CHALMERS
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Modeling Detention and Pollutant Fate in Bioretention Systems

Master's Thesis in the Master's Programme Infrastrucutre and Environmental Engineering

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Department of Civil and Environmental Engineering
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Examensarbete BOMX02-16-3333 / Institutionen för Bygg- och Miljöteknik,
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Cover: The Kviberg raingarden and part of the adjacent parking area

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ABSTRACT

In an urban environment increased stormwater runoff is expected due to lower infiltration properties of materials used as roofs and other paved structures. As accumulation of pollutants on urban surfaces is continuously present the receiving waters have the potential to be exposed to environmental risks during rain events. One way to lower pressure on recipients is to implement low impact development practices, for example bioretention cells, green roofs, grass swales, permeable pavement or ponds. Explicit methods for modeling the effects of such structures have been included in the 2016 release of MIKE URBAN from *DHI*. In the fall of 2015 the first public bioretention facility was finalized in Gothenburg and features in total 700 m^2 of bioretention area, which is managing stormwater from adjacent parking areas. Using the Kviberg bioretention design the aim of this study is to evaluate the expected retention achievable through the new MIKE URBAN features. Two different methods will be used to describe retention of flows and pollutant fate respectively. Additionally, a sensitivity analysis, on selected parameters in the reference design, will result in a hypothesis on which influences the efficiency the most. Beside technical input from *Kretslopp och Vatten* theory on characteristic pollutants in stormwater, bioretention systems and their pollutant removal mechanisms is studied and used in the model. The modeling sessions conclude that the reference design, of the current bioretention area in Kviberg, performs according to the conventional alternative where urban water is retained using basins. The sensitivity analysis shows that spatial- and soil media properties will have minor impact on retention of flows. Most influencing the result is the infiltration capacity to the surrounding soil which indicate a local dependency. Modeling for pollutant fate include defining scripts of removal mechanisms of different pollutants using another software called ECOLab. These are later associated with relevant nodes in the MIKE URBAN model. The results show good removal efficiency which compares well to average numbers. However, the absence of available mathematics, regarding the pollutant fate, forced on simplifications which increases the uncertainty. Further work suggested is in-data refinement and verification of the model through flow measurements. Compared to approximate ways for evaluating bioretention designs the method used in this report is scientific and have the potential to be more reliable as pollutant removal scripts are developed.

Key words: modeling, low impact development, LID, bioretention, pollutant fate

Modellering av utjämning och föroreningsreduktion i regnträdgårdar

Examensarbete inom Masterprogrammet Infrastrucutre and Environmental Engineering

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SAMMANFATTNING

Inom stadsmiljö är ökad dagvattenavrinning förväntad till följd av lägre infiltrationsegenskaper hos material som används för tak och andra belagda ytor. Vid nederbörd kan avrinning innebära en miljörisk eftersom deposition av föroreningar ständigt förekommer på hårdgjorda ytor. Ett sätt att minska den förorenande effekten hos recipienter är att implementera anläggningar för lokalt omhändertagande av dagvatten. Några exempel är regnträdgårdar, gröna tak, gräsbeklädda diken, genomsläpplig asfalt eller dammar. Metoder för att utvärdera effekten av sådana strukturer har inkluderats i 2016 års utgåva av MIKE URBAN från *DHI*. Under hösten 2015 färdigställdes den första kommunala regnträdgården i Göteborg. Denna innefattar totalt 700 m^2 regnträdgård som hanterar och renar dagvatten från närliggande parkeringsytor. Syftet med denna studie är att utvärdera vilken fördröjning av dagvatten som går att uppnå i Kvibergs regnträdgård genom att modellera området i MIKE URBAN. Två olika metoder används för att modellera retention av flöden respektive retention av föroreningar. Dessutom genomförs en känslighetsanalys på valda parametrar i referensdesignen som resulterar i en hypotes kring vilka som påverkar retentionen mest. Utöver input från *Kretslopp och Vatten* har teori om karaktäristisk förorening i dagvatten samt regnträdgårdar och deras renande mekanismer studerats och använts i modellen. Modelleringen visar på att referensutformningen av den nuvarande regnträdgården presterar i enlighet med ett konventionellt alternativ där utjämning sker med hjälp av magasin. Känslighetsanalysen resulterar i att rumslig utformning och jordegenskaper har mindre inverkan på utjämning av flöden. Mest påverkan fås då infiltrationskapacitet till omgivande jord varieras, vilket indikerar ett lokalt beroende. Programvaran ECOLab används för att beskriva renande mekanismer i regnträdgårdar. Dessa skript kopplas därefter till relevanta noder i MIKE URBAN modellen. Resultaten visar på god rening som jämför sig väl med genomsnittliga värden. Dock har avsaknad av explicit matematik, för föroreningsreduktion i regnträdgårdar, påtvingat förenklingar i modellen som ökar osäkerheten. Ytterligare arbete består i att förfina indata och verifiera modellen mot flödesmätningar. Jämfört med approximativa metoder att utvärdera designen av regnträdgårdar är metoden använd i detta arbete fullkomligt vetenskapligt och har potential att bli mer pålitlig allteftersom skript för avlägsnande av föroreningar fortsatt utvecklas.

Nyckelord: modellering, lokalt omhändertagande av dagvatten, LOD, regnträdgård, avlägsnande av föroreningar

Contents

Preface

This Master's Thesis was commenced in January 2016 and completed in June the same year. During these months selected new features in the MIKE URBAN software from DHI have been evaluated. Office space and supervision have been provided at DHI Sverige in Gothenburg and the examiner have been Britt-Marie Wilén at Chalmers University of Technology. A great thank you is sent out all personnel at DHI Sverige, Kretslopp och Vatten and Chalmers that have been helpful throughout the process.

1 Introduction

As precipitation occurs in an urban environment, the increased ratio of hard surfaces implies larger runoff volumes compared to the former pre-developed state (Erickson et. al., 2013). This is due to the decreased infiltration properties of materials often used as roof materials and other paved structures. Urban runoff management have historically been focused on quantitative aspects where accumulated runoff water is transferred directly to the receiving water (Stahre, 2008). However, during the last forty years there has been a transition from the traditional urban drainage towards sustainable urban drainage, where qualitative parameters have become more important.

Regarding recipient water quality much effort has been put to reduce the amount of pollution from point sources (Björklund, 2011). Nevertheless, nonpoint pollution is still affecting the quality of these waters. Nonpoint pollution origin from human activities, for example transport and construction. The stormwater runoff quality is, to some extent, related to the kind of surface from where runoff is occurring (Eriksson, 2007). Also the ambient air quality and aerial deposition of pollutants contributes to the pollution composition within the specific catchment.

Considering both stormwater quality and peak flows, alternative methods are introduced to ease stresses in urban environments (Roldin, 2012). These methods, called low impact development (LID), have become increasingly relevant. The low impact development concept refers to a range of structural measures that mimic detention- and purifying processes that is occurring naturally, for example sedimentation, filtration, sorption, plant uptake and others (Field et. al., 2006). Further alternatives are various types of permeable pavements and asphalt, grass swales, rain barrels or ponds for example. Beside quantitative and qualitative aspects, benefits of implementing low impact development structures apply in two more fields; amenity and biodiversity (CIRIA, 2015). The pollutant removal efficiency of low impact development structures has frequently been evaluated during the past twenty years (Stormtac, 2016).

The main low impact development structure covered in this report is bioretention cells, which are landscaped compressions containing an engineered soil media overlaying a drainage layer of coarser material (CIRIA, 2015). Retention of stormwater is obtained both through infiltration to surrounding soil and storage in the void space. Bioretention is to be further explained later in the report.

Explicit methods for modeling a number of low impact development structures are implemented in the 2016 MIKE URBAN CS software. Through the catchment based method, the software includes a module for evaluating quantitative retaining effects. By defining and associating ECOLab scripts to the model pollution removal aspects can also be modeled through the network based method.

1.1 Aim

The aim of this study is to evaluate the possibilities of using computational tools to model the function and efficiency achieved using low impact development systems, specifically bioretention cells. The efficiency will be compared to conventional solutions and a zero alternative where nothing is done to control flows. By performing a sensitivity analysis, on selected in-data, the study should result in a hypothesis on which parameters that are influencing the functionality of the system the most. More precisely the following questions are to be answered:

- ✓ What retention can be expected in the studied bioretention area?
- ✓ What mechanisms determine the retention in a bioretention area?
- ✓ How are these mechanisms considered in the software used?
- ✓ Which parameters influence the achievable retention the most?

1.2 Study area description

The outcome of the report will mainly become a desk study that aims towards understanding the retention effects using bioretention areas for managing urban stormwater. Despite this, the Kviberg raingarden is yet used as the study area. Since the Kviberg development is quiet new the required in-data for the model is available and form a realistic base for the model. Future verification of the model is also possible, when accurate concentrations of pollutants can be measured.

In Gothenburg the first public bioretention area was taken into operation in the fall of 2015 (Vårt Göteborg, 2015). The bioretention area, which holds around 700 square meters of vegetated area, is situated in the district of Kviberg and manages runoff stormwater from an adjacent parking lot, see Figure 1. The raingarden area considered in this work is handling runoff from the western parking area and is about 285 m^2.

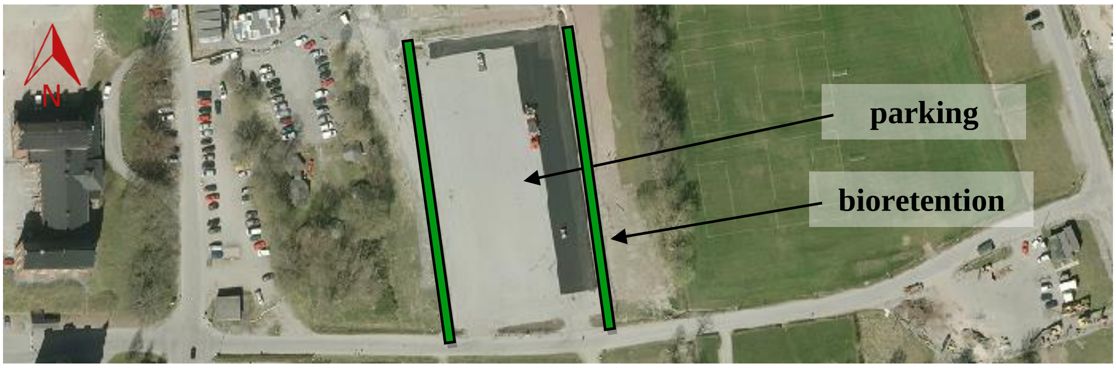

Figure 1. Orthophoto of the study area. Runoff from the parking area is directed towards the bioretention areas.

1.3 Delimitations

Low impact development is a conceptual idea that include a number of structural implementations and the literature review of this report will just briefly cover other implementations than bioretention areas due to the study area of choice.

The Kviberg raingarden is relatively young due to its operational initiation in the fall of 2015. Verification of the constructed model, through field testing, would therefore be unreliable and will not be included in the study. Instead the model will be tested using the *Stormtac* register over results from previous studies of similar projects.

In the model, runoff pollutant concentrations are constant. No regard has been taken to pollutant build up on the surfaces or dilution due to varying runoff volumes, implying that first flush phenomenon therefore is ignored throughout modeling. However, these processes can be described using MIKE URBAN.

The fate of different pollutants in bioretention systems are found difficult to describe mathematically and for this study only copper and phosphorus are considered. However, the processes described for copper is also applicable for other metals.

Seasonal and thermal variations on pollutant loads have not been considered.

2 Background

To gain knowledge on how to interpret the results from the modeling session a literature study was performed. The literature study is covering what pollutant to expect in urban runoff, what low impact development are currently practices and what processes that are determining the retention effects in a bioretention system. A description on how retention effects are accounted for in the software is also covered in this section.

2.1 Stormwater pollutants

As previously stated nonpoint sources of pollution to aquatic systems have been less dealt with in the past considering qualitative aspects. This is in comparison to point sources. Urban runoff may contain a variety of pollutants that may cause both human and environmental health risks (LeFevre et. al., 2015). Beside health implications towards exposed humans and aquatic environments the problems of stormwater pollution can also be both technical and aesthetic (Eriksson, 2007). Priority pollutants in urban stormwater runoff include nutrients, heavy metals, organic compounds, pathogens, suspended solids, and salts (Weiss P. et. al., 2008). Which pollutants that are found and at what concentration level is highly dependent on the specific catchment and the present land use (Wium-Andersen et. al., 2011).

First flush is a phenomenon implying that the initial pollution concentrations in stormwater may be higher than the event mean concentration (Davis and McCuen, 2005). Build-up of pollutants on hard surfaces during dry weather may occur for a number of reasons, for example traffic related and atmospheric deposition. The accumulation can be assumed to start from zero after each rain event and have been found to increase exponential in the initial phase (Egodawatta et. al., 2009). Also snow allows for accumulation for longer periods and it has been shown that pollution concentration generally is higher in meltwater that storm runoff (Muthanna et. al., 2006).

Characteristic pollutant composition from parking areas have been compiled in Table 1 and 2. Here the mean concentration is calculated from seven previous studies which are considering specifically pollutant concentrations from parking areas, see appendix 1 for full evaluation.

Table 1. Characteristic parking area pollution concentration in runoff

Pollutant	TSS	COD	Pb	Cu	Cd	Zn	N
Avg. conc. [mg/l]	130	150	0.086	0.037	0.002	1.08	1.83
Max conc. [mg/l]	420	200	0.3	0.1	0.004	3.6	3.2
Reference	see appendix 1						

Table 2. Characteristic parking area pollution concentration in runoff (continued)

Pollutant	P	Hg	Cr	Oil	PAHs	Fe	NH4
Avg. conc. [mg/l]	0.31	0.0002	0.02	3.55	0.0015	0.0011	0.34

Max conc. [mg/l]	0.76	0.0002	0.039	6.80	0.0021	0.0011	0.34
Reference	see appendix 1						

The European union water framework directive was adopted in 2000 as a reaction to increasing demands from environmental organizations and citizens for cleaner water bodies (EC, 2015). The directive includes a list of 33 priority substances for which environmental quality standards were set in 2008. These include selected chemicals, plant protective products, biocides, metals and groups of polycyclic aromatic hydrocarbons. Locally, the Gothenburg municipality, through the environmental office, has its own regulation regarding outlet concentration for a number of pollutants. Table 3 and 4 summarizes the limiting release concentration set for Gothenburg municipality. As seen here most substances, nutrients, suspended solids and oil exceed the limiting values and must be dealt with.

