Aalto University
School of Engineering

School of Engineering
Degree Programme in Transportation and Environmental Engineering

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Biofiltration for stormwater management in Finnish climate

Master's thesis for the degree of Master of Science in Technology submitted for inspection, Espoo, 14 October, 2016.

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Abstract of master's thesis

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Title of thesis Biofiltration for stormwater management in Finnish climate

Degree programme Degree Programme in Transportation and Environmental Engineering

Major Water and Environmental Engineering **Code** R3005

Thesis supervisor Professor Harri Koivusalo

Thesis advisors D.Sc. Gerald Krebs, M.Sc. Antti Auvinen

Date 14.10.2016 **Number of pages** 70 **Language** English

Abstract

Stormwater is traditionally drained from the source as fast as possible to receiving waters. However, along with rapidly increasing urbanization, the adverse effects of stormwater on the environment are recognized and new management strategies are developed with the aim to mimic the predevelopment state of urban areas. Relatively new techniques that rely on these kinds of principles are referred to as Low Impact Development (LID) systems in the USA, Water Sensitive Urban Design (WSUD) in Australia and Sustainable Urban Design Systems (SUDS) in the UK.

This study investigated the suitability of one of the LID techniques, biofiltration, for treating stormwater generated on a traffic area in Finnish climate conditions. The aim of this study was to define general guidelines for implementing biofiltration systems in the urban context. Additionally, the goal was to find effective design recommendations for a filtration system, which is to be built in Vantaa in southern Finland to manage and treat the stormwater generated on a new roundabout and its surroundings. Biofiltration systems work also as delaying structures but this study focused primarily on the stormwater quality issues.

This study is divided into literature review and design work. The literature review focused on presenting and comparing implemented biofiltration designs and their performance and the identification of the city areas where biofiltration systems could be integrated. Furthermore, the aim was to find the optimal structure for the conditions of the planned site and define the required reduction rates for selected pollutants by comparing stormwater pollutant concentrations to reference values defined in Stockholm. The information obtained from the literature was applied to practice in the design work.

The design catchment was modeled with the rainfall-runoff simulation model SWMM (*Storm Water Management Model*), the response of the catchment area to rainfall data was analyzed, and the hydrological effects of different filtration structures were modeled. The modeling objective was to identify the correct dimension and the best parameter combination for the designed structure for stormwater management in Vantaa.

The performance of biofiltration as a treatment system for stormwater is based on filtration of water through the soil layers of the structure and partly on the uptake of the nutrients by vegetation. According to literature, biofiltration is capable to efficiently remove heavy metals and suspended solids from stormwater whereas the effectiveness of nutrient removal has been shown to vary more and to be significantly lower. Even leaching of nitrogen and phosphorus from the growth media has been reported in various studies. In addition, proper maintenance of the biofiltration units has been proved to be essential for maintaining the good performance.

Keywords Stormwater quality, biofiltration, stormwater management, SWMM

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Diplomityön tiivistelmä

Tekijä Maria Suihko

Työn nimi Huleveden biosuodatus Suomen ilmasto-olosuhteissa

Koulutusohjelma Rakennus- ja yhdyskuntatekniikka

Pääaine Vesi- ja ympäristötekniikka **Koodi** R3005

Työn valvoja Professori Harri Koivusalo

Työn ohjaaja(t) TkT Gerald Krebs, DI Antti Auvinen

Päivämäärä 14.10.2016 **Sivumäärä** 70 **Kieli** Englanti

Tiivistelmä

Hulevedet on perinteisesti johdettu suoraan vesistöihin ja niiden hallinta on tyypillisesti perustunut nopeaan pois johtamiseen valunnan syntyalueelta. Tiivistyvän kaupunkirakenteen myötä hulevesien haitalliset vaikutukset ympäristöön on kuitenkin tunnistettu ja näiden vaikutusten ehkäisemiseksi on kehitetty uusia, huleveden laatua parantavia hallintamenetelmiä. Veden luonnollista kiertokulkua jäljitteleviin hallintaratkaisuihin viitataan maailmalla hieman sijainnista riippuen joko termeillä LID (Low Impact Development), WSUD (Water Sensitive Urban Design) tai SUDS (Sustainable Urban Design Systems).

Tässä työssä selvitetään erään LID-menetelmän, biosuodatuksen, soveltumista tiealueen hulevesien käsittelymenetelmäksi Suomen ilmasto-olosuhteissa. Tavoitteena on tunnistaa suodatusalueiden suunnitteluun liittyviä keskeisiä seikkoja ja suosituksia biosuodatusalueiden sijoittamiseen kaupunkiympäristössä. Tämän lisäksi tavoitteena on suunnitella Vantaalle biosuodatusalue, jolla tullaan käsittelemään suunnitteilla olevan liikenneympyrän ja sen ympäristön hulevedet. Biosuodatusalueet toimivat myös hulevettä viivyttävinä rakenteina, mutta tässä työssä keskitytään erityisesti huleveden laatuun ja sen parantamiseen.

Työ jakaantuu kirjallisuusosioon ja varsinaiseen suunnittelutyöhön. Kirjallisuusosio keskittyy ympäri maailman tehtyihin tutkimuksiin ja niiden tuloksiin biosuodatusalueiden rakenteesta ja toiminnasta. Työssä tunnistettiin keskeiset parametrit biosuodatusalueen suunnittelussa sekä kaupunkiympäristön kohteet, joiden hulevesien käsittelyyn biosuodatus soveltuu parhaiten. Vantaan biosuodatusalueelle määriteltiin mahdollisimman optimaalinen rakenne-ehdotus. Suunnittelutyön ohella arvioitiin biosuodatusalueelle vaadittava puhdistusteho vertaamalla kirjallisuudessa esitettyjä huleveden laatuparametreja Tukholmassa määriteltyihin raja-arvoihin.

Vantaan biosuodatusalueen suunnittelussa hyödynnettiin SWMM:ia (*Storm Water Management Model*). Suunnittelualueen valuma-alue mallinnettiin ja alueella syntyvä hulevesien valunta määritettiin käytettävissä olevien sadantatietojen perusteella. Mallinnuksen tuloksena biosuodatusalueelle määriteltiin tarvittava koko ja rakenne vertailemalla erilaisia rakenneratkaisuja.

Biosuodatus perustuu pääasiassa huleveden suodattumiseen rakennekerrosten läpi. Kirjallisuuden perusteella biosuodatuksella pystytään poistamaan hulevedestä tehokkaasti metalleja ja kiintoainesta. Sen sijaan ravinteiden osalta puhdistustulokset ovat vaihtelevampia ja jopa ravinteiden huuhtoutumista on havaittu erityisesti vastarakennetuilta, ravinteikkaan kasvualustan sisältäviltä biosuodatusalueilta. Hyvän puhdistustehon saavuttamiseksi ja ylläpitämiseksi rakenteen huolellinen suunnittelu ja ylläpito on todettu tärkeäksi.

Avainsanat Hulevesien laatu, biosuodatus, hulevesien hallinta, SWMM

Acknowledgements

This study was carried out at the Aalto University School of Engineering as a part of the research project *'STORMFILTER – Engineered Infiltration Systems for Urban Stormwater Quality and Quantity, 2015-2017'*. The project is a research project led by VTT (Technical Research Centre of Finland Ltd) in cooperation with Aalto University and University of Helsinki together with 17 Finnish partners covering municipalities, material producers and stormwater management designers.

The project is jointly funded by Tekes (Finnish Agency for Technology and Innovation), industrial partners, VTT and Aalto. Moreover, MVTT (Maa- ja vesitekniikan tuki ry) provided additional funding for this thesis. I am very grateful for all the funding. I also want to acknowledge Finnish Meteorological Institute (FMI) for providing the meteorological data for this study and the city of Vantaa for the spatial and other data required in the planning process.

I wish to thank my supervisor Professor Harri Koivusalo and my instructors D.Sc. Gerald Krebs and M.Sc. Antti Auvinen for all the guidance and valuable feedback during this process. In addition, it is also important for me to acknowledge all the people I met in Aalto and in Vantaa while working with this thesis. Thank you for good conversations and the great company during lunch and coffee breaks.

I would also like to thank Pekka Stén for the several excursions that familiarized me with the branch of water services. Furthermore, I owe gratitude to my parents and siblings for all the support throughout my studies. My dad deserves a special mention for giving me valuable advice especially in the final stage of this work and I would particularly like to express my gratitude to my mom for the patient encouragement during the times I needed it the most.

Finally, big thanks go also to my dear friends, old and new, who have both helped and supported me and provided me for the most welcome counterbalance to the studying. Thank you for sharing with me several memorable experiences, events and trips that have brought lots of joy into the mundane life.

Espoo 4.10.2016

Maria Suihko

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Abbreviations

ADT	Average Daily Traffic
Al	Aluminum
Cd	Cadmium
Cl	Chloride
Co	Cobalt
COD	Chemical Oxygen Demand
Cr	Chromium
CSO	Combined Sewer Overflow
Cu	Copper
DOC	Dissolved Organic Carbon
EMC	Event Mean Concentration
EML	Event Mass Load
Fe	Iron
FMI	Finnish Meteorological Institute
LID	Low Impact Development
Mn	Manganese
N	Nitrogen
Na	Sodium
Ni	Nickel
P	Phosphorus
PAH	Polycyclic Aromatic Hydrocarbons
Pb	Lead
PCB	Polychlorinated Biphenyl
S	Sulfur
SEPA	Swedish Environmental Protection Agency
SWMM	Storm Water Management Model
TN	Total Nitrogen
TOC	Total Organic Carbon
TSS	Total Suspended Solids
US EPA	US Environmental Protection Agency
VDR	Vantaa Design Rain
Zn	Zinc

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1 Introduction

Urbanization alters the natural water cycle. Naturally, part of rainwater returns to the atmosphere through evaporation or transpiration, some of it infiltrates and becomes groundwater and part of it becomes surface runoff. Both groundwater and runoff usually end up in surface water, the latter much faster. These natural processes are disturbed when the landscape is modified and ground is covered with impervious surfaces.

When the natural hydrological system is disturbed and the impervious area increased, runoff rates and volume are increased and runoff travels faster which results in greater peak flows. At the same time infiltration is decreased reducing the groundwater recharge. (Butler and Davies, 2004; Dietz, 2007; Harbor, 1994; Hsieh and Davis, 2005)

A study conducted in Lahti (Valtanen et al., 2014a) indicated that urbanization enhances runoff rates especially during the warm period. Their results also showed that compared to low-density areas, in city center areas the peak flows and average runoff rates are significantly higher during summer period and smaller events produce detectable runoff. However, the differences in the generation of runoff between different land use intensities diminish during the cold season as the runoff-contributing area is enlarged due to freezing of the ground. During the cold season the stormwater quantities can be similar in areas with different imperviousness. Furthermore, the amount of snow melt in city areas is affected by ploughing and the transportation of the snow.

1.1 Stormwater management

Stormwater originates from any form of precipitation that has fallen on a built-up area. If not drained properly, stormwater can cause inconvenience, health risks, flooding and damages (Butler and Davies, 2004). Traditionally, in many urban areas stormwater is drained with artificial systems such as pipes and structures that collect the water and convey it away from the source. In older areas the drainage is generally based on combined sewers that collect both wastewater and stormwater. Hence, increasing amount of stormwater runoff due to intensified urbanization can lead to combined sewer overflows (CSOs) if the available system capacity of the sewer network is exceeded. (Montalto et al., 2007)

Stormwater was first considered as a potential source of pollution in 1980s (Trafikverket, 2011). Stormwater is known to be a significant source of various pollutants including metals and nutrients that can cause deterioration of water quality in streams, lakes and shallow groundwater (Ahiablame et al., 2012; Borris et al., 2014; Dietz, 2007; Hsieh and Davis, 2005). Despite the growing knowledge on urban runoff pollutants, most of the stormwater is still conveyed untreated to surface waters in sewers or open ditches (Valtanen, 2015). For example, in Finland the quality concerns of stormwater have generally been neglected and treatment of stormwater has been focused on its quantitative management. However, increasing concerns have been arisen regarding the effect of stormwater pollutants on receiving water bodies. The earliest city plan where stormwater management has been taken into account in Finland is Gerby's city plan in Vaasa from the year 1983 (Kuntaliitto, 2012). In Vantaa conventional peak flow management was improved and expanded in the early 2000s. In 2009 the city developed its own stormwater program which emphasizes on natural stormwater management and biodiversity conservation. The recent city planning has followed the guidelines of the program.

1.2 Towards the best management practices

Due to realization of the adverse impacts of urbanization and artificial stormwater management techniques, the management objective shifted towards more sustainable options. Improved stormwater management aims to replicate the predevelopment state of the catchment area and is based more on attenuating and retaining stormwater flows as well as improving stormwater quality (Bratieres et al., 2008; Liu et al., 2014). Improved urban stormwater management relies on the best management practices (BMPs) that are land development strategies designed to improve runoff characteristics disturbed by urbanization. The main concept is to treat and reduce runoff naturally as near the source as possible considering also aesthetical aspects (Ahiablame et al., 2012; Hsieh and Davis, 2005). Techniques that rely on these kinds of principles are referred to as Low Impact Development (LID) systems in the USA, Water Sensitive Urban Design (WSUD) in Australia and Sustainable Urban Design Systems (SUDS) in the UK (Bratieres et al., 2008). The first moves towards more sustainable management were taken in Australia already in 1960s when stormwater management was incorporated into greenspace areas (Figure 1) (Roy et al., 2008).

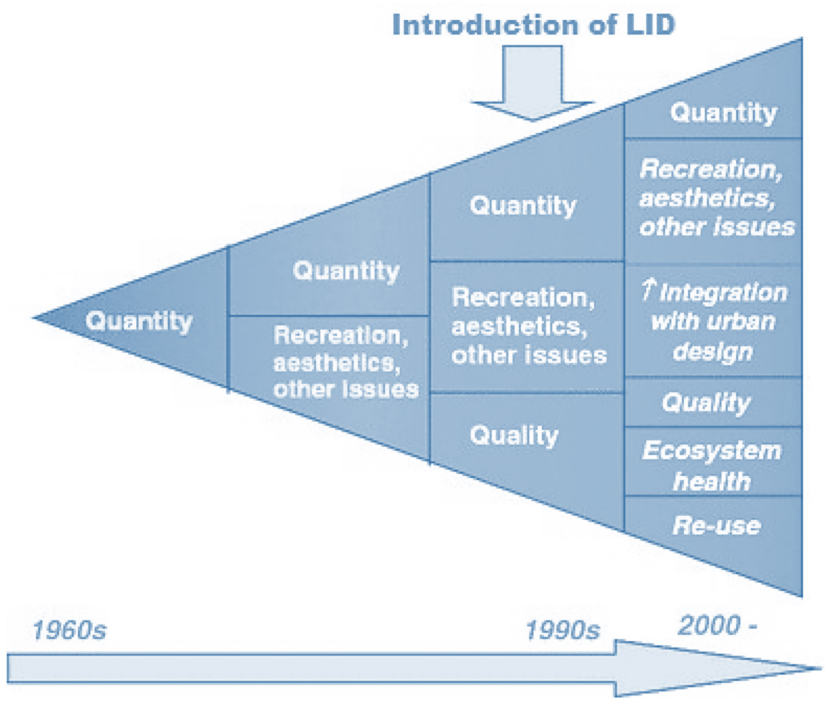

Figure 1 *Development of objectives of stormwater management (adapted from Roy et al., 2008).*

LID practices are used to improve water quality, manage stormwater runoff and protect the environment from the adverse effects of stormwater pollutants. The most commonly utilized structural LID practices are biofiltration, permeable pavement, green roof, and swale systems (Ahiablame et al., 2012). Biofiltration refers to filtration systems that include vegetation. Especially biofiltration is seen as an effective alternative with several advantages. Biofiltration systems can reduce overall flow volumes and attenuate flow peaks and hence help restoring the natural hydrological cycles at some level (Hatt et al., 2009). As summarized by the studies cited above, biofiltration was shown to be an effective treatment method and furthermore, biofiltration cells can rather easily be retrofitted into urban environment where they also serve aesthetic values.

Biofiltration is one of the most popular stormwater control measures and according to many studies it is supposed to be one of the best management practices for pollutant removal (Davis et al., 2009; Hatt et al., 2009; Hsieh and Davis, 2005). However, in Finland biofiltration has not been widely implemented and there are concerns regarding especially its winter performance.

In the literature, biofiltration can also be called as bioretention or rain garden (e.g. Davis et al., 2009). In this thesis, the term biofiltration is used to refer to the various systems that mimic the natural hydrological process of filtration.

1.3 The objectives of the study and study methods

The first objective of this study is literature research on stormwater pollutants and their removal by biofiltration. The reviewed literature summarizes results from scientific articles, databases and other publications. While all related articles are studied, the focus lies on those that report research conducted in rather similar climatic conditions to Finland.

The second objective of the study is, based on the literature review, the design of a filtration system in a traffic area within the city of Vantaa. The catchment area for the filtration unit will mainly consist of a roundabout that is going to be built in eastern Vantaa in a traffic area with an estimated average daily traffic (ADT) of 18 000 at the maximum. In the design process the Storm Water Management Model (SWMM, version 5.1) developed by US Environmental Protection Agency (USEPA), is used to model the filtration system and the runoff properties of the catchment area. Utilized precipitation and air temperature data covers almost five years of data measured in Kumpula, Helsinki, approximately 10 km south-west from the design site.

This study focuses on water quality issues but water quantity cannot be neglected in order to understand the impacts of stormwater as a pollution source. The concentrations of different pollutants vary according to different rain events and catchment characteristics. Hence, instead of solely focusing on concentrations, the relation of different storm events and pollutant loads is studied. Based on literature, biofiltration and its performance is studied and a design suggestion for a filtration system is presented. Other topics covered in this study are regulations concerning stormwater quality and general guidelines concerning biofiltration as a stormwater treatment method in the urbanized environment.

This thesis aims to answer the following questions:

- Is biofiltration an efficient technology for treatment of stormwater in Finnish climate conditions?

- What issues should be considered when designing a biofiltration system?
- What kind of materials and structures should be used in biofiltration?
- How efficient treatment of stormwater is required?
- What kind of measurements are required in a biofiltration planning process?
- What kind of rain events can be identified and how do they affect stormwater quality?
- What kind of further studies should be carried out in this research field in Finland?

2 Literature review

In this chapter, the state of the art, challenges and solutions of stormwater management are discussed. First, the issues concerning stormwater quality are discussed and then biofiltration technology is presented as a promising solution for the concerns both in terms of stormwater quantity and quality.

2.1 Stormwater quality

The quality of stormwater depends on the characteristics of the catchment area. Different surfaces can be qualified by several characteristics such as development age, material composition of the surface, type and degree of utilization, weathering processes, surface slope and spatial location. The surfaces generating urban runoff can be divided into three main types that are partly sealed surfaces (e.g. urban green spaces and porous pavements), impermeable roof surfaces and impervious road surfaces. (Göbel et al., 2007)

In addition to catchment properties, runoff and rain event characteristics, such as intensity, depth and duration, affect the stormwater quality. The composition of stormwater also varies with time, both in terms of a single rain event and between different seasons. For instance, the amount of certain impurities due to heating, traffic and accelerated weathering (gases, studded tires) are increased during winter and pollutants are accumulated in the snowpack, which can result in momentarily high concentrations in runoff during the melting period. (Trafikverket, 2011; Valtanen et al., 2015; Westerlund and Viklander, 2006) Hence, the characterization of a typical composition of stormwater is challenging. Furthermore, comparison of different studies and their results requires caution due to inaccuracy of runoff measurements and differing sampling methods. (Kotola and Nurminen, 2003; Bäckström et al., 2006) However, some general conclusions can be drawn and assumptions of the quality based on the properties of the catchment area are possible.

Road design and construction, pavement characteristics, road inclination, climate conditions, time interval between rain events, type of traffic and road maintenance all affect generation of runoff on road areas (Göbel et al., 2007; Larm, 2000; Vägavdelningen, 2001). It is suggested that average daily traffic (ADT) correlates with the concentrations of stormwater pollutants related to traffic and in general pollutant concentrations from urban highways were reported to be higher than concentrations from nonurban highways. However, the relation between traffic intensity and pollutant concentrations is not fully straightforward and there are also several studies that have not been able to confirm the correlation (e.g. Kayhanian et al., 2003). In small roads with an ADT of less than 2 000, it is usually sufficient to drain stormwater into open ditches that treat the water by filtration and sedimentation (Trafikverket, 2011). It has generally been concluded that when the amount of traffic exceeds 15 000 vehicles per day, stormwater treatment should be required (POLMIT, 2002). At the Vantaa design site of the current study this limit of 15 000 ADT is predicted to exceed in the future.

Treatment of runoff from road areas in Finland is still rare. Some detention and protection structures are implemented mainly in groundwater areas. In groundwater areas there is approximately 750 km of roads that need de-icing during the winter months. In these areas the use of salt is minimized and protective structures are implemented. However, there is still around 110 km of road that would urgently require groundwater protection. (Tiehallinto, 2009) In the current study site in Vantaa, the Fazerila groundwater recharge area is located close to the design site, which is one reason why it was decided that the stormwater requires treatment.

2.2 Stormwater pollutants

Atmospheric deposition, substances originated from corrosion of roofs, nutrients and other substances accumulated on different urban surfaces are washed away in stormwater (Larm, 2000). Typical urban stormwater pollutants include nutrients such as nitrogen (N) and phosphorus (P), solids, metals, fertilizers, pesticides, oils and hydrocarbons (Valtanen, 2015). Stormwater from dense urban areas commonly contains high levels of nutrients (N and P), and runoff from industrial areas high concentrations of suspended solids, lead (Pb), zinc (Zn) and copper (Cu). Stormwater from roofs is generally considered as clean but depending on the material, roofs can contribute to high metal (Cu and Zn) concentrations in stormwater. (Larm, 2000)

Traffic and road materials are recognized to be a significant source of several pollutants and among urbanized areas roads generate the most contaminated stormwater (Lind et al., 2001; Magnus Hallberg, 2007). Generally, stormwater from traffic areas contains the highest concentrations of especially oil, cadmium (Cd), nickel (Ni), iron (Fe) and has high chemical oxygen demand (COD). Among traffic areas, parking lots are usually the least polluting areas (Larm, 2000).

