DEGREE PROJECT

Evaluation of stormwater quality improvement from bioretention

Comparing filtermedia and vegetation

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Sammanfattning

Eftersom den urbana befolkningen fortsätter att växa blir stadsområdena större, och med det ökar behovet av hantering av dagvatten. Den stora mängden hårdgjorda ytor leder inte bara till höga tillfälliga volymer och flöden, utan även till en ökning av föroreningar i dagvattnet. Dessa förorening hamnar vanligtvis i vårt ytvatten där de kan ha skadliga effekter på miljön. Det finns flera typer av anläggningar för att minska föroreningarna i dagvatten, men en av de mest populära är biofilter, även känt som rain gardens eller bioretention. Biofilteranläggningar kan ha olika design beroende på det regionala klimatet och avsedda designmål. Detta har lett till ett behov av att undersöka vilka filtermaterial och konfigurationer som fungerar bäst i olika scenarier. Denna studie fokuserar på att utvärdera påverkan av filtermaterial och växtlighet på avlägsnande av totalt suspenderade partiklar (TSS), kväve och fosfor, samt tungmetallerna zink (Zn), koppar (Cu), bly (Pb) och kadmium (Cd).

Studien jämför två filtermaterial, ett sandbaserat och ett med kolmakadam. Dessutom har två av fyra filter växter, en av varje filtermaterial. Studien utförs in situ i Sätra, Stockholm. Provtagning utfördes under naturliga regn under perioden 02/10/2022 till 03/07/2023 och under 11 olika regn. Prover togs från en inflödespunkt till ett av filtren och fyra utloppspunkter, en från varje filter.

Resultaten visade att koncentrationerna av totala suspenderade partiklar (TSS) i inflödesvatten är något högre än i utflödet från vissa filter, utan statistiskt signifikanta skillnader. För metaller är koncentrationerna av totalt zink lägre i vissa filter med statistisk signifikans, medan löst zink visar liknande trender. Koncentrationerna av totalt koppar och bly varierar, men avlägsningsgraderna är generellt låga, med några fall av läckage. Analys av näringsämnen visar betydande skillnader i totalt och löst fosfor, där sandbaserade filter visar positiva avlägsningsgrader, medan kolmakadam uppvisar läckage. Former av kväve uppvisar varierande mönster, med vissa filter som läcker kväve.

Sammanfattningsvis observerades inga signifikanta trender mellan in- och utflöden för totalt och löst bly (Pb), koppar (Cu), zink (Zn) och kadmium (Cd). Detta kontrasterar mot tidigare litteratur, som konsekvent visar god avlägsnande av metallföroreningar. Vad gäller näringsämnen presterade kolmakadam med växter (SSB+PL) dåligt, med högre nivåer av fosfor, totalt kväve och nitrit/nitrat än inflödet, vilket tyder på läckage av näringsämnen. Det kan därför inte rekommenderas att använda detta filtermaterial i Stockholmsområdet eftersom recipientvattnet, Mälaren, är extra känsligt för höga näringsbelastningar. Sandbaserade filter presterade bättre än kolmakadam i avlägsnande av TSS, vilket understryker vikten av filtermaterialet. Dock förbättrade inte filtren överlag signifikant kvaliteten på dagvattnet.

Eftersom liknande studier har gett bättre resultat med liknande filtermaterial och uppställningar kan de dåliga resultaten i denna studie bero på potentiella konstruktions- eller designfel, inklusive felaktiga lutningar, läckage och oregelbunden vattenfördelning, vilket påverkar filtrens effektivitet. Resultaten understryker behovet av ytterligare undersökningar av faktorer som påverkar prestandan hos biofilter för att optimera deras positiva miljöpåverkan.

Abstract

As the urban population keeps growing urban areas become larger and with that the need for urban stormwater management increases. The large number of impervious areas not only lead to high peak volumes and flows but also lead to an increase in stormwater pollution. This pollution usually ends up in open water where it may have detrimental effects for the natural environment. There are several types of quality treatment facilities that may be implemented to reduce pollution, one of the most popular being bioretention, also known as rain gardens or biofiltration. Bioretention facilities can have different design based on the regional climate or intended design objectives. This has lead to a need to research which filter materials and configurations work best in different scenarios. This study focuses on the impact of filter material and vegetation on the removal of total suspended solids (TSS), Turbidity, Nitrogen, and phosphorus as well as the heavy metals: Zinc (Zn), Copper (Cu), Lead (Pb), and Cadmium (Cd) (Total and dissolved).

The study compares two filter materials, one which is sand-based and one structural soil amended with biochar. Furthermore two out of four filters had plants, one of each filter material. The study was conducted in-situ in Sätra, Stockholm. Sample collection was done on natural rain events during the period 02/10/2022 and 03/07/2023 on 11 different rains. Composite samples were taken from one inlet point to one of the filters and all four outlet points.

Results showed that Total Suspended Solids (TSS) concentrations in influent water were slightly higher than in effluent from certain filters, with no statistically significant differences. For metals, total zinc concentrations were lower in certain filters with statistical significance, while dissolved zinc shows similar trends. Total copper and lead concentrations vary, but removal rates were generally low, with some instances of leaching. Nutrient analysis reveals significant differences in total and dissolved phosphorus, with sand-based filters showing positive removal rates, while structural soil and biochar filters exhibit leaching. Nitrogen forms variable patterns, with some filters leaching nitrogen.

In conclusion, no significant differences between input and output were observed for total and dissolved lead (Pb), copper (Cu), zinc (Zn), and cadmium (Cd). This contrasts with previous literature, which consistently has good metal pollutant removal. In terms of nutrients, the structural soil and biochar filter with plants performed poorly, exhibiting higher phosphorus, total nitrogen, and nitrite/nitrate levels than the influent, suggesting nutrient leaching. It may therefore not be recommended to use this filter material in the Stockholm area since the receiving water body, Mälaren, is extra susceptible to high nutrient loads. Sand-based filters outperformed the structural soil and biochar filters in removing TSS and lowering turbidity, highlighting the importance of filter material. However, overall, the filters did not significantly enhance stormwater quality.

As similar studies have yielded better results with similar filter materials and setups the poor results in this study may be due to potential design and construction flaws, including poor slopes, leakage, and irregular water distribution, impacting filter effectiveness. The findings underscore the need for further investigation into the factors influencing the performance of bioretention filters to optimize their environmental benefits.

Table of Contents

1 Introduction 5
1.1 Aim and objectives 7
1.2 Delimitations 7
2 Literature review 8
2.1 Stormwater and stormwater management 8
2.2 Pollution sources 8
2.3 Pollutants in stormwater 9
2.4 Stormwater quality treatment 13
2.5 Bioretention, biofiltration 14
3 Methods and materials 19
3.1 Test site 19
3.2 Specifics of stormwater biofilter 20
3.3 Sampling procedure 22
3.4 Sample analyses 23
3.5 Data analyses and calculations 26
4 Results 27
4.1 Precipitation data 27
4.2 Means and standard deviations. 28
4.3 Total suspended solids and turbidity 29
4.4 Metals 30
4.5 Nutrients 34
5 Analysis and discussion 38
5.1 Metals 38
5.2 Nutrients 39
5.3 TSS and Turbidity 40
5.4 Influencing factors 40
6 Conclusions 42
7 Recommendations for further investigations and research 43
8 References 44

1 Introduction

Currently, 55% of the world's population lives in urban areas. Projections show that this is expected to increase to 68% by 2050. Since the global population is also steadily growing the number of people living in urban areas is projected to increase by 2.5 billion. With an increasing urban population, ensuring sustainable urban development will have to be prioritized (UN, 2018).

To ensure sustainable development, the UN has created the sustainable development goals. Several of them pertain to water management and in turn stormwater management. The goals are most pertinent to stormwater are:

(UN, 2024)

With an increased urban population, the fiscal area of urban communities will grow. Due to urban development, permeable natural surfaces are converted to impermeable surfaces. This changes what happens with the stormwater. Forested areas allow 70% to 90% of rainfall to infiltrate, the remaining runoff is slowed down further by the resistance created by plants leading to low runoff peaks. In urban areas infiltration is often impossible leading to larger runoff rates ranging from 10% in low density areas up to 95% in ultra urban areas (Davis & McCuen, 2005).

Urban areas produce more pollution as increased runoff volumes lead to increased opportunities for water to detach and pick up pollutants which ultimately end up in natural waterways. Furthermore, urban activity also increases local pollution loads. Ecosystems in receiving waterways are often unable to cope with these pollution loads leading to detrimental effects (Davis & McCuen, 2005). Pollutants that can be found in stormwater runoff are amongst others heavy metals, polycyclic aromatic hydrocarbons, mineral oils, salts and nutrients (Göbel et al., 2007).

To not further degrade the quality of receiving water bodies stormwater from urban areas must be treated. This can be done either through source control, large scale treatment facilities or treating water in connection to the catchment area or pollution source (Lidström, 2020). Source control is a highly effective method which in many instances has already been implemented. This means controlling which pollutants are actually released into the environment through for example upgrading cars or switching from lead-based paints (Lidström, 2012). This method of prevention is mainly applicable to point-source pollution, whereas non-point source pollutants need to be treated at a larger scale.

Large scale treatment facilities are systems where stormwater is combined with the sewer system and all the water is treated extensively in treatment plants before re-release into the natural environment. This method of treatment was implemented in Sweden around the 1950s. Beyond large volumes to treat, the main issue with this system is the large variation in flows leading to the need for overflow systems which may lead to large pollution releases into receiving waters (Lidström, 2012).

The last alternative is treatment which can be implemented either in connection to the pollution sources or catchment areas. The methods for this kind of treatment often fall under the umbrella of low impact development (LIDs), Sustainable drainage systems (SuDS), sponge city and best management practice (BMP) (Fletcher et.al. 2014). However, these solutions need to be designed on a case-to-case basis considering both the quantitative needs as well as the qualitative needs of the catchment area. This leads to several treatment options differing in scale and purpose (Lidström, 2012).

The scale of these implementations ranges from localised (ex. green roofs) to close to the source (bioretention) and larger area collected treatment (sedimentation basin, constructed wetlands). These different scales of treatment all use naturally occurring phenomena such as sedimentation, filtration, adsorption, and plant uptake to clean the stormwater (Lidström, 2012).

Biofilters, also known as bioretention or rain gardens, are quickly becoming one of the most popular technologies to treat pollution in stormwater runoff. (Zhang et al., 2021) They have gained popularity due to being small in size, their relative cost effectiveness and their provided aesthetic benefits (Spraakman et.al. 2020). The system is typically placed at or near the source and consists of a vegetated basin or trench containing a soil and/or sand-based media for filtration. Through the filter the stormwater is subjected to several treatment processes such as sedimentation, filtration, adsorption and biological uptake. The specific quality of the treatments and the overall pollutant removal depends highly on design and configuration of the filter (Zhang et al., 2021).

Furthermore, design objectives for bioretention differ based on regional climate, local legislation and site specific needs. Whilst laboratory scale experiments are reliable and more easily replicable the results from these studies may be difficult to translate to real life applications (Spraakman et.al. 2020).

The soil media in bioretention cells is the primary element that affects the efficiency of said cell. For most research the soil media type is chosen based on local regulations or common guidelines. However, these guidelines may not always deliver the most optimal results. Furthermore, many different amendments may be used to optimize results further (Spraakman et.al. 2020).

Although vegetation is commonly used in bioretention the effect of vegetation on the performance of the bioretention is not often discussed. A large percentage of the reported result of biofilter research was pertaining to hydrological and water quantity processing in contrast to the research and results on water quality and contamination (Spraakman et.al. 2020). Based upon these three aspects there are still knowledge gaps existing within the bioretention framework.

1.1 Aim and objectives

The aim of this thesis was to further expand the knowledgebase on the function of biofilters on stormwater quality. In this case in particular the effects of filter material and plants on the performance of biofilters located in a Swedish climate were evaluated.

The objectives of the study were as follows:

- How effective are the different biofilter media at removing pollutants compared to each other?
- How does this configuration compare to other studies?
- What percentage of pollutants are removed from the stormwater through the biofilter?