Table 3. Limiting release concentration of different substances set for Gothenburg municipality (Miljöförvaltningen, 2013) compared to characteristic runoff concentration according to Table 1 and 2

Parameter	Total-P	Total-N	TSS	As	Cd	Cr	Cu	Pb	Hg
Limit value	0.050	1.25	25	0.015	0.0004	0.015	0.010	0.014	0.00005
Runoff conc.	0.31	1.83	130		0.002	0.02	0.037	0.086	0.0002
Unit	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l

Table 4. Limiting release concentration of different substances set for Gothenburg municipality (Miljöförvaltningen, 2013) compared to characteristic runoff concentration according to Table 1 and 2 (continued)

Parameter	Ni	Zn	PCB	TBT	Oil	Bens(a)pyren	MTBE	Bensen
Limit value	0.04	0.03	0.000014	0.000001	1	0.00005	0.5	0.010
Runoff conc.		1.08			3.55			
Unit	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l

2.1.1 Nutrients

Addition of nutrients to aquatic environments, like streams, reservoirs and lakes, may increase plant growth rate (Erickson et. al., 2013). The process is called eutrophication and the primary nutrients present in urban runoff is nitrogen and phosphorus. Beside nutrient enrichment in aquatic systems further implications can be reduced water clarity and increased presence of undesired algae and other plants. Also dissolved oxygen in the water body is consumed during decomposition and oxidation of organic material which imply oxygen depletion and death to aquatic life.

Nitrogen, as one of the primary nutrients, may be present in a variety of chemical forms (Li and Davis, 2014). Particulate organic nitrogen (PON) and different forms of dissolved forms, for example ammonium (NH3), nitrate (N03), nitrite (NO2) and dissolved organic nitrogen (DON). Excess nitrogen addition to aquatic environments can cause eutrophication, which implies harmful algal bloom and degradation of aquatic habitat quality. Table 5 present a typical distribution of dissolved and particular nitrogen in urban runoff.

Like nitrogen, phosphorus is a primary nutrient (Davis and McCuen, 2005). Addition of phosphorus to stormwater runoff is generally present through wash-off of excess fertilizers but can also be added due to decay of organic material and animal feces. Nutrient spreading through atmospheric deposition is also a possibility (CIRIA, 2015). Phosphorus is an important biochemical element which can be found in various organic forms (Davis and McCuen, 2005). The basic form of phosphorus present in water is Ortho phosphorus and, depending on the current pH, $H_2PO_4^-$ or HPO_4^{2-} can also be formed. The total phosphorus is however the sum of these three. Phosphorus also has a strong affinity for soils and sediments and transport through particulate matter is a common phenomenon. Table 5 present a typical distribution of dissolved and particular phosphorus in urban runoff.

Table 5. Distribution of nutrients in particular and dissolved form

Nutrient	Particular form [%]	Dissolved form [%]	Reference
Phosphorus	61	39	Stormtac, 2015
Nitrogen	57	43	Li and Davis, 2014

2.1.2 Metals

Metals occur in the environment for natural reasons but in an urban environment anthropogenic activities, which releases metal, origin from industrial processes, fossil fuel combustion and vehicle wear (Clemens, 2006). Most metals in aquatic systems are divalent cations with oxidation of +II and they are commonly bound to inorganic species or organic matter (Davis and McCuen, 2005). Cadmium, copper, zinc and lead are metals of extra concern (Erickson et. al. 2013). It has been found that exposure to low concentrations of metals may alter the behavior and competitive advantage among invertebrates which could change the balance of ecosystems in a long term perspective. At moderate concentration the presence of metals can reduce growth, reproduction and survival abilities in aquatic organisms. Metals accumulate in freshwater biofilms which is feeding fish and invertebrates. A result is that metals are transferred and through the food chain and that bioaccumulation will continue. Exposure to large concentrations of metals can even be lethal. One factor that governs the toxicity of a metal is the bioavailability, which is a measure on what fraction of the substance that reaches the organism (Gupta and Sandalio, 2012). Abiotic and biotic stress factors, like exposure to heavy metals is affecting plant growth and their productivity (Gupta and Sandalio, 2012). Dissolved metals are of concern because they are more bioavailable and toxic than metals bound to particles (Santore et. al., 2001). In general, there is no exact correlation between metal content in soil and metal content in plants (Clemens, 2006).

The ratio of metals in dissolved and particular form respectively is presented in Table 6. These values are adapted from the Stormtac registry and used as in-data for the model.

Table 6. General proportions of dissolved/particulate metal concentrations according to Stormtac (2015)

Metal	Pb	Cu	Zn	Cd	Cr	Ni	Hg	As
Dissolved [%]	15	45	44	46	39	47	85	50
Particular [%]	85	55	56	54	61	53	15	50

2.1.3 Polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbons, PAHs, have been identified as a compound with severe impact on aquatic environments and human health (Watts et. al., 2010). Similar to heavy metals, PAH compounds have been found to cause both acute and chronic toxic effects towards aquatic flora and fauna (Marsalek et al. 1999). Despite the natural existence of over 100 different PAH compounds, the majority found in the environment originate from anthropogenic sources (Diblasi et. al., 2009). Generally, PAH have a relatively low solubility and high affinity towards organic carbon (Simon and Sobieraj, 2006). PAH compounds are organic and based on two or more aromatic rings where greater number of rings implies less solubility in water (Davis and McCuen, 2005). Naphthalene is the simplest PAH which consist of two aromatic rings. Several PAH compounds are proven to be very carcinogenic (substance known to cause cancer), for example benzopyrene. PAHs can be present in stormwater for both natural causes and human processes and often origin from different industrial activities and vehicular exhausts (Watts et. al., 2010). PAHs are also subject for atmospheric deposition. Wik and Dave (2009) state that fuel, oil and tire wear is a significant source of PAH compounds. According to Nielsen et. al. (2015) PAHs are often associated with colloidal material. The same study also indicate that more traffic activities imply increased levels of PAHs in the runoff water. PAH substances are also subject for bioaccumulation in aquatic species and through the food chain (Weiss, 2008). Like other anthropogenic organic pollutants respiration implications to aquatic organisms are common.

2.2 Bioretention systems

Many end-of-pipe practices are designed to both retain flows and remove pollutants (Scholes et. al. 2008). Removal is obtained through physical, physicochemical and biological processes, such as sedimentation, filtration, sorption, nitrification, decomposition and phytoremediation. The concept of low impact development refers to a number of structural implementations that allows for both peak flow reduction and pollutant removal. Beside implementing low impact development, nonstructural practices should be encouraged (Field et. al., 2006). Through, for example, public education, proper planning of new development and regular street maintenance a reduction of pollutant load can be obtained.

Implementing bioretention systems is a way to reduce discharge peaks and treat pollution rates in urban runoff due to rain events (CIRIA, 2015). A bioretention area aim towards managing the runoff from the most frequent rain events and include physical, chemical and biological processes to remediate the stormwater (Randelovic, 2016). Typically, a bioretention area consists of an excavated basin filled with porous media overlying a non-capillary layer of coarse material, for example macadam (Henderson et. al., 2007). A common design implies gentle slopes to prevent wash out of the filter media (CIRIA, 2015). Storage of stormwater runoff is governed by the cavity in the drainage layer and storage depth above the filter material. Figure 2 display a conceptual scheme of the structure of a bioretention area. Processed runoff stormwater is managed and discharged through an underdrain system or partially infiltrated to the surrounding soil (CIRIA, 2015). Efficiency of the infiltration to the surroundings is highly dependent on the infiltration capacity of the soil. Other aspects to a bioretention area is the self-irrigating and fertilizing mechanisms and biodiversity contribution.

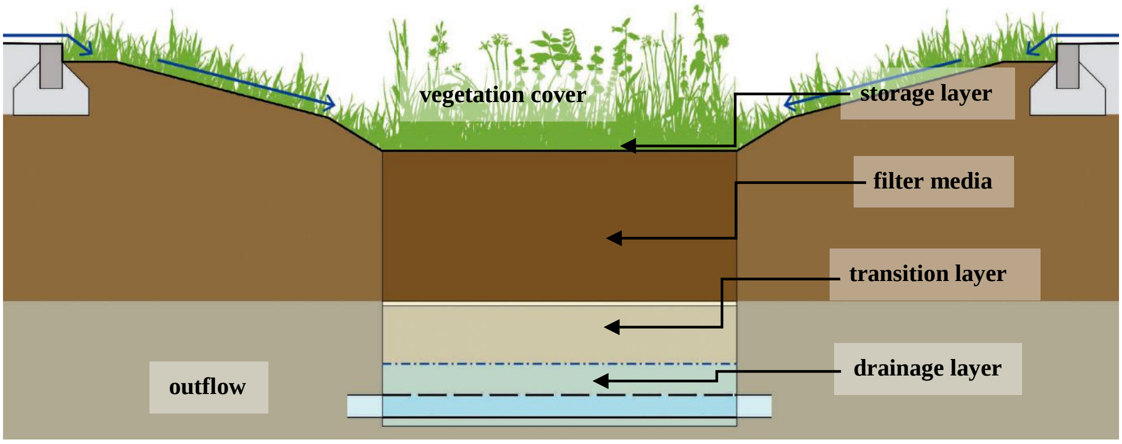

Figure 2. Conceptual drawing of a bioretention area. Figure adapted from CIRIA (2015).

Bioretention systems are considered to function as discontinuous treatment facilities operating in two phases (Randelovic, 2016). One phase is the active phase, when rain events causes ponding on the surface and filtration through the soil media. The second phase is the passive phase which is present during dry weather. Here pollutants retained in the soil media and captured water is treated through plant uptake and microbes. Removal of particulate polluting substances is achieved through sedimentation and filtration through the engineered soil media and in the vegetated surface (CIRIA, 2015). Dissolved substances are commonly removed from the runoff through adsorption to the soil and suspended particles or by plant uptake (Blecken et. al., 2011).

2.3 Pollution fate in bioretention systems

Mechanisms for pollution removal identified in low impact development structures include physical, thermal, biological and chemical processes (Erickson et. al. 2013). Physical treatment is mainly achieved through sedimentation, filtration and infiltration.

2.3.1 Sedimentation

Removal of suspended particulates from a water body through gravitational settling (Erickson et. al. 2013). Sedimentation is a major pollution removal mechanism regarding soil particles and suspended solids which is generally achieved in constructed wetlands and ponds but also ponded water in a bioretention cell.

2.3.2 Filtration

Passing through a granular media suspended particles are retained in the process called filtration (Erickson et. al. 2013). Accumulation of retained solids in the filter media will eventually cause clogging to the filter, which implies lower infiltration capacity. In bioretention filtration of ponded runoff occurs through the vegetation and soil media.

2.3.3 Sorption

Adsorption is the process where dissolved ions are attached to the surface of solid particles which in later step can be removed through sedimentation or filtration (Erickson et. al. 2013). The process is often referred to as cation exchange, specific adsorption, co-precipitation and chelation (LeFevre et. al. 2015). Sorption can be used to remove dissolved constituents from stormwater (Erickson et. al. 2013) and dissolved metal is subject for sorption processes (LeFevre et. al. 2015).

2.3.4 Phytoremediation

Phytoremediation utilizes plants and associated microbes for environmental cleanup (Pilon-Smits, 2005). Plants take up nutrients during growth and the process of photosynthesis converts carbon dioxide, nitrate, phosphate and water to algae and producing oxygen (Erickson et. al. 2013). The process is dependent on bioavailability of pollutants (Pilon-Smits, 2005). For example, better small particle soils allow more water being held and increases the bindings sites for ions.

2.3.5 Biological processes

Denitrification is a reaction that converts nitrate to nitrogen gas and is promoted by bacteria under anaerobic conditions (Erickson et. al. 2013). Typically, this process takes place in sediments and the reaction requires a source of organic matter. Degradation of organic matter is another biological process where organic matter is oxidized to carbon dioxide by microbial respirators (Erickson et. al. 2013).

2.3.6 Nutrient fate

In a typical bioretention configuration removal and transformation of dissolved nutrients occur through a combination of adsorption, precipitation, ion exchange and biological processes (Davies et al. 2009). The main mechanism of particulate phosphorus removal in bioretention systems are filtration of and adsorption of dissolved phosphorus (Hunt et. al. 2012). Filtration is very effective in bioretention systems and particulate phosphorus often follow the fate of other particulate matter.

Selecting a media with low organic matter content and low phosphorus index has been emphasized to prevent the bioretention cell itself to act as a source of phosphorus (Paus et. al., 2014). Media with low soil phosphorus and high cation exchange capacity (CEC) is recommended for efficient phosphorus removal (Hunt et. al., 2006).

Dissolved nitrogen, mainly nitrite and nitrate, is highly soluble and does not sorb to bioretention media or soil (Davis et al. 2006). The fate is decided through a series of biochemical reactions governed by microorganisms. First step is ammonification of organic nitrogen to ammonia or ammonium. Then oxidation, first to nitrite and then to nitrate through the process of nitrification. In the last step nitrate can be converted to nitrogen gas through denitrification by bacteria under anoxic conditions. Nitrogen gas is considered a suitable end product due to it is not bioavailable. Bioretention cells are generally aerobic unless they are modified to include an anoxic zone (Hunt et. al., 2006). Therefore, entering nitrate typically passes through and the influent organic nitrogen and ammonium are partially or completely converted to nitrate.