Compared to stormwater generated in arable land, stormwater from central city areas has been examined to contain even 100 times more Pb and 10 times higher concentrations of suspended solids, P and biological oxygen demand (BOD). (Kotola and Nurminen, 2003) For example, in comparison to stormwater generated on roofs, the difference in pollutant concentrations is considerable. Thus, even though the amount of runoff from highway areas may be rather small, controlling and treating highway runoff can result in relatively substantial environmental benefit since highways contribute significantly to total pollutant loadings of urban areas (Muthanna et al., 2007b).

2.2.1 Organic compounds, suspended solids and nutrients

Most of the pollutants present in stormwater are adsorbed into the particles, especially if pH of the water exceeds 7 (Ekvall et al., 2001; Kotola and Nurminen, 2003). Due to large amount of suspended solids stored in snow, also the pollutant concentrations are generally highest during winter and spring (Ekvall et al., 2001). Therefore, considering stormwater quality, suspended solids have a significant role. Substantial removal rates of some pollutants such as heavy metals (Pb, and chromium (Cr)), volatile oil hydrocarbons and polycyclic aromatic hydrocarbons (PAH) can be achieved simply by removing solids from stormwater (Inha et al., 2013). According to studies conducted by Blecken et al. (2010b) also phosphorus and suspended solids removal are significantly correlated. In the water quality computation scheme of SWMM the pollutant removal is linked to suspended solids removal.

Organic compounds in stormwater originate mainly from traffic and gasoline. Therefore, these substances are leaching into stormwater especially from gas stations, crossroads and parking areas. Oils originate mainly from vehicles and polychlorinated biphenyl (PCB) compounds from industry. Nitrogen and phosphorus end up in stormwater from wet-deposition, traffic, combustion of fossil fuels, animal feces, decomposition of organic compounds and fertilizers. (Kotola and Nurminen, 2003)

It has been shown that the pollutant concentrations increase with increasing amount of traffic (Barret et al., 1998; Larm, 2000). However, other significant factors that impact the concentrations in road runoff include antecedent dry period, seasonal cumulative rainfall, total event rainfall and maximum rain intensity, drainage area and land use (Kayhanian et al., 2003). The amount of traffic is proposed to have the most apparent impact on electric conductivity, chloride (Cl) content and ammonium nitrate concentrations (Inha et al., 2013). Large amount of traffic indicates higher level of management and hence use of de-icing salts that contribute most clearly to the sodium (Na) and Cl content of stormwater.

Stormwater generated on highway areas is generally loaded with fine particles that are carried as suspended solids by stormwater runoff (Kotola and Nurminen, 2003). The suspended material mainly consists of particles of the eroded road material, sand and rubber particles of tires. The total load of the suspended particles is called total suspended solids (TSS). Due to increased, more intense and varied runoff, erosion in urbanized areas is enhanced which increases the weathering of different surfaces and thus concentration of suspended solids in stormwater. In Sweden, for instance, it is estimated that approximately 130 000 tons of road material is eroded every year and transported in runoff into ditches, lakes and sea (Trafikverket, 2011). Particles not only carry other pollutants that are bound to TSS but they also degrade the quality of the receiving waters by increasing turbidity, inhibiting plant growth and reducing species diversity. Fish spawning beds and the habitats of bottom-dwelling biota are destroyed by excess sediments. (Shammaa and Zhu, 2001)

2.2.2 Metals

Metals in runoff are of particular concern as they are not degraded by the environment. Hence the effects of metals can be short-term toxic shocks due to momentarily high concentrations or long-term impacts due to mass accumulation over time (Semadeni-Davies, 2006).

Traffic, weathering of building materials and atmospheric deposition are the most significant sources of heavy metals such as Pb, Cu and Zn that end up in urban runoff (Davis et al., 2003). Generally the metal concentrations in stormwater increase during winter time due to application of gravel which enhances wear and tear of different materials (Helmreich et al., 2010). The amount of Pb in stormwater has decreased significantly due to the introduction of lead-free gasoline during 1990s (Ekvall et al., 2001; Kotola and Nurminen, 2003). Studies conducted in Helsinki during years 1977–1979 showed Pb concentrations of 0.092–0.43 μg/l whereas in 2001 the concentrations were 0.006–0.011 μg/l (Kotola and Nurminen, 2003).

Metals in stormwater are generally present in various forms which has important implications to the design of the treatment method. Pb is usually strongly bound to particles while Cd, Cu and Zn exist predominantly in dissolved form (Gnecco et al., 2005). The dissolved fraction is potentially the most toxic one due to its possible bioaccumulation in living organisms. Hence, the reduction of the dissolved fraction is of particular importance. The bioavailability of metals in water phase depends on the retention time and the interaction with other elements and substances present in water. (Fritioff and Greger, 2003)

Valtanen et al. (2014b) studied the concentrations of different pollutants and their forms in different catchment areas in Finland. According to their studies characteristics of the catchment area as well as the seasonal variation has an impact on the form in which metals are present in stormwater. In the city center area the proportion of dissolved metals (excluding Mn) was shown to be approximately twice as high during the warm period than during the cold period.

2.2.3 Pollutant buildup and wash-off

Stormwater quality in urban areas is the product of two processes, the build-up phase and the wash-off phase. The accumulation of a variety of constituents takes place during dry weather periods and during rain events the constituents are transported along with stormwater. (Berretta et al., 2007)

The pollutant buildup on roads and the wash-off are complex and site-specific processes. It has been concluded that the capacity of runoff to mobilize and transport the pollutants of the catchment area increases with the rainfall intensity (Borris et al., 2014). Moreover, dissolved and particulate pollutants act differently. For example, dissolved metals, such as Cd are leached into stormwater at relatively low rainfall intensities whereas higher intensities are required to mobilize particulate metals, such as Pb (Lind et al., 2001). In addition, several studies have shown that the rainfall depth is the most influential factor affecting the pollutant wash-off loads (Borris et al., 2014).

The studies concerning accumulation of pollutants are partly controversial and drawing unambiguous conclusions is impossible (e.g. Helmreich et al., 2010; Kayhanian et al., 2003). Generally, it is thought that the longer the dry period, the more pollutants are accumulated on different surfaces. However, it has also been argued that wind-removal of pollutants affect the buildup insomuch that the antecedent dry period becomes insignificant in explaining the amount of pollutant accumulation (Lind et al., 2001). It has also been claimed that the rate of pollutant build-up changes over time and the rate of build-up is highest just after a rain event or street cleaning and gradually reduces to a near constant value after about two weeks of dry days (Egodawatta et al., 2013; Borris et al., 2014).

Pollutant build-up and wash-off are also influenced by seasonal differences. During warm periods, rain events wash off pollutant build-up whereas during cold periods pollutant build-up within the catchment may continue until the spring snowmelt. (Valtanen et al., 2015) Furthermore, it is assumed that climate change will intensify precipitation and therefore increase runoff peak flows. This is assumed to have a further impact also on the wash-off processes of pollutants and hence the quality of stormwater. The climate-related changes in quality should be taken into consideration when assessing required stormwater management structures. (Borris et al., 2014)

2.2.4 Pollutant loads and concentrations

There are several factors affecting the concentrations of different pollutants. Concentrations decrease as total event rainfall increases whereas higher rainfall intensities can result in greater pollutant concentrations as rain events with higher intensities are able to mobilize more particulates which pollutants are usually bound to. Moreover, antecedent dry period enables pollutant buildup which tends to result in higher pollutant concentrations in stormwater. (Kayhanian et al., 2003) In Table 1 the assumed effect of average daily traffic (ADT) on mean pollutant concentrations is described as well as the different sources of typical stormwater pollutants. The values within parenthesis show the deviation of the mean values.

Table 1 *Example concentrations of pollutants in road runoff (Trafikverket, 2011).*

Pollutant group	Source	Parameter	Concentration of pollutants in stormwater, dispersion		
			10 000–15 000 ADT	**15 000–30 000 ADT**	**> 30 000 ADT**
Particles	Road material, brake pads, exhaust fume, tires, corrosion, vehicles	Suspended solids	mg/l **75** (50–200)	mg/l **100** (50–1000)	mg/l **1000** (100–5000)
Metals	Road material, brake pads, corrosion, vehicles, oils, gas, color, tires, catalytic converters	Lead (Pb)	µg/l **20** (5–40)	µg/l **25** (5–50)	µg/l **30** (20–1000)
		Zinc (Zn)	**100** (50–300)	**150** (50–500)	**250** (100–1000)
		Copper (Cu)	**35** (10–50)	**45** (10–100)	**60** (10–800)
		Cadmium (Cd)	**0.5** (0.1–0.2)	**0.5** (0.2–1)	**0.5** (0.5–100)
Organic compounds	Exhaust fumes, tires, oils	PAH	µg/l **0.5** (0.1–1)	µg/l **1.0** (0.1–10)	µg/l **1.5** (0.1–10)
Nutrients	Exhaust fumes, oils	Nitrogen (N) Phosphorus (P)	mg/l **1.2** (0.05–2) **0.15** (0.1–0.2)	mg/l **1.5** (0.05–8) **0.20** (0.1–0.5)	mg/l **2.0** (1–10) **0.25** (0.1–3)

There are several studies concerning stormwater pollutants and their concentrations (e.g. Göbel et al., 2007; Helmreich et al., 2010; Kayhanian et al., 2003; Vezzaro and Mikkelsen, 2011). The concentration of certain pollutants in stormwater is typically presented as Event Mean Concentration (EMC) that can be defined as

$$EMC = \frac{M}{V} = \frac{\int_0^T q(t)c(t)dt}{\int_0^T q(t)dt} \tag{1}$$

where T is the duration of the monitored event, M is the total contaminant mass transported during the monitored event characterized by a runoff volume V, and $c(t)$ and $q(t)$ indicate the pollutograph and the hydrograph respectively (Berretta et al., 2007). The concentrations of different pollutants vary remarkably between different runoff events and even within a single event. The variation of concentrations and EMCs are illustrated for three events in Figure 2. Due to the aforementioned high variability, the estimation of stormwater quality and pollutant loads based on EMCs contains significant uncertainty and is only partly representative.

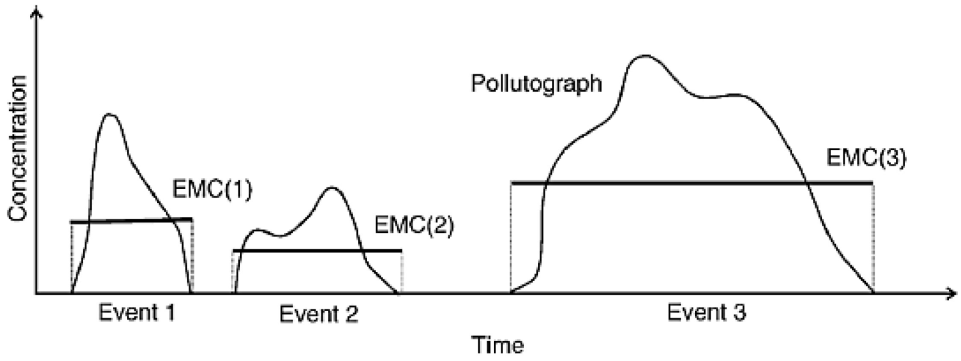

Figure 2 *Variation of concentrations of pollutants and the explanation of EMC (Göbel et al., 2007).*

Due to the large variation in pollutant concentrations of stormwater, quality management requires a site-specific design. It is essential to define the aim of the management and the desired treatment results. Moreover, it is reasonable to define target pollutants and focus the treatment on them. When considering the target pollutants, also the condition of the recipient should be taken into consideration as the most harmful substances in a certain area can depend on the ecological response of the receiving water (Larm, 2000).

Valtanen et al. (2015) investigated key urban runoff event variables that control Event Mass Loads (EMLs) and EMCs. They calculated EML as the sum of pollutant mass loads. Mass loads (M_L) are determined by multiplying each discrete concentration (C_i) within an event with its corresponding runoff volume (V_i):

$$M_L = \sum_i C_i V_i \qquad (2)$$

Valtanen et al. (2015) studied the seasonal variation of the variables and the impacts of differences in catchment characteristics on stormwater quality under varying climatic conditions. The study was conducted in three study catchments located in the city of Lahti that is a city located approximately 100 km North-East of Vantaa. The concentrations studied were total nitrogen (tot-N), total phosphorus (tot-P), total organic carbon (TOC), TSS and total heavy metals including both dissolved and particulate fractions (Cr, Mn, Co, Ni, Zn, Cu, Pb, Al). Runoff events were identified and based on meteorological data, divided into cold and warm period events starting from the first snowfall and freezing temperatures and ending at the end of spring snowmelt.

Event variables used by Valtanen et al. (2015) were runoff duration, mean runoff intensity, peak flow and antecedent dry period. Stepwise multiple linear regression analysis (SMLR) was used to detect relationships between runoff factors and stormwater quality. According to the study, runoff variables explained 60–90% of variation in the event loads during the cold seasons. Event pollutant loads were shown to increase as runoff duration and volume increased. Runoff duration and event duration combined with runoff intensity were found to be the key variables in explaining the loads of the catchment in city center areas (imperviousness 62% and 89%). Peak flow was shown to have the most significant impact on EMLs during warm period while runoff duration was among the most significant variables in explaining runoff quality during cold period.

Valtanen et al. (2015) showed that increasing imperviousness leads to decreased water quality and in particular increased TSS, tot-N, TOC and Mn, Co, Ni and Cu loads during cold periods. Hence in addition to hydrological variables, catchment variables (land use type, imperviousness) were found to be important in explaining the water quality variation. (Valtanen et al., 2015) However, mechanisms that affect pollutant loads (EML) differ from those affecting pollutant concentrations (EMC). Regression models using event and catchment characteristics proved to explain well particularly pollutant loads of warm and cold seasons whereas modeling the variation in pollutant concentrations is not equally simple. More accurate evaluation of factors affecting concentrations require more data on pollutant sources. (Petrucci et al., 2014)

The prediction of stormwater quality is challenging since there are numerous aspects that affect the composition. Modeling of the processes is also typically difficult due to lack of sufficient long duration data collected at the same site. However, in order to design optimal stormwater management facilities, it would be desirable to be able to model these processes and provide computational estimates of the stormwater quality. (Gnecco et al., 2005)

Generally, the rather small but frequent rain events are the ones that play the key role in transporting pollutants and contribute most to the yearly pollutant loads. Therefore, if the goal is to remove pollutants rather than aim at detention of stormwater flows, these smaller events should be the base for the design of a management facility. (Larm, 2000)

2.2.5 First flush

It can be concluded that the "first flush" of stormwater is of worst quality with the highest pollutant concentrations. The first flush refers to the phenomenon that takes place in the beginning of a rain event when the main proportion of debris accumulated on impervious surfaces is washed off by stormwater. (Deletic, 1998; Inha et al., 2013; Kotola and Nurminen, 2003)

The first flush is a slightly controversial but generally recognized phenomenon which has been reported in several studies (Sansalone & Buchberger, 1997; Deletic, 1998; Lee et al., 2002). As an example, in Sweden the variation of pollutant concentrations of stormwater during a rain event was studied in two different road areas, a highway with the average daily traffic (ADT) of 17 900 and a traffic light-regulated urban road with ADT of 11 500. In both cases it was shown that the first 30% of runoff transported 50-60% of the total mass of accumulated dissolved and particulate pollutants from the road areas. Based on the results, it was concluded that the first flush effect from single rain events can cause high concentrations of pollutants which may be detrimental to the environment and cause toxic shocks. (Lind et al., 2001) Also Gnecco et al. (2005) investigated the first flush effect of different types of urban surfaces. They observed good correlation between EMC of total suspended solids (TSS) and maximum rainfall intensity of the event.

Through treatment of stormwater at the source, the toxic effects of the first flush can be prevented or at least reduced if the high concentrations can be reduced prior to discharge to the receiving waters.

2.2.6 Measuring and monitoring of stormwater quality

Due to the several factors affecting the quality and sampling, measurements of stormwater quality should be long-term and carefully planned in order to obtain representative data. The type of sampling can be automatic or manual and the sampling strategies differ between flow-proportional, time-proportional, first flush, mixed and random sampling (Huber et al., 2016). The first flush effect must be taken into consideration to avoid distorted data and assume too high concentrations. (Airola et al., 2014)

Flow proportional samples can represent for example a period of one month. In order to include seasonal variation, certain sampling periods according to the seasons should be selected. Furthermore, samples from at least three precipitation events should be captured. (Larm, 2000)

The quality of stormwater is often estimated by monitoring the amount of TSS. Leecaster et al. (2002) suggested that in order to sample TSS adequately within an event, at least 12 flow-weighted samples should be taken. Furthermore, in order to estimate mean annual loads at a reasonable level of accuracy, pollutographs of seven storm events are required to be sampled within a year.

Turbidity has been shown to be a useful predictor for TSS but not for other pollutants (e.g. Deletic, 1998). Therefore, other pollutants, such as metals should be analyzed separately. Continuous turbidity measurements allow to capture the short term quality variation. Systematic errors must be eliminated though, by ensuring frequent calibration and data verification. If grab-sampling is used, the sampling interval should not exceed three days (Fletcher and Deletic, 2007). A good sampling method for monitoring the quality of stormwater generated on roads is to take the samples from the “drip pipes” installed in bridges (Inha et al., 2013).

Besides stormwater quality, also the runoff quantity and the associated rainfall need to be monitored. Stormwater runoff rates can be monitored using flow meters that can be installed into a stormwater sewer pipes if the drainage of the area is managed with a piping system. Precipitation is commonly measured using tipping bucket rain gauges. In order to monitor the efficiency of a stormwater treatment method, it is desirable that the collected samples are of the same water volume at the inlet and outlet of the certain structure.

Airola et al. (2014) studied stormwater quality in Helsinki and reported that the most significant substances in runoff are N, P, Cl, Cu, Zn and oil hydrocarbons. Based on the results of the study, treatment of stormwater from large parking areas is recommended.

Airola et al. (2014) compared the concentrations of harmful substances in stormwater from Helsinki to limiting values suggested by the County of Stockholm and to the limiting values and environmental quality norms defined in the Government Decree on substances harmful or hazardous to the aquatic environment (1022/2006). The limiting values of Stockholm are based on several studies and the environmental quality criteria of EU Water Framework Directive (2000/60/EC). The values are divided into five categories according to the location of the pollution source in the catchment area and the size of the receiving waterway. If the limits were followed, stormwater treatment would be generally required in industrial areas, city center areas, large parking areas and dense residential areas.

Results of Airola et al. (2014) can only be taken as approximate values due to the relatively small amount of data from Helsinki. In addition, the industrial areas of Helsinki do not represent heavy industry but offices and car shops etc. where the most polluting factor is road traffic. The limiting values defined in Stockholm are adopted in this study as a baseline for defining the required reduction rates for the designed filtration system.

2.3 Biofiltration

Treatment systems that rely solely on sedimentation have been reported to be insufficient for removing of fine particulates and dissolved pollutants (Haile et al., 2015). In order to enhance the treatment efficiency, filtration of stormwater can be considered as an additional treatment method.

Biofiltration has become one of the most popular management technologies among LID systems. Biofiltration units are engineered structures that mimic the natural hydrological process of filtration. Most of the water is stored in the structure and further infiltrated in the underlying soil or drained but also evapotranspiration occurs depending on the conditions. The configurations and appearances of biofiltration cells vary according to the local conditions and the target pollutants. In addition to efficient pollutant removal, design flexibility is one of the main advantages of this technology. (Bratieres et al., 2008; Hatt et al., 2009; Henderson et al., 2007)

Too often well-designed biofiltration facilities are not properly installed or their maintenance is neglected. The proper installation and maintenance of biofiltration facility is essential for the good performance of the system (Brown and Hunt, 2012). For example, the selected excavation technique can significantly affect the permeability of the system. If the treated water is infiltrated underneath the structure, it is preferable that the soil remains less compacted, and thus the rake method of excavation is recommended instead of the conventional scoop method. (Brown and Hunt, 2010)

The performance of biofiltration for stormwater management and treatment has been studied widely (e.g. Blecken et al., 2010a; Fletcher and Deletic, 2007; Hunt et al., 2006; Muthanna et al., 2007b). A common procedure to investigate the performance in terms of hydrologic mitigation and stormwater treatment, is the direct observation at field-scale biofiltration facilities. Furthermore, in some studies artificial containers called mesocosms were applied to simulate biofiltration systems (e.g. Blecken et al., 2010a; Henderson et al., 2007; Liu et al., 2014).

In the following sections the operational principle, structure alternatives and maintenance of biofiltration systems are discussed. Moreover, studies about pollutant removal in biofiltration systems are presented and the impacts of different conditions on the performance are discussed. Finally, the questions concerning implementation of biofiltration in the urban environment and regulations concerning stormwater management are pointed out.

2.3.1 Operational principle and typical structure

Biofiltration systems generally consist of a top layer, filtration media, storage layer and a drainage layer. Stormwater runoff is first filtered through the vegetation and then vertically through the soil filter media. Therefore, the permeability of the upper layer of the system should be sufficiently high to allow infiltration. Filtered water is either infiltrated on site or collected in under-drains located at the base of the system and then lead to receiving waters or the stormwater network. (Hatt et al., 2009; Henderson et al., 2007) An underdrain is required if infiltration into the ground is prohibited or the soil underneath has a low infiltration rate, e.g. less than 13 mm/h (Liu et al., 2014). It is suggested that infiltration should be restricted to areas with limited use of groundwater and only relatively clean runoff should be allowed to infiltrate (Marsalek, 2003).

Treatment in biofiltration is based on various processes including sedimentation, fine filtration, adsorption, chemical reactions and biological uptake. Ponding of the water at the surface occurs once the soil pore space capacity of the media is exceeded. (PGC, 2007; Henderson et al., 2007; Davis et al. 2006) Occasional runoff ponding on the surface can be allowed but with respect to pollutant removal, storing runoff temporally in the media layer is more efficient (Hsieh and Davis, 2005).

The treatment media is generally porous soil with a topping layer of hardwood mulch and vegetation which also prevents the system from erosion. As rapid infiltration of water is desired, the soil has typically a high sand content but to promote pollutant attenuation also low levels of silt and clay are usually required. (Davis et al., 2001a) However, systems can vary significantly in size and shape (Henderson et al., 2007).

