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Performance Examination of Sustainable Urban Drainage Systems

A Multi-Criteria Analysis for the city of Gothenburg

Master's thesis in Infrastructure and Environmental Engineering

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Master's Thesis ACEX30-18-95
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Abstract

Increasing urbanization processes, together with the expected increase in the precipitation as a result of climate change, have led to the necessity of improving existing stormwater management systems to mitigate the pollution of water bodies, the emergence of health risks, and urban flooding events.

The thesis aims to study a stormwater treatment system installed in Gothenburg, Sweden, and to evaluate the expected performance of nine different Best Management Practices (BMPs) for stormwater by taking into account social, economic, and environmental aspects. The method consisted of site investigations, analysis of previous sampling campaigns, literature reviews on state-of-art urban drainage systems, and the development and implementation of a Multi-criteria analysis (MCA) to support future decision-making processes. Although the results from the sampling campaigns are inconclusive, there is substantial evidence to support the hypothesis that the treatment system currently installed does not operate appropriately. The literature review showed wide ranges of the expected performance of the BMPs, fluctuating mainly as a function of local aspects and operation and maintenance actions. Sustainable urban drainage systems must be considered as an integrated strategy, where various water treatment alternatives in a treatment train lead to proper management of runoff quality and quantity while achieving social amenity in the areas.

The MCA allowed the ranking of the different BMPs according to the preference of involved key-players: wet retention ponds, dry detention basins, swales, and green roofs are always the preferred options. The implementation of exclusion criteria, representing mainly physical or interest constraints, is an essential aspect for performing site-specific studies. Despite high uncertainties linked to the subjectivity of the method, MCA is considered an excellent pedagogical tool that allows the identification, understanding, analysis, and discussion of the different urban aspects that influence the selection of drainage system. Additionally, identification and inclusion of different actors with expertise in environmental, ecological, social, urbanistic, economic, and technical fields, leads to a lower uncertainty in the MCA results, achieving the implementation of integrated stormwater systems with environmental, economic, and social benefits.

Keywords: *Best Management Practices (BMP); Decision aiding tools; Multi-criteria analysis (MCA); Performance Evaluation; Stormwater Management; Sustainable Development; Sustainable Urban Drainage Systems (SUDS)*

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„ When I have thus got them all together in one View, I endeavour to estimate their respective Weights; (...). And tho' the Weight of Reasons cannot be taken with the Precision of Algebraic Quantities, yet when each is thus considered separately and comparatively, and the whole lies before me, I think I can judge better, and am less likely to make a rash Step; and in fact I have found great Advantage from this kind of Equation, in what may be called Moral or Prudential Algebra. "

Benjamin Franklin in a letter to Joseph Priestley
outlining a technique for decision-making.
London, September 19, 1772

1. Introduction

As a result of the globalization and the cultural and economic interconnection around the globe, the increase of the urban population has been a trend for more than 50 years (United Nations, 2015). Accompanied by the global population growth, the movement of people from rural to urban areas led to a historical milestone in 2007; the urban population exceeded for the first time the rural population on the planet. The tendency of increasing urban and suburban areas is projected to continue and, as a result, by the year 2050, 64% of the population is expected to live in urbanized regions (Figure 1). The global urbanization processes have led to significant environmental impacts around the globe, in such a way that the changes to the natural conditions and processes within urban and suburban areas are considered to be one of the most radical of any human activity (National Academy of Sciences, 2008).

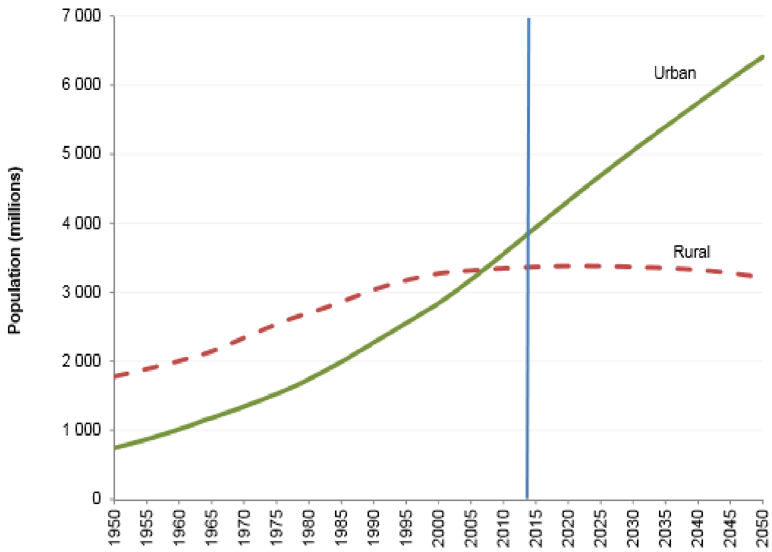

Figure 1: The world's urban and rural populations, 1950-2050. Source: (United Nations, Department of Economic and Social Affairs, Population division, 2015)

The water resulting from precipitation in an urbanized area contains pollutants which originate from the interaction between rain, air, and activities involved in the catchment area. The maximum amount of water depends exclusively on the characteristics of the storm events, but its impacts depend on different surrounding factors such as the percentage of impermeable surfaces in the catchment area and the intensity of pollutant emissions. The interaction between human activity and the natural water cycle creates the need for developing drainage systems in urban areas (Butler & Davies, 2004). Pollution of water bodies, emergence of health risks, and flooding are some of the problems associated with improperly managed wastewater. The consequences vary significantly according to the quality and quantity of the water discharged. Factors such as wealth, climate characteristics, intensity of urbanization, history, and politics are factors that determine the extent and nature of water drainage systems (Butler & Davies, 2004). Countries like Germany and the United Kingdom have more than 90% of their population connected to sewers systems, while countries such as Indonesia, due to its demographics distribution and history, usually lack proper and unified drainage systems.

The anthropogenic impact on the global climate is an increasing concern, as well as the impacts on human settlements associated with the climate change. Projections and models show a significant increase in flood risks in Central and Western Europe as a result of global warming

(Alfieri, et al., 2018; Butler & Davies, 2004). Therefore, one of the current challenges associated with drainage systems is the increase in sewer flood risks. To complement the scenario, the quality of the stormwater is of particular interest due to the environmental requirements needed to protect the receiving water bodies.

The United States Environmental Protection Agency (USEPA) released in the year 2010 a menu of Best Management Practices (BMP) for stormwater management to implement control measures directed to flooding prevention, erosion reduction, and to improve the water quality of the receiving waters (United States Environmental Protection Agency, 2018). The BMPs include structural and non-structural (managerial) practices. The selection and implementation of long-term and cost-effective drainage systems involve processes that are constrained by environmental, institutional, planning, and regulatory domains (Ellis, et al., 2004). Hence, not only drainage engineers are involved in the processes that lead to the implementation of BMPs. A wide variety of stakeholders and key-players need to be involved in these decision-making activities to achieve an adequate solution for all the interested groups. Decision-making processes require the implementation of methodologies or decision-making aids to support the decisions taken, assuring their transparency and accessible audit trail.

The present study describes the work developed on a stormwater treatment facility located in the Brottkärr area, south of the city of Gothenburg, during the first semester of the year 2018. The City of Gothenburg (Göteborg Stad), under the direction of the department Kretslopp och Vatten, aims to increase the understanding of the different stormwater solutions installed in the city regarding pollutant removal and flow control efficiency, long-term performance, lifetime costs, and receiving water impacts. This report contains critical concepts about stormwater runoff and management, as well as an analysis of the performance and the pollutant reduction potential of the installed treatment facilities. The results obtained from the in-situ analysis performed on the facilities form part of a multi-criteria analysis, where different stormwater treatment options are compared using defined criteria that include technical, environmental/ecological, social/community, and economic factors. This analysis is developed under the scope of supporting future decision-making processes that could end in the installation and proper maintenance of new sustainable treatment facilities.

2. Aims, hypothesis, and implementation

This study aims to increase the understanding of a treatment facility installed in the Brottkärr area in Gothenburg, which consists of a detention basin and a manhole filter to treat stormwater. Furthermore, with the information gathered from sampling campaigns and literature review, a multi-criteria analysis is developed to compare different treatment options and support future decision-making processes that could lead to the implementation of long-term and cost-efficient stormwater treatment options in the city. The specific objectives are to:

1. Review the local environmental policies and regulations regarding stormwater.
2. Conduct a literature study on the current state of the art of stormwater generation and stormwater management.
3. Study the hydraulic behavior of the installed detention basin and filter. Monitor the influent and effluent water quality and analyze the performance of the installations
4. Give recommendations to achieve a proper reduction of priority pollutants in the area, as well as maintenance requirements and possibilities for improvement of the stormwater system.
5. Identify the BMPs of interest that would be included in the multi-criteria analysis, considering local preferences.
6. Establish categories for BMPs evaluation that include social, environmental, economic, and technical criteria.
7. Evaluate the expected performance, based on a literature review, of the different BMPs against the defined criteria.
8. Develop a multi-criteria analysis (MCA) process that could support future decision-making processes for stormwater BMPs.

The installation of stormwater treatment options in the city of Gothenburg has been directed to comply with the environmental requirements stipulated by the Swedish Environmental Protection Agency. The efforts have been focused on mitigating the pollution in sensitive water bodies in the city, where the installation of end-of-pipe solutions is the most common practice. In some cases, the selection of treatment facilities is based on previous experience and market availability. It is hypothesized that this scenario has led to the implementation of treatment alternatives that do not always produce the desired results and entail high needs and maintenance costs (which usually are not carried out throughout the entire lifespan of the systems). Treatment options which provide social benefits, such as improving the visual environment or the possibility of public recreational activities, are generally not considered. Alternatives other than those commonly used can generate better results regarding the reduction of pollutant concentrations and water volumes, without leaving aside benefits or positive impacts on communities.

Multi-criteria analysis methods are useful tools that can be used to include social aspects, without neglecting those considered conventionally, e.g., economic and technical. The method allows evaluating the different alternatives according to the preferences of the interested parties and their individual performance, resulting in the ranking of the various treatment alternatives. The influence on the result of each aspect can be analyzed to make a decision that generates the maximum benefit to the environment and the communities.

3. Background information

The following section describes the fundamental concepts of the study, focusing on stormwater runoff, drainage systems, and decision aiding methods.

3.1 Urban stormwater generation

The hydrologic cycle is defined as the driving force that leads to the transfer of pollutants between all the environmental compartments (van der Perk, 2012). The hydrologic cycle can be summarized in four principal components, which work together as a continuum all along the environmental compartments:

1. Precipitation
2. Surface runoff and ground infiltration
3. Water bodies recharge
4. Evaporation and transpiration

The water takes different types of solutes along the cycle. Therefore, these solutes are either retained or transported from one environmental compartment to another. The input of pollutants to each of the environmental compartments highly depend on the site-specific activities and characteristics of the area of influence.