2.3.7 Metal fate

The fate, toxicity and treatment efficiency of metals in urban runoff depends on the chemical form of metal (Davis and McCuen, 2005). Metals are common to be adsorbed to suspended solids and once adsorbed their fate is controlled by the transport of particulate matter. Metal ions and metal hydroxides generally bind to negatively charged sorbent surfaces (Erickson et. al. 2013). This implies that dissolved metal is low but suspended solids can hold high levels of heavy metals. As metals do not degrade in the environment they are more likely be incorporated in the crystalline structure of a mineral over time (Davis and McCuen, 2005). The adsorption processes are difficult to distinguish and therefore the net of the initially dissolved metals in stormwater are subject for sorption (LeFevre et. al., 2015). Metal sorption is frequently described by an equilibrium sorption model, for example linear or the Freundlich isotherm. Metal concentration, pH, ionic strength and competing cations influence the rate of sorption in the solutions. In analogy ionic radius, valance and degree of hydration are characteristics of the specific metal that affects the sorption rate. However, due to low solubility in soil, some metals are not subject for plant uptake (Gupta and Sandalio, 2012). Some metals, for example, are chromium, silver and tin.

Beside filtration and sorption, plant roots accumulate metals through diffusion of metal ions to the root endodermis and metabolic processes (Alloway, 1995). The rate of uptake is altered through plant species, evapotranspiration rate and the root surface area. Hyperaccumulators is the conceptual name of a group of vegetative species that are extra capable of accumulating metals (Salt et. al., 1998).

In a bioretention system the overlaying mulch provide several opportunities for metal adsorption (Hunt et. al. 2012). The soil media has also been proven to bind metals through sorption. Most metal found bound in bioretention systems have been in the top 20 centimeters. Humic substances, like fulvic and humic acids contain for example carboxyl and phenolic groups that make them suitable as sorbent media (Sparks, 2003).

Theoretically, the temperature should affect the sorption removal efficiency. Lower molecular activity and increased viscosity is the result of decreased temperature would also decrease the metal sorption (Benjamin, 2002). However, several studies imply that, within the range of 2-20 degree Celsius, the temperature has minor significance on the efficiency of sorption (LeFevre et. al., 2015).

2.3.8 Polycyclic aromatic hydrocarbon fate

Influent concentration of hydrocarbons corresponds well with the incoming total suspended solids (Diblasi et. a. 2009). Sorption is the dominant removal process regarding hydrocarbons in bioretention systems (LeFevre et. al., 2015). Sorption to soil organic matter is reversible and slow desorption can imply subsequent biodegradation while regaining sorption capacity. PAHs are also subject for biodegradation and phytoremediation (plant uptake) but these are considered slower processes in comparison. Since multiple-ring PAH show very low solubility in water these tend to adsorb to soils and sediments (Davis and McCuen, 2005).

Considering a bioretention system the fill media layer and overlying mulch provide a number of opportunities for the adsorption of both metals and petroleum-based pollutants (Hunt et. al. 2012). Polycyclic aromatic hydrocarbons and other hydrophobic organic compounds will partition into organic matter at either the surface mulch or in the soil media. Typically, PAHs are captured on particulate matter within the top few centimeters of the fill media and mulch.

2.3.9 Bioretention removal efficiency

Paus et. al. (2014) concludes lower efficiency of a bioretention area for the first few years of service. Nevertheless, the removal efficiency of a number of bioretention areas have been studied around the world throughout the past 20 years. In Table 7 and 8 the average numbers on removal efficiencies for some pollutants have been adapted to this study. The compilation has been accessed from the Stormtac database. Note that these efficiencies are adapted from studies worldwide and does not fully represent characteristic values for Swedish conditions.

Table 7. Average pollutant removal efficiency according to Stormtac (2015).

Pollutant	**TSS**	**P**	**PO_4-P**	**N**	**NH_4**	**Pb**	**Cu**
Efficiency [%]	80	65	55	40	70	80	65

Table 8. Average pollutant removal efficiency according to Stormtac (2015) (continued).

Pollutant	**Zn**	**Cd**	**Cr**	**Ni**	**Hg**	**PAH16**	**Oil**
Efficiency [%]	85	85	25	75	50	85	60

2.3.10 Vegetative properties

The presence of the vegetative cover helps to slow flows and facilitate long term infiltration (Emerson and Traver 2008). Vegetation is also recommended to promote the process of phytoremediation but the effects have not yet been quantified (Hunt et. al., 2012). The selected plants should be adapted for temporary wet and dry conditions (CIRIA, 2015). Voluminous root systems are most likely to be required in order to provide effective treatment.

2.3.11 Filter media properties

Suspended solids and particulate matter only require a shallow media depth according to Li et. al (2008). However, a minimum of 0.3 meter is suggested for plant survival and growth (Diblasi et. al., 2009). The infiltration rate should be less than 0.04 mm/s for proper removal of particulate matter. Removal of dissolved phosphorus, through sorption, require relatively high hydraulic retention time and therefore a deeper soil media (Hsieh et al. 2007). Commonly 0.6 to 0.9 meter soil media are used when designing for designed phosphorus removal. Hunt et. al. (2012) suggest an infiltration rate between 0,007 to 0,028 mm/s for phosphorus removal. An overlying layer of mulch have been proven to have good effect on trapping hydrocarbons (Hunt and Lord, 2006). Here around 75 to 100 mm should be adequate.

2.3.12 Storage layer properties

The storage layer is the top part of a bioretention system where ponding of water is allowed (Hunt et. al. 2012). The depth of the storage layer should be large enough to store event runoff allowing for percolation through the soil media (Davis et. al., 2012). The storage layer volume and available media storage volume (porosity) corresponds to the total available retention volume.

2.4 Modeling tools description

In the modeling session the Kviberg raingarden is used as case study and the model was constructed using the 2016 release of MIKE URBAN CS from DHI. The MIKE URBAN software is a GIS enabled tool used for modeling urban water systems (DHI, 2016e). The 2016 release also include features that enable modeling the effect of implementing low impact development structures to an urban stormwater system. This model description covers two ways of doing so, the catchment based method and network based method.

Assessing capacity or efficiency of an implemented low impact development practice in a catchment is described in the integrated low impact development module and is further referred to as **catchment based modeling**. The other method studied is detailed hydraulic assessment of low impact development where retention is described through implementation of structures to the modeled network. Also being able to associate ECOLab scripts to selected parts of the network various treatment of stormwater can be described and simulated in the model. This way of modeling is further referred to as **network based modeling**.

2.4.1 Catchment based modeling

The 2016 release of MIKE URBAN include a module that enables the user to define and deploy a low impact development structure in an urban stormwater model. Available low impact development structures to choose from are bioretention cells, raingardens, green roofs, infiltration trenches, permeable pavement, rain barrels and vegetative swales (DHI, 2016a). The performance of these structures are calculated with respect to storage and infiltration practices which makes them improve quantitative aspects (DHI, 2016a).

The low impact development module is integrated with the kinematic wave runoff model and the MIKE 1D hydraulic engine, which is based on the dynamics of Saint-Venant differential equation (DHI, 2016b). The MIKE 1D engine include a hydro-dynamics module allowing modeling the behavior of river and pipe networks, advection-dispersion module, for sediment transport, ECOLab module and several rainfall runoff modules.

The kinematic wave is based on Manning’s kinematic solution (DHI, 2015). The required in-data for the model is characteristic length and slope of the catchment area, manning number and type of catchment.

As the low impact development controls are deployed per catchment the low impact development structure area is subtracted from the impervious area (DHI, 2016b). In the defined pervious area infiltration is described by the Horton infiltration model, see equation 1. Impervious areas are routed by the kinematic wave runoff model.

$$f_p = f_c + (f_0 - f_c)e^{-kt} \qquad \text{[eq. 1]}$$

f_p = infiltration capacity at time t
k = capacity decrease rate constant
f_c = equilibrium capacity
f_0 = initial infiltration capacity

Low impact development functions are defined in the LID control panel of the program. An illustrative picture on how these structures are specified is shown below in Figure 3.

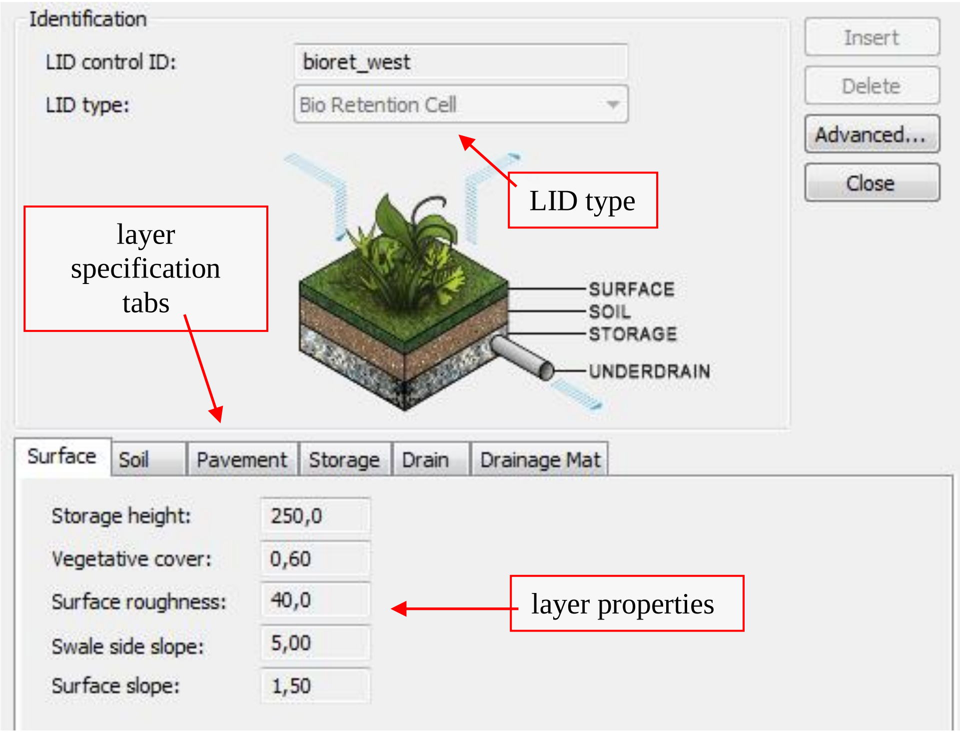

Figure 3. Low impact development control panel

Below the complete in-data needed to fully specify a bioretention cell in the low impact development control windows is displayed in Table 9. Deployment and of the low impact development unit is later done per catchment as previously described.

Table 9. Required in-data to setup the bioretention cell (DHI, 2016c)

Layer	Parameter	Unit	Remark
Surface	Storage depth	[mm]	Storage capacity above surface
	Vegetative cover	[%]	Amount of the surface covered with vegetation
	Roughness	[M]	Manning's number
	Slope	[%]	Slope of the bioretention cell
Soil	Thickness	[mm]	Thickness of the soil layer
	Porosity	[%]	Porosity of the soil layer
	Field capacity	[%]	Pore water after excess water has drained away
	Wilting point	[%]	Pore water relative to total where only bound water remains

	Infiltration capacity	[mm/h]	Soil property, infiltration to underlying storage zone
	Leakage capacity	[mm/h]	The rate of water leaving the soil layer into storage.
Storage	Thickness	[mm]	Thickness of the storage layer
	Porosity	[%]	Porosity of the storage layer media
	Infiltration capacity	[mm/h]	Infiltration capacity of surrounding soil
	Clogging factor	[%]	Amount clogging
Drain	Capacity	[mm/h]	Coefficient that determines flow through the underdrain as function of stored water height
	Exponent	[%]	Exponent that determines flow through the underdrain as function of stored water height
	Offset height	[mm]	Pipe offset, from bottom of the biobed

2.4.2 Network based modeling

The catchment based modeling of a low impact development structure in MIKE URBAN provide an integrated interface with a number of included functions which is easy to use. However, the retention is here only described in quantitative aspects. Therefore, the retention of pollutants in bioretention cells must be assessed using a more detailed method. The *network based method* is basically performed by defining soakaway nodes, in relevant node positions, to represent the bioretention areas and later connect a treatment process to these nodes. The treatment processes are defined using an external software called ECOLab. Both soakaway nodes and ECOLab will be further explained shortly.

In order to have the ECOLab templates to function a transport model must be used. In this case the transport of pollutants is described using the advection-dispersion module (DHI, 2016c). The advection-dispersion equation (IWMI, n.d.) is displayed below as equation 2.

$$\frac{\partial c}{\partial t} = -\frac{\partial}{\partial x_i} \cdot (cv_i) + \frac{\partial}{\partial x_i} \cdot \left(D_{ij} \cdot \frac{\partial c}{\partial x_j}\right) + R_c \qquad i, j = 1,2,3 \qquad \text{[eq. 2]}$$

c = concentration in the solute
R_c = sources or sinks
D_{ij} = dispersion coefficient tensor
v_i = velocity tensor

2.4.3 The soakaway node

Per definition a soakaway is an underground cavity filled with a porous media and connected to an inlet (Roldin, 2012). It can therefore be used to represent the functionality of a bioretention area. A soakaways allows for temporarily storage and slow percolation into the surrounding soil of stormwater runoff from roofs, roads or other impermeable areas (CIRIA, 2015). Typical filling materials used for these purposes are gravel, macadam or plastic cassettes (Roldin, 2012). The functionality of a soakaway depend on its geometry, size and soil properties. Both surrounding and internal soil. A rough conceptual drawing of the soakaway node is displayed in Figure 4 below.