There are several different structures presented in the literature for different biofiltration systems. The most simplified ones consist of a sand filter with organic top layer. The recommended depth is between 0.7 and 1.25 m (Hunt et al., 2006) but rather efficient pollutant removal can be achieved already with filter beds with only 0.5 m depth (Davis et al., 2009). For instance, the required structure depth for metal removal is less than for other pollutants (Blecken et al., 2010a).

According to the *Low Impact Development Stormwater Management Planning and Design Guide* (CVC−TRCA, 2010) the gravel storage layer of a biofiltration unit is recommended to be at least 300 mm deep and granular material should consist of clear stones with a diameter of 50 mm. To separate the gravel storage from the filter media, it is recommended to place a 100 mm deep layer of pea gravel on top of the gravel storage layer. The filter media soil mixture is recommended to consist of sand (85 to 88 %), fines (3 to 5 %) and organic matter (8 to 12 %). An example of a structure for a biofiltration system is presented in Figure 3. The vegetation of the top layer is not shown in the figure.

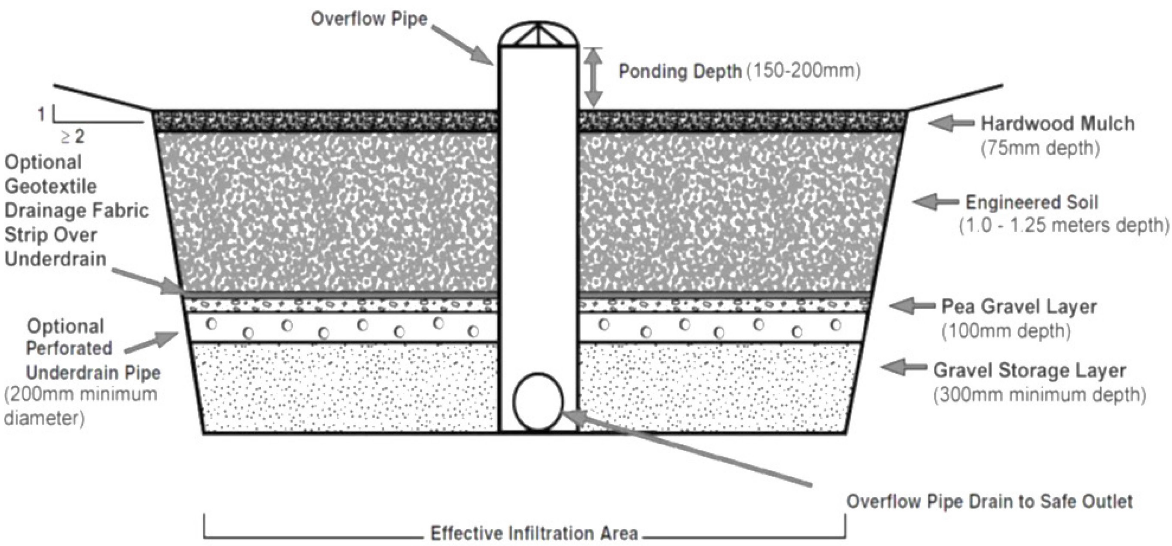

Figure 3 *An example of structure of a biofiltration facility (CVC−TRCA, 2010).*

The structure of biofiltration has been shown to have no or insignificant impact on the removal of suspended solids and heavy metals whereas nutrient removal has been found to be highly dependent on the design. For instance, Fletcher et al. (2007), found that the filter depth seems to be more relevant in terms of the system retention capacity than in terms of pollutant removal. However, Davis et al. (2006) reported that with increasing filter depth the total phosphorus removal has increased while metal adsorption to soils occurred mainly in the top layer.

The phosphorus content of the filter media affects the phosphorus removal. To ensure effective removal and to avoid leaching of nutrients, the filter media should have low initial phosphorus content. Nitrogen removal is a more complicated process that is influenced by the moisture conditions of the media. Drying of the filter media should be avoided to ensure long-term nitrogen removal. (Hatt et al., 2009)

Suspended solids are typically removed through sedimentation in the basin and filtration in the media. To avoid clogging of the system, the biofiltration unit itself should not be used as a sediment trap but pretreatment of the stormwater should be included to the system. (Liu et al., 2014) If TSS is the target pollutant, the key factor determining the performance of the biofiltration system is the percentage of mean annual flow treated which is dependent of the infiltration rate of the filter media. With total phosphorus being the target pollutant, many configurations are effective. Vegetation can improve the phosphorus removal but it has to be ensured that there is no excessive organic matter in the media to avoid leaching. (Fletcher et al., 2007)

Larger storm volumes have been found to decrease the performance of biofiltration which implicates that the correct sizing in relation to the catchment area is essential (Fletcher et al., 2007). The removal efficiency of pollutants is enhanced with lower inflow volumes as the smaller events cause lower perturbation and increase hydraulic retention time in the media. Hence it is recommended that the area of the biofiltration system is maximized (Bratieres et al., 2008; Brown and Hunt, 2011; Davis et al., 2003).

2.3.2 Vegetation

The performance of the biofiltration system and the desired pollutant removal is also partly dependent on vegetation and the depth of the media (Davis et al., 2009). The vegetation of the top layer can enhance especially the nutrient removal efficiency of the filtration unit (Le Coustumer et al., 2007). However, when selecting the appropriate vegetation for a biofiltration system it should be taken into consideration that the growth conditions may be very stressful and challenging due to varying amounts of nutrients, heavy metals, salt and wetting and drying periods (Bratieres et al., 2008; Cappiella et al., 2006; Manousaki and Kalogerakis, 2011; Szota et al., 2015).

Phytoremediation refers to the treatment of environmental problems by the use of vegetation. This treatment through plants mitigates the environmental problem so that the contaminated material does not need to be excavated and disposed but the pollutants can be removed by harvesting the plants. Phytoremediation has been studied with a conclusion that plants with a high ability of metal accumulation may be used to reduce Zn, Cu, Pb, and Cd concentrations in stormwater. The uptake process of plants depends on the bioavailability of the metals in the water phase. (Fritioff and Greger, 2003) For example *Vinca minor* (dwarf periwinkle) provides efficient accumulation of metals (Muthanna et al., 2007a).

Fritioff and Greger (2003) studied metal uptake capacity of several plants in Sweden, 7−15 km south of Stockholm. They reported that the submerged and free-floating species had a higher metal accumulation capacity than the terrestrial species studied. The results showed that the terrestrial plants *Impatiens parviflora* (small balsam) and *Filipendula ulmaria* (meadowsweet) could be used for effective uptake of Cd and the other terrestrial species showed efficient uptake ability of Zn. It is desirable that the metals would accumulate both in roots and shoots of the plants. The submerged and floating species of wetland and ditch systems are capable to bind metals in the shoots and roots whereas terrestrial and emergent plants have high accumulation only in the roots. However, the capability of terrestrial plants to bind especially Cd and Zn to their roots can stabilize these metals in soil. (Fritioff and Greger, 2003)

In order to fully exploit the advantages of phytoremediation, the plants of the system should flourish in the demanding conditions. Therefore, the vegetation of biofiltration system should comprise native plants that are resilient to the local climate conditions. There are only few studies concerning vegetation in cold climates but some good vegetation options identified are *Potamogeton natans* (broad-leaved pondweed), *Alisma plantago-aquatica* (common water-plantain), *Filipendula ulmaria* (Fritioff and Greger, 2003) and *Hippophaë rhamnoides* (sea buckthorn) for places with drier conditions (Muthanna, 2007). Hyperaccumulator plants could be used to enhance metal uptake and in particular to prevent leakage of bioavailable Cu and Zn into recipients.

Due to a rather fast infiltration process the role of vegetation is probably small in the direct uptake of the pollutants during a rain event but the plant uptake may have significance in the long-term, especially concerning nitrogen removal. To complete the nutrient removal process the vegetation must be cut and removed from the facility. (Davis et al., 2006) Furthermore and more importantly, the vegetation has an impact on the structure and consistency of the soil. Vegetation contributes to maintaining the hydraulic conductivity since the root growth counters compaction of the soil and reduces clogging of the filter media through creation of macropores into the media (Hatt et al., 2009; Le Coustumer et al., 2007).

Plants with thick roots enhance the soil porosity most effectively whereas dense fine root patterns provide the best conditions for nutrient removal (Read et al., 2009). In addition to the advantages with respect to the treatment efficiency and hydraulic conductivity of the media, the vegetation provides an aesthetic value.

2.3.3 Construction and maintenance

There are several possibilities for the structure of a biofiltration system but from the perspective of construction and maintenance, a simple uniform profile is suggested as a more cost-effective alternative than a profile with an infiltration media of several different layers (Hsieh and Davis, 2005). As previously stated, the proper maintenance of a biofiltration system is essential for the system to perform as expected. The lack of maintenance is the most common cause of malfunctioning stormwater management system (Boise Public Works, 1999).

Biofiltration systems are typically dimensioned based on the volume of runoff to be treated. The runoff volume is typically defined as a result of a design rain event. The four determining factors of a design rain are duration, intensity, depth, and return period, which is the average recurrence interval over an extended period of time (Kuntaliitto, 2012). However, the design flow volumes and rates can also be determined by the objectives for the site. The objectives can vary from water quality control and groundwater recharge concerns to controlling peak discharges for large storms that are typically rare. In the USA, LID systems are typically designed to capture and treat the runoff volume from small storms ranging from 12 mm to 25 mm of runoff which are also related to a certain percentage (typically 70-90%) of the total annual runoff volume. Generally, at new construction sites the biofiltration systems are designed to treat 90% of the storm events when also the pollutant load capture is maximized. However, systems sized for smaller treatment volumes can also be beneficial if the available space is insufficient. (Clar et al., 2004)

One approach to define the runoff volume to be treated is the use of runoff coefficient. Runoff coefficient describe the proportion of precipitation or melting that is transformed into runoff. Therefore, the required treatment volume can be calculated as the product of rainfall (mm) and the runoff coefficient. Runoff coefficient depends primarily on land use, soil, vegetation type, and slope but also on rainfall characteristics such as the intensity, the duration, and the antecedent conditions. Typical runoff coefficients range from 0.70−0.95 for impervious surfaces and from 0.05−0.35 for pervious surfaces. Increasing surface slope increases the coefficient. Typical values of runoff coefficients for urban areas are presented in Table 2.

Table 2 Typical values of runoff coefficient (Butler and Davies, 2004)

Area description	Runoff coefficient	Surface type	Runoff coefficient
City center	0.70–0.95	Asphalt and concrete paving	0.70–0.95
Suburban business	0.50–0.70	Roofs	0.75–0.95
Industrial	0.50–0.90	Lawns	0.05–0.35
Residential	0.30–0.70		
Parks and gardens	0.05–0.30		

Biofiltration systems require regular maintenance to ensure their function and to maintain their aesthetical appearance. Inspections are required as a part of a maintenance program and for the first year it is suggested that the system is inspected semi-annually and after large storm events (BoisePublicWorks, 1999). After that, annual inspections should be sufficient but the time interval for future maintenance practices should be identified according to the actual, observed requirements. Documentation of inspections and maintenance practices is recommended. (Clar et al., 2004, p 7-18) It is suggested that an operation and maintenance plan is prepared already during system design. When planning the maintenance, it is essential to interact with different professionals and personnel responsible for the maintenance. The plan is recommended to comprise site plans, design plans, material specifications, inspection frequency information, landscape design plans, inspection and maintenance forms, safety information, responsible personnel and the scope of work. (BoisePublicWorks, 1999)

The inspection frequency is mainly affected by the design (vegetation, accumulation of sediments and debris) of the system, seasonal conditions, and characteristics of the drainage area (e.g. highways, industrial sites). Maintenance practices may include removing sediments and debris (may require excavations), mowing, removing weeds, seeding and other measures to repair damages caused by erosion. (BoisePublicWorks, 1999) In some sources it is suggested that it is sufficient to remove the accumulated sediments every 7 years (Haile et al., 2015). However, site-specific factors should be considered.

Long term treatment performance depends on the hydraulic conductivity and the sorption capacity of the filter media that reduce over time (Blecken et al., 2010b). To maintain an adequate hydraulic conductivity and to avoid system flooding, removal of excess sediments by scraping off the top layers is required (Blecken et al., 2010a). Removing accumulated fine sediments from the top of a biofiltration system can enhance the performance of the system. In a study of two biofiltration cells, the top 75 mm of fill media was excavated which increased the surface storage volume by almost 90% and the infiltration rate increased tenfold. Furthermore, overflow volume decreased from 35-37% to 11-12% (Liu et al., 2014).

Clogging not only decreases hydraulic performance of a biofiltration system but also affects the pollutant removal. Le Coustumer et al. (2009) studied the impact of the variation of hydraulic conductivity on the performance of a biofiltration system. The hypothetical catchment of 1 ha drained into a biofiltration system with an area of 1.0% of the catchment area and a ponding depth of 10 cm. The study showed that the percentage of the mean annual flow treated (hydrologic effectiveness) and total nitrogen (TN) removal decreased with hydraulic conductivity. TN removal and hydrologic effectiveness were at their highest (51% and 84%, respectively) when the hydraulic conductivity was 200 mm/h. With the hydraulic conductivity decreasing to 50 mm/h, TN reduction fell to 47% and hydraulic effectiveness to 57%. Therefore, clogging of the system results in discharges of untreated runoff to receiving waters and failure of pollutant removal efficiency. The results of the study are merged in Figure 4.

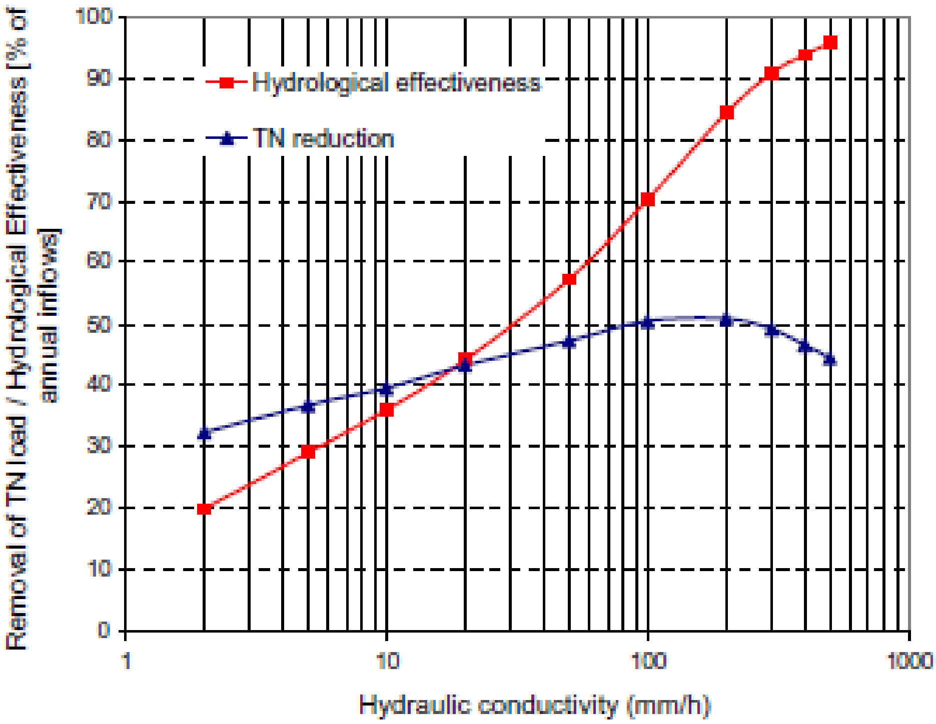

Figure 4 *Evolution of hydrological effectiveness and TN load removal (Le Coustumer et al. 2009).*

2.3.4 Nutrient and sediment removal

There is limited data on the effectiveness of biofiltration at the field scale but nutrient removal has been studied widely in laboratory conditions. TSS is efficiently removed by filtration and removal of phosphorus has been shown to be rather efficient (e.g. Blecken et al., 2010b; Henderson et al., 2007; Lucke and Nichols, 2015). However, nitrogen removal is a more complex process due to many forms of nitrogen and its ability to change the form from one to another (Fletcher et al., 2007). Since the removal of nitrogen appears to be rather dependent on the vegetation of the biofiltration system, in cold climates such as in Finland, nitrogen removal may be a hard task.

The study conducted by Davis et al. (2006) belongs to the rather few field experiments of biofiltration pollutant removal. The study was conducted in two different sites with fixed runoff loading of 4.1 cm/hr for 6 h duration over an area of around 5.3 m^2. The first facility constructed contained sandy loam topsoil covered with 5 cm of mulch and thick growth of grasses, few shrubs and small trees. The facility had been operating already for 10 years by the time of the experiments. On the bottom of the facility a 15-cm diameter perforated pipe was installed to collect the treated water. Ponding of 20 cm was allowed during a rain event. Grab samples were collected every 25−30 minutes. The second facility had a media consisting of a mixture of 50% construction sand, 20−30% leaf mulch and 20−30% topsoil. Some grasses, bushes and small trees grew on the top, and at the bottom an underdrain was installed. Ponding water of 15 cm was allowed and grab samples were taken every 30 min. Good reductions in phosphorus (65−87%) were reported in both study sites. Treatment efficiency of nitrogen varied from 49 to 59% but removal of nitrate was poor (15−16%). The factors affecting the removal efficiency were studied and according to the experiments, phosphorus removal of the facilities increased with the depth up to 60 to 80 cm whereas it appeared that the nitrogen removal occurred mostly in the top few centimeters.

Henderson et al. (2007) used biofiltration mesocosms to study the removal of dissolved nitrogen, phosphorus and carbon by six different biofiltration systems. The columns studied had different filter media (gravel, sand and sandy-loam) and were either vegetated or non-vegetated. According to their studies, the vegetated columns were the most effective and removed 63−77% of nitrogen and 85−94% of phosphorus loads, and all of the columns removed 48−66% of the carbon from the stormwater. Leaching of nitrogen and phosphorus was observed from the non-vegetated columns which was also reported by other studies. Non-vegetated soil-based filters were found to be unsuitable for nutrient removal. (Hatt et al. 2007) Also Davis et al. (2003, 2001a) had similar results in phosphorus removal (approximately 80%) and 60−80% in ammonium removal whereas nitrate removal appeared to be rather low and leaching from the facility was observed.

In a large-scale laboratory study of Fletcher et al. (2007) the optimal design of biofiltration system for removal of sediment, nitrogen and phosphorus was investigated. The study comprised 140 biofiltration columns with different structures in terms of filter media, depth and vegetation. The performance of the columns was tested with different storm volumes and input concentrations. All structures were found to be effective in TSS and phosphorus removal with average removal rates of 98% and 80%, respectively. As in several other studies, nitrogen removal varied though, and like in the studies of Davis et al. (2003, 2001a) and Henderson et al. (2007), leaching of nitrogen was observed from some structures. However, with a specific selection of plants and media type a simultaneous reduction of 50−70% of nitrogen and 90% of phosphorus was achieved. The best removal was achieved with a filter media of sandy loam and sandy loam mixed with vermiculite/perlite. Leaching of phosphorus was observed when compost material was added. Compost materials in filter media blends can facilitate denitrification due to their content of organic carbon (Liu et al., 2014). However, to avoid leaching, it should be assured that the compost materials do not contain excessive nutrients.

Adding of mixtures such as water treatment residuals that contain aluminum have been shown to increase phosphorus removal (Liu et al., 2014). To achieve phosphorus removal but avoid leaching of phosphorus, the fill soil of the system should have a relatively low P-index which signifies values between 10 to 30 ppm (Hunt & Lord, 2006). If the phosphorus content of the growing media is too high, also leaching of phosphorus from the structure may occur (Bratieres et al., 2008; Davis et al., 2001a; Hatt et al., 2009; Hunt et al., 2006).

Leaching of nutrients was observed also in biofiltration systems constructed in Tikkurilantie in Vantaa (Lehikoinen, 2015). Shortly after construction the outflow from the filter was of worse quality than the inflow. However, it has been concluded that the best treatment efficiency will be achieved after some time after the construction of the structure, when the structure has been settled (Davis et al., 2003). Therefore, to obtain information of the performance of the biofiltration systems of Tikkurilantie, systems should be monitored again after they have settled.

2.3.5 Metal removal

There are numerous promising studies about metal removal efficiency of biofiltration. Batch and column studies along with pilot-scale laboratory systems have shown greater than 90% concentration reduction of Cu and Zn and over 80% removal of Pb (Davis et al., 2001b, 2003; Hatt et al., 2007; Hunt et al., 2006). However, field tests have shown more variation in removal efficiencies for these metals. According to studies conducted by Davis et al. (2003), the age of the biofiltration system impacts on the pollutant removal. Removal rates varied from 43−70% for a newly constructed biofiltration facility but reached to over 90% for older system with appropriate vegetation.

Metal removal depends on the distribution of metals into solid and dissolved phases. The sorption processes of dissolved metals are primarily controlled by pH (Blecken et al., 2010a). In road runoff generally over 50% of metals are bound to suspended solids and exist in particulate form. Cd is mainly present in liquid form and the fraction of liquid Pb can also be varying. (Ekvall et al., 2001; Helmreich et al., 2010)

Rather shallow structures are found to be functional considering metal removal (Davis et al., 2001b). According to studies, removal of Cu, Pb and Zn mainly occurs in the surface layers of the filter bed and the concentrations of these metals in the media decrease with increasing filter bed depth. (Blecken et al., 2010a; Haile et al., 2015) This is an advantage concerning the maintenance of a system as a high portion of the accumulated metals can be removed from it by replacing the upper soil layer (Blecken et al., 2010a). However, the concentrations of chromium (Cr), cobalt (Co) and nickel (Ni) increase with the depth whereas barium (Ba), manganese (Mn) and strontium (Sr) distribute uniformly over the filter media. (Haile et al., 2015)

Moreover, initial concentration and length of exposure in a filter media can have an impact on metal removal rate (Reddy et al., 2014). Metal removal is mainly based on surface adsorption to negatively charged surfaces of the filter materials. The chemical processes occurring in the media are cation-exchange with humic material, coprecipitation, and organic complexation which means that the metal ions become strongly bound to the material. The particle size of the substances to which metals are adsorbed defines the possible removal process. (Muthanna et al., 2007a; Reddy et al., 2014) Fine particles have relatively high surface area which facilitates the adsorption (Haile et al., 2015). In addition, the plants contribute to the removal of dissolved metals but the process is slower compared to soil adsorption (Muthanna et al., 2007b).

