all samples in the field right after sampling (Paper III, IV), using a field multi-meter (HI 991300, Hanna Instruments). Total suspended solids (Paper III, IV) were measured using Whatman GF/C 1.2μm pore size glass microfibre filters in 3 replicates (NorskStandard, 1983). The metal samples (Paper III, IV) were analyzed using a High Resolution Inductively Coupled Plasma-Mass Spectrometer[3]. The samples were stored in sterile 50ml centrifugal tubes and kept in the same tube through the whole analysis procedure. The dissolved samples were filtered using cellulose-nitrate 0.45μm pore size filters, which were washed 7-8 times with deionized water. The total metal samples were digested in a microwave oven with 10% HNO_3, and then diluted 16 times (0.1M HNO_3) prior to analysis. The HR ICP-MS detection limits for copper, zinc, and lead are 0.125, 0.2, and 0.01 μg/L respectively, with a relative standard deviation (rsd) of less than 10%. The COD concentrations were measured with Dr. Lange cuvettes for COD (LCK 314, 15-150 mg/L), and standard deviation of 0.6 mg/L and a 95% confidence Interval (CI) of $\pm$1.5 mg/L. The particle size classification (Paper IV) was determined using a particle size analyzer (Beckman Coulter LS 230).

The soil samples for Paper III and IV were dried and sieved to remove particles larger than 2 mm, then the sample was boiled with aqua regia. Plant samples were dried and crushed, then nitric acid and hydrogen peroxide were added and the samples were digested in a microwave. Both plant and soil samples were then analyzed using an Inductively Coupled Plasma-Mass Spectrometer [4]. The CEC was determined by shaking the soil sample with 1 molar ammonium acetate and then extracted and analyzed using an ICP-AES.

3.4 Hydrologic modeling and snow storage

In order to evaluate the sizing of bioretention areas for cold climate conditions a review of the eight most commonly used methods was performed, including snow

[3] In the following referred to as HR ICP-MS
[4] In the following referred to as ICP-AES

storage estimation (Paper V). Design and sizing of bioretention areas were evaluated for hydrologic function using RECARGA (Atchison and Severson, 2004), a model developed at the University of Wisconsin, USA to model infiltration and ground water recharge from bioretention areas. The model can simulate up to three soil layers, and allows for field measured user inputs for hydraulic conductivity, depths, drainage pipes, evaporation rates, and inflow rates. The model uses the Green-Ampt infiltration model (Mein and Larson, 1973) for initial infiltration into the soil surface and the van Genuchten (van Genutchen, 1980) relationship for drainage between soil layers. The model does not account for snow and snowmelt dynamics. It was, however the only model available for long term continuous simulations. The inflow pumped into bioretention box 1 for the hydrologic performance testing (Paper II) was used in the simulation as the inflow in REGARGA. Snow storage was estimated based on 100%, 50%, and 25% of total snow volume storage. This was compared to actual observed monthly melt cycles in Trondheim over the past 15 years (1990-2005).

Chapter 4

Summary of the scientific papers

The results from the field and laboratory experiments of the performance of bioretention boxes have been reported in five peer-reviewed manuscripts and papers for international scientific conferences and journals. In this section the motivation and main results from each paper are summarized to give the reader a guide through motivation behind each paper with respect to the objectives of the thesis, and to place the papers in relation to each other and the overall objectives of the thesis.

4.1 Paper I

Building a bioretention area in a cold climate

This paper describes the design and experimental setup of bioretention box 1, how it was constructed and the instrumentation for monitoring. An initial water balance from the first months of operations is performed to verify the data collection procedures and performance of bioretention box 1. The main motivation behind this paper was to describe the methods and setup chosen to study bioretention in cold climate.

This paper describes an experimental field setup and initial hydraulic testing of a pilot size bioretention system built in a cold climate at RUHRS in Trondheim, Norway. Some of the challenges of the setup was to create a system that could be monitored continuously, while at the same time be as close to a real field installed unit at possible. Some of the cold climate adaptations to the design features included that the box was lowered into a hole in the ground and suspended with cables attached to a wooden frame. This would help insure a relatively natural level of snow accumulation. The drainage pipe from the box to the collection tank was placed as deep below ground as possible, still allowing for gravity flow into the collection tank and with a 3% slope to avoid standing water in the pipe and reduce the chance of freezing in the pipe.

The hydraulic detention in the bioretention box was compared to a calculated runoff volume from an impervious surface equal to the drainage area for the bioretention box and to the measured runoff from a field snowmelt lysimeter, functioning as an impervious surface. The reduction in peak runoff was 49% and 50% respectively compared to the calculated runoff and the snow lysimeter over a 10 week period in November 2004 to end of January 2005. The weekly water balance in the system showed an error in the system averaging 1.2%, indicating good control of the water movement in the system (Table 4.1). The event based reduction in peak flow rates will vary dependent on pre event temperature, snow cover, and stored water in the bioretention system.

Table 4.1: Weekly water balance of the bioretention system

week	start date	end date	beginning weight (kg)	water drained (kg)	precipitation added (kg)	end weight (kg)	error %
1	15.11.2004	22.11.2004	911.9	11.2	80	976.2	-0.5
2	22.11.2004	29.11.2004	976.1	2.2	38.3	998.4	-1.4
3	29.11.2004	06.12.2004	998.4	33.2	56	1047.6	2.5
4	06.12.2004	13.12.2004	1047.6	125	85.1	993.6	-1.4
5	13.12.2004	20.12.2004	993.7	60.4	71.9	1019.2	1.4
6	20.12.2004	27.12.2004	1019.2	1.4	18.4	1043.3	0.7
7	27.12.2004	03.01.2005	1043.3	37.6	55.7	1078.1	1.6
8	03.01.2005	10.01.2005	1077.9	27.8	34.9	1082.5	-0.2
9	10.01.2005	17.01.2005	1082.6	26.7	28.4	1064.6	-1.9
10	17.01.2005	24.01.2005	1064.8	2.9	38.5	1097	-0.3

4.2 Paper II

Seasonal climatic effects on the hydrology of a cold climate rain garden

In this paper the hydrology and especially the winter hydrology of the system is closely examined using data from bioretention box 1 and 2. The storm lag time, the weekly hydraulic detention and the peak runoff reduction are analyzed for the different seasons with the objective to identify performance differences in the cold versus the warm season. The motivation behind this paper was to use long term continuous monitoring data of the system to analyze the seasonal hydrologic performance. The hydrologic performance is important to document before pollutant retention can be investigated, as without hydrological function it can not be a viable stormwater treatment option.

This paper evaluates the performance of the two bioretention boxes, in this paper called small rain gardens, with respect to winter hydrology. One rain garden, bioretention box 1, received runoff from a small residential watershed over a 20 month study period and a second rain garden, bioretention box 2, with a shorter study period of 7 months, was used for control. The objective of the study was to investigate to what extent the cold climate conditions would influence the hydrology and performance of the rain gardens. The hydraulic detention, storm lag time and peak flow reduction were measured and compared between the seasons. The seasons were defined based on the 30-year monthly average temperature in Trondheim from 1960 to 1990. This was done to avoid unseasonably warm or cold months skewing the results over the study period. No significant difference between seasonal lag time temperaturescould be found, however a clear decreasing trend in lag time between rain, rain-on-snow and snowmelt was found (Table 4.2). The hydraulic detention was shortest in the winter season with temperatures below 0 °C, 0.65 week compared to 1.0 week hydraulic detention in the summer season. The average peak flow reduction for the 44 storms in the study period was 42% compared to 27% peak flow reduction for the winter season, (below 0 °C), storms only. This indicates that the performance of the rain garden is reduced in the cold season. To further investigate what caused this change in peak flow reduction, the weekly hydraulic detention time (total weekly inflow divided by total weekly outflow) was used. In bioretention box 1, which received runoff, the hydraulic detention time was found to be 0.84 (±0.73) for the whole study period, and 0.65 (±0.47) for the cold season and 1.0 (±0.67) for the warm season. Bioretention box 2, received only precipitation had a hydraulic detention of 1.91 (±3.1)). This indicates that the performance of the rain garden can be expected to be lower during times with below 0 °C, and during snowmelt events the performance also decreased. To investigate the factors that influence the hydraulic detention and peak flowrate a Pearson correlation was performed. A strong positive correlation was found between one day since last wetting event and lag time, but difference was found between one day and multiple days. A positive correlation was also found between air temperature and hydraulic detention. This indicates that the time between events and seasonal air temperatures are key parameters in the hydraulic performance of cold climate rain gardens.

Table 4.2: Lag times in the bioretention box sorted by season and by type of event

	Mean Lag time (min)	Average intensity (mm/hr)
All events	90	2.76 (1.91)
Above 12 °C	69	2.85 (1.88)
Between 0-12 °C	97	2.38 (2.07)
Below 0 °C	59	3.13 (0.74)
Rain events	117[a]	
Rain on snow events	47[a]	
Snow melt events	30[b*]	

Lag times followed by the same letter are not significantly different at CI=0.95
Standard deviations listed in parenthesis
* Only 3 snowmelt without precipitation events were recorded.

4.3 Paper III

Seasonal copper, zinc, and lead removal in a cold climate rain garden

Having established the hydrologic function of the system, this paper examines the rainfall runoff pollutant retention in bioretention box 1 over two seasons *representing different biological activity levels. The motivation behind the paper was to examine pollutant retention in early spring versus full summer performance. The spring and fall season have similar temperature and conditions for biological activity in the root zone, and represent 4-6 months of the year in Norway. Hence satisfactory pollutant retention during more than the warm summer months is important.*

Rainfall runoff simulations in April, with low biological activity, and little above ground biomass were compared to August with high biological activity, and large above ground biomass volume. Three runoff events created from historical data from RUHRS were used to simulate rainfall runoff inflow into the bioretention box in April and then again in August. For the April events tunnel wash water from a 4km long highway tunnel, diluted to match typical road runoff concentrations was used, while for the August events synthetically mixed metal concentrations mixed with stormwater and sediments from the stormwater channel at RUHRS were used.

Peak flow reduction and total volume reduction were significantly higher in August compared to April. The April peak flow reduction was 13% versus 26% in August, and the total volume reduction was 13% in April versus 25% in August. The increase in peak flow and volume reductions in August can be attributed to plant water consumption and higher evaporation rates. The partially frozen soil in April could create channelized flow through the soil media decreasing volume and peak flow reductions. The variable hydraulic loading rates from the three different inflow hydrographs did not have an effect on the metal retention in the bioretention box within the tested hydraulic loading rates (1.4 to 7.5 mm/hr precipitation). The mass removal of zinc was constant at 90% for both seasons. Mass removal of lead was slightly higher in August compared to April (83 versus 89%). Copper was the only metal showing a significantly lower removal in April (60%) versus August (75%). The concentration reduction ranged from 82-95% for zinc and lead, while copper had a lower concentration reduction (40-67%) (Figure 4.1). The mulch layer and the soil were identified as the major sinks for the removed metals. The mulch retained 50% of the copper, 20% of the zinc, and 17% of the lead, the soil retained 43% of copper, 77% of zinc and 82% of lead. While the plant metal uptake was estimated to 2% lead, 3% copper and 7% zinc

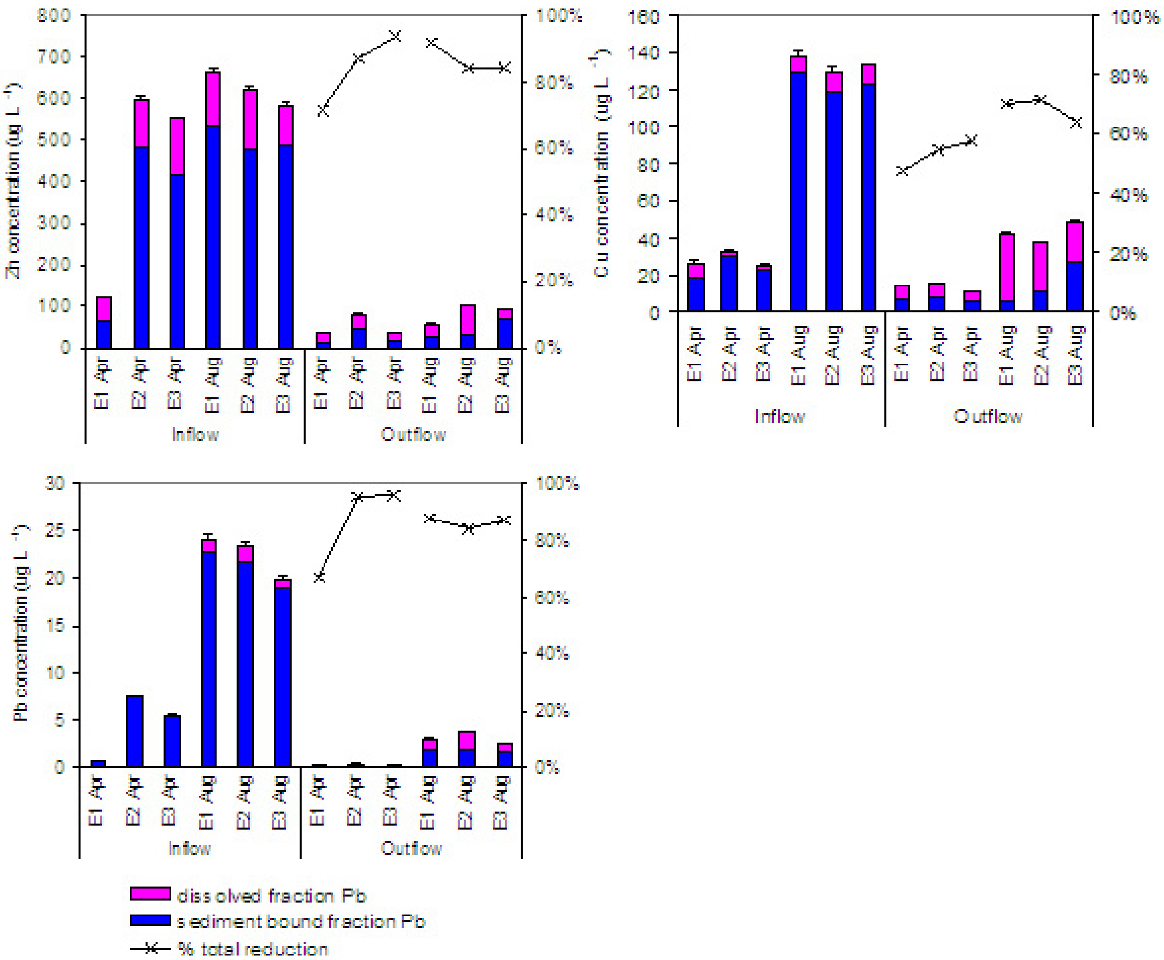

Figure 4.1: Inflow and outflow concentrations for zinc, copper, and lead in April and August

based on estimated total plant biomass. The plants played a minor role in metal removal, but an important role in root zone development and adding aesthetical value to the system with above ground biomass.

4.4 Paper IV

Snowmelt pollutant retention in bioretention areas

Snowmelt is a major hydrological event in cold climates and pollutant retention during spring snowmelt is important to prevent toxic shock loads of pollutants in *receiving waters during this season. With this background the motivation for the fourth paper was to investigate the snowmelt pollutant retention in bioretention box 1 and 2 and to compare and contrast these results with rainfall-runoff pollutant retention from Paper III.*

Snow accumulating in urban areas and alongside roads can accumulate high pollutant loads and the subsequent snowmelt can produce high pollutant loads to receiving waters. This paper examines the treatment of roadside snowmelt in bioretention with respect to pollutant removal, pollutant pathways, and major sinks in the bioretention system. Bioretention was used to treat snowmelt from three urban roads; an urban residential road (1500 cars/day), an urban collector road (5000 cars/day), and an urban highway (47000 cars/day) in Trondheim, Norway. Metal retention in the bioretention boxes had a mass reduction in zinc, copper, and lead in the range of 89-99%, and concentration reductions in the range 81-99%. The top mulch layer was the largest sink for the retained metals with up to 74% of the zinc retained in the mulch layer. The plant metal uptakes were only 2-8% of the total metal retention, however the plants still play an important role with respect to root zone development, improved soil infiltration, and regeneration.

Dissolved pollutants in snowmelt tend to leave with the first portion of melt water, creating an enrichment ratio with respect to the average pollutant concentrations in the snow as defined by Viklander and Malmqvist (1993)

$$\text{Enrichment Factor} = \frac{\text{Concentration in first 20\% of meltwater}}{\text{Average concentration in meltwater}}$$

The effect of this enrichment ratio was examined through the bioretention system, and found to be less predominant than typically reported for untreated snowmelt. The enrichment factors were in the range of 0.65 - 1.51 for the studied metals. The enrichment factors varied between the sites, but not so much between the metals for each site. The urban residential road had the highest enrichment factors, 1.5 to 1.22. The urban collector road had a slight enrichment factor in the range of 1.06 to 1.2, while the urban highway had the lowest enrichment factor of less than 1 for all the metals (Figure 4.2).

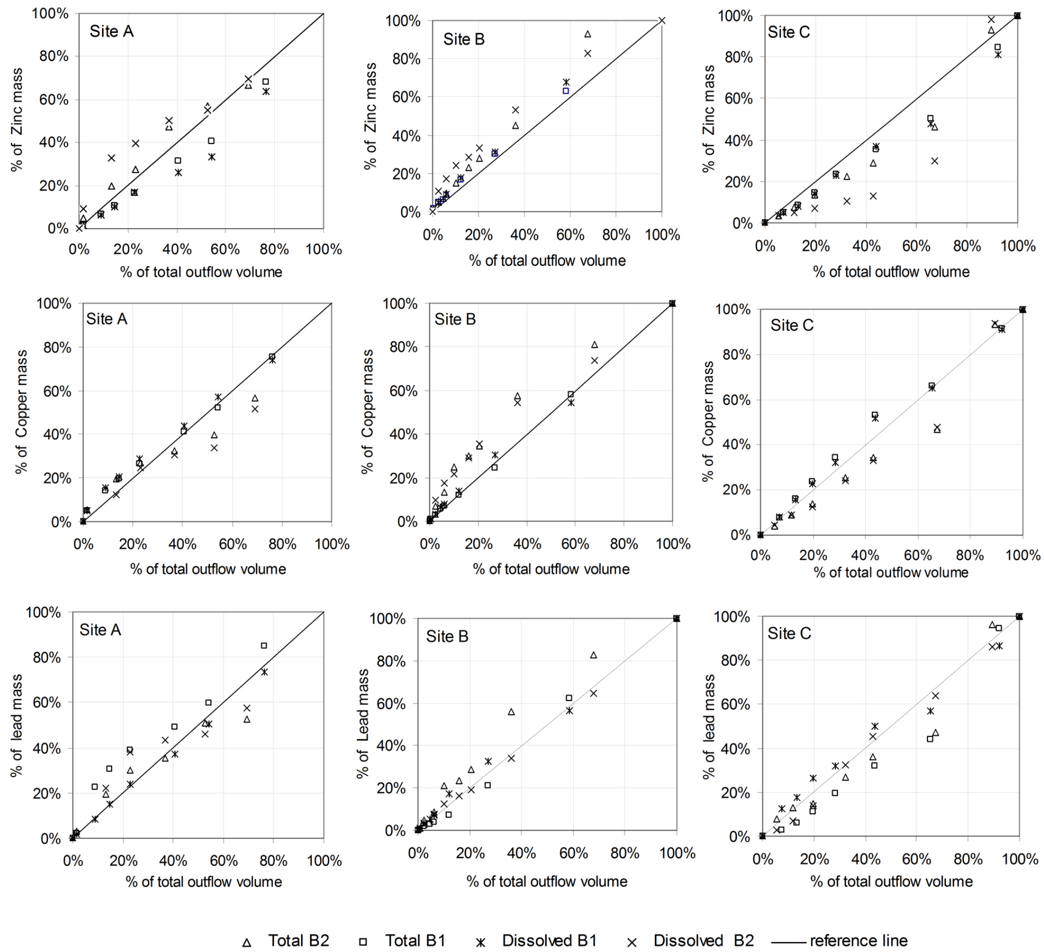

Figure 4.2: Soluble and insoluble metal concentrations in the outflow as a function of outflow volume

Comparing the chloride, salt concentrations at the three sites the urban highway had a much lower chloride concentration than the other two sites, and deicing salts have been found to shift the partitioning coefficient. The bioavailable (dissolved) copper and zinc concentration in the outflow. While an increase in dissolved copper had been observed in the rainfall runoff studies, dissolved zinc only increased in the snowmelt study. This should be further investigated either by use of hyper accumulating plants or amendments to the retention media.

4.5 Paper V

An evaluation of applying existing bioretention sizing methods to cold climates with snow storage conditions

This last paper in the paper collection that makes up this thesis discusses sizing and design of bioretention facilities in cold climate areas with respect to required surface area and snow storage needs. A continuous model, RECARGA is used to simulate the different sizing methods using observed data from the field investigations. The main objective of the paper was to evaluate the applicability of current sizing methods for use in cold climate areas with snow storage requirements.

Eight of the current and most commonly used sizing and design methods proposed for bioretention facilities were evaluated for rainfall runoff and snow storage volumes for a costal cold climate in Trondheim, Norway. The RECARGA bioretention infiltration model was used to compare the performance of the methods using 10 months of observed data from bioretention box 1. To verify the applicability of the model to simulate the field situation the design parameters for bioretention box 1 was entered into the model and simulated using the same inflow that was observed in the box over 10 months (Figure 4.3). This revealed a good fit between simulated and observed outflow for the warmer season, with some overestimation of peak flow rates for the warmer months and into the fall before snowfall events. The overestimation can be due to the organic matter content in the soil, which is not accounted for in the model, but which can cause added retention time in the system. A poor fit with respect to time of outflow was observed for the cold season, which was expected since RECARGA does not account for snow and snowmelt. This poor fit could result in reported overflow events in the winter months, which did not take place, as the precipitation fell as snow, and not as rain. Equally in the snowmelt season the model would not account for a possible snowpack on the system that could underestimate the actual flowrates or overestimate if the infiltration rate in the media was reduced due to snow and ice. It was still concluded that the model, given the known constraints adequately represented the situation.

The surface areas, total ponding time, number and duration of overflow events, and snow storage volumes were compared (Table 4.3). The two smallest surface area methods produced several overflow events for the rainfall simulations, however most of them occurred in the winter, and were in reality snowfall events and not precipitation events. Though the simulation results should not be compared with respect to volumes and peak flowrates due to the limitations in the model, the differences in design methods can still be seen. It is clear from a rainfall runoff perspective that the smaller methods are adequate, which would be expected as the rainfall intensities are relatively low here, compared to the east coast of the USA where most of these models were developed.

Table 4.3: Summary of available methods for sizing bioretention areas applied to the pilot project at Risvollan.

No.	Method	Surface area *(m2)*	% of watershed *(%)*	% of pilot bioretention area *(%)*	Number of overflows	Total overflow time *(hrs)*	Number of times ponded	Total ponding time *(hrs)*	Longest ponding time *(hrs)*	Max ponding depth *(cm)*
1	Rational	0.95	5	100	5	22.1	115	119	15.5	15
2	PGC 5-7%	0.95	5	100	5	22.1	115	119	15.5	15.0
3	WDNR	1.60	8	168	0	0	48	37.4	8.8	7.1
4	PGC_1.27	1.69	8	178	0	0	53	30	7.8	3.8
5	PGC_Comp. CN	1.92	10	202	0	0	45	18.4	3	1.1
6	SCS Runoff	3.09	15	325	0	0	10	4.5	0.4	0.2
7	Haddam	3.39	17	356	0	0	3	0.12	0.07	0.1
8	RFM-Darcy	4.87	24	513	0	0	0	0	0	0.0

The snow storage estimated volumes were based on average annual snow fall volumes in Trondheim. It was found that even in a costal cold climate with several intermittent melt cycles, the snow storage requirements were an important design parameter. If more than 25% of the total snow volume should be need to be stored, the snow storage volume became the critical design parameter. Comparing the need for snow storage and the land constraints often seen in urban areas, the Prince Georges County method storing 1.27 cm of the runoff volume from impervious areas gave a good combination of storing between 25-50% of the snow volume and requiring only 8% of the drainage area. The use of bioretention areas as local snow deposits appears most feasible when used in combination with a snow management policy of storing the most heavily polluted snow on the bioretention areas and transporting less polluted snow to stormwater conveyance systems or central snow deposits.

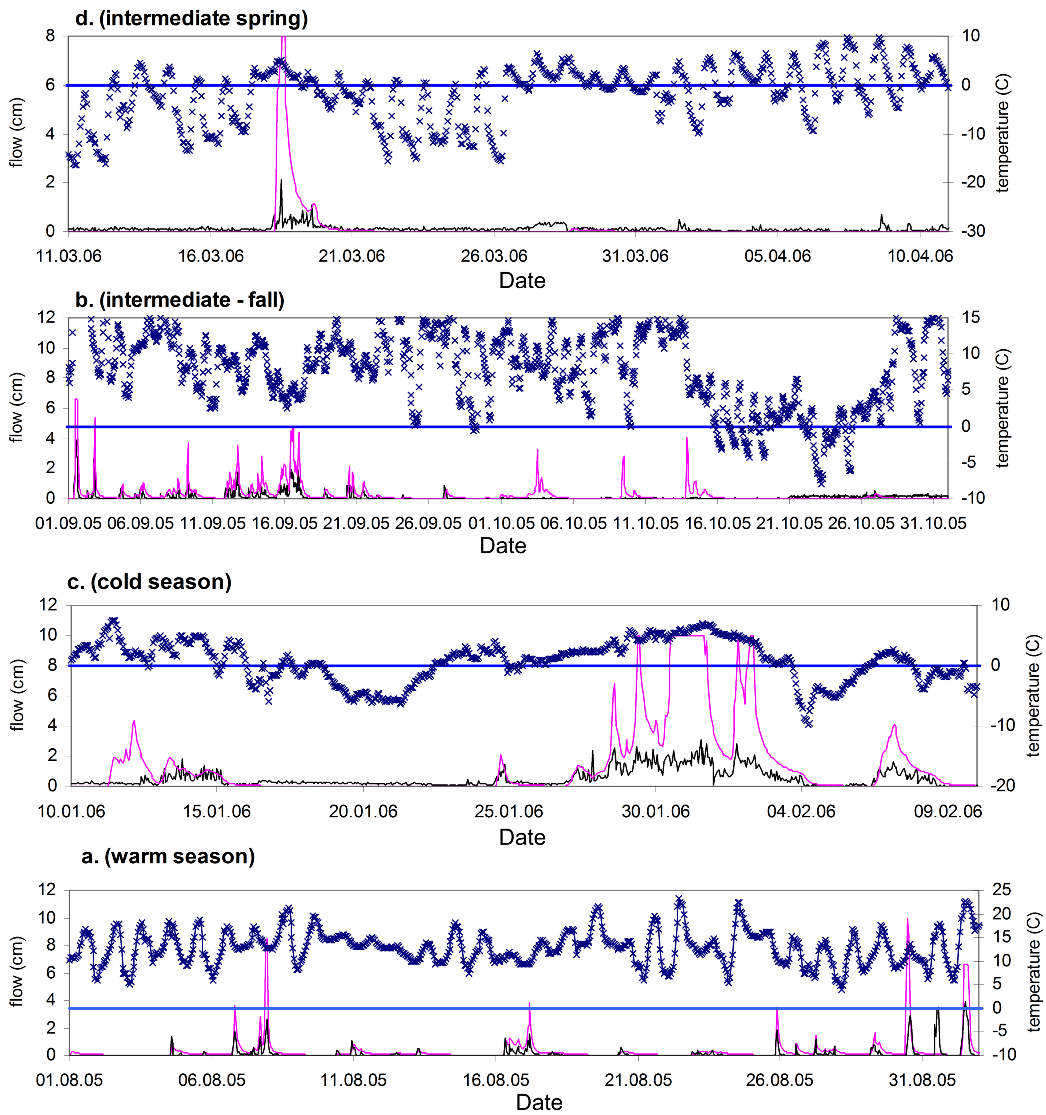

Figure 4.3: Simulated versus observed flowrates in bioretention box 1 for the four seasons

Chapter 5

Discussion

In this section the discussion focuses on the comparison of the results from the five papers, and discuss the results from the paper with respect to the objectives of the thesis and a comparison to relevant studies from the literature. The results from the papers will not be discussed in detail as they are summarized in the previous chapter, and the complete papers follow in Appendix A.