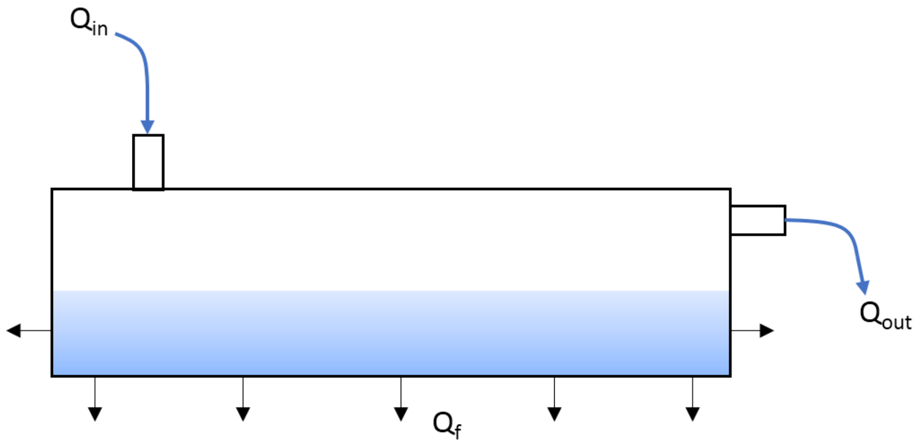

Figure 4. Schematic principle of a soakaway according to DHI (2016d)

The mass balance of the soakaway is governed by the equations 3 and 4. Equation 5 requires the conductivity to be equal both through the sides and the bottom. In Table 10 the required in-data for the soakaway node is explained.

$$\frac{dh}{dt} = \frac{1}{l \cdot w \cdot \theta} \cdot \left(Q_{in}(t) - Q_f(t) - Q_{out}(t)\right) \qquad \text{[eq. 3]}$$

$$Q_f = K \cdot \left(l \cdot w + 2 \cdot h \cdot (l + w)\right) \qquad \text{[eq. 4]}$$

h = hydraulic head
l = length of the soakaway
w = width of the soakaway
θ = porosity
K = conductivity of surrounding soils
Q_{in} = flow into soakaway
Q_{out} = emergency outflow
Q_f = infiltration flow to surrounding soils

Table 10. Required in-data for defining the soakaway node in MIKE URBAN

Parameter	***Unit***	***Remark***
Elevation data	m	Height data
Basin geometry	*	Specified dimensions of the soakaway
Infiltration method	1,2,3	1-no inf., 2-constant inf., 3-inf. sides/bottom
Infiltration rate	m/s	Only for inf. method 2
Porosity of fill media	%	Porosity of fill material
Initial water level	m	Default value = 0
Conductivity (sides/bottom)	m/s	Different conductivity through bottom / sides

Dimensions of the soakaway is defined through constructing a geometry input file with the MIKE URBAN software. This is done by defining the area in XY-plane and YZ-plane at selected Z-levels.

2.4.4 ECOLab

The ECOLab software is a user interactive programming interface allowing the user to modify or construct templates used to describe present aquatic processes related to water quality (DHI, 2016c). A variety of ECOLab scripts have been predefined by DHI and is included with the installation of the software itself. Most of the existing templates state processes occurring in aquatic systems and natural watercourses and none of these explicitly state characteristic processes within a bioretention area. However, the ECOLab environment is fully dynamic which enables the user to customize and defining new processes. The 2016 release of MIKE URBAN CS allows for importing ECOLab scripts to the hydrodynamic model to describe, for example, purifying processes within a bioretention cells (DHI, 2016d). This can be done as long as the processes can be expressed in a consistent model. An ECOLab script is possible to apply to any desired node structure in the model.

The way ECOLab scripts are associated to the model are visualized in Figure 5. The kinematic wave describes the process of how runoff is generated and runoff concentrations are stated as input data. Advection-dispersion describes the transport of pollutants in the system. At the soakaway nodes the MIKE 1D send the generated pollutant concentration to the ECOLab template, which calculates the reduction and sends a new concentration back to MIKE 1D at each time step.

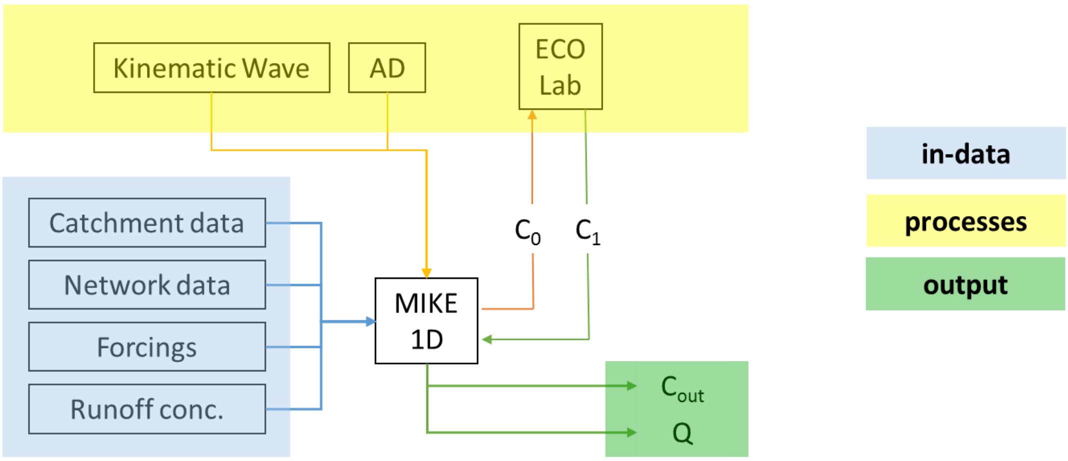

Figure 5. Conceptual visualization on how ECOLab-couples to MIKE 1D

2.4.5 Sensitivity analysis

For the sensitivity analysis a number of size and design related parameters will be selected for further evaluation. Motivation on the specific parameter will be given in this chapter. Performing the sensitivity analysis will be through evaluate the reference in-data in ±20 % intervals individually and compare the accumulated runoff from the catchments.

Infiltration capacity to the surrounding soil

According to SGU (the geological survey of Sweden) the study area is situated on postglacial clay, see Figure 6. Hillel (1982) state that clayey soils has an infiltration rate between 0 and 5 mm/h. Compared to sand, that might have infiltration rates above 20 mm/h, the infiltration capacity of the surrounding soil is considered to have severe impact on the effectiveness of a bioretention area. This could also imply a location dependency, on the regional scale, where some areas might be more suitable than others for bioretention. Since the exact infiltration capacity on site is not measured this parameter is subject for the sensitivity analysis.

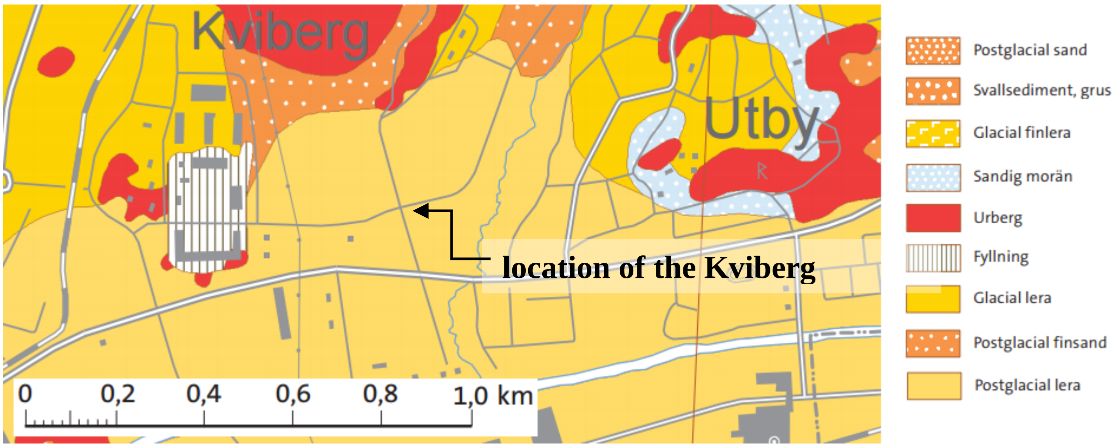

Figure 6. Soil profile map of the study area according to the geological survey of Sweden (SGU).

Vegetative cover

The vegetative cover parameter has been estimated to 60 % for the model since there is no way to measure this parameter at present time due to the young age of the study area. Therefore, this parameter is subject for the sensitivity analysis.

Surface storage

In the reference design the surface storage height is 250 mm (Sweco, 2014). Altering this parameter will reduce or increase the storage capacity above ground and therefore also subject for sensitivity analysis.

Soil layer

The soil layer thickness and porosity determines the amount of water that can be held in the layer and the sensitivity analysis will therefore cover these parameters. The soil infiltration capacity is a parameter that determines the rate of flow through the soil media layer, which can be altered depending on the soil composition. The soil used in the Kviberg retention has an infiltration capacity of 80 mm/h (Sweco, 2014). A lower infiltration capacity implies increased ponding in the surface storage and vice versa.

Storage layer

Also the storage layer thickness and porosity are selected for sensitivity analysis due to their potential impact on retention capability.

3 Methodology

Beside performing a literature study on retaining mechanisms in bioretention cells one part of the study have been to evaluate methods for modeling low impact development structures, using the software MIKE URBAN from DHI. The raingardens in Kviberg, located in eastern Gothenburg, and their surrounding runoff areas are assigned as the case study area. In-data to set up the model is provided from the municipality through the department of water supply in Gothenburg, Kretslopp och Vatten. Due to the recent initiation of the facility proper in-data was available. Software orientation and supervision throughout the modeling phase will be provided by DHI Sweden.

The modeling phase should answer the questions what retention to expect in the Kviberg raingarden and how the software can be used to evaluate alterations of the current design. In order to reach this a hydrodynamic model of the study area is needed to be constructed.

Qualitative and quantitative detention effects are intended to be modelled for three different scenarios to enable comparison to the bioretention option.

- ✓ 0-alternative: Base scenario where nothing, besides pipes and manholes, is implemented to manage stormwater runoff
- ✓ Conventional alternative: Conventional detention using basins where 10 mm/m^2 of the connected surfaces is stored according to Kretslopp och vatten guidelines
- ✓ Bioretention alternative: Retention adapting the Kviberg raingarden design to the model.

3.1 Reference model setup

To build up the model a variety of resources are needed and these are stated in Table 11. Beside this data, catchment runoff properties and pollutant concentrations are required and have been adapted from literature.

Table 11. Model in-data requirements to construct the hydrodynamic model of the case study area

In-data	Source	Remark
Orthophoto	Kretslopp och vatten	Georeferenced aerial photo
Network data	Kretslopp och vatten	Relevant nearby network data, for example links and manholes
Topology map	SLU geodatabase	Height data on 2-meter resolution
Precipitation series	DHI, Göteborg	Rain data from Torp (2013-2016)
Evapotranspiration series	DHI, Göteborg	Potential evapotranspiration
Bioretention cell properties	Kretslopp och vatten	Information on spatial preferences, soil properties etc.

The in-data provided from Kretslopp och Vatten are an orthophoto and the relevant nearby stormwater network. As visible in Figure 7 the orthophoto is up to date and it is possible to see where the parking lot is constructed. Underlying the orthophoto and network data there is a topology map which is obtained from the SLU geodatabase. The resolution here is 2 meter which is considered enough for further work.

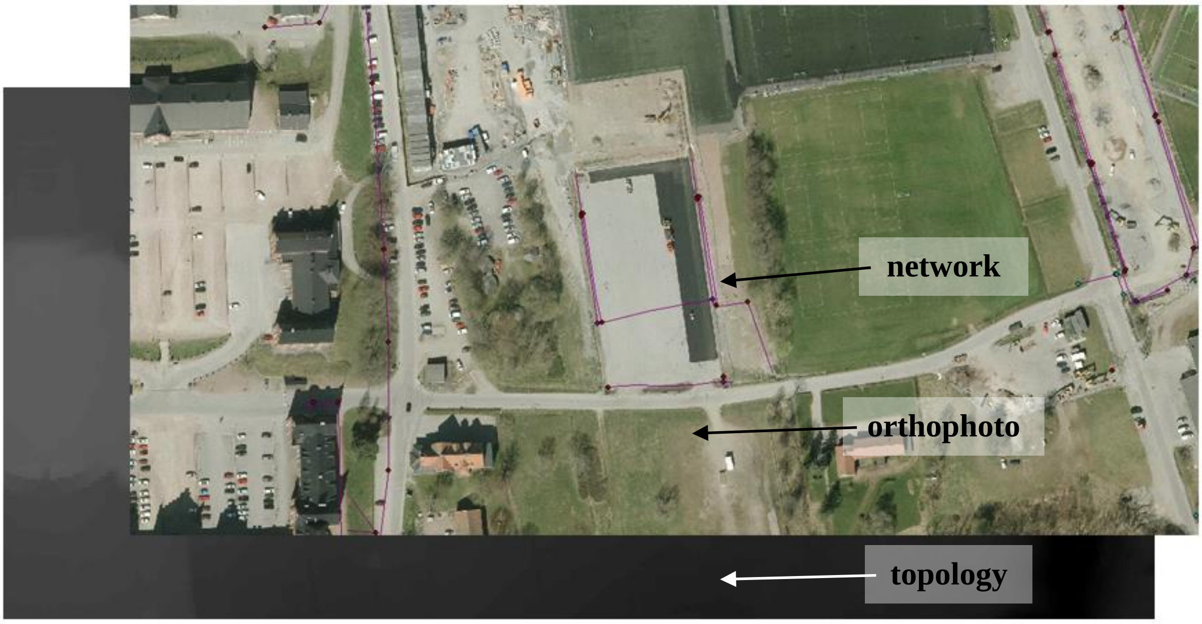

Figure 7. Conceptual in-data description. Network data overlying the orthophoto map overlying the topology map

Building up the MIKE URBAN model is done through defining the catchment areas, manholes and links. To allow for realistic setup for the low impact development controls later the total catchment is divided into 14 subcatchments. The subcatchments are estimated using the orthophoto since georeferenced material has not been available. Manholes are set to be 1 m in diameter and the invert level is set to be 1,8 meter below ground level. The ground level is defined from assigning the pixel value from the topology map. Minor adjustments have been made to make the gravity control function. Links dimensions are set according to in-data provided by kretslopp och vatten, see appendix 2 and 3. Runoff from each sub-catchment is connected to the nearest node. Figure 8 shows the finished reference model that is used throughout the project. This model is however altered to measure the effect of different implementations.