Reddy et al. (2014) conducted several batch experiments to study the extent of adsorption and removal of metals of four different inorganic filter materials. The studied materials were calcite, zeolite, sand and iron and the heavy metal contaminants included Cd, Cu, Pb, Ni, Cr, and Zn. The metal concentrations were varied in the study. They represented high concentrations in stormwater and were 30 mg/l for Cd, 5 mg/l for Cr, 5 mg/l for Cu, 50 mg/l for Pb, 100 mg/l for Ni and 50 mg/l for Zn. Furthermore, additional tests at concentrations of one-half, five times and ten times the above-mentioned concentrations for each metal were conducted. (Reddy et al., 2014)

Based on the results a recommended filter size and treatable stormwater volume were defined. The selection of filter materials was found to be essential. The maximum removal rates of 95−100% for Cd, Cu, Pb and Zn were achieved by calcite, zeolite and iron filings, 90% removal of Ni was achieved by zeolite and 100% of Cr was removed by iron filings. Sand was found to produce the lowest results with maximum removal rates of 8-58%. It was concluded that a combination of filter materials should be investigated if the goal is simultaneous removal of multiple heavy metals as none of the materials achieved the maximum removal rate for all metals. (Reddy et al., 2014) The properties of the filter materials studied are presented in Table 3. The studied materials have high porosity and as shown in the table, according to the study the hydraulic conductivities of the materials are very high, ranging from 0.3 (10 800 mm/h) to 0.6 cm/s (21 600 mm/h).

Table 3 *Properties of the filter materials studied by Reddy et al. (adapted from Reddy et al., 2014).*

Filter material	Average particle size, D50 (mm)	Dry density (g/cm3)	Organic content (%)	pH	Hydraulic conductivity K (cm/s)
Calcite	0.7	1.6	0	9	0.3
Zeolite	1.2	1	8.8	7.8	0.4
Sand	0.6	2.8	0.3	8.4	0.3
Iron Filings	0.9	2.3	0	5.3	0.6

Seelsaen et al. (2006) studied heavy metal removal efficiency of compost material, sand, packing wood, ash zeolite and Enviro-media. Enviro-media refers to infiltration treatment media containing a blend of other tested materials. Compost material was found to have the best properties for sorption of metal ions of Cu, Zn and Pb. However, leaching of dissolved organic carbon (DOC) was significantly higher compared to the other materials. Minimal DOC leaching and excellent heavy metal removal was achieved with various combinations of different materials. Paus et al. (2014) also studied the effects of compost material on metal removal and reported that the removal of Cd and Zn was increased with increasing volume of compost material. However, increasing compost material volume resulted in lower hydraulic capacity and significant release of P. Therefore, it was suggested that a second layer is added beneath the filtration media to promote phosphorus retention.

Temperature has been shown to not affect metal removal. Muthanna et al. (2007) investigated heavy metal removal in a biofiltration media in a cold climate with a small pilot sized biofiltration box built in Trondheim, Norway. Three runoff events were used in the study and the water used was tunnel wash water from a 4 km long highway tunnel. Studies were conducted in April and in August. According to the investigations, metal retention was good for both seasons. Mass removal rates for zinc, lead, and copper were 90%, 82% and 72%, respectively. The dominant processes in metal removal were adsorption and mechanical filtration through the growing and filter media but also plant uptake of 2-7% was documented. The study showed that hydraulic loading or the cold climates may not affect the metal removal performance of biofiltration. However, freezing of the media must be prevented to allow for infiltration.

As mentioned in the section 2.3.2, plants have been shown to remove metals but in comparison to the filter media the total amount of accumulated metals in plant tissue is remarkably lower. The removal efficiency is also dependent on temperature and the uptakes were reported to be significantly higher at warmer temperatures (Blecken et al., 2010a). Davis et al. (2001b) and Muthanna et al. (2007a) estimated that the fraction of metals that are removed from stormwater by plant uptake is between 5 and 10%.

2.3.6 Performance in cold climates

Widespread adoption of LID design in cold climate conditions is hindered by concerns related to poor winter performance. Freezing of the filter media and decreasing biological activity are the main concerns. (Roseen et al., 2009) Furthermore, stormwater generation and pollution transport during winter differs significantly from summer and autumn. During winter, the contributing area of runoff can be greater due to frozen soil and especially during rain-on-snow events, the entire catchment can be contributing to runoff. Moreover, summer rainstorms are generally short and intense whereas snowmelt can persist for days, which means that the drainage system may be at full capacity for days to weeks. (Semadeni-Davies, 2006)

There are several studies with different results on biofiltration performance in cold climates. According to Blecken et al. (2010a), pollutant removal of biofiltration systems performs well in low temperatures and phosphorus and TSS removal are not influenced by low temperatures. However, nitrogen removal is low even though leaching does not occur like in warm temperatures. On the contrary, Muthanna et al. (2008) conducted a study focusing on hydraulic performance of biofiltration in cold climate and concluded that temperature and antecedent dry days have a significant effect on hydrologic performance and that the performance can be expected to be lower when the temperature stays below 0°. The two investigated facilities were pilot-sized with a total filter media depth in the range of 55−60 cm. The frost line in the area was estimated to be at 1−2 m. Thus, with a drain pipe below the frost line the winter infiltration could have increased.

The depth of the frost line influences the performance of biofiltration systems. Freezing of water in the structure reduces the performance by diminishing the water storage available. In a study conducted in Norway the peak flow and total volume reduction were found to halve in spring compared to autumn due to partial freezing of the soil and biomass (Muthanna et al., 2007b). Hence a well-drained soil media is recommended to prevent ice formation in the media and to assure sufficient infiltration capacity of the system (Blecken et al., 2010b). Increasing hydraulic conductivity reduces lag time and hydraulic detention which can have impact on the performance of the system. However, this can be compensated with a lower hydraulic loading rate by increasing the biofiltration area. It is also essential that standing water in the drainage pipes is avoided to prevent freezing of the system. A minimum slope of the drainage pipes of 3% is recommended (Muthanna et al., 2008).

When planning a stormwater management system in cold climates it has to be taken into account that the quality of snowmelt may also be worse than runoff generated during other seasons as the pollutants are accumulated with the snow throughout the winter. Moreover, the de-icing salts used during winter affect the stormwater quality both directly and indirectly. Chloride used in de-icing mixtures is toxic itself and it also changes toxicity of other substances. For instance, the salts can increase metal mobility by changing the ratio of bound to dissolved metals. (Marsalek, 2003; Semadeni-Davies, 2006)

Common road salts used in de-icing contain Na (40%) and Cl (60%). In addition, an anti-clumping agent is often added and some impurities such as P, sulfur (S), N, Cu and Zn can be present. (Marsalek, 2003) Some studies have shown that Cl concentrations of runoff from major multi-lane divided highways can reach a level of acute toxicity during winter time and periods of snowmelt (Marsalek et al., 1999; Marsalek, 2003).

Mechanical filtration of particle bound metals works in low temperatures but if the media freezes and cracks are occurring the metals can penetrate into deeper filter layers. (Blecken et al., 2010a)

2.3.7 Implementation in urban framework

At least three factors should be considered when selecting an appropriate LID system: compatibility of the technology with the land use type and site conditions such as space available, construction and maintenance costs, and the effectiveness of the technology in removing the target pollutants of concern. Biofiltration can be applied to a wide range of different urban environments. Depending on the design, urban retrofit sites, parking lots, roads and streets, highways and residential areas are suitable for biofiltration. Furthermore, roof tops can be connected to biofiltration systems to treat the runoff from roofs. (Clar et al., 2004)

National, legal mandates to control stormwater management do not exist in the USA and Australia; therefore, regulations are defined at the local level of states or cities. This results in inconsistent management policies. Moreover, there are no uniform performance standards or guidelines available. (Roy et al., 2008) Also in Finland, common established practices concerning stormwater management using LID do not exist. For instance, there is no uniform notation for the facilities of stormwater management in the city plan. Requirements for delaying or infiltration on slots can be required in city plans and in construction permits (Kuntaliitto, 2012).

Design of a stormwater management strategy should be tightly connected to urban planning. The management solutions require space and the land use of different areas impacts on the selection of the most suitable management solution for different areas. Therefore, stormwater management needs to be taken into consideration in planning of urban infrastructure. Retrofitting of biofiltration systems into existing urban landscape is usually possible, but when the areas for these management systems can be reserved already in the planning phase they can be more easily and sensibly located.

In Vantaa the starting point for the stormwater management is that the runoff from a lot must not increase as a consequence of construction. The stormwater flow from the lot is estimated according to runoff coefficients before construction and a design rain of 150 $l\ s^{-1}ha^{-1}$ and a duration of 10 min. In road areas the rule of thumb is that 100 m^2 of impervious area requires 1 m^3 of stormwater retention. The volume for the runoff that must be delayed is calculated as a result of the design rain lasting for 10 min both in lots and road areas. (Vantaan kaupunki, 2014)

Experiences around the world indicate that biofiltration systems can be used for management of stormwater that is generated on roads and traffic areas as well as in parking lots. In addition to quantity management, the capability of biofiltration in removing pollutants can be exploited. In Vantaa, biofiltration has been used for quality management in snow deposit sites and some roads with heavy traffic (Vantaan kaupunki, 2014).

In areas, where infiltration of stormwater to the ground is not recommended (e.g. groundwater recharge areas), the benefit of biofiltration is the ability to treat and delay the runoff before draining it from the sensitive area. If the efficiency of the treatment can be guaranteed, infiltration on site is naturally recommended. Risk assessment has to be made based on the specific conditions of the implementation site. (Kuntaliitto, 2012) The probable pollutants entering the system should be determined and the structure and material selected based on the information about the local conditions.

Biofiltration is suitable for local stormwater management and, because of its proven efficiency in removing pollutants from stormwater, it can be used to enhance the stormwater quality and protect sensitive recipients in urban environments.

2.4 Regulations concerning stormwater management and quality

Limiting values for the concentration of harmful substances in stormwater have not been defined and hence one option is to compare the quality parameters to environmental standards of surface and groundwater quality as well as to quality requirements and recommendations for domestic water (Inha et al., 2013).

2.4.1 EU Water Framework Directive 2000/60/EC

Directive 2000/60/EC of the European Parliament and of the Council was established in 2000 for a framework for Community action in the field of water policy. The initial aim of the directive was that a good chemical and quantitative status for all water within the member countries would have been achieved by the year 2015. The objectives of the directive were to improve the state of the aquatic ecosystems and prevent them from further deterioration.

The Framework directive was nationally implemented in Finland by Act on Water Resources Management (1299/2004) and its complementary regulations in Government Decree on Water Resources Management Regions (1303/2004) as well as by Government Decree on Water Resources Management (1040/2006) and Government Decree on Substances Dangerous and Harmful to the Aquatic Environment (1022/2006). The latter includes environmental quality standards defined for heavy metals including Cd, Pb, Hg and Ni (Table 4).

Table 4 *The Environmental Quality Standards for priority substances in EU surface water (1022/2006).*

Name of Substance	AA-EQS21 Inland Surface waters (µg/l)*	AA-EQS21 Other surface waters (µg/l)**	MAC-EQS22 Inland surface waters (µg/l)	MAC-EQS22 Other surface waters (µg/l)
Cadmium and its compounds (depending on water hardness classes)***	≤ 0.08 (Class 1) 0.08 (Class 2) 0.09 (Class 3) 0.15 (Class 4) 0.25 (Class 5)	0.2	≤ 0.45 (Class 1) 0.45 (Class 2) 0.6 (Class 3) 0.9 (Class 4) 1.5 (Class 5)	
Lead and its compounds	7.2	7.2	not applicable	not applicable
Mercury and its compounds	0.05	0.05	0.07	0.07
Nickel and its compounds	20	20	not applicable	not applicable

AA: annual average

MAC: maximum allowable concentration

EQS: Environmental Quality Standards

* Lakes and rivers

** Transitional, coastal and territorial waters

*** For Cadmium and its compounds the EQS values vary dependent upon the hardness of the water as specified in five class categories (Class 1: < 40 mg CaCO3/l, Class 2: 40 to < 50 mg CaCO3/l, Class 3: 50 to < 100 mg CaCO3/l, Class 4: 100 to < 200 mg CaCO3/l and Class 5: ≤ 200 mg CaCO3/l).

2.4.2 National legislation

There is no legislation concerning the treatment and quality of stormwater but stormwater management is primarily regulated at the local level in cities. Hence, the stormwater management policies are inconsistent. However, there is legislation covering the organization of stormwater management. Above all the current legislation determines the liability distribution concerning the planning of stormwater management.

The most essential laws regarding stormwater management are Land Use and Building Act (132/1999), Water Services Act (9.2.2001/119), Water Act (587/2011) and Flood Risk Management Act (24.6.2010/620). Other legislation related to stormwater management include Act on Water Resources Management, Environmental Protection Act (527/2014), Nature Conservation Act (1096/1996) and Highways Act (503/2005).

Any project that has an impact on quality or quantity of groundwater suitable for water supply requires a permit subject to Water Act (2:1.1). This has to be taken into account when designing stormwater management solutions in groundwater recharge areas (Kuntaliitto, 2012). Sewerage of stormwater is part of water supply service and hence the regulations concerning these issues are in Water Services Act. According to the act, municipalities are responsible for arranging stormwater sewerage in their areas.

In the Land Use and Building Act (103 a§) stormwater is defined as rain or meltwater that is accumulated on ground, on roofs or on other surfaces in developed areas. Stormwater management is defined as measures that are focused on infiltration, retention, conveyance and sewerage of stormwater. The stormwater system of a municipality consists of areas and structures that are designed for stormwater management excluding stormwater sewers subject to Water Services Act.

The goals of stormwater management are defined in the Land Use and Building Act. The aim is to develop systematic management especially in areas covered in the city plan, further infiltrating and delaying stormwater in the areas where it is accumulated, preventing the environmental detriments and damages and detriments for real estates while also considering the changing climate and contributing the reduction of the amount of stormwater lead to waste water sewers (103 c§). An owner or a tenant of a real estate is responsible for management of stormwater generated on the area of the real estate (103 e§). In principle, if infiltration is not possible and the stormwater from the real estate is not lead to stormwater sewer owned by municipality, the owner of the real estate must lead the stormwater to a stormwater management system owned by the municipality (103 f§). If there is a stormwater management system on the real estate, the owner or the tenant is responsible for the system and the equipment and structures that are part of it. Moreover, it must be integrated to the system owned by municipality. However, in areas covered in city plan the municipality is responsible for stormwater management.

According to the Land Use and Building Act municipality can give more specific regulations of stormwater management. Such regulations concern stormwater quality, quantity, infiltration, delaying and monitoring and real estate level management of stormwater (103 j§). Furthermore, municipality can accept a stormwater management plan which presents the stormwater management solutions and structures implemented in the municipality (103 l§).

2.4.3 Reference values for stormwater quality in Sweden

Based on several studies conducted in Stockholm during 1990s a classification of recipients and stormwater quality has been made in terms of pollutant concentrations (Ekvall et al., 2001). The substances studied include metals (Pb, Cu, Zn, Cd, Cr, Ni and Hg), polyaromatic hydrocarbons (PAHs), nutrients (P and N), oil and suspended solids (SS) that are all found to be common in stormwater. The classification is divided into three classes as shown in Table 5.

Table 5 *Division of stormwater into different classes 1−3 (Ekvall et al., 2001).*

Substance	Unit	Low concentrations (class 1)	Moderate concentrations (class 2)	High concentrations (class 3)
SS	mg/l	< 50	50−175	> 175
N	mg/l	< 1.25	1.25−5.0	> 5.0
P	mg/l	< 0.1	0.1−0.2	> 0.2
Pb	µg/l	< 3	3−15	> 15
Cu	µg/l	< 9	9−45	> 45
Zn	µg/l	< 60	60−300	> 300
Cr	µg/l	< 15	15−75	> 75
Hg	µg/l	< 0.04	0.04−0.2	> 0.2
Ni	µg/l	< 45	45−225	> 225
Cd	µg/l	< 0.3	0.3−1.5	> 1.5
Oil	mg/l	< 0.5	0.5−1.0	> 1.0
PAH	µg/l	< 1	1−2	> 2

Compared to the environmental quality criteria defined for lakes and watercourses by the Swedish Environmental Protection Agency (SEPA) (Table 6), there are fewer classes and the limiting values for different classes are lower in the classification made by Ekvall et al. (2001).

Table 6 *Environmental quality criteria; metals (Swedish EPA, 2000).*

METALS (µg/l)		**Cu**	**Zn**	**Cd**	**Pb**	**Cr**	**Ni**	**As**
Class	Description							
1	Very low concentrations	≤ 0.5	≤ 5	≤ 0.01	≤ 0.2	≤ 0.3	≤ 0.7	≤ 0.4
2	Low concentrations	0.5−3	5−20	0.01−0.1	0.2−1	0.3−5	0.7−15	0.4−5
3	Moderately high concentrations	3−9	20−60	0.1−0.3	1−3	5−15	15−45	5−15
4	High concentrations	9−45	60−300	0.3−1.5	3−15	15−75	45−225	15−75
5	Very high concentrations	> 45	> 300	> 1.5	> 15	> 75	225	> 75

The concentration values used in stormwater classification are event mean concentrations (EMCs) and it should be noted that concentrations during first flush may occasionally rise to a significantly higher level. When planning the actions required to reduce the environmental effects of stormwater it should always be considered how big the annual load from different parts of the subcatchment is. (Ekvall et al., 2001.) In conjunction with annual average values, also the characteristics of the recipient should be considered when prioritizing the actions to be taken in catchment scale. Above all, it should be kept in mind that according EU Water Framework Directive the state of the watercourses must not be deteriorated. (Riktvärdesgruppen, 2009.)

Proposals for limiting values for stormwater quality have also been defined for several municipalities in Sweden (Riktvärdesgruppen, 2009). The values defined in Stockholm are presented in Table 7. Uncertainty of variation of stormwater quality has been taken into account and the values are defined as annual averages. In order to take the uniqueness of every recipient into account, the values have been divided into two different classes of recipients. Limiting values are intended to be used as reference values and as a base for investigations that indicate when and what kind of measures should be taken.

Table 7 *Proposed limiting values for stormwater discharge (Riktvärdesgruppen, 2009).*

		Smaller lakes, watercourses, bay		**Bigger lakes and sea**	
Substance	Unit	Direct discharge	Discharge to sub-basin	Direct discharge	Discharge to sub-basin
SS	mg/l	40	60	50	75
N	mg/l	2.0	2.5	2.5	3.0
P	mg/l	0.16	0.175	0.2	0.25
Pb	µg/l	8	10	10	15
Cu	µg/l	18	30	30	40
Zn	µg/l	75	90	90	125
Cr	µg/l	10	15	15	25
Hg	µg/l	0.03	0.07	0.05	0.07
Ni	µg/l	15	30	20	30
Cd	µg/l	0.4	0.5	0.45	0.5
Oil	mg/l	0.4	0.7	0.5	0.7

Airola et al. (2014) compared the limiting values shown in Table 7 to concentrations obtained from stormwater quality measurements in Helsinki. Based on the investigations they concluded that most of the concentrations of different measured substances remained below the limiting values used in Stockholm and there does not appear to be general need for stormwater treatment in Helsinki. However, to preserve the good quality of streams the loads of especially Cu, Zn, N and Cl should be controlled. Moreover, it was shown that treatment of stormwater generated in e.g. parking areas would be reasonable.

In the current study the Swedish limiting values (Riktvärdesgruppen, 2009) are used during the analysis of the data. The estimated concentration distributions are compared to these values and the required reduction rates are defined so that the outflow concentrations would meet these requirements.

3 Methodology for planning and assessment of the filtration system

The methodology of this study is presented in Figure 5 and discussed in the following sections.

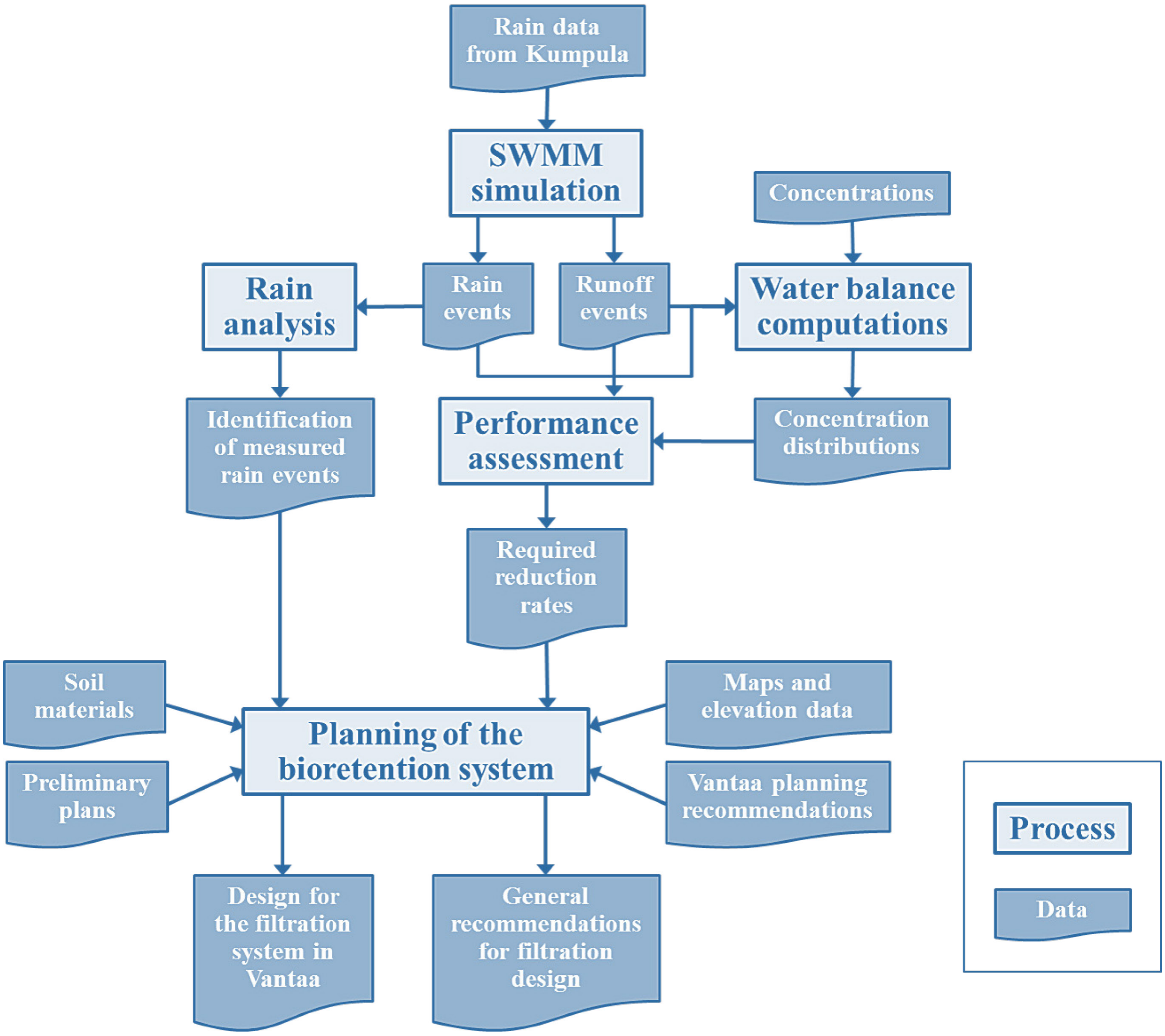

Figure 5 *The methodology of the study.*

The main objective of the planning process was to define the size and structure for a filtration system that can retain the amount of runoff generated by a design rain on the design catchment and to define the required removal rates of selected target pollutants. The idea was that based on the removal rates and the required hydraulic capacity, the proper material for the filter media could be selected. The design rain used in this study is the design rainfall used by the city of Vantaa (intensity of 9 mm/10 min).