5.1 Hydraulic retention

The bioretention boxes used in this study simulate systems with a water tight liner and an underdrain used for detention of stormwater. Bioretention areas can also be used for groundwater recharge through infiltration and then no underdrain or liners are needed, however that requires suitable soil for infiltration and evaluation of the groundwater pollution risk. The storm lag time and the weekly hydraulic retention in the system were compared for each season (months were divided into seasons based on 30-year average temperatures) (Paper II). The average seasonal detention time in the system ranged from 97 minutes for the spring and fall events and down to 59 minutes for the winter events. Due to the large standard deviation in the dataset the lag times were not significantly different. These lag times are based on runoff from a small urban catchment, Risvollan (20ha) scaled down to the design inflow area for the bioretention box. The Risvollan catchment has a quick response time with typical lag times from precipitation starts to runoff is seen at the outlet of 5-10 minutes. Hence an increased lag time of 50-70 minutes through a bioretention area for all the impervious surface runoff would have a significant effect on the peak rate and time to peak in the watershed. The simulated storm lag times (Paper V) were found to be similar to the observed lag times. The model does not report average lag time, but examining the plotted simulated and observed runoff it could be seen (Paper V). The peak flow reduction for all the 44 storms included in the hydrologic performance analysis (Paper II) was 42%. However the simulated outflow had a much higher peak outflow, making the peak flow reduction much less for most cases (Paper V). The winter months and the snowmelt season had the largest discrepancy between the observed and simulated peak outflow, however due to the model limitations for winter conditions this was expected. The peak outflow is also over estimated for all the storm events in the summer of some of the fall events, though some events in the fall had a good fit. The overestimation of peak outflow rates in the model must be a function of inaccurate simulation of water retention in the system. This could be due to the organic matter content in the soil and top mulch layer retraining more water than observed by the model. Though the accurate representation of the storm lag time indicates that the model does a good job modeling infiltration in the system. Since the system is an exfiltration system with an underdrain the total volume of runoff would only be marginally reduced by ET and soil storage, especially in the winter months. In 2005, the observed difference between inflow and outflow was 3.6% over the whole year, and the simulated RECARGA estimated for ET was 1.0%. If accounting for the observed error in the system reported in Paper I to be 1.2% the observed and simulated ET are relatively close. More importantly the bioretention boxes kept infiltrating water throughout the whole cold season, due to the high infiltration capacity. Average infiltration was measured to 10-12 cm/hr based on three sets of double ring infiltration tests performed at the beginning and again at the end of the 22 months of operation for bioretention box 1. The high infiltration rates ensured draining of the soil media to avoid water filled pores freezing and forming a concrete frost layer. The infiltration rate was maintained over the 2 year study period. The infiltration rate in bioretnetion box 2 after 8 months of operation was also in the same range measured by the same method. The plants together with the top mulch layer are both important in avoiding clogging. The same was documented in a long term laboratory study of bioretention columns (Hsieh and Davis, 2005b).

5.2 Metal retention

The average decrease in total metal concentration for copper, zinc, and lead were fairly constant for rain and snowmelt events with relatively large decreases, up to more than 90% decrease in concentration, especially of zinc and lead (Paper III, IV) (Table 5.1), while the picture was different for the separate particulate and dissolved fractions. The dissolved copper concentration increased through the system, resulting in a negative percentage change for all seasons. The dissolved zinc concentration had a relative large decrease in concentrations for the rainfall runoff events, and a large increase (leaching) for the snowmelt experiments (Table 5.1). Dissolved lead concentrations showed a slight decrease or remained constant for both rainfall runoff events and snowmelt events. This indicates a good retention of particulate matter and particulate heavy metal, while variable performance for the dissolved fraction. Since the dissolved fraction is the bioavailable fraction that is most toxic to micro invertebrates an overall decrease in total concentration, but an increase in dissolved fraction can be an overall negative impact.

Table 5.1: Average percentage reduction of copper, zinc, and lead for rainfall runoff events in early spring, late summer, and snowmelt.

	Avg. change in total (%)			Avg. Change in dissolved (%)		
	Cu	Zn	Pb	Cu	Zn	Pb
Summer precipitaiton runoff *	68 (±4)	87 (±5)	86 (±2)	-190 (±114)	69 (±16)	13 (±20)
Spring precipitation runoff*	53 (±5)	84 (±12)	86 (±17)	-147 (±154)	73 (±13)	-22 (±48)
Snowmelt**	59 (±33)	88 (±9)	97 (±3)	-157 (±80)	-854 (±143)	17 (±15)

* Based on three events from bioretention box 1
** Based on six events from bioretention box 1 and 2

However, percentage changes in concentrations only gives a partial picture, a mass balance is needed for a more complete picture. Comparing the metal retention in the bioretention boxes based on percentage changes in concentrations can be misleading since the inflow concentrations varied greatly, and it can be easier to remove a higher percentage with a higher inflow concentrations. There is also the issue of water that is retained in the bioretention box and is consumed by the plants and evaporated, hence reducing the water volume leaving the system which will increase the relative concentration of metals in the outflow water. Total zinc had a 96% mass reduction from snowmelt, and 92-96% for the spring and summer rainfall runoff events. The dissolved zinc mass had a reduction from 77-91% for the summer and springs events, while a leaching of -372% for the snowmelt events (Paper III, IV) (Table 5.2). This indicates that the mechanisms for retention of dissolved zinc that were active during the spring and summer events were not active during the cold season or that the presence or absence of another compound changes the adsorption rate. The presence of deicing salt is the main difference between the April and August rainfall runoff studies and the April snowmelt study. The snowmelt increase in dissolved zinc can be related to the high chlorine (road salt) content in the meltwater. Previous studies have shown that deicing salts increased the dissolved zinc and cadmium concentrations in meltwater, while copper and lead appeared to be organically bound and less affected by deicing salts (Bäckström et al., 2004; Amrhein et al., 1992). Zinc was more easily leached in the presences of deicing salts, indicating an ion exchange or chloride complexation (Bäckström et al., 2004). The soil temperature was also different for the spring rain fall events and the snowmelt event, though they both occurred in April. The soil temperature difference was due to the water temperature of the rainfall runoff inflow in April with an average inflow water temperature of about 8-12 °C, and the summer events between 17-18 °C, compared to the snowmelt water, which would be just above zero degrees. The early spring events which also began when the soil media was partially frozen quickly heated up the soil media due to the warmer inflow water, while this would not be the case for the meltwater. This was also seen when comparing the soil temperature profiles for the two events (Figure 5.1). This could affect the microbiological activity in the soil for the snowmelt compared the rainfall runoff.

Copper had a variable retention in the bioretention system. The total copper mass was retained for all events in the range from 46-89%, however the total retention in the spring rainfall runoff events were much lower than the snowmelt

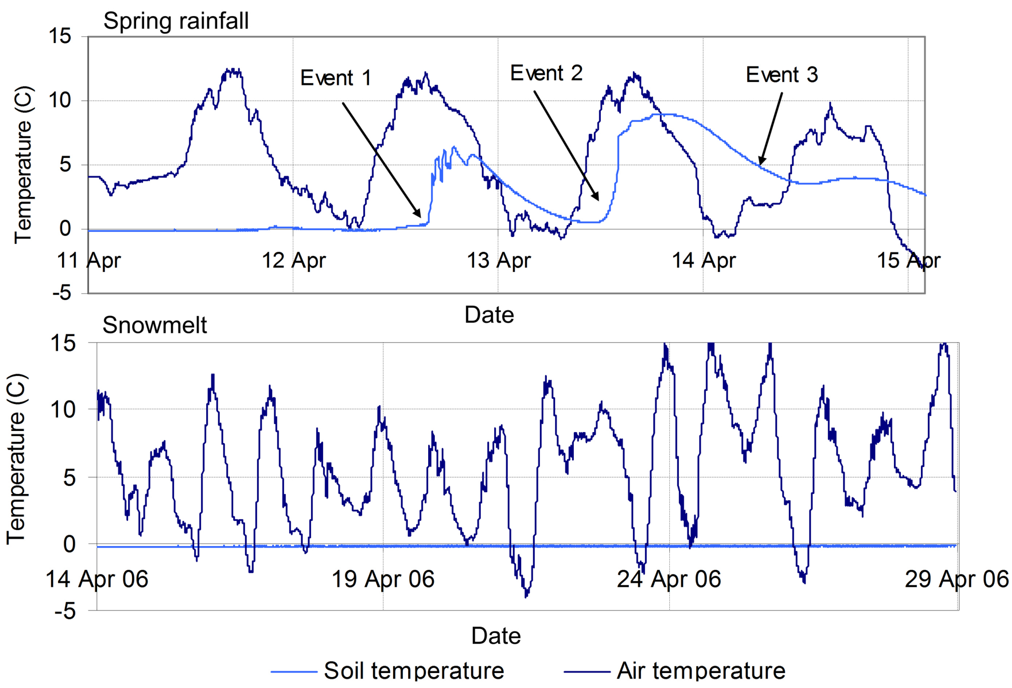

Figure 5.1: Comparing soil temperatures for the rainfall runoff events in April 2005 to the snowmelt events in April 2006. The water temperature for the rainfall runoff events rapidly heats the soil media. The two April events had comparable air temperatures.

and summer rainfall runoff events (Table 5.2). Dissolved copper was leached from the system for all instances; however snowmelt events had the lowest leaching (14%) but not the lowest dissolved fraction (Paper III, IV). The retention of total and dissolved lead was good, above 85% for total lead, though with a lower retention of dissolved than total lead. For the spring rainfall runoff events some leaching of dissolved lead was measured however it was small amounts, the difference between mass in and mass out was 0.011 mg. The HR ICP-MS detection limit of 0.01 μgL^{-1} for a 10% relative standard deviation results in a mass uncertainty of 0.001 mg for the applied volume (Paper III, IV).

The results show leaching of copper for all seasons and for both snow and rainfall runoff, while zinc appears to be leached in snowmelt but not in rainfall runoff situations. A laboratory leaching test (Paper III) showed leaching of all the metals. For the leaching test the soil media was divided into three layers, an upper, a middle and a bottom layer. Lead leached in the top soil layer

Table 5.2: Mass removal of metals in rainfall runoff compared to snowmelt runoff in the bioretention boxes.

	Zinc		Copper		Lead*	
	total	*dissolved*	*total*	*dissolved*	*total*	*dissolved*
Summer Rainfall runoff						
Mass in (mg)	344 (±7.6)	66 (±2.1)	75 (±1.7)	6 (±0.3)	12380 (±0.3)	740 (±0.01)
Mass out (mg)	27 (±3.5)	16 (±0.7)	18 (±1.2)	12 (±0.8)	1130 (±0.05)	530 (±0.01)
% retained	92 %	77 %	76 %	-113 %	91 %	29 %
Spring Rainfall runoff						
Mass in (mg)	253 (±5.8)	60 (±0.5)	15 (±1.0)	2 (±0.1)	2730 (±0.04)	12 (±0.001)
Mass out (mg)	10 (±1.5)	5 (±0.4)	8 (±0.4)	3 (±0.1)	420 (±0.09)	23 (±0.001)
% retained	96 %	91 %	46 %	-72 %	85 %	-92 %
Snowmelt						
Mass in (mg)	301 (±15.4)	2 (±0.2)	110 (±7.8)	8 (±0.2)	19320 (±0.71)	79 (±0.005)
Mass out (mg)	12 (±4.0)	9 (±0.9)	12 (±1.5)	9 (±0.6)	200 (±0.01)	33 (±0.002)
% retained	96 %	-372 %	89 %	-14 %	99 %	59 %

* All lead values are in µg

however low leaching values from the bottom two layers indicating a downward movement of soluble lead, which could lead to increased leaching of lead in the long term though this was not yet seen in the field studies. The bottom layer had higher clay content than the top layer, which could contribute to increased sorption of lead onto clay particles. The leached copper decreased sharply from the top to the middle layer and then increased again in the bottom layer. The average copper leaching was 19.9 μgL^{-1} which was in the same range as observed leaching in the field experiments. No leaching of zinc was observed in the bioretention boxes for the rainfall runoff events, however in the laboratory extraction some leaching of zinc was seen, with increased leaching moving down from the top to the bottom soil layer with an average of 23 μgL^{-1} (Figure 5.2).

When comparing the mass transformation of copper for the different events, grouped into three seasonal events; summer rainfall runoff, spring rainfall runoff, and early spring snowmelt, with soil temperature, and pH of the inflow and outflow there are no clear indication why the copper leaching for the summer events was so high (Table 5.3). The leaching seems to decrease with decreasing soil temperatures and increasing pH values. The inflow pH increases from 7.27 in the summer to 8.34 for the snow, however, the outflow pH is fairly constant around 7.2. The snowmelt events and the spring rainfall runoff events also had a small mass addition of soluble copper, though for the spring event the percentage increase is high. The relative small changes in mass from inflow to outflow

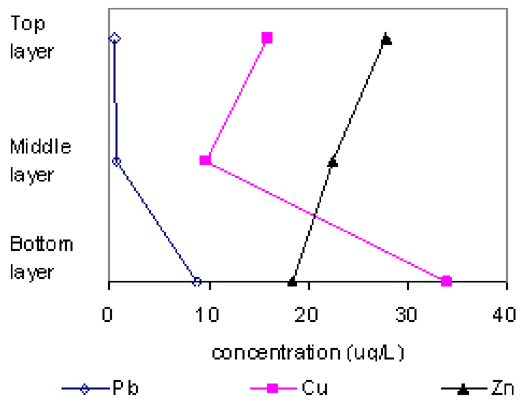

Figure 5.2: Leaching of copper, zinc, and lead from the different layers of the soil media.

with respect to the detection limit of copper for the HR ICP-MS, (0.125μgL^{-1}), increases the uncertainty of the measurements.

Table 5.3: Comparison of the copper mass transformation and related physical parameters for the three seasons.

	1	2	3	4	5	6	7	8	9
Summer	74.7 / 5.7	18.3 / 12.1	8	66	6.4	113	7.3	7.2	12.7
Spring	15.4 / 2.0	8.3 / 3.4	13	41	1.4	72	8.1	7.2	3.3
Snowmelt	109.6 /8.0	12.1 / 1.51	7	75	1.1	14	8.3	7.3	-0.2

Note:

1	Total/dissolved copper inflow (mg)
2	Total/dissolved copper outflow (mg)
3	% dissolved Cu of total Cu in inflow
4	% dissolved Cu of total Cu in outflow
5	Mass increase of soluble Cu (mg)
6	% mass increase of soluble Cu
7	pH in the inflow
8	pH in the outflow
9	Average soil temperature over events

McBride et al. (1997) found that the soluble zinc and lead contents were more correlated with pH and total metal content in the soil than soluble copper, and do not tend to complex strongly with soluble organic matter like copper. Furthermore a stronger correlation was found between free metal copper (Cu^{+2}) and organic matter than with total soluble copper and organic matter. This suggests that it is the free metal activity that is directly controlled by sorption. Total soluble copper is influenced by soluble organic matter, inorganic ligand concentrations and reactivity as well as dispersed colloidal particles that have not been removed by filtration. This makes it complex to identify the individual factors responsible for the total soluble copper content. However this suggests that the organic matter and especially the dissolved organic matter in the soil media is responsible for the copper leaching. Hsu and Lo (2000) investigating the effect of dissolved organic carbon on leaching of Zn and Cu from swine manure compost. The leachability of the metals were found to be independent of the total metal content, but rather a function of dissolution of organic carbon as a result of pH changes. This increase in dissolved organic carbon substantially modified the copper solubility, while having only negligible effect on the dissolved zinc content. The dissolution of organic matter and subsequent formation of organometallic complexes indicated that copper is primarily bound to organic matter, while the zinc sorption to organic matter is low. The organic matter content in the two bioretention boxes were 8.7 and 10.7% and in addition the top mulch layer consisted of shredded bark and partially composted leaf litter. Based on the literature findings, the mulch and also the soil organic matter is most likely responsible for the copper leaching from the media.

5.3 Particle retention

Retention of total suspended solids, (TSS) was good for all seasons and for both the simulated rainfall runoff in April and August as well as observed rainfall runoff measured with stormwater from the Risvollan watershed (with and without snow cover) and snowmelt (Paper III, IV). The top mulch layer served as the first trapping barrier for the particles, and especially after the snowmelt a thick layer of particles and grit could be seen on top of the mulch (Figure 5.3). Comparing the mass removal rates, it can be seen that the highest loadings also have the largest removal rates. The average TSS outflow concentration was 7.7 mg/L and the average percentage mass reduction was 91% (Table 5.4). The snowmelt events have the highest mass removal rates (99.9%) followed by warm season rainfall events (91%), and then winter storm events (86%).

In December 2005 several precipitation (snow and rain) events resulted in several melt cycles and runoff events over a period of two weeks. The inflow TSS

Figure 5.3: The top mulch layer on bioretention box 1 after the snowmelt studies in April 2006.

Table 5.4: Comparison TSS mass removal rates for rainfall, rain on snow, and snowmelt events over the study period.

	TSS inflow (mg/L)	Volume inflow (L)	Mass inflow (g)	TSS outflow (mg/L)	Volume outflow (L)	Mass outflow (g)	Mass reduction (%)
E1 (April 2005	26	148	4	6	117	1	82
E2 (April 2005	180	172	31	30	167	5	84
E3 (April 2005	150	242	36	11	220	2	93
E1 (August 2005)	89	148	13	2	105	<1	98
E2 (August 2005)	102	172	18	4	143	1	97
E3 (August 2005)	108	242	26	9	189	2	93
Snow A (April 2006)	2931	115	336	6	127	1	100
Snow B (April 2006)	4362	106	462	5	110	0	100
Snow C (April 2006	9613	137	1313	6	104	1	100
*Winter storm 10.12.2005	114	325	35	4	146	1	98
*Winter storm 11.12.2005	29	725	20	12	487	6	72
*Winter storm 12.12.2005	31	306	9	4	314	1	87
*Winter storm 13.12.2005	29	203	6	6	248	1	77
*Winter storm 14.12.2005	53	384	20	4	325	1	94

*These events were with storm water from the Risvollan catchment, a urban residential watershed with 26% impervious cover, while the other events are with road runoff and road snowmelt.

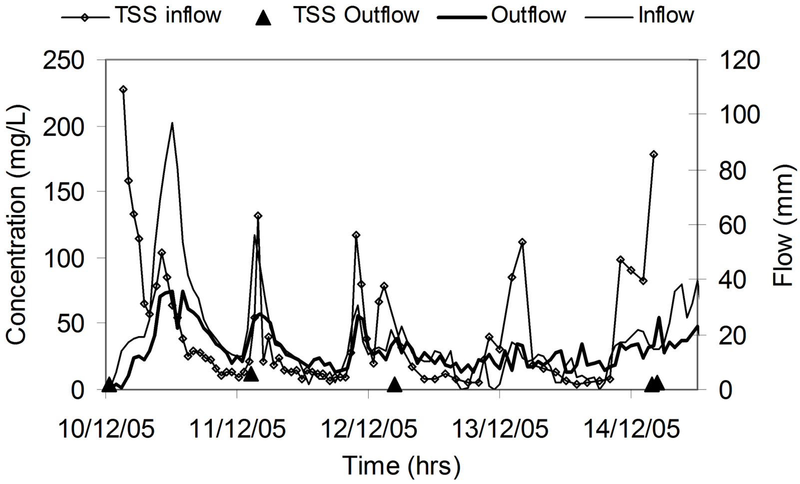

Figure 5.4: Inflow, outflow, and TSS concentrations for a winter storm in December 2005. At the onset of the storm it was a rain-on-snow event, and by the end it was a winter rainfall event.

concentrations were highly variable and exhibited a clear first flush pattern at the start of the runoff events. Despite the variable inflow TSS concentrations the TSS outflow concentrations were consistently low through out the period (Figure 5.4). This was stormwater with runoff from the Risvollan watershed, which is a townhouse residential area mixed with roads, not urban street runoff only, which the April and August runoff events represents. The reduced TSS trapping efficiency during winter storms can possible be compensated for by a reduced hydraulic loading rate and increased retention times, though this would affect the sizing of the system.

The high reduction in particles should be compared to the natural suspended sediment concentrations in receiving streams. If the outflow TSS concentration is substantially lower than the mean values prior to installing the bioretention this can alter the downstream sediment carrying capacity of the stream, which can actually lead to increased downstream bank erosion. However in urban streams bank erosion due to increased flow rates, and undercutting of banks and loss of bank vegetation due to alter flow patterns are more likely. In this setting, bioretnetion can be one measure to reintroduce more natural flowrates.

5.4 Post experiment soil and plant analysis

The plants in a bioretention facility have several functions; they consume water, improve root zone infiltration, pollution retention, and provide aesthetic value in the urban landscape. Plant metal sampling before, during and after the experiments revealed a large variability in plant metal uptake between the species (Paper III, IV). The Vinca Minor (common name Lesser periwinkle) plant, with the highest metal uptake was the least water tolerant species and possible not suited for bioretention due to risk of drowning. The best performing plants with respect to hydrologic function, the Hippophäe Ramnoides (common name Sea Buckthorn) had the lowest metal uptake with minor copper uptake but no detectable change in zinc or lead. Based on these findings an annual summary of metal loadings and plant accumulation was performed (Table 5.5).

Table 5.5: Estimated annual accumulation of metals in the plants based on average annual snow and rainfall.

	Cu	Zn	Pb
Seasonal plant metal accumulation (mg)	46	201	4
Total snowmelt inflow mass (mg)*	2890	7965	510
Total rainfall inflow mass (mg)**	700	5369	110
Total annual mass loading (mg)	3591	13333	620
% seasonal plant uptake	1.3	1.5	0.7

* The annual snowmelt inflow metal concentrations were estimated based on average concentrations from Paper IV times annual snowvolumes from Paper V and 20m2 area (drainage area of the bioretention box)
** The annual rainfall concentrations were found using average concentrations from investigations in paper III times the annual precipitation as rain volume and drainage area.

It is clear that the plants play a minor role in metal uptake. For the snowmelt only 2-8% of the metal retention could be attributed to plant uptake based on estimated biomass (Paper IV), and the same, 2.5-4% was found for the rainfall runoff events from April and August (Paper III). On an annual basis, based on annual average values this can be expected to be even smaller, less than 2%. Even if the bioretention medium was assumed to be planted with all Lesser periwinkle, the plant with highest metal accumulation rates, the annual metal retention in the plants would account for less than 6% of the total annual metal retention in the system. The plants accumulation of zinc was more successful than copper and lead, which corresponds to findings in terrestrial plant species used for stormwater ditches in Sweden (Fritioff and Greger, 2003).

5.5 Life cycle assessment

The largest metal sink was found to be the organic top mulch layer, with up to 74% zinc, 13% copper and 66% lead (Paper IV). From a lifecycle point of view this can be positive, since exchanging the top mulch layer is a relative easy maintenance task, compared to exchanging plants or soil medium. The second largest sink was the soil medium it self, where a tendency to downward movement of metals were seen (Paper IV), which could indicated an increased leaching from the system in a few years if the simulation period had been longer. A lifecycle estimate of the bioretention box based on annual rainfall runoff and snowmelt pollutant loadings resulted in an estimated lifecycle of 11 years based on the limiting metal, which in this case was zinc (Table 5.6). This estimate was based on highway pollutant loadings, which are higher than residential and urban areas. Bioretention areas used to treat residential and urban areas would be expected to have a longer lifecycle. This estimate was also based on uniform metal accumulation in the soil, which is not the case as most of the metals accumulate in the mulch and upper soil layers. By exchanging the mulch on a 3-7 year cycle the lifespan of the system can be prolonged. Also using hyper accumulating pants and regularly harvesting the biomass will prolong the lifecycle of the system.

Table 5.6: Life cycle estimation for the soil media in the bioretention box.

	Cu	Zn	Pb
Avg rainfall concentrations (ug/L)*	60	150	17
Avg. Snowmelt concentrations (ug/L)*	111	425	44
Avg. Seasonal loadings rainfall (mg)	702	1755	199
Avg. Seasonal loadings snowmelt (mg)	699	2678	277
Total annual loading (mg)	1401	4433	476
Soil			
1 $cmol_c$ metal converted to mg (assume all 2+)	318	327	1036
Total CEC capacity (mg per box)**	47289	48704	154303
years to fill up the box (years)	34	11	324

*used values from Westerlund, 2006
** Assume that 15% of the CEC capacity is available for metal uptake

Chapter 6

Conclusions and Recommendations

Two bioretention boxes consisting of mixed local vegetation, sandy loam soil, and a top mulch layer were used to investigate the hydrological function and pollutant retention in cold climate areas. These boxes were used to identify seasonal differences in pollutant retention, storm lag times, and peak flow reductions that would influence the design and sizing of bioretention in cold climates.

6.1 Conclusions

The costal climate in Trondheim, where the field experiments took place, has highly variable winter seasons, which was reflected in the hydrologic performance of the bioretention boxes, which showed highly variable lag times with large standard deviations. No significant difference in lag time was found between the seasons (when seasons were defined by 30 years average monthly temperatures). The significant difference was found however, when the storms were divided in type of event; rainfall runoff, rain-on-snow, and snowmelt, with a decreasing lag time in the same order. A Pearson correlation revealed a strong posisitve correlation between zero and 1 day since previous event, but no difference between one or more days. There was also a positive correlation between average daily air temperature and weekly hydraulic retention, indicating a higher hydraulic retention for warmer conditions. The bioretention boxes showed reduced hydraulic performance during the winter, but infiltration was maintained, and no overflow events were recorded.

Snow storage calculations based on average annual snow volumes in Trondheim indicated that snow volume became the deciding sizing factor if more then 25-30% of the total snow volume should be stored on the bioretention areas. If using bioretention for snowmelt treatment is coupled with urban snow management such as sorting of the most heavily polluted snow, and central snow deposits for less polluted snow it can be a viable solution.

The pollutant retention in the system was especially investigated with respect to heavy metals and particles. Typical urban road rainfall runoff was investigated over two seasons, early spring with low biological activity and partially frozen soils, and late summer with high biological activity and warm weather. Then continuous particle retention over one winter season was investigated using stormwater from the local urban residential catchment. The average particle retention in the system was 91% mass removal. The snowmelt and summer precipitation events had consistently high removal rates, while the winter season had a more variable removal rate, from 72-98%. Later snowmelt pollutant retention was investigated colleting snow from three urban roads with different traffic densities. The total zinc retention in the bioretention boxes was above 90% mass reduction for both rainfall runoff and snowmelt. Total lead retention was also very good for all seasons, with more than 85% reduction by mass. The copper retention was more variable, and ranged from 46% by mass in spring rainfall runoff to 89% for snowmelt. The percentage change in concentrations between inflow and outflow were consistently above 85% for zinc and lead, while copper varied from 69-53% with the lowest concentration decrease for the snowmelt events. Dissolved metal retention was highly variable and changed from an increase by mass for all instances for copper to a reduction for lead. The dissolved zinc mass was reduced for all rainfall runoff events, but increased for the snowmelt events. This can most likely be attributed to deicing salts concentrations, which have been shown to cause an ion-exchange with zinc. The increased dissolved copper concentrations were found to most likely be linked to OM content in the soil, and concentrations of dissolved organic carbon. The snowmelt events had the highest inflow concentrations, so even though the percentage reduction was fairly constant the outflow concentrations from the snowmelt events were higher than for the rainfall runoff events.

The main sinks of metals were the mulch, the soil, and the plants in that order, with 2-8% accumulation in plants, compared to 74% in the mulch for zinc and 13% copper and 66% lead. The plants played an important role in regenerating the system in the spring, changing a thick gray layer of particles and pollutants from the snowmelt studies into a green lung by early summer. This makes bioretention an attractive addition to the urban landscape in cold climate.

6.2 Recommendations for future research

Bioretention involves many complex physical and chemical processes dealing with a highly variable inflow - urban stormwater. Many topics that are whole study areas by themselves are covered to some extent in this research. To fully understand and be able to accurately predict their performance in different climatic settings and to develop climate specific design considerations more research should be undertaken.

- A more comprehensive laboratory scale research for plant selection involving local plants should be conducted to identify plants that are suitable both with respect to the hydrology of a bioretention and that can retain high concentrations of metals.

- In order to better understand the temperature influence on the soil and plant metal interactions a laboratory scale experiment using several replications and controlled temperature changes with the aim to identify the key parameters that are affected by low temperatures.