3.1.1 Precipitation

Weather is the driving force for watershed runoff and is a determinant factor in the design of stormwater treatment options (Tetra Tech, Inc., 2008). Methods that represent and predict precipitation events are crucial tools used in the design, analysis, and operation of drainage systems (Butler & Davies, 2004). Measured rain data are usually expressed as *depth* (mm) and *event duration* (minutes). The information gathered allows the derivation of different properties such as *rain intensity* (rain depth over the duration) and *frequency* (N); information which is conveniently expressed as *intensity-duration-frequency* (IDF) graphs (Figure 2). IDF relations are derived from rainfall frequency analysis for particular locations. The frequency of events is also usually expressed as *return period* (T). Rain events are classified with return periods of T years when the magnitude is exceeded on average once every T year.

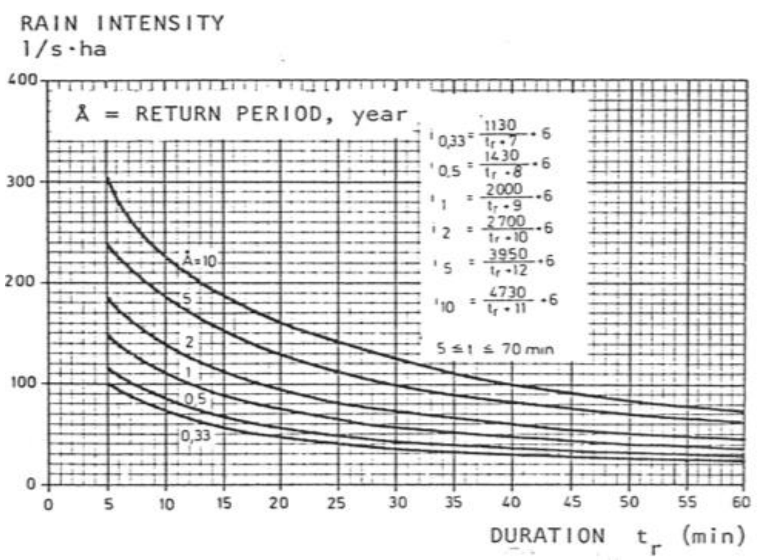

Figure 2: Example of an intensity-duration-frequency curve. Source: (Arnell, 1978)

Rainfall intensity varies throughout the storm duration. Storm profiles, or hydrographs, are used to express the rain depth variation as a function of time. Convective storms usually present the highest intensities near the beginning of the storm, while highest intensities are usually recorded near the middle of the duration in frontal storms (Butler & Davies, 2004). This information plays an essential role in design procedures. A simplification in the classification of rain events can be achieved by expressing the intensity as a function of the area in liters per second. According to the intensity, rain events can be classified into three categories (Table 1).

Table 1: Rain event classification. Adapted from: (Steinmetz & Krampe, 2009)

Rain event Clasification	Intensity
Weak	< 7 l/(s*ha)
Moderate	7-21 l/(s*ha)
Strong	> 21 l/(s*ha)

The rain event information required for engineering tasks depends on the objectives. As an example, the information used for calculating maximum flows rates in storm sewers is of interest for design and planning procedures. Table 2 exemplifies data requirements for different engineering tasks.

Table 2: Requirements for rainfall data in different applications of urban drainage. Source: (Butler & Davies, 2004)

Engineering task	*Rainfall record duration (yrs)*	*Rain gauge location (relative to catchment)*	*Temporal resolution (min)*	*Spatial resolution (km^2/gauge)*	*Synchronisation error (min)*
Design/planning					
Sewers	>10	near vicinity	block rain	homogeneous	≤30
CSO volumes	>5	near vicinity	≤15	homogeneous	≤30
Checking/evaluation					
Sewers	>20	adjacent	1	homogeneous	≤10
CSO volumes	>10	adjacent	5	≤5	≤5
Analysis/operation					
Calibration/ verification	several events	within	2	2*	0.25
Real-time control	on-line	within	2	2*	0.25

* No less than 3 in total

3.1.2 Global Climate Change

The Intergovernmental Panel on Climate Change (IPCC) has reported the global impacts on precipitation associated with climate change. Data-sets presented in the Fifth Assessment Reports, developed by IPCC, show an increase in the global average precipitation (Hartmann, et al., 2013). In addition to these findings, the observed trends show a spatial variability around the globe. Significant increases were reported for eastern and northwestern North America, Europe (except Spain and the Mediterranean coast), Russia, South America, and Australia; while declines in precipitation were reported for Africa and different (relatively small) scattered regions around the globe (Figure 3).

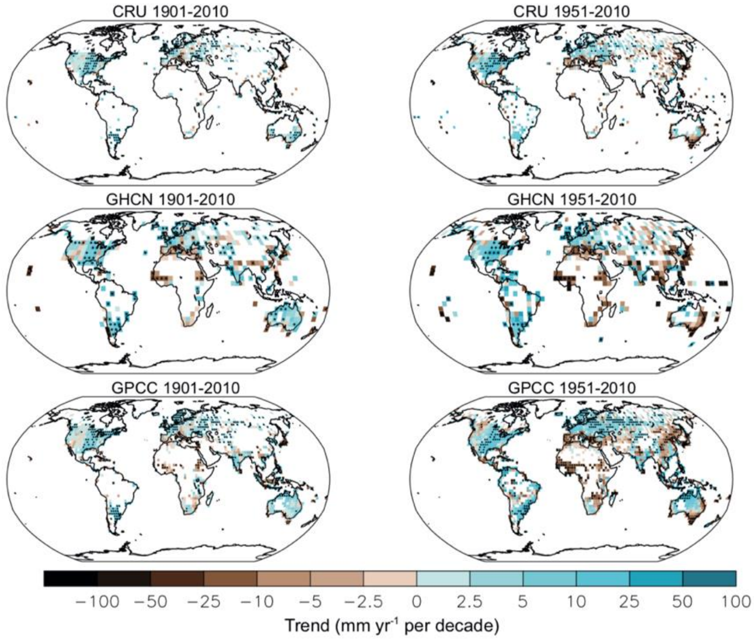

Figure 3: Trends in annual precipitation for 1901-2010 (left) and 1951-2010 (right) Based on the data sets from the Climate Research Unit (CRU), Global Historical Climatology Network (GHCN), and Global Precipitation Climatology Center (GPCC). White areas represent incomplete or missing data. Source: (Hartmann, et al., 2013)

3.1.3 Climate change effects in Sweden and Gothenburg

Research results and climate models show that a rain event with a return period of 10 years could happen twice as often in the future in Sweden (SMHI, 2012). The results of climate models for the years 2021-2050 and 2069-2098 in the Västra Götaland region show a 10-30% increase (Figure 4) of annual precipitation at the end of the century with regards to the reference period (1961-1990) (SMHI, 2011). The spatial distribution of the precipitation along the region shows a higher increase along the coastal areas of the region, where the city of Gothenburg is located (Figure 5). Heavy rain frequency, expressed as rain events with a precipitation above 10 mm per day, is also expected to increase in the region in the studied periods.

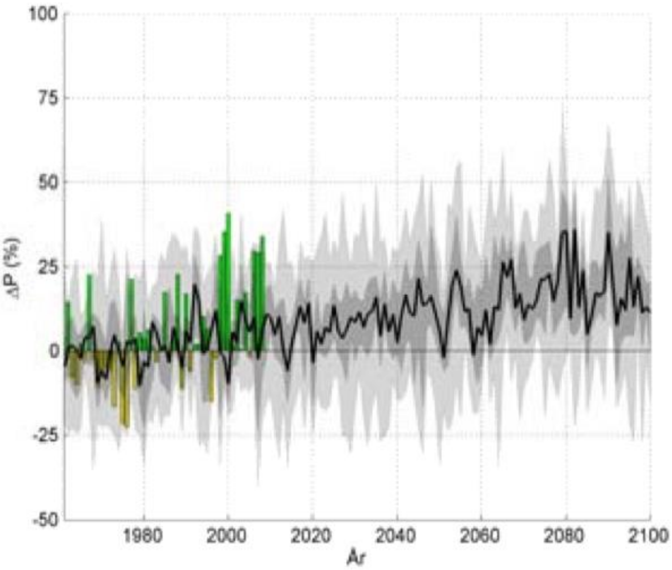

Figure 4: Estimated increase of the annual precipitation in Västra Götaland region. Black lines represent mean values. Shaded areas represent maximum and minimum value, as well as 75, and 25 percentiles of the climate estimations. Observed values are expressed as green (higher values) or yellow (lower values) columns when comparing to the average values of the reference period. Source: (SMHI, 2011)

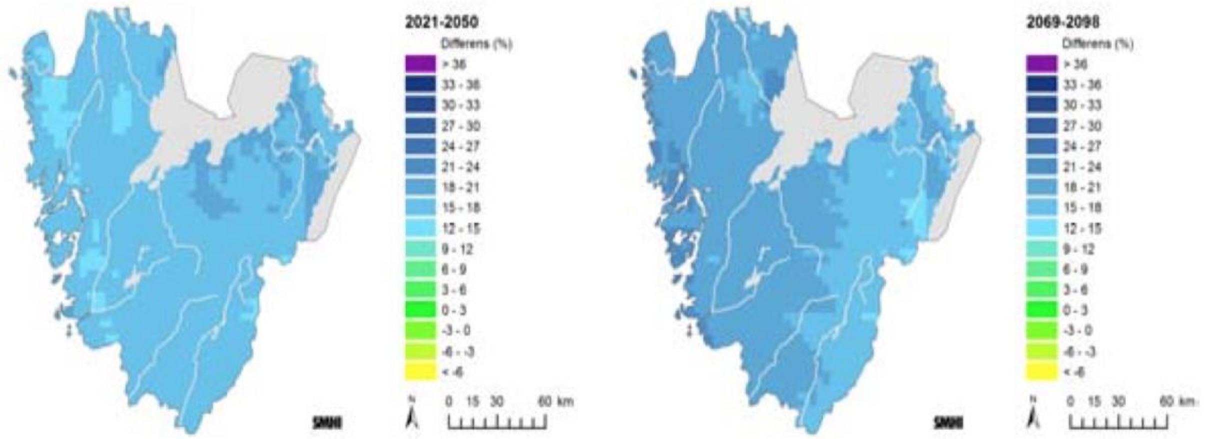

Figure 5: Spatial distribution of the precipitation in the Västra Götaland region. The graphs show the differences between the observed precipitation during the period 1961-1990 and the model results for the periods 2021-2050 (left) and 2069-2098 (right). Source: (SMHI, 2011)

Furthermore, the models and research on climate change effects in the region show results such as (Bergqvist, 2014; SMHI, 2011):

- A total increase in 4º C at the end of the century with respect to the mean temperature recorded during the period of reference. High seasonal temperature variations will lead to shorter winters.

- A total increase of around 5-10% in groundwater levels (present in coarse grain soils) at the end of the century with respects to the reference period.
- A decrease in the snow periods that could result in a maximum of 15 days per year of snow at the end of the century.
- An increase in precipitation during the winters and higher evapotranspiration during summer will lead to high seasonal variations on the flow along the water bodies in the region. Overall, a 10% increase in the water flow is predicted to occur at the end of the century in all the water bodies of the region.