To estimate the amount of runoff entering the filtration unit, the contributing catchment area of the filtration system was defined and the hydrology of the catchment was simulated with Storm Water Management Model (SWMM). Based on the simulation results of the design rainfall, the size of the filtration area was defined and the filtration module was activated and parameterized in the hydrological model.

The model was run with measured precipitation data of over five years (rain data from Kumpula) and the inflow and outflow events of the filtration system were computed. The model output was analyzed and the inflow and outflow events of the filtration system were combined. Distributions of certain stormwater pollutant concentrations were developed based on the literature. Thereafter, the concentration values were randomly assigned to the inflow events (using the defined distributions) and the outflow concentrations were calculated based on the mass balance of the system. Finally, by comparing the outflow concentrations with the limiting values defined in Stockholm, the required reduction rates for the pollutants were defined.

The design site of this study is presented in section 3.1 and in the section 3.2 the design considerations are discussed. The data and tools of this study are presented in the section 3.3 and SWMM model development and simulations are elaborated in the section 3.4. Finally, the section 3.5 presents the processing of the simulation results.

3.1 Design site

The filtration system designed in this study will be installed in Vantaa, southern Finland and the precipitation data used in the planning process is measured in Kumpula, Helsinki (Figure 6).

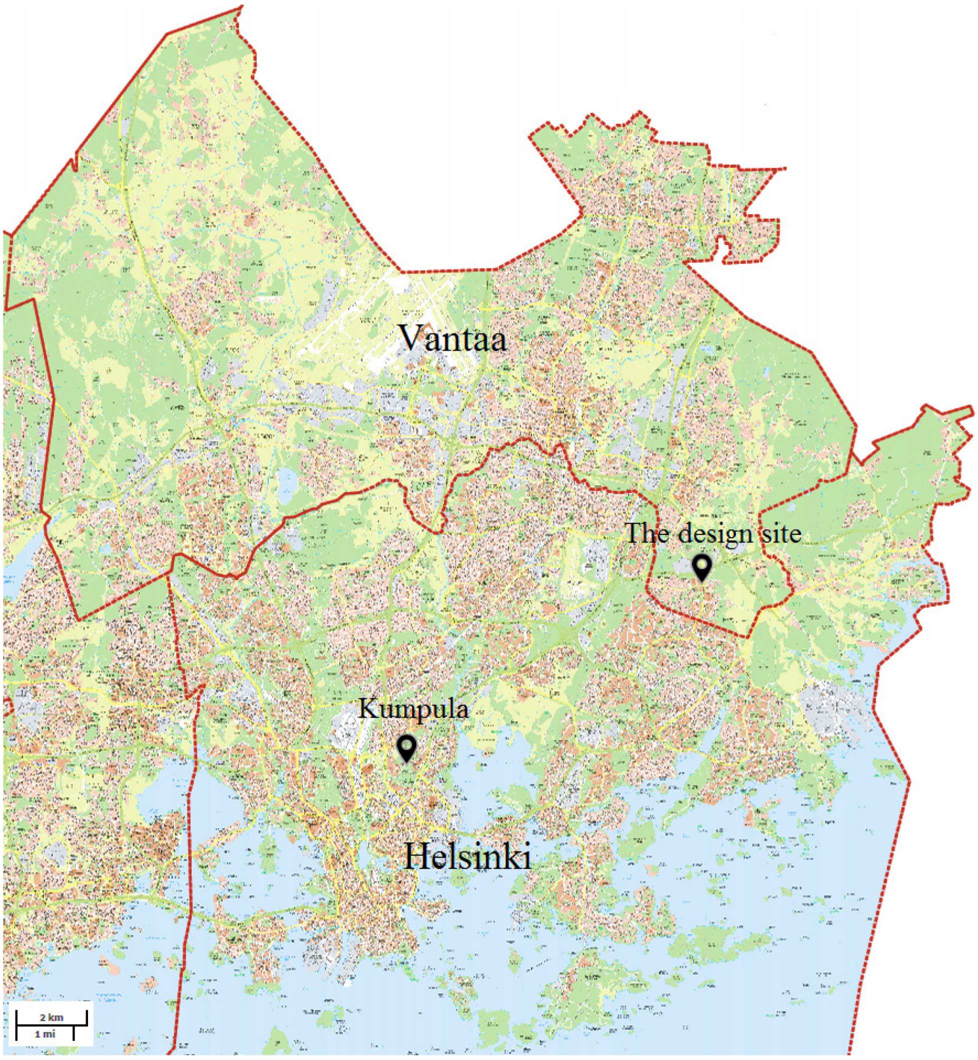

Figure 6 *The location of Kumpula and the design site (HSY, 2016).*

Currently the catchment area of the design site consists of the junction of Maratontie and Länsimäentie and its adjacent areas (Figure 7). The two roads of Maratontie and Länsimäentie are characterized by rather high traffic loads with 5 000 ADT to 18 000 ADT, respectively. The city of Vantaa has decided to replace the current junction with a roundabout. At the same time a filtration system will be installed to provide treatment and retention for stormwater generated on the road surfaces. Currently the stormwater management consists of stormwater inlets on the road area and a network draining runoff to an open ditch that conveys the water further to the stormwater network outside the design site.

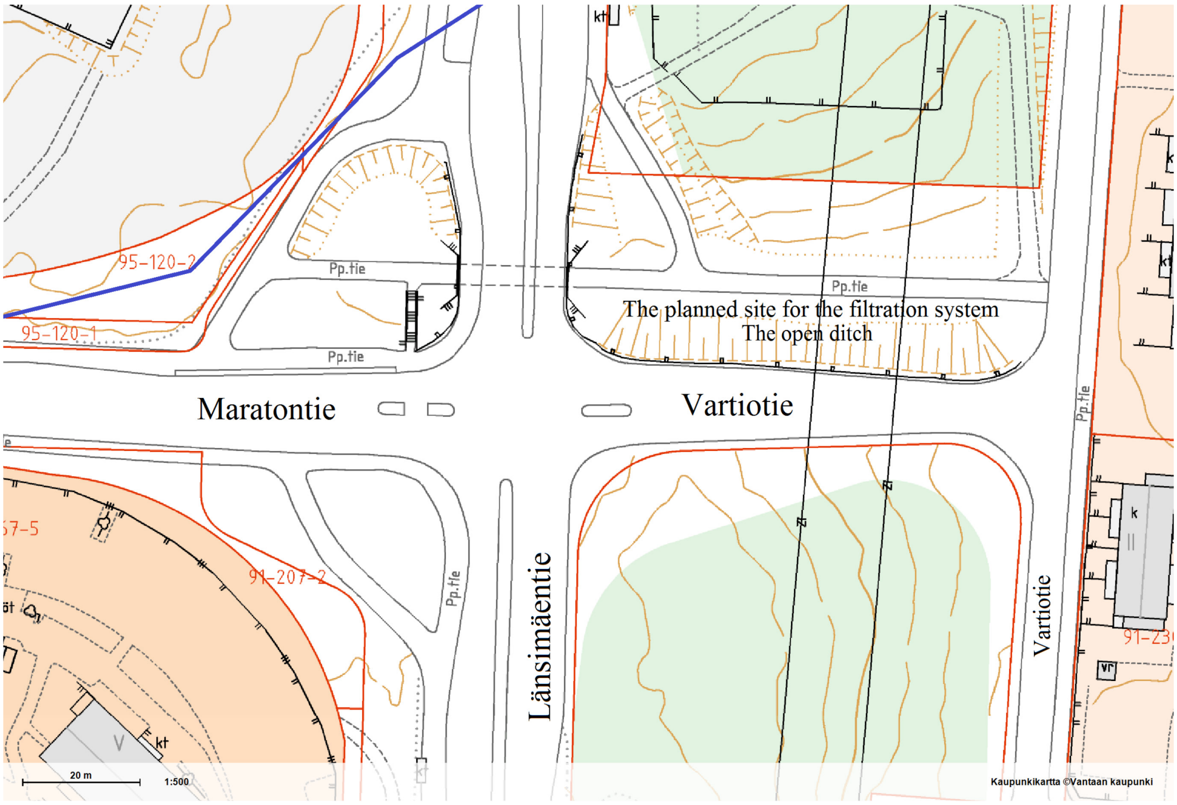

Figure 7 *The current junction of Maratontie and Länsimäentie. The boundary of the groundwater recharge area is marked with blue line. (Vantaan karttapalvelu, 2016)*

The open ditch will be replaced with the designed filtration system (Figure 7). The target site is located nearby a groundwater recharge area. Therefore, a bentonite layer will be installed at the bottom of the filtration unit to prevent the water from infiltrating in site. The drainage of the filtration system will be connected to the existing stormwater pipe network and hence the treated water is conveyed away from the design site. The planned layout of the roundabout is presented in Figure 8. The drainage of the area is planned to drain all the runoff gravitationally from all of the road areas to the filtration system.

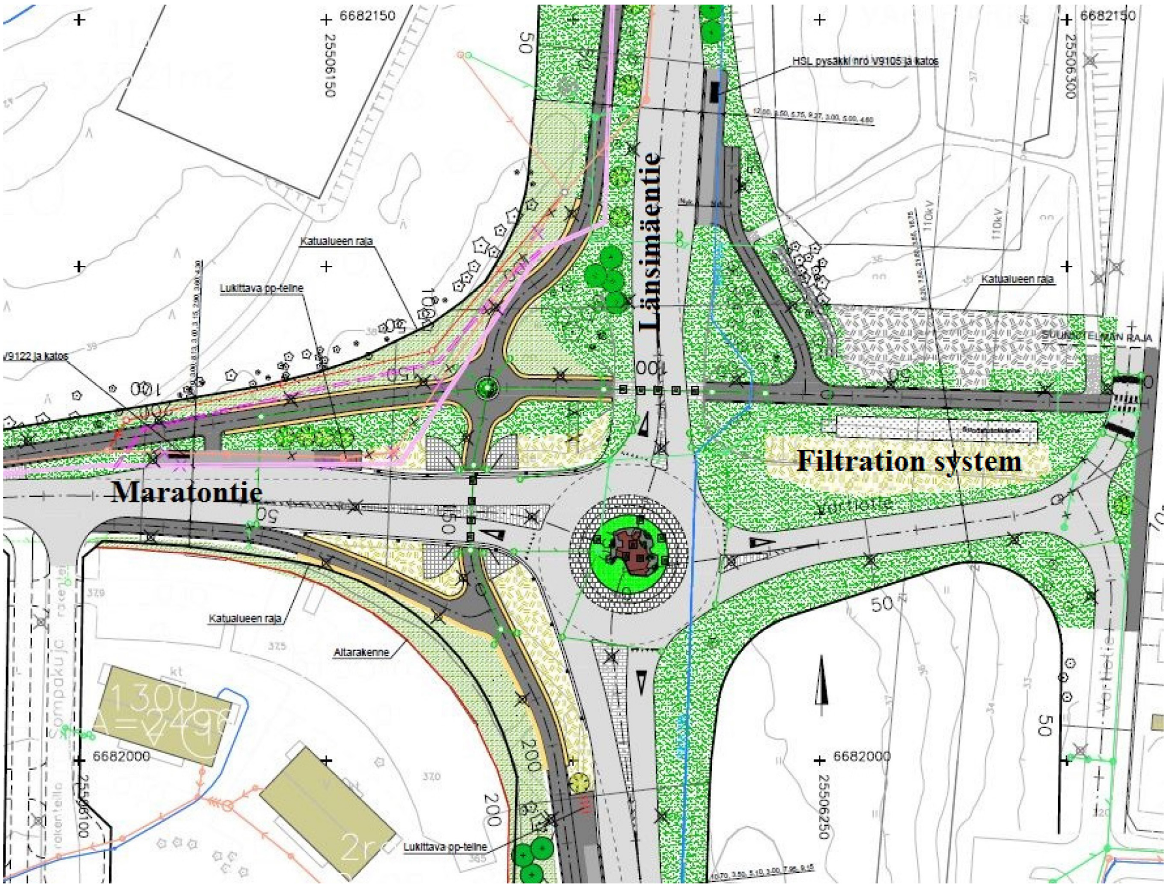

Figure 8 *The planned layout of the roundabout in the junction of Maratontie and Länsimäentie.*

3.2 Design considerations

According to the literature cited in section 2.3.3, several aspects need to be taken into account when designing a filtration system. Regardless of the stormwater treatment objective, defining the contributing catchment and the amount of runoff is the first step in the design process as the size of the required filtration system can be estimated. Hence, the amount of stormwater sets the baseline for the design.

The conditions on the site of installation and target pollutants are the main factors that define the required structure for the filtration facility. Climate conditions and characteristics of the catchment area, such as land use, affect the stormwater quality and possible restrictive factors such as the frost line. The selection of target pollutants is significant for the design as the structure affects the removal of different pollutants. As stated previously in sections 2.3.4 and 2.3.5, heavy metals and suspended solids can be removed effectively with various soil-based filter media approaches whereas for nutrient removal the conditions in the treatment media are more significant. Therefore, the design of the structure and plant selection depend on the composition of the stormwater, the target pollutants and the climate conditions (Bratieres et al., 2008; Hatt et al., 2009).

It has been shown that the rather small but frequent rain events are the ones that play the key role in transporting pollutants and hence contribute to the largest part of yearly pollutant loads (Larm, 2000). Therefore, it is suggested that stormwater treatment facilities are designed for these smaller events and less frequent and larger events are taken into account during design if detention of stormwater flows is the objective. However, in this study the filtration capacity was designed based on the runoff volume generated by the design rain used in Vantaa. The Vantaa design rain event (VDR) is defined as an event that lasts for 10 min and produces 150 l $s^{-1}ha^{-1}$ of runoff or 9 mm/10 min of precipitation.

Considering the efficiency of the system an important design parameter is the hydraulic conductivity of the media, which influences both the amount of runoff treated and the effectiveness of the pollutant removal. A higher hydraulic conductivity enables higher infiltration rate and hence higher amount of water to be treated. Furthermore, high hydraulic capacity prevents the media from freezing over. On the other hand, high infiltration rate means lower pollution removal since pollutant removal requires some retention. Values of the saturated hydraulic conductivity of common soil materials are presented in Table 8. Hydraulic conductivities over 200 mm/h can be considered as high and conductivities below 20 mm/h as low. Recommendations for the hydraulic conductivity of filtration media vary from one country to another. For instance, in Australia the recommended hydraulic conductivity is between 50 and 200 mm/h and in Austria between 36 and 360 mm/h whereas in the USA and in New Zealand a hydraulic conductivity of at least 12.5 mm/h is required. (Le Coustumer et al., 2009)

Table 8 *Hydraulic conductivity of common soil materials (Krebs et al., 2014).*

Soil material	Hydraulic conductivity (mm/h)
Sand	235.6
Loamy sand	59.8
Sandy loam	21.8
Loam	13.2
Clay	0.6

Overall, the challenge in the design is to find a balance between a sufficiently high hydraulic conductivity and efficient removal of target pollutants. It is recommended that especially in cold climates the structure consists of a relatively thin (100 mm) topsoil or mulch layer that promotes a sufficient sorption capacity and a coarse filter media, which provides sufficient water percolation. If the filter media is rich in organic matter, leaching of metals, such as Cu, can occur along leaching of dissolved organic materials. (Blecken et al., 2010a) These challenges were considered also in the design process of this study. The structure was designed without vegetation due to possible leaching of nutrients from the growing media and to rather insignificant benefits in terms of pollutant removal. Furthermore, to reduce the risk of freezing of the structure during winter, the hydraulic capacity of the filtration media was assumed to be high and the drainage layer was designed so that the water would not stay in the layer but drain rather fast from the structure.

In order to reduce the amount of solids entering the filtration area, a shallow detention basin was designed as a pretreatment unit for the filtration. Based on the literature the removal of TSS appeared to be necessary in terms of treatment efficiency and lifespan of the system (e.g. Haile et al., 2015). The size of the basin was defined based on the values for sedimentation of different sized particles presented in RIL (Karttunen, 2004, table 141).

3.3 Data and tools

The catchment area of the design site was defined and analyzed with ArcMap and SWMM (2015, version 5.1) was used to simulate the catchment hydrology and to define the amount of runoff entering the filtration unit. ArcMap is the main component of Esri's ArcGIS suite of geospatial processing programs. It was used to edit and analyze the geospatial data for the study. The simulation results were then analyzed with a spreadsheet computation tool (Microsoft Excel, version Office 2013) and the rainfall-runoff events were combined with concentration data obtained from the literature.

The main step of this study were hydrological simulations that were performed with SWMM. The hydrological model of the catchment area of the designed filtration system was developed based on the data of the design site and rainfall and air temperature data measured in Kumpula, Helsinki (Figure 6). SWMM was used to simulate the filtration system inflow based on which the filtration unit was designed. After implementing the filtration system in the model, the outflow of the filtration unit was simulated. As a result, a large number of event inflows and outflows with associated flow reductions were obtained and analyzed in the spreadsheet program. Thereafter, inflow concentrations of selected pollutants were added randomly to the different-sized events. It was assumed that the inflow is mixed with the storage water of the structure and the outflow concentrations were calculated to equal the mass storage divided by the water storage and inflow. The mass balance of the pollutants was added to the calculations as the smallest inflow events did not produce instant outflow and thus some outflow events were generated by several inflow events. The required reduction rates for the pollutant concentrations were defined by comparing the outflow concentrations to the reference values found in the literature.

The Technical Research Centre of Finland Ltd (VTT) conducted laboratory studies for different filter materials and their ability to remove pollutants from synthetic stormwater. The preliminary results of these experiments were also available for this study.

In this study measurements of stormwater quality from the study site were not available and hence values of concentrations for different pollutants were obtained from the literature. The variation of stormwater quality and different concentrations were found to be remarkable and therefore any typical values for pollutants could not be defined. Furthermore, it was concluded that the target pollutants are copper (Cu), lead (Pb) and zinc (Zn). These metals appeared to be among the most often studied ones and also VTT had selected them for the laboratory tests.

3.3.1 Meteorological data from Kumpula

The meteorological data used in this study covered a period of over five years, from September 2010 until the end of the year 2015. The data included rainfall data at four-minute interval and daily air temperature data. The data was measured by the University of Helsinki with an OTT PLUVIO weighing rain gauge in Kumpula. Kumpula is located 10 km south-west from the design site. The weights measured were converted to millimeters and the recording time steps were regularized to be exactly four minutes as the raw data had varying time steps between 3−5 min. The data was also matched with other daily data measured in Kumpula by Finnish Meteorological Institute (FMI). The data was scaled so that the daily accumulations match FMI's daily accumulations and missing data was filled with FMI 10-minute data if available.

Precipitation and air temperature data from Kumpula was analyzed and used to simulate the long term function of the treatment unit. In SWMM the evaporation was set to be calculated based on the temperature data and the modeled runoff and precipitation events were determined with statistical analysis tools available in SWMM.

3.3.2 Data for pollutant concentrations

Since measurements were not available about pollutant concentrations or the build-up and wash-off rates, it was decided that instead of simulating these processes and the treatment efficiency of the filter media, required reduction rates were estimated. Moreover, since quality measurements of the stormwater generated on the area were not available, concentrations for different pollutants in stormwater were estimated based on literature values. The concentrations of different pollutants were found to vary significantly in the literature (Göbel et al., 2007; Vezzaro and Mikkelsen, 2011).

Due to rather similar climate conditions of Finland and Sweden, estimates for concentration distributions were computed based on studies conducted in Stockholm during 1990s. Based on the median, minimum and maximum values of the data, distributions for different concentrations were estimated by assuming that shape of the distribution is logarithmic. The concentration values used in the analysis are presented in Table 9.