1.2 Delimitations

The study was limited to four (4) filters, with different designs through filter media and plants, located in Sätra in Sweden in the outskirts of Stockholm. To evaluate the quality of influent and effluent water, 11 rain events were sampled.

The study was limited to measuring the pollutants total suspended solids (TSS), Turbidity, Nitrogen, and phosphorus as well as total and dissolved concentrations of the heavy metals: Zinc (Zn), Copper (Cu), Lead (Pb), and Cadmium (Cd).

2 Literature review

2.1 Stormwater and stormwater management

Due to human activity affecting the natural water cycle, urban drainage systems are needed in developed areas. The two main ways humans effect the cycle is by taking water from the cycle to provide for human life and the change of land use. In nature or near-natural areas when water falls on a surface some water returns to the atmosphere through evaporation, or transpiration by plants, some infiltrates through the surface and some runs off the surface. Depending on the surface, the proportions in which this happens changes (Butler & Davies, 2011).

In urban areas infiltration is reduced due to the addition of impervious surfaces. Tree removal, surface levelling, soil flipping, and surface compaction are also likely to reduce infiltration and increase stormwater runoff. The high number of impervious surfaces in urban areas lead to higher peak flow and volumes (Butler & Davies, 2011).

Other than quantity the quality of stormwater is also impacted by urbanization. Urban land surfaces are subject to the build-up of pollutants during dry weather, much of which can be attributed to human activity. During rain, these pollutants are washed off into receiving water bodies deteriorating the water quality (Butler & Davies, 2011, Akan & Houghtalen, 2003). This non-point pollution is the primary source of water quality impairment in the United States and many other countries (Akan & Houghtalen, 2003).

Historically stormwater management has been about leading away runoff as quickly as possible from the urban area to the receiving water. From the middle of the 70's stormwater management has instead started focusing on long term sustainable stormwater management. In order to reach this objective not only should quantity be considered but also quality. Even later values such as biodiversity, aesthetic and recreational values of water were also incorporated into sustainable stormwater management (Lidström, 2012).

2.2 Pollution sources

The contamination of stormwater depends on the contamination of the rain as well as the pollutants that the rain can wash away from different surfaces. The runoff water has a highly varying quality depending on the surface, for example roads, roofs or gardens (Lidström, 2012). According to Müller et al. (2020) the major pollution sources are atmospheric deposition, vehicular transportation related activities and metallic building envelopes. These sources have also been studied in far greater detail than other sources due to their early identification as major sources.

Rapid advances in clean manufacturing and pollution control have lead to some literature being considered as historical data. Müller et al. (2020) discuss pollutants based on the sources that emit them covering drainage surfaces such as roads, building materials, parks and lawns separately from linked activities such as vehicular transport, road maintenance, gardening and washing of buildings and structure surfaces. They also touch upon pollution released by the urban drainage system from ex. green infrastructure, stormwater control measures, misconnections and pipe materials (Müller et al., 2020).

2.3 Pollutants in stormwater

2.3.1 Particulates

Particulates in stormwater are more commonly referred to as total suspended solids (TSS). It is a common parameter to analyse in stormwater research and is an important factor for classifying stormwater quality. The particles can affect both the function of stormwater systems as well as the water quality in recieving waters and is therefore often a basis when selecting and designing stormwater systems. Two of the largest sources of particulate matter are road surfaces and construction sites. The structure of TSS varies largely both in particle size, density, shape, and chemical and biological characteristics (Viklander et al., 2019).

TSS are linked to pollutants such as phosphorus, nitrogen, organic compounds, and heavy metals. The particles function as carriers for other pollutants that adhere to the particle surface. This makes the origin of the suspended solids of upmost importance since it influences the pollutants it can carry. These pollutions come from anthropocentric sources such as for example traffic (Viklander et al., 2019; Wakida et al. 2014). For example, Jai et al. (2004) found 60– 80% of phosphorus and lead, 50– 60% of nitrogen, and 30– 40% of zinc in road runoff to be associated with particulates. They also found that finer particles have a larger amount of sediment bound contaminants. In cold climate countries the quality of stormwater and the sediments present are highly effected by the chosen method for snow management. In places where gravel and sand are used more of sand and gravel is present in the stormwater from snow melt (Viklander et. al., 2019).

2.3.2 Metals

Metals are one of the most common pollutant groups in relation to stormwater. They are hugely widespread and serve many purposes. Metal pollution was earlier associated with large industries and manufacturing but in the western world pollution from these sources has decreased heavily due to regulations and improved standards (Viklander et al. 2019). Another reason for less pollution from factories in the western world may be due to relocation of heavy industries to other parts of the world. Corrosion and consumption of wares are the most common pollution sources today. Traffic and metallic building envelopes are often quoted as large sources of metal pollution. Metals are of great interest in stormwater research due to being widespread as well as having a large potential toxicity. The most studied metals are zinc, copper and lead followed by cadmium, chromium, and nickel as these are most prevalent. Metals may be toxic to aquatic life but in high concentrations can also be toxic to humans and other animals (Viklander et al. 2019).

Søberg (2014) found that the concentrations of heavy metals in stormwater usually fall in the following intervals when conducting a review of the literature about the subject:

Cd: <0.1 – 15 µg/L;

Cu: <1 – 656 µg/L (< 100 g/L except for four values)

Pb: <1 – 690 µg/L (< 100 g/L except for three values)

Zn: 0.02 – 2000 µg/L (vary greatly)

Cr: 0.1 – 222 µg/L (mainly < 50 g/L)

Ni: 0.2 – 125 µg/L (mainly < 40g/L).

Søberg (2014) also found that low temperatures and runoff from snowmelt increase metal concentrations in stormwater.

Lead - Pb

Pb concentrations have been steadily decreasing in stormwater the last few decades due to the phasing out of leaded gasoline. Lead has also been replaced in other vehicle related uses such as tires and brake linings, lubrication oils and grease, lead based paints and roads and tire balancing weights. However, tires still contain Pb (Huber et al., 2016).

As usage of lead has decreased so have lead concentrations in for example streams from the Baltic sea. In Sweden, the lead concentrations in groundwater have also decreased since the 90s. Already in very low concentrations lead can be harmful for humans and cause damage to the nervous system. Lead can also affect the central nervous system of animals (Naturvårdsverket, 2018).

Zinc - Zn

According to Huber et al. (2016), zinc concentrations around the transport sector have neither decreased nor increased during the last decades. However according to a Naturvårdsverket (2018) in Sweden the total emission of Zinc in the air has decreased by around 40% since the 1990s. The burning of biomass for electricity and heat is the single largest source to zinc pollution in the air (Naturvårdsverket, 2018). Zn is used for galvanized car part and safety rails as well as in structural elements, batteries, tires, brake linings, and motor oils and grease. The highest pollution loads are due to corrosion of galvanized elements and site-specific traffic conditions that affect brake and tire wear. (Huber et al. 2016, Naturvårdsverket, 2018).

Zinc forms relatively strong complexes with dissolved organic Carbon (DOC) and is mostly dissolved only at low pH-values (Naturvårdsverket, 2018). In 2005, Zn was identified as an element of increasing concern due to it being the second highest heavy metal concentration after Fe in most dust, air, and water samples (Preciado and Li (2005) in Huber et al, (2016)). Zinc is needed in small amounts for animals and plants but in larger quantities it can become toxic (Naturvårdsverket, 2018).

Copper - Cu

Copper is present naturally bonded in different minerals, dissolved in water or in the ground and sediments. In Sweden, the largest contributor to copper emissions is the transport sector. A large part of the emissions come from brake pads. These emissions

are predominantly to the air but accumulate on different surfaces and are then washed off and transported by stormwater (Naturvårdsverket, 2018).

The effects of copper depend on the form in which it is which determines its bioavailability. Predominantly aquatic flora and bacteria and microorganism in soil are negatively impacted by copper. Humans are mainly exposed to copper through food and water. Too high intakes of copper can lead to nausea and vomiting and other stomach and intestinal related issues as well as liver damage in some cases (Naturvårdsverket, 2018).

Cadmium – Cd

Since cadmium exists naturally in Swedish mountain ranges low background concentrations are present in soil and groundwater. Nowadays the use of cadmium in Sweden is highly regulated and most cadmium that reaches the air is due to combustion of fossil fuels, trash, metal production and the paper industry. High concentrations of cadmium in the air have been observed in urban areas where the cadmium is bound to particles. This cadmium can later enter into the stormwater (Naturvårdsverket, 2018).

According to Naturvårdsverket (2018) cadmium in water is mainly present in dissolved ion-forms, in complexes with inorganics and in complexes with organics. At low pH cadmium more easily leaches from soils. Cadmium also binds loosely to soil particles making them easier for plants to absorb. Cadmium is harmful for the environment and inhibits chlorophyll production in plants. High cadmium halts can cause damage to kidneys, lower bone density, increase risk of hormonal cancers and heart disease in humans. Furthermore, high cadmium halts may affect the reproduction of animals (Naturvårdsverket, 2018).

2.3.3 Nutrients

Phosphorus - P

Produced phosphorus is used as fertilizer (90%) and in metallurgy to make pyrotechnical products, cleaning agents and medicine. Phosphorus is a natural compound present in all living things. Phosphorus mainly enters natural waters through runoff from artificial fertilizer, industries, washing and cleaning agents and private drains (Naturvårdsverket, 2018).

Along with nitrogen high phosphorus levels in natural waterways may lead to eutrophication and the subsequent detrimental environmental effects. This eutrophication is mainly due to cyanobacteria experiencing rapid massive growth, When the cyanobacteria die off, toxins can be released into the water leading to diseases or death in animals (Naturvårdverket 2018; Li & Davis, 2016).

For humans, high phosphorus intake could lead to kidney damage and may affect the skeletal system (Naturvårdsverket, 2018). Phosphorus in urban runoff is present in dissolved forms and phosphorus associated with particulate matter. The dissolved forms are mainly organic phosphorus and phosphate (Li & Davies, 2016).

Nitrogen - N

Excessive nitrogen pollution has been globally identified in a large portion of water bodies and is only predicted to intensify in the future due to future land use activities. High nitrogen loads in urban runoff and flood water can lead to eutrophication and

algal proliferation in natural waterbodies. This negatively impacts the environments, human health, and the economy (Li et.al. 2023).

Nitrogen concentrations are dependent on land use activities. Sources of nitrogen in stormwater vary but are mainly atmospheric deposition, anthropogenies such as fertilizer, automotive detergent and pet litter and organic materials such as leaf litter and grass clippings (Li et.al. 2023).

Nitrogen is present in both organic and inorganic forms and is crucial for biological life. Nitrogen can occur in several forms in stormwater, including inorganic forms such as ammonium, nitrite and nitrate as well as organic forms such as dissolved organic nitrogen and particulate organic nitrogen. Later studies have shown that a large portion of the nitrogen in stormwater is organic nitrogen (Jani et.al. 2020). Nitrogen has a complex biogeochemical cycle and is difficult to remove due to its high solubility. The process of nitrogen removal is often slower than the removal of other pollutants. Effective nitrogen removal is highly dependent on physical processes, biological processes, and chemical reactions (Li et.al. 2023). The main processes include assimilation, absorption, mineralization, nitrification, and denitrification as illustrated by Figure 1.