The increase in precipitation and rain intensity predicted for Europe will lead to an increased risk of flooding, which is the most frequent natural disaster in the region (IPCC, 2012). The economic losses linked to flood hazards have increased in the previous decades. These predictions are of particular interest within urban drainage. The implications of such predictions are also associated to (Butler & Davies, 2004):

- Surface flooding and deterioration of the drainage systems due to the increase of the flows (which can exceed the design capacity).
- Greater mobilization of pollutants that leads to impaired receiving water quality.
- Increased flows of diluted wastewater arriving at the wastewater treatment plants, which leads to a lower efficiency in biological treatments.

The high cost of renovating and implementing significant upgrades to the existent sewer networks makes it an improbable line of action. Therefore, different alternatives such as the Sustainable Urban Drainage Systems (SUDS) have been developed to complement already existing sewer networks, leading to new perspectives in the stormwater management field.

3.1.4 Runoff generation

Urbanization and agricultural processes lead to alterations of the natural environment. The changes in the characteristics of the terrain impacts, in a significant way, the behavior of the water in the altered areas. Besides, impervious surfaces have been recognized as an intensity indicator of the urban environment, becoming an important issue that determines the habitat health (Brabec, et al., 2002). The increase of artificial surfaces, constituting mostly of low permeability materials in urbanized areas, is the primary factor by which the runoff generation is increased (Figure 6).

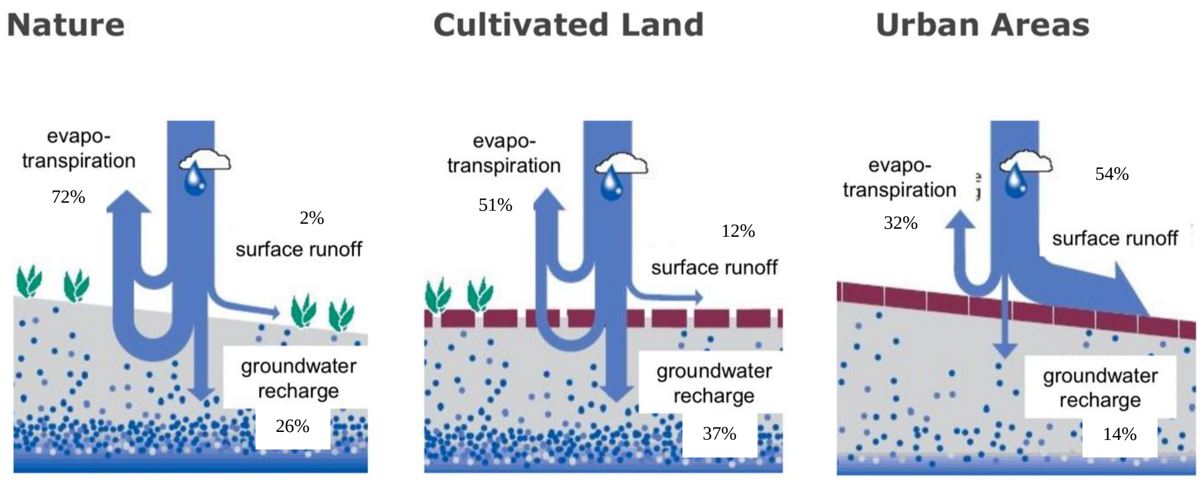

Figure 6: Effects on stormwater behavior due to urbanization. Adapted from: (Dittmer, 2017)

The behavior of water in urbanized areas varies as a function of rain duration, rain intensity, and characteristics of the catchment area. Although higher imperviousness leads to decreased infiltration and higher runoff, not all the water that reaches the ground transforms into runoff water (Dittmer, 2017). Water loss processes such as wetting of surfaces, infiltration, evapotranspiration, and depression storage occur before runoff generation (Figure 7). However, higher rain volume results in higher percentage of runoff.

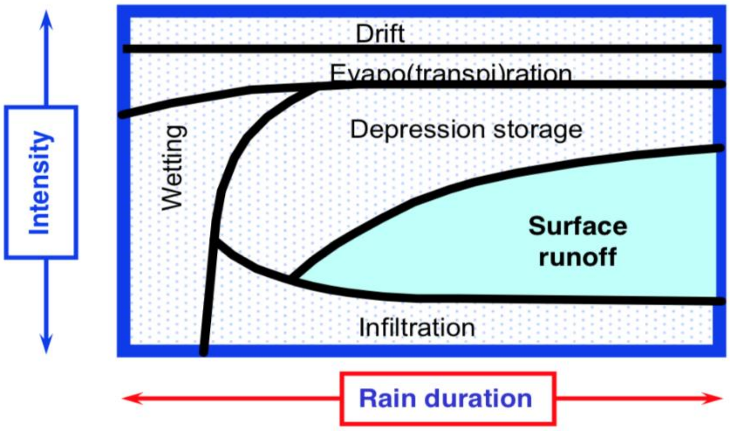

Figure 7: Runoff generation. Source: (Dittmer, 2017)

The remaining volume of water is directed along the artificial ground surface through a process named surface routing (Figure 8). The relationship between rainfall characteristics and surface runoff is called the runoff coefficient. Surface runoff travels faster over impermeable areas than over natural surfaces. For the dimension of sewer systems and storage structures, the peak runoff and mean runoff concepts are of particular interest. Flow peaks and flow volume can increase by a factor of 2 to 10 due to urbanization processes (Hammer, 1972).

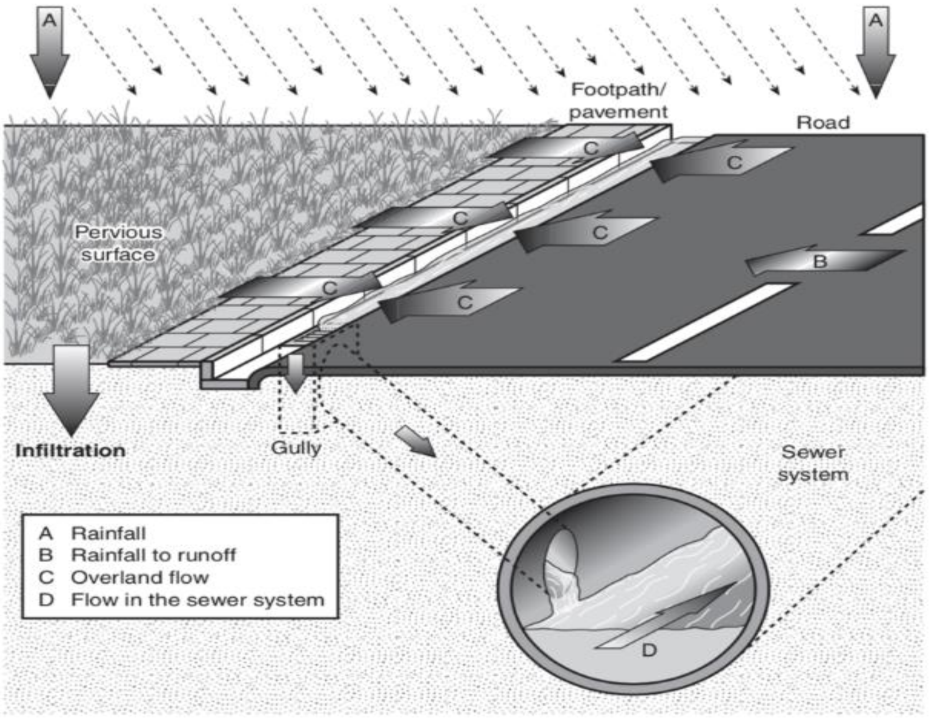

Figure 8: Stormwater runoff generation processes. Source: (Butler & Davies, 2004)

3.2 Stormwater pollutants

Stormwater contains a mixture of contaminants that range from natural organic and inorganic pollutants to anthropogenic substances derived from transport, commercial, and industrial activities (Butler & Davies, 2004). Diffuse spills of contaminants, air-borne pollution, and substances produced by traffic and construction, are the main sources of pollutants in urban runoff (Hvitved-Jacobsen, et al., 2010).

The diffuse characteristics of stormwater pollution imply a high complexity regarding water management and control. Identification of the numerous dispersed stationary and mobile sources is the main reason for this complexity. Due to the high intensity of emissions in urbanized areas, the occurrence of pollution is assumed as a continuous at the urban surfaces (Hvitved-Jacobsen, et al., 2010). Dry periods lead to the accumulation of pollutants, which is a function of the intensity of activities performed in the catchment area and their extension. The identification of illegal water discharges and activities (such as spills, leaks from industrial activities, and accidents) is essential to assess stormwater pollution in an area. Hvitved-Jacobsen et al. (2010) suggest a systematic framework to assess and predict stormwater pollution problems. The procedure is based on pollutant pathways, and it is described as follows:

- Assessment of the catchment area characteristics and identification of the nonpoint diffuse pollutant sources.
- Identification of relevant pollutants regarding impacts, quantity, and occurrence.
- Identification of the pollutant’s pathways, which include transportation and transformation.
- Determination of the pollutant loads.
- Determination of the potential effects.

It is essential to recall the role that plays the characteristics of the catchment area in terms of generation, transport, transformation, and retention of pollutants. Table 3 summarizes the parameters of interest in urban runoff and describes examples of their sources in urbanized areas, typical concentrations in stormwater runoff, and the potential impacts on the aquatic environment. The pollutants concentrations in water runoff varies with regards to the contact surface. Table 4 shows ranges of pollutants reported on rainwater, roof, and low/high-density traffic areas runoff. Detailed information on the specific pollutants is explained in the following subsections.

Table 3: Parameters commonly analyzed in urban runoff, their sources in urban areas and potential effects on receiving waters. Source: (Göteborg Stad, 2017; Björklund, 2011; United States Environmental Protection Agency, 1999)

Pollutants	Examples of compounds	Typical concentrations	Examples of sources	Examples of impacts
Solids	Total Suspended Solids	20-2,890 mg/l	Erosion related to the different types of anthropogenic and natural activities that occur in the catchment area. Corrosion of surfaces and vehicles.	Increase in the turbidity of the water, which affects aquatic life. Suspended solids promote the storage and transport of contaminants such as metals.
Biochemical organic matter	BOD COD	200-275 mg COD/l	Animal feaces and plant decay.	Decrease in levels of dissolved oxygen that can lead to anoxic conditions in the receiving water bodies.
Nutrients	Nitrogen (TKN, NOx, org.- N) Phosphorus (TP, soluble-P)	0.4-20 mg TN/l 0.02-4.30 mg TP/l	Degradation of organic material resulting from plant, animal, and human waste. Use of fertilizers. Combined sewer systems overflow. Atmospheric deposition.	Eutrophication enhancement that leads to excessive plant growth, leading to a decrease in the dissolved oxygen of water bodies.
Metals	Cu, Zn, Hg, Cd, Pb, Ni, Cr	Dependant on the element, species, occurrence, and fate. See Table 4	Corrosion and wear of vehicles and roads. Corrosion of building material. Atmospheric deposition link to industrial emissions.	Increase in the toxicity of water bodies affecting aquatic life.
Organic compounds	PAHs PCBs	Dependant on the species, occurrence, and fate. See Table 4	PAH´s: Combustion of organic materials related to vehicle emissions, oil, wood, and waste incineration. PCB´s: e.g. insulating materials, flame retardants, building materials.	Increase in the toxicity of water bodies affecting aquatic. Some Organic compounds are classified as carcinogenic, mutagenic, and teratogenic.
Pathogens and virus	Total Coliforms	400-5,000 Fecal Coliforms/ 100 ml	Animal and human feaces.	Exposure of aquatic life to diseases. High impacts on human concerns that limit the activities developed in the water bodies.