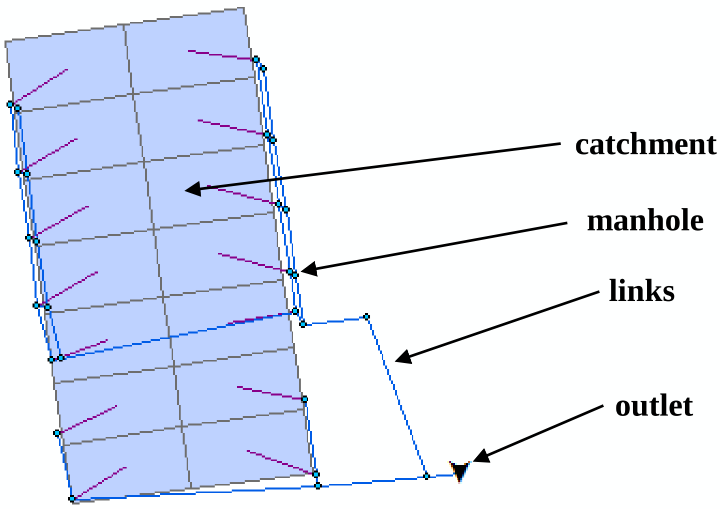

Figure 8. Study area defined in MIKE URBAN as catchments, links, manholes, weirs and outlet

The runoff model used throughout the modeling phase is the kinematic wave theory. The kinematic wave runoff model requires in-data that is characteristic for a parking area. The total parking runoff area is approximately 5288 m^2. According to Davis and McCuen (2005) the runoff coefficient of asphalted surfaces is 0.85. Other required data is presented in Table 12 and is used for all subcatchments and all simulations.

Table 12. Required in-data for kinematic wave runoff model

Parameter	Unit	Value	Remark	Reference
Catchment length	[m]	100	Characteristic length of the catchment	Sweco, 2014
Slope	[‰]	10	Average slope of catchment	Sweco, 2014
Impervious (steep)	[%]	0	Proportion steep impervious areas	Davis and McCuen, 2005
Impervious (flat)	[%]	85	Proportion flat impervious areas	Davis and McCuen, 2005
Pervious (low)	[%]	15	Proportion low permeable areas	Davis and McCuen, 2005
Pervious (medium)	[%]	0	Proportion medium permeable areas	Davis and McCuen, 2005
Pervious (high)	[%]	0	Proportion high permeable areas	Davis and McCuen, 2005

3.1.1 Precipitation data series

For all the results, precipitation data from the nearest measuring station have been used but in different time spans. The total time span of the series is from 2013 up to now. To see how runoff peaks are reduced using both conventional detention and the reference bioretention design compared to the zero alterative a 25-hour rain event is used which represent a rain event with 2 year return time. Initial simulations, during the model setup, were done using this same rain event to enable quick troubleshooting and to verify the functionality of the model. When performing the sensitivity analysis and accumulation of pollutants for the network based modeling rain data covering 365 days were used, starting 2015-01-01. Figure 9 display the actual precipitation series used.

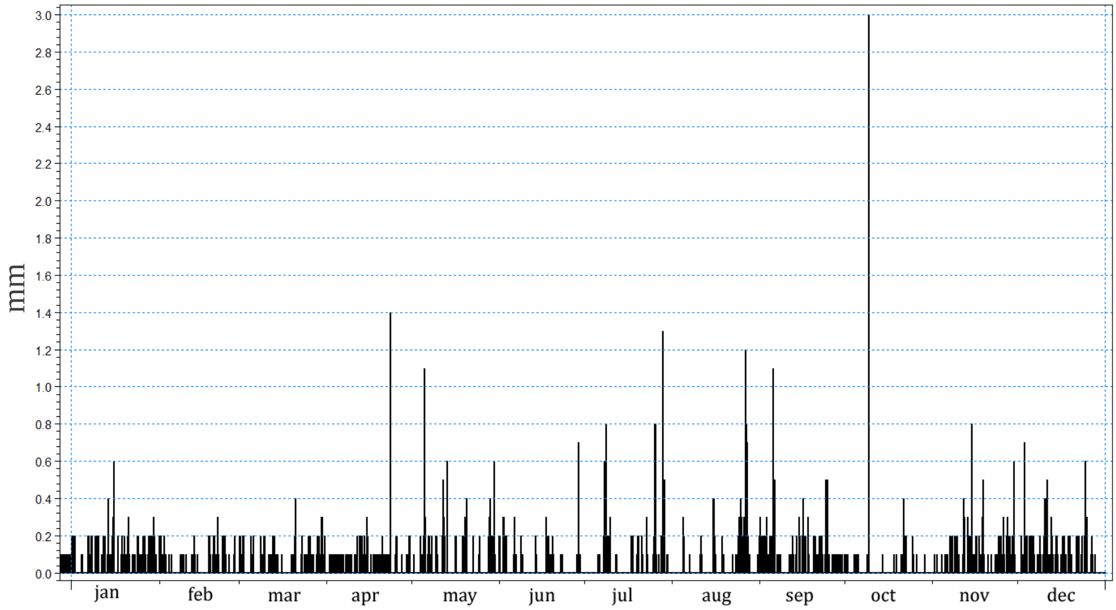

Figure 9. The 2015 precipitation series measured at Torp used throughout modeling

3.1.2 Evapotranspiration data series

To enhance the reality aspect of the model a potential evapotranspiration time series on the same time span used for the rain series was included to the model, see Figure 10. The potential evapotranspiration is defined as the evapotranspiration from a grass surface which is not short on water in the root zone and where no heat storage occurs (SMHI, 2014).

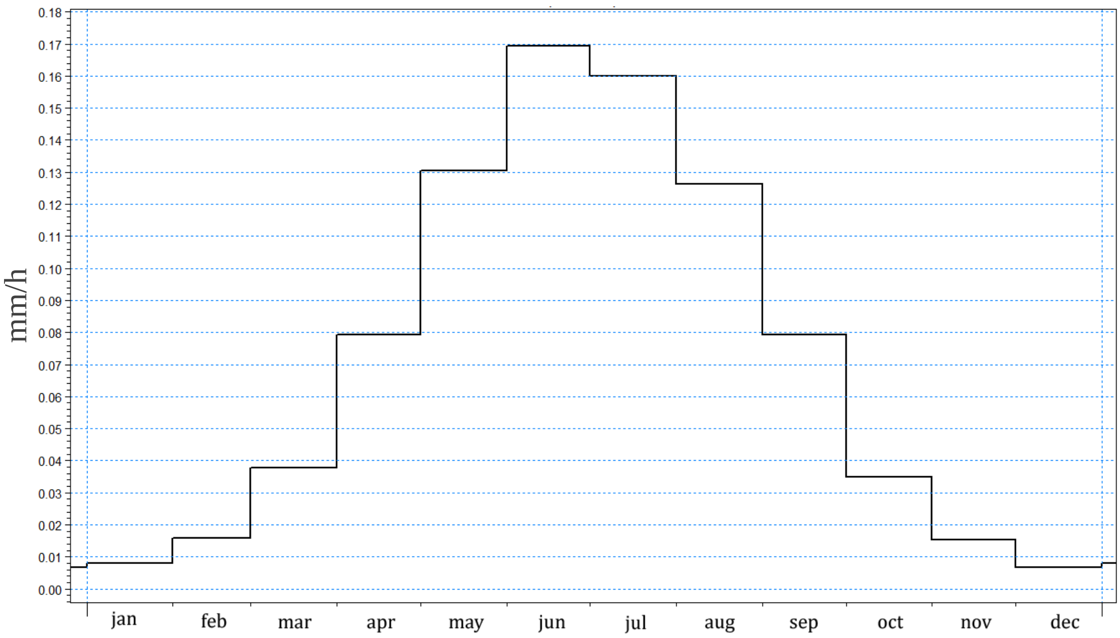

Figure 10. Synthetic potential evapotranspiration series used throughout modeling

3.2 Catchment based modeling adaption

The raingarden areas at Kviberg are constructed as trenches 1.4 meters wide along both sides of the parking lot, see Figure 1. One important fact is that the raingardens are divided into 15 meter sections to provide flow control and prevent flushing. As the low impact development controls are deployed per catchment in MIKE URBAN it was found necessary to also divide the total catchment accordingly. Defining the low impact development controls in MIKE URBAN requires a number of parameters. These parameters and what values that have been used to define the reference design can be studied in Table 13.

Table 13. In-data for setup the catchment based bioretention model. Adapted from the Kviberg case

	Parameter	**Unit**	**Value**	**Remark**	**Reference**
Surface	Storage depth	[mm]	250	Storage capacity above surface	Sweco, 2014
	Vegetative cover	[%]	60	Percentage covered in vegetation	Assumption
	Roughness	[M]	40	Manning's number	McCuen, 1996
	Slope	[%]	1,5	Slope of bioretention cell	Sweco, 2014
Soil	Thickness	[mm]	1000	Thickness of soil layer	Sweco, 2014
	Porosity	[%]	50	Porosity of soil layer	Sweco, 2014
	Field capacity	[%]	20	Volume of pore water after excess water has drained away	DHI, 2015
	Wilting point	[%]	10	Pore water relative to total where only bound water remains	DHI, 2015
	Infiltration capacity	[mm/h]	80	Soil property	Sweco, 2014
	Leakage capacity	[mm/h]	10	The rate of water leaving the soil layer into storage.	Default
Storage	Thickness	[mm]	450	Thickness of storage layer	Sweco, 2014
	Porosity	[%]	0,3	Porosity of macadam	DHI, 2015
	Infiltration capacity (surrounding soil)	[mm/h]	1	Infiltration capacity of surrounding soil (assuming clay)	Hillel, 1982
	Clogging factor	[%]	0	Ignoring clogging	-
Drain	Capacity	[mm/h]	3	$Q=C*h^n$. assigned parameter assuming n=0 → Q=C [l/s].	DHI, 2015c
	Exponent	[%]	0	$Q=C*h^n$. Rate of flow through the underdrain.	Assumption
	Offset height	[mm]	100	Pipe offset, from bottom of biobed	Sweco, 2014

One of the aims of the study have been to compare the effects of bioretention systems to a conventional alternative using retention basins. Therefor the model is altered with basin structures in nodes according to Figure 11. The basins are designed to hold 10 mm rain on the connected surfaces according to kretslopp och vatten regulation. When running the conventional alternative the deployed low impact development structures, explained above, are inactivated from the model.

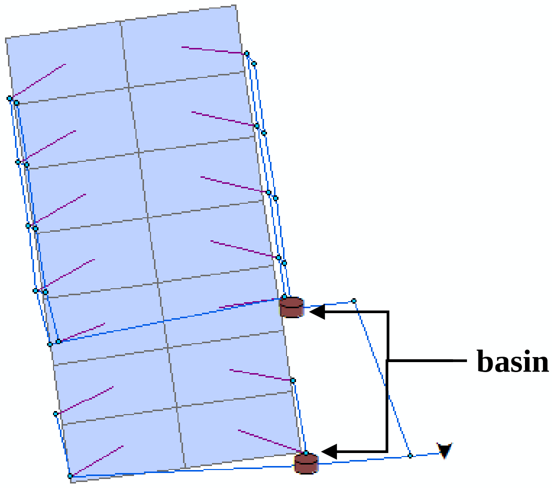

Figure 11. Model adapted for conventional retention simulation using detention tanks

3.3 Sensitivity analysis

The sensitivity analysis will be performed on the catchment based modeling parameters. Through testing the selected parameters in a ±20 percent interval, from the reference case, it is possible to see how different parameters affect the flow retention. Table 14 present the in-data used in the model. Here one simulation is run for each alteration.

Table 14. Selected parameters for sensitivity analysis

Interval	Infiltration capacity [mm/h]	Surface storage height [mm]	Soil layer thickness [mm]	Storage layer thickness [mm]	Storage layer porosity [1/1]	Soil layer porosity [1/1]	Soil infiltration capacity [mm/h]	Vegetative cover [%]
-20 %	0,8	200	480	360	0,24	0,4	64	48
-10 %	0,9	225	540	405	0,27	0,45	72	54
±0 % (ref)	**1**	**250**	**600**	**450**	**0,3**	**0,5**	**80**	**60**
+10 %	1,1	275	660	495	0,33	0,55	88	66
+20 %	1,2	300	720	540	0,36	0,6	96	72

3.4 Network based modeling adaption

Altering the model for network based modeling implies connecting the catchment runoff to soakaway nodes and couple ECOLab scripts, featuring treatment processes, to these nodes, see Figure 12. This means that the soakaway node allow for reduction of flows and treatment of incoming stormwater.

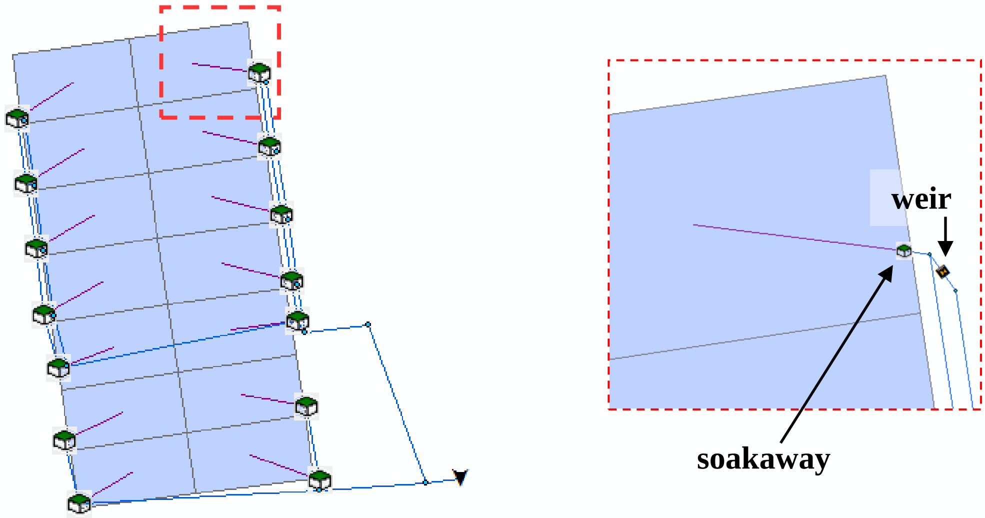

Figure 12. Model adapted for soakaway infiltration and network based modeling (+detailed view)

The soakaway nodes are calibrated to represent the flow retention achieved using the low impact development functions from the catchment based modeling. Table 15 conclude the in-data for this to happen. Thereafter ECOLab templates are defined and associated to the soakaway nodes to represent the pollutant removal processes in the bioretention cell.