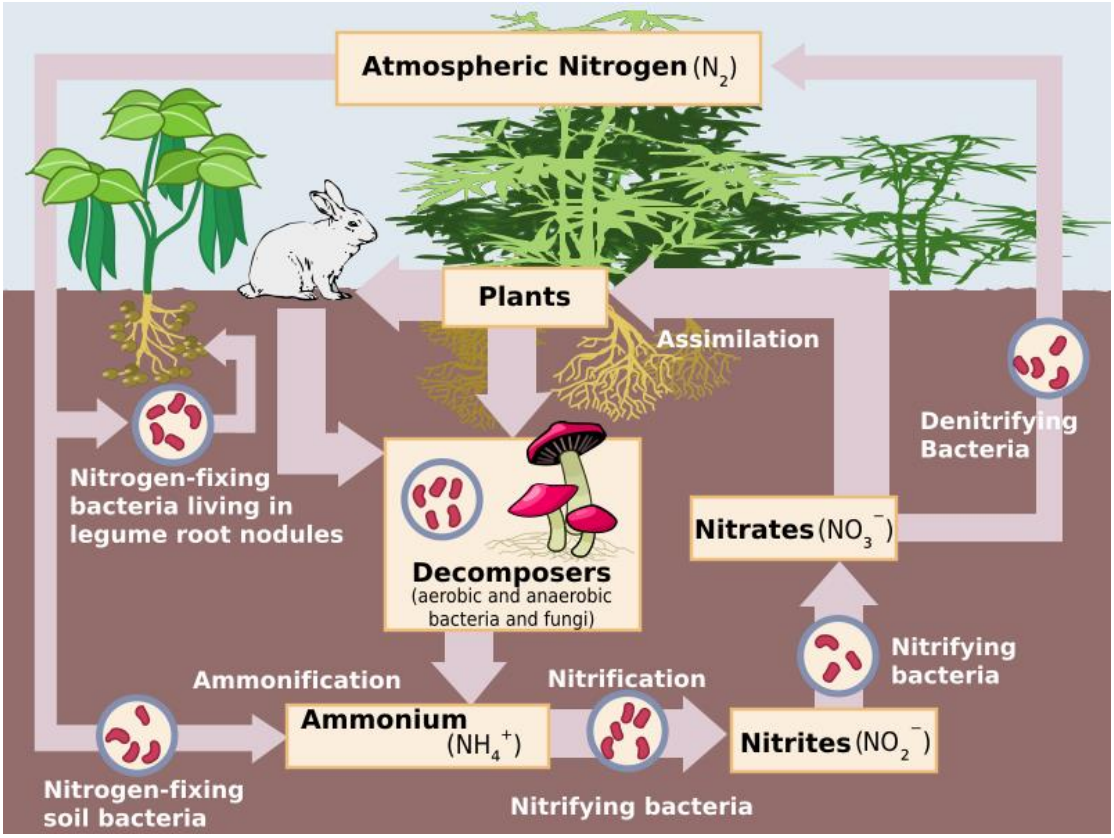

Figure 1: Illustration of the natural nitrogen cycle (Wikipedia, 2024)

During assimilation inorganic nitrogen forms (NH4¬+, NO2- and NO3-) transform into plant biomass through microorganisms and are stored as organic nitrogen. The nitrogen is temporarily stored in plants and may be released again by decaying plant mass. In mineralization organic nitrogen is converted to ammonium (NH4¬+). Nitrification is defined as biological oxidation of ammonium to nitrate with nitrite.

Denitrification is a process where nitrate is converted into dinitrogen gas (N_2) which is later released into the atmosphere or fixed to plant roots. A process of anaerobic ammonium occurring in anoxic condition also exists where ammonium oxidates to N_2 gas using NO_2 (Osman et. al. 2019, Li et.al. 2023).

2.4 Stormwater quality treatment

There are several techniques and types of facilities that can be used to treat pollution in stormwater runoff. When choosing which system to implement the status of the receiving water, the expected pollutions and the phases of the particulates must be considered. Since stormwater management simultaneously deals with quantity and quality a balance between the two must also be stricken when choosing which technique to implement. The techniques most commonly used today fall under the umbrella of LIDs (low impact development), SUDS (which are concepts that share similar values but have different names in different part of the world). The similar values are about:

The below techniques are the most commonly used for quality improvement but may in some cases also have quantity control possibilities. They are presented from the smallest to largest facility (Blecken, 2016).

Filters in manholes

Filters in manholes require a large amount of maintenance and the quality improvement can vary largely depending on manufacturer. However, it could be a viable way to treat stormwater.

Swales

Swales are one of the simplest and rudimentary stormwater treatment facilities to improve quality as well as lower peak flows. Treatment from swales alone is not a complete treatment system but may provide a good pre-sedimentation treatment before other facilities.

Green roofs

Green roofs effectively delay water runoff but do leach nutrients in many instances. Results regarding metals vary highly, but due to high retention volumes outgoing concentrations are often low.

Infiltration

Infiltration units can under many circumstances effectively clean stormwater. The effectivity is dependent on the material used, the quality of incoming water and the age of the facility. The facility is prone to clogging and may in some instances leach pollutants.

Biofiltration/Bioretention/rain gardens

Biofiltration is a popular and versatile stormwater quality treatment option. Treatment of total metals, phosphorus, suspended materials and micropollutants is generally high. Dissolved metals can also be treated but with a more varying effect. To successfully treat nitrogen a submerged zone is often needed. The most commonly used filter materials are well-draining sand and topsoil mixtures. Plant may be used to further increase treatment possibility. Pre sedimentation is an important amendment to prevent clogging.

Sedimentation basin/pond

Sedimentation ponds utilize sedimentation in order to treat stormwater. This makes them mainly capable of treating TSS and pollutants that may absorb onto the TSS surface. Sedimentation basins need to carefully consider the inflow and outflow options as to prevent resuspension of the TSS. Ponds need to be maintained through sediment removal on a cycle of a couple of years. Sediment from ponds can be rich in bioavailable metals and should be handled with care.

Constructed wetlands

Constructed wetlands utilise sedimentation as well as different biochemical processes to treat stormwater. Through these processes the constructed wetlands are better at treating nutrients and dissolved pollutants than other facilities such as treatment ponds. The effectivity of the wetland may vary over the seasons due to many of the treatment techniques being temperature dependent. Constructed wetlands like other systems need consistent management in order to function properly (Blecken, 2016).

2.5 Bioretention, biofiltration

As the focus of this study is to evaluate the effects of filter material and plants in bioretention, more details are described here. Bioretention is an increasingly popular low impact development interventions for stormwater management. The system is placed close to the source to locally manage the runoff. The technology is intuitive and is therefore widely accepted by the public (Zhang et al., 2021).

A bioretention system, also known as rain garden, is composed of plants and soils and helps filter hazardous particles and metals out of stormwater. The bioretention system utilizes chemical, biological and physical processes to filter stormwater. The stormwater enters the facility through some type of collection and/or inlet structure which typically includes a pretreatment measure. This is to reduce surface clogging as well as reduce filter surface erosion and vegetation smother. The pretreatment can be for example a rock beaching, a sediment forebay or swales, and/or filter strips (Hunt et al., 2015; Söderberg, 2019).

Stormwater inflows often exceed the infiltration capacity of the bioretention facility which is why they usually have a 10-30 cm ponding zone to temporarily hold larger volumes of water. The facility also often includes an overflow system which is located at around 30 cm above the filter surface, which allows water to (untreated) bypass the system into the stormwater collection system in case of excessive stormwater flows (Söderberg, 2019; Pan et al., 2022).

The filter material typically consists of either natural soils or engineered media and is usually a layer of 70 to 90 cm. The filter material needs to have good hydraulic conductivity providing both adequate retention, necessary for adsorption to occur, and infiltration capacity, as well as physical and chemical properties to support plant life, enhance treatment and prevent clogging. Under the filter material is usually a 20-50 cm filler layer followed by a 15 to 30 cm gravel layer (Söderberg, 2019; Pan et al., 2022).

Another usual part of the bioretention system is the vegetation. The vegetation can help to prevent clogging and maintenance and enhances the filter materials porosity. It also supports the growth of biofilm and facilitates the transport of oxygen to the filter

material which enhances microbial activity. Vegetation also directly takes up certain pollutants and has an indirect influence on soil pH (Söderberg, 2019; Pan et al., 2022).

There are two types of bioretention systems. The Anti-seepage type has an impermeable membrane and relies on an underdrain in the gravel layer for drainage; whilst the exfiltration type does not have a waterproof treatment that allows the treated runoff to penetrate into the ground and subsequently the groundwater. The exfiltration system does however often still have an underdrain to ensure proper drainage in the system (Pan et al., 2022).

The runoff flow and volume are controlled partially by the ponding zone which retains water. As well as the slow infiltration into the surrounding ground and an increased possibility for evapotranspiration. The biofiltration system's main purpose is to reduce the number of pollutants in stormwater. The biofilters generally reduce metals, nutrients, and particles such as microplastics. As they are mainly designed for treatment and not volume/flow peak reduction they are often designed based on a maximum of a five year return period rain which in stormwater cases is quite low (Hunt et al., 2015).

Bioretention systems are very flexible in terms of design in both size, shape and appearance making them easily integrated into various landscapes. They also provide an aesthetic value for people to enjoy. A large part of the maintenance of bioretention systems are related to the aesthetic values of the system. This means trimming and pruning plants as well as mowing pretreatment areas such as swales. Another important maintenance aspect is preventing clogging of the system. This is both in relation to the bioretention outlet as well as removing biological films and sediment on the surface of bioretention systems. This is done by ensuring the outlets are free from litter and debris as well as removing the top layer of the filtered soil as needed. The need for maintenance can be minimized by incorporating pretreatments (Hunt et al., 2015).

A drawback that may occur if the system is not functioning correctly, or if it is not well-maintained, is that water can stay in the retention area leading to smells as well as mosquitos (Trowsdale & Simcock, 2011). One non quality based advantage to the bioretention system is that the system is very aesthetically pleasing. This aesthetic value can also serve as a tool to reconnect communities to the natural water cycle as well as have a positive impact on the local microclimate. It also provides habitat and protection of biodiversity and is for the most part self-irrigating and self-fertilizing. The footprint of these systems is also relatively small in comparison to their catchment area (Söderberg, 2019; Hunt et al., 2015).

2.5.1 Treatment from bioretention

TSS

Biofiltration systems are generally effective at removing Total Suspended Solids (TSS) with generally over 80% total removal efficiency. With higher efficiency for larger particles, >50 μm. However, new systems may initially leach significant TSS. The removal of TSS may over time lead to a decrease in the filter materials hydraulic conductivity leading to decreased lifespans of the media (Kratky et. al., 2017)

Heavy metals

Generally, the efficiency of total metal removal is at least 80-90% (Kratky et. al., 2017; Søberg, 2014; Blecken, 2010). Søberg (2014) found that outflow concentrations also for the most part seemed independent from inflow concentrations.

Dissolved metals have not been studied in many studies and reported results gave both effective removal as well as leaching. Particulate metals are easily intercepted by filtration media. However, the dissolved metals are mainly removed through medium sorption capacity. Adding organic matter could enhance cation exchange capacity and increase heavy metal removal but can also increase nutrient leaching (Kratky et. al., 2017). Another study found that a saturated zone also is beneficial for removing heavy metals (Søberg, 2014).

Phosphorus

The effects of bioretention on phosphorus concentrations vary widely. In some cases, effluent concentrations are higher than the influent concentration. But there are also cases where reduction has taken place (Qiu & Wang, 2013) (Roy-Poirier, Champagne, & Filion, 2010).

Filtration mechanics such as those present in bioretention are generally sufficient for adequate removal of particulate phosphorus. Dissolved phosphorus removal relies mainly on the mechanics of adsorption onto the media although vegetative uptake and microbial immobilization also are important. Media selection and characteristics are therefore of the upmost importance for the bioretention facilities' phosphorus removal efficiency. The phosphorus uptake via adsorption is dependent on the media's adsorption capacity as well as the medias previous exposure history to phosphorus. Bioretention media such as sand, topsoil and organic components will have an inherent background amount of phosphorus. This phosphorus is in most cases held via adsorption but may also, especially in the organic compounds, be bound as inorganic or organic phosphorus. The media will over time be saturated with phosphorus and will then demonstrate adsorption breakthrough and exhaustion. Meaning no more phosphorus can be adsorbed and it may start leaching into the effluent (Qiu & Wang, 2013) (Li & Davies, 2016).

Adsorption of phosphorus in biofiltration has been linked to amorphous iron oxide and aluminium oxide. Higher levels lead to a greater adsorption capacity of phosphorus. Studies have shown that amending media with iron or aluminium can both increase the adsorption rate of phosphorus in bioretention as well as reduce leaching. Amendments to increase iron and aluminium in bioretention are for example Iron shavings, steel wool, water treatment residuals and fly ash (Li & Davies, 2016).