Table 4: Value ranges of pollutant concentrations from rainwater, roofs runoff, low/high-density traffic areas. Source: (Göbel, et al., 2007)

Pollutants	Example of compounds	Rain water	Roofs	Low density traffic areas	High density traffic areas
Solids	Total Suspended Solids	0.2-52 mg/l	13-120 mg/l	74 mg/l	66-937 mg/l
Biochemical organic matter	BOD	1-2 mg BOD5/l	4-16.1 mg BOD5/l	-	2-36 mg BOD5/l
	COD	5-55 mg COD/l			63-146 mg COD/l
Nutrients	Nitrogen(TKN, NOx, org.- N)	0.01-0.19mg Ptotal/l	0.06-0.5 mg Ptotal/l	-	0.23-0.34 mg Ptotal/l
	Phosphorus (TP, soluble-P)	0.1-2 mg NH4/l	0.1-6.2 mg NH4/l		0.5-2.3 mg NH4/l
		0-7.4 mg NO3/l	0-4.7 mg NO3/l		0-16.0 mg NO3/l
Metals	Cd	0.01-3.9 µg Cd/l	0.02-1.0 µg Cd/l	0.02-0.5 µg Cd/l	0.3-13.0 µg Cd/l
	Zn	0.5-235 µg Zn/l	24-4880 µg Zn/l	15-1420 µg Zn/l	120-2000 µg Zn/l
	Cu	1-355 µg Cu/l	6-3416 µg Cu/l	21-140 µg Cu/l	97-104 µg Cu/l
	Pb	2-76 µg Pb/l	2-493 µg Pb/l	98-170 µg Pb/l	11-525 µg Pb/l
	Ni	1-14 µg Ni/l	2-7 µg Ni/l		4-70 µg Ni/l
	Cr	2-8 µg Cr/l	2-6 µg Cr/l		6-50 µg Cr/l
Organic compounds	PAH	0.04 - 0.76 µg PAH /l	0.35 - 0.6 µg PAH /l	-	0.24-17.1 µg PAH /l
Main ions	Na, Mg, Ca, K, SO4, Cl	0.22-20.0 mg Na /l	1-1900 mg Ca /l	-	5.0-474.0 mg Na /l
		0.03-0.33 mg Mg /l			1-1.4 mg Mg /l
		1.1-67.13 mg Ca /l			13.7-57.0 mg Ca /l
		0.46-0.65 mg Mg /l			1.7-3.8 mg Mg /l
		0.56-14.4 mg SO4 /l			5.1-139 mg SO4 /l
		0.2-5.2 mg Cl /l			3.9-669.0 mg Cl /l

3.2.1 Pollutant sources and transport

The primary pollutant sources in a catchment area include vehicle emissions, corrosion and abrasion; building and road corrosion and erosion; animal feces; street litter deposition; biodegradable matter such as fallen leaves and grass residues; and spills (Butler & Davies, 2004; Brown & Peake, 2006). Additionally, atmospheric pollution resulting from activities such as heating, industry and waste incineration, and vehicular traffic contribute to atmospheric fallout. Pollutants from these sources can be transported by wind, settle, or be absorbed and dissolved by precipitation. In Gothenburg, the dilution of atmospheric pollutants by precipitation is the dominant source of N, P, Pb, Zn, and Cd (Butler & Davies, 2004). Vehicles emit volatile solids and polycyclic aromatic hydrocarbons (PAHs) resulting from the combustion of fuels and lubricants. Also, wear of vehicle components leads to emissions of hydrocarbons and heavy metals. Erosion from the urban environment, which includes but is not limited to roads and buildings, produce particles of brick, concrete, and glass, which constitute, together with urban debris, the suspended solids' fraction in the water. Corrosion of metallic surfaces releases toxic elements such as Cr, Zn, and Cu; de-icing procedures lead to the increase in the annual chloride loads in stormwater. Also, sodium chloride enhances pollutant emissions due to the acceleration of corrosion of vehicles and metal structures.

The flow of pollutants highly depends on the urban area and rain event characteristics (Hartmann, et al., 2013). Different methods are used to express the pollutant concentration in stormwater, where the *event mean concentration*, a simplified method that assumes a constant level of pollutants in the stormwater for each rain event, is defined as the most straightforward method. A drawback is the lack of information regarding water quality variations throughout the length of the rain event. Therefore, this method is only used when the total pollutant load is required.

Study of pollutants build-up and wash off is a common method to predict the stormwater quality. Factors such as land use, population, traffic flow, street cleaning, seasonal variations, meteorological conditions, dry periods, and surface types are used to estimate the build-up processes of pollutants (Butler & Davies, 2004). Further, wash off processes are influenced by rainfall characteristics, topography, solid particle characteristics, and street surface type. Mathematical approaches are used to assess the accumulation and wash off of pollutants. The reported concentrations of pollutants present a high variability as a result of the factors previously exposed. The stormwater quality can vary by a factor of 10 between "clean" and "dirty" catchment areas, while quality variations by a factor of 3 have been reported between single events in a single defined catchment area (Ellis, 1986).

The initial portion of a rain-event runoff, called the first flush, is assumed to be more polluted than the later portions (Hathaway, et al., 2012). Different methods are used to assess the first flush of pollutants. For example, threshold methodologies are used to define the first flush effect by comparing the fraction of total pollution transported in a segment of the total runoff volume. However, the accuracy of the first flush term and its influencing factors are not entirely understood. Some authors have defined the first flush as a function of the intensity of a rain event and the percentage of impervious zones in the catchment area (Lee & Bang, 2000). Other authors have not found any relation between the pollutant load distribution and rainfall and catchment area characteristics (Saget, et al., 1996).

3.2.2 Impacts of stormwater

The stormwater impacts on an area can be defined by hydrologic, chemical, biological, or physical processes (Erickson, et al., 2013). The impacts of stormwater pollutants on water bodies can be divided into acute and accumulative effects (Hvitved-Jacobsen, et al., 2010). Bacterial contamination, high concentrations of soluble substances, and solids that cause turbidity conditions are examples of acute toxic effects which result from pollutant discharges after storm events (Pettersson, 1999). The variability of the pollutant loads between events plays a vital role in the chemical and physical processes that occur in water bodies, particularly in extreme events where higher runoff is achieved. On the other hand, cumulative effects, such as eutrophication due to the over-discharge of nutrients, occur in relative long-terms (Figure 9). The spatial and temporal effects on receiving water bodies are shown in Appendix 1.

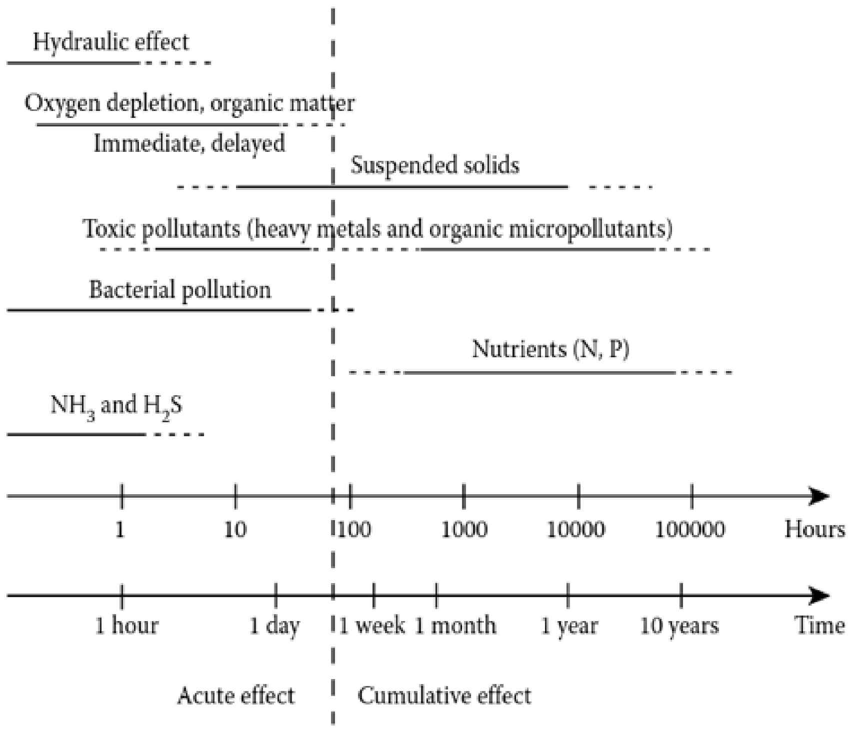

Figure 9: Timescale effects of intermittent pollutant discharges. Source: (Hvltved-Jacobsen, et al., 1994)

3.2.3 Frequently occurring pollutants in stormwater

The pollutants relevant in urban stormwater include dissolved and suspended solids, biodegradable organic matter (oxygen-consuming materials), nutrients, heavy metals, organic compounds, and pathogenic microorganisms (Butler & Davies, 2004; Hvitved-Jacobsen, et al., 2010).

3.2.3.1 Suspended solids

Suspended solids follow complex processes that characterize its movement throughout the system (Butler & Davies, 2004). Physical processes include particle degradation, agglomeration, and flocculation; while chemical and biochemical processes include dissolution, hydrolysis, precipitation, and biological oxidation. Every particulate-generating activity in the catchment area is identified as a source of pollution.

Sediments settle on surfaces and are transported by overland flow to the urban drainage system, where they are intended to be captured in gully pots before their entrance to the piped system. Transport of solids in the drainage systems depends on the physical and chemical characteristics of the solids, characteristics of the flow, and characteristics of the drainage systems (Butler & Davies, 2004). Small particles with low density can remain in suspension along the entire system under normal flow conditions. On the other hand, larger or denser particles settle forming sediments, which can be re-suspended due to high flows. Different settling points can be identified along the entire system. Therefore, sediment removal can be achieved by different actions such as street sweeping, gully pot implementation, sewer cleaning, and grit removal in the water treatment plant.

3.2.3.2 Biodegradable organic matter

The biodegradable organic matter is of particular interest due to the rapid consumption of dissolved oxygen that can affect the survival of aquatic species and performance of the drainage system. Biological oxygen demand (BOD) and chemical oxygen demand (COD) are the most common parameters used to express the organic matter. As mentioned previously, BOD concentrations in domestic sewage effluents are higher than in urban stormwater runoff. The BOD concentrations in stormwater runoff are linked primarily to plant decaying material and animal waste generated in the catchment area (Hvitved-Jacobsen, et al., 2010; Erickson, et al., 2013).

3.2.3.3 Nutrients

Nutrients are assimilated by living organisms to promote their growth and development (van der Perk, 2012). The type and amounts required for the adequate development of the biota depend on each organism, but in general, nutrients include proteins, carbohydrates, fats, minerals, among other components. The term nutrient is used to refer specifically to N and P. These elements make up the group of primary macronutrients required by plants.