- Further investigate the long term fate of heavy metals in the bioretention media, if the downward movement of metals would lead to eventually leaching, and how long time this process would take. This could lead to better life cycle predictions for the systems and is also important with respect to ground water protection and the use of impermeable liners.

- Investigate the retention of deicing salts and the long term fate of these substances in bioretention facilities. What are harmful concentrations for the vegetation, and if soil amendments can improve dissolved metal retention, which is likely to increase with increase in deicing chemical concentrations.
- Advances in bioretention modeling to incorporate both winter hydrology with snow storage capabilities and pollutant retention in one model. This could improve the winter design and sizing specifications

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Appendix A

Scientific Papers

Paper I

Building a bioretention area in a cold climate

T. M. Nordberg, S. T. Thorolfsson

Proceedings of the 10th International Conference on Urban Drainage, August 2005, Copenhagen, Denmark

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Building a bioretention area in a cold climate

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Abstract

This paper describes an experimental field work setup for testing the performance of bioretention areas in a cold climate setting at Risvollan Urban Hydrological Station **i**n Trondheim, Norway. Bioretention focuses on water retention, peak flow reduction, and water quality improvement with respect to heavy metals and sediments. However, in colder climates the performance of bioretention areas are to a large extent unknown. The most problematic with winter conditions are the many interchanged snow and rainfall events, creating rain-on-snow events, resulting in ice formation, then melting and often refreezing. This causes blockage of stormwater inlets and elevated risk of flooding. The focus of this paper will be on the hydraulic retention properties of the system. The performance of the bioretention area will be evaluated based on peak runoff reduction and detention capabilities. The results so far indicate promising results with respect to detention capabilities also during typical coastal winter conditions. The outflow from the bioretention area was compared to runoff from an equal size impervious area. The average reduction in peak flow rates compared with calculated impervious surface runoff was 49 %, and 50% when compared with runoff from an impervious snow melt lysimeter. The actual reduction will vary depending on pre event temperature, snow cover, and stored water in the bioretention system.

Keywords

Bioretention; cold climate; Risvollan Urban Hydrological Station; urban hydrology

Introduction

Alternative and new approaches to control urban stormwater are important to reduce future flood risk, combined sewer overflows (CSOs), and protect receiving waters from water quality impairments. If stormwater management is handled on a local level, with the focus on preserving water balance and quality on the local watershed level, CSOs and risk of flooding due to capacity problems in the sewer system can be reduced. The main challenge in cold climate regions that differ from more temperate climates are the often many intermixed periods of snow and rain resulting in ice formation, heavy melting and refreezing. This results in blockage of inlets, excessive ponding on roads, and elevated risk of floods as a result of inadequate capacity of the pipe network to handle the midwinter melts and rain events. Bioretention could be potentially better solution if it will function throughout the year. It will offer retention of peak flow rates with slow release water back into the sewers or into a downstream creek depending on the pollution loads.

Biological retention (bioretention) combines natural treatment with engineered design to maximize the benefits for both water quality and quantity (Davis *et al.*, 2001). A few studies have been carried out on bioretention efficiency, but they have all been done in temperate climates under summer conditions. Davis *et al.* (2001) conducted a laboratory study of bioretention areas for urban stormwater treatment. Two indoor laboratory scale bioretention areas were built and synthetic runoff was applied. The study focused on metals and nutrient removal from the test facilities. The pilot study showed high removal of metals, exceeding 90% and medium removal of phosphorous and nitrogen (60-80%). A field scale test of bioretention area performance was recently reported by Davis *et al.* (2003). In this study two existing bioretention areas in Maryland, USA, were used to apply a synthetic runoff and record the treatment efficiency with respect to heavy metals. The study concluded that metal removal is flow dependant in the upper portions while this had no effect on metal removal from the lower portions. This suggests that in shallow bioretention areas (less than 30 cm) the loading flow rate is very important for the performance of the system. Overall the field test also showed very promising removal rates for metals, approaching 100% in some instances.

Methods

A pilot scale bioretention box was built at Risvollan Urban Hydrological Research Station to test the performance of the system on a continuoysly basis, and especially through out the winter months. In this section the study watershed and the pliotsize bioretentionbox setup are described in detail.

Study watershed

Risvollan Urban Hydrological Station is an urban hydrologic research station 4 *km* south east of the Trondheim city center. The station has been in operation since 1986 and has long time-series of high quality meteorological and hydrological data, including precipitation, air temperature, wind speed, relative humidity, radiation, stormwater runoff, and sanitary sewer flow (Thorolfsson *et al.*, 2003). The Risvollan watershed is 20 *ha* with a 26% impervious land cover, rooftops and paved roads, the remaining (74%) of the watershed is covered with park and lawn areas (pervious surfaces). It is a residential area with mostly townhouse type buildings. Average annual precipitation in the watershed is 900 mm/yr, out of which 30-40% is snow and average temperature in July is 13.9 ºC, and -1.3 ºC in January (Thorolfsson *et al.*, 2003)

Description of Experimental setup

The bioretention box consists of a water-tight plastic box (width: 88,2 *cm*, length 109,1 *cm*, height: 80 *cm*). Media was filled to a height of 60 *cm* in the box, leaving 20 *cm* freeboard to allow for standing water in the box during runoff events. The bioretention box was designed to handle the design runoff, a 2 year storm event without overtopping the 20 *cm* allowable ponding depth. This will capture all the runoff from all storms smaller than 2 years return interval and the first flush from larger storms.

To make the media for the box topsoil was mixed with sand to make a mixture with 8.7% organic matter. The mineral component had 92.6% sand, 4.5% silt and 2.8% clay in one sample and 88.2% sand, 9.1% silt and 2.6% clay in another sample. This indicates a slightly uneven mixing of the media. The media was classified as a sand and as a loamy sand in the two samples.

In order to have a complete control of the water balance in the bioretention box a wooden frame with four cables and s-beam load cells were used to suspend the bioretention box. Turn buckles are used to ensure that the box is always level. The s-beam load cells measure the weight of the box in each corner. A hanging system was preferred over mounting the strain gages on concrete pads and placing the bioretention box on top, as freezing and thawing could more easily corrupt the weight of the box, and permanently mounting the box would make it difficult to make modifications during the study period. At the bottom a 20 *mm* drain pipe drains the outflow from the box into a storage tank in the basement of the measuring station. This pipe has a 3% slope to avoid water freezing in the pipe, and hence blocking the drainage. The rate of change of water level in the tank is measured by a pressure transducer placed at the bottom of the tank. The area of the tank is 1/10 of the bioretention box to easily equate the water level in the box with *mm* of outflow from the box. This system is the same as used for the lysimeter at the station that measures snowmelt (Thorolfsson and Høgeli, 1994). The drainage system of the box can be seen in figure 1 and a picture of the setup can be seen in figure 2.

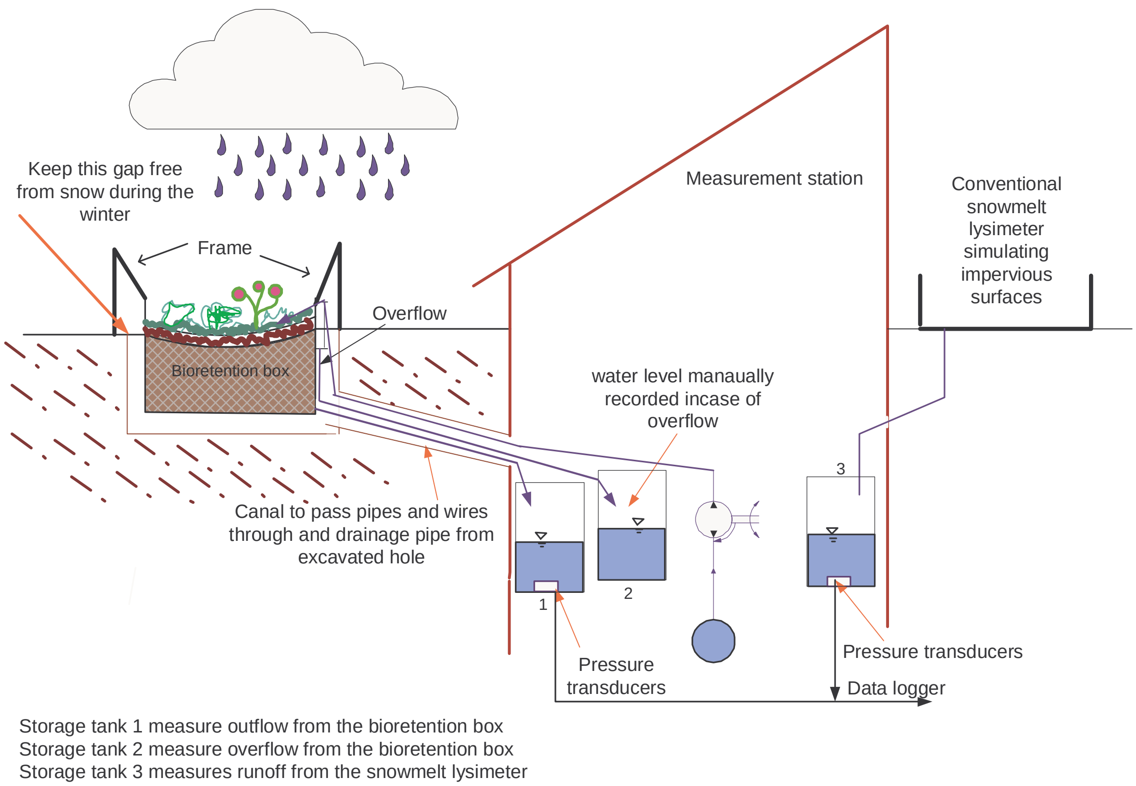

Figure 1. Outflow volume measurement

It was decided not to insulate the box, or install other devices to avoid freezing of the box to the side walls of the hole, as it was seen during operation in the fall months that this would be less of a problem than first anticipated. After a snow fall the gap between the box and the side walls of the hole are manually cleaned out to avoid compaction and clogging of snow in this gap. It is suspected that the soil temperature in the box will be slightly lower than in the surrounding soils as the side walls of the box is exposed creating more surface area for heat exchange. It was also seen during melt periods that the bottom of the hole seem to melt slower than the surrounding areas, creating a cold pocket at the bottom of the hole.

The vegetation used in the box was chosen based on the location and climate. Cold resistant species that also were drought and water tolerant were chosen. Native species were preferred, as they have proved to survive in the climate and are already part of the natural vegetation landscape in the area. The selected plants are listed in table 1.

Table 1. Plant species used in the bioretention box

Common Norwegian name	Latin name	Type of plant
Strandkattehale	Lythrum salicaria	Flower
Sverd Iris	Irsi pseuacorus	Flower
Gravmyrt (evergreen)	Vinca Minor	Small ground cover shrub
Tinved	Hippophae rahmnoides	Shrub

Figure 2. Picture of the setup 28th of September 2004.

Monitoring scheme and data analysis

The data from the station and the bioretention area are collected at 2 minute intervals, to ensure that the more rapid changing hydrology of a small urban catchment is captured. The data is stored on a datalogger from which it can be downloaded onto a portable storage device or a computer. The water balance of the system was calculated as

$$\frac{\Delta Weight}{\Delta time} = Initial\ Weight\ +\ Precipitation\text{ - }Outflow$$

Detention time in the bioretention box was compared to runoff from an impervious surface. The impervious surface runoff was calculated using a finite difference scheme as used in HEC1 (USACE, 1998) to estimate runoff across the impervious surface.

The bioretention box was constructed as an infiltration box, only receiving direct precipitation naturally, and then a hose pump transfers stormwater from the stormwater channel at the station into the box based on the stormwater runoff hydrograph. Until the spring of 2005 the box has only received precipitation and not additional runoff. This option was chosen for two reasons, first in order to setup and validate the data collection from the box before runoff studies are carried out. Secondly, the data from the box functioning as infiltration box will also give valuable data as for the performance of infiltration practices such as green roofs and grass swales with respect to capacity and efficiency in reducing the net runoff from these surfaces versus impervious surfaces during winter months.

Results and Discussion

The focus of the field study the first six months in operation has been the hydraulic detention time of the system during periods of intermittent freezing and thawing, rain, snow event. The bioretention box was compared to a snow melt lysimeter, functioning as an impervious surface and synthetic runoff from an impervious surface created by finite difference scheme and the precipitation records from the site. The main question was to what extent would the bioretention box detain runoff compared to an impervious surface during intermittent rain and snow events.The bioretention box is a closed system, hence all water entering the box would also leave through the drainage pipe, and hence no net loss of water to groundwater infiltration or deep percolation would be found.

The precipitation onto the bioretention box is being measured, as described above, both by precipitation gages and four strain gages in each corner of the box. The accuracy of the strain gages is ±0.1%. With a 0.962 m^2 surface area the strain a gages will detect 1 *mm* of water, adding just under 1 *kg* to the total weight of the box. Weekly water balances form mid November 2004 until end of January 2005 are shown below in table 2.

Table 2. Weekly water balance

week	start date	end date	beginning weight (kg)	water drained (kg)	precipitation added (kg)	end weight (kg)	error %
1	15.11.04	22.11.04	911.9	11.2	80.0	976.2	-0.45 %
2	22.11.04	29.11.04	976.1	2.2	38.3	998.4	-1.38 %
3	29.11.04	06.12.04	998.4	33.2	56.0	1047.6	2.51 %
4	06.12.04	13.12.04	1047.6	125.0	85.1	993.6	-1.41 %
5	13.12.04	20.12.04	993.7	60.4	71.9	1019.2	1.37 %
6	20.12.04	27.12.04	1019.2	1.4	18.4	1043.3	0.68 %
7	27.12.04	03.01.05	1043.3	37.6	55.7	1078.1	1.55 %
8	03.01.05	10.01.05	1077.9	27.8	34.9	1082.5	-0.24 %
9	10.01.05	17.01.05	1082.6	26.7	28.4	1064.6	-1.85 %
10	17.01.05	24.01.05	1064.8	2.9	38.5	1097.0	-0.32 %

The uncertainty in the water balance of the system is 2% .The overall the weekly water balances are within the uncertainty comparing beginning and ending weight of the bioretention box with the exception of week 3, with an error of 2.51%. The overall low discrepancies in the water balance indicate a good control of inflow and outflow form the system. Evaporation is not included in the water balance as it can be assumed to be extremely low during this time of year in Trondheim, with short daylight hours, resulting in very low solar radiation values. This is an addition that should be included into the balance during the spring, summer, and early fall months, as this can be a considerable amount during the warmer seasons.

To compare the detention and peak flow reduction of the system a period of sixteen days from December the 3rd to the 19th was chosen as a representative period. During this period several heavy precipitation events occurred in for of rain, just following the first snowfall of the year in late November. When the precipitation started, the ground was snow covered and represented a typical problematic runoff event with partly snow blocked partly frozen inlets. Figure 3 shows the outflow from the Bioretention box versus the calculated impervious surface runoff. On December 7th a particular heavy rainfall occurred, more than 23 *mm* precipitation came in 1 hour between 12:56 and 13:56 in the afternoon. The max intensity reached 1.9 *mm* over 2 min, just 10 minutes into the event 7.3 *mm* had accumulated. This created a peak runoff from the impervious surface of 165.6 l/hr per m^2, the peak is not shown in the graph as it would have made the scale on the primary y-axis too large to see the bioretention box outflow. It takes almost four days of rain before runoff is seen from the bioretention box as a detectable amount. The time of initial delay before runoff is seen from the box will be influenced by the pre event snow cover, temperature and laps time since previous precipitation event. Prior to December 3rd it had been dry for 3 days. The first snowfall of the season had occurred a few weeks earlier in November. This snow was still on the ground in early December as the temperature stayed below zero until 29th of November. When the precipitation event started on the 3rd of December it was about 20-30 *cm* snow cover on the bioretention box and it was drained for most of the water from previous events. This would result in a longer initial delay than would be expected without the snow cover.

The runoff from the bioretention box was also compared to runoff from the snow melt lysimeter, functioning as runoff from an impervious surface area. The bioretention box showed similar retention capabilities compared to the snow melt lysimeter as the caluclated impervious runoff. It had a retention effect until the saturation point, upon which no clear effect of the system could be seen anymore. Figure 4 shows a typical week in January 2005 comparing the snow melt lysimeter outflow and the bioretention box outlfow. On certain occasion the bioretention box actually gave higher runoff rates than the impervious surface, like was the case on January 15th. Releasing stored water at the saturation point at a higher rate than the precipitation producces runoff on the impervious area.

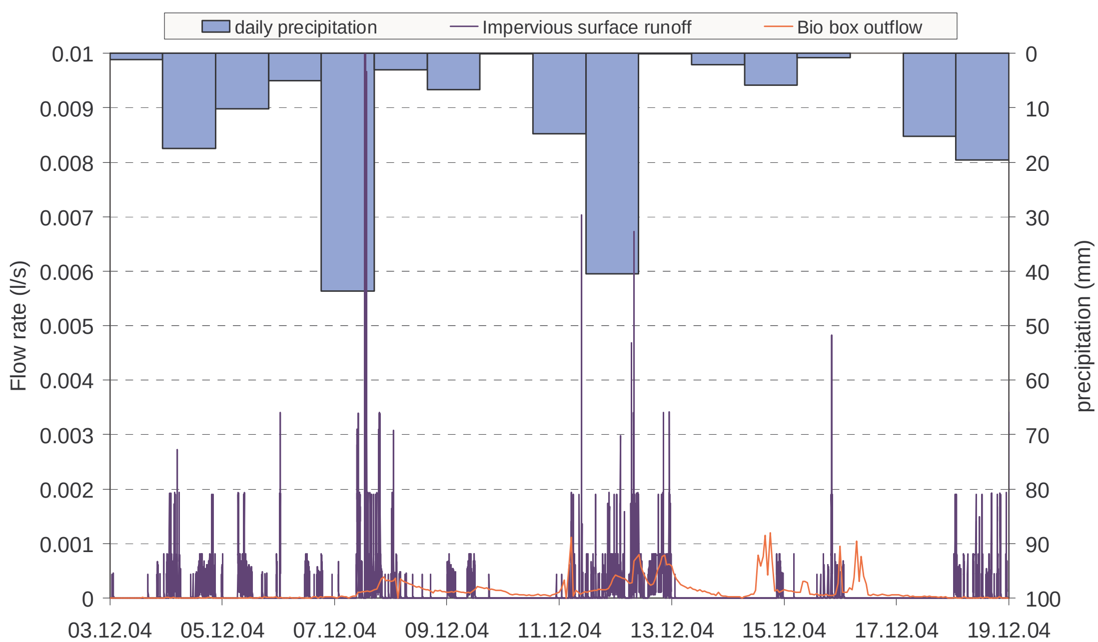

Figure 3. Outflow from Bioretention box and calculated impervious surface runoff

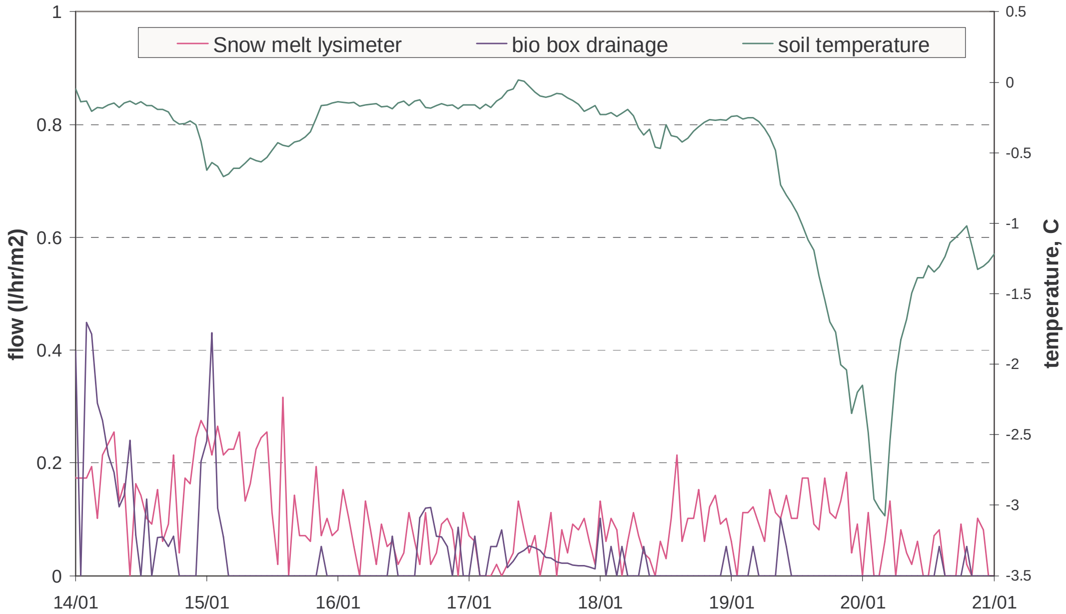

Figure 4. Outflow from the bioretention box compared to the snow lysimeter impervious surface for a week in January 2005.

Figure 5 shows the detention effect in the outflow from the box compared to the calculated impervious surface runoff situation and the snow melt lysimeter. There is a reduction in the peak runoff by 100 %, typically in the beginning of runoff events where lag between precipitation and runoff from the box is much longer than the lag time on the impervious surface.

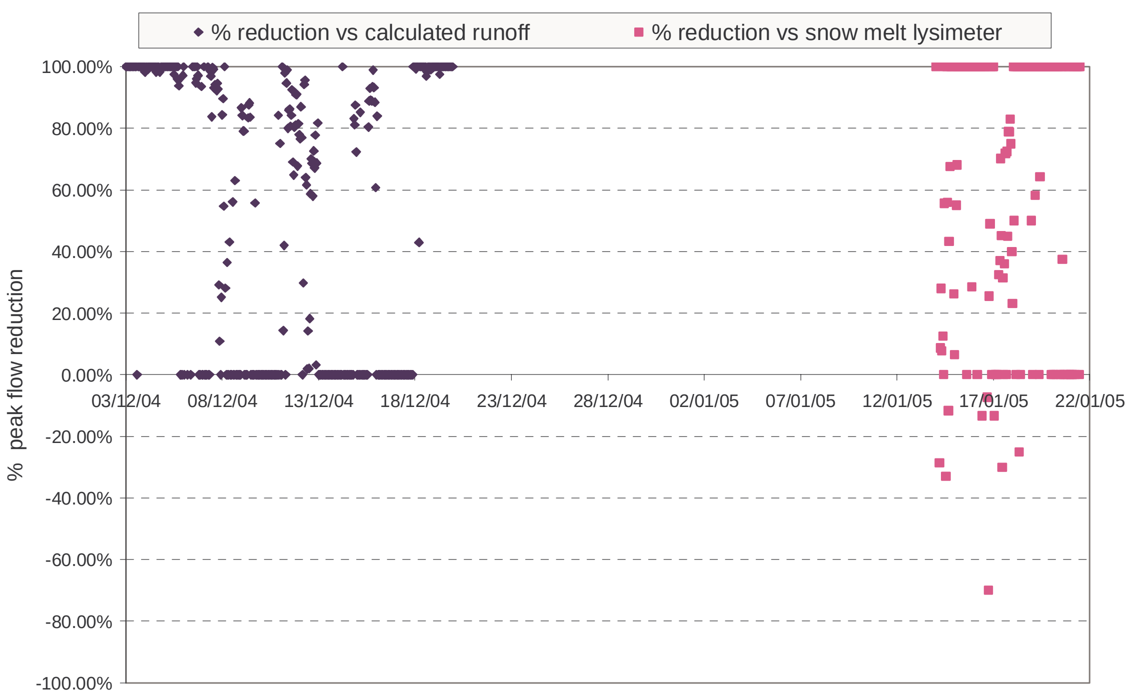

Figure 5. Percentage reduction in peak flow rates through the bioretention box compared to the calucalted runoff and the snow melt lysimeter.

The average peak flow reduction was 49% for the calculated runoff in December and 50% for the snow melt lysimeter comparisons in January. The median reduction was 64% and 100% for the calculated runoff and snow melt lysimeter comparison respectively. The lower average reduction compared to the median reduction can be explained by the many instances of 0% reduction that occurs when there is still flow from the bioretention box, after the flow from the impervious surface has ceased. For the snow melt lysimeter comparison there were also several instances of negative reductions, where the outflow from the bioretention box exceeded the outflow from the snow melt lysimeter.

Conclusions

This paper describes an experimental field work setup for testing the performance of bioretention areas in a cold climate setting at the Risvollan measuring station in Trondheim, Norway. The setup was built to study the performance of such a system through the whole year with especial emphesis on the cold season.

- A 49% average reduction in peak runoff compared with an calculated impervious surface runoff situation.
- A 50% average redution in peak runoff compared to the snowmelt lysimeter was observed
- The bioretention area typically generated no runoff until precipitation had ceased for smaller events.
- A reduction in peak runoff was seen also druning frozen soil event in December 2004.

The bioretention box should be tested for another season to get more data about the perfornace during different precipitation events. Several studies relating to heavy metal redution and total syspended soilds reduction are aslo planned over the next year at different weather conditions.

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Paper II

Seasonal climatic effects on the hydrology of a cold climate rain garden

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Seasonal climatic effects on the hydrology of a rain garden

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Abstract

This paper evaluates the performance and winter hydrology of two small scale rain gardens in a cold climate coastal area, in Trondheim, Norway. One rain garden received runoff from a small residential watershed over a 20 month study period and a second rain garden with a shorter study period of 7 months, was used for control. The objective of the study was to investigate to what extent the cold climate conditions would influence the hydrology and performance of the rain gardens. The hydraulic detention, storm lag time and peak flow reduction were measured and compared between the seasons. No significant difference between seasonal lag time could be found, but a clear decreasing trend in lag time between rain, rain-on-snow and snowmelt was found. The hydraulic detention was shortest in the winter season with temperatures below 0°C, 0.65 week compared to 1.0 week hydraulic detention in the summer season. The average peak flow reduction for 44 storms in the study period was 42%, compared to 27% for the winter seasons, indicating that the performance of the rain garden is reduced in the cold season (below 0°C). The average hydraulic detention time for the rain garden was 0.84 (±0.73) week with runoff inflow and 1.91 (±3.1) weeks with precipitation only. A strong positive correlation was found between the time since last wetting event and lag time, and between air temperature and hydraulic detention. This indicates that the time between events and seasonal air temperatures are key parameters in the hydraulic performance of cold climate rain gardens. The rain gardens were not used for snow storage areas, and a volume requirement for this was not evaluated in the study.

KEY WORDS: Rain garden, hydrology, cold climate, stormwater

INTRODUCTION

Rain gardens, also called bioretention areas, are becoming popular stormwater treatment options, and are perhaps one of the most commonly used stormwater practices from the low impact development (LID) concept. A rain garden normally consists of a sandy loam soil, a mulch layer, and plants designed for retention, infiltration and treatment of stormwater (Clar, *et al.*, 2004). Though the mulch layer can be omitted, several previous studies have documented the high pollutant adsorption capacity of mulch (Davis, *et al.*, 2001; Jang, *et al.*, 2005). Rain gardens can have an impervious boundary at the bottom, and function as a filtration and retention system, or as a ground water recharge system without the impervious boundary, where the natural soil infiltration capacity is sufficient. The most important hydrological processes in a rain garden include infiltration, interception, evaporation, and transpiration. These functions should work together to control peak flow and reduce total volume from small storms. The design objectives for rain gardens include; water quality treatment, infiltration, and maintaining or restoring local water balance (Winogradoff, 2002). Rain gardens can also be a part of a blue-green interface in the urban environment with more visible surfaces in the urban landscape.

The main functions of a rain garden and related to water quality improvements of stormwater and to retain and dampen peak flows and volumes of smaller storm events. The hydrologic functions, such as infiltration and transpiration have to function adequately for the water quality functions of the system to perform satisfactorily. Despite this, and their common usage, little research has been conducted on their performance, especially with respect to hydrology (Dietz and Clausen, 2005). The research that has been conducted has focused on summer conditions or temperate climates without a predominant dormant winter period. A study from Haddam, Connecticut, studied the performance of two rain gardens. The rain gardens performed well with respect to peak flow reduction and infiltration. The rain gardens had an impervious lining resulting in that 98.8% of the total inflow left the rain garden as subsurface flow, but no overflow problems were reported. The peak flow reduction was only reported for storm event, with 65% peak flow reduction. The hydraulic detention, defined by weekly inflow divided by weekly outflow, in the system was reported at 0.99 ±0.53 (Dietz, 2005). This is a measure of water detention in the system, and an indication of water storage in the system.