Table 9 *Concentration values used in the study (Ekvall et al., 2001).*

Substance	Unit	Background value	Roads (ADT 8 000−19 000)	
			Median	Min-Max
Pb	µg/l	0.24	15−21	2−94
Cu	µg/l	0.5	52−74	2−240
Zn	µg/l	2	180−310	9−1200

3.4 Stormwater Management Model (SWMM)

Computational models based on physical laws and mathematics can be applied to simulate filtration processes and characterize the water fluxes into, within, and out of the system. Modeling assists in the design as it simplifies the filtration system and enables the evaluation of pollutant treatment performance. (Liu et al., 2014) The Storm Water Management Model (SWMM) developed by U.S. Environmental Protection Agency (US EPA) (e.g. Rossman, 2010) has been widely used for modeling urban stormwater. SWMM was initially developed in 1970s and ever since it has been continuously maintained and updated. Both stormwater quantity and quality can be simulated with the model. In addition, the simulation of treatment facilities is included in the software. (Borris et al., 2014)

In SWMM catchments are treated as nonlinear reservoirs with inflows including precipitation and runoff from adjacent catchments and outflows and losses comprising surface runoff, infiltration and evaporation. The catchments may be subdivided into pervious and impervious subareas. Runoff from impervious areas occurs if rainfall exceeds the depression storage depth while in pervious areas, in addition to storage depth, also the infiltration rate of the catchment must be exceeded. For either type of sub-area, there are several parameters to be defined to compute the runoff for individual subcatchments. These parameters include area, overland flow width, ground slope, percentage of imperviousness and surface roughness (Manning's *n*). (Borris et al., 2014; Rossman, 2010)

3.4.1 Model development and hydrological simulations

In this study, SWMM was used to model the hydrology of the design catchment. The area around the roundabout was inspected and the catchment area was estimated using ArcMap. In ArcMap the catchment area was delineated by creating a digital elevation model (DEM) based on the elevation data of the area. Furthermore, the existing stormwater network was added to the model. The network and elevation data was provided by the city of Vantaa. Once the catchment area was defined, it was divided into subcatchments that consisted either of pervious or impervious areas. The definition of subcatchments was conducted in ArcMap using aerial data. In order to validate the catchment area and to get a better understanding of the existing conditions, the design site was also visited and the model updated according to the on-site observations. The catchment area is presented in Figure 9. The total size of the catchment area is around 0.9 ha.

Figure 9 *The catchment area and its subcatchments.*

The parameters defined for each of the subcatchments were slope (S), flow width (FW), flow length, Manning's *n* for overland flow (N_imperv and N_perv) and the surface depression storage (S_imperv and S_perv). The values for the parameters were defined based on a SWMM calibration by Krebs et al. (2014). The subcatchments were divided into different surfaces that have homogeneous hydrological properties. Parameter values used for the model and the division of the areas into different categories are presented in Table 10. The flow path length was measured for each subcatchment in ArcMap in the direction of the flow. For the green areas flow path length was defined as the square root of flow length. The flow width was calculated by dividing the area of a subcatchment by its flow path length. Surface slopes for individual subcatchments were taken from the catchment digital elevation model. The parameter values that depend on perviousness or imperviousness of a subcatchment were set to the same value for all corresponding areas.

Table 10 *Parameter values used in the modeling (Krebs et al., 2014).*

The runoff model was created by transferring all the data about the catchment area into SWMM. The catchment area divided into the subcatchments is presented in Figure 10. First, the inflow to the filtration system was computed. The generated catchment runoff was

Categories of the subcatchments	Imperviousness	Manning's n	Surface depression storage
Roofs	100 %	0.012	0
Roads	89 %	0.011	0.42
Extensions of the road area	87 %	0.02	0.39
Green areas, lawn/vegetation	0 %	0.238	4.22
Green areas, vegetation/lawn	0 %	0.326	3.59
Green areas, vegetation	0 %	0.667	4.13

collected in one point defined as the catchment outflow. Secondly, the filtration system was added to one of the subcatchments and its dimensions were defined based on the amount of system outflow generated by VDR (9 mm/10 min) and the assumed filter materials. The outflow curve of the catchment into the filter for runoff produced by VDR (9 mm/10 min) (see section 34) is presented in Figure 11.

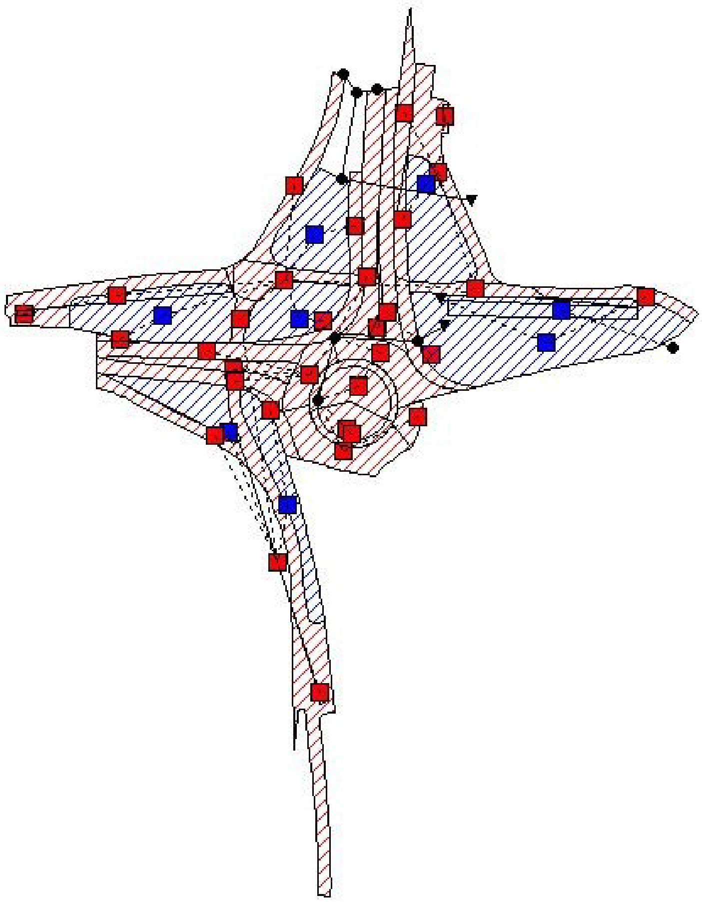

Figure 10 *The modeled catchment. Red squares indicate impervious subcatchments while blue squares indicate pervious subcatchments.*

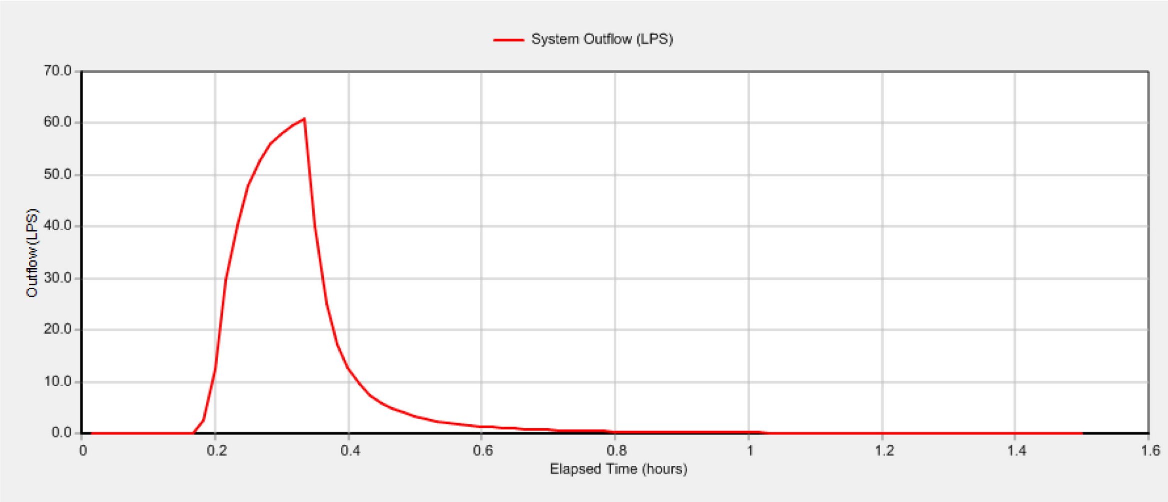

Figure 11 *Outflow curve after Vantaa design rain 150 l/s/ha (= 9 mm/10 min). LPS refers to l/s. (SWMM 5.1).*

Once the filtration module was implemented into the model, the model was run with the rainfall data from Kumpula for a simulation period of over five years. Thereafter, the rainfall and runoff events were divided using the statistics tool included in SWMM. The minimum separation time of the precipitation events was set to 6 h.

The water balance of the filter was inspected and the rainfall and runoff data analyzed. In order to analyze the water balance of the modeled system and to estimate pollutant concentrations for the inflows and outflows of the filtration unit, rain events, inflow events and outflow events calculated by SWMM were combined.

3.4.2 Parameters for the filtration unit

In SWMM the LID system is created in the LID control editor that includes different types of LID structures. *Bio-Retention Cell* was selected as the structure type and the size and the parameters for the filtration unit were defined based on the water volume produced by the design event with the prerequisite that no surface runoff is generated. The filter was modeled to consist of a surface layer with 200 mm ponding depth, soil layer with thickness of 450 mm and a drainage layer of 200 mm. The value for hydraulic conductivity was set to the same as for loamy sand adopted Krebs et al. (2014). The preliminary soil parameters were defined as presented in Figure 12.

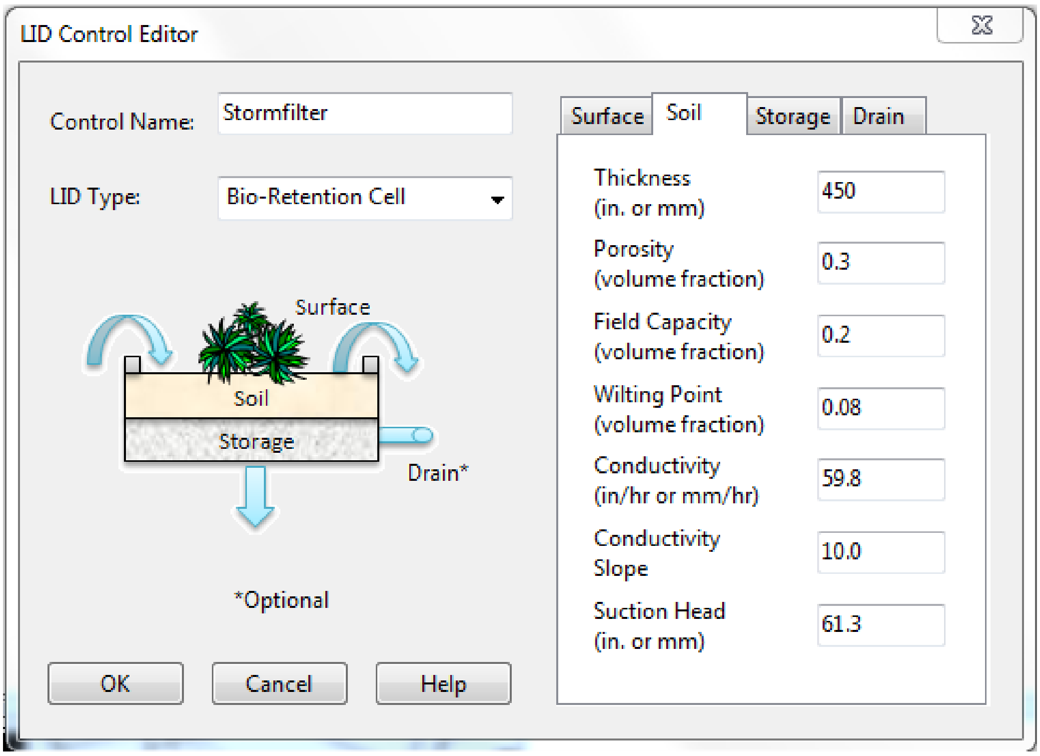

Figure 12 *Soil parameters used in the preliminary design (SWMM 5.1).*

3.5 Processing of the SWMM simulation results

When the inflow and outflow events of the filtration unit were obtained from SWMM, the assumed quality of the stormwater was defined in terms of concentrations of the three target pollutants (Cu, Pb, Zn). The SWMM simulation results, including precipitation, inflow and outflow events, and daily evaporation, were combined for computation of event-based water balance. Due to the great variability in pollutant concentrations, the concentrations were assigned to the inflow events using predefined concentration distributions. The concentrations for the outflow events were calculated based on the mass balance of the pollutants in the filtration unit.

The overall flow of the data processing computations is outlined in Figure 13 and explained in more detail in the following sections.

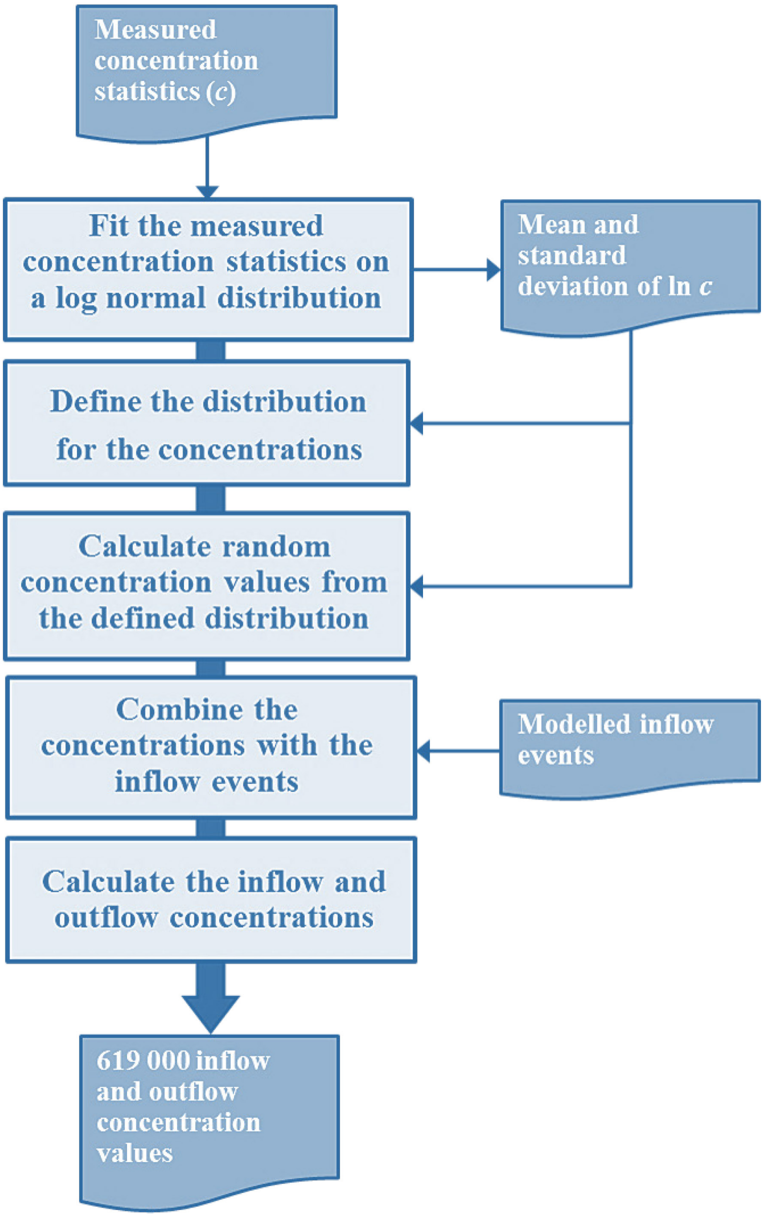

Figure 13 *Processing of the data.*

3.5.1 Probability distributions of the target pollutants

The concentration distributions were created for each metal to be able to conduct the random simulations of the expected stormwater quality. It was assumed that the concentrations follow lognormal distributions. Then, if the variable c represents concentration values, the probabilities of $x = \ln c$ form a normal distribution:

$$f(x|\mu, \sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \qquad (3)$$

where μ is mean, and σ is standard deviation of $\ln c$.

The concentration reference data of each metal consisted of minimum value, maximum value and median value (Table 9). In order to be able to create the concentration distribution, the mean value and standard deviation for the lognormal distribution of the concentrations were estimated by fitting the assumed lognormal distribution against the reference data. Numerical estimates of mean, minimum and maximum of a lognormal distribution were used to find the values for mean and standard deviation of $\ln c$.

The numerical estimates of the minimum and maximum were calculated as the natural logarithm raised to the power of the normal inverse cumulative distribution with probabilities of 0.01 for the minimum and 0.99 for the maximum. The normal inverse function is defined in terms of the cumulative distribution function:

$$x = F^{-1}(p|\mu,\sigma) = \{x: F(x|\mu,\sigma) = p\} \tag{4}$$

where μ is the mean, σ is the standard deviation and the probability p is defined as:

$$p = F(x|\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{x} e^{\frac{-(t-\mu)^2}{2\sigma^2}}\,dt \tag{5}$$

The result, x, is the solution of the integral equation with the desired probability p. The calculations were done in the spreadsheet program. The numerical estimates of mean, minimum and maximum were compared to the minimum and maximum values of the concentration data. The best fitting values for the mean and standard deviation of each metal concentration distribution were identified so that the difference between the numerical estimates of minimum and maximum and the initial minimum and maximum values was minimized.

3.5.2 Concentrations of the inflow and outflow events

Once the parameters for the distributions were discovered, the concentrations were combined with the modeled inflow and outflow events so that the event-based water balance and mass balance of the pollutants were combined in the spreadsheet program. Water balance components were the modeled precipitation events (P), inflow (R_{in}) and outflow (R_{out}) events of the filtration facility, evaporation (E) and water storage (S) of the filter. The water balance of the system was defined as:

$$S_{t+1} - S_t = R_{in,t} - R_{out,t} + P_t - E_t \tag{6}$$

First, the aim was to estimate the reductions in pollutant concentrations that would result solely from the reduction in water volume and the mixing effect inside the filter. Hence, the outflow concentrations (C_{out}) were calculated so that the pollutant mass inflow (m_{in}) and the mass storage (m_{sto}) of the media was divided by the amount of outflow (R_{out}) and the water storage (S) of the media:

$$C_{out} = \frac{m_{in} + m_{sto}}{R_{out} + S} \tag{7}$$

where $m_{in} = R_{in} \times C_{in}$, $m_{sto,t+1} = m_{sto.t} + m_{in} - m_{out}$ and $m_{out} = C_{out} \times R_{out}$. Secondly, the outflow concentrations were compared to Swedish limiting values and to define the required reduction rates for the pollutants, a reduction of certain percent of the pollutant mass was added to the mass balance and the values for the outflow concentrations were calculated again. The required reduction rates were defined so that 95% of the outflow concentrations would stay within the defined reference value. Then the calculations were carried out again with the reduction and new values for the outflow concentrations were obtained.

The concentration from the distributions were combined with the inflow events so that randomly selected concentrations from the distributions were combined with the modeled inflow events. To calculate the changing inflow concentrations, the probability p was sampled from the uniform distribution and then changed to c using the inverse logarithmic distribution.

Thereafter, the corresponding outflow concentrations were calculated based on the mass balance of the system. There were 619 inflow events that all were associated with a random concentration. The corresponding outflow concentrations were calculated at the same time. The combining of the concentrations to the 619 events was repeated 1000 times. Hence, two data sets of 619 000 concentration values (inflow and outflow) were obtained.

4 Results and discussion

In this chapter the modeling results of SWMM are analyzed and discussed and the suggestion for the structure of the filtration system is presented. Furthermore, the required reduction rates defined for the selected pollutants are presented.

4.1 Precipitation and temperature data from Kumpula

The SWMM statistics tool identified 892 precipitation events during the modeled period. Number of precipitation events, and runoff events described as inflow and outflow to the filter are presented in Table 11. According to the simulation which included the modeled filtration cell, 30 % of the rainfall events do not generate inflows to the filtration and 4 % of the inflow events do not produce outflow from the filtration unit. The filtration facility seems to be capable of storing some of the runoff which enables attenuation of the runoff and reduction of the peak flows.

Table 11 *Number of events modeled in SWMM (SWMM 5.1).*

Initial data from SWMM	
	Number of events
Precipitation	892
System outflow (inflow to the filtration)	620
Outflow from the filtration	595

The annual amounts of precipitation were compared to values given by FMI (2016). According to the FMI data, annual precipitation varies from 650 mm to 750 mm. According to the statistics, the year 2012 was exceptional with an annual precipitation ranging from 825–900 mm (FMI, 2016). The measured annual values from Kumpula were in the same range. The annual amounts of precipitation for the years 2011–2015 and the largest events during these years are presented in Table 12. As shown in the table, the years 2011 and 2012 have been more rainy than the other three years. The largest single event in terms of the amount of precipitation occurred in 2013 and produced 68.8 mm of rain.

Table 12 *The annual amounts of precipitation and the largest events (SWMM 5.1).*

Year	Annual total (mm)	Annual event average (mm)	Largest event of the year		
			Date	Event total (mm)	Duration (h)
2011	816	5.2	8/30/2011	45.3	20
2012	980	5.3	9/22/2012	38.9	34.9
2013	624	3.9	8/12/2013	68.8	62.1
2014	634	3.8	8/20/2014	30	11.7
2015	664	4.0	1/31/2015	35	73.9

In addition to the amount of rainfall, rain intensity is important considering pollutant wash off (Borris et al., 2014). According to the different characteristics of rain events, they can be divided into summer and winter events (FMI, 2016). Usually during summer time there can be heavy showers. Generally, in summer the majority of the precipitation events are showers that occur during afternoon and last from 20 minutes to roughly four hours. On the other hand, winter rain events can last several hours. According to FMI (2016), heavier but usual downpours can be defined in several ways: 2.5 mm/5 min; 7.0 mm/h; 15 mm/12 h; 5.5 mm/30 min; 10 mm/4 h or 20 mm/24 h.

Based on the average rainfall intensities of the events, there were six events (0.7%) that produced over 7 mm/h and 197 (22%) events that exceeded 20 mm in 24 hours and hence were comparable to the heavy downpour defined by FMI (2016). The peak intensity momentarily exceeded 7 mm/h in 141 events (16%). The intensity of precipitation can vary significantly during short time intervals. Considering the performance of a filtration unit it matters whether the rainfall intensity is high during the whole event or the intensity is high only momentarily. Once the pores of the media are filled with water, field capacity is exceeded and the excess water has not had time to infiltrate or drain, the water starts ponding on the surface layer and finally surface runoff is generated. This can be the case if the rainfall intensity stays high for a longer time or exceeds the hydraulic conductivity of the media. The current filtration unit for Vantaa is designed to treat all the water produced by the Vantaa design rain event (VDR) even if the hydraulic capacity of the filter media would be halved. This safety factor is due to possible clogging of the filter media.

In terms of average intensity, only one event, which occurred 08/12/2011 can be considered as a heavy downpour according to FMI (2016) as the average intensity was 8.8 mm/h. Furthermore, the data from Kumpula was compared to the intensity of VDR (54 mm/h). There were three events that had momentarily higher intensity than the design rain. All the three rainfall events have occurred in the summer time, either July or August and the duration has varied from 2.4 to 9.6 hours. Therefore, the characteristics match well to the description of FMI of typical heavier summer showers. However, the highest intensities have probably been very short-time peaks as the average intensities are significantly lower than the peak values. The data concerning these three events with the highest intensities is presented in Table 13.