Nitrogen

Total nitrogen (TN) that enters bioretention facilities is temporarily stored in microorganisms and plants and may eventually be removed through denitrification and optional plant harvest. Nitrogen transformation processes in bioretention can be highly impacted by multiple design criteria and environmental factors. This includes soil saturation rate (presence of a saturated layer), carbon sources, antecedent dry periods, intensity of rain event and presence of plants (Li et.al. 2023) as well as available N, organic carbon, sub-oxic and anoxic conditions and available denitrifiers (Osman et.al., 2019).

Filter media depth plays a significant role in pollutant removal. Deeper filter media achieves greater total nitrogen reduction. Filter media type is also essential for good nitrogen removal in bioretention. The filter material provides microbial conditions and electron donors as well as nutrient sorption. Different particle sizes in filter media further improve nitrogen treatment (Osman et.al., 2019).

There is a significant variance reported of TN removal rates (Li et.al. 2023). Nutrient concentration in filter material before raining affects the variance in the pollution removal via the bioretention system (Osman et.al., 2019).

Lab experiments and some field works support that an internal water storage layer in bioretention enhances denitrification. This due to creating a more consistent anoxic environment. This does however reduce the bioretention volume reduction capacity and increases flood risks (Li et.al. 2023).

Plants also reduce total nitrogen in bioretention (by 59-79%) as well as nitrite/nitrate levels. Although plants enhance nitrogen removal through assimilation, they also contribute to the uptake of 57% of all dissolved N. Plant containing systems achieve a nitrite/nitrate removal rate of 54% compared to 15% for non-vegetated systems. The nutrient uptake from plants is directly influenced by factors such as root structure, density, plant size, biomass growth rate and soil media nutrients. Deeper plant roots increase the assimilation process and thereby increase nitrogen retention. Plant diversity has also shown to increase nitrogen removal (Osman et.al., 2019).

2.5.2 Plants

The role of plants on the quality control aspect of bioretention has been subject to several studies and was early on recognized as a contributing factor.

Several studies showed that vegetation could improve nutrient uptake across a variety of media textures, and that the uptake exceeded plant nutrient needs suggesting other factors at play. Vegetation also helps to prevent clogging of biofilters (Skorobogatov et.al., 2020; Lange, 2021).

Several studies have also shown a linkage between vegetation and improved metal treatment, by affecting soil structure, organic matter amount, pH and the occurrence of preferential flow paths (Lange, 2021).

Only some plant species have the ability to improve nutrient uptake. Studies conducted on the linkage between plant traits and biofilter performance showed that root length, root depth and root mass were the most impactful parameters. Later studies have pointed out the lack of understanding surrounding the processes between vegetation and pollutant uptake which may be the reason for the lack of understanding on the subject (Skorobogatov et.al., 2020).

Plant uptake can be a contributing factor to pollutant removal (especially nutrients) and the uptake is species-specific. Some studies also showed that plants with higher growth rate, extensive root systems and higher biomass could remove more nutrients. The harvest of biomass is however essential since failure to do so may lead to nutrient return due to plant decomposition and litterfall. However, this action itself is argued to sometimes directly lead to leaching (Skorobogatov et.al., 2020).

Plants may also actively take up heavy metals and translocate them to their aboveground tissue. For this purpose, hyperaccumulating plants may be of use.

however non hyperaccumulating plants with high biomass production may also be equally or more effective. (Lange, 2021)

All in all, the literature and studies are inconclusive regarding the role of vegetation in bioretention. (Skorobogatov et.al., 2020)

2.5.3 Biochar

Biochar is pyrolyzed carbon-rich material obtained from plant-based/waste biomass used as an amendment in some biofiltration facilities. Studies suggest it may be a good absorbent of phosphorus due to its high specific surface, has a string binding ability for heavy metals due to an abundance of oxygen functional groups and can be sued as a carbon source to provide an electron donor in denitrification. No consistent evidence that biochar enhances pollutant removal. Improper use of biochar may not promote nitrate removal but will instead hinder denitrification, and an excessive amount of carbon may also lead to nitrogen leaching (Chen et. al. 2022, Song et. al. 2023)

3 Methods and materials

3.1 Test site

The biofilter test site is located in Sätra, Stockholm at the coordinates 59.289248, 17.929440. The biofilters are located in a separation strip between the road, Eksätravägen, and Sätrahallens parking lot. The catchment area is approximately 3300 m^2.

The biofilters are situated in a vegetation strip located between a smaller road and the parking lot, see Figure 2. There are four different biofilters located in the strip.

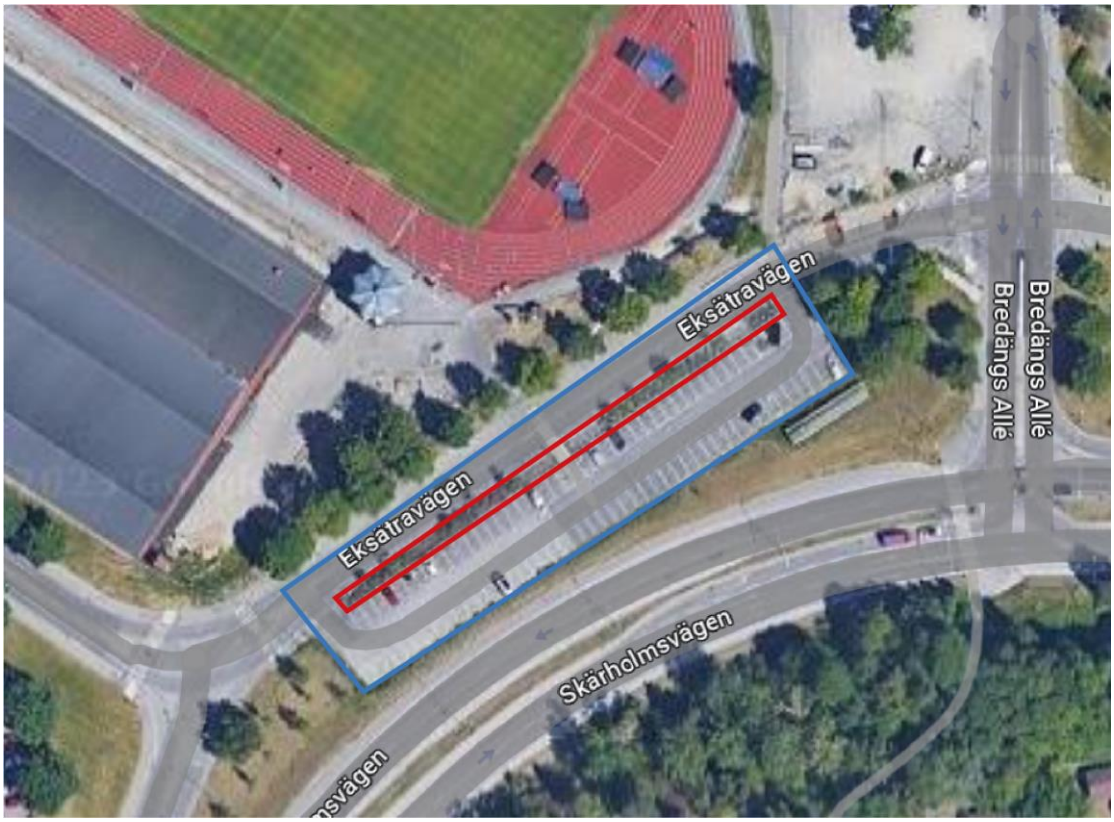

Figure 2: Aerial photo of the area. Catchment area marked in blue and vegetation strip with biofiltration marked in red.

There are two inlets for each filter, one located on the roadside and one on the parking lot side. The parking lot and road were designed with slopes allowing for good drainage to the filters, see *Figure 3*.

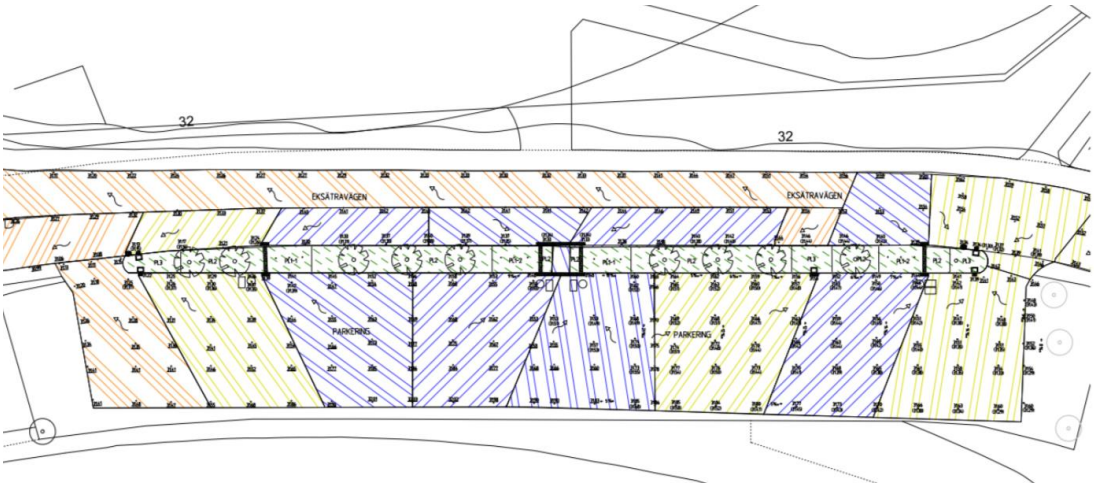

Figure 3: Blueprint of the proposed drainage slopes

3.2 Specifics of stormwater biofilter

The four filters are constructed according to the technical drawings in *Figure 4*. The filters are contained by concrete basins. A corrugated steel channel leads the water from the inlets into the filter. The channels also house a small pre-sedimentation basin. Water can enter the filter when the water in the pre-sedimentation basin is higher than 4 cm. Above the filter material there is space of approximately 10 cm for ponding in case of high stormwater volumes. The filter material is covered by a 6 cm layer of coarse gravel (8-16 mm) to prevent the filter material from being washed away.

The filter material depth is 50 cm. Under this there is a drainage layer with gravel with grain sizes between 2-5 mm. This layer is 50 mm deep and contains a 95 mm drainage pipe that leads water to the outlet which is located in a sampling manhole, *Figure 5*.

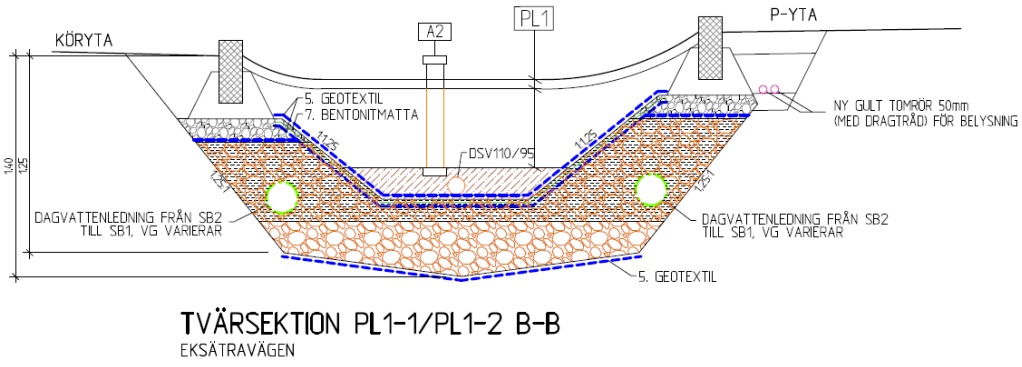

Figure 4: Technical drawing of cross section for the bioretention filters.