*Table 15. In-data used for soakaways to represent the effect from the catchment based modeling. *The basin geometry is designed according to the spatial properties of the bioretention cells.*

Parameter	***Value***	***Unit***	***Remark***
Elevation data	Pixel value	m	Height data
Basin geometry	*	-	Bioretention cell size and proportions defined
Infiltration method	3	-	1-no inf., 2-constant inf., 3-inf. sides/bottom
Infiltration rate	-	m/s	Only for inf. method 2
Porosity of fill media	50	%	Porosity of fill material
Initial water level	0	m	Default 0 but possible to have initial water in the node
Conductivity (sides/bottom)	0,00010	m/s	Different conductivity through bottom / sides

ECOLab scripts are defined for reduction of copper and phosphorus in this study. Due to limited mathematical support for the processes described in section 2.4 the templates used are incomplete and require further work to fully represent the reality. Nevertheless, the following paragraphs will present what processes have been accounted for in the model.

3.4.1 Heavy metal adaption

The differential equation for heavy metal equilibrium, considering both particular and suspended matter, used in this study is simplified and stated as equation 5 and 6.

$$\frac{d[Me(P)]}{dt} = sorption - filtration - sedimentation \qquad \text{[eq. 5]}$$

$$\frac{d[Me^{n+}]}{dt} = -sorption \qquad \text{[eq. 6]}$$

Below Figure 13 shows how the constructed ECOLab script handles incoming metal. Here incoming metals is divided into particular and dissolved. The dissolved part is transformed to particularly bound metal through the sorption equation (eq. 7) and thereafter follow the fate of the total suspended solids.

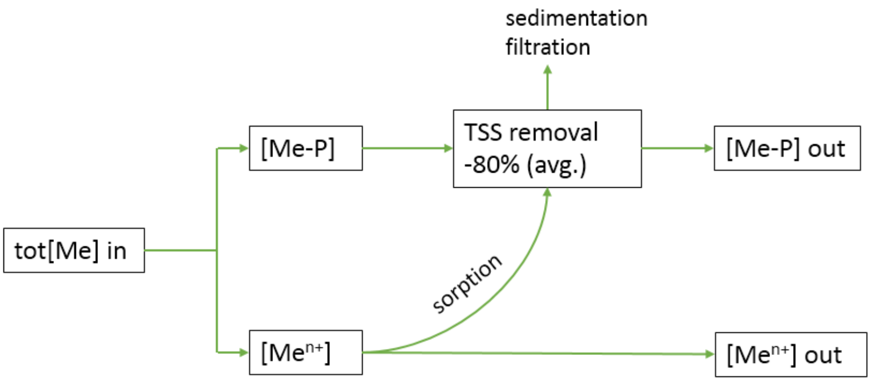

Figure 13. Conceptual metal removal schematics.

$$sorption = -K_d \cdot k_w \cdot [TSS] \cdot [Me^{n+}] \qquad \text{[eq. 7]}$$

K_d = Relation between heavy metal in suspended matter and concentrations in water phase
k_w = desorption rate in water [d-1]
[Men+] = dissolved heavy metal concentration [mg/l]
[TSS] = suspended solids concentration [mg/l]

3.4.2 Phosphorus adaption

Equations 8 and 9 state the differential equations for how dissolved and particular phosphorus have been considered. In similarity with the heavy metal adaption Figure 14 show the removal principle. Particular phosphorus follows the fate of the suspended matter and is removed with 80 percent. Dissolved phosphorus is removed partly through sorption which is estimated as the first order decay.

$$\frac{d[P\_particular]}{dt} = -filtration - sedimentation \qquad \text{[eq. 8]}$$

$$\frac{d[P\_dissolved]}{dt} = -sorption\ (first\ order\ decay) \qquad \text{[eq. 9]}$$

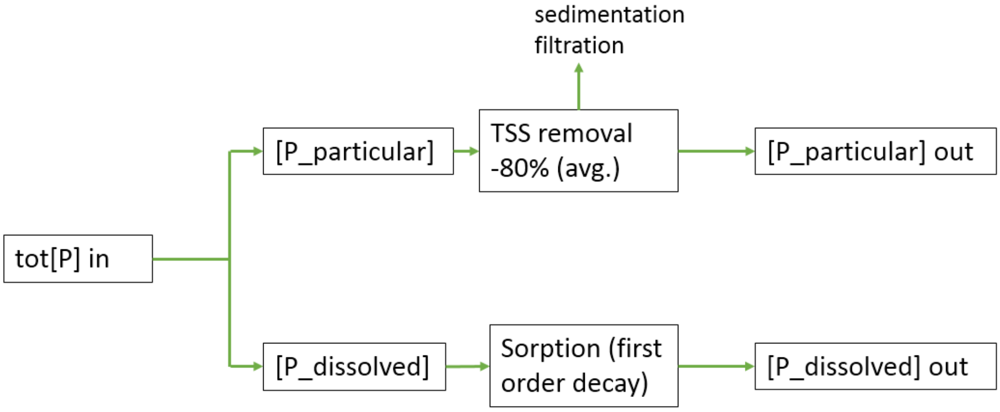

Figure 14. Phosphorus removal schematics adapted to model

$$sorption\ (first\ order\ decay) = [P\_dissolved]_{in} \cdot e^{kt} \quad \text{[eq. 10]}$$

k = removal efficiency coefficient [d-1]
t = concentration time [s]

4 Results

This section will cover the results from the stated catchment based model and associated sensitivity analysis. Following the sensitivity analysis, the results from the network based modeling will be presented.

4.1 Catchment based modeling

At catchment based modeling, the efficiency regarding quantitative aspects of the bioretention system can be determined. Here three different scenarios have been simulated to represent the zero alternative, the conventional alternative and the bioretention alternative that previously have been stated and specified in the method chapter. The accumulated flow downstream the system for all three scenarios are stated in Table 16. From the simulations, that was run for the year 2015 it can be concluded that bioretention alternative retain 50,2 % accumulated flow.

Table 16. Accumulated discharge downstream the system comparing the three scenarios

	Reference scenario	**Conventional scenario (10 mm)**	**Bioretention scenario**
Accumulated discharge [m^3]	10706	10706	5330
Retention efficiency [%]	0	0	50,2

No reduction of accumulated flows is noticeable for the conventional alternative in Table 16 but looking to one single rain event it is possible to see the effects. Comparing the three scenarios during a 2-year rain event, during the same year, it is possible to see the peak flow reduction of implementing a bioretention system. According to Figure 15 the current bioretention system setup is performing according to the conventional management practice.

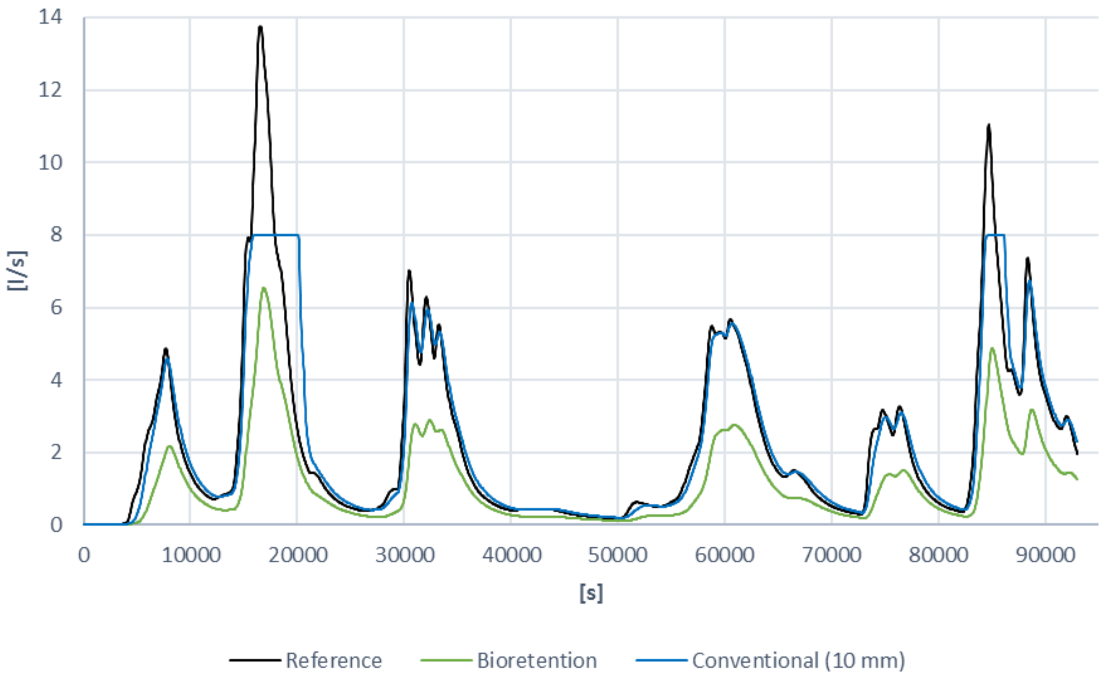

Figure 15. Peak flow reduction using the implemented Kviberg bioretention system compared to conventional management

4.2 Sensitivity analysis

The sensitivity analysis performed on selected parameters defined in section 3.2.1. is presented in this section. Since the catchment based method is easily modified and tested the sensitivity analysis does only cover results related to flow reductions. The parameters have been evaluated in ±20% intervals referred to their initial values. From Figure 16 it can be concluded that the infiltration capacity to the surrounding soil is the most affecting parameter. The figure should be interpreted as if the infiltration capacity was lowered by 20 percent the accumulated annual flow would increase by 19,1 percent.

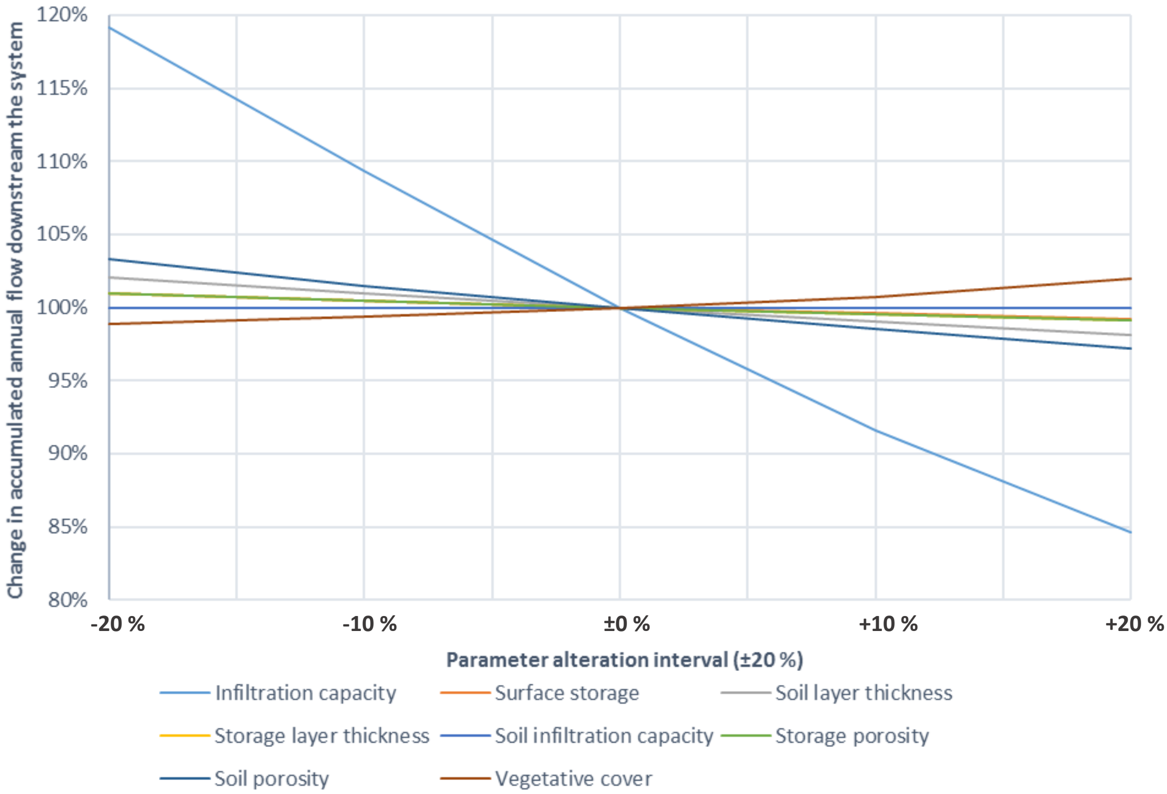

Figure 16. Results from the sensitivity analysis

Excluding the infiltration capacity to the surrounding soil in Figure 17 a more detailed view on the other parameters can be inspected. The figure shows that the soil porosity and soil layer thickness are the second and third most affecting parameters. The vegetative cover evaluation is tilted to the opposite direction compared to the others. This is to be interpreted as if the vegetative cover is lowered more runoff stormwater is enabled to infiltrate. Also the soil infiltration capacity parameter does not vary in the ±20 % interval.