Table 13 *Precipitation events with the highest peak intensities (SWMM 5.1).*

Event (start date)	Peak intensity (mm/h)	Average intensity (mm/h)	Total duration (h)	Total amount (mm)
07/28/2012	82.104	3.1	3.3	10.3
08/22/2011	77.916	3.9	9.6	37.6
08/12/2011	62.788	8.8	2.4	21.1

As it can be noticed from the Kumpula precipitation data and as it has been stated previously in this section, large rainfall events (> 20 mm/day) are rather rare and occur maybe once a year or even once a decade. The frequency of more unusual and infrequent rainfall events can be estimated based on historical rainfall data. Data of frequencies of different sized rainfall events can be extracted from Figure 14 that is created by FMI (2016). The graph can be interpreted in the following way: if it rains 10 mm during 10 minutes, the probability of an event of the same size to occur is once in five years. That is near the size of the design event of Vantaa. Thus, the occurrence of the design event is around the same, once in five years.

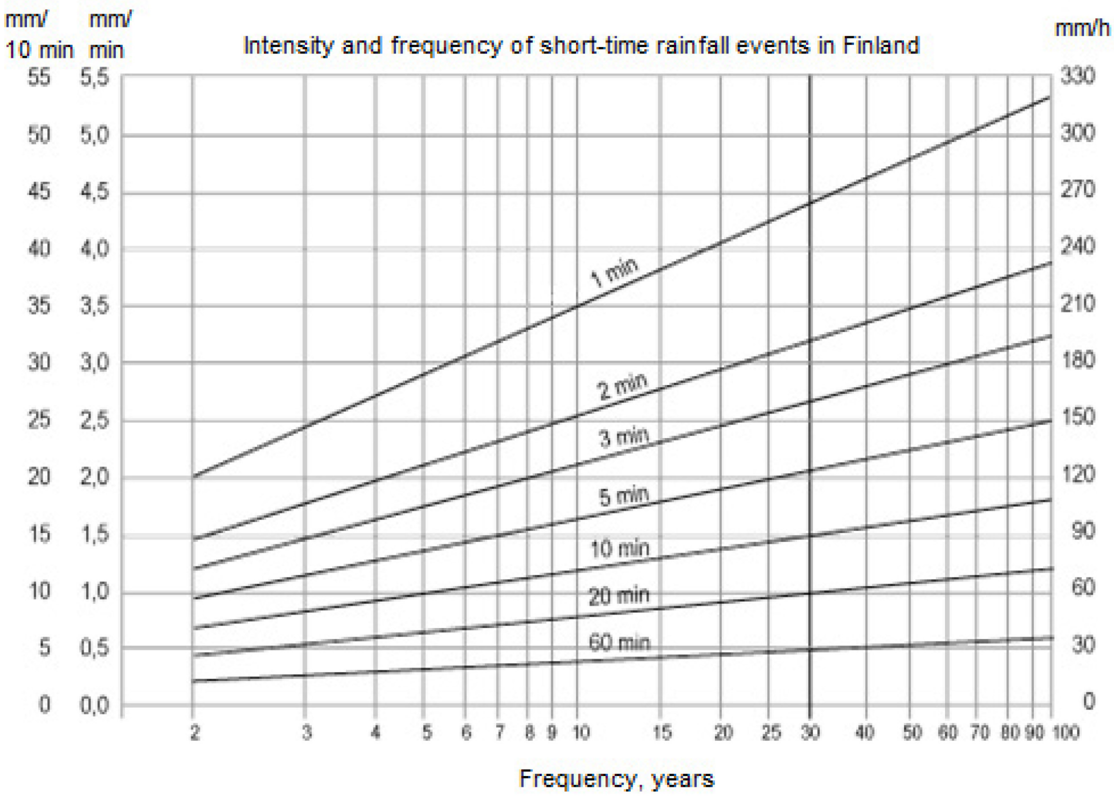

Figure 14 *Probability of high rainfall events in Finland (adapted from FMI, 2016).*

The rain data can be divided into different rain event categories in terms of their impact on runoff quality. Pitt (1999) suggests that the categorization is based on possible pollutant discharges of different events. He presents three classes that are based on the size of the event: rains that are less than 12 mm, rains between 12 mm and 38 mm and rains greater than 38 mm. Common rains that are less than 12 mm in depth have relatively low pollutant discharges. However, they are considered as key rains when runoff-associated water quality violations (e.g. bacteria) are of concern. Hence, runoff from these rain events should be captured and treated. The majority, nearly 90%, of the events based on Kumpula data belong to these key rains.

Rains between 12 and 38 mm are significant when pollutant loads are in focus. According to Pitt (1999), these rains account for about 75% of the runoff pollutant discharges. The runoff from these larger rains should be treated to prevent pollutant discharges from entering the receiving water bodies. Almost 10% of rainfall events analyzed belong to this class. Furthermore, the highest peak intensities are mainly related to the events of this class which supports the fact that the pollutant loads can be significant due to enhanced wash-off process that result from the joint effect of large water amount and high intensity.

If the duration of VDR is expanded to an hour, the total amount of precipitation is 54 mm. Rains associated with drainage design are generally the ones greater than 38 mm. However, relatively small part of the annual pollutant load is associated with these rain events and pollution control design based on them is costly. (Pitt, 1999). Therefore, it is questionable to design LID systems solely according to design events like those represented by the design rain used in Vantaa. Treatment systems used to manage the smaller events can also have some benefit in reducing pollutant loads of the larger events that makes them more cost efficient. Hence, gaining information about the actual conditions of the site is valuable. That local data should form the offset for the design process rather than a fixed design value. Considering more local conditions can also widen the possibilities to take advantage of the LID technologies as some stable design requirement may be challenging to fulfil especially if there is not sufficient space available.

Moreover, it is clear that the larger events are not that significant due to their rather small occurrence. In the analyzed rainfall data, only 0.4% (4 events) of all the events produced over 38 mm of rain. Among the analyzed data from Kumpula, the largest fraction (38%) of the event sizes ranges from 1 mm to 6 mm and almost a same-sized fraction comprises the events that are smaller than 1 mm. The median precipitation size of all of the events is 1.8 mm and the average is 4.5 mm while the average duration of all the events is 9 h. The number of annual events varies from 156 (year 2011) to 187 (year 2012) and annual median precipitation event ranges from 1.3 mm to 2.1 mm in size.

The distribution of the rainfall events in terms of size is presented in Figure 15. The common rains are further divided into three classes so that the distribution between these smallest events can be observed. A clear majority of the rains are small events that are easily captured and treated but can have a great impact on stormwater quality.

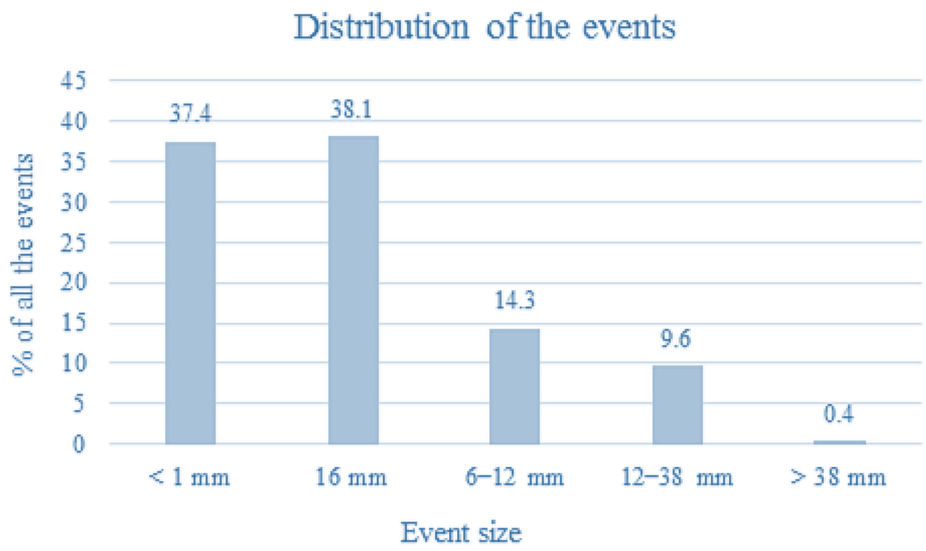

Figure 15 *Distribution of the events in terms of total amount of precipitation.*

The smallest rainfall events do not produce any runoff as the water is infiltrated in the pervious areas or starts ponding on the impervious surfaces. In 61% of analyzed events smaller than 1 mm, no runoff to the filter was generated. It was observed that when runoff was generated as a result of an event smaller than 1 mm, there had previously been larger event that was followed by the smaller event. Moreover, the amount of runoff generated was relatively little. The average size of a runoff event related to the smallest precipitation events (< 1 mm) that produced runoff is 2.38 m^3 while the average runoff event of all the events is 21.5 m^3. Therefore, the smallest events are significant only if the surface depression storage of the runoff contributing area is filled up as a result of a larger event prior to the smaller one. Furthermore, most of the runoff events occurred during fall, spring or winter. This matches well with decreased evaporation during these seasons and increased contributing area due to freezing of the ground of the pervious areas.

Due to the seasonal variation in pollutant concentrations and state of the substances, the data of the study was divided into warm and cold period events. The periods were defined so that cold period covers months from October to March and warm period from April to September. According to the data, there were more events during cold period and a slightly larger majority consisted of key rains (less than 12 mm) (Pitt, 1999) than in warm period. Considering filtration performance, the cold period is the most challenging time as there is a risk of freezing and ice formation on the top of or inside the structure, which can cause malfunction of the filtration unit. Then the runoff may bypass the filter and remain untreated. Moreover, as previously stated, due to the usage of salts the state of the pollutants can change from solid to liquid when the substances are more easily moved through the filter along the infiltrated water. Furthermore, due to the application of gravel, enhanced abrasion increases the metal concentrations of stormwater. Therefore, it is essential that the runoff can be captured and the treatment is efficient especially in wintertime.

Some of the modeled rain events were combined into a single aggregated event if it could be assumed that all of the contributory events affected the runoff event. This was the case when there were two or more rainfall events during one day but only one runoff event. It is obvious that the water entering into the filter reduces the capacity and the filtration outflow is a result of the two or more rainfall events.

4.2 Runoff events

Considering the design of the filtration system, all analysis with respect to runoff was done with the model that included the filtration cell. According to the simulation, there were 619 runoff events producing inflow to the filtration during the monitored period starting from September 2010 until the end of the year 2015. Moreover, there were 595 outflow events from the modeled filtration unit. A fraction of around 30% of the precipitation events did not produce any runoff to the unit.

The design event used in Vantaa was compared to the modeled events based on actual data measured in Kumpula. The average size of a runoff event from the design catchment was 21.5 m^3 while the runoff event produced by the design event used in Vantaa was 34.5 m^3. Furthermore, the design rain produced a peak flow of around 60 l/s to the filtration system. During the measured period of five years the size of the Vantaa event or larger with respect to solely runoff volume and peak flow, appeared 136 and 3 times, respectively. It should be noted though, that there is also significant difference in the duration of the events. The largest runoff events produced by Kumpula rain data resulted from rainfall events of several hours whereas the design event lasts for 10 minutes. According to the simulation, the largest momentary peak flow to the filtration area was 95 l/s. However, the average flow rate of that event was only 4 l/s whereas the average value for the peak flow of all the events was 5 l/s.

Without the filtration facility, there were 427 events of outflow from the whole catchment area compared to 595 with the filtration unit. The average total amount of an outflow event was increased from 12.5 m^3 without the filtration, to 22.7 m^3 with the system. The outflow increased because infiltration is prevented in the filtration system. Thus, more runoff will be drained from the catchment area as the runoff is lead straight to the system instead of the pervious subcatchment in which the filtration will be installed. The maximum peak flow from the catchment area without the filtration was 109 l/s and 110 l/s with the filtration system. The average peak flow was reduced from 6.5 l/s without the filtration to 2.1 l/s with the filtration. Hence, according to the simulation the filtration system will even out the peaks of runoff in most of the cases.

4.3 Size of the filtration unit

The dimensioning of a filtration structure is generally based on the amount of runoff resulting from a predetermined design rain. According to a large-scale laboratory study of 125 biofiltration columns conducted in Melbourne, Bratieres et al. (2008) concluded that an optimally designed biofilter covers at least 2% of its contributing catchment area and its filter media consists of sandy loam. The amount of annual precipitation is about the same in Melbourne and in Southern Finland but due to entirely different climates the results gained cannot be directly applied in Finland.

In Finland the instructions for dimensioning of the facilities vary and they are not based on actual field studies. As an example the requirements for the volume of the facilities is set to 1 m^3 per 100 m^2 of impervious pavement or it may have been specified that the facilities should be emptied within 12 hours. It may also be required to reserve 5–15% of a lot area for pervious surfaces in order to delay stormwater generated on the lot. (Kuntaliitto, 2012). As mentioned in section 3.2, in Vantaa the design rain used in designing stormwater management systems is 9 mm/10 min or 150 l $s^{-1}ha^{-1}$ (Vantaan kaupunki, 2014).

4.3.1 Layout of the filtration unit

The design of the filtration cell is based on SWMM results obtained with VDR as the input. In the Vantaa design site, the infiltration to the underlying ground will be prevented due to the groundwater recharge area located nearby. Thus perforated underdrain pipes will be installed at the bottom of the structure and impervious material will be installed on the sides and bottom of the structure.

The filtration cell will consist of engineered filter media with depth of 450 mm, a storage layer of gravel with depth of 200 mm and a drainage layer where the underdrain pipes will be placed. Ponding of 200 mm is allowed on the top of the structure. Overflow pipe works as a secondary drainage system which is required for extremely large rains that are infrequent and rare but cause extensive flooding when occur. The suggested design for the filtration system is presented in Figure 16 and Figure ***17***. All runoff from the catchment area is first lead to a sedimentation basin. The size of the filtration unit together with the pretreatment pond is 149 m^2.

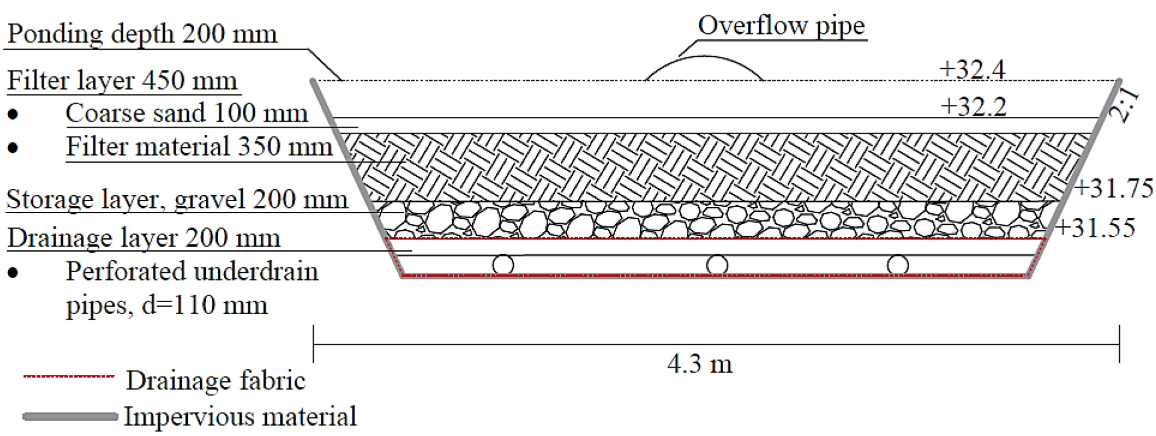

Figure 16 *Cross-section of the filtration structure designed for Vantaa.*

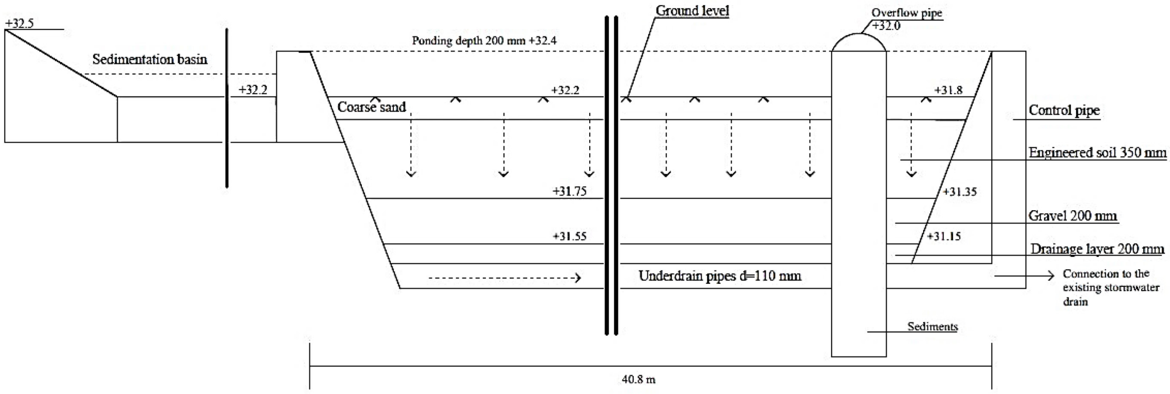

Figure 17 *Longitudinal section of the filtration structure.*

4.3.2 Parameters for the SWMM filtration model

The hydrological model of the design site was run with both the VDR and the precipitation data of Kumpula. In order to model the effects of the LID system on the runoff, the parameters of the LID system were perturbed.

The parameters for the final design of the filtration facility were defined according to the expected runoff volume of VDR and the materials that are tested by VTT. No surface runoff was allowed as the city of Vantaa wanted to assure all water to pass through the filter even in case of an event sized as the design event. Based on that and on the requirements due to the existing stormwater network, the area for the filtration system was set to 140 m^2 with width of 3.5 m and length of 45 m. Consequently, the structure was designed to follow the alignment of the existing drainage ditch. The total depth of the structure was designed to be 1 050 mm which includes 200 mm ponding depth on the surface.

The ponding depth was set to 200 mm so that even in the case of a heavy downpour the stormwater would not bypass the filtration area but rather start ponding and then slowly infiltrating into the media. According to the simulations, the ponding depth had a great impact on the capacity of the structure to store the water during rainfall events sized as the design rain. The inclination of the structure was set according to Vantaa design suggestions for drainage ditches and other parameters were estimated based on the information available. The parameters used in the simulation for the surface of the filtration unit are presented in Figure 18.

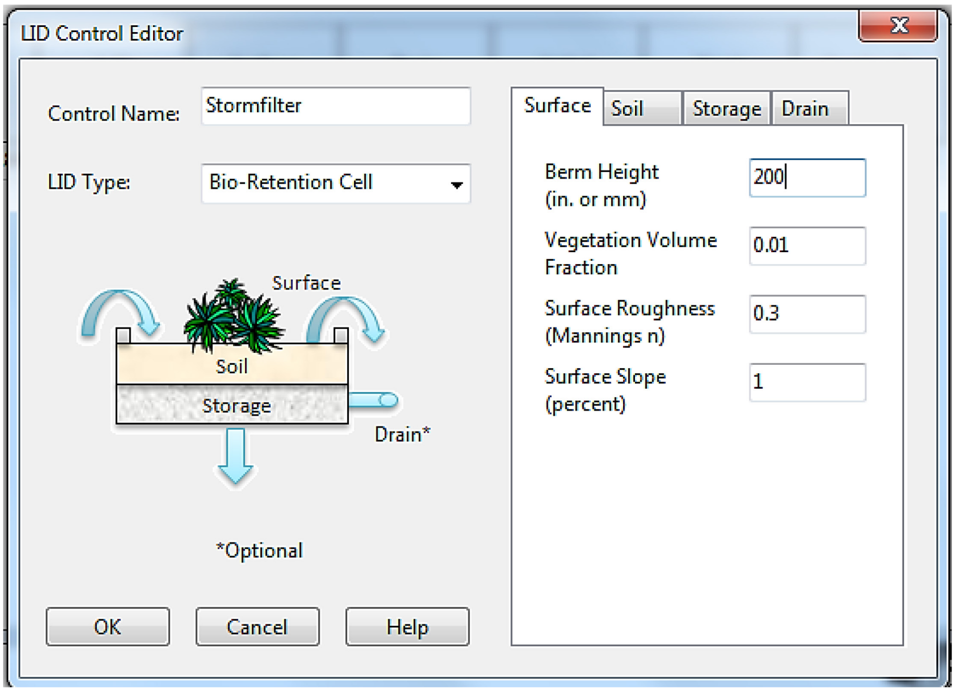

Figure 18 *Surface parameters for the filtration unit (SWMM 5.1).*

The parameters defined for the filtration soil media included porosity, field capacity, wilting point, hydraulic conductivity, suction head and conductivity slope (Figure 19). Parameters that appeared to have the largest impact on the hydraulic capacity of the filter were the saturated hydraulic conductivity and the porosity of the filtration media. The porosity of the designed structure was estimated to be rather high as the structure was assumed to include soil with high volume of pore space. The hydraulic conductivity (mm/hr) of the assumed material was taken from the properties of suggested materials that will be further studied in VTT.

The hydraulic conductivity of the filter media plays a key role in the performance of the system and the recommendations for its value vary between different countries. As stated in the section 3.2, in the USA guidelines require conductivity at least 12.5 mm/h while in Austria the recommended value is between 36 and 360 mm/h. It has been suggested that to determine the design hydraulic conductivity a safety factor of at least 2 should be used. This is due to clogging which reduces the conductivity over time. (Le Coustumer et al., 2009) The filtration was designed with a hydraulic conductivity of 155 mm/h. The hydraulic conductivity of the material was assumed rather high but it was also verified by modeling that no surface runoff would be generated even if the conductivity was halved.