Nutrients undergo relative rapid cycling (van der Perk, 2012). Physical and chemical processes determine the transfer of nutrients from organism to organism, which is achieved under natural conditions along trophic levels by predation. Organic matter is then taken up by decomposing bacteria, leading to the mineralization of nutrients. Pollutant emissions in the atmosphere, the use of fertilizers, and human wastes enhance the loads of nutrients in the different environmental compartments. The hydrologic cycle helps in the transport of nutrients, leading to an enhancement in certain areas. This process is also referred as eutrophication. Oligotrophic, mesotrophic, and eutrophic ecosystems are defined based on their degree of eutrophication. Eutrophic ecosystems have high productivity of biomass which, in water environments, lead to significant variations of dissolved oxygen due to an increase in phytoplankton, weed, and aquatic macrophytes that lead to oxygen depletion and public health drawbacks (van der Perk, 2012).

3.2.3.4 Metals

Metals are naturally present in the earth´s crust. As a result, they can cause natural contamination of water bodies. Despite the existence of some specific and unique cases around the globe, high concentrations of heavy metals are linked mostly to anthropogenic activity. Due to their high availability and potential toxicity, the main groups of heavy metals linked to urban drainage are Cu, Pb, Zn, Cd, Ni, and Cr (Butler & Davies, 2004; van der Perk, 2012; Björklund, 2011). The main problem associated with metals is the bioaccumulation of these non-degradable inorganic substances in the environment and organisms, and the transfer of them through the trophic levels in the food chains. The toxicity of metals occurs in the organisms due to their interaction with organic compounds. This interaction causes the death of the cells. Considering criteria like frequency of occurrence in the environment, linked to toxicity and therefore exposure to human lives, heavy metals are ranked as the most hazardous substance in the environment (Xue, et al., 2017). Different geochemical processes affect the retention of heavy metals in the environment or organisms (bioavailability), and therefore, their toxicity. Metals can occur in soluble state, attached to particles, or in different oxidation numbers. Their toxicity, fate, and transport highly depend on the speciation (Wuana & Okieimen, 2011). The procedures established for their removal highly depended on the same factor. The attachment of metals to suspended solids is of interest. Adsorption causes the heavy metals to attach to different compounds (e.g., organic compounds, suspended solids, clay minerals), which depending on various factors precipitate and form fixed sediment. The adsorption, as well as the complexation and precipitation of heavy metals, highly depends on the pH of the water.

3.2.3.5 Organic compounds

Organic compounds are present in stormwater in particulate and soluble states. These pollutants include a variety of compounds which are mostly constituted from C, O, and H, and can contain small amounts of N, P, S, and other chemical elements (van der Perk, 2012). The carbon structure determines the substance´s physicochemical properties, which affect the fate and persistence in the environment. Many organic compounds present an inherent resistance to biotic and abiotic degradation (Björklund, 2011). Some organic pollutants bioaccumulate in the environment and bio magnify in the organisms throughout the trophic levels, causing harmful effects on the ecosystems and organisms due to their toxicity (cancer, allergies, and disruption of the immune system are examples of the impacts on the health of organisms). Depletion of dissolved oxygen in water bodies is another effect of such compounds. The different organic compounds are usually classified as a function of their defined properties (e.g., Volatile Organic Compounds or VOCs), but also as a function of their sources and use (e.g., petroleum products and pesticides, respectively). PAHs, chlorinated hydrocarbons, and petroleum derivates are particularly important for water contamination. Although organic compounds occur under natural conditions, most of them are human-made and industrially produced. Human exposure to organic compounds is mainly achieved by ingestion of different products exposed to contaminated water and the inhalation of contaminated air (World Health Organization, 2018).

3.3 Stormwater management

The development of an urban area has a profound impact on the water behavior. Impermeable surfaces lead to a faster movement of the water when compared to natural surfaces and can lead to flooding and increased pollution (Butler & Davies, 2004). Natural and piped systems make up the first distinction between drainage systems. Mitigation of impacts on piped systems relies on the so-called “end of pipe solutions”, while the use of natural drainage mechanisms is defined by the term “Best Management Practices (BMPs) or “Sustainable Urban Drainage Systems” (SUDS).

3.3.1 Traditional Approach

Wastewater and stormwater are the main types of flows that an urban drainage system handles. The term sewerage includes all the elements of the system, e.g., pipes, manholes structures, pumping stations.

Combined sewer systems transport wastewater together with stormwater in the same piped systems, leading it to end of pipe solutions such as wastewater treatment plants. Under dry weather conditions, the system carries mainly domestic and industrial wastewater. During rainfall events, the flow increases, up to fifty to hundred times, due stormwater drainage (Butler & Davies, 2004). Usually, due to economic aspects, the drainage systems and treatment plants are not designed to handle the massive flows resulting from rain events throughout the entire network. Therefore, the flows exceeding a certain level are diverted from the sewer system and discharged directly into water bodies. The structures that handle and divert these exceeding flows are called Combined Sewer Overflows (CSO). These structures are intended to retain the first flush of pollutants during a rain event and direct it to the wastewater treatment plant. The exceeding flow, containing a considerable amount of pollutants but assumed to be a highly diluted mixture of storm- and wastewater, is then discharged to a receiving water body.

Separate systems consist of a parallel piped system which transport storm- and wastewater separately. The main advantage of this system is the avoidance of CSOs. On the contrary, the main disadvantages consist of higher costs of installation and the discharge of stormwater without treatment. Figure 10 outlines the combined and separate sewer systems separately, emphasizing in the water sources and the interaction with urban elements in the catchment area. The advantages and disadvantages of both systems are described in Appendix 2.

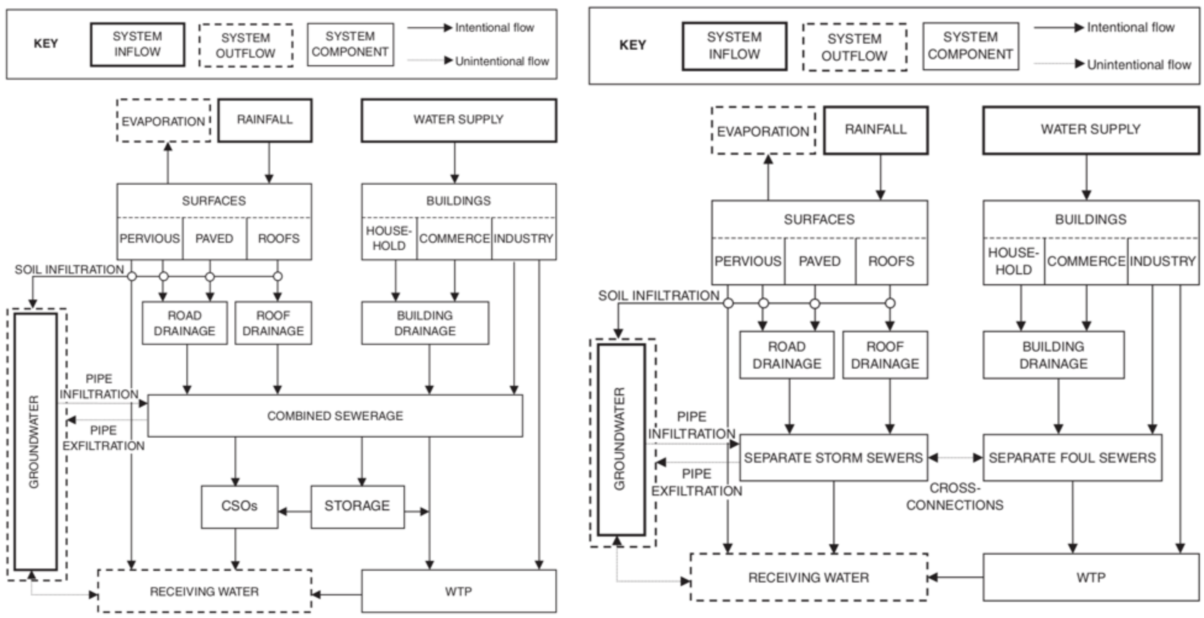

Figure 10: Urban water systems: Combined (left), Separate (right). Source: (Butler & Davies, 2004)

Problems such as discharge of untreated wastewater through CSOs lead to the need of improved runoff management. An increase in the transport capacity of the sewers cannot always be achieved, due to the high costs related to the modifications of the existing infrastructure.

3.3.2 Sustainability in Urban Drainage Systems

Reducing the hydraulic load on the drainage system is an alternative to increase the transport capacity of the system (Stahre, 2006). Various methods of local water detention have been studied and proposed to handle the water before it is incorporated into the conventional drainage system. These methods are named Best Management Practices (BMPs) and correspond to less cost-intensive measures when compared to modifications in the entire drainage system. The BMPs aim to achieve a transition from the traditional approach by handling the quantity and the quality of water while including social aspects involved in the urban water drainage (Figure 11). Other labels, such as SUDS, "Low Impact Development" (LID), "integrated catchment planning," "Green infrastructure", and "ecological stormwater management" are used around the world to express the same line of action.

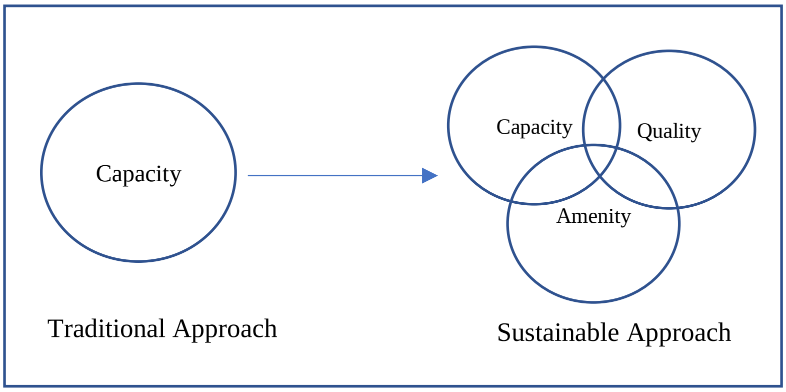

Figure 11: Urban drainage transition concept. Adapted from: (Stahre, 2006)

The official definition of BMPs consists of four elements listed below (Rossmiller, 2014):

1. Structural, physical, or managerial practices (e.g., activity schedules, prohibition of practices, maintenance schemes) directed to the prevention and reduction of water pollution.
2. Structural systems, activities, procedures, practices, and methods, which aim to control site runoff and the emission of contaminants and spillage (or leaks) of substances, sludge, or waste.
3. Programs, technologies, processes, measures, or devices that assist with the control, prevention, removal, or reduction of pollution.
4. BMPs are classified into two major categories: source or treatment controls. Source controls practices consist mostly of operational practices that aim to prevent contamination at the point of emission, by decreasing pollutants avoiding their interaction with stormwater. On the other hand, Treatment controls refer to methods for water treatment that aim to remove pollutants already present in stormwater.