In a cold climate region, winter infiltration is a key factor in the performance of rain gardens during the winter and snowmelt seasons. Several field studies have been conducted to measure infiltration into frozen and partially frozen soils (Granger, *et al.*, 1984; Kane, 1980, Brun, 1990, Kok and McCool, 1990). The common finding from these field studies was the importance of pre freezing soil water content for the infiltration rate into the frozen soil. Several studies have also fond an inverse relationship between total moisture content and infiltration (Zhao and Gray, 1999). The soil moisture content during freezing has been shown to create three types of soil frost; porous frost, granular frost, and concrete frost (Stoecker and Weitzman, 1960). Concrete frost occurs when the saturated soil freezes. Granular frost occurs when unsaturated frost freezes, and results in a more permeable soil, for which the infiltration rates can exceed that of unfrozen soil (Stoecker and Weitzman, 1960). Porous frost occurs with soil moisture levels in the middle range. Several studies have also shown that the shape of the infiltration curve for frozen and unfrozen soil are similar (Xiuqing and Flerchinger, 2001). This indicates that infiltration should be maintained during the cold season in a well drained soil where concrete frost is avoided. Reported infiltration rates for sandy loams recommended for use in bioretention areas range from 5-10 cm /hr (Beven, 2001). A study from Sweden using two sandy soils also showed that the rate at which infiltrated water refreezes in the soil can greatly affect the infiltration rate, especially in the upper 50cm of the soil (Stähli, *et al.*, 1999).

The depth of the frost line will also influence the performance of rain gardens in cold climates. In Norway the frost line varies from 1.2 m in the south to 3.4 m in the north, in Trondheim it is 1.8 m. The rain garden will therefore be partially or completely frozen depending on the depth. For rain gardens with drain pipes above the frost line it is important to avoid standing water in the drain pipe, as this will cause blockage when freezing. A rain garden that is well drained, where concrete frost is avoided and adequate slope on the drain pipe prevents standing water should be able to perform year around in a cold climate. This hypothesis formed the motivation for this research. The main objectives of this study were to examine the winter hydrology and performance of a rain garden in a costal cold climate region. It was the aim of the study to increase the knowledge about infiltration, hydraulic detention time, lag time and peak flow reduction through the rain garden in the winter season and also to investigate to what extent these parameters differed from the summer conditions.

METHODS

Study watershed

Risvollan Urban Hydrological Research Station (RUHRS) located 4 km south east of Trondheim city centre, in the Risvollan watershed (N63° 20', E10° 18'). The station has been in operation since

1986, collecting high resolution meteorological and hydrological data, including precipitation, air temperature, wind speed, relative humidity, radiation, and stormwater runoff. Average annual precipitation in the watershed is 900 mm/yr, out of which 30-40% is snow (Thorolfsson, *et al.*, 2003). The Risvollan watershed is 20 ha with a 26% impervious land cover made up of rooftops and paved roads, the remaining (74%) of the watershed is covered with park and lawn areas (pervious surfaces). It is a residential area with predominantly townhouse type buildings and approximately 1500 residents (Figure 1).

Experimental setup

The field experiment method described below is similar to the description in Muthanna and Thorolfsson (2005). The rain garden was sized based on the first Prince George’s County bioretention design manual (Prince_George's_County, 1993). The rain garden was designed to receive runoff from a 20m^2 impervious surface area utilizing 5% of the drainage area for the bioretention area. This resulted in a bioretention area of 0.96m^2. The rain gardens were constructed of a water-tight polyethylene plastic box (width: 88 cm, length 109 cm, and depth 80 cm). At the bottom, 10 cm of gravel (d_{50} = 20mm) was used, and a thin plastic mesh was placed to avoid clogging of the gravel layer due to the soil on top. The soil media placed above the gravel layer was 50 cm thick, followed by a 5-10cm mulch layer to cover the soil and improve pollutant retention, leaving 15 cm freeboard to allow for standing water in the box during runoff events. The first rain garden was constructed in the summer of 2004, while the second was constructed in fall 2005. Top soil mixed with sand was used for both the gardens. The soil and sand was mixed to be equal in the two system, but the final physical properties of the soil in the two gardens differ slightly (Table 1). At the bottom a 20 mm PVC tube drained the outflow from the box into a storage tank in the basement of the measuring station. The drainpipe had a minimum slope of 3% to avoid water freezing in the pipe, thus avoiding blocking the drainage. The rate of change of water level in the tank was measured by a pressure transducer (0 – 160 mbar range) placed at the bottom of the outflow tank. The area of the tank was 1/10 of the rain garden box to easily equate the water level in the tank with mm of outflow from the rain garden (Figure 2).

The inflow to the rain gardens was pumped using a variable speed hose pump (Bredel SPX 10) and a frequency inverter to convert the flow in the stormwater channel to a voltage input signal to the pump. This system also allowed for variable inflow sources, either the stormwater channel from the Risvollan watershed, or alternate inflow could be easily used with an inflow tank and the pump system.

The vegetation used in the box was chosen based on the location and climate. Hardy, cold resistant species were chosen. Native species were preferred, as they have been proven to survive in the climate and are already part of the natural vegetation landscape in the area (Table 2). For rain garden 1 s-beam load cells were installed using cables and turn buckles to weigh the system and record delta-change in total weight. However for the construction of the second rain garden this was not done as the pressure transducers measuring the outflow from the box had proven to be very reliable, thus making the weighing system somewhat redundant.

Sampling and analysis methods

The soil temperature in the two rain gardens was measured using two termistor temperature sensors (Campbell Scientific, number 107). The temperature probes were placed 15 cm below the surface in the middle of the rain garden boxes. The temperature sensor is 10 cm long and was therefore located between 15 and 25 cm deep in the soil. The levels in the outflow tanks were measured using a pressure transducer (0-160mbar). The strain gages on rain garden 1 were s-shaped strain gages (0-1000kg). The data from the various sensors were recorded using a Campbell Scientific data logger (CR10X) and Labview (National_Instruments, 2004). The data was recorded on a 2 min interval and automatically transferred by a FTP server from the field station. A web-cam was also installed at the field station and used to take pictures of the rain garden every 15 minutes. The pictures were used for verification in analysis of the storm events to identify rain, snow, or melt water events.

The water balance in the rain gardens were compared on a monthly basis summing inflows and outflows. The winter snow accumulation could affect the monthly water balance if snow was stored on the ground over several months, however in a costal climate like Trondheim the winter months have frequent intermittent snow accumulation and melt periods. In a more inland climate where the snow accumulates over several months the snow storage would have to be accounted for in the monthly water balance. The potential evapotranspiration (PET) was estimated using Penmans method (Penman, 1963, and Jensen, *et al.*, 1990).

To evaluate the lag time between inflow and outflow in the system, all storms from the whole study period were analyzed. Lag time was defined as the time, measured in minutes, from when inflow to the rain garden started to when outflow occurred in the underdrain. This does not measure the lag time in the study watershed. Storm events were defined as the time period from onset of precipitation to the time when runoff recessed back to the base flow levels in the stormwater channel. In some cases this could be several days, with intermittent stops in precipitation too short for runoff to cease. For those instances the whole period from onset of first precipitation event until runoff ended was considered one storm event. To evaluate the seasonal hydraulic detention the weekly inflow was divided by the weekly outflow over the study period (Dietz, 2005). The same definition as used by Dietz, was chosen for comparison reasons. Hydraulic detention on a weekly basis gives a measure of the rain gardens ability store water between events. However, this dimensionless number can be skewed by storm duration or time of occurrence, but with 20 months of data the average hydraulic detention can indicate a rain gardens average ability to store water between events. The peak flow reduction for each individual storm was calculated by the following equation:

$$Peak\ \ flow\ reduction(\%) = \left(1 - \frac{q_{\max-outflow}}{q_{\max-\inf low}}\right) \times 100$$

$$where: \quad q_{\max} = \max imum \quad flowrate$$

To give a better indication of the long term performance of the rain garden box the average peak flow reduction for each runoff event; rainfall runoff, rain-on-snow, and snowmelt was calculated by taking the average of all the individual storm peak flow reductions. Analysis of variance (ANOVA) and averages were used to identify significant differences in lag time and hydraulic detention between the seasons. Minitab 14 (Minitab, 2004). Statistical software was used to perform the analysis, to identify the factors influencing the lag time in the system Pearson correlation between lag time and air temperature, days since last wetting event in the rain garden, and snow cover at onset of runoff event was computed.

RESULTS AND DISCUSSION

The two rain gardens performed well over the 20 and 7 month study periods for rain garden 1 and rain garden 2 respectively. The study included two full winter seasons for rain garden 1 and one winter season for rain garden 2. No overflow events were recorded and all the inflow left as either subsurface flow or evapotranspiration. To evaluate the seasonal performance the results were analyzed based on four seasons, based on the 30 year normal average monthly temperature in

Trondheim. This resulted in summer months defined as months with average temperature above 12°C, as the 30 year normal average temperatures for June, July and August are above 12°C. Winter months were defined as months with average temperature below 0°C, and autumn and spring was defined as between 0°C and 12°C (Table 3). This division follows the 30 year normal average monthly temperatures, which will minimize the effects of unseasonable warm or cold temperatures in the study period.

Water balance

Rain garden 1 received precipitation only as inflow from September 2004 to April 2005, the first winter season. From April 2005 until end of March 2006 precipitation and inflow from stormwater runoff was pumped into the rain garden. Rain garden 2 received precipitation from October 2005 to end of March 2006.   In 2005 10% of the total inflow to rain garden 1 was precipitation and 90% was runoff while for the 3 first months of 2006 only 4.6 % of the inflow was precipitation and 95.4 % was runoff from the catchment.

The difference between inflow and outflow includes both evapotranspiration and measurement error. Based on a previous analysis of weekly water balance over a 10 week period from November 2004 to January 2005, a 1.2% residual between inflow and outflow from rain garden 1 was found based on precipitation inflow only (Muthanna and Thorolfsson, 2005). This was measured during the time of the year with very low evaporation and transpiration rates and low and short daylight hours reducing the evaporation additionally. This residual therefore can be used as an indication of the error in the system.

For the entire study period the difference between inflow and outflow to the rain gardens were compared to calculated evapotranspiration on a monthly basis (Figure 3) with a good fit between the estimated evapotranspiration and measured residuals. In April and May 2005 the PET exceeded the total residual water in rain garden 1. This indicates that the actual evapotranspiration was lower than the potential (PET). Comparing the residuals over the winter season with very low evapotranspiration indicates a 1.4% residual error in the system.

Lag time retention

Over the whole study period 44 storms were identified as single events that could be analyzed. The precipitation pattern in Trondheim often results in intermittent showers with medium to low intensity that can continue for multiple days, especially in the fall and winter. This makes it difficult to identify the beginning and end of the events, and while the first few showers might not produce much runoff, the combined effect of several intermittent showers over a few days will produce runoff. All precipitation events that produced runoff were included in the analysis. The duration of the 44 selected storms will therefore vary from a few hours to several days, and the precipitation varied from 0.7 mm for a short storm to a 136.5 mm large storm event over several days (Table 5).

The lag time for 44 storms over the 20 months study period for rain garden1 were analyzed, 28 rain events, 13 rain-on-snow events (include rain on frozen ground events), and 3 snowmelt events. The snowmelt events are runoff created only from heat induced snowmelt. The precipitation intensity and initial conditions will influence the lag time, however that is true for all seasons. The average lag time for all events was 90 min, with slightly longer average lag events in the 0-12°C range and a shorter lag time for events in the above 12°C range. The average lag times were related to the average maximum precipitation intensity, with the shortest lag time for the season with the highest average max intensities (Table 4). The data set was found to be normally distributed (p=0.05) and an ANOVA test indicated no significant difference between the mean lag times for the various seasons. However, if the precipitation events were divided by type of event; rain, rain on snow or snowmelt a significant difference was found between the rainfall and snowmelt event. However the snowmelt events contained only 3 events, making further investigations necessary to verify these findings. Between the rainfall and rain on snow events a p value of 0.06 indicated a significant difference at the 90% confidence interval, but just short of the 95% confidence interval. The below zero °C events (3 events) were all rain on snow events with the shortest lag time and highest average maximum intensity.

The lag time in the system could be influenced by antecedent soil moisture content (time since last inflow event), snow cover, and temperature. To investigate the correlation between these factors and the lag time a Pearson correlation test was used. The lag time showed a strong positive correlation (lag time increased with length of antecedent dry weather period (ADWP)) with more than 1 day since last wetting event (p=0.05), but no difference was seen between 1 day and multiple days. No other significant correlation could be found for the factors that were tested, indicating that time since previous event is the single most important factor determining the lag time in the system. A weak negative correlation between type of event (rain, rain-on-snow, or snowmelt) was also found. The seasonal variations however were less than the effect of antecedent moisture content. Two storms from each season were plotted with inflow, outflow and precipitation (Figure 4) giving a visual inspection of the variations in the storm events.

A typical winter problem in costal cold climate regions like Trondheim is rain on snow covered ground events. Several such events occurred over the 20 month study period and for every event the rain garden was able to infiltrate the inflow and no overflow occurred. These events typically begin with a solid snow cover that is rapidly decreased with increased temperatures and precipitation in the form of rain. Figure 5 shows three pictures from a storm event in December 2005 lasting over multiple days with shorter intermittent stops in precipitation. When precipitation started there was 5 to 10 cm snow on the ground (Picture A), then all the snow melted during the rain portion of the event (Picture B), before it got colder and the last portion of the precipitation fell as new snow (Picture C). The initial lag time for this event from runoff began (inflow to the rain garden) and outflow started was 20 min and 37% reduction in peak flow.

During the first winter season (2004/2005), rain garden 1 was not insulated. After a snow fall, the gap between the box and the side walls of the hole would be manually cleaned out to avoid compaction and clogging of snow in the gap as this would prevent accurate readings of the strain gages. It was suspected that the soil temperature in the rain garden would be slightly lower than in the surrounding soils as the side walls of the box is exposed creating more surface area for heat exchange. But the open system seemed to create a cold pocket at the bottom of the hole and leave the box more exposed to sudden changes in soil temperature. The second winter season (2005/2006) the gap between the rain garden boxes and the holes were covered with 5 cm insulation boards. This prevented snow and rain from entering into the gap, and also created a more stable soil temperature in the rain garden (Figure 6).

Hydraulic detention and peak flow reduction

The hydraulic detention time was calculated on a weekly basis and the weeks were sorted into seasons based on the thirty year normal temperature distribution in the watershed. For rain garden 1, the hydraulic detention for the first 7 months of operation was analyzed separately as the rain garden only received precipitation during these months. This could be compared to rain garden 2, which also only received precipitation only the first seven months of operation. The average hydraulic detention time was 1.81 (±1.85) for rain garden 1 and 1.93 (±3.1) for rain garden 2 with only precipitation. Rain garden 1 had a hydraulic detention of 0.84 (±0.73) weeks with stormwater runoff inflow. The yearly average hydraulic detention of rain garden 1 is slightly lower then the 0.99 week retention time reported by Dietz and Clausen, 2005). The seasonal hydraulic detention times (Table 6) showed that spring has the lowest retention time, 0.41 weeks while summer had the longest retention time.

The spring season had the lowest lag time, and the lowest hydraulic detention time. The spring season also had the highest snowmelt rates. This could indicate that snowmelt decreases the lag time and the hydraulic detention in the rain garden, however additional snowmelt data (snowmelt without rainfall) should be collected to investigate this further. The weekly inflows correspond to the seasonal precipitation pattern in Trondheim with fall and winter being the wettest seasons and spring the driest season. Larger daily temperature fluctuations causing frequent thawing and freezing of the top soil layers increasing the chance of canalized flow through the soil matrix could possibly explain the lower retention time for the spring season. The snow pack on the rain garden stored from the winter melting in the spring will also cause higher outflows compared to inflows, due to the water in the snow being released and added to the total inflow volume, thus inflating the retention time in winter while decreasing it in spring. However due to the large standard deviation no significant difference in hydraulic detention time between the seasons could be observed.

The average weekly inflow to the rain gardens were fairly constant through the year, so this cannot explain the difference in hydraulic detention. For rain garden 1, with the runoff inflow, the lowest hydraulic detention is seen in the coldest season and the longest hydraulic detention is found in the warmest season. A correlation using a Pearson correlation revealed a positive correlation between hydraulic detention and average temperature (correlation coefficient 0.270, and p value 0.076). The p-value is not strong enough to reject the null hypothesis that they are equal, at confidence interval 0.95. However considering the large natural variability in the system, it indicates that the hydraulic detention in the system is positively correlated to the air temperature. But for rain garden 2, receiving only precipitation, no correlation between hydraulic detention and air temperature was found (correlation coefficient -0.022, and p value 0.913).

The average peak flow reduction for all the 44 storm events was 42%. The below zero temperature range had lower reduction that the other seasons, with only 27% peak flow reduction. This indicates that the rain garden is less capable of retaining the flow in the cold season. The peak flowrate is also reduced as is supported by the lower hydraulic detention time. The coldest season also had the highest average maximum intensities, which also differs from more temperate climates where the maximum intensities are often seen in the warmer season. Freezing of the outlet drain pipes for the rain gardens was only observed for one occasion for rain garden 2 in March 2006. The freezing was attributed to the lack of insulation of the drain pipe which would normally be present for a fully buried pipe, which would be the case for field installations.

CONCLUSION

Two pilot sized rain gardens in a costal cold climate region were used to investigate the hydraulic performance of rain gardens during the cold season, and to what extent the performance was affected by climatic factors. The findings indicate that the hydrologic performance of the rain gardens was strongly related to temperature and antecedent dry weather period. The average lag time in the rain garden decreased from 69 min in the warm season to 59 min in the cold season, however the longest lag time, 97 min, was found in the spring and fall temperature range. The lag times were not found to be statistically different between the seasons. When the average maximum intensity was taken into account, it revealed that the cold season has the highest average maximum intensity, while the spring and fall seasons had the lowest average maximum intensity, which could explain the increased lag time. The total depth of the soil medium in the rain garden was 55-60 cm including the mulch on top. This rather shallow depth was chosen based on previous studies by Davis *et al.* (2001), that showed that soil media depths above 45cm did not have any effect on the heavy metal removal in the system. However, it is possible that from a winter hydrology point of view a deeper media would change the behaviour properties. The frost line in southern parts of Norway is at 1.2 m, here it is possible that a rain garden with a drain pipe below the frost line would increase winter infiltration in the system, by ensuring frost free conditions at the bottom of the system.

A significant difference was also found between lag times for rain events (117 min) and snowmelt events (30 min), however only 3 snowmelt events without accompanying precipitation were observed, compared to 28 rain events, additional snowmelt data should therefore be collected to verify these findings. The rain gardens were designed using a method based on a temperate climate, without considering snow storage, which was not considered in the analysis in the study either. Snow was allowed to accumulate on the rain gardens as it fell as precipitation but no storage of snow removed from other impervious areas was permitted. In addition to the volume concern with snow and snowmelt, the water quality dynamics of snowmelt is different from rainfall runoff water quality dynamics (Oberts, 2003; Viklander, 1997; Westerlund, 2005). These are important factors and should be further investigated with respect to sizing of a rain garden in areas with regular winter snow accumulation and its implication for snowmelt in rain gardens.

The water balance in the system had a higher error in the cold period than the warm period, but this could also be due to that most of the precipitation falls in the cold season. The hydraulic detention time for the rain garden with runoff inflow was found to be 0.84 ±0.73 weeks for the whole study period, and 0.65 (±0.47) for the cold season and 1.0 (±0.67) for the warm season. The hydraulic detention times were not fond to be statistically significantly different between the seasons. This indicates that the performance of the rain garden can be expected to be lower during times with below 0 °C, and during snowmelt events the performance also decreased. Using a sandy soil with more than 90% sand instead of a sandy loam, which is most often recommended, was done to improve winter infiltration in the rain garden. This will also affect the lag time and hydraulic detention in the system, but this can be compensated with a lower hydraulic loading rate, by increasing the rain garden area to drainage area ratio and allowing for storing of standing water in the rain garden.

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Table1. Soil physical properties for the two rain gardens

	Rain garden 1	Rain garden 2
Clay (%)	2.6	2.9
Sand (%)	92.7	88.3
Silt (%)	4.7	8.8
Organic matter (%)	8.7	10.7
Bulk density (g/m3)	0.79	0.84
Soil porosity (%)	49	48
pH soil	6.88	6.79
pH mulch	5.5	5.6

Table 2. Plant species used in the two rain gardens

Common name	Latin name	Type of plant
Sea-buckthorn	Hippophae rahmnoides	Shrub
Purple-loosestrife	Lythrum salicaria	Flower
Yellow Iris	Iris pseuacorus	Flower
Lesser Periwinkle	Vinca Minor	Ground covering ever green

Table 3. Monthly average temperatures during the study period, based on daily observations and normal temperatures 1961-1990.

Temperature (°C)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2004 [1]									10.0	4.2	-0.2	-0.1
2005 [1]	0.8	2.4	-0.6	5.3	7.3	11.2	15.7	12.8	9.8	6.3	2.6	-2.8
2006 [1]	-1.2	-1.6	-5.4									
Normal[2] (1960-1990)	-3.0	-2.5	0.0	3.0	9.0	12.0	13.0	12.5	9.0	5.5	0.5	-2.0

1) Temperature observations at Risvollan
2) Temperature observations at Voll Meteorological Station, situated a 1.8 km from the study area

Table 4. Average seasonal lag times and precipitation intensities in rain garden 1 for the 44 events over the study period.

	Mean Lag time (min)	Average intensity (mm/hr)
All events	90	2.76 (1.91)
Above 12 °C	69	2.85 (1.88)
Between 0-12 °C	97	2.38 (2.07)
Below 0 °C	59	3.13 (0.74)
Rain events	117[a]	
Rain on snow events	47[a]	
Snow melt events	30[b*]	

Lag times followed by the same letter are not significantly different at CI=0.95
Standard deviations listed in parenthesis
* Only 3 snowmelt without precipitation events were recorded.

Table 6. Seasonal hydraulic detention time and average weekly inflows to the two rain gardens over the study period.

	Hydraulic detention time		Average weekly inflow	
	Rain garden 1 (weeks)	Rain garden 2* (weeks)	Rain garden 1 (L)	Rain garden 2* (L)
All	0.84 (±0.73)	1.9 (±3.1)	397	21
Below 0 °C	0.65 (±0.47)	2.0 (±3.1)	434	19
Between 0-12 °C	0.93 (±0.90)	1.73 (±3.2)	405	24
Above 12 °C	1.00 (±0.67)		304	

* Only precipitation inflow to this rain garden, no runoff

Table 5. Summary of all storm events with runoff that entered into rain garden 1 over the study period.

Date	Type	Duration	TSPE*	Snow cover	Max Intensity	Avg. Intensity	Avg. Soil temp.	Avg. Air temp.	Lag time	Total inflow	Tot. Precip.	Tot. outflow	Vol. red.	Peak red.
		(hr)	*(days)*	*(y/n)*	*(mm/hr)*	*(mm/hr)*	*(°C)*	*(°C)*	*(min)*	*(mm)*	*(mm)*	*(mm)*	*(%)*	*(%)*
12/04/2005	R	4.2	1	n	1.5	1.3	0.0	8.7	59	154	5.5	122	21%	19%
13/04/2005	R	4.6	0	n	7.4	3.7	4.5	10.4	51	179	16.9	166	7%	4%
14/04/2005	R	6.5	0	n	2.3	1.6	7.0	10.5	35	252	10.4	227	10%	17%
04/05/2005	R	9.8	0	n	6.0	0.8	8.3	3.9	250	8	7.8	4	43%	95%
06/05/2005	R	6.9	0	n	6.0	1.1	7.4	5.4	238	6	6.3	5	20%	95%
14-15/05/2005	R	31.5	0	n	1.5	0.2	7.2	5.0	60	8	7.55	1	86%	91%
24/05/2005	R	4.5	4	n	2.2	0.7	11.8	10.2	30	3	3.3	2	41%	91%
27-28/05/2005	R	13.6	0	n	0.6	0.7	9.6	6.2	168	22	9.07	14	37%	18%
6-8/06/2005	R	79.6	8	n	1.2	0.2	9.3	7.2	320	13	12.5	10	23%	5%
17-19/06/2005	R	25.7	9	n	1.9	0.2	13.5	11.7	780	8	8.2	5	34%	88%
21-23/06/2005	R	60.0	0	n	4.6	0.8	14.2	12.9	180	26	25.7	24	6%	1%
26-28/06/2005	R	45.3	0	n	1.9	0.3	10.8	8.7	160	23	22.6	16	29%	53%
12-13/07/2005+	R	28.0	4	n	3.4	0.4	16.1	14.4	48	208	12.5	168	20%	50%
6-7/08/2005	R	7.1	0	n	3.1	4.8	12.8	13.5	20	221	34	170	23%	24%
20/08/2005	R	7.5	1	n	0.8	0.3	14.0	12.9	148	29	2.6	21	29%	45%
22-23/08/2005	R	27.2	1	n	1.1	0.2	13.3	13.8	146	50	6.7	33	34%	38%
25-27/08/2005	R	49.7	0	n	5.3	0.5	12.2	10.9	28	157	22.6	110	30%	46%
29/08/2005	R	8.0	1	n	2.3	0.8	10.6	12.5	28	62	6.5	42	33%	37%
30/08/2005	R	4.2	0	n	1.5	1.3	10.7	12.4	45	154	5.5	109	29%	35%
31/08/2005	R	4.6	0	n	7.3	3.7	12.4	16.5	33	179	16.9	135	24%	16%
01/09/2005	R	6.5	0	n	2.3	1.6	13.9	21.6	22	252	10.4	198	21%	27%
02/09/2005	R	13.5	0	n	3.5	0.7	14.0	13.2	36	24	9.6	17	27%	71%
08/09/2005	R	4.5	0	n	1.5	0.9	12.7	12.8	56	32	3.9	21	37%	70%
11-17/09/2005	R	130.4	1	n	3.0	0.6	8.5	7.4	114	196	77.9	177	9%	19%
18-19/09/2005	R	8.4	0	n	0.9	0.5	8.4	10.8	76	10	3.9	10	4%	53%
2-4/10/2005	R	40.5	1	n	2.3	0.3	8.4	9.4	116	145	13.9	90	38%	40%
09/10/2005	R	6.5	2	n	1.7	1.4	8.0	6.5	102	90	8.8	2	98%	84%
13-16/10/2005	R	36.8	2	n	3.8	0.4	9.3	4.2	120	148	14.3	74	50%	94%
26/10/2005	R/S	25.0	0	y	0.8	0.2	0.1	7.3	48	47	5.6	118	-148%	1%
13-30/11/2005	R/S	400.0	0	y	5.2	0.2	0.8	0.5	32	3086	93.6	3072	0%	71%
10-17/12/2005	R/S	167.0	7	y	4.3	0.7	-0.1	2.0	100	2163	111.8	2162	0%	63%
11-15/01/2006	R/S	56.0	8	y	2.7	0.3	-0.5	3.2	78	558	14.5	501	10%	12%
22-24/01/2006	R/S	63.1	1	y	1.5	0.2	-1.9	1.1	66	85	11.3	83	2%	30%
26/01-04/02/2006	R/S	180.0	1	y	5.9	0.8	-1.2	2.8	46	3047	136.5	2990	2%	73%
04-10/02/2006	R/S	136.0	0	y	2.3	0.4	-0.4	-1.5	64	463	56	426	8%	17%
19-28/02/2006	R/S	184.3	5	y	3.7	0.2	-0.4	-3.5	70	419	33.7	391	7%	0%
17-21/03/2006	R/S	78.0	10	y	3.4	0.4	-1.5	-0.9	42	441	31.2	432	2%	53%
27-30/03/2006	R/S	56.0	1	y	1.1	0.2	-2.9	1.1	30	124	8.9	114	8%	33%
01/04/2006	R/S	4.8	0	y	0.6	1.0	-0.9	2.4	10	16	1.6	7	54%	0%
02/04/2006	M		0	y			-0.9	4.8	30	4		11	-176%	71%
04/04/2006	R/S	6.3	1	y	0.2	1.0	-0.9	2.7	10	3	0.7	17	-521%	30%
07/04/2006	M		2	y			-0.1	6.5	40	2		6	-290%	2%
08/04/2006	M		0	y			-0.1	6.6	20	27		25	7%	26%
9-11/04/2006	R/S	4.8	0	y	0.7	0.3	-0.2	2.5	20	92	1.9	50	45%	32%

R= rain R/S= rain-on-snow M=snowmelt without precipitaiton
*TSPE = time since previous events in days

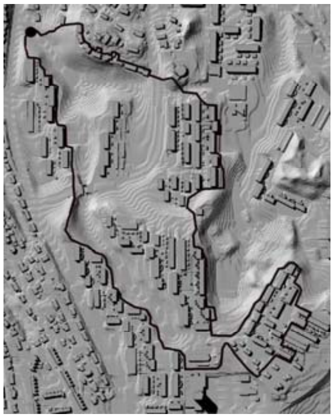

Figure 1. Digital elevation map (DEM) of the watershed with buildings included in the model, and grid cells of 1 by 1 meter. Watershed outlet at location marked with a dot in top left corner.