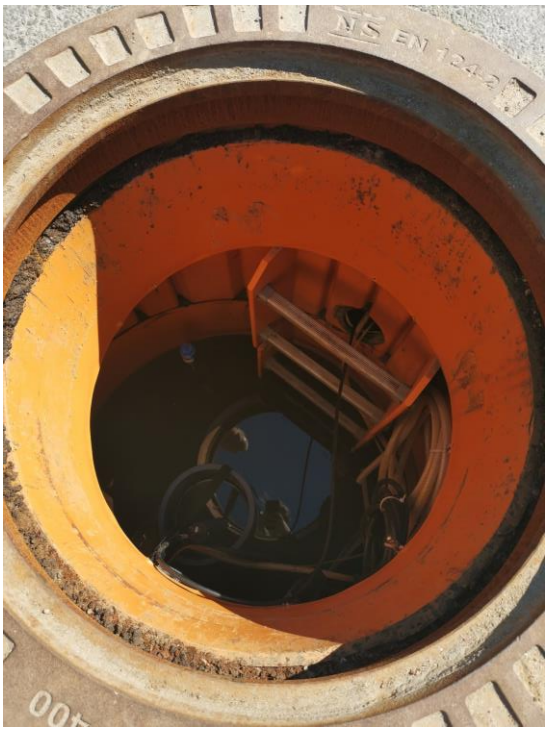

Figure 5: Sampling manhole

The filter material in the bioretention filter is either a sand-based filter material similar to those tested by Träff, (2022) and Fahlbeck (2021) or Structural soil amended with biochar that is used in plantation beds in Stockholm municipality (Stockholm stad2017). Two of the four filters are planted with the species Festuca Ovina, see *Figure 6*.

Figure 6: On the left a filter with plants and on the right a filter without plants. The configuration according to Table 1.

Table 1: Configurations of the tested filters

Number	Name of filter	Filter material	Plants
1	***SND+PL***	Sand-based filter material	Yes
2	***SSB+PL***	Structural soil and biochar (Stockholm stad)	Yes
3	***SND***	Sand-based filter material	No
4	***SSB***	Structural soil and biochar (Stockholm stad)	No

The sand-based filter material consists of sand fractions according to Table 2.

Table 2: Sand fractions in sand-based filter material

Size fraction	Share
0.2-0.5 mm	25%
0.5-1 mm	25%
1-2 mm	25%
2-4 mm	10%
Topsoil	15%

The other filter material is based on the recommendations for structural soil of Stockholm city (Stockholm stad, 2017). This material is amended with biochar. The material has the following mixture of materials:

Table 3: Material fractions in structural soil filter material

Material fraction	Share
Macadam 8-16 mm	75%
Macadam 2-5 mm	12.5%
Compost and biochar	12.5%

3.3 Sampling procedure

Sample collection was done during natural rain events in the period between 02/10/2022 and 03/07/2023. The samples were collected by using ISCO portable samplers. One ISCO unit was used per filter and an additional one was used for influent samples collected at the inflow point of filter 4, samples from this source are denoted SW for stormwater.

The programming of the sampler was based on the weather forecast from SMHI. The samples were taken on a flow-based program meaning a certain volume needed to pass through the filter for the sampling to start and subsequentsamples to be taken. Based on the weather forecast the samplers were programmed to cover the whole rain event. Each sampler was reprogrammed in advance of each rain event to maximize sample collection. For the samples from the filter effluents, samples were taken from the corresponding sample manhole. The samples for the influent were taken directly from the small pre-sedimentation bay at filter 4 see Figure 7.

Figure 7: Inflow sample site, debris was removed before rain events.

Samples were composite samples meaning all samples from a filter were collected in the same 9-L bottle. Meaning the subsequent concentrations were a mean for the whole rain event.

Stormwater from the different rain events was collected and sent to ALS Scandinavia in Danderyd for analysis. The samples were collected from the main 9 L bottle by vigorously shaking the bottle and pouring it over into the sample bottles provided by the laboratory.

3.4 Sample analyses

The analysis by ALS Scandinavia was done both on a sample prepared according to SS 28150:1993 and a sample prepared by filtration (filter porosity: 0.45 µm).

The samples were analysed according to the methods described in Table 4

Table 4: Methods used for analysis of samples

Sample	Method of Analysis
Metals (1), total	Analysis of metals in polluted water with ICP-SFMS according to SS-EN ISO 17294-2:2016 and US EPA Metod 200.8:1994 after digestion.
Metals (1) and phosphorus, dissolved	Analysis of metals in freshwater with ICP-SFMS according to SS-EN ISO 17294-2:2016 and US EPA Method 200.8:1994. Sample is acidified with 1ml HNO3 per 100 ml before analysis.
Total phosphorus	Spectrophotometric determination of total phosphorus with a low reporting limit, P-tot, according to methods based on CSN EN ISO 6878 and CSN ISO 15681-1.
Total Nitrogen (TN)	Determination of total nitrogen in water with catalytic combustion according to SS-EN ISO 20236:2021 ed.1.
nitrite and nitrate nitrogen, sum (NO_2^-, NO_3^-)	Spectrophotometric determination of total nitrite and nitrate nitrogen according to a method based on CSN EN ISO 11732, CSN EN ISO13395, CSN EN 16192, SM 4500-NO2(-) and SM 4500-NO3(-). Filtration of cloudy samples is included in the method.
Ammoniac and ammonium as NH_4 Ammoniac- and ammoniumnitrogen sum ()	Spectrophotometric determination of ammonium, NH4, with low LOQ according to method based on CSN EN ISO 11732, CSN EN ISO13395, SM 4500-NO2, SM-4500-NO3. Filtration of cloudy samples is included in the method.
TSS	Determination of suspended solids according to SS-EN 872:2005 ed. 2.
Turbidity	Determination of turbidity according to SS EN ISO 7027-1:2016 ed. 1.

(1) Metals include Zn, Cu, Pb, Cd, Cr and Ni.

Detections limits for measurements are reported in Table 4.

Table 4: Detection limits

Sample	**Limit of detection**	**Unit**
Zn total	4.0	µg/l
Zn dissolved	0.2	µg/l
Cu total	0.1	µg/l
Cu dissolved	1.0	µg/l
Pb total	0.50	µg/l
Pb dissolved	0.01	µg/l
Cd total	0.050	µg/l
Cd dissolved	0.002	µg/l
Cr total	0.90	µg/l
Cr dissolved	0.01	µg/l
Ni total	0.60	µg/l
Ni dissolved	0.05	µg/l
P total	0.030	mg/l
P dissolved	1	µg/l
TSS	2	mg/l
Turbidity	0.20	FNU
Total Nitrogen (TN)	0.10	mg/l
Nitrite and nitrate nitrogen, sum (NO_2^-, NO_3^-)	0.060	mg/l
Ammoniac and ammonium as NH_4	0.050	mg/l
Ammoniac- and ammoniumnitrogen sum ()	0.040	mg/l

3.5 Data analyses and calculations

The graphical and statistical analyses were done using Minitab. Metals, TSS, Phosphorus and Nitrogen data were presented in individual interval plots with a confidence level of 95%. A one-way ANOVA was performed on the datasets to ascertain means as well as standard deviations. Based upon how large variance is between data groups either a Tuckey pairwise comparison or a Games-Howell statistical analysis was performed to ascertain whether means were statistically significant.

The removal was analysed by calculating percentage removed for each filter and each event. Subtracting the effluent from the influent and then dividing by the influent resulting in a percentage of removal. All effluents were compared to the same influent located by filter 4.

$$Removal\ rate = \frac{C_{influent} - C_{effluent}}{C_{influent}}$$

The data was then presented in individual interval plots with a confidence interval of 95%. In cases were needed a Games-Howell pairwise comparison was performed to ascertain statistical significance.

4 Results

4.1 Precipitation data

Precipitation events and precipitation depths are presented in Table 5.

Rain data presented below is based upon predicted precipitation from SMHI. The number of events measured vary depending on the filter site. The filter at sites 1 and 3 had the fewest sampled rain events as presented in Table 5. The water in the inlet is the untreated stormwater and will therefore be denoted as SW.

Table 5: Data from the measured rain events including precipitation data, duration and measured rain events from the different sampling sites.

Rain event	**Date**	**Duration [h]**	**Rain depth [mm]**	**Data collected from sampler**				
				SW	**1**	**2**	**3**	**4**
A	02/10/2022	19	13.2	x	x	x	x	x
B	17/10/2022	38	10.1	x		x		x
C	18/10/2022	7	5.4	x		x		x
D	18/01/2023	22	10.0	x		x	x	x
E	20/02/2023	18	6.9	x	x	x	x	x
F	27/03/2023	74	20.9	x	x	x	x	x
G	25/04/2023	4	4.6	x	x	x	x	x
H	02/05/2023	20	11.2	x	x	x		x
I	17/05/2023	14	5.1	x	x	x	x	x
J	19/06/2023	21	5.2	x	x			x
K	03/07/2023	38	21.9	x	x	x	x	x
Total	**11**			**11**	**8**	**10**	**7**	**11**

4.2 Means and standard deviations.

In Table 6 and Table 7 means and standard deviations are presented for all pollutant sources and filters. Where SW is the stormwater inlet, SND+PL is the sand-based filter with plants, SND is the sand based filter, SSB+PL is the structural soil and biochar filter with plants, and SSB is the structural soil and biochar filter.

Table 6: Mean values and standard deviations for total and dissolved metals.

		SW	SND+PL	SND	SSB+PL	SSB
ZN_TOT	**Mean**	141.7	97.1	25.94	34.1	147.5
µG/L	**StDev**	86.9	95.3	6.61	32.3	149.3
ZN_DISS	**Mean**	46.7	33.9	6.603	14.21	55.6
µG/L	**StDev**	54.9	59.8	2.535	19.59	108.8
CU_TOT	**Mean**	40.5	54.9	15.56	20.41	33.02
µG/L	**StDev**	35	83.8	5.78	11.5	27
CU_DISS	**Mean**	16.39	18.13	10.68	14.1	16.87
µG/L	**StDev**	19.28	16.91	4.99	6.35	21.9
PB_TOT	**Mean**	4.711	4.37	3.220	2.872	4.2
µG/L	**StDev**	2.593	4.72	1.349	2.457	3.59
PB_DISS	**Mean**	0.304	0.3264	0.3975	0.2661	0.2392
µG/L	**StDev**	0.35	0.1316	0.2348	0.135	0.221
CD_TOT	**Mean**	0.07513	1.42	0.085	0.0831	0.0749
µG/L	**StDev**	0.03059	3.75	0.0341	0.0605	0.0358
CD_DISS	**Mean**	0.02298	0.0495	0.043	0.0488	0.02448
µG/L	**StDev**	0.01496	0.0314	0.032	0.051	0.0198

Table 7: Mean values and standard deviations for TSS, turbidity and nutrients

		SW	SND+PL	SND	SSB+PL	SSB
TSS	**Mean**	142.5	39.8	44.7	61.5	119.5
mg/L	**StDev**	103.8	28.3	28.8	68.4	138.1
Turbidity	**Mean**	178.9	80.6	55.8	59.3	188.8
FNU	**StDev**	104	68.4	29.9	57.6	202.9
P_Tot	**Mean**	0.1935	0.0785	0.07129	0.669	0.2579
mg/L	**StDev**	0.109	0.0524	0.02605	0.344	0.2256
P_Diss	**Mean**	76.2	28.8	29.46	680.1	160.4
µg/L	**StDev**	100.7	21.59	15.04	298.3	217
Nitrogen_Tot	**Mean**	2.301	1.729	2.899	5.83	2.515
mg/L	**StDev**	2.071	0.995	0.662	3.33	1.843
nitrite and nitrate nitrogen. sum	**Mean**	0.455	0.2868	1.682	4.441	0.801
mg/L	**StDev**	0.688	0.1721	0.49	2.856	0.879
Ammoniac and ammonium as NH4	**Mean**	0.1011	0.0953	0.05	0.0508	0.0879
mg/L	**StDev**	0.0935	0.1054	0.00	0.00253	0.0723
Ammoniac- and ammoniumnitrogen	**Mean**	0.0792	0.0745	0.04	0.0405	0.0689
mg/L	**StDev**	0.0718	0.0812	0.00	0.001581	0.0554

4.3 Total suspended solids and turbidity

The interval plot in Figure 8 shows that the TSS concentration in the influent water (SW) is slightly higher than that in the effluent of SND+PL, SND and SSB+PL. The TSS concentration in the effluent water from SSB is approximately on the same level as the influent water. Doing an ANOVA followed by a Games-Howell pairwise comparison analysis does not show that there is a statistically significant difference between any of the means of the samples. Thus, in this study none of the filters have a significant effect on the total suspended solids. The outliers seen in the graph are not from the same rain event.