To achieve sustainable urban drainage systems, the involvement of different stakeholders is of vital importance. The principal stakeholders include decision-making, technical, and social parties. New planning dimensions have been achieved with regards to urban drainage, resulting in the integration of drainage facilities into the urban landscape by considering values such as:

- Economic
- Aesthetic
- Recreational
- Cultural
- Historic
- Educational
- Environmental
- Ecological
- Biological

3.3.3 Sustainable drainage and treatment options

Sustainable urban drainage infrastructure should have the ability to handle stormwater safely and to guarantee the proper operation of the systems without stressing resources, environment, and public health (Upadhyaya, 2013). The processes by which BMPs work are sedimentation, filtration, sorption, plant uptake, infiltration, percolation, surface runoff, slow water drainage and detention, volatilization, and microbial degradation (Horner, 1995). The BMPs can be categorized with regards to their location throughout the urban water path: inlet and source control, site control, and regional control (Stahre, 2006). The installation of the different devices and treatment facilities is recommended based on the stage of the surface water management train (Figure 12). Despite the fact that the use of different BMPs throughout the entire water paths leads to better results, it is not always achievable. Therefore, the drainage solutions must aim to the upper part of the management train, and when the drainage needs cannot be achieved in that particular stage, the designers must move forward down in the line of action (Butler & Davies, 2004).

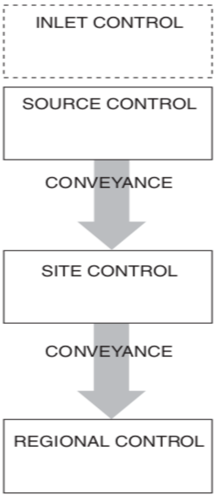

Figure 12: Surface water management train.
Source: (Butler & Davies, 2004)

It is important to recall that the distribution of precipitation events plays an essential role in the long-term hydraulic and pollution removal performance of BMPs (Tetra Tech, Inc., 2008). BMPs usually perform more efficiently for small rain events because they operate below their hydraulic design capacity. Even though two locations have the similar annual average precipitations, BMPs placed in a location with smaller but more frequent storm events will have a best long-term cumulative performance than the one located in an area with mostly large events. Frequency analysis of rain events is crucial to understand the reduction potential of BMPs.

Specific alternatives for stormwater management and reduction of pollutants chosen for the study are described below, and additional information including expected performance with regards to technical, social, economic and environmental aspects is discussed in Section 6.2 and summarized in Appendix 6:

3.3.3.1 Green roofs

Green roofs may reduce the amount of water while retaining pollutants. Green roofs consist of layered structures which include vegetation, soil and substrate, and various type of materials that allow the proper and desired water drainage (Figure 13). The components vary according to the different roofs types, and specific location constraints (Woods-Ballard, et al., 2015).

By increasing the permeable zones in a catchment area, light rainfall can be entirely absorbed by the vegetation cover, leading to no generation of runoff. The hydraulic performance of a green roof highly depends on factors such as the antecedent soil moisture in the system (Woods-Ballard, et al., 2015). Studies in Sweden have shown that the yearly runoff volume can be reduced by half with the use of green roofs (Stahre, 2006). Studies have also reported reductions on the peak sewer flows ranging between 30-40% (Maskell & Sherriff, 1992). The soil type and grass species are the two main factors on which the performance of green roofs rely on (Rossmiller, 2014).

Through physical, biological, and chemical processes, pollutants in the rainwater are retained in green roof structures. The pollutant retention potential highly depends on the vegetation and materials used, as well as on the maintenance of the system. Problems might occur when owners over-fertilize the green roofs, introducing nutrients into the system. Another benefit of green roofs is reduced energy consumption linked to the improvement of the thermal performance of buildings. Green roofs provide a highly valuable amenity. In addition to the aesthetic value of this system, they also bring significant ecological value due to the enhancement of urban biodiversity.

Despite the fact that green roofs are designed for minimal maintenance, the monitoring and maintenance requirements are usually high. These systems required maintenance related to mowing, litter removal, plant replacement and removal (invasive vegetation), and leakage maintenance. Additionally, fire hazards are also present in this type of SUDs. Therefore, fire retardant materials need to be considered in the design processes and the proper maintenance of monitoring (Jotte, et al., 2017; American Society of Civil Engineers, 2014).

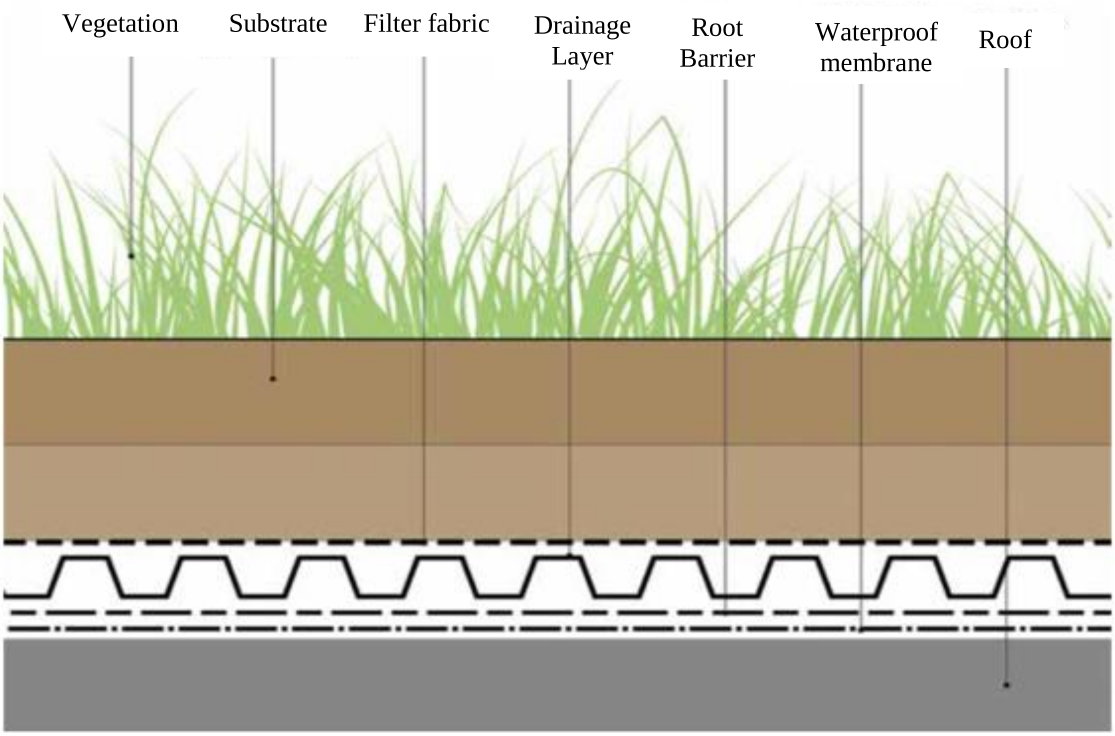

Figure 13: Typical section of a green roof. Source: (Woods-Ballard, et al., 2015)

3.3.3.2 Pervious pavements

Pervious pavements are commonly used to achieve surface runoff percolation while allowing the presence of pedestrian and vehicular traffic (Figure 14). Materials such as coarse gravel, natural stones, concrete blocks with open cells, and porous asphalts are used to achieve water infiltration (Stahre, 2006). Reservoirs can be placed below the permeable surface to store runoff before infiltration into the subsoil (Rossmiller, 2014). Pervious pavements are divided into three main categories: permeable pavements, porous pavements, and reinforced grass/gravel (Woods-Ballard, et al., 2015). Permeable pavements consist of the proper placement of impermeable materials, allowing a space between them where water infiltrates. On the other hand, porous pavements are surfaces of porous asphalt which enables the water to infiltrate in the soil. Because these systems intend to handle the total runoff volume, the soil infiltration capacity is a crucial aspect. Different design recommendations are presented by Woods-Ballard, et al. (2015) as a function of the coefficient permeability of the soils.

Previous pavements have an important reduction potential of pollutants such as heavy metals, oil and grease, sediments and to some extent, nutrients (Pagotto, et al., 2000; Woods-Ballard, et al., 2015; Tota-Maharaj & Scholz, 2013; Legret, et al., 1999; Novotny, et al., 2010). The principal processes by which pollutants are removed are filtration, adsorption, sedimentation, as well as biodegradation of organic pollutants. The use of different materials such as adsorption geomembranes can enhance the retention of pollutants.

Pervious pavements present risks of clogging linked to dust and sediments trapped in the structure. The clogging of the structure reduces the performance of the system (United States Environmental Protection Agency, 1999). As a consequence, regular monitoring and maintenance are required to guarantee proper operation of the system. Removal of weed, sweeping actions, water jet wash, brushing, and suction sweeping are commonly used remedial actions. The potential use of the space for a wide range of activities is considered as a central aspect in the implementation of pervious pavements. However, they do not provide any biodiversity benefits.

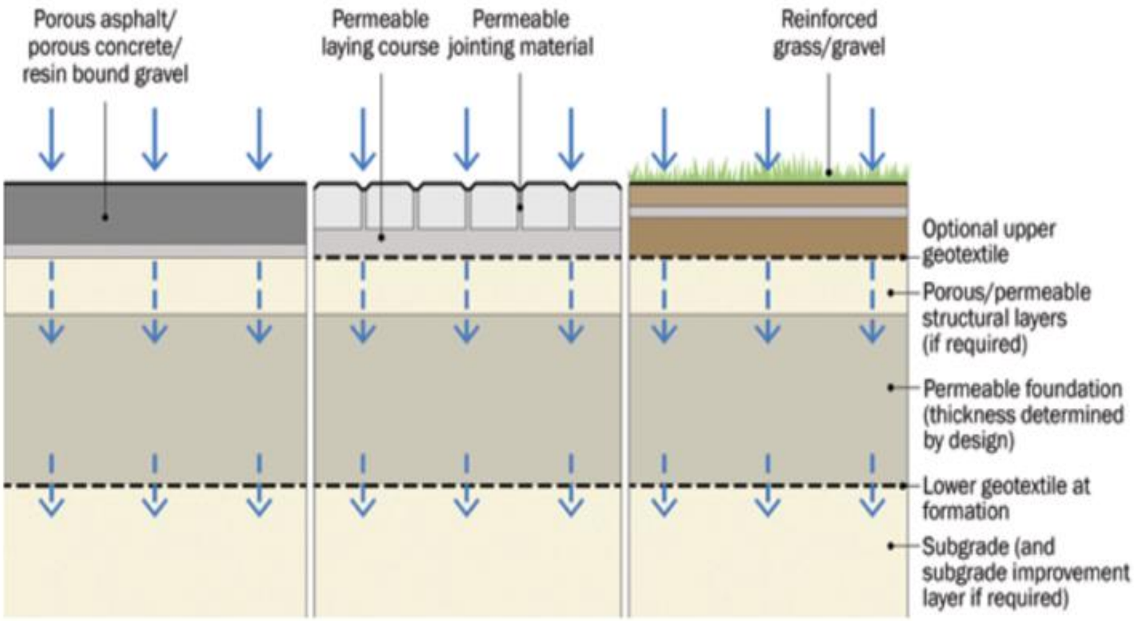

Figure 14: Section view of three types of pervious pavements. Source: (Woods-Ballard, et al., 2015)

3.3.3.3 Infiltrations Systems

Soakaways and infiltrations trenches are the two most common infiltration devices used as source control. Soakaways consist of excavations filled with void-forming material that stores waters while it infiltrates into the surrounding ground (Woods-Ballard, et al., 2015) (Figure 15). Different types of materials (coarse gravel, brick, rubble, geo-cellular units, concrete, among others) are used to achieve the storage of water and further percolation. Infiltration trenches can be defined as linear soakaways which are most commonly used to distribute the water into a more extensive infiltration area, achieving a proper operation in spaces characterized by a lower permeability of the soil. These systems present an important drawback: their high probability of clogging failures due to high sediment and silt loadings (United States Environmental Protection Agency, 2009; Jotte, et al., 2017). Therefore, they are characterized by high monitoring and maintenance needs.