Some of the parameters were defined by following the suggestions in the user's manual of SWMM. According to the manual, the value for the conductivity slope ranges from 30 to 60 and it describes the slope of the curve of log (*conductivity*) versus soil moisture content (dimensionless). The suction head is the average value of soil capillary suction. The wilting point describes the soil moisture content at which plants cannot survive and only water bound in soil particles remains. Thus, it is the minimum for the soil moisture content and can be achieved only through evaporation. Field capacity describes the moisture content after all free water has drained off and below this level, vertical drainage does not occur. (Rossman, 2010)

Parameters for the storage and drainage layers were the void ratio, the seepage rate, the clogging factor, the flow coefficient, the flow exponent, and the offset height (Figure 19). The void ratio describes the volume of void space relative to the volume of solids in the layer and typical values range from 0.5 to 0.75 for gravel beds (Rossman, 2010). The seepage rate was set to zero as infiltration from the design structure will be prevented. Clogging was neglected mostly because of the design that includes an underdrain. The flow coefficient was defined based on the capacity of the existing stormwater network (54 l/s) and a typical value for flow exponent was used.

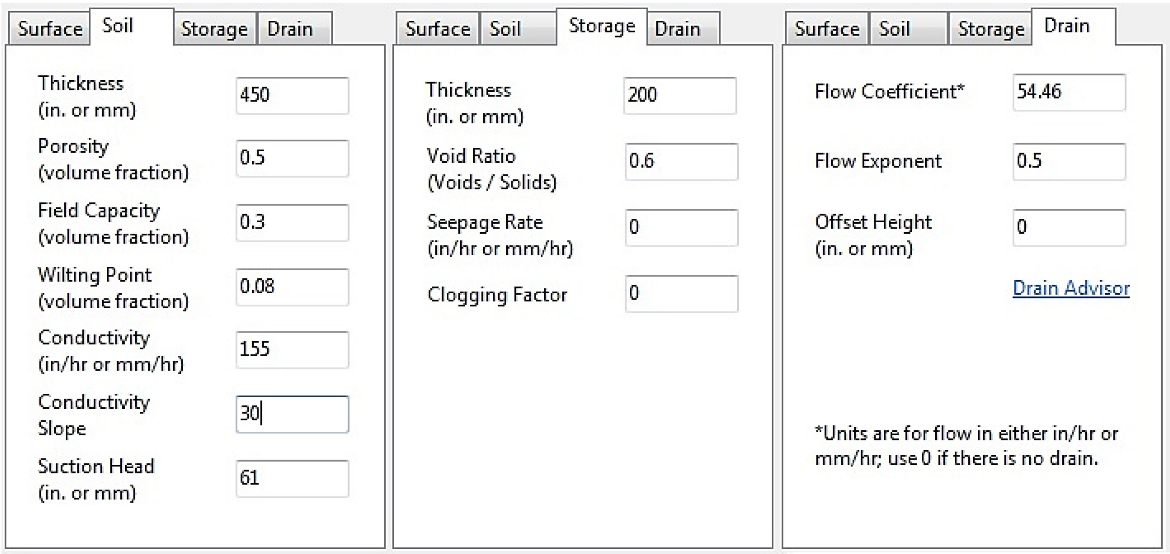

Figure 19 *Parameters used for soil, storage and drain of the modeled filtration unit (SWMM 5.1).*

In addition to the parameters of the filtration cell, attention was paid to selecting appropriate time steps for the simulation (Figure 20). With the detailed report for the LID unit it was checked that the chosen time steps did not cause any clear instabilities in the simulation. The reporting time step is used when computed time series are written in SWMM output file. The output file is used for plotting time series in the graph panel and SWMM computes the statistics based on the plotted time series which is why it is important to choose the time step carefully. Too large values may miss extremes computed in SWMM but small values increase the size of the output file. The reporting time step is recommended to be the same as routing time step whereas model instabilities and continuity errors can be reduced by decreasing the routing time step. (James, 2009) The reporting value (Figure 20) was set to 2 seconds like the routing time even though the raw data was four-minute data.

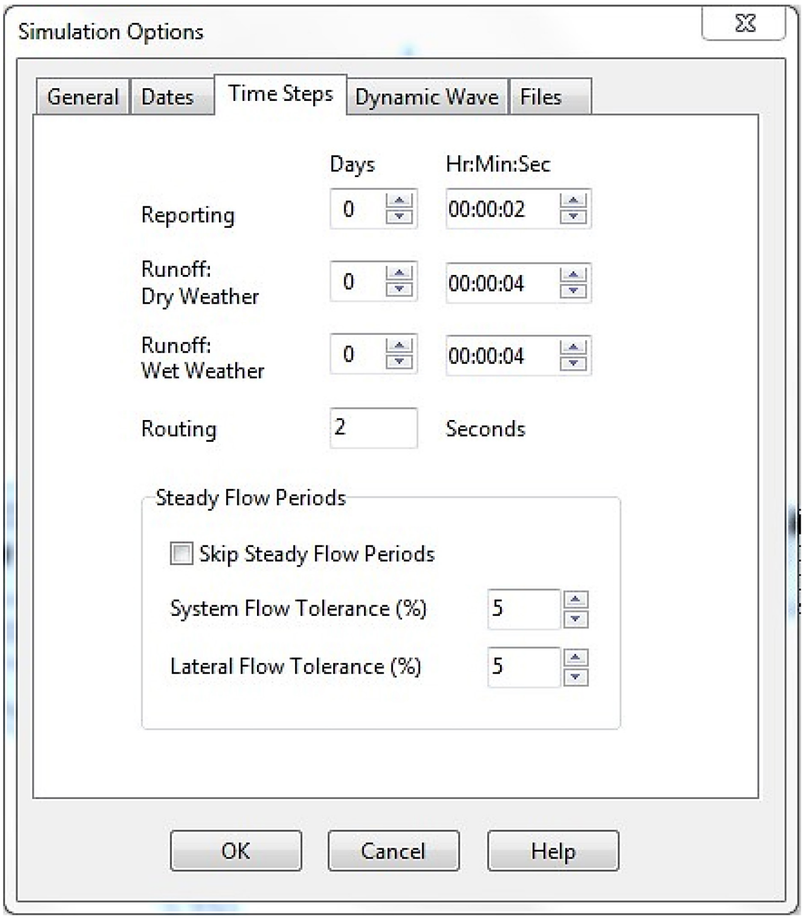

Figure 20 *Time steps for the simulation (SWMM 5.1).*

4.4 Target pollutants and concentrations

The selected target pollutants were Zn, Cu and Pb. Minimum values, maximum values and medians of concentrations of these substances in stormwater were looked up from a summary that was comprised of several studies conducted in Sweden. The concentrations were measured in Stockholm during 1990s (Ekvall et al., 2001).

When the concentrations of target pollutants were randomly coupled with the inflow events, the outflow concentrations could be calculated. The first assumption was that there occurs no removal of mass in the filter but the inflow is mixed with the water within the filter. The outflow concentrations were calculated according to Eq. 7. As a result, all the peak concentrations were lowered in the outflow but the median of the concentrations was increased. Furthermore, the average values of the outflow concentrations were clearly above the reference values they were compared to (Table 14, values for discharge to sub-basin).

Table 14 *Reference values used in this study (Riktvärdesgruppen, 2009).*

		Smaller lakes, watercourses, bay	
Substance	Unit	Direct discharge	Discharge to sub-basin
Pb	µg/l	8	10
Cu	µg/l	18	30
Zn	µg/l	75	90

4.4.1 Distributions of the pollutant concentrations

After calculating the outflow concentrations separately for each metal, the probability distributions for the varying concentrations of inflow and outflow were created. The probability distribution for concentrations of Pb is presented in Figure 21. The mean concentration for inflow is around 26 µg/l and median around 21 µg/l. As it can be seen from the Figure, the median of the outflow is a little higher, 23 µg/l, while the mean value is 25 µg/l. According to the created distribution, only 2% of the outflow concentrations stayed within the limits of the reference value of 10 µg/l (in Table 14).

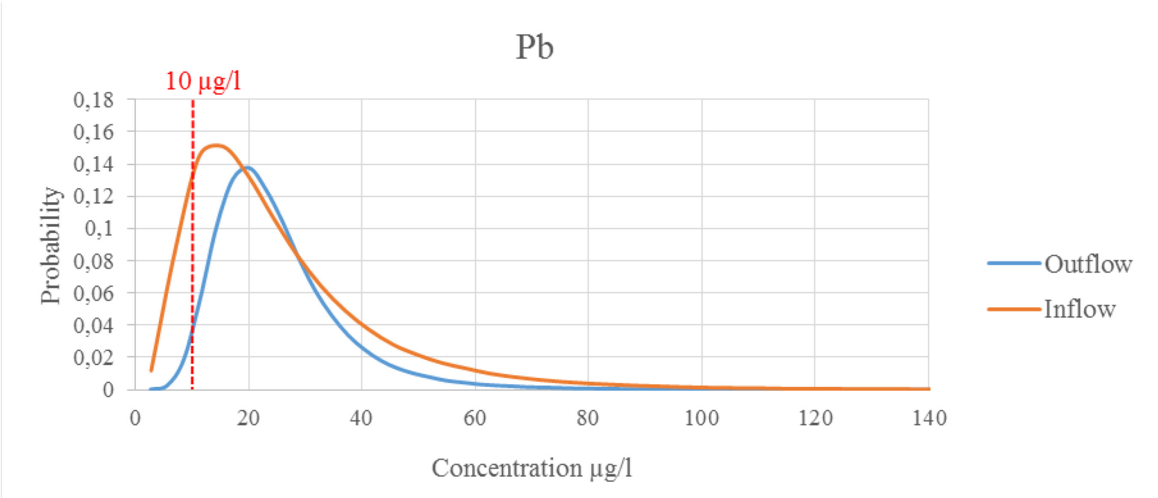

Figure 21 *Probability distribution of concentrations of Pb.*

The distribution of concentrations of Zn is presented in Figure 22. The concentrations of Zn varied the most in the data from Stockholm. The median was between 180 and 310 µg/l and the measured maximum was 1 200 µg/l. It is probable that the maximum has been and individual case and measured during first flush, for instance. However, the concentrations of Zn in road runoff have been clearly higher than concentrations of the two other metals in other studies as well. According to the distribution, 95% of the concentrations are less than 530 µg/l. The mean of the distribution of inflow concentrations is 270 µg/l and the median

202 µg/l while for the outflow the values are 262 µg/l and 228 µg/l, respectively. According to the results, the reference value of 90 µg/l is exceeded in 98% of the concentration values.

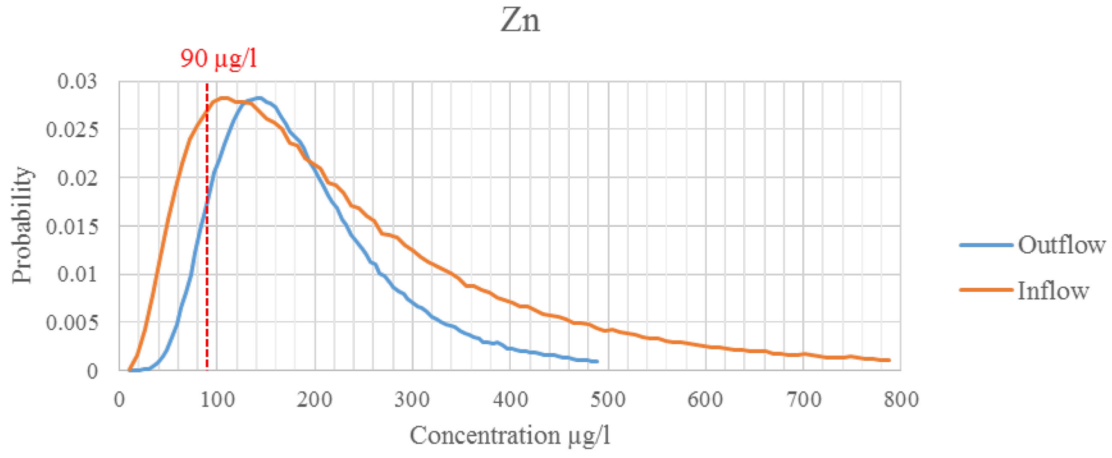

Figure 22 *Probability distribution of concentrations of Zn.*

The probablity distribution of inflow and outflow concentrations of Cu is presented in Figure 23. Similar to the Zn and Pb concentrations, the probability mass is clearly moved to the right which indicates a rise in the median value. The mean of the inflow concentrations is 72 µg/l and the median 60 µg/l. The median of the outflow is 64 µg/l and mean 70 µg/l. The suggested reference value of 30 µg/l was exceeded in 98% of the concentrations.

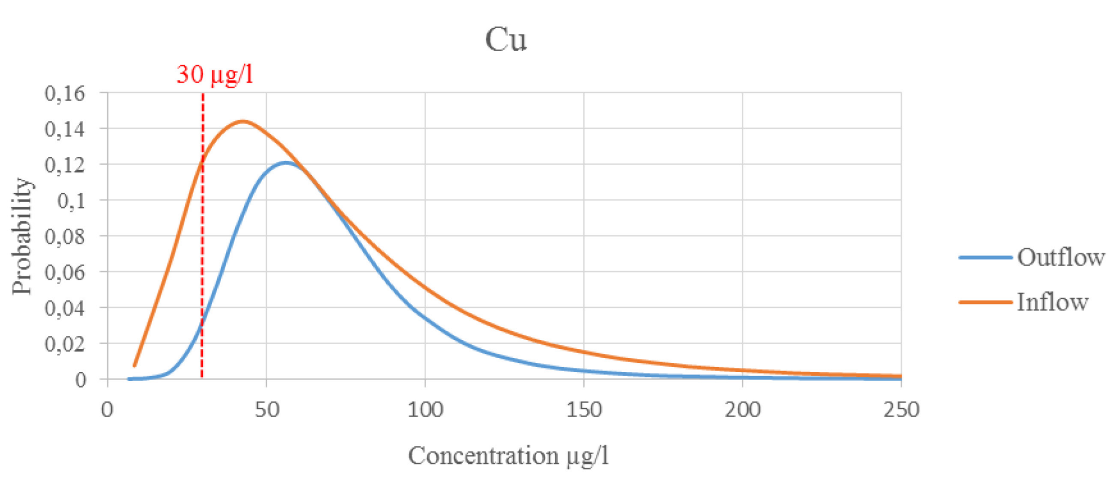

Figure 23 *Probability distribution of concentrations of Cu.*

The obtained probability distributions show that with estimated stormwater quality based on the concentration distributions, the reference values are not met and a reduction of metals in the filtration system is necessary. Considering the mean outflow concentrations, the concentrations of Pb and Cu can be deemed as high and the concentrations of Zn moderate according to the division made by Ekvall et al. (2001).

4.4.2 Required reduction rates

According to the analysis of the estimated concentration distributions of the target pollutants, the required reduction rates were defined by comparing the calculated outflow concentrations to the reference values defined in Stockholm. The required reduction rates were defined for each metal so that 95% of the outflow concentration values stay below the reference values listed in Table 14.

In order to reduce the outflow concentrations to the suggested level, the required mass reduction rate for Pb is around 78%, for Cu 76% and for Zn 83%. It is recognized that it is possible that the concentrations rise above the threshold values for instance during first flush but it must be noted that despite the momentarily high concentrations the more diluted events form the biggest fraction that contribute to the total pollutant load.

Considering the required rates, the studies of metal removal seem promising since depending on the material, the removal rates for all of the metals have been between 72 – 100% (Muthanna et al., 2007b; Reddy et al., 2014). Thus, it can be assumed that with filtration it is possible to remove the required percentage of the metals.

4.5 Limitations and uncertainties

The hydrological model created in this thesis is based on rainfall data measured in different location than the design site. According to Krebs et al. (2014) if the objective is to reproduce the dynamics of urban runoff measured at a high temporal resolution the rainfall gauge should be located close to the catchment. However, in this study the objective was to create a simple model of the design site and its catchment and to use real data to be able to estimate the amount of water entering the filtration area. Possible errors in the hydrological model may have resulted from errors in rainfall measurements. However, the rainfall data was checked for obvious errors. Parameterization of the catchment area and its subcatchments was done according to previous studies and can be assumed rather reliable considering the expected level of accuracy of the model.

Some error to the modeling results may derive from the model setup. The computational time steps were perturbed so that the lowest possible value for the computational continuity error was reached. Even though the model was built as carefully as possible, it is evident that there is some uncertainty in the model output. As there was no actual flow data available for the calibration, the simulation could not be validated either. According to SWMM, errors in the simulation were small, -0.01 % for surface runoff and -0.01 % for flow routing.

As there were no quality measurements available, the quality of stormwater was entirely hypothetical and based on measurements taken in Stockholm. Parameter values vary greatly between different catchments, which is why the transferability of the results from one catchment to another is limited and without data it is impossible to accurately estimate how the water quality response to different events varies between catchments. Therefore, the concentrations used in this study are rough estimations.

Furthermore, the distributions were created based on the concentration data that included only minimum, maximum and median values. Based on that, the mean and standard deviation of lognormal distribution of the concentrations were estimated. The values chosen represented the best fit with the measurements but there was some error with the reference minimum and maximum values compared to the corresponding values taken from the estimated distribution. Furthermore, due to limited literature data, it is impossible to say whether the reported maximum values were unrealistic and only exceptional results of first flush, for instance. There was also uncertainty in combining of the rain and runoff events since previous events affect the following ones. Moreover, the variation of the concentrations was event-based which means that the concentrations were assumed to stay the same over an entire event, which in reality is not the case.

5 Conclusions and recommendations

The main objectives of this thesis were to study the suitability of biofiltration in stormwater management in Finnish climate conditions and to design a filtration system to treat road runoff generated on a catchment located in Vantaa. The essential system characteristics and steps of the design process were identified and instructions for the maintenance were compared and compiled. Furthermore, the required efficiency in terms of reduction rates was estimated for the three metals typically present in stormwater: Cu, Pb and Zn. SWMM was used to simulate the hydrology of the design catchment and to define the required size for the filtration system. As there were no measurements available from the design area, rainfall data from Kumpula and pollutant concentration data from Stockholm were used in the study to outline the structure for the filtration system, estimate stormwater quality and define required pollution reductions.

Biofiltration had been found to be an efficient method for stormwater treatment in various conditions but the technology has also its weaknesses. There are rather few studies regarding biofiltration performance in cold climates even though that is one of the main concerns of the technology. In cold climates the soil media may freeze, which results in reduced hydraulic capacity and treatment efficiency. Therefore, it is essential that especially in areas where the structure is above the frost line the media should have high hydraulic conductivity (> 200 mm/h) to improve the winter infiltration. To prevent water freezing in the pipes, they should be installed with a sufficient inclination to assure flow. However, if the media is prevented from freezing, the temperature has no significant impact on the performance of biofiltration.

Another concern is clogging of the media, which also reduces hydraulic capacity and the removal efficiency of biofiltration. Hence, it is suggested that a pretreatment is installed to reduce the amount of solids entering the system and that the structure is maintained regularly by removing the excess solids from the surface. This is especially important if the stormwater can be expected to contain high amounts of solids, like runoff generated on roads.

The material and structure for the biofiltration should be selected according to the objectives of the stormwater management. Biofiltration can be used for both detention and quality management of runoff. If detention and controlled infiltration into the soil is the objective, the hydraulic capacity of the system is the defining factor. Defining the target pollutants is essential, as the structure also determines the pollutant removal efficiency. If the focus is on quality management of the runoff prior to leading to receiving waters, the structure should be designed according to the requirements concerning the removal of selected target pollutants. Furthermore, it is advisable that the structure is rather simple to facilitate the maintenance.

The main objective of the filtration system designed for Vantaa is to treat the road runoff and control its drainage to the existing stormwater network. The area of the filtration system was defined based on SWMM simulations. The size of the area was set to 140 m^2 with width of 3.5 m and a length of 45 m such that the structure follows the alignment of the existing drainage ditch. A sedimentation basin of around 1 m^3 (width 4.3 m, length 2.5 m, ponding depth 0.1 m) will be installed prior to the filtration system. The total depth of the filtration structure is designed to be 1 050 mm. The structure consists of 200 mm ponding depth on the surface, 450 mm of infiltration media, and 200 mm of storage. The drainage layer is 200 mm and houses the drain pipes. Infiltration on the site is prohibited due to a groundwater recharge area, which is why water is lead away from the site. This is mainly a measure of precaution in case of malfunction of the biofiltration system after an accidental release of dangerous substances on the road area.

The target pollutants, Cu, Zn and Pb, were selected to represent the water quality in this study. Cu and Zn are mainly present in stormwater in solid form whereas Pb can also occur in dissolved form. The estimated reduction rates that should be achieved with the selected material were around 78% for Pb, 76% for Cu and 83% for Zn. The reduction rates according to preliminary results of the studies conducted in VTT range between 57% and 98% for Cu, 73% and 100% for Pb and 15% and 95% for Zn. Hence, with the right selection from the studied materials it is possible to achieve the required reduction rates.

It is essential that stormwater management is designed and LID technologies applied under consideration of the climate and local conditions, both the catchment characteristics and sensitivity of the receiving waters. Most of the measurements and studies available were conducted in conditions that differ from the climate in Finland. Therefore, the guidelines based on the studies differ and are site specific, which is why some caution should be taken when applying the guidelines in Finland. For instance, the hydraulic conductivity of the media needs consideration. Moreover, it has been shown that it is rather challenging to remove many pollutants in the same unit and therefore it is reasonable to define target pollutants. Typical stormwater pollutants can be estimated based on the land use of the catchment area.

Furthermore, it is recommended to develop a maintenance plan for the designed system and monitor the quality by taking water samples of inflow and outflow in order to gain information on the performance of the system. During the first year of the performance, the system should be monitored semi-annually and then after every larger storm.

When designing filtration systems, the catchment area must be defined to estimate the amount of runoff. Modeling software such as SWMM are useful tools in the design process when designing LID systems with minimal data. As the amount of runoff defines the starting point for the design, with rainfall data and some aerial photos it is possible to develop a hydrological model and to analyze the catchment response to precipitation and to estimate the amount of runoff generated. Furthermore, comparing of different scenarios and LID structures is straightforward with the model.

In most cases, the design of LID systems is based on a certain design storm. However, it would be beneficial to move forward to more site specific design so that the local conditions could be better considered when the systems are applied. For instance, in some areas there is not enough space available, but applying biofiltration systems could be advantageous even though size requirements according to design storm would not be fulfilled.

Due to limitations of local data the results of this study are mainly theoretical. More quality measurements are needed in Finnish climate conditions to better understand the composition of stormwater and how it is formed. Furthermore, more field studies of implemented structures in cold climates are needed to gain understanding of the performance of biofiltration in such conditions.

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