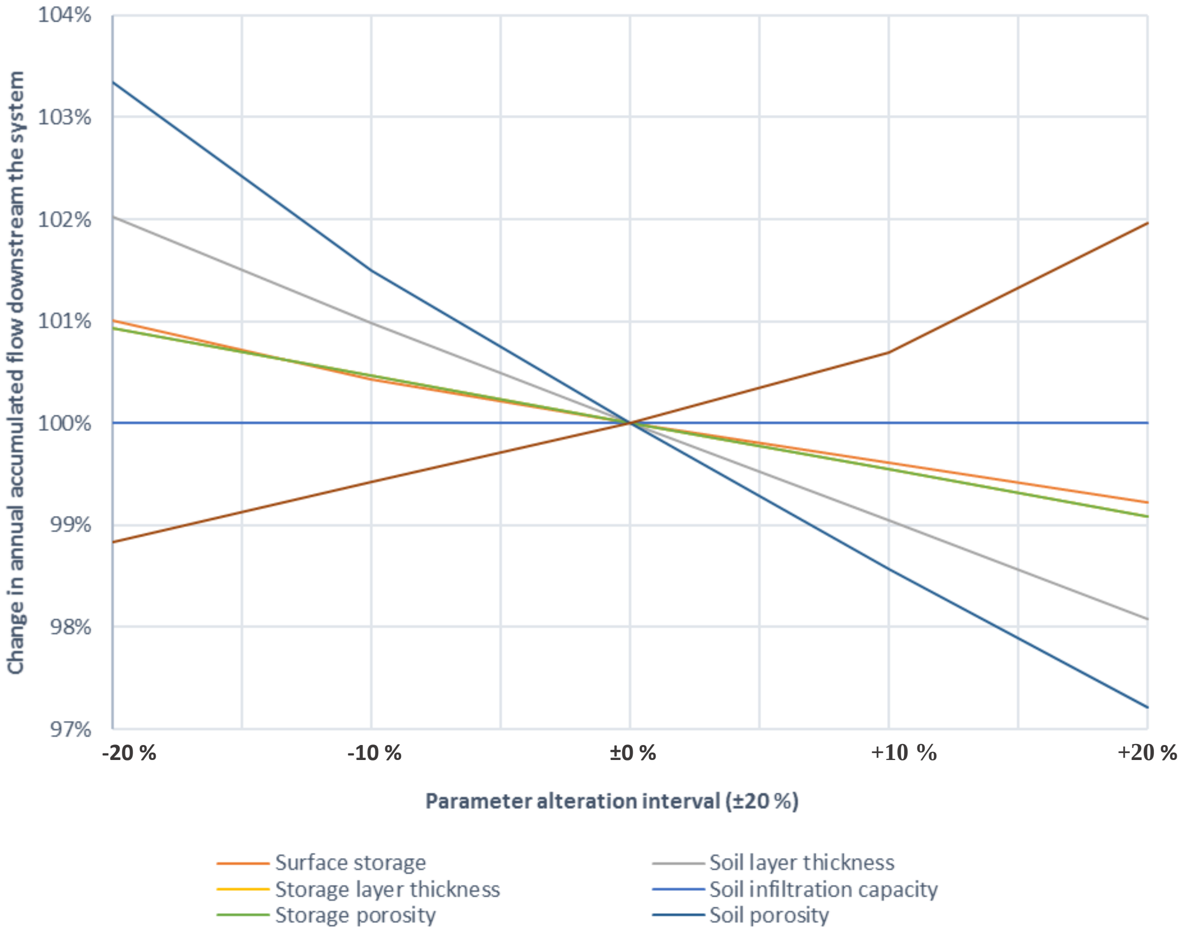

Figure 17. Results from the sensitivity analysis (detailed view)

4.3 Network based modeling

First step in the network based modeling is to have the soakaway nodes perform according to the catchment based modeling regarding the flow control. Figure 18 display how the defined soakaways, that are calibrated, perform in comparison to the low impact development controls.

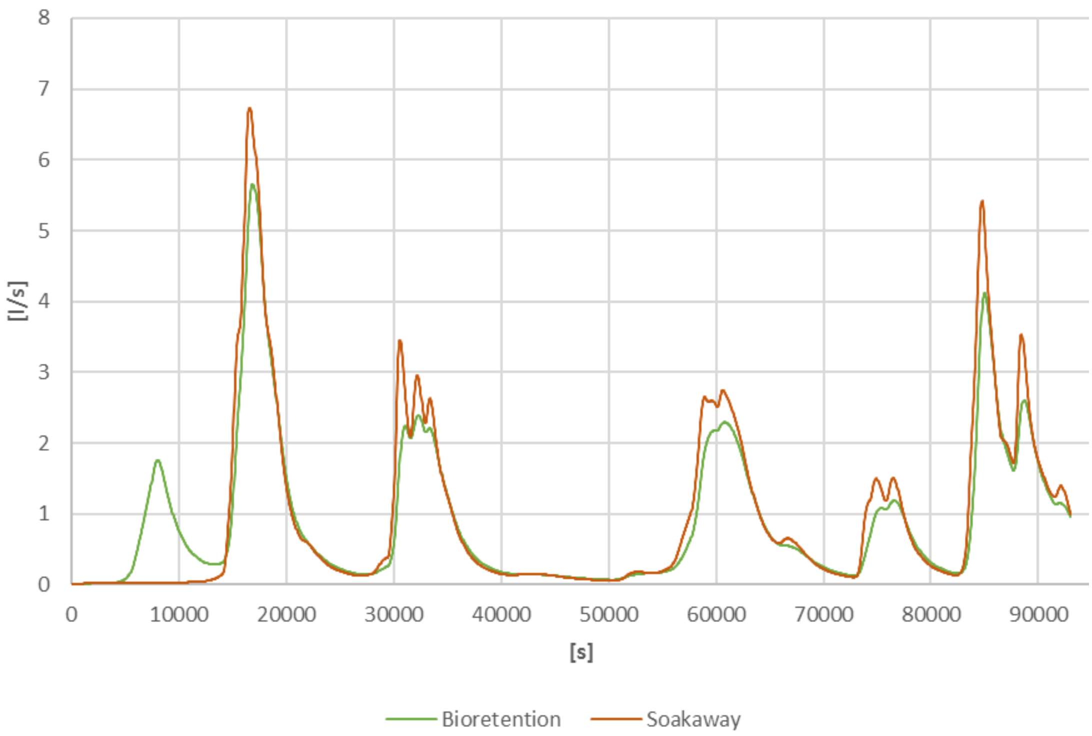

Figure 18. Soakaway node calibrated corresponding to results from catchment based model

Ecolab scripts can be associated to any node in the MIKE URBAN software. In this study copper and phosphorus have been subject for further evaluation and scripts are connected to the soakaway nodes in the model, which represent the bioretention cells. Accumulated pollutant loads downstream the system is evaluated and presented in Figure 19 and 20.

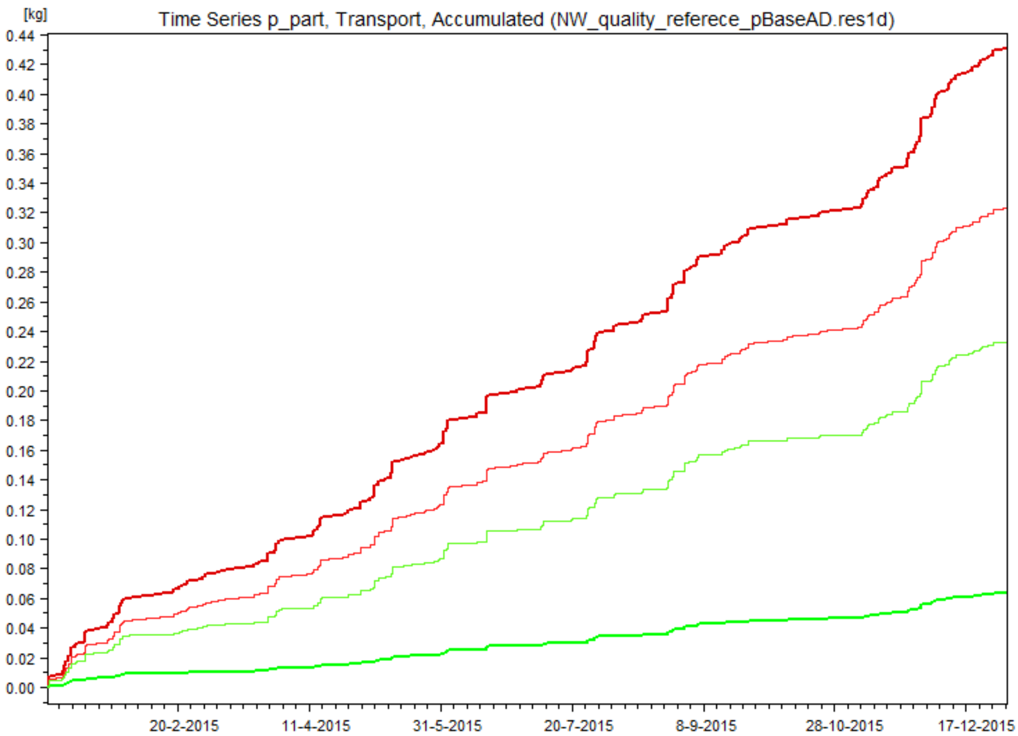

Figure 19. Annual accumulation of phosphorus

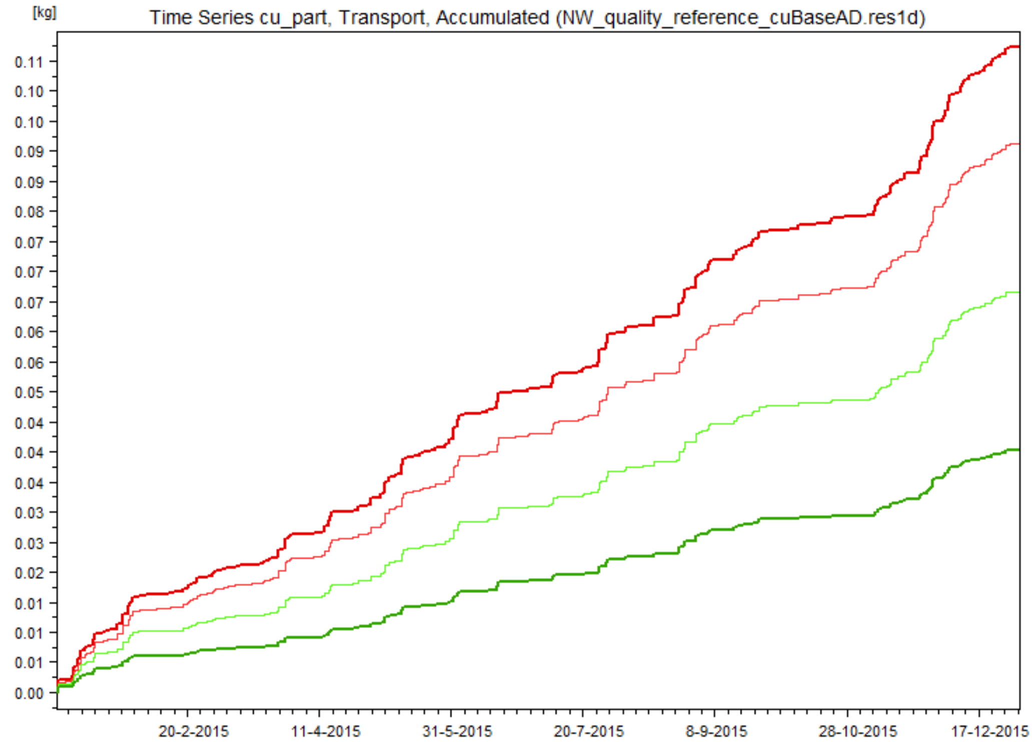

Figure 20. Annual accumulation of copper

In Table 17 the compiled results from applying the defined ECOLab scripts are displayed. As shown the total copper reduction was modeled to be 63,1 % and the total phosphorus removal was 57,8 %.

Table 17. Accumulated pollutant masses (2015 rain series). Comparing bioretention system effect to 0-alternative

Pollutant	**0-alternative accumulation [kg]**	**Bioretention accumulation [kg]**	**Model removal efficiency [%]**	**Reference removal efficiency [%]**	**Reference**
Cu (dis)	0,091	0,030	67,0	-	-
Cu (part)	0,107	0,043	59,8	-	-
Cu (tot)	**0,198**	**0,073**	**63,1**	**65,0**	Stormtac (2015)
P (dis)	0,32	0,23	28,1	-	-
P (part)	0,43	0,086	80,0	-	-
P(tot)	**0,75**	**0,316**	**57,8**	**65,0**	Stormtac (2015)

5 Discussion

Closing the results chapter, it is clear that there is a lot of useful aspects to the evaluated parts of the new MIKE URBAN features, if the interest is to study the behavior of bioretention cells. It is important to understand that this study is referring to an existing facility that has been designed using other methods than the one described in this report. The Kviberg raingarden facility have been grateful as study area since proper and reliable in-data have been available which could easily be adapted for the model. Nevertheless, some estimations and simplification have been necessary to do in order to completely define the study area in the software. In addition, not being able to fully describe the present treatment dynamics for different pollutants in bioretention, this work should be considered as a conceptual study on how the software can be used and how results can be presented.

The study is based on the Kviberg raingardens but reality is more complex, which is worth mentioning. Modeling is always a way of describing the reality and depending on the resolution and detail put in varying resolution of results are achieved. In this particular case the model is setup as a theoretically fully functioning facility where ground water flow or other forms of undesired water are not considered. If the model was to be verified towards measurements such unknown water would be detected and the model would be subject for further work to calibrate its function.

Simplifications were done considering the absence of mathematics regarding present treatment mechanisms in a bioretention cell. Information available on the remediation efficiency of bioretention areas are often empiric and very little explicit mathematics are stated or studied. As for now the processes are very simplified saying that 80 percent of all particular matter is removed regardless of anything and both dissolved copper and phosphorus is removed through sorption processes described in different ways mathematically. All and all there are two processes per substance defined which in reality is not the case. For example, removal of dissolved copper or phosphorus is not only governed by sorption to soil media and particulate matter, but also subject for plant uptake and biological processes. Nevertheless, the obtained results show almost as good treatment effect as in the Stormtac registry. This implies that the removal processes defined might be overestimated or that other processes are not very significant. However, the processes defined are ideal and does not relate to any outer thermal or seasonal variations which could be easing the observed effect in this study.

The drainage specification, when defining the bioretention cells for the catchment based model, follows the formula $Q=C*h^n$. This is telling that the outflow through the drain is a function of the water head above and a reasonable value for exponent have been difficult to obtain. Therefore, n is assumed to be zero so that the drainage equals the drainage coefficient, $Q=C$. The drainage is constant and determined only by the slope and diameter of the drainage pipe.

The characteristic runoff concentrations for phosphorus and copper, stated in the background chapter, is further used as in-data for the model. These values are obtained from several literature sources and can more specifically be studied in appendix 1. Though several of the references used here are measurements from Swedish parking areas the mean values are also the result from including measurements from parking areas abroad. To increase the accuracy of the model site-specific measurements on the actual runoff concentration should be performed and used as in-data for the model. To further enhance the model pollutant accumulation on the catchment surfaces can be studied. This is possible to describe in the used software.