Infiltration systems are mostly used to handle the runoff from residential areas, and their performance in terms of pollutant retention and peak flow reduction is highly dependent on the infiltration capacity of the soil and the depth of the groundwater level (Butler & Davies, 2004). When the infiltration structures are located in fine-grained soils, the infiltration rate is minimal, and in some cases, the water needs to be drained to a separate sewer system (Stahre, 2006). These systems do not possess any amenity value or public risks due to its subsurface characteristics. However, the structures do not interfere with the surface area and therefore allow their use for other types of activities or enhance the biodiversity or aesthetic value.

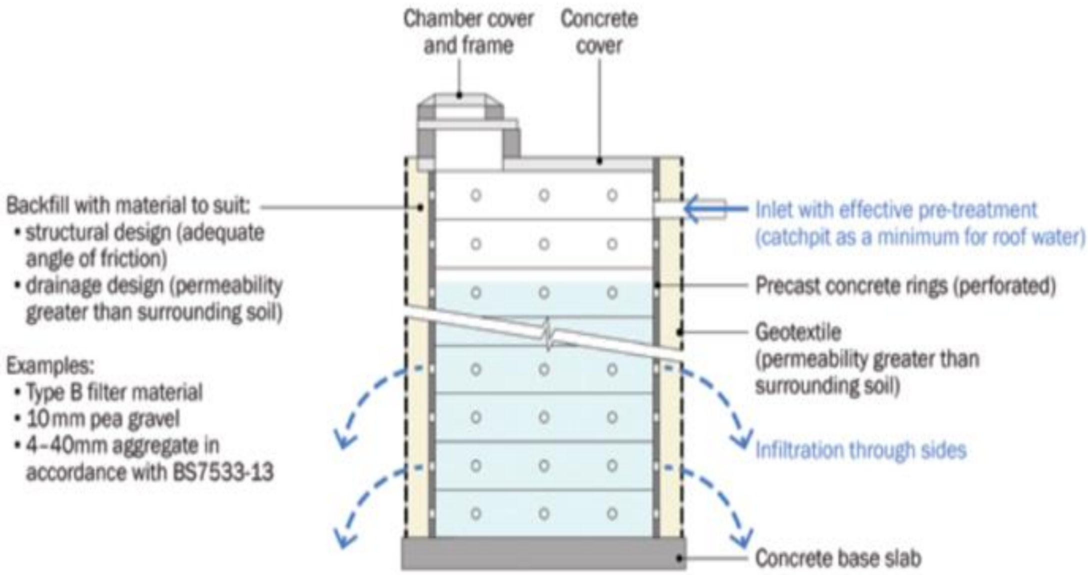

Figure 15: Soakaways. Source: (Woods-Ballard, et al., 2015)

3.3.3.4 Swales

Swales consist of a shallow vegetated open channel that conveys, treats, and attenuates runoff from roads, paths, and car parks (Woods-Ballard, et al., 2015)(Figure 16). This type of systems enhances open spaces and are usually used to replace conventional pipe systems while achieving removal of sediments and associated pollutants (e.g., nutrients, oil/grease, and metals) by sedimentation and infiltration processes (Rossmiller, 2014; Stahre, 2006). Additionally, photolysis and volatilization processes can accomplish the removal of organic pollutants. Biodegradation and plant uptake assist in the removal of nutrients and dissolved metals. The inclusion of filter bed can form part of the design processes, providing additional treatment while preventing waterlogging in the system.

The linear characteristics of a swale allow its installation and easy incorporation in areas nearby roads (Woods-Ballard, et al., 2015). On the other hand, the features of a swale present a problem in highly dense urban areas where space is a limitation. These systems have an optimal operation and pollutants reduction potential for small rain events. But instead, they require peak flow conveyance structures to handle the amounts of water associated with large rain events. The enhancement of the visual environment is achieved through vegetation, which needs to follow planting strategies for optimal operation. They are usually shallow surface structures that do not present high risks. Nevertheless, depending on the on the location and the public exposure, barriers may be required to mitigate risks associated with vehicles.

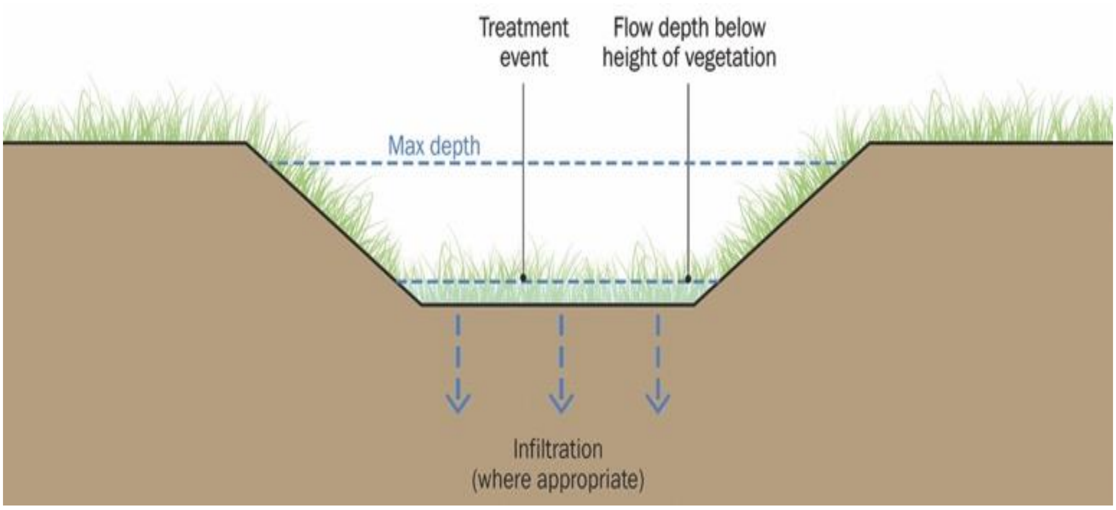

Figure 16 Section view of a Swale. Source: (Woods-Ballard, et al., 2015)

3.3.3.5 Dry detention basins

Dry detention basins are designated flooding areas used for temporary water storage and retention of pollutants, which can be designed to handle rain events with a return period of 2 to 100 years (Erickson, et al., 2013; Stahre, 2006; Rossmiller, 2014)(Figure 17). These systems consist of a depression ground surface fitted with water inlets and outlets that allow collection of stormwater while achieving a flow attenuation (Woods-Ballard, et al., 2015).

The water detention time is a crucial aspect in the retention of pollutants. Longer water detention times achieve a higher removal of contaminants such as sediments, nutrients, heavy metals, oxygen-demanding pollutants, and organic pollutants. The settling of solid particles produces most contaminant removal. Retention of 30-65% of total suspended solids and 15-45% of total phosphorus has been reported across the United States (Erickson, et al., 2013; Rossmiller, 2014). The use of vegetation enhances the potential of pollutant removal (Woods-Ballard, et al., 2015). Although, hard surface detention ponds are commonly used in highly densified urban areas as public spaces where playgrounds or sports facilities are often located. The exposure of these systems to the public involves the need to develop information campaigns to reduce health risks and system failures risks associated with clogging of the inlet and outlet structures due to litter. The features of a dry detention pond need regular maintenance to achieve a proper performance of the system. These maintenance needs are highly dependent on the specific design of the system, but usually, they do not encompass high costs. The activities that make up the operation and maintenance of dry detention basins include removing of litter and cleaning, grass mowing, structures inspection, and occasional remedial actions.

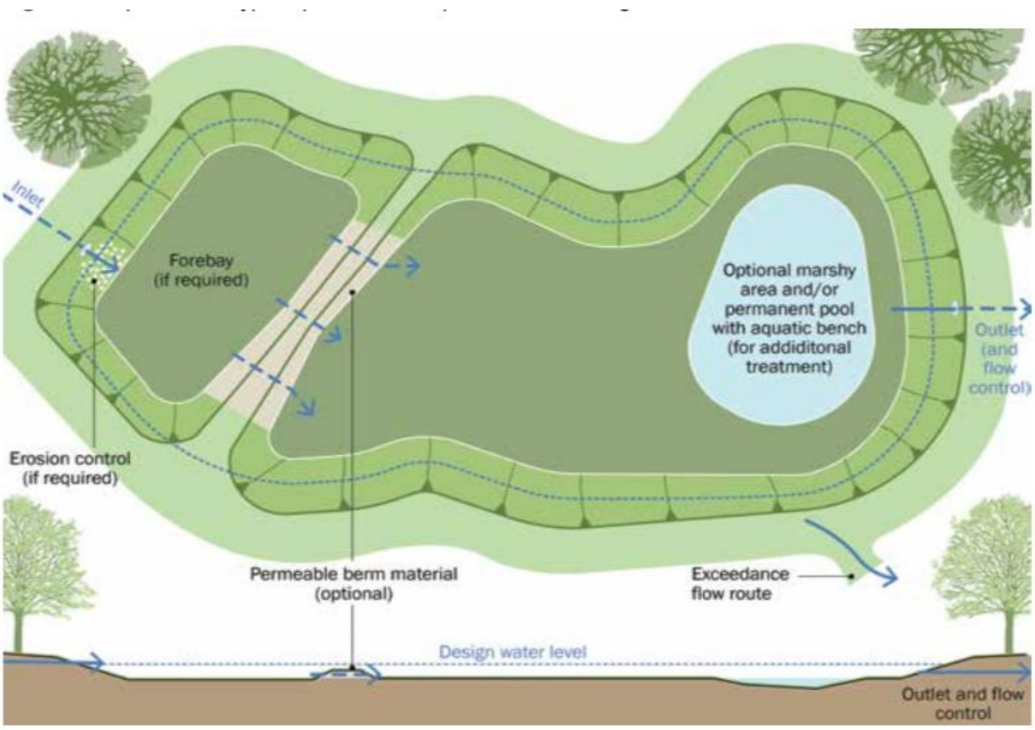

Figure 17: Plant and section view of a dry detention basin. Source: (Woods-Ballard, et al., 2015)

3.3.3.6 Wet retention basins

Wet retention basins, also referred as ponds, are systems that consist of a permanent pool of water that aim to attenuate the peak flows and treat the pollutants of stormwater runoff. Although, volumetric control is not a feature of ponds due to the lack of water interception. These systems usually contain vegetation that enhances the removal of contaminants by adhesion and aerobic decomposition (Woods-Ballard, et al., 2015). The volume of the pond and the water detention time affects directly the performance of the systems in term of sedimentation of particles and attenuation of peak flows. Large volumes usually provide more extended detention periods that allow higher efficiencies in particle removal.