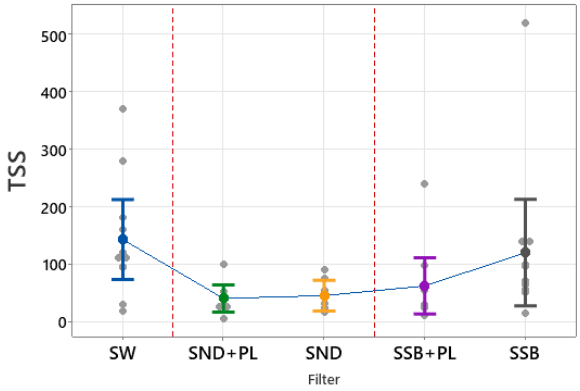

Figure 8: Interval plot of TSS Concentration expressed in mg/l with a 95% confidence interval, individual values indicated with grey dots and mean value indicated by coloured dot.

In ***Fel! Hittar inte referenskälla.*** an interval plot of total suspended solids removal shows no statistically significant difference according to a grouping analysis using the Games-Howell method. However, the two sand-based filters do consistently have positive removal rates whilst the skeletal soil and biochar filters in instances have negative removal rates suggesting leaching of TSS.

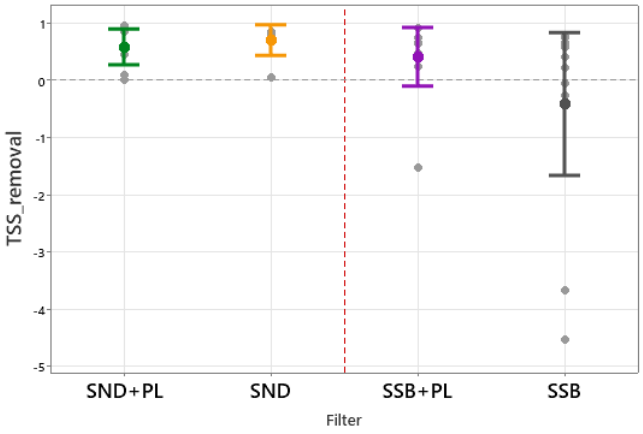

Figure 9: Interval plot of TSS removal rate expressed as a ratio. Individual values are shown in grey and mean and 95% confidence interval in colour.

The interval plot for turbidity, **Fel! Hittar inte referenskälla.**, looks very similar to the one for TSS, which is expected since the two are closely linked. For turbidity the differences are also statistically non-significant.

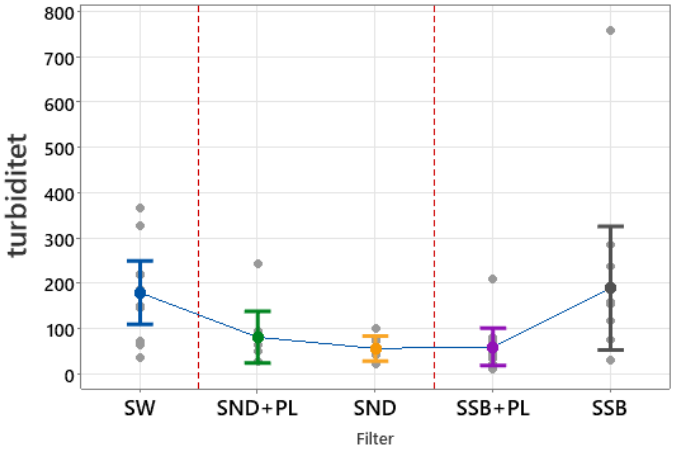

Figure 10: Interval plot of turbidity.

4.4 Metals

4.4.1 Zinc

The interval plot in **Fel! Hittar inte referenskälla.** shows that the concentration means of total zinc are lower in the samples from SND, and SSB+PL compared to SW, SND+PL, and SSB. Although SND+PL has a lower mean than SW and SSB, it is only slight.

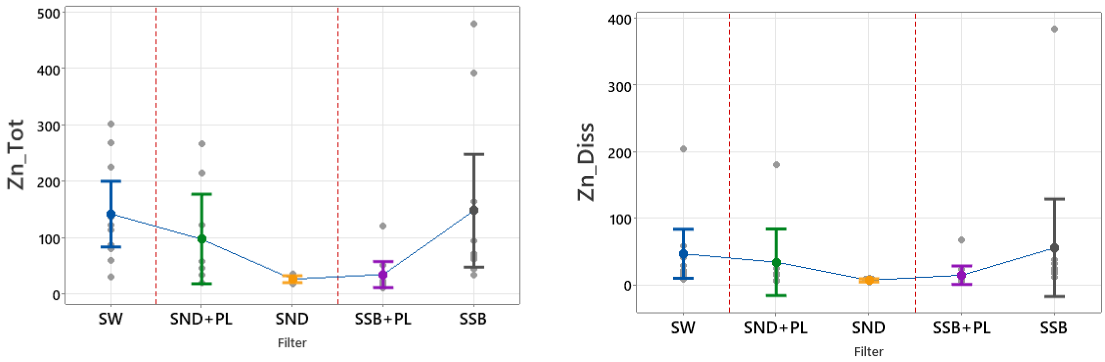

Figure 11: Interval plot of total and dissolved Zinc. Grey dots indicate individual values. Mean, and 95% confidence interval is indicated in colour.

Through a Games-Howell statistical analysis, **Fel! Hittar inte referenskälla.**, it is confirmed that SND and SSB+PL are differed from SW with a statistical significance. However, they do not have a statistically significant difference compared to the other effluents.

Table 8: Games-Howell grouping information on total Zinc samples

Filter	N	Mean	Grouping		
SW	11	141,7	A		
SND+PL	8	97,1	A	B	C
SND	7	25,94		B	C
SSB+PL	10	34,1			C
SSB	11	147,5	A	B	C

Means that do not share a letter are significantly different.

Dissolved zinc shows similar trends as total zinc. However, when performing a Games-Howell method comparison no statistically significant difference between means was found.

From the interval plot in **Fel! Hittar inte referenskälla.**, depicting removal rates, we can observe that for total zinc, SND is the only filter that consistently has a removal rate above zero. However, the mean removal rate for SND+PL and SSB+PL are also positive, with only one instance having a negative removal rate. SSB has a mean below zero and has several instances with negative removal rates.

For dissolved zinc SND still outperforms the others but also has one instance where removal is zero. Otherwise, the results are similar to that of total zinc.

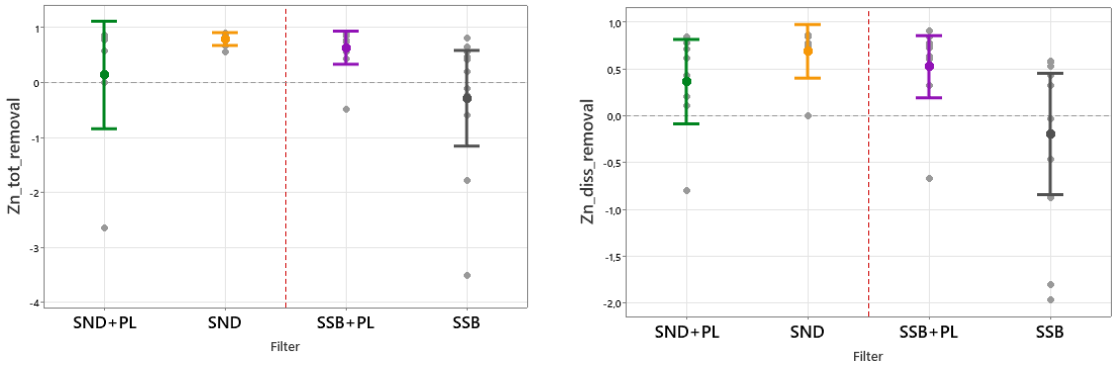

Figure 12: Interval plot of removal rates of total zinc and dissolved zinc respectively. Grey dots indicate individual values. Mean, and 95% confidence interval is indicated in colour.

4.4.2 Copper

From **Fel! Hittar inte referenskälla.** it is evident that the concentration of total copper was slightly higher in SW and SND+PL compared to SND, SSB+PL and SSB. There is a higher variance in the SND+PL dataset compared to the others.

Conducting a pairwise Tuckey and Games-Howell analysis reveals no statistically significant difference between means. For dissolved copper similar results were observed, however, the differences between means were less. A pairwise Tuckey and Games-Howell analysis for dissolved copper did not show statistical significance between groups.

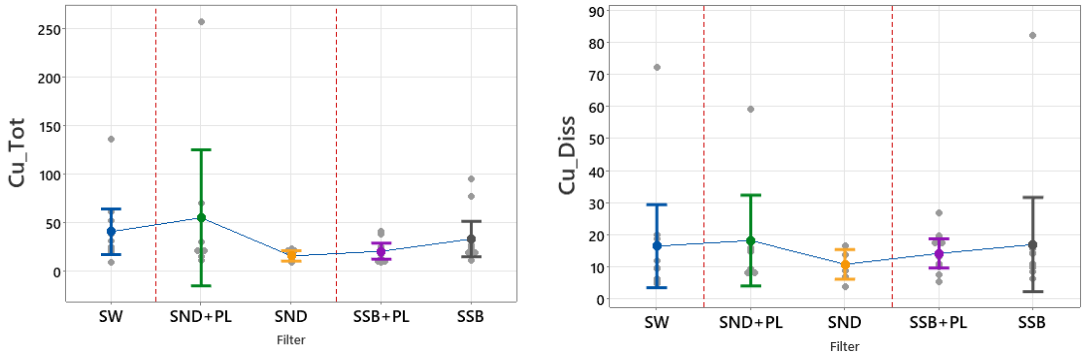

Figure 13: Interval plot of total and dissolved copper in µg/l. Individual values are shown as grey dots and means and confidence intervals are denoted in colour.

Removal rates for copper are very low for all filters as seen in **Fel! Hittar inte referenskälla.**. The maximum observed removal of total copper for a single rain event is 82% from the SND filter, the average for SND is 48% which is also the highest across the different filters.

All filters have instances where the removal rate is negative meaning they at times leach copper. For dissolved copper the rates are more even across the filters however the maximum removal rate does not exceed 50% and all mean values are below zero meaning the mean removal rates are negative.

From pairwise comparisons no statistical significance was seen between filters.

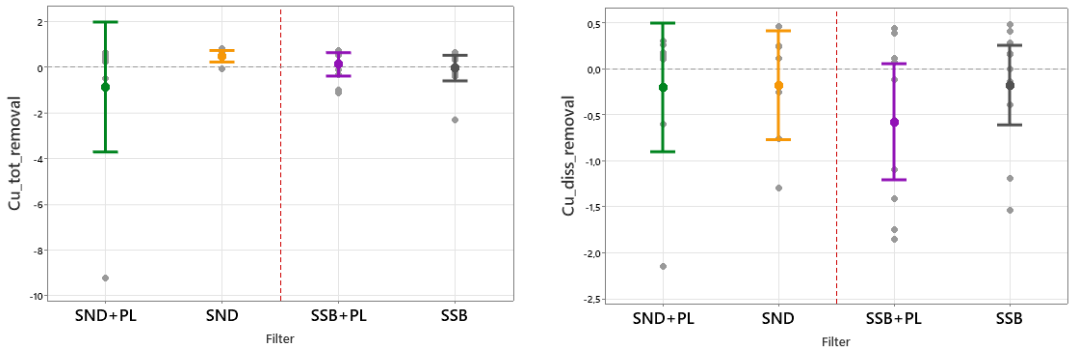

Figure 14: Interval plots of removal rates for total and dissolved copper.

4.4.3 Lead

A Tuckey pairwise comparison and Games-Howell grouping test for total lead did not show any groupings with statistical significance. This is further corroborated by the interval plot, **Fel! Hittar inte referenskälla.**, since the means do not differ much. For dissolved lead we once again have no statistically significant difference between means, and the interval plot in **Fel! Hittar inte referenskälla.** once again corroborates.