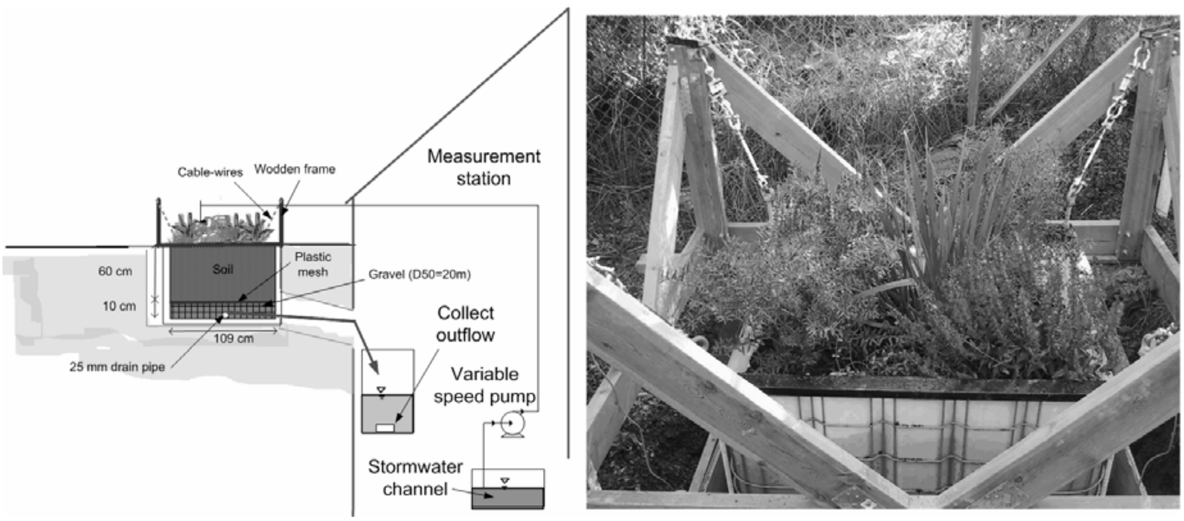

Figure 2. Rain garden setup at Risvollan. This schematic shows rain garden 1, but two identical setups were installed at the station.

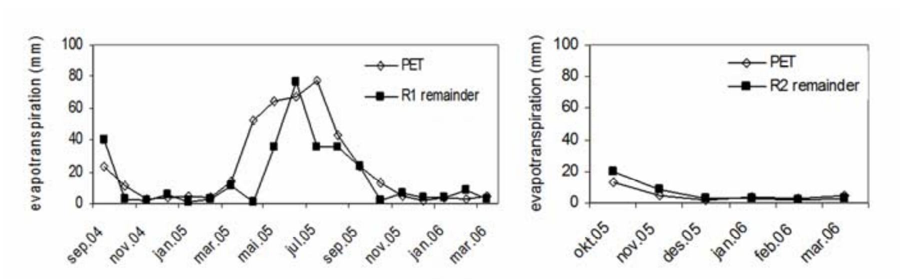

Figure 3. Estimated evapotranspiration and difference between inflow and outflow for rain garden1 (R1) and rain garden 2 (R2)

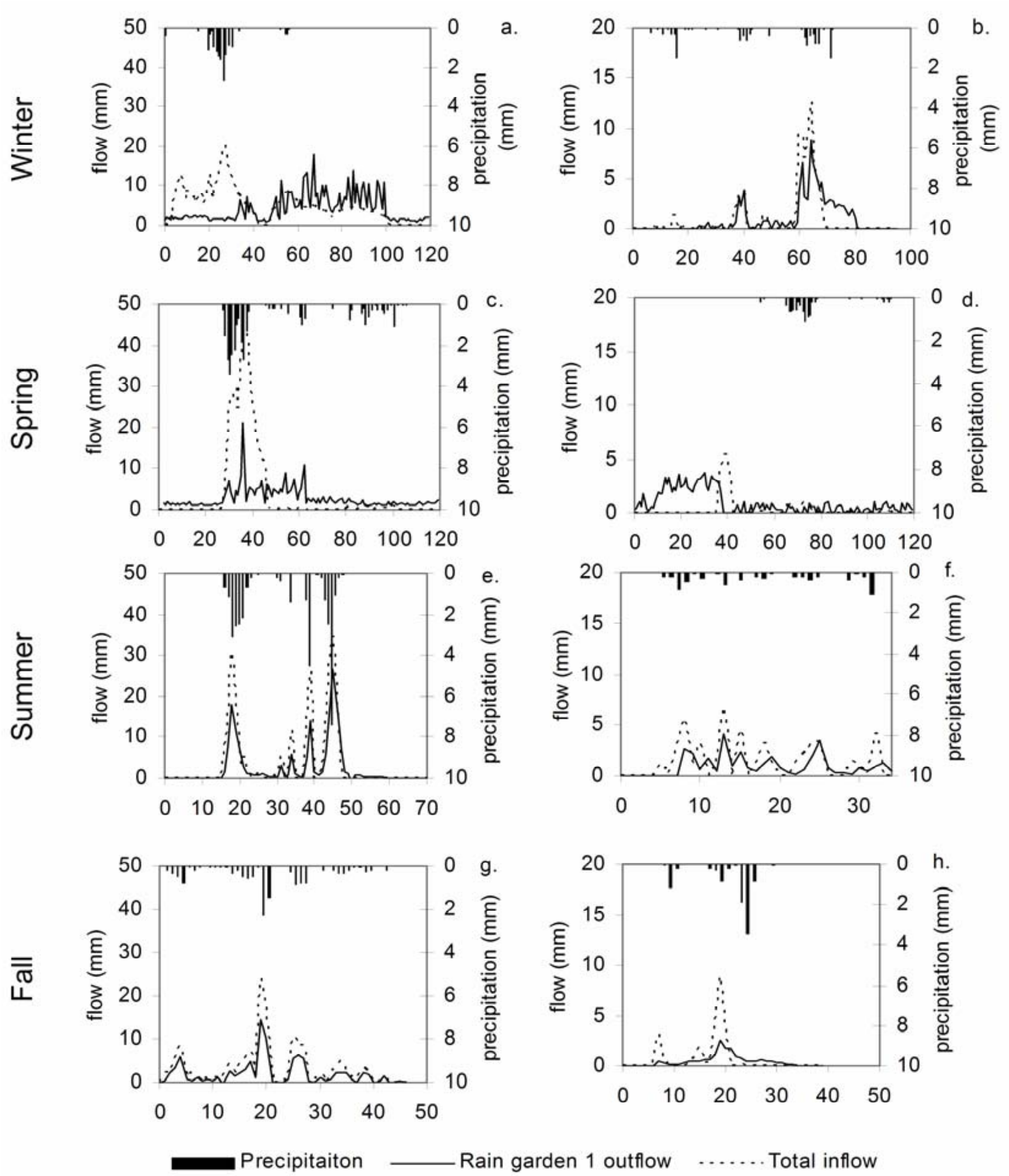

Figure 4. Seasonal inflow and outflow hydrographs and precipitation hyetograph from rain garden 1

Figure 5. Snow cover on rain garden 1 before, during, and after an event in December 2005.

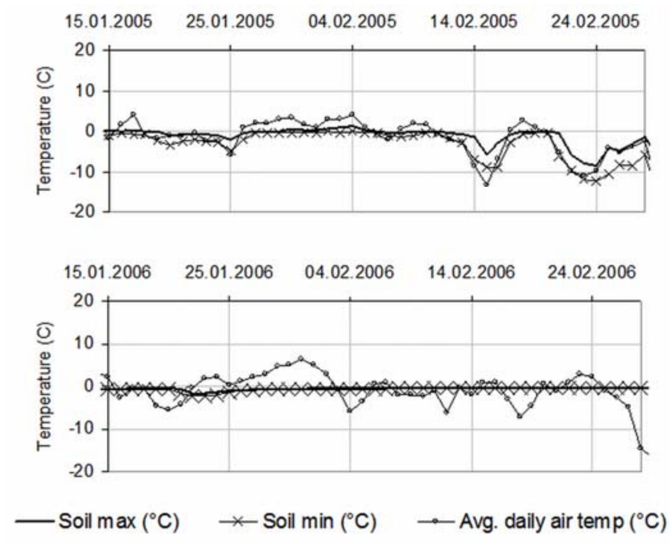

Figure 6. Daily maximum and minimum soil temperature and daily average air temperature over two winter seasons, the first season without insulation and the second season with insulation.

Paper III

Heavy metal removal in a cold climate rain garden

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Heavy metal removal in cold climate bioretention

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Abstract

A bioretention media is a stormwater treatment option designed to reduce peak runoff volumes and improve water quality through soil infiltration and plant mitigation. To investigate the heavy metal removal in a bioretention media in a cold climate setting, a small pilot sized bioretention box was built in Trondheim, Norway.

The system was sized using the Prince Georges County bioretention design method from 1993. Three runoff events, created using historical data, were undertaken in April and then again in August. Both the peak flow reduction and the total volume reduction were significantly lower in April compared to August. Peak flow reduction was 13% in April versus 26% in August and the total volume reduction was 13% in April versus 25% in August. Metal retention was good for both seasons with 90% mass reduction of zinc, 82% mass reduction of lead and 72% mass reduction of copper. Plant uptake of metals was documented between 2-7%; however adsorption and mechanical filtration through the mulch and soil column were the most dominant metal retention processes. The metal retention was independent of the selected hydraulic loading rates (equivalent to 1.4 to 7.5 mm hr^{-1} precipitation) showing that variable inflow rates did not affect the treatment efficiency of the system.

1. Introduction

A wide range of inorganic compounds have been identified in stormwater, Heavy metals (copper (Cu), zinc (Zn), cadmium (Cd), and lead (Pb)) together with PAHs, sediments and de-icing salts are the most common pollutants in road runoff (Makepeace et al., 1995). Vehicle brake emissions and tire wear have been identified as the most important sources of copper and zinc respectively. Building sidings were important sources of copper, zinc, lead, and cadmium, while atmospheric deposition was a source of copper, cadmium, and lead (Davis et al., 2001a). Especially highways have been found to contribute more than 75% of total metal loadings, even though they often occupy a relative small percentage of the total area (Ellis et al., 1987). Toxicity screenings have also found as much as 20% of samples from urban highways severely toxic, compared to only 1% of urban stormwater samples as a whole (Marsalek et al., 1999). Hence controlling and treating highway runoff can involve treating a relative small portion of the flows for a large environmental benefit

Bioretention areas, also called rain gardens, have become a frequently used best management practice (BMP) to retain pollutants from road runoff. Bioretention areas consist of a sandy loam soil medium, a mulch layer, and plants designed for retention and treatment of stormwater through infiltration, adsorption, ion-exchange, volatilization, decomposition, and plant uptake (Clar et al., 2004; USEPA, 2000). A long-term continuous field scale rain garden project in Connecticut, collecting roof runoff in a residential area, monitored the performance of two rain gardens. Metals and nutrients were sampled, but only nutrients were analyzed, as most of the metal samples were below detection limits (Dietz and Clausen, 2005). The rain gardens were found to be performing well with respect to flow reduction, with a 98% infiltration of the inflow and a geometric average weekly inflow divided by weekly outflow of 0.95±0.35 and 0.99±0.53 weeks for the two gardens (Dietz, 2005). Laboratory and event based field testing of bioretention performance with respect to metal retention have shown an above 90% concentration reduction of copper, zinc, and lead. However plant uptake accounted for only approximately 5 % removal by mass. In comparison the mulch layer accounted for 20% of the copper, 10% of the lead, and 34% of the zinc (Davis et al., 2001b). Field test of existing established bioretention areas had a wider performance range with respect to metal removal. The field test reported from 42-70% metal removal for a less developed bioretention facility to over 90% in well developed bioretention facility with good vegetation (Davis et al., 2003).

Metal retention in the soil media can be related to cation-exchange (non-specific adsorption), co-precipitation, and organic complexation (Alloway, 1995). In addition, plant uptake of metals also contributes to the retention of dissolved metals at a slower rate. Plants however, are important in the interaction between the plant roots, the rhizosphere, and the surrounding soil interaction by improving infiltration, soil texture, and preventing clogging (Gregory, 2006). Metal retention is determined by the size fraction of the particles to which the metals are adsorbed. Depending on particle size, metals are retained by trapping the suspended sediment, soil sorption or by plant uptake and biological activity in the soil medium. Copper and zinc in stormwater from highway and residential areas have been found to be associated with particles > 5µm or dissolved (defined by passing through a 10 kilo Daltons (kDa) ultrafilter), while lead has been found to be associated only with particles > 5µm (Tuccillo, 2006). Uptake of metals in plants commonly used for stormwater installations have also been demonstrated, but with higher uptake in aquatic plants where both roots and shoots are in direct contact with the polluted water (Fritioff and Greger, 2003). Aquatic plants (Elodea Canadensis and Potamogeton natans L.) uptake of metals (Cu, Zn, Cd, and Pb) at different temperature and salinity concentrations have shown that metal uptake in the plant tissue increased with increasing temperature and decreasing salinity. This can be a concern for cold climate bioretention facilities during snowmelt, which creates runoff with low temperatures and high salinity concentrations. The concentrations of metals were also higher in plants with lower total biomass (Fritioff et al., 2004), but the effect of temperature on terrestrial plant uptake of metals has not been documented. The zinc, lead and total petroleum hydrocarbons uptake were compared for five emergent species in a constructed wetland, Typha latifolia and Sparganium were found to be the most suited for metal uptake and storage. It was also found that Iris, a very common plant in stormwater treatment systems, was the least favorable of the five species (Ellis et al., 1994).

The objectives of the study presented were to compare the metal retention in a bioretention media for different hydraulic loading rates and during two seasons; late winter / early spring (frozen soil, dormant vegetation and low biological activity) and full summer (maximum vegetation cover and high biological activity). The experiments sought to investigate to what extent the cold climate and dormant above ground biomass affected the systems performance both with respect to hydraulic loading rate and metal retention. A qualitative comparison of the results from the two seasons was performed.

2. Experimental Section

2.1. Design and Construction.

A bioretention box was constructed in the summer of 2004 using design specification from the first Prince George's County bioretention design manual (Prince George's County, 1993). The box was designed to receive runoff from a 20 m^2 impervious surface area utilizing 5% of the drainage area for the bioretention box. This resulted in a bioretention box with surface area of 0.95 m^2. The system consists of a water-tight plastic box (width: 88.2 cm, length 109.1 cm, and height: 90 cm). The box was filled with a sandy soil (60 cm), gravel at the bottom (10 cm) and mulch on the top. The total soil volume in the box was approximately

0.57 m^3. The bioretention box was suspended with four cables attached to the wooden frame. Strain gages (S-shaped) were connected on each cable to weigh the box. At the bottom a 25 mm PVC tube drained the outflow from the box into a storage tank in the basement of the measuring station (Figure 1). Outflow rates were measured with a pressure transducer (0-160 mbar), and water was pumped into the box with a hose pump (Bredel SPX 15) controlled by a frequency inverter.

(Figure 1)

2.2. Soil and Vegetation

The vegetation in the bioretention box was hardy cold resistant plants with minimal maintenance requirements. Native species were used in the project. Based on these criteria Lythrum salicaria, Iris pseuacorus, Vinca minor and Hippophaë rahmnoides were chosen giving a good mixture of small shrubs, evergreens and perennials. Topsoil with a high organic matter (OM) content (8.7%) mixed with sand was used as retention medium, creating a sandy soil with the following composition; 2.6 % clay, 92.7 % sand, and 4.7% slit. The high sand content was chosen to ensure adequate infiltration during the winter months to avoid standing water in the media which would freeze and form an impervious surface preventing further infiltration. The soil cation exchange capacity (CEC) was 45 ($cmol_c$ kg^{-1}). The soil pH was 6.88, and the mulch pH was 5.5, all measured at the start of the study period.

2.3. Hydraulic Loading rate

The hydraulic loading rates were chosen based on historic precipitation records from the Risvollan Urban Hydrologic Research station (RUHR), where the bioretention box was located. Average annual precipitation in the watershed is 900 mm yr^{-1}, out of which 30-40% is snow. Average 24 hour temperature in April is 4 ºC, and 13.2 ºC in August (Thorolfsson et al., 2003). The precipitation events chosen for the study were based on historical data recorded from September 2004. Historic precipitation records were used to simulate a real runoff situation as closely as possible. Different duration and intensities were chosen to investigate the influence of hydraulic loading rate on the performance of the system. The first event, E1, had a duration of 4.2 hours with 151 mm total runoff (max rainfall intensity 2.2 mm hr^{-1} and average 1.3 mm hr^{-1}). The second event, E2, lasted 4.6 hours with 179 mm runoff (max intensity 7.4 mm hr^{-1} and average 3.5 mm hr^{-1}), while the last event, E3, lasted 6.6 hours with 251 mm runoff (max intensity 2 mm hr-1and average 1.4 mm hr^{-1}). The three events were first used for the set of runs on April 12th, 13th and 14th 2005. And then again for the second set on August 30th and 31st and September 1st.

2.4. Pollutant loadings

Various sources of stormwater for the inflow were considered. For the April events, the final choice fell on tunnel wash water from the Hell Tunnel, a 4 km long highway tunnel. The tunnel is cleaned twice a year, and the spring cleaning coincided with the time of the planned study and had the advantage of being representative road runoff. Based on typical pollutant concentrations in runoff from Scandinavian (Petterson et al., 1999; Roseth et al., 2003; Westerlund, 2005) and European roads (Boller, 1997; Crabtree et al., 2005), and typical concentration levels in the tunnel wash water (Roseth et al., 2003), a wash water dilution of 1:6 (mixture A, Table 1) was used for the first event (April, E1). This resulted in metal concentrations that were generally lower than the road runoff values found in the literature. This was probably due to a change in policy which increased water volume during washing, diluting the concentrations. In order to have inflow concentrations in the same range as found in the literature the two following events in April (E2 and E3) had a dilution of 1: 2 (mixture B, Table 1). In all three events the tunnel wash water was diluted with water from the stormwater channel at the RUHR station. During dry periods this channel carries a base flow of approximately 5 L s^{-1} originating from shallow groundwater flow and possible leakage from the water distribution network, typically with very low turbidity, less than 5 mg L^{-1} TSS and pH between 7 and 8.

The ratio between mixture A and B was 1:3 in dilution, but the same 1:3 relation between the metal concentrations was not seen. This could be due to heterogeneous metal concentration in the tunnel wash water that was stored in a 1000 liter tank, but more likely the difference was caused by the water from the stormwater channel used for dilution, as this water was not analyzed separately for TSS and metal concentrations prior to mixing. For the August events no tunnel wash water was available, so stormwater from the stormwater channel at RUHR was mixed with concentrated metal solutions, and sediments from the bottom of the stormwater channel. Sediments from the channel were used to get a representative particle size distribution and composition (Mixture C, Table 1). The metal concentrates were mixed to achieve the same concentrations as in mixture B from the April events. However the resulting concentrations in mixture C were much higher, especially for total copper and lead, while the dissolved fractions were similar for the A and B mixtures. The higher total copper and lead concentrations were due to the metal concentrations in the sediment added from the RUHR stormwater channel. The concentrations of metals in the sediment were not measured prior to making mixture C.

(Table 1)

2.5. Sampling

Samples were taken from the inflow as it entered the bioretention box and from the composite outflow tank, where the outflow from the bioretention box was collected. In addition spot samples were taken from the outflow before it entered the collection tank during peak outflow. For the April events 4, 5, 7 samples were taken for events E1, E2, and

E3 respectively. For the August events 5, 5, 6 samples were taken for the events E1, E2, and E3 respectively. The samples were stored in 1 liter bottles, and kept in a cooler until the end of the event. Prior to sampling the bottles were acid washed and rinsed at least seven times in distilled water. All samples were stored at 4°C until they were analyzed. Total suspended solids (TSS) was analyzed after each event, while metal samples were prepared and kept in sterilized 50 mL centrifugal tubes and analyzed after each season, stored for less than 7 days.

2.6. Analysis methods

Total suspended solids were measured using Whatman GF/C 1.2 µm pore size glass microfiber filters in 3 replicates (Norwegian Standard, 1983). The pH was measured as the samples were collected in the field, with a field pH meter (HI 991300, Hanna Instruments). The metal samples were analyzed using a High Resolution Inductively Coupled Plasma-Mass Spectrometer (HR ICP-MS). The dissolved samples were filtered using a cellulose-nitrate 0.45µm pore size filter. The total metal samples were digested in a microwave oven with 10% HNO_3, and then diluted 16 times (0.1M HNO_3) prior to analysis. The HR ICP-MS detection limits for copper, zinc, and lead are 0.125, 0.2, and 0.01 µg L^{-1} respectively, with a relative standard deviation (rsd) less than 10%. Soil sample were dried and sieved to remove particles larger than 2mm, and then the sample was boiled with aqua regia. Plant samples were dried and crushed, then nitric acid and hydrogen peroxide were added and digested in a microwave. Both plant and soil samples were then analyzed using an Inductively Coupled Plasma-Mass Spectrometer (ICP-AES). The CEC was determined by shaking the soil sample with 1 molar ammonium acetate and then extracted and analyzed using an ICP-AES.

A standard t-test assuming equal variances was used to determine if there was a significant difference between the April and August results. Minitab 14 statistical software was used to perform the analysis (Minitab Inc, 2004). Percentage retention of pollutants in the system was calculated by subtracting outflow from the inflow concentration and dividing the result by the inflow concentration. To compare the pollutant pathways through the bioretention media the volume of outflow compared to the mass of metals in the outflow was compared for the two seasons.

3. Results and discussion

3.1. Flow and hydraulic loading

The lag time between start of inflow to the bioretention box and the first outflow was seen at outlet was approximately 50 min, except for the first event (E1) in April, which had a lag time of 25 min (Figure 2). The shorter lag time for, E1 in April compared to the other events can be explained by the presence of frozen soil, -.1°C measured 20 cm below the surface, prior to the start of inflow, possibly causing preferential flow through the system. The inflow stormwater had a temperature close to the air temperature, 12°C, which heated the soil column. Between events the soil column was cooled by the surrounding soil masses, causing large fluctuations in soil temperature over the three days of the events in April.

(Figure 2)

The average peak flow reduction over the three events was 13% in April versus 26 % in August. The total volume reductions were also higher in August, 25% than April, 13%. The antecedent moisture conditions in the bioretention box prior to the first events in April and August were not measured, but the initial weight measured by the strain gages was 1086 kg in April and 1095 kg in August. The above ground biomass in August would add a few kilograms compared to April, but the antecedent moisture condition was most likely slightly wetter prior to the first event in August compared to April. However, after the first event the box would be saturated and then left to drain for 24 hours before the next event the following day, producing similar starting conditions for the second and third events, E2 and E3 for both April and August. The higher peak flow reduction in August can be attributed to a more homogenous distributed soil column with less canalization, often formed in partially frozen soils, which would increase the soil infiltration time in August, The increased volume reduction in August is most likely due to increase in the plant water consumption and evaporation rates. The reduced peak flow and volume reduction in the early spring events indicate a reduced hydraulic function during the cold months. This can be compensated with a lower hydraulic loading rate by increasing the bioretention to drainage area ratio.

3.2. Metal Concentrations

The soil medium is assumed to be the main medium for attenuation of metals in a bioretention box (USEPA, 2000). Laboratory adsorption tests of metals onto sandy loam soils have shown that copper and lead have highest adsorption rates for pH 5-8, while zinc has best adsorption from pH 6-8 (Davis et al., 2001b). This indicates that a pH around 6 should be ideal for the metals of concern. In April the inflow pH varied from 6.8 to 7.8 and the outflow from 7.1-7.3. In August the inflow pH was more stable in the range 8.1-8.2, and outflow pH again 7.1-7.3.

The inflow concentrations between the events varied a great deal for the six events, but the same variation was not seen in the outflow from the bioretention box (Figure 3). Zinc inflow concentrations were between 550 – 660 µg L^{-1} for all the events except the first event in April, with a concentration of 120 µg L^{-1}. The zinc outflow concentrations did not show any significant difference between the outflow concentration for the mixture A and B events in April (Figure 3). However, comparing the average outflow concentrations showed a significantly higher outflow concentration in August than April, while the percentage reduction was relatively constant between 92-95% (Table 2). The copper reduction in the system was significantly lower in April versus August, with 40% and 67% decrease in outflow concentration respectively (Table 2). This could be due to the five times higher inflow concentration in August compared to April, or possible change in plant uptake or organic matter complexation of copper in the soil and mulch as a function of soil and air temperature. The inflow and outflow concentrations of lead followed the same pattern as for zinc, with a fairly constant percentage reduction, but significantly higher outflow concentrations in August, possible due to change in plant uptake or soil retention processes, however it can not be ruled out that the higher inflow concentration in August also influenced the outflow concentration.

(Table 2)

The changing inflow rates following the inflow hydrograph appeared to have no effect on the outflow concentrations. The August outflow copper concentrations all had an initial spike in concentration (Figure 3), but this was not found to correspond with a peak in outflow rates (Figure 2). This agrees with the findings by Davis et al. (2001b) investigating hydraulic loading rates using outflow ports at different depths through a bioretention box (total media depth 61 cm). It was concluded that the deeper outflow was independent of hydraulic loading rates (ranging from 2-8 cm hr^{-1}), while some dependency was seen in the upper outflow ports. In this study a real historical hydrograph was chosen to reproduce actual rainfall events as close as possible. The results demonstrate that the bioretention box can retain constant high levels of metals independent of rainfall intensities which indicate that it will perform over a wide range of natural precipitation events.

(Figure 3)

The overall reduction of lead and copper levels were slightly lower, while zinc reductions were comparable to than that previously reported by Davis (2001b). Compared to a previously reported field study involving two different sites (Davis et al., 2003) the retention of zinc was comparable to the best performing site, while lead and copper removal rates were in-between the reported values.

To investigate if there was a change in metal solubility through the system, dissolved metal fractions were measured for all the samples. For the inflow mixed from the tunnel wash water used in the April events, the dissolved metal fractions in the inflow were generally lower than the August inflow which was mixed from stormwater and added metals (Figure 4). The average dissolved zinc retention in the system was 70% in concentration and 79% in mass. The retention varied little for all the events. The dissolved lead fraction appeard to increase through the column in April (-88%) but decreases through the column in August (19%), however the dissolved fraction was small compared to the total lead for all the events. The dissolved lead inflow and outflow values for April were 0.05 and 0.026 μg L^{-1} (±0.1 μg L^{-1}) respectively. The values from August range from 1.4-1.1 μg L^{-1} (±0.3 μg L^{-1}). The dissolved copper concentrations increased for all the events both in April and August, with less than 10 μg L^{-1} dissolved copper in the inflow for all the events and as high as 44 μg L^{-1} in the outflow. While the April events showed only a minor increase from inflow to outflow that August events had a large increase.

These results could suggest leaching from the soil, in order to investigate this further a laboratory scale soil extraction test was conducted using 600 ml soil in a glass jar with a tap at the bottom and a small pump adding deionized water to the column at 120 mL hr^{-1} for 6 hours. The soil medium was divided into three layers; top (0-20 cm), middle (20-40 cm) and bottom (40-60 cm) and each layer was leached tested separately, measuring only what was leached for that layer. The extraction showed some leaching of all the metals. There was evidence of leached lead in the top soil layer and low leaching values from the two lower layers. The movement of leached lead downward in the soil column could mean higher leaching of lead ad the concentration of lead in the bottom layer increases. The leached copper (avg. 19.9 µg L^{-1} over all three layers) was the same concentration as observed in the August outflow (avg. 19.49 µg L^{-1}). No leaching of zinc was observed in the bioretention box, however in the laboratory extraction some leaching (avg. 22.99 µg L^{-1} over all three layers) occurred, and some leaching of lead (avg. 3,4 µg L^{-1} over all three layers) was measured.