The built-in low impact development module in MIKE URBAN is referred to as catchment based modeling throughout the report and the results output are entirely in terms of flow losses in the system. Defining in-data is easily done in the user interface, where spatial and soil media properties are defined for each layer of the bioretention area. Comparing the results here to any alternative can display differences in water level, accumulated discharge and peak flow reduction. Beside modeling bioretention systems in this section of the software other low impact development practices can be studied, for example green roofs, infiltration trenches, permeable pavement and rain barrels. It is also possible to combine a number of these structures to achieve the desired function.

The sensitivity analysis was performed to get an idea on which parameters are affecting the design of a bioretention cell the most. The ambition was to include treatment parameters in the sensitivity analysis but the complexity in describing the system made it impossible. However, according to the result chapter the sensitivity analysis performed shows minor differences on parameters other than infiltration capacity to surrounding soils, which is considered to be the key parameter. This is of course only valid within the selected interval of ±20 percent from the reference design values. The greatest variations are observed when altering the infiltration capacity to surrounding soils. That other parameters did not affect the efficiency more was surprising. One reason could be that the layer thicknesses (the z-axis) in the ±20 percent interval are not that significant when looking to the complete volume. Since one bioretention cell is defined as approximately 1.4 times 15 meter and the layers are tested individually the volumetric change is lower than ±20 percent.

Effects from introducing the reference bioretention design to the subcatchments defined is very much impacting the accumulated discharge downstream the system. As shown in the sensitivity analysis the infiltration capacity parameter is very much affecting the efficiency. Since this parameter is not measured and should be between 0 and 5 mm/h, according to literature, this parameter comes with great uncertainty. To obtain reliable results the surrounding soil infiltration capacity is suggested to be measured.

Considering the water quality results these have been compared to average data from the Stormtac database. As seen in Table 17 the copper removal efficiency compares well. However, since the ECOLab script used in this case is very basic and lacks many of the stated removal mechanisms in the background section, one could expect the results to be lower. The method as it is to model pollutant reduction is pretty straight forward and the complexity lies in describing all present processes considering the occurring polluting substances.

Coupling ECOLab templates to desired nodes in an existing MIKE URBAN model to simulate pollutant removal is a pretty straight forward process in its essence. However, the difficulties lie in defining the treatment processes since explicit dynamics of pollutant removal in bioretention systems is not very well defined in literature at present time. Much of the information available on the matter origin from empirical studies that is considering concentrations in opposing concentration out. The question is whether scientific methods of describing the actual processes, which have been used in this study, compares to the faster way adapting average data obtained through former studies to estimate the pollutant removal efficiency. The short answer is that average data is accurate enough for smaller contexts as there is no standards in the field. However, due to thermal-, societal- and regional variations, in both runoff concentrations and potential treatment efficiency, an average value can be very misleading depending on where and when bioretention is up for discussion. However, just the possibility of coupling ECOLab to the MIKE URBAN software is considered a leap forward to enhance models to transition towards more qualitative aspects of modeling gravity sewer systems.

Advantages in bioretention as a concept is that retention of flows can be obtained and at the same time achieve reduction of pollutant loads. Despite the uncertainty in this particular modeling session this information is also supported through literature. The use of bioretention for mitigating flows and pollutant loads should therefore be considered as an alternative to conventional management. In an urban environment there is potential to implement small scale low impact development structures, for example refuges. A disadvantage in the method used in this study is that it is very time consuming to try define something that is not that well defined. The future work in modeling pollutant fate the way it has been attempted in this study is to keep develop templates in ECOLab. Not only regarding the fate of pollutants used in this study but also other metals, nutrients and PAHs.

Due to the recent operational initiation of the facility, in the fall of 2015, the Kviberg bioretention area has not been subject for testing throughout this study. Rough estimations say that full operational service of a bioretention area is achieved first after a few years of operation. Any measurements at present time would have been misrepresentative at this time, which have been the fundamental reason why calibration have not been performed. However, an interesting aspect at this point could be to document the maturation of the facility but this have not been the aim for the study and such work would span over at least a couple of years. But for further work the model should be verified to measured data.

6 Conclusion

Beside mitigating flows during rain events bioretention systems also have the potential to reduce pollutant loads on recipients. Mechanisms like sedimentation, filtration, sorption, plant uptake and other biological processes contribute to pollutant removal in bioretention. Despite the assumptions made and the uncertainty in the model the results show good removal efficiency regarding phosphorus and copper, which is also supported by literature. The retention obtained in the Kviberg raingarden design is considered to be according to the conventional alternative or even better.

Surprisingly spatial properties of the cross section of a bioretention cell showed minor influence on the retention. Most influence on the retention was achieved when altering the infiltration capacity to surrounding soils. The second most influencing was the soil layer thickness.

Parameters in the software used for catchment based modeling is easily altered to different designs. For the network based modeling there is some work to be done in order to describe present treatment mechanisms properly.

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Appendix I – Evaluation of characteristic pollutant concentrations

Reference		1 (min)	1 (max)	1 (avg)	2 (min)	2 (max)	2 (avg)	3 (min)	3 (max)	3 (avg)	4 (avg)	5 (avg)	6 (avg)	Max	Mean	Min
Pollutants	*TSS [mg/l]*	20,0000	100,0000	60,0000			150,0000	10,0000	420,0000	215,0000	152,0000	49,5000	149,1360	420,0000	129,2727	10,0000
	COD [mg/l]	100,0000	200,0000	150,0000										200,0000	150,0000	100,0000
	Pb [mg/l]	0,0300	0,1500	0,0900	0,3000	0,3000	0,3000	0,0030	0,0600	0,0315		0,0049	0,00432	0,3000	0,0861	0,0030
	Cu [mg/l]	0,0500	0,1000	0,0750	0,0300	0,0300	0,0300	0,0160	0,0980	0,0570		0,0130	0,01224	0,1000	0,0374	0,0122
	Cd [mg/l]	0,0020	0,0040	0,0030				0,0000	0,0019	0,0010				0,0040	0,0020	0,0000
	Zn [mg/l]	3,6000	3,6000	3,6000	0,1000	0,4000	0,2500	0,0500	0,7800	0,4150		0,0720		3,6000	1,0843	0,0500
	N [mg/l]							0,5000	3,2000	1,8500	1,9600	1,6800		3,2000	1,8300	0,5000
	P [mg/l]							0,0200	0,2000	0,1100	0,1800	0,1900	0,76128	0,7613	0,3103	0,0200
	Hg [mg/l]							0,0002	0,0002	0,0002				0,0002	0,0002	0,0002
	Cr [mg/l]							0,0010	0,0390	0,0200				0,0390	0,0200	0,0010
	Oil [mg/l]							0,3000	6,8000	3,5500				6,8000	3,5500	0,3000
	PAHs [mg/l]							0,0010	0,0021	0,0015				0,0021	0,0015	0,0010
	Fe [mg/l]											0,0011		0,0011	0,0011	0,0011
	NH4 [mg/l]											0,3400		0,3400	0,3400	0,3400

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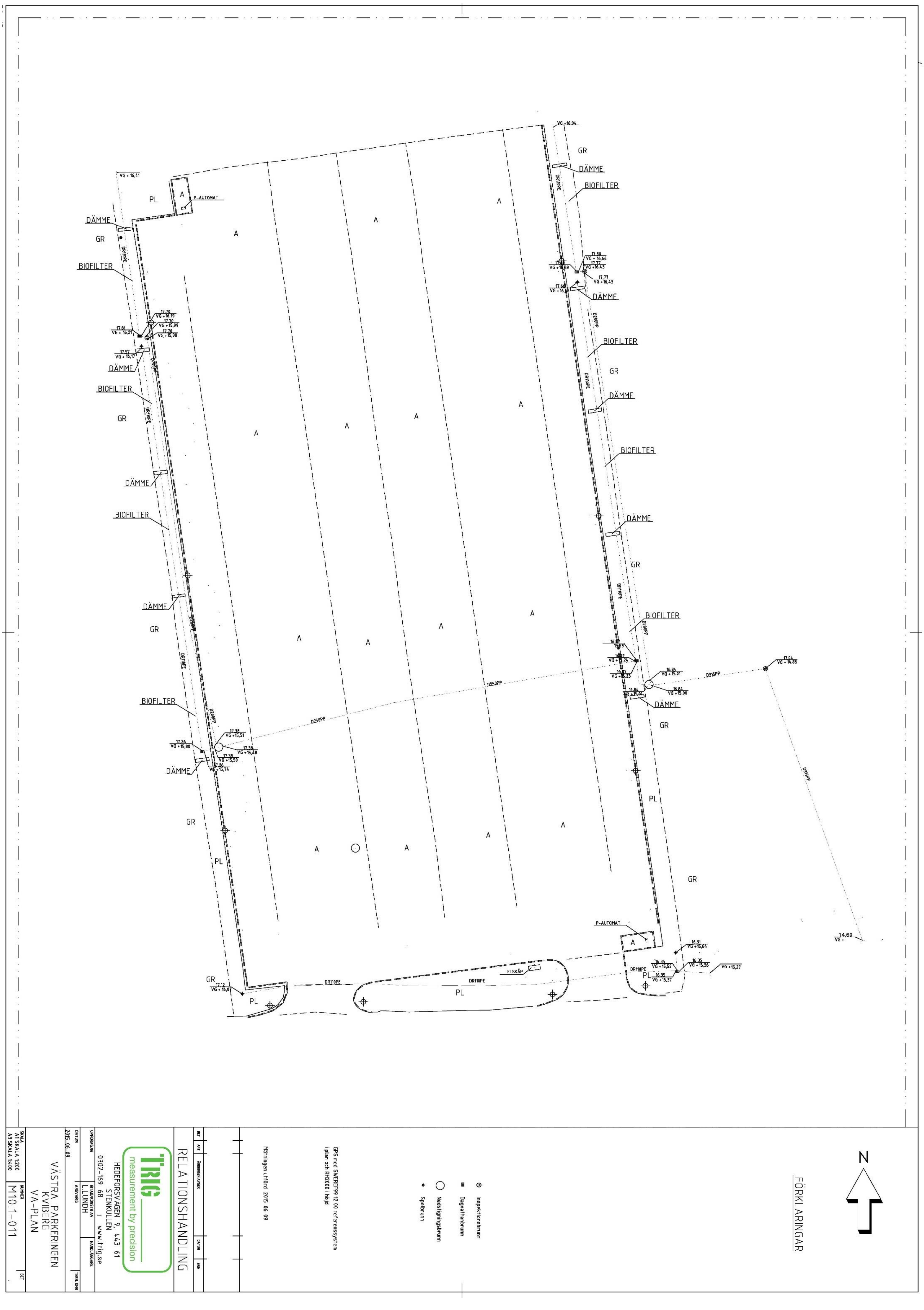
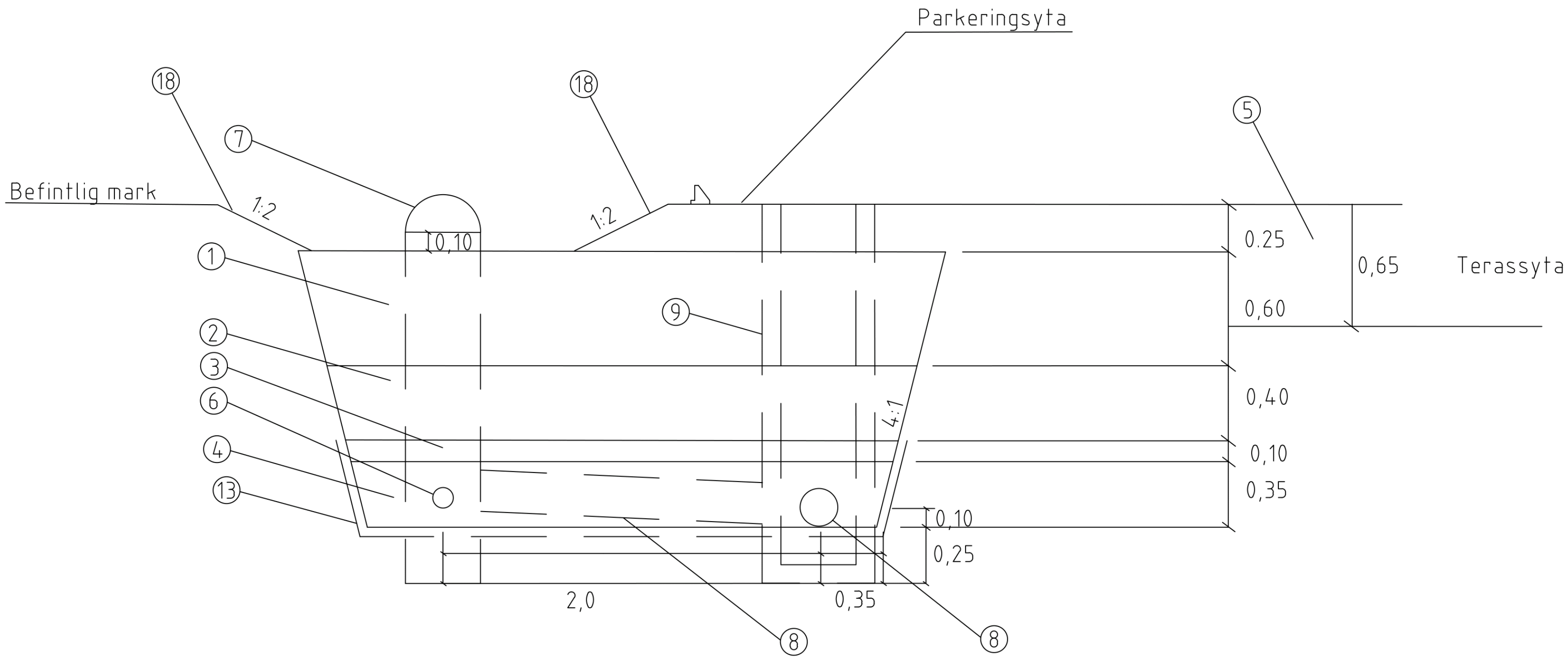
Appendix II – Kviberg raingarden design (overview)



Appendix III – Kviberg raingarden design (cross section)



Cross section of bioretention area used throughout modeling

Appendix IV – Annual accumulation of phosphorus and copper