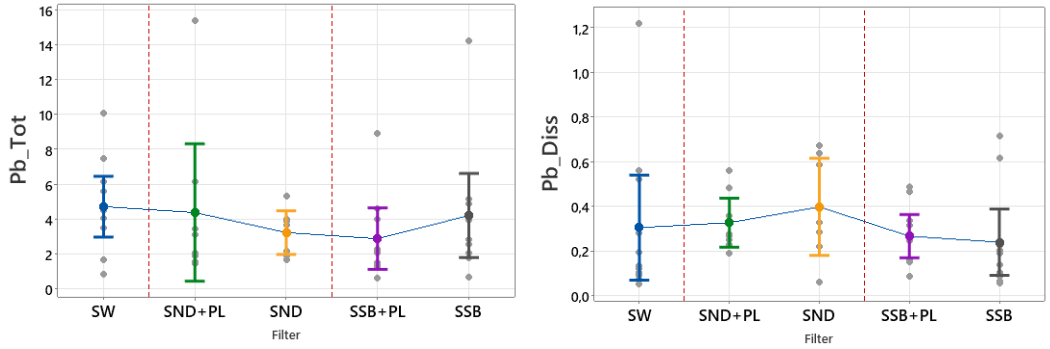

Figure 15: Interval plot of total and dissolved lead in µg/l. Individual values are shown as grey dots and means and confidence intervals are denoted in colour.

Fel! Hittar inte referenskälla. illustrates the lead removal rates through interval plots. Based on this total lead removal rates are around zero. The SND and SSB+PL filters have a positive mean value whilst SSB and SND+PL have a mean below zero. However, all filters have individual values above and below the zero-mark meaning there are some instances where the filters do remove lead and others were lead leaches from the filters. For the dissolved lead all means are below zero suggesting the filters predominantly leach lead in this study.

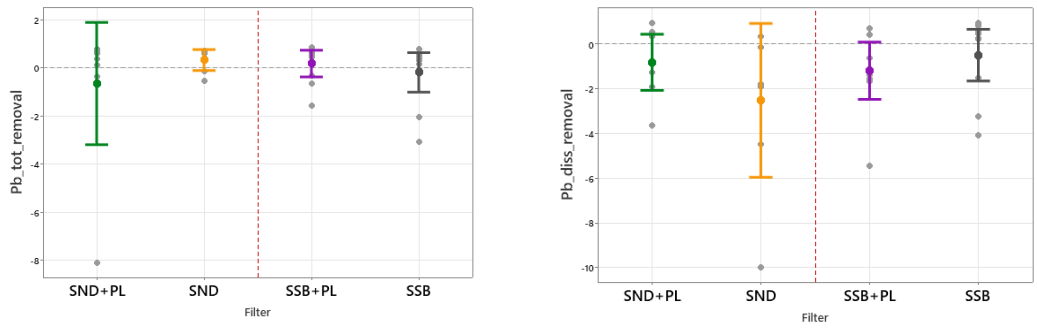

Figure 16: Interval plots of removal rates for total and dissolved lead.

4.4.4 Cadmium

As can be seen in Figure 17 for total cadmium most of the values are at or below the detection limit. Due to this no trends can be seen from this graph. Only SND+PL has a value that is not at the detection limit.

For dissolved cadmium some trends can be seen. The SND+PL, SND and SSB+PL have slightly higher means and variances than SW and SSB. However, there is no statistically significant difference between the means when doing a Games-Howell analysis.

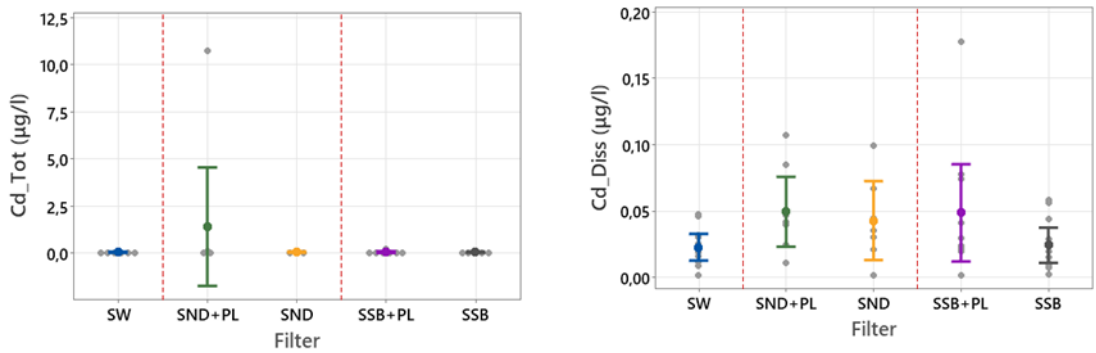

Figure 17: Interval plots for total and dissolved cadmium.

4.5 Nutrients

4.5.1 Phosphorus

Fel! Hittar inte referenskälla. shows data for total (left) and dissolved (right) phosphorus measured in influent and effluent. The interval plots show similar distribution between the filters for total and dissolved phosphorus. SW, SND and SND+PL have similar lower means and variances compared to the SSB and SSB+PL filters. SSB+PL does however have a higher mean than SSB.

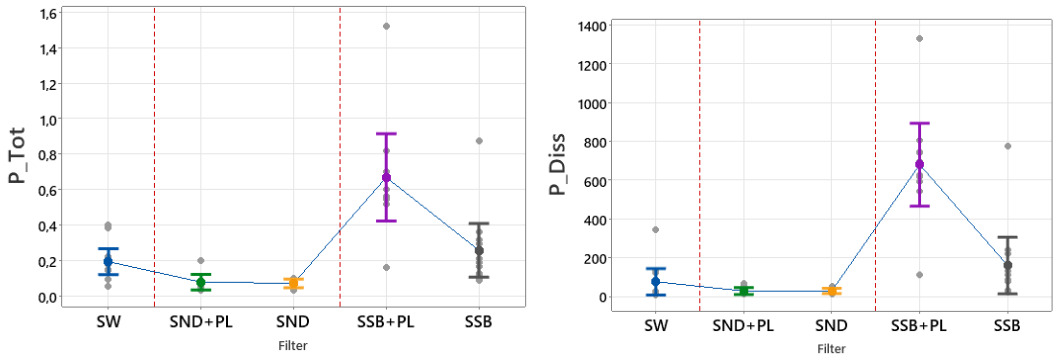

Figure 17: Interval plots of total (mg/l) and dissolved (µg/l) phosphorus.

A Games-Howell comparison on the total phosphorus sample, **Fel! Hittar inte referenskälla.**, shows that the SSB+PL mean is statistically significant different from the others. A statistically significant difference is also observed between the SND filter and SW and SSB+PL. For the dissolved phosphorus SSB+PL is statistically significantly different from the other datasets as can be seen in **Fel! Hittar inte referenskälla.**.

Table 9: Games-Howell grouping information on total phosphorus samples

Filter	N	Mean	Grouping		
SSB+PL	10	0,669	A		
SSB	11	0,2579		B	C
SW	11	0,1935		B	
SND+PL	8	0,0785		B	C
SND	7	0,07129			C

Means that do not share a letter are significantly different.

Table 10: Games-Howell grouping information on dissolved phosphorus samples.

Filter	N	Mean	Grouping	
SSB+PL	10	680,1	A	
SSB	11	160,4		B
SW	11	76,2		B
SND	7	29,46		B
SND+PL	8	28,80		B

Means that do not share a letter are significantly different.

The mean removal rate of total phosphorus is above zero for both sand-based (SND) filters whilst the means for the two structural soil and biochar (SSB) filters are below zero, being -3.99 and -xx for SSB+PL and SSB respectively. The large negative number indicates leaching of total phosphorus from at least the SSB+PL filter but also possibly from the SSB filter. **Fel! Hittar inte referenskälla.**.

The results from the dissolved phosphorus are similar however none of the filters have a mean above zero. Once again seems to be a qualitative difference between the SND filters and the SSB filters.

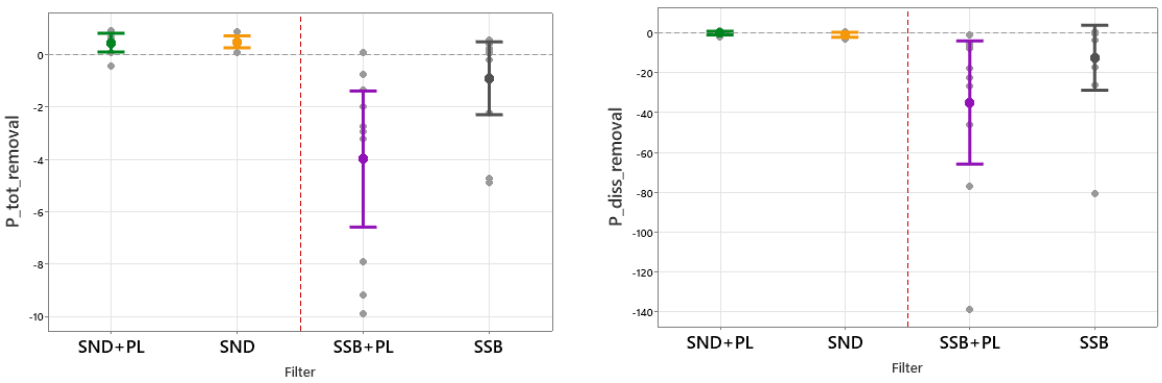

Figure 18: Removal rates of total and dissolved phosphorus.

4.5.2 Nitrogen

Total nitrogen and nitrite- and nitrate nitrogen have similar graphs, **Fel! Hittar inte referenskälla.**, whilst the two different ammoniac-ammonium graphs are similar. Both ammoniac and ammonium graphs have a substantial number of values at/or below their respective detection limits. This suggests that values are very low, and no trends may be observed

The other two forms of nitrogen (total nitrogen and nitrite and nitrate nitrogen) on the other hand have values well above the detection limit. For total nitrogen SSB+PL has a higher mean value than the other sample groups however it is only statistically significantly different from the SND+PL filter as analysed with Games-Howell, **Fel! Hittar inte referenskälla.**.

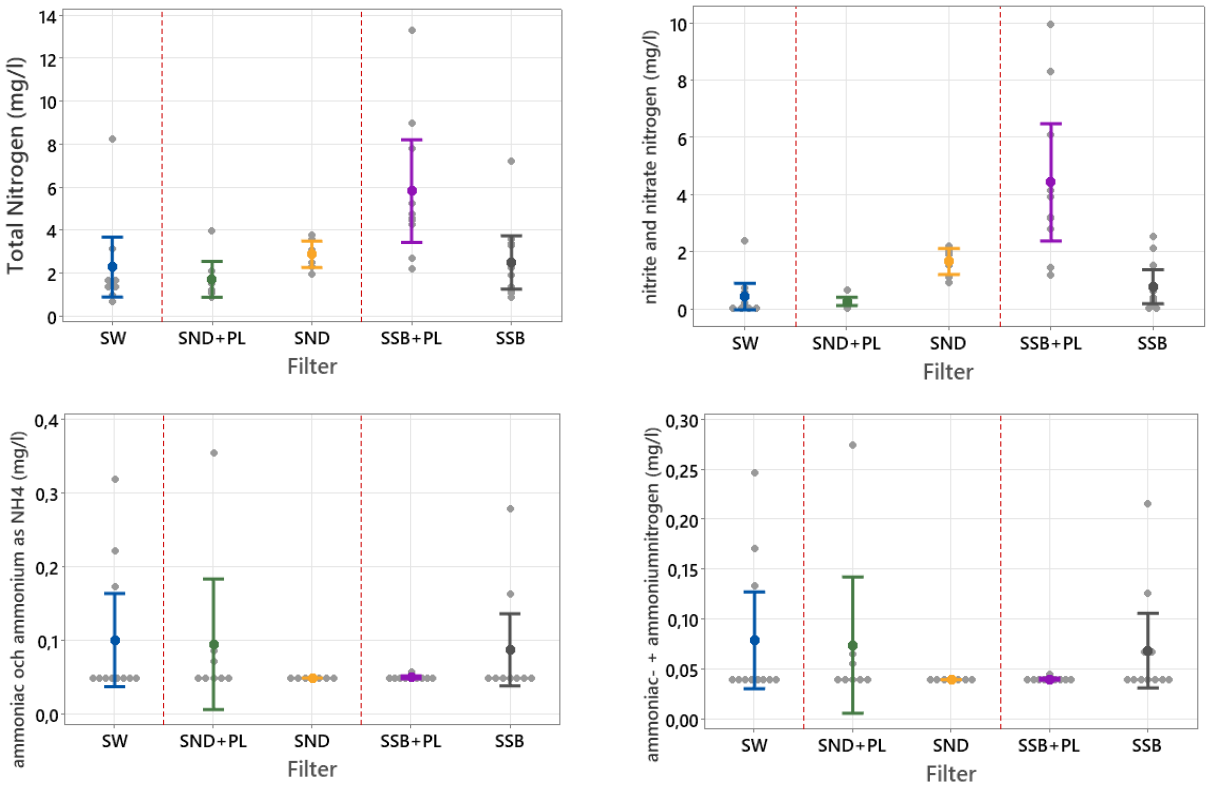

Figure 19: Interval plots of different nitrogen forms in the bioretention unit.