(Figure 4)

A study investigating the extractability and mobility of zinc and copper in sandy soils reported a sharp change in mobility above 100 mg kg^{-1} concentrations for copper and 60 mg kg^{-1} for zinc. The initial soil metal concentrations were more important than pH alone. With a high soil concentration, the leaching became sensitive to changes in pH, and increased exponentially for pH values less than 7 (Zhang et al., 2006). The pH in the outflow from the bioretention box was stable at 7.1-7.3 for all events. The soil metal concentrations in the bioretention box were also well below 100 mg kg^{-1}.. A study investigating the solubility of metals in contaminated soils found that the soluble zinc and lead contents were more correlated with pH and total metal content in the soil than soluble copper, and did not tend to complex strongly with soluble OM like copper. Furthermore a stronger correlation was found between free metal copper Cu^{2+} and OM than with total soluble copper and OM, this suggests that it is the free metal activity that is directly controlled by sorption (McBride, 1997). The soluble copper is influenced by soluble OM, inorganic ligand concentrations and reactivity and dispersed colloidal particles too small to be separated by filtration. This makes it complex to identify the individual factors responsible for the total soluble copper content. However this suggests that the OM and especially the dissolved OM in the soil media is responsible for the copper leaching and is more important than in which form the copper enters the soil media (particulate or dissolved) (McBride, 1997). Another study investigating the effect of dissolved organic carbon on leaching of Zn and Cu from swine manure compost (Hsu and Lo, 2001), found that the leachability of the metals were independent of the total metal content, but rather a function of dissolution of organic carbon as a result of pH changes. An increase in dissolved organic carbon substantially modified the copper solubility, while having only negligible effect on the dissolved zinc content. The dissolution of OM and subsequent formation of organometallic complexes indicated that copper is primarily bound to OM, while the zinc sorption to OM is low. The organic matter content in the bioretention box was 8.7 and in addition the top mulch layer consisted of shredded bark decaying over time. Based on the literature findings the mulch and also the soil OM is most likely responsible for the copper leaching from the media. A thorough evaluation of the sampling procedures, materials in the bioretention filter, and laboratory analysis methods were conducted and no indication of sample contamination or copper source in the materials could be identified.

3.3. Metal Mass Balance

To investigate the flow, sinks, and transfer of metals in the system, a mass balance based on the measured concentration was performed. The total inflow of zinc into the bioretention box over all the events was 597 mg, and only 63 mg left the bioretention box in the outflow. This is a 90% mass retention of zinc in the system. The retention for lead was 82% and 72% for copper. Comparing the concentrations, the dissolved copper leaving the bioretention box had increased, however looking at the mass balance the April events show a slight increase of 1 mg, and a doubling from 6 to 12 mg in August. The increase in dissolved copper concentration for the August events was almost 200% (from 6.7 to 18.4 µg L-1) while the actual mass increase was a 100% from 6 mg to 12 mg (Table 3). The reduction in water volume leaving the bioretention box increased the actual concentration of dissolved copper, which was most likely just transported through the system, and some copper was added to the soluble phase as well. The mass balance comparison between April and August events indicates no difference in mass removal of zinc and lead between the seasons, while copper had a significantly higher mass removal in August (75%) versus April (69%) (Table 3).

(table 3)

Composite soil and plant tissue samples were collected before the runoff experiments (natural) and after both sets of runs in August. An intermediate mulch and top soil sample was also taken after the April events. A clear accumulation of metals in the top soil and mulch layers were seen with a higher accumulation in the mulch (Table 4). This corresponds to results from previously reported laboratory studies by (Davis et al., 2001b), where the mulch was found to have absorbed most of the retained metals. The plant tissue samples showed relative high accumulation of zinc and copper in the Vinca minor, while the Hippophaë rhamnoides showed an increase in the zinc and copper concentrations in the twigs and leaves, and a decrease in the roots, which could indicate a transport of zinc and copper from the roots into the twigs and leaves, but no further uptake of zinc and copper in the plant from the soil water interface. The lead concentrations showed some accumulation in the Vinca minor, while no detectable difference could be found in the Hippophaë rhamnoides.

(table 4)

A study from 2003 investigating metal accumulation in submerged, free floating, emergent, and terrestrial plants found that zinc and cadmium had a concentration factor (concentration in plants related to concentration in surrounding soil) above 1 in terrestrial and emergent plants (Fritioff and Greger, 2003). The plants used in the study were different than the plants used in the bioretention box, however the Vinca minor plant tissue showed a 1.14 concentration factor for zinc compared to the surrounding top soil (Table 4). However the Vinca minor is relative sensitive to standing water and prone to drowning under prolonged wetting. A well drained bioretention media with minimum standing water would be required for this plant, however with suitable conditions it has shown promising metal accumulation results for use in cold climate bioretention.

To identify the major metal sinks in the system an estimation of plant biomass was performed. This was done for the combined plant biomass in the bioretention box on a dry weight basis. The combined plant metal uptake was estimated to 2% lead, 3% copper and 7% zinc. This is in the same range as was reported by (Davis et al., 2001b), though with different plant species. The mulch retained 50% of the copper, 20% of the zinc, and 17% of the lead and the remaining 43% of copper, 77% of zinc and 82% of lead was retained in the soil column. The mechanisms responsible for the removal in the mulch and soil can be expected to be a combination of mechanical filtration and adsorption processes. Metal particles in road runoff have been found associated with the smallest particles sizes in urban runoff. Westerlund et al. (2006) found the strongest correlation between particles 4-6 μm and Cu, Zn, and Pb. Urban highway runoff were found to have a particles size distribution from 0 to 9500 μm but the majority of the Zn, Cu, and Pb concentrations were found bound to particles less than 100 μm (Sansalone and Buchberger, 1997). Based on these findings some of the removed metals can be assume to be too small to settle out by mechanical filtration, leaving specific and non specific sorption as the most dominant processes. The mulch layer was 5 cm thick compared to the 55cm thick soil column, making the mulch layer the most efficient metal sink in the system; in addition the mulch serves as weed control and aesthetic value in combination with the plants. The mulch layer is also the easiest part of the system to regularly exchange, as it only covers the top few centimeters of the system. The plants also had other important functions in the system, making them an essentially part despite the minor metal uptake. First the roots help improve root zone development in the soil which maintains infiltration. Secondly they are a key part of nutrient removal in bioretention systems, and they have a high aesthetical value for use in stormwater treatment systems in urban areas. In cold climates with snowmelt leaving the topsoil and mulch layer covered with a thick layer of gray sediments and pollutants they also serves as a regenerator of the bioretention areas in the spring, turning the gray layer of muddy sediments into a green vegetation plot. The metal accumulation in more local plant species should be investigated to find the most area specific suitable bioretention box plants.

Estimating the soil metal sorption capacity based on the average annual loadings suggest that soil metal accumulation will not be the limiting factor in the system. It will take 10-20 years before the soil would need to be exchanged, while the mulch would need more frequent replacement about every 4-5 years. The top mulch layer made of bark will gradually decompose and need to be refilled as a regular maintenance activity. Harvesting the pant biomass will prolong the lifespan and remove metals from the system. Several studies have identified vegetation that can hyperaccumulating metals (Hammer et al., 2003; Hasan et al., 2007; Yanqun et al., 2004). The use of hyperaccumulating pants to increase metal accumulation in plant biomass could make it a significant sink that can be easily harvested to regenerate the system.

4. Conclusions

The variable hydraulic loading rates from the three different inflow hydrographs did not have an effect on the metal retention in the bioretention box within the tested hydraulic loading rates. The peak flow and total volume reduction was halved in April compared to August due to partially frozen soil and less above ground biomass in April. The mass removal of zinc was constant at 90% for both seasons. Mass removal of lead was slightly higher in August compared to April (83 versus 89%). Copper was the only metal showing a significantly lower removal in April (60%) versus 75% in August. The mulch layer and the soil were identified as the major sinks for the removed metals, while the plants played a minor role for metal removal (2-7%), but an important role in root zone development and adding aesthetical value to the system with above ground biomass.

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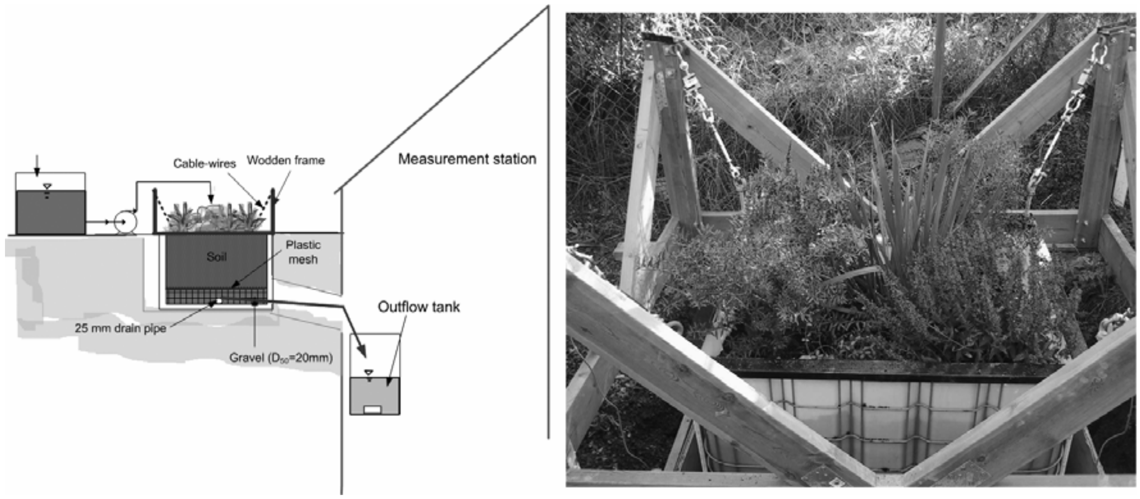

Figure 1. Bioretention box setup (left) and a picture of the bioretention box in September 2004 (right)

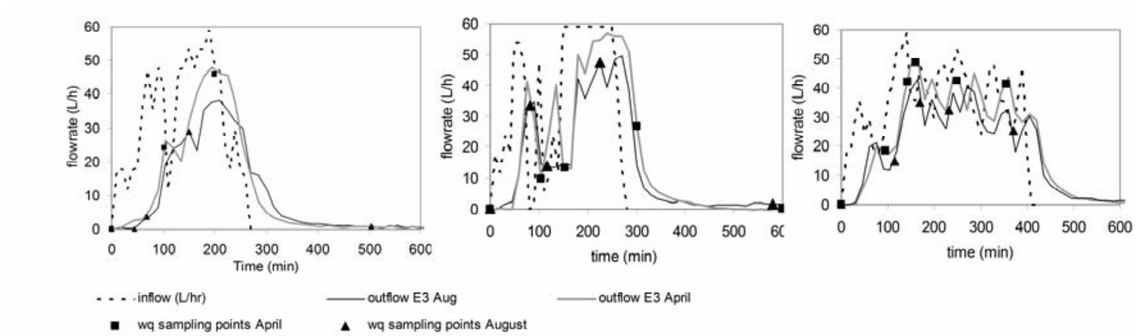

Figure 2. Inflow and outflow hydrograph from the system with sampling times indicated on the graphs.

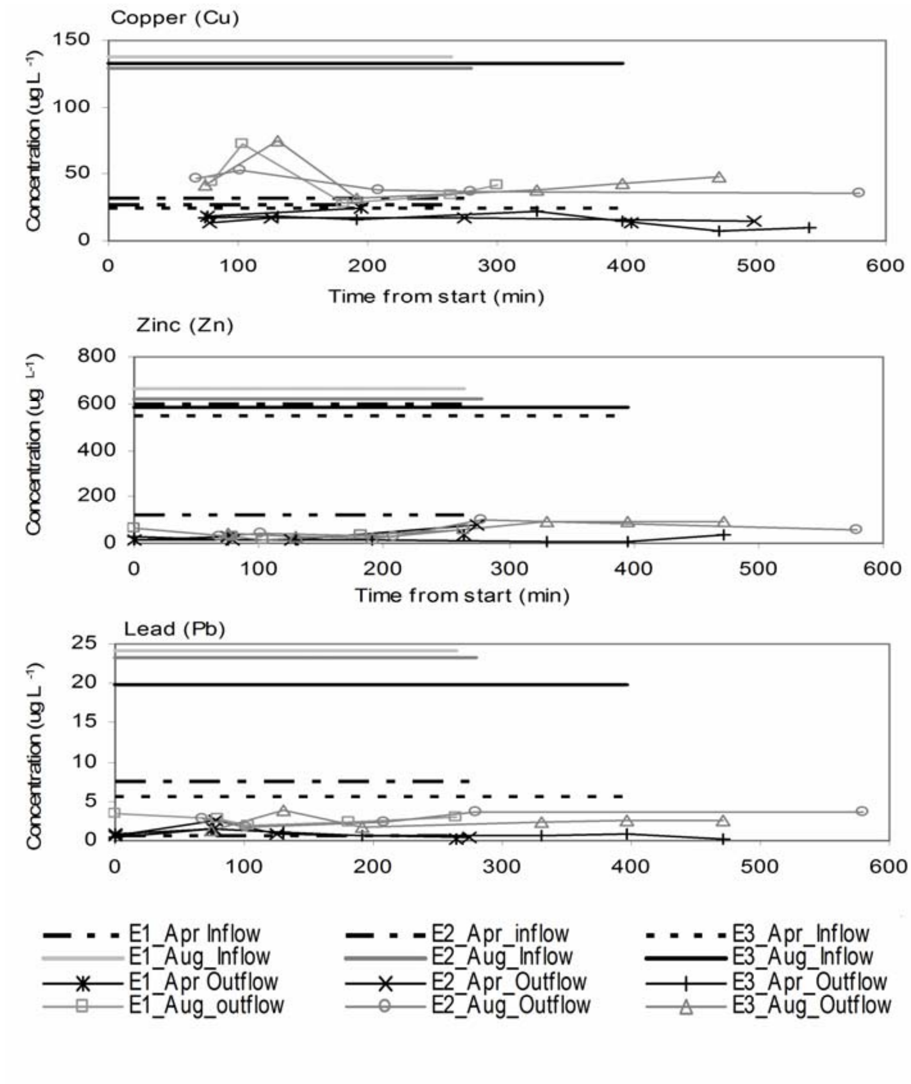

Figure 3 Time series metal concentrations in inflow and outflow.

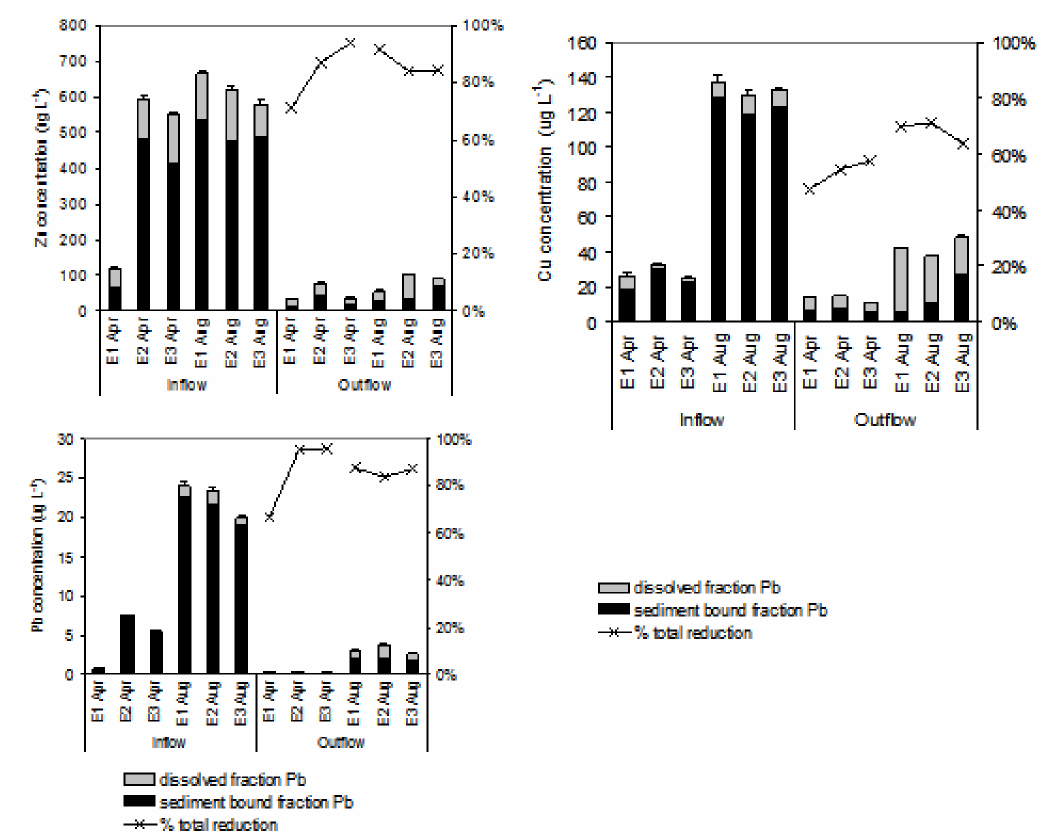

Figure 4. Metal concentrations in the inflow and outflow and percentage retention in the system.

Table 1. Inflow concentrations to the bioretention box for the events. Mixture A and B were based on tunnel wash water, while mixture C was made from water from the stormwater channel mixed with bottom sediments and added metals.

Description[1]	Copper[2] (ug L^{-1})		Zinc[2] (ug L^{-1})		Lead[2] (ug L^{-1})		TSS[2] (mg L^{-1})	pH
	Total	Dissolved	Total	Dissolved	Total	Dissolved		
mixture A	27	8.4	120	55	0.7	0.03	26	8.2
mixture B	29	1.8	574	125	6.5	0.02	165	8.0
mixture C	133	9.9	620	122	22.4	1.4	114	7.3

1) mixture A = tunnel wash water diluted 1:6, mixture B= tunnel wash water diluted 1:2, mixture C = stormwater with added TSS and metals

2) The concentrations are the average inflow values:

Copper Sulphate (CuSO4x5H2O)

Zinc acetate (Zn(O2CCH3)2,2H2O)

Lead II ethanoate (Pb(O2CCH3)2,H2O)

Table 2. Average total metal inflow and outflow concentrations.

		Inflow			Outflow		
		Copper	Zinc	Lead	Copper	Zinc	Lead
April	Mean Concentration ($\mu g\ L^{-1}$)	26[a]	412 [a]	4.4 [a]	15.2[a]	22[a]	0.8[a]
	Standard deviation ($\mu g\ L^{-1}$)	7.8	233	3.0	5.9	19	0.7
	Reduction (%)				40	95	82
August	Mean Concentration ($\mu g\ L^{-1}$)	126[b]	584 [a]	21.1[b]	41.7[b]	49[b]	2.5[b]
	Standard deviation ($\mu g\ L^{-1}$)	32	149	5.6	16.6	31.0	1.0
	Reduction (%)				67	92	88
Overall	Mean Concentration ($\mu g\ L^{-1}$)	83	521	13.9	30.2	38	1.8
	Standard deviation ($\mu g\ L^{-1}$)	56	195	9.4	17.9	29	1.2
	Reduction (%)				63	93	87

Means followed by different letters for the same variable are significantly different at CI 95% using a paired t-test analysis

Table 3. Mass balance of metals entering and leaving the bioretention box

		Inflow		**Outflow**	
		Total mass in (mg)	Dissolved mass in (mg)	Total mass out (mg)	Dissolved mass out (mg)
April	Zinc	253	60	25	12
	Copper	15	2	6	3
	Lead	3	<0.0	0.5	<0.0
August	Zinc	344	66	38	17
	Copper	75	6	19	12
	Lead	12	0.7	1.3	0.5

Table 4. Soil and plant metal concentrations before and after the events in April and August

Sample	**Zinc** (mg kg^{-1})	**Copper** (mg kg^{-1})	**Lead** (mg kg^{-1})
Soil:			
Natural mulch	113	5.4	<4
Natural top 10cm soil	22.2	20	<4
Mulch and top 10cm soil after April events	48	33	<4
Mulch after August events	157	19	<4
Top 10cm soil after August events	105	25	5.5
Plants			
Natural:			
Hippophaë rhamnoides L roots	45.5	14.8	0.3
Hippophaë rhamnoides L twigs and leaves	26	4.7	0.2
Vinca minor leaves	41	3.3	0.2
Vinca minor roots	32.8	16.3	0.4
After August events			
Hippophaë rhamnoides L roots	35	9	0.3
Hippophaë rhamnoides L twigs and leaves	31	7	0.2
Vinca minor leaves	86	25	0.7
Vinca minor roots	120	21	1.7

Paper IV

Snowmelt pollutant retention in bioretention areas

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Snowmelt pollutant removal in bioretention areas

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Abstract

Snow accumulating in urban areas and alongside roads can accumulate high pollutant loads and the subsequent snowmelt can produce very high pollutant loads to receiving waters. This paper examines the treatment of roadside snowmelt in bioretention with respect to pollutant removal, pollutant pathways, and major sinks. Bioretention was used to treat snowmelt from three urban roads, residential, medium, and high density traffic roads in Trondheim, Norway. Metal retention in the bioretention boxes had a mass reduction in zinc, copper, and lead in the range of 89-99%, and a decrease in outflow concentrations in the range 81-99%. The top mulch layer was the largest sink for the retained metals with up to 74% of the zinc retained in this mulch layer. The plant metal uptakes were only 2-8% of the total metal retention, however the plants still play an important role with respect to root zone development and regeneration. Dissolved pollutants in snowmelt tend to leave with the first portion of meltwater, creating an enrichment ratio with respect to the average pollutant concentrations in the snow. The effect of this enrichment ratio was examined through the bioretention system, and found to be less predominant than typically reported for untreated snowmelt. The enrichment factors were in the range of 0.65 – 1.51 for the studied metals.

Introduction

Bioretention facilities, also called rain gardens provide stormwater retention and treatment, and add vegetation to the urban environment. They can also add recreational value by making nature and natural vegetation more accessible to the urban population. The active processes in bioretention facilities include infiltration, adsorption, decomposition, volatilization, organic complexation, and ion-exchange (Clar, et al., 2004). Metal retention in the soil media can be related to cation-exchange (non-specific adsorption), co-precipitation, and organic complexation (Alloway, 1995). In addition, plant uptake of metals also contributes to the retention of dissolved metals at a slower rate. Plants however, are important in the interaction between the plant roots, the rhizosphere, and the surrounding soil interaction by improving infiltration, soil texture, and preventing clogging (Gregory, 2006). Laboratory and event based field testing of bioretention performance with respect to metal retention have shown an above 90% removal of copper, zinc, and lead. However plant uptake accounted for only approximately 5 % removal by mass. In comparison the mulch layer accounted for 20% of the copper, 10% of the lead, and 34% of the zinc (Davis, *et al.*, 2001). Field tests of existing established bioretention areas had a wider performance range with respect to metal removal. The field test reported from 42-70% for a less developed bioretention facility to over 90% in well developed bioretention facility with good vegetation (Davis, et al., 2003).

The use of in situ infiltration practices has been recommended as treatment for urban snowmelt with high concentrations of soluble pollutants (Oberts, 2003). Infiltration uses the ion-exchange capacity in the soil, or engineered infiltration media, to adsorb soluble pollutants (Oberts, 2003). For successful infiltration of melt water adequate infiltration rates are very important, 1.3 cm/hr as a minimum rate and clay contents less than 30% has been reported in the literature (Caraco and Claytor, 1997). The pre-freezing soil water content is also important, as high soil water content at the time of freezing can lead to the soil becoming an impervious layer with close to zero infiltration, also referred to as concrete frost. Granular or porous frost however will maintain and can even exceed the infiltration capacity of the unfrozen soil (Granger, et al., 1984, Kane, 1980). The use of biological elements in treatment systems for meltwater, such as the use of vegetated swales with plant roots to enhance infiltration, and vegetated cover to promote sheet flow has been reported as recommended modifications to cold climate best management practices (BMPs) (Oberts, 2003, Caraco and Claytor, 1997). These findings suggest that bioretention offers a great possibility for use both as a snow deposit and for retention of pollutants from the melt water. The mixed vegetation enhances infiltration and plant roots have been shown to be active even during the cold season for potential pollutant adsorption. The mulch layer prevents clogging and retains pollutants from the snowmelt.

The main pollutants in road runoff include copper, zinc, lead, cadmium, sediments, PAHs, and de-icing salts (Makepeace, et al., 1995). The sources are the same for the rain and snow, however the resident time in the snow can be up to several months long, compared to a resident time of hours for rainfall runoff. The sources of metal in road runoff can be divided into pavement wear (40-50% of particulate mass), tire wear (20-30% of particulate mass) and the remaining 15% comes from engine and brake parts and 3% from urban atmospheric deposition not related to road activities (Kobriger and Geinopoles, 1984). Pollutant loads and pathways in snow and snowmelt pollutant transport differ from rainfall runoff pollutant loads and pathways. Pollutants in the snowpack can be transported hydraulically during snowmelt, and also by snow drift and removal, which again are affected by other climatic and meteorological factors (Oberts, 1990). Snow can store pollutants over long periods, and in climates with a long sustained cold period in the winter the snowpack can be several months old by the time it melts. Snow removal and road maintenance with sand and de-icing salts, vehicle and road wear and tear all contribute to accumulation of pollutants in the snowpack (Malmqvist, 1978). A study from northern Sweden comparing melt water runoff and rain runoff concluded that the concentration of sediments were significantly higher in the melt period, and a stronger correlation between total suspended solids (TSS), particle sizes and metal (Cd, Cu, Ni, Pb, and ZN) concentrations (Westerlund and Viklander, 2006). Snow handling and management will also greatly affect snow quality and pollutant pathways, and with snow, unlike rain, this pathway can be selected more easily based on management strategy (Reinosdotter and Viklander, 2005).

Studies on snowmelt and pollutant pathways in snowmelt have identified an enrichment factor of dissolved pollutants in the early stages of snowmelt. In one study from Japan, 50-90% of the dissolved pollutants were transported with the first fraction of meltwater while the tail end contained a larger concentration of particulate matter (Ecker, et al., 1990). Enrichment factors measured in the first 20% of runoff volume at snow deposits in Luelå Sweden, were in the range of 1.2 to 2.0 for copper, zinc, and lead (Viklander and Malmqvist, 1993). The reason for this can be found in the metamorphoses of snow, driven by thermodynamic instabilities and water vapor transport along gradients in the snowpack. This causes a concentration of dissolved phase in the liquid-like layer on the surface of the ice crystal, causing it to be washed with the first melt water (Daub, et al., 1994). The partitioning coefficient of metals in snow controlling the amount of metal in dissolved and particulate bound phase are affected by the temperature and salinity content of the snowpack. Increasing salinity or decreasing temperature will increase the concentration of dissolved, bioavailable metals (Warren and Zimmerman, 1994). This shift from particulate to dissolved phase could also affect the treatment efficiencies of best management practices (BMP), such as ponds where sedimentation of particulates is one of the prime functions (Novotny, et al., 1999).

The objective of this article is to evaluate the metal retention, the fate of chloride, and retention of organic pollutants in a bioretention facility during snowmelt. Snow from three streets; low, medium, and high traffic density, was used to investigate to what extent the pollutant composition and concentrations in the snow affected the retention in the bioretention. The metal retention and pollutant pathway and enrichment factors through the biofilter for the three different sites were compared to the pathways and enrichment factors of no treatment snowmelt. The chloride concentrations in the snow and in the outflow from the bioretention boxes were also compared to investigate the fate the most commonly used de-icing agent, sodium chloride, through the system.

Experimental Section

The setup of the study involved three parts, the design and construction of the bioretention boxes, the selection and characterization of the snow sampling sites, and the laboratory analysis of the water, soil, and plant samples.