Table 11: Games-Howell grouping information on total nitrogen samples.

Filter	N	Mean	Grouping		
SSB+PL	10	5,83	A		
SND	7	2,899	A	B	
SSB	11	2,515	A	B	
SW	11	2,301	A	B	
SND+PL	8	1,729		B	

Means that do not share a letter are significantly different.

For the nitrite and nitrate nitrogen a Games-Howell grouping shows the groups as seen in **Fel! Hittar inte referenskälla.**. It shows that SSB+PL is statistically different from all other collections points except SND. Furthermore, SND is statistically significant different from SW and SND+PL. With both SSB+PL and SND having higher means than SW it can be assumed that these filters leach nitrogen.

Table 12: Games-Howell grouping information on nitrite and nitrate nitrogen samples.

Filter	N	Mean	Grouping		
SSB+PL	10	4,441	A		
SND	7	1,682	A	B	
SSB	11	0,801		B	C
SW	11	0,455			C
SND+PL	8	0,2868			C

Means that do not share a letter are significantly different.

5 Analysis and discussion

5.1 Metals

In this study no significant differences between input and output have been observed for total and dissolved Pb, Cu, Zn and Cd. This in contrast to the literature presented in literature review where most biofiltration sites consistently had good removal rates.

In the study by Träff (2022) all filters have a positive mean removal rate for total and dissolved zinc whilst in this study one filter has negative mean removal rate. The filters in Träff (2022) study always have a positive removal rate for copper whilst two of the filters in this study have a low or negative mean removal rate. For dissolved copper all mean removal rates are above zero in Träff (2022) whilst in this study they are all negative. For lead, results are similar with Träff (2022) having positive mean removal rates for all filters whilst the SND+PL and SSB filters in this study have negative removal rates. For dissolved lead Träff (2022) once again has positive mean removal rates whilst all of the removal rates in this study are negative.

In Fahlbecks (2021) study mean removal was generally high (59,3%-94%) for total Cu, Pb and Zn which contrasts with this study where leaching was present in several filters and several pollutants. Fahlbeck (2021) does state that removal rates for dissolved fractions were lower, and leaching did occur which may be more similar to this study however in this study both copper and lead only had negative mean removal rates whilst zinc did have some positive mean removal rates.

The influent water did contain pollution loads consistent with the literature presented by Söberg (2014), this suggests that low removal rates where not due to extremely low pollution loads in the influent water.

An indication of whether result from this study would be acceptable in a real life can be gained from comparing the mean concentration of pollutants in the outflow water with guidelines from Miljöförvaltningen Göteborg Stad (2020) presented in Table 13.

The concentration of total zinc from all filters except SND are above the guidelines. For dissolved zinc both SND and SSB+PL filters have values lower than the guidelines. For copper (total and dissolved) the filters SND and SSB+PL have a mean output lower than the guidelines. For lead all filters and the inlet water are below guidelines. For cadmium only the SAND+PL filter has a concentration of total cadmium that is above the guidelines. In this case the concentration in the stormwater (inlet) also was below the guidelines. Overall, the filters may produce acceptable results in regards to heavy metals, however since the filters do in cases leach metals they may not actually improve stormwater quality.

Table 13: Guidelines on pollution concentrations in stormwater from Miljöförvaltningen Göteborg Stad (2020)

Ämne/parameter	Riktvärde
Arsenik	16 µg/l
Bly	28 µg/l
Kadmium	0,9 µg/l
Koppar	10 µg/l
Krom	7 µg/l
Kvicksilver	0,07 µg/l
Nickel	68 µg/l
Zink	30 µg/l
Oljeindex	1000 µg/l 500 µg/l inom Göta älvs vattenskyddsområde 100 µg/l nära råvattenintag (ca 1-2 km uppströms)
Suspenderat material	25 mg/l
pH	6,5-9
Fosfor*	Platsspecifikt vid behov, utgå från 50 µg/l
Kväve*	Platsspecifikt vid behov, utgå från 1250 µg/l

5.2 Nutrients

For total phosphorus the concentration in all filters was higher than the guidelines. Whilst for dissolved phosphorus the two sand-based filters mean concentrations were below the guidelines, Miljöförvaltningen Göteborg Stad (2020). For nitrogen none of the filterers are below guidelines.

Although none of the filter stand out in any positive capacity the structural soil and biochar filter with plants (SSB+PL) performs worse than the other filters. Compared to the influent water the mean value of the SSB+PL filter is 153% higher for total nitrogen, 876% higher for nitrite and nitrate nitrogen, 792% higher for dissolved phosphorus and 245% higher for total phosphorus. This suggests leaching of nutrients from this filter. Since this filter does contain larger amounts of organic material from compost, biochar, and plants this is not entirely surprising. The nitrogen and phosphorus values from this filter also have a substantially higher variance than that of other filters, which could be due to changes in seasonal climate, for example due to seasonal plant decay leading to more phosphorus and nitrogen from the filter. Colder temperatures may also lead to less microbial activity hindering the processes for phosphorus and nitrogen fixation.

Due to the many data points at or below detection limits for ammoniac and ammonium these levels can be assumed to be very low. With the slightly higher values for the filters SND+PL and SSB it might suggest slightly lower levels of nitrification happening in these filters.

Due to the results, it is suggested to not use structural soil and biochar without or especially with plants if the biofilter is intended to treat nutrient pollution in the stormwater. Since the stormwater from this particular site drains into Mälaren, which has to decrease its nutrient concentrations in order to achieve good quality according

to the EUs water framework directives, treating stormwater with a focus on nutrients should be a high priority (Mälarens vattenvårdförbund, n.d.) The widespread use of structural soil and biochar in Stockholm municipalities own plant beds may therefore not be advisable if the plant beds also serve the purpose of stormwater treatment.

5.3 TSS and Turbidity

Comparing the filters total suspended solid concentration to the guidelines from Miljöförvaltningen Göteborg Stad (2020) the concentration from all filters was higher than the guidelines.

The two sand-based filters seem to have performed better at removing both TSS as well as turbidity. The filter that performs worst is SSB, which suggests that the filter may contain particles that are easily washed away with the stormwater. There may be cases in which this flushing out of particles may become lower and disappear over time, however, in some cases the opposite can also happen when particles in the filter are resuspended over time.

For TSS the sand-based filters do deliver improvement whilst the structural soil-based filters do not always deliver improvement. However, since rates do vary between zero and 100% even for the two better filters the improvement is not as significant as compared to similar studies such as those from Träff (2022) where sand based filters consistently removed above 70% of TSS and Fahlbeck (2021) where mean removal rate was 96.9% (SD ±17.6).

Relatively high TSS loads in stormwater may lead to further pollution loads due to the particulate matter being an optimal adsorption site for other pollutants. Since the influent levels of TSS are within normal ranges for similar stormwater research (Blecken, 2010) and previous studies have shown promising results at treating suspended solids, different filter materials or filter construction may have more success at treating the stormwater.

5.4 Influencing factors

Based upon the results above, the conclusion can be drawn that the filters do not significantly increase the quality of the stormwater. Whilst values from some filters and effluents are better than the influent there is no consistent improvement of the stormwater quality.

As mentioned before bioretention in general has high performance pertaining to pollutant removal and studies with similar filter materials, such as Träff (2022) and Fahlbeck (2021). Better results in other studies therefore may not only be due to filter material and plants. Instead, the filter location, construction, study, and setup may have caused these results and will therefore be discussed further below.

Due to the configuration of the filters on the site, water levels entering the filters was often low and therefore prohibited sampling. From observations on site, during rainfall, it was noted that large volumes of rainwater did not actually enter the filters but instead created puddles along the road and at the cross walk. These puddles indicate that the slopes that might have been planned and indicated on drawings such as *Figure 3* and *Figure 4* were not correctly constructed. This is not a unique phenomenon as shown in Beryani et al. (2021) who studied the operational status of twenty-six biofilters located in Sweden. The study showed that several of the filter did not meet their design objectives. As the filter materials in many of the biofilters was

similar the study concluded that the difference in performance was due to the maintenance and construction.

Another reason for the relative low function of the filters may be due to stormwater being able to circumvent the filters. This could be due to the sample manhole not being weatherproof allowing for leakage. The water from the parking lot that is supposed to enter the filters flows right over the manhole, this would mean untreated stormwater entered the samples directly which may have affected the data.

These observations may suggest that the design or construction of these bioretention filters are not ideal for water entering the filters which may influence both the study and the effectiveness of the filters. Further studies into why projects such as these do not reach their design goals should be conducted in order to ensure that the theoretical benefits can be fully obtained.

During the sample period the individual filters also received quite varying amounts of water making comparisons between the filters on site harder. With the irregularity in the amount of water reaching the different filters comparing all effluents with water from one single influent point may further have skewed results. Furthermore, the season was relatively dry which may have contributed to skewed results due to high pollution build up and dry filters. The effects of dry filter material and consecutive dry-days has amongst other been studied in Blecken et al. (2009) where filters performed significantly worse after an antecedent dry period exceeding 3-4 weeks in regards to heavy metal removal. This study also found that introducing a submerged zone could in some part counteract the effect of long dry periods.

6 Conclusions

This study aimed to evaluate the impact of two different filter materials and vegetation types on the pollutant removal efficiency of a bioretention system. The filters in this study, however, did not perform as effectively as those in comparable research. Given that the two sand-based filters used were similar to those in other studies, it is unlikely that the filter material itself was the main factor behind the poorer performance. Differences between the filters were primarily observed in nutrient concentrations, particularly nitrogen and phosphorus. The filter containing structural soil, biochar, and vegetation exhibited worse performance than the other filters. Since the filter with just structural soil and biochar performed better, the findings suggest that the combination of vegetation with the filter material may be responsible for the leaching of nutrients.

The filters also failed to consistently remove pollutants. In fact, for several pollutants—including metals, nutrients, and suspended solids—some filters actually contributed to increased leaching. Given that biofilters in other studies generally report higher removal rates with similar filter materials, the results of this study are likely influenced by additional factors. Potential issues could include poor construction of the filters, runoff characteristics from the surrounding area, extended dry periods, or low inflow volumes into the filters.

These findings emphasize the need for careful consideration when implementing bioretention systems in real-world scenarios, beyond theoretical models. The study also highlights the importance of continuous monitoring and maintenance to ensure long-term functionality. Although a biofilter may appear to be functioning well from the outside, it may not consistently achieve its design goals without proper construction and regular maintenance. The research underscores the challenges of translating theoretical designs into practical applications and reinforces the critical need for meticulous construction and implementation to achieve the intended environmental benefits.

7 Recommendations for further investigations and research

As this study did not produce results in agreement with those of previous studies it would be interesting if further research was done into why this filter did not perform as expected. Due to the suspicions about water circumventing the filters and not entering the filters, studies on why and how this is happening may be of interest. Going in either the direction of: where do the discrepancies between planning and constructions happen and why?; or: how does the water travel, does it circumvent the filters, does it enter other parts of the facility and how can this be prevented.

Another interesting aspect for further research is the effects of seasonal variation on bioretention filters as well as continued studies into how vegetation affects the pollution removal in filter.

Yet another interesting facet to consider may be how bioretention facilities function in periods of low and inconsistent rain and what steps could be taken to ensure good performance after these dry periods.

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