Bioretention boxes and experimental setup

Two pilot size bioretention boxes were built in September 2004 and October 2005 at the Risvollan Urban Hydrological Research Station in Trondheim, Norway. The biofilter consisted of sandy loam soil, gravel at the bottom with an underdrain, and a 5cm thick mulch layer on top. The bioretention boxes were built to have the same physical composition, yet minor differences in the two medias existed (Table 1). The cation exchange capacity (CEC) was much higher in bioretention 1 than 2. One possible reason for this could be the time of measurement, CEC was measured in the soil prior to the snowmelt study, at a time which the bioretention 1 had been in operation 12 months longer than bioretention 2. The plants used in the boxes included perennial flowers; yellow iris (Iris pseuacorus) and purple-loosestrife (Lythrum salicaria), a shrub sea-buckthorn (Hippophäe rahmnoides), and the ground covering plant Lesser periwinkle (Vinca Minor). The plant selection was based on commonly used plants for stormwater treatment (Lythrum salicaria and Iris pseaucorus), and plants that are native to Trondheim (Hippophäe rahmnoides).

Table 1. Soil physical and chemical composition for the two rain gardens at time of construction

	Bioretention 1	Bioretention 2
Clay *(%)*	2.6	2.9
Sand *(%)*	92.7	88.3
Silt *(%)*	4.7	8.8
Organic matter *(%)*	8.7	10.7
Bulk density *(g/cm3)*	0.79	0.84
Solid particle density *(g/cm3)*	1.05	1.18
pH soil	6.88	6.79
pH mulch	5.5	5.6
CEC ($cmol_c$/kg)*	55.2	20.0

* The CEC was measured at the time of construction for bioretention 2, when bioretention 1 had been in operation for 12 months already, which can explain the large difference in CEC measured in the two systems.

Snow collection sites

Snow was collected at three locations in February and March 2006. The three collection sites were chosen based on traffic density. The low density site with a traffic density of 1550 vehicles/day was a typical suburban residential street with single family homes and townhouses (Site A). The medium density (Site B), with 5000 vehicles/day was an urban collector road, and a high density road (Site C), with 47000 vehicles/day was a main highway (Figure 1). The traffic density figures were obtained from the Norwegian Directorate of Public Roads.

Site A: Harald Bothnersvei Site B: Utleirveien Site C: Elgesetergata

Figure 1. The three study sites on the second collection day, 27th of March 2006, a few days after the last snowfall.

The average annual precipitation in Trondheim is 900 mm/yr, out of which 30-40% is snow. In the main snowmelt season, March and April, the average 24 hour temperature is 0ºC and 4ºC, respectively (Thorolfsson, et al., 2003).

Sampling

Snow was collected on the 23rd of February and 27th of March 2006. Each time approximately 75 liters of snow was collected in 3 white plastic bags for each site and stored in freezers at -18 ºC until the snowmelt study started in mid April. During the snowmelt study a tarp was constructed over the two bioretnetion boxes in order to prevent precipitation contamination of the tests. The snow from Site A, the residential street, was applied to the bioretention boxers first, on April 14th 2006, as this snow was expected to have the lowest pollutant concentrations. The snow from the two sampling days was mixed homogenously and applied in equal volumes to the two bioretention boxes, i.e. 75 liters each. Subsequently, Site B, the medium density site, was applied on April 21st, after all the melt water from Site A was drained from the filters and allowing for a 24 hours rest period for the media. Finally, Site C was applied to the filters on April 27th 2006, again 24 hours after the last snowmelt from Site B left the boxes.

The flow from the underdrains, the soil temperatures, and soil moisture content were measured continuously and logged on a Campbell Scientific data logger (CR10X). In addition meteorological data, air temperature, wind speed, solar radiation, and relative humidity were available on a 2 minute resolution from the Risvollan Urban Hydrologic Research Station, at the same location. Samples were taken based on volume drained from the filters, and the first three samples were all sampled from within the first 15 liters drained from the tank. Less frequent samples were taken, at approximately 10 liter intervals for the next three and then 15-20 liter intervals for the last two samples. A total of eight samples were taken from each bioretention box for each site. The time of sampling was the same for both the bioretention boxes, however there were minor variations in the flowrate through them. To account for this exact time and volume were noted for each sample. These volume based outflow samples are referred to as S1 through S8 for each of the tree sites.

Initial soil, mulch and plant samples (roots and shoots) were collected prior to installation of the bioretention areas. The soil and the mulch was sampled using a composite sample of 15 grab samples, and the plants were sampled by making a composite sample of all same species plants. Prior to the snowmelt study, after the bioretention areas had been in operation for 19 and 6 months respectively the mulch, top soil layer, and above ground plant material were sampled again using composite grab samples. At this point only the top soil layer could be sampled due to frozen soil and to avoid damaging the soil column prior to the experiments. The plants roots could not be sampled due to the frozen ground. Three weeks after the snowmelt experiments, complete soil column samples with 10cm increments, plant roots and shoots, and the mulch layer were sampled again.

Analysis methods

The pH was measured as the samples were collected in the field, with a field pH meter (HI 991300, Hanna Instruments). Total suspended solids was measured using Whatman GF/C 1.2 µm pore size glass microfibre filters in 3 replicates (NS4733E, 1983). The metal samples were analyzed using a High Resolution Inductively Coupled Plasma-Mass Spectrometer (HR ICP-MS). The samples were stored in sterile 50ml centrifugal tubes and kept in the same tube through the whole analysis procedure. The dissolved samples were filtered using a cellulose-nitrate 0.45µm pore size filter. The total metal samples were digested in a microwave oven with 10% HNO3, and then diluted 16 times (0.1M HNO3) prior to analysis. The HR ICP-MS detection limits for copper, zinc, and lead are 0.125, 0.2, and 0.01 µg/L respectively, with a relative standard deviation (rsd) of less than 10%. The particle size classification was determined using a particle size analyzer (Beckman Coulter LS 230). The COD concentrations were measured with Dr. Lange cuvettes for COD (LCK 314, 15-150mg/L), and standard deviation of 0.6mg/L and 95% confidence Interval (C.I.) of ±1.5 mg/L.

Soil sample were dried and sieved to remove particles larger than 2mm, then the sample was boiled with aqua regia. Plant samples were dried and crushed, then nitric acid and hydrogen peroxide were added and the samples were digested in a microwave. Both plant and soil samples were then analyzed using an Inductively Coupled Plasma-Mass Spectrometer (ICP-AES). The cation exchange capacity (CEC) was determined by shaking the soil sample with 1 molar ammonium acetate and then extracted and analyzed using an ICP-AES. Enrichment factors of dissolved pollutants in the snowmelt were calculated by the same procedure used by Viklander and Malmqvist (1993), as shown in equation 1.

$$Enrichment\ Factor = \frac{Concentration\ in\ first\ 20\%\ of\ meltwater}{Average\ concentration\ in\ meltwater} \qquad [1]$$

Results and Discussion

Metal concentrations

The chemical and physical composition of the snow from the three sites showed highest pollution loads for the high traffic road (Site C). The zinc concentration was almost 5 times higher than Site B, the residential area (Table 2). The conductivity and chlorine concentration was highest for Site B, the medium density collector road. It might have been expected that Site C should have a higher chloride concentration due to more salt applications, however Site B is located at a higher elevation (64 msel) and with less traffic, hence more salt is needed to keep the road free of ice and snow. Site A is at the highest elevation (ca 125 msel) however de-icing agents are not frequently applied to residential roads in Trondheim. These roads are cleared for snow and then anti-slipping agents such as gravel and sand are used. The three roads are also maintained by three different entities, Site A, the residential road is a city road, Site B, the urban collector road, is a county road, while Site C, the urban highway, is a state road. The different entities might have different policies on road salt applications.

The changes in concentrations between snow and outflow varied between the metals, between total and dissolved phase, and between locations (Table 2). The largest changes in snow to outflow concentrations were seen at Site C, for all the metals, with more than 90% lower concentrations in the outflow compared to the snow. The most variable change in concentrations were seen at Site A where total copper only had a 24% lower outflow concentration than in the original snow, while zinc and lead had more than 80% lower outflow concentrations. Site B, the urban collector road, fell in between the residential road (Site A) and the highway (Site C).

Table 2. Chemical and physical composition of the snow collected at the three study sites and the mean outflow concentrations from the bioretention boxes. RMS of average concentrations in RMS column for each site.

		Site A		Site B		Site C	
		(µg/L)	RMS	(µg/L)	RMS	(µg/L)	RMS
Snow	Total copper	123.4	0.7	200.4	3.2	543.3	29.1
	Dissolved copper	36.4	0.7	19.0	0.2	13.5	0.4
	Total zinc	386.4	8.7	537.6	29.6	1465.3	49.8
	Dissolved zinc	7.2	0.6	6.1	0.6	2.6	0.2
	Total lead	24.6	1.6	34.8	0.9	93.7	1.5
	Dissolved lead	0.299	0.003	0.181	0.001	0.187	0.007
	Total Cadmium	0.302	0.012	0.442	0.026	1.524	0.011
	Dissolved Cadmium	0.021	0.000	0.021	0.002	0.013	0.001
	Chloride	48974	1616	215754	7336	20863	563
Outflow	Total copper	92.6	10.4	75.4	8.0	52.0	6.5
	Dissolved copper	60.3	17.6	55.1	7.1	42.6	13.7
	Total zinc	72.6	14.7	85.8	22.5	36.4	13.4
	Dissolved zinc	57.1	17.7	63.0	24.9	27.1	9.2
	Total lead	1.6	0.1	1.1	0.1	0.6	0.1
	Dissolved lead	0.204	0.012	0.179	0.013	0.153	0.013
	Total Cadmium	0.043	0.018	0.060	0.021	0.093	0.033
	Dissolved Cadmium	0.041	0.006	0.057	0.011	0.052	0.016
	Chloride	55785	10205	85923	17203	136005	21143

USEPA National Recommended Water Quality Criteria (USEPA, 2006): Values in µg/L and acute values first and chronic values in parenthesis. Cadmium 2(0.25), copper 13(9), lead 65(2.5), zinc 120(120)

The changes in concentrations followed the loadings, that the largest change in concentration was seen at the site with the highest snow metal concentrations to begin with, indicating that the change in total concentration is a function of loading concentrations. The dissolved concentrations had a more variable change. Dissolved copper, zinc, and cadmium all had a negative change with higher outflow concentrations than snow concentrations, while lead had a positive change with lower outflow concentrations. Lacking available national recommendations for stormwater in Norway, the outflow concentrations were compared to current US national recommendations (USEPA, 2006), while zinc, lead, and cadmium values were all within the limits, all the copper concentrations were above the recommended values, and at times several times higher.

Mass balance

An overall mass balance on the total inputs and outputs from the system was performed to investigate the overall performance of bioretention for treatment of snowmelt. In total, over the three applications on the two boxes, snow water equivalent of 357 liters was applied, 340 liters of which was collected in the outflow again. This is a mass recovery of 95.3%, the remainder of the water was retained in the soil column and not retrievable. The total pollutant retention in the system was very good for metals and sediments, with an above 95% reduction in total metal mass and above 99% reduction in TSS (Table 3). Dissolved metals had a more varied result, with good retention of soluble lead while some leaching zinc was observed. The dissolved copper mass in and out are very similar, and within the overall uncertainty of the measurements (discussed in the following section), indicating that dissolved copper mass is transported directly through the bioretention without any adsorption. The organic substances, measured in COD were reduced by 57% mass which is a lower reduction than a previous reported laboratory scale study using synthetic runoff (Hong, et al., 2006). A slight increase in chloride mass could be seen through the system, however accounting for uncertainties in concentrations (discussed in the next section) the chloride remained unchanged through the system. It is also possible that continuous testing of the facility over 2 years prior to this study had left some residual chloride in the soil column that was washed out with the snow melt. In either case, it can be seen that chloride for the most part is transported directly through the system without any reductions in mass loads. The total metal retention was strongly correlated to TSS reduction and all above 95% mass reduction, which is excellent retention for a full-scale outdoor study.

Table 3. Summary of mass balance of snow input and outflow metals, chloride, particles, and COD

	In		Out		% mass retained	
	Total	Dissolved	Total	Dissolved	Total	Dissolved
Snow volume (L)	357		340.7		4.7 %	
Zinc (mg)	301	1.8	11.6	8.7	96 %	-372 %
Copper (mg)	110	8.0	12.1	9.1	89 %	-14 %
Lead (mg)	19	0.1	0.2	0.0	99 %	59 %
Cadmium (mg)	290	6.3	14.7	26.0	95 %	-310 %
Chloride (g)	30		33.1		-10 %	
COD (g)	49		20.7		57 %	
TSS (g)	2112		1.8		99.9 %	

Pollutant accumulation in soil, plants, and mulch

The accumulation sinks for the retained pollutants were analyzed to identify where the majority of pollutants were retained and if difference existed between the different plant species.

The accumulation of metals in the plants roots and shoots varied greatly between the species. The Vinca minor, a ground covering evergreen had a clear accumulation of metals in the above ground biomass. Unfortunately an error occurred during post snowmelt sampling and the below ground sample of the Vinca minor could not be used. However since it is a terrestrial plant the uptake must occur in the root zone, indicating a good transport of metals from the roots to the shoots in the plant. The copper concentration remained nearly unchanged between pre snowmelt and post snowmelt measurements, but showed accumulation 250% higher compared to natural levels from the start of operation due to preceding stormwater experiments. The lead showed 250% and zinc had 140% higher accumulation post snowmelt compared to pre snowmelt. The Hippophaë rhamnoides, a small shrub, showed a lower accumulation and only minor differences between the natural and post snowmelt results in the twigs (Figure 2).

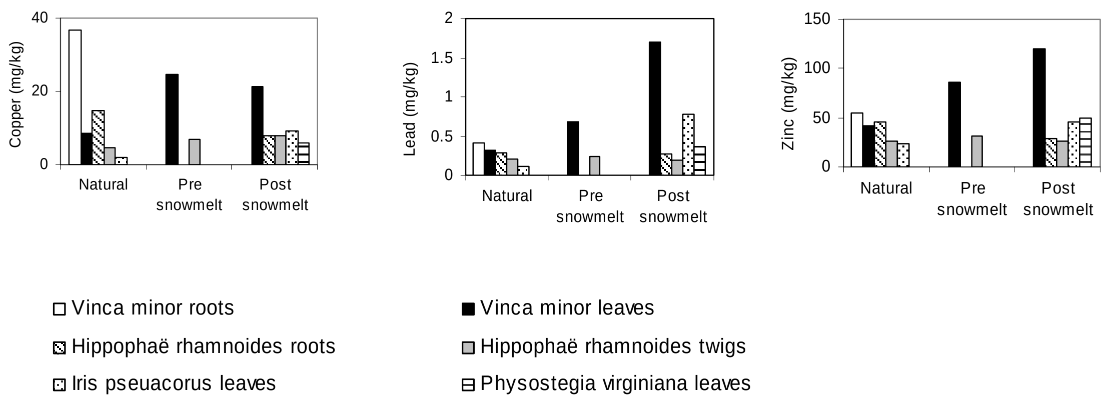

Figure 2. Plant metal concentrations in above ground biomass, twigs and leaves, and roots for natural conditions, before the snowmelt experiment and three weeks after the snow melt experiment.

The top mulch layer showed a clear accumulation of all the three metals (Figure 3b), which supports previously published studies investigating metal retention in mulch (Davis, et al., 2001, Jang, et al., 2005). Comparing pre snowmelt levels to post snowmelt levels the metal concentrations in the mulch layer were 160%, 110%, 120% higher respectively for copper, lead and zinc. Metal concentration as a function of soil depth did not reveal a clear trend. Small increases in metal concentrations were seen at the bottom of the soil column, while no difference was measured at the top portion of the column (Figure 3a). Davis et al. (2001) reported no apparent variation of metal concentrations in the soil core depth in the postmortem analysis of the soil and no significant soil adsorption of metals was seen. However this can be a function of total metal mass added to the system compared to the soil mass in the system and possibly the resolution of the measurement technique.

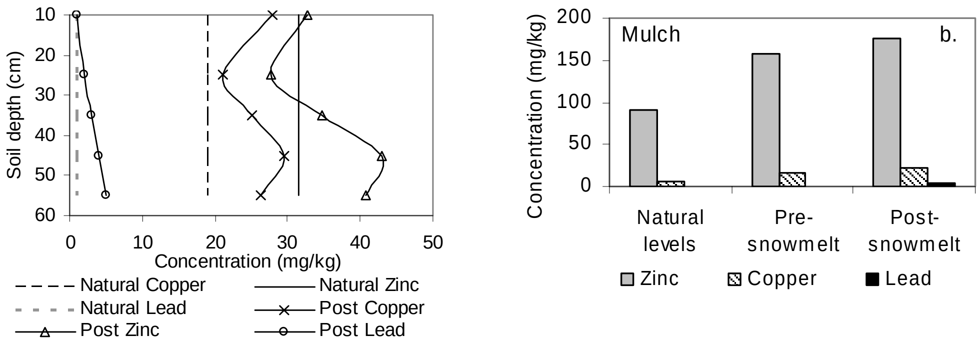

Figure 3. Soil depth profiles of metal accumulation in the bioretention areas (a) and in the top mulch layer (b)

The dissolved copper and zinc mass in the outflow indicated some leaching from the soil column. A laboratory leaching test was performed to investigate this. De-ionized water was slowly pumped, 2ml/ min, into a column of 600ml, of soil from the bioretention boxes for approximately 6 hours. The results revealed a leachate concentration of copper and zinc in the range of 30-40μg/L. This is in the same range as the increased dissolved fraction in the outflow, except for the first few samples from Site B and 2.

A mass balance on the metal mass input, output and retention in the system was performed. Based on known volumes of soil and mulch and estimated plant biomass, the main sinks can be identified. The 5cm thick top mulch layer retained approximately 74% of the zinc, 13% of the lead, and 66% of the copper by mass that was retained in the system. This was higher than the number reported by Davis et al. (2001). However the snow contained a much higher concentration of TSS, and after the snow had melted a gray layer of sediments was left on the mulch. This could have contributed to a higher retention in the mulch layer initially and possible some of the metals would be transported further down in the soil column with subsequent rain events. The plant biomass was not harvested, making only an estimate of the plant metal retention possible. Analyzing the total plant metal uptake estimating the plant biomass showed that approximately 6% of zinc, 8% of copper and 2% of lead retention can be attributed to plant uptake, which is in the same range reported by Davis et al. (2001) in a laboratory study. This would leave 20% zinc, 28% copper, and 85% lead of the retained metal mass to be retained in the soil column, possibly due to the large volume of soil compared to the small mass of metals added, although this could not be confirmed. In order to increase the plant uptake of metals, hyper accumulating plants could be used, though the plants would also need to be cold resistant and be able to grow well in a short growing season. Most plants found to hyper accumulate metals are either aquatic plants or terrestrial plants grown in a water solution (Kholodova, et al., 2005 and Fritioff and Greger, 2003).

This does not represent a complete mass balance but it clearly indicates that the most important mechanisms of metal removal in the system are through mechanical filtration, trapping suspended solids, and adsorption onto the top mulch layer. In spite of the minor role the plants might play in metal uptake they are still an important part of the bioretention system with respect to nutrient removal, rootzone development for improved infiltration and reducing clogging, rhizospere biofilms, and regeneration of the system. The snow carries a large amount of particles and pollutants and after snowmelt in the spring a thick layer of sediments and dirt covers the ground and the winter dormant plants. Then two months later this gray layer of dirt and pollution had been transformed into green vegetation. The plant biomass from bioretention system can also be harvested, thereby removing metals from the system.

Inflow and outflow pollutant compositions

Having confirmed that the bioretention facility could retain pollutants from urban snowmelt by looking at the overall change in concentrations and mass reductions, the timeline and site specific composition and concentration were investigated.

The time line for application of snow from the different sites started with the residential snow (Site A), which lasted 6 days (April 14^{th} to 20^{th}) with a 24 hour rest period before the start of the urban collector road (Site B), which also lasted 6 days (April 21^{st} to 26^{th}) following a 24 hour rest period. The final one, the urban highway (Site C) began on April 27^{th} and lasted until May 2^{nd}. The average air temperatures were 4.5°C, 6.7°C, and 8.7°C respectively for Site A, B and C.

The total metal retention increased with increasing metal concentration in the snow. Lead concentration had good overall retention for all sites, from 93 to 99%. The dissolved lead fraction was the same in the snow and in the outflow from the bioretention boxes, indicating no retention of dissolved lead and a virtually complete retention of particulate bound lead. Zinc also showed consistently high retention from 81% in the snow from the residential site (Site A) to 97% retention for the urban highway site (Site C). Copper had a more variable performance with 25% retention for the residential site (Site A) and 90% retention for the urban highway site. For Site A and B both copper and zinc had higher outflow concentrations for the first sample and then a steadily decreasing concentration.

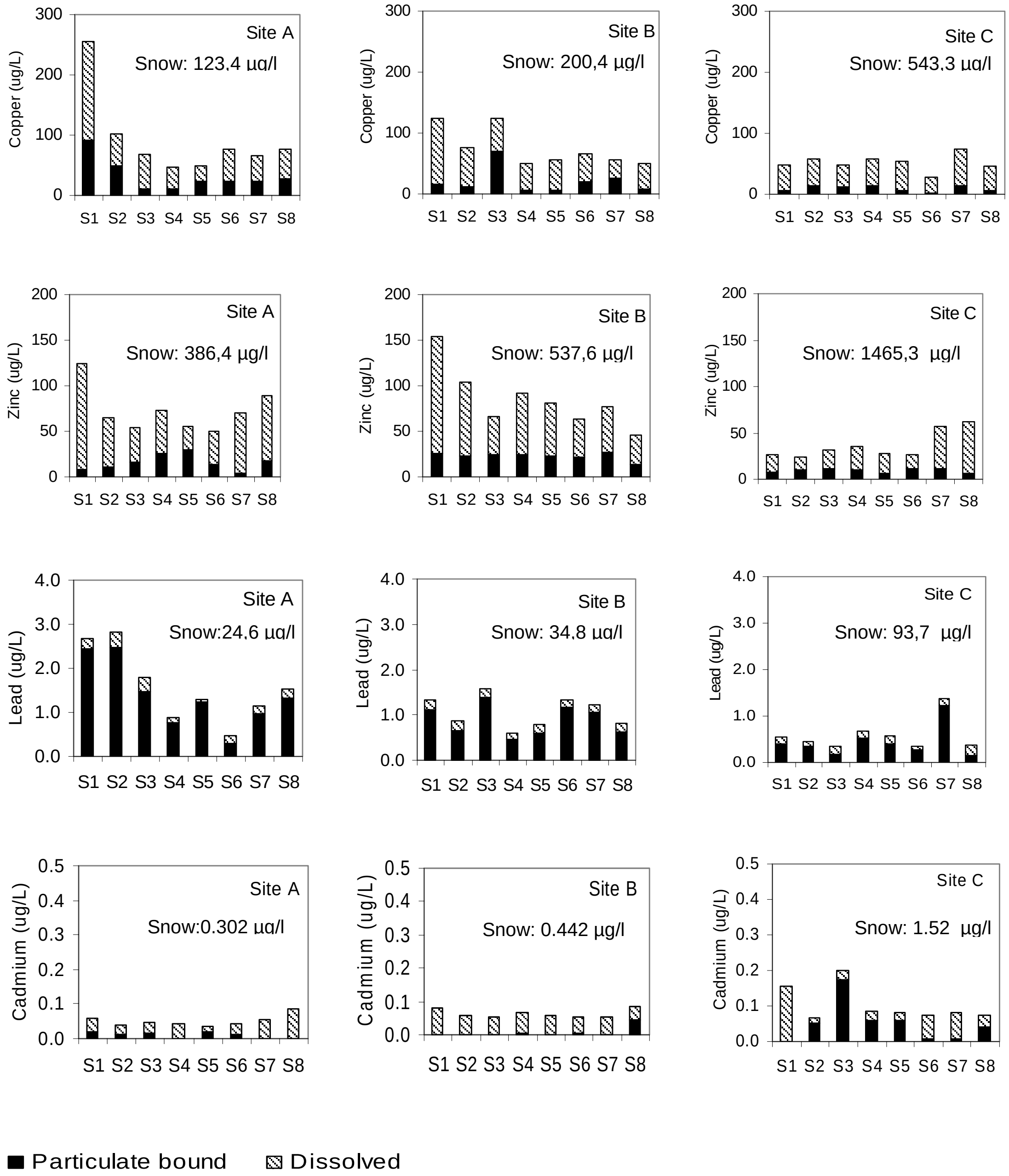

Figure 4. Average metal concentration in the bioretention outflow for the three snow sites, where S1 through S8 represents the outflow samples collected at set volume of outflow intervals. The snow metal concentrations are listed in Table 2, but omitted here due to the large scale difference

The same trend was not seen for Site C, which has a consistently low outflow concentration (Figure 4). This could be due to a higher average air temperature for Site C melt, improving the performance of the bioretention.

Organic substances

Snow also accumulates oil and grit over the winter months that will be transported with the melt water. A test for chemical oxygen demand (COD) in the snow showed little variation between the three sites; from 121mg/L at the residential street (Site A) and 146 mg/L for the urban highway (Site C). The outflow was nearly constant for all three sites, with an average reduction of 67-71% (42 mg/L COD in the outflow). Site A and B had a lower COD concentration for the first sample (first 20% of runoff volume) compared to the other samples (50, 80, 100% of volume). The same trend was not seen for Site C, where the outflow COD concentrations were constant through the samples. This variation could be due to the type of organic compounds in the snowmelt. A previous study of snowmelt chemodynamics found that water soluble organics would leave with the front of the melt water, while the particulate bound organics would leave with the tail of the melt water (Schöndorf and Herrmann, 1987). A laboratory study on sustainable oil and grease removal from bioretention media found an approximately 90% removal of hydrocarbon contaminants through filtration in the mulch layer and subsequent microbial activity in the mulch layer (Hong, et al., 2006). Further studies of snowmelt dynamics through the bioretention system should be investigated with respect to microbial activity in the mulch layer during the melt season compared to the summer season.

Sediments and Chloride

Total suspended solid retention was more than 99% for all the sites, inflow concentration ranged from 2900 to more than 9600 mg/L (Figure 5) while the outflow concentration was less than 10mg/L for all the samples. Particle size distribution analysis of the inflow and outflow revealed a different particle size distribution for snow and outflow from the bioretention (Figure 5). The mean particle size for the snow was 13-17µm while the outflow particles were an order of magnitude larger, 144-154µm. Analysis of some of the outflow samples for total volatile solids indicates that the outflow particles were almost all organic and probably result from detached biofilm in the outflow pipe or collection tank. Only 0.9-1.3% of the particles in the snow were less than 5µm in size. The dissolved fractions in the snow with exception of copper for Site A and B were less than 2%. Site A had 30% dissolved copper in the snow. Strong correlation between dissolved metal fractions and suspended solids and chloride has been reported (Reinosdotter and Viklander, 2005), however for this study, Site A had the lowest suspended solids and chloride concentration of all three sites.

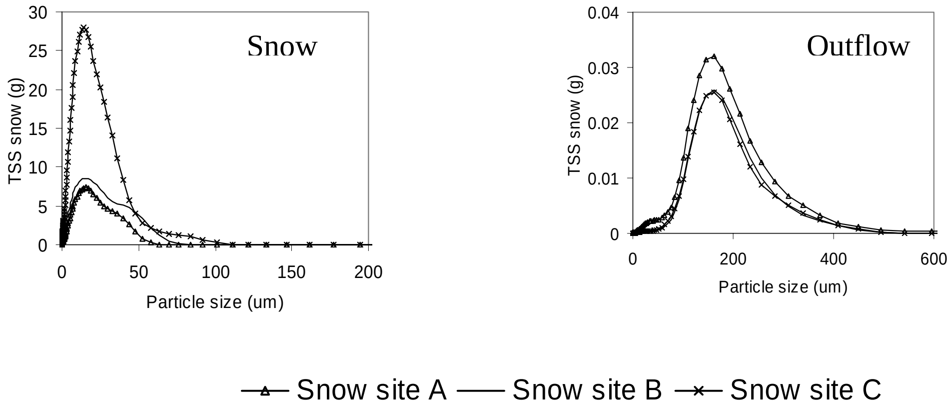

Figure 5. Particle size distribution in snow and outflow from bioretention boxes for the three different snow collection sites.

A Pearson correlation between total metal concentration and suspended solids in the snow revealed a strong correlation for all metals except for copper at Site A, which had the highest fraction of dissolved copper, 30% in the snow. In the outflow from the bioretention boxes no correlations between TSS and zinc or copper were found, as the zinc and copper in the outflow was mainly dissolved. A weak correlation was seen between TSS and total lead for Site C, but not for the other two sites.

Pollutant pathways

The pathways of pollutants through the bioretention filter were compared with the pathways without any treatment. This comparison was done to investigate to what extent the bioretention filter changes the enrichment factor of dissolved pollutants in the front end and particulate bound pollutants in the tail end of the melt water flow. Comparing the mass accumulation of metals over time, both dissolved and particulate versus outflow volume gives a picture of the pathways of the pollutants through the bioretention boxes (Figure 6). The collector road (Site B), showed a positive enrichment for all the metals, while Site A, the residential road had a more mixed picture with positive enrichment of zinc and copper, and neutral to negative for lead. For Site A and B the enrichment ratios were positive for all three metals, ranging from 1.5 to 1.1. Site C, the urban highway showed a slight negative enrichment of all the dissolved metals, which could indicate an initial retention with subsequent wash out of the dissolved metals (Table 4). The enrichment ratios for Site A and B, however were not as strong as reported in the literature (Viklander and Malmqvist, 1993, Ecker, et al., 1990) indicating that the bioretention system to some extent was capable of reducing the elevated front end concentrations of dissolved metals. The enrichment of tail end particulates was not seen either, however with the high TSS removal in the system this would not be expected.

Table 4. Enrichment factors in the bioretention outflow

	Site A (1500 vehicles/day)	Site B (5000 vehicles/day)	Site C (47000 vehicles/day)
Copper	1.51	1.17	0.97
Zinc	1.22	1.20	0.65
Lead	1.44	1.06	0.97

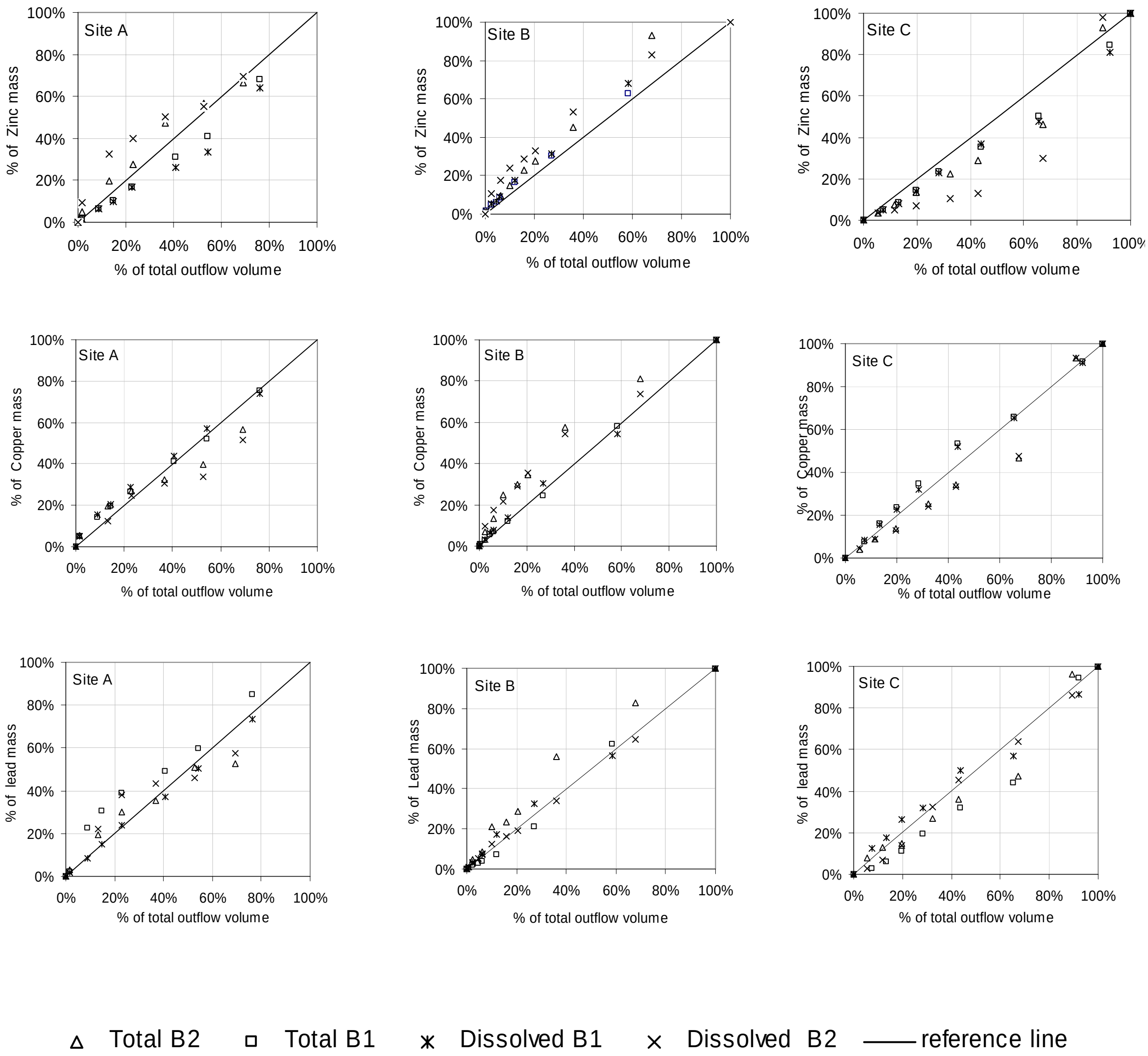

Figure 6. Dissolved and total metal mass fractions versus fraction of total outflow volume for zinc, copper and lead in the two bioretention boxes. Where B1 = bioretention box and B2 = bioretention box 2.

The chloride concentrations at the three sites were very different. Site B had a chloride concentration 10 times higher than Site C, 202.2 versus 21.1 mg/L, while Site A had 50.3 mg/L. In the literature elevated chloride concentrations have been shown to be linked to the dissolved metal fraction (Warren and Zimmerman, 1994, and Reinosdotter and Viklander, 2005), but this could not be found in this study. It is possible that some of the chloride had washed off the road in Site C prior to collection due to the lower elevation and therefore higher average temperatures. The there was also a tendency that the chloride was temporarily retained in the system between the Site B and the Site C snow application. The outflow from Site B had a 55% reduction in chloride, while Site C had a large increase, 21 mg/L in and 140 mg/L out.

Conclusions

The bioretention boxes ability to treat snowmelt from road side snow was good overall both with respect to concentrations and mass loads. The decrease in concentrations of metals through the bioretention were from 81-99% with one exception for the copper concentration for Site A, which had the lowest inflow concentration and also the lowest reduction (25%). The mass reductions of metals were excellent for all the sites with 89 to 99% mass reduction of metals from the snow to the outflow melt water. The top mulch layer was responsible for the most significant metal retention, with up to 74% of the zinc retained here. The plant metal uptake was found to be in the range of 2-8%, by estimating the final plant biomass, however the plants function in the system to improve infiltration, and rootzone biofilms are still very important for the overall function of the system. The bioretention boxes reduced the effect of the enrichment factor of soluble bioavailable metals found in the front end of snowmelt. Heavy loading of particles and particle bound pollutant in the tail end of the snowmelt runoff was also not observed. However the bioavailable (dissolved) copper and zinc concentration in the outflow increased which should be further investigated either by use of hyper accumulating plants or other retention media.

Acknowledgements

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Paper V

An evaluation of applying existing bioretention sizing methods to cold climates with snow storage conditions

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An evaluation of applying existing bioretention sizing methods to cold climates with snow storage conditions

Evaluation de l'application des methodes existantes de dimensionnement du procédé de bioretention aux climats froids et en présence des neiges provenant de la chaussée

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RESUME

Huit des méthodes courantes de dimensionnement et de conception proposées pour des équipements de bio-rétention ont été évaluées pour, les ruissellements de précipitations, et les volumes de stockage de neige pour un climat côtier froid à Trondheim, Norvège. Le modèle d'infiltration de bio-rétention de RECARGA a été employé pour comparer les performances des méthodes en utilisant 2 ans de données observées à partir d'une boîte de bio-rétention à échelle pilote. Les superficies, le temps d´accumulation total, le nombre et la durée des événements de débordement, et la zone de stockage de neige ont été comparés. Il a été constaté que même pour un climat côtier froid avec plusieurs cycles de fonte intermittente les conditions de stockage de neige sont signifiantes, et si plus de 25% de tout le volume de neige doit être stocké ceci devient le paramètre majeur de conception.

ABSTRACT

Eight of the current sizing and design methods proposed for bioretention facilities were evaluated for rainfall runoff and snow storage volumes for a costal cold climate in Trondheim, Norway. The RECARGA bioretention infiltration model was used to compare the performance of the methods using 10 months of observed data from a pilot scale bioretention box. The surface areas, total ponding time, number and duration of overflow events, and snow storage volumes were compared. It was found that even in a costal cold climate with several intermittent melt cycles the snow storage requirements were an important design parameter, and if more than 25% of the total snow volume should stored this became the deciding design parameter.

KEYWORDS

Bioretention design, cold climate, snow storage, urban stormwater

1 INTRODUCTION

Bioretention facilities for stormwater management consist of a sandy loam soil medium, an optional but most often recommended top mulch layer, and suitable plants (Clar et al., 2004). Plants and mulch layer can be optimized depending on the main pollutants of concern, and the local climate. Several studies have investigated pollutant retention in mulch (Jang et al., 2005 and Ray et al., 2006)) and plants (Fritioff and Greger, 2003 and Fritioff et al. 2004). The design objectives include; water quality treatment, infiltration of design storm, and restoring or maintaining local water balance (Winogradoff, 2002). Bioretention facilities are also important design tools in adding vegetation to the urban environment and incorporating a blue-green interface.

The design and sizing of bioretention facilities was first developed by Prince George's County in Maryland (USA) as described in the first bioretention manual from 1993 (PGC, 1993). Since then a wide range of sizing methods have been developed based on different criteria from pollutant retention based on storing the first flush to local groundwater recharge. However, they have all been developed in US with local or regional precipitation patterns and none of the design methods incorporate snow storage, which would be required in cold climate areas. Dietz (2005) conducted a review of five different sizing methods; the Prince Geroge's County methods storing first 1.27cm of impervious runoff, using 5-7% of the area for bioretention (PGC, 1993), and composite curve number (CN) method (Winogradoff, 2002), the Wisconsin Department of Natural Resources method (WDNR, 2003), and the SCS runoff depth method (Hunt and White, 2001) and compared them to an roof runoff rain garden in Haddam, Connecticut, which was designed to store 2.54cm of the first runoff. The Haddam rain garden was the largest in surface area, and proved through long term field monitoring to retain 98.8% of the inflow, concluding that this was an adequate site for Connecticut, and that several of the other methods would have been under designed (Dietz, 2005).

Snow storage raises the question of local or central snow deposits and what portion of the snow volume should be stored for treatment and if some of the snow can be disposed off without treatment. Reinosdotter et al. (2003) compared local and central snow deposits in northern Sweden and found that the environmental benefits in reduced CO_2 and NO_x emissions as a results of less transport and cost benefits were in favor of local deposits given that they did not pose a flooding or drainage problem during the melt seasons and that affordable land was available in the city center. The bioretention areas can function as local snow deposits with environmental control, as liners can be used to protect groundwater, soil and plant media can be optimized for pollutant removal, especially metal and particles. Separating snow based on quality can be a space saving alternative, and several studies have shown a large variation in urban snowmelt quality (Viklander, 1997, and Reinosdotter and Viklander, 2005). A v-shaped geometry for snow storage areas has been shown to be more efficient in control particles and for possible further treatment of the snowmelt (Wheaton and Rice, 2003).

2 METHODS

2.1 Sizing Methods

Eight of the most commonly used sizing methods were reviewed and evaluate for size and volume requirements with respect to a cold climate setting. More than these eight methods exist, however several methods with different names are based on the same governing equations, and for these only one method was selected, like several differentiations of the methods using the rational formula combined with the impervious drainage area. The selected methods were compared using input parameters from the small pilot scale bioretention box (Muthanna and Thorolfsson, 2005) installed at Risvollan Urban Hydrologic Research station (Thorolfsson et al., 2003) based on the Prince George's County 5-7% area method. The hydraulic conductivity was based on field measurements of the pilot facility, 10cm/hr. No recharge was permitted and all the water entering the facility had to leave as evapotranspiration (ET), outflow in the underdrain or overflow. A summary of the selected methods and their governing equations are presented in Table 2 with a short description of each method.

2.2 Evaluation Criteria

The different methods were compared based on the required surface area, given a soil depth of 55 cm, and a 5 cm top mulch layer. Comparing the different methods on an event basis would not give a complete picture of the performance of the system and would make it difficult to compare with the observed field data. Therefore in order to get a better understanding for the effect the different sizing methods had on the continuous performance of the facility the RECARGA model was used to model the different designs. The RECARGA model (Atchison and Severson, 2004) is an event or continuous based model to simulate the hydrologic function of bioretention facilities. The observed pilot bioretention outflow was compared to the simulated outflow calculated in RECARGA using the same inflow time series as was the inflow to the pilot bioretention area. Using the same inflow data series as seen in the pilot bioretention area eliminates any discrepancy in the model as result of method for runoff generation calculations.

The bioretention facility as designed by the various methods were simulated with 10 months of continuous data from RUHR using data from 2005-2006 and the pilot size bioretention facility located at the station (Table 1). This time series was chosen to be able to compare the observed and simulated flows for the method used for the pilot bioretention box. The number, total duration and max duration of ponding and overflows events were compared for the different sizing methods.

Month	Inflow (cm)	Month	Inflow (cm)
July 2005	35.11	December 2005	286.6
August 2005	92.8	January 2006	379.7
September 2005	146.8	February 2006	194.3
October 2005	43.4	March 2006	53.8
November 2005	291.1	April 2006	5.3
daily max (cm)		108.6	
Avg daily inflow (cm)		124.4	
# days with inflow		122 of 254	

Table 1. Summary of inflow records (2005-2006)

To evaluate the snow storage requirement the annual snowfall in Trondheim was evaluate using three storage volumes, 100, 50, and 25%. The 100% volume assumed that the entire snow volume would have to be stored. The second, 50% assumed some mid winter melting and some sorting of snow pollutant concentrations. The third scenario storing only 25% of the volume accounting for several mid winter melt periods and advanced snow management with respect to pollutant concentrations in the snow.

Table 2. Summary of the different sizing methods with governing equations

Method	Description	Govering equations	Variable description
Rational (The rational method)	The raional method and a treatment coefficient are used. When the drainage area is100% impervious this method is equal to the impervious area method.	$A_{bio} = C \times A \times T$	A_{bio} = bioretention surface area, C = runoff coefficient, A = total drainage area, T = treatment factor (%)
PGC 5-7% Prince George's County 5-7% area method (PGC, 1993)	This method sizes the bioretention facility based on a percentage area of the total drainage area.	$A_{bio} = A_{drainage} \times P$	$A_{drainage}$ = the total drainage area, P = the the percentage area to treat
WDNR Wisconsin Dept. Natural Resources Homeowners manual (WDNR, 2003)	This proecedure is for homeowners that wants to build a bioretention facility for their own lot. It is a very simple method that does not require advanced knowledge of hydrology.	$A_{bio} = A_{drain} \times S_f$	A_{bio}=surface area of rain garden, A_{drain}= runoff area (typical roof or drive way), S_f=sizing factor dependant upon soiltype, depth of facility, and overlandflow distance
PGC_1.27 Prince Georges County 1.27cm storage method (PGC, 1993)	The volume requirment to store the first 1.27 cm is calculated and converted to a surface area by dividing by depth.	$A_{bio} = A_{imp} \times 1.27/100 \times 1/d_{bio}$	A_{bio}=surface area of rain garden, A_{imp}= impervious surface area, d_{bio}=depth of the facility
PGC composit CN Prince George's County Composite CN-number method (Winogradoff, 2002)	Curve numbers (CN) based on pre and post development. Then based on local rainfall inforamtion a design stom is identified and and the required storage volume is found based on the first 1.27 cm (1/2 inch) of runoff.	$CN_c = CN_p + \left(P_{imp}/100\right) \times \left(98 - CN_p\right) \times (1-0.5R)$	CNp. is the post development curve number calculated as a composite of the different land uses., P_{imp} is the % of impervious land cover, R is the ratio of disconnectivity, R will always be equal to 1 for for any BMP that intercepts the water before it enters a stream.
SCS runoff SCS runoff depth method (White and Hunt, 2001)	Soil Conservation Service (SCS) curve number is used to calculate the area required to store the first 2.54cm of runoff. The size of the bioretention is calculated based on the SCS runoff depth method	$D_{runoff} = \frac{P - 0.2S^2}{P + 0.8S}$ $\quad S = \frac{1000}{CN} - 10$	Where D_{runoff} = runoff depth, P = the precipitation set to 2.54cm, CN= curve number (normally 98 for impervious surfaces).
Haddam Haddam rain garden , (Dietz, 2005)	This method is based on the composite CN method (PGC 2002) but the first 2.54cm runoff volume instead of 1.27 is stored	$CN_c = CN_p + \left(P_{imp}/100\right) \times \left(98 - CN_p\right) \times (1-0.5R)$	Same as for the PGC composit CN method above
RFM_Darcy Runoff Frequency Spectrum (RFS) – Darcy's Law Method (based on Scheuler, 1987)	Another variation of the percentage of impervious area method that incorporates the use of return storm statistics to determine the water quality volume (WQv) that should be treated in the bioretention facility. The area of the bioretention facility is based on the percentage impervious area and the sizing of the filter bed is based on Darcy's law.	$R_v = a + b \times l$ $\quad WQ_v = \frac{P \times R_v \times A}{1000}$ $A_f = (WQ_v)(d_f) / \left[k \times (h_f + d_f) \times t_f\right]$	Rv = volumetric runoff coefficient, *a* and *b*= constants (0.05 and 0.009) respectively, *I*= impervious % of watershed, WQv (m^3) = water quality volume (first 1.27 or 2.54 *cm* of runoff) , *P* = rainfall depth *(mm)*, A_f = filter bed surface area *(m2)*, d_f =depth *(m)*, k = permeability coefficient *(m/day)* , h_f = allowable ponding depth *(m)*, t_f = design drawdown time *(days)*

3 RESULTS

3.1 Simulated versus observed flow

For the warm season, illustrated with simulations from August 2005 (Figure 1a) the model shows a good fit with the observed data with respect to shape of outflow curve and duration of outflow, however the peaks tend to be overestimated for the simulated outflow. For the intermediate temperature (fall) season in addition to overestimate of peaks there are some discrepancies in the shape of the outflow curve, especially as the temperature falls close to zero degrees Celsius with precipitation as snow or rain (Figure 1b). For the large storm event during November 20th the simulated flow indicates an overflow event, with a flat peak, while no overflow was seen in the observed data. This can be explained by intermittent snow and rain fall during this period causing prolonged runoff events that continues over long time as the snow melts over the second half of November.

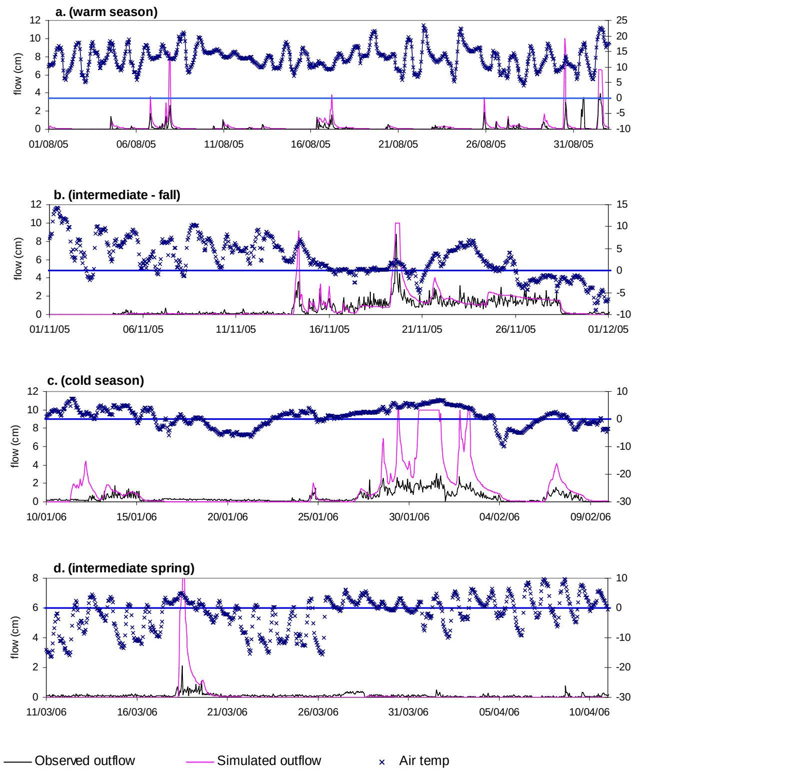

Figure 1: Simulated and observed outflow from the pilot bioretention area during four seasons.

During the cold season the observed and simulated data show a poor fit (Figure 1c), which can be explained by that the RECARGA model does not account for snow accumulation and melt, as can be seen in Figure 1c, the first event in January 2006 is a snowfall event not a rainfall event as simulated by RECARGA. The spring events (Figure 1d) are also poorly simulated where most of the melt water trickles out of the box. The last snow and rain event in mid marched trickled out of the box over several weeks due to partly frozen soils and some ice formation on top of the mulch.

3.2 Surface area, overflow and ponding time

The required surface area for each method was calculated based on the same input parameters and compared to a pilot bioretention area (designed using the Prince George's County 5-7% of watershed area method). The results show a large variation in required surface area, from $0.95m^2$ to $4.9m^2$, more than 5 times larger (Table 3). Only the Rational method and the PGC-5-7% method produced overflow during the time of simulation. The total ponding time varied from 119 hours for the smallest to zero hours for the largest design. The rational and the PGC 5-7% area methods yield the same results since the simulated areas is a 100% impervious, however in a mixed landuse watershed the rational method would yield a smaller surface are than then PGC 5-7%. For this simulation two methods can be seen to result in 5 overflows and more than 22 hours of total overflow time (Table 3). The WDNR method is the first method not to result in overflow, however this method is aimed at small bioretention facility treating roof runoff from single family homes, making it less suitable for urban street and parking lot runoff. This leaves the PGC 1.27cm storage as the method that adequately handles the inflow with acceptable ponding times and depths. This method covers 8% of the drainage area and is 78% larger than the pilot area used for field studies. The larger seem to be unnecessarily large for the local climatic conditions. In general the rainfall intensities often seen on the east coast of the United States will be significantly larger than what is typical in Trondheim, however the duration of rainfall can be longer in Trondheim, especially in the fall.

No.	Method	Surface area *(m2)*	% of watershed *(%)*	% of pilot bioretention area *(%)*	Number of overflows	Total overflow time *(hrs)*	Number of times ponded	Total ponding time *(hrs)*	Longest ponding time *(hrs)*	Max ponding depth *(cm)*
1	Rational	0.95	5 %	100 %	5	22.1	115	119	15.5	15
2	PGC 5-7%	0.95	5 %	100 %	5	22.1	115	119	15.5	15.0
3	WDNR	1.60	8 %	168 %	0	0	48	37.4	8.8	7.1
4	PGC_1.27	1.69	8 %	178 %	0	0	53	30	7.8	3.8
5	PGC_Comp. CN	1.92	10 %	202 %	0	0	45	18.4	3	1.1
6	SCS Runoff	3.09	15 %	325 %	0	0	10	4.5	0.4	0.2
7	Haddam	3.39	17 %	356 %	0	0	3	0.12	0.07	0.1
8	RFM-Darcy	4.87	24 %	513 %	0	0	0	0	0	0.0

Table 3: Surface area requirement for a bioretention area based on design metho**d**

3.3 Snow storage

Snow storage requirements will differ greatly from a cold costal climate to an inland climate. In the costal regions with intermittent melt periods only portions of the total snow volume will be on the ground at any given time during the wither, while in an inland climate most of the snow volume can be on the ground when the spring melt starts. From a simple calculation based on snow volumes in Trondheim, where 30-40 % of the annual precipitation (900 mm/yr) falls as snow (Thorolfsson et al., 2003), it can be seen that even the Return frequency method (method no. 8) results in a snow storage depth of 2.2 meters if the entire snow volume should be stored. Two meters was chosen based on practical issues and safety issues related to having more than 2 meter high snow piles in the urban landscape. This is assuming all the snow from the 20m^2 drainage area is collected and stored on the bioretention area for infiltration and treatment. However, all this volume would not have to be stored as in a coastal climate like Trondheim there are several melt periods during the winter months.

If the total snowfall from a season should be stored in the bioretention area even the RFM-Darcy method, with the largest surface area would accumulated more than 2 meters of compacted snow (Table 4). Even if only 50% of the snow volume should be stored only the three largest surface area methods would be large enough. For storing 25% of the snow volume all methods except the two smallest ones, the rational method and the PGC 5-7% of the area method would be too small. When Comparing snow volume requirements and rainfall runoff size requirements (table 3 and 4) it can be seen that for storing 25% of the snowfall volume coincides with the methods that are adequate for the rainfall runoff as well. Storing more than 25% of the snow volume will make this volume the deciding design parameters, while if 25% of less is required to be stored the bioretention area can be designed using rainfall runoff parameters.

No.	Method	Surface area *(m2)*	Storage depth (100%)* *(m)*	Storage depth (50%)* *(m)*	Storage depth (25%)* *(m)*
1	Rational	0.95	11.1	5.5	2.8
2	PGC 5-7%	0.95	11.1	5.5	2.8
3	WDNR	1.60	6.6	3.3	1.6
4	PGC_1.27	1.69	6.2	3.1	1.6
5	PGC_Comp. CN	1.92	5.5	2.7	1.4
6	SCS Runoff	3.09	3.4	1.7	0.9
7	Haddam	3.39	3.1	1.6	0.8
8	RFM-Darcy	4.87	2.2	1.1	0.5

Assuming a Snow Water Equivalent (SWE) of 60%

The hatched area indicate storage requirements exceeding 2 meters in depth.

Table 4: Snow storage depth calculated and a percentage of seasonal snowfall stored

To investigate the actual number of winter melt cycles in Trondheim, the daily temperature average for 15 years from 1990-2005 was analyzed. It was found that Trondheim on average has 8, 6, 7, 23 days in December, January, February, and March respectively with above zero degrees Celsius (24 hour average), which would induce snowmelt if a snow cover existed. This suggests that a sizing method that would store between 25-50% of the total snow volume would store most of the winter snowfall In Trondheim.

4 CONCLUSION

The design of bioretention areas in cold climates should be based on both rainfall runoff and snow storage requirements, which will differ in inland climates and costal climates. Snowmelt quality should be the basis for considering storing only portions of the snow volume form the heaviest pullulated areas. Based on the observed field data and modeling using RECARGA the Prince George's County 1.27cm storage method (PGC, 1993) combines snow storage and rainfall runoff with a reasonable landuse requirement, 8% of impervious area in the watershed, with respect to cost of land in urban areas. The snow storage requirements might be larger in inland climates, and need to be considered. Using bioretention areas along roadsides and traffic islands as snow storage also have to be discussed with respect to traffic safety, risk of local flooding and drainage problems in the snowmelt.

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Appendix B

About the author

I was born in Trondheim February 4^{th} 1975, but after a few years I moved to Asker, outside Oslo, where I attended primary and secondary school. Then in 1991 I moved to Sandefjord to attend Skagerak International School, and completed my International Baccalaureate in 1995. My university career started at Virginia Polytechnic Institute and State University (Virginia Tech), in Blacksburg, Virginia in August 1995. In December 1998 I graduated with a *Bachelor of Science in Biological Systems Engineering*, Land and Water resources. I decided to stay at Virginia Tech for graduate school and from January 1999 until January 2001 I was a master student working with Professor Mary Leigh Wolfe. The research topic was risk assessment of nitrogen and phosphorous pollution in agricultural watersheds. I graduated from Virginia Tech in 2001 with a *Master of Science in Biological Systems Engineering.*

In February 2001 I started working as a water resources engineer for CH2M Hill, a civil engineering consultancy in Herndon, Virginia. In January 2003 I moved back to Norway after 7.5 years in the US and began my PhD studies at the Norwegian University of Science and Technology in Trondheim.

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Trondheim, March 2007