The performance of ponds is highly linked to the design, proper maintenance, and proper operation of the system (Woods-Ballard, et al., 2015). Management plans need to be established to ensure the adequate implementation of maintenance and remedial actions. The different design characteristics for ponds define the management features. Nevertheless, primary operations include the removal of litter and debris, maintenance works on vegetation, monitoring to the different structures (inlet, outlet, and pretreatment structures), and occasional removal of sediments.

The public acceptance is strongly related to the aesthetic value, where highly contaminated ponds usually have negative aesthetic value and are associated with high public risks. Additionally, the enhancement (or negative impacts o-) the biodiversity is also related to the concentration of pollutants in the system. On the other hand, ponds with low pollution levels have a great aesthetic, educational, and recreational value, as well as a habitat value for different animal species.

3.3.3.7 Manhole filters

Manhole filters are structures which use physical and chemical processes to achieve pollutant removal (Woods-Ballard, et al., 2015). These systems differ depending on the type or manufacturer of the filter, but the principal processes that occur inside the filter´s structure are sedimentation, filtration, sorption, and precipitation. Filtration devices are useful for the removal of suspended particles which, due to its small size, are not directly affected by gravitational processes. Filters can also remove dissolved solids, but their performance is highly dependent on the technology used in the system. The filtering media is the essential element in terms of pollutant retention. A wide range of materials can be used as filtering media, from which the most common are leaf compost, pleated fabric, cellulose, activated charcoal, perlite, and sand (Woods-Ballard, et al., 2015). Peak flows are one of the main problems associated with these systems because they do not hold a proper capacity of flows reduction. Therefore, peak flow conveyance structures need to be installed upstream to control the flows. Additionally, overflow structures are usually placed in the system to prevent structural damage.

The reliability of these systems also depends on the sediment loading rates. Filters present a high probability of clogging under high sediment loadings, which leads to continuous monitoring, maintenance, and replacement needs. The underground (hidden) characteristics imply a difficulty in the identification of malfunctioning or failure events. The frequency of filter replacement varies as a function of different aspects such as the site- and system-specific characteristics.

Filtering systems are usually sold under prefabricated standards, and their capital cost is often lower when compared to other structures. The wide variety of filter designs available on the market provide a wide range of treatment processes that lead to different results. The nature and load of pollutants, as well as the characteristics of the filter, determine the performance of a specific device to treat the stormwater runoff appropriately. The manufacturers provide clear guidance with regards to the systems which they produce. Filters do not provide amenity nor biodiversity benefits, but their underground characteristics allow the utilization of surface areas to different types of activities.

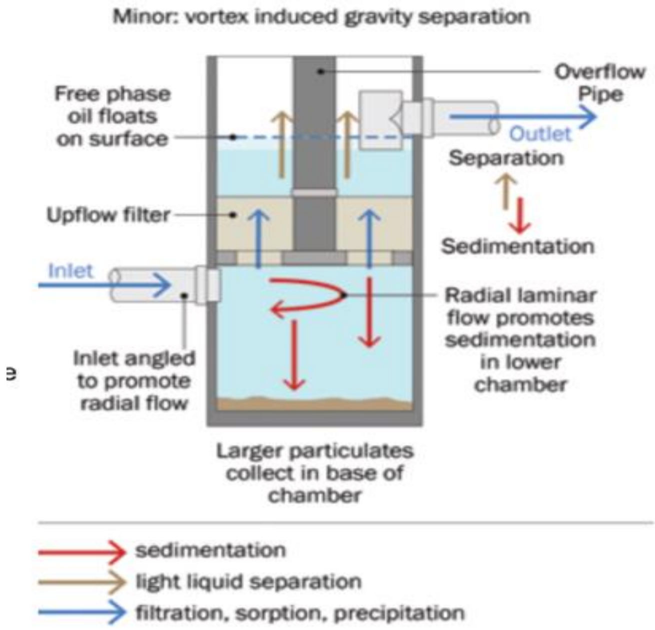

Figure 18: Typical treatment processes which occur in a manhole filter. Source: (Woods-Ballard, et al., 2015)

3.3.3.8 Subsurface detention basins

Underground detention basins, also referred as attenuation storage tanks, consist of an underground structure used as for temporary runoff storage that is followed by a controlled release of water. A wide variety of options exist in the market, ranging from plastic or concrete pipes to plastic, concrete, or geo-cellular boxes that fulfill the function of water storage. The size and shape of the underground detention basins vary with regards to the different site-specific requirements, as well as their intended performance. The primary objective of this structures is to attenuate the water flowing into the system, in order to control peak flows and obtain a discharge of a proper amount of water into the treatment system located downstream. This means that this type of systems does not generate benefits in terms of water quality when they are used in isolation (Woods-Ballard, et al., 2015).

Plastic corrugated structures are usually employed as underground detention basins. In some cases, treatment can be achieved by using perforated pipes which allow the infiltration of water, but these alternatives are highly dependent on the soil permeability. On the other hand, geo-cellular storage systems, consisting of plastic modules with high porosity, are also a common practice in some European countries due to their high-volume storage capacity. The structural strength of this type of structure allows its implementation in areas with vehicular traffic, which decreases the surface space requirements and limits the interaction with the public. These characteristics also make difficult the monitoring and maintenance operations due to the difficult access that can be presented according to the design characteristics. Depending on the system, and the exposure to the number of suspended solids reaching the system, failure scenarios can lead to concurrent deficiencies due to lack of monitoring and maintenance.

Underground storage tanks may enhance public amenity levels if their use is intended for the storage of water for later use. This type of system is not associated with any type of biodiversity improvement.

3.3.4 Integrated urban planning

The obstacles encountered by integrated planning are more pronounced in large cities, where it has been evidenced that the staff in the city's administrations are reluctant to new ideas linked to sustainable urban drainage systems (Stahre, 2006). However, the results of implementing this new approach have led to very innovative, successful, and interesting results regarding drainage solutions. The Scharnhauser Park in Ostfildern, Germany, is an excellent example of the implementation of successful BMPs. The urban planning process, developed under a sustainable approach, led to the installation of drainage swales, open channels, green rooftops, and water detention spaces (Knox, 2012). The BMPs installed can handle, without a problem, water runoff from a rain event with a return period of 100 years in an area characterized by low soil permeability (Figure 19). The integrated approach, which compromises the installation of different BMPs along the water path, considers the entire process as a treatment train and has led to significant results in terms of water volume attenuation, pollutant reduction, and social enhancement.

Figure 19: Scharnhauser Park, Stuttgart, Germany. Sources: Left Picture (Knox, 2012); Right picture: (Dittmer, 2017)

3.3.5 Example of stormwater management approach – relevance of public participation

The United States Environmental Protection Agency developed stormwater monitoring programs where the different characteristics concerning water quantity and quality where identified (United States Environmental Protection Agency, 2000). The Stormwater Phase I plan was developed in 1990 to follow the Clean Water Act (CWA), which aimed to create the instruments to address stormwater runoff in medium and large municipalities, as well as other defined areas such as industrialized zones. Following the programs developed in Phase I, Stormwater Phase II expanded the practices to achieve a reduction on the pollution associated with stormwater runoff, including components such as (Upadhyaya, 2013) :

- Public education and outreach
- Public involvement
- Illicit discharge detection and elimination
- Construction site runoff control
- Post-construction runoff control
- Pollution and prevention for municipal operations

Different approaches to stormwater management have been developed. The California Stormwater Quality Association (CASQA) sets a management approach where six different types of outcome levels are introduced and defined as the back structure of strategic planning. These different outcomes establish the measurability and the requirements needed to achieve successfully the planning and assessment tasks, which present a relation between them. In other words, the outcomes are seen as a progression of conditions that need to be evaluated, addressed, and further developed to achieve the objectives. The outcomes are grouped into three principal managerial components (California Stormwater Quality Association, 2015):

- Stormwater Management Programs: Defined as the various activities that are defined under a specific program.
- Target Audiences: Directed exclusively to the behavior of the audiences which are exposed to the programs. Additionally, includes all the factors that can influence these behaviors such as public knowledge, awareness, and general understanding of the problems. A wide range of different behaviors can be evaluated, and they are usually classified as a function of the water sources. For example, municipal sources include audiences such as road workers, municipal employees, staff; residential sources contain audiences such as homeowners, gardeners, school children; industrial and commercial sources include owners, operators, employees; construction and development sources include developers, engineers, contractors, among others.
- Sources and impacts: Correspond to all the physical components of the management approach, where the generation, transport, and fate of pollutants inside the urban environment are assessed.

From the previous program, it is essential to recall the importance of integrated urban participation, highlighting the necessity to include social, industrial, and commercial key-players in the processes of development, assessment, and improvement of the stormwater systems. In conjunction with the technical, environmental, and economic aspects, the community interaction component must be appraised in the evaluation of stormwater management systems in an urban area. Besides being economically and environmentally acceptable, any stormwater management technology must also be accepted by residents in residential areas (Apostolaki, Jefferies, & Wild, 2006). This aspect strongly relates, while giving more weight and importance, to the sustainability approach in urban drainage.

3.4 Stormwater regulation in Sweden

The Water Framework Directive (WFD) regulates and sets out the rules to mitigate the detriment of the European water bodies (European Parliament, 2000). By implementing management plans, environmental quality standards (EQS), and program measures, European countries were required to achieve by the year 2015 a good ecological and chemical status for their inland surface waters, transitional waters, coastal water, and groundwater (Michanek, 2011). Among the objectives stated by the WFD, the discharges of priority hazardous substances should be gradually ceased. Despite the fact that stormwater does not form an explicit part of the directive, the focus directed to pollution and maintenance of good water quality is strongly involved in stormwater management (Söderberg, 2011).

Requirements on stormwater management are imposed through the elaboration of action plans that lead to a mitigation of the impacts on water recipients. The Swedish Environmental Code contains no explicit regulations regarding stormwater (Lindh, 2013). However, the term is regulated as wastewater and drainage water. Wastewater is defined under the legal term "environmental hazardous activities", requiring water treatment before discharge. Söderberg (2011) considers this aspect as a contradictory fact due to the actual lack of treatment of CSOs. On the other hand, stormwater resulting from areas outside of zoning districts and cemeteries is regulated as road runoff, directed to the land drainage actions, and defined under the legal term "water operation".

The water authorities define the EQS as regulations that aim to protect human health and environment by maintaining good water quality for all water bodies (Lindh, 2013). Threshold standards are defined as the maximum concentrations of contaminants allowed and are determined based on the recipients and their expected water quality. Under the stormwater framework, Söderberg (2011) considers EQS as a good instrument to attack diffuse sources of pollutants due to the focus on recipient's minimum quality levels instead of individual standards of discharges.

The Planning and Building Act (PBL) plays an essential role in establishing the provisions directed to the planning of land, water, and construction areas (Boverket, 2016). In this respect and based on the Public Water Services Act (SFS 2006:412), the municipalities have a legal influence on installation and management of water supply and sewerage facilities (considering certain conditions established by the act). Therefore, municipalities are the responsible entities, dealing with water and land use in the area, to achieve the objectives and EQS compliancy. The Swedish Transport Administration (Trafikverket) is the responsible authority at the moment of dealing with stormwater from non-municipal roads.

3.5 Decision aiding tools

Decision-making processes consist of three major components: decision makers, decision alternatives, and consequences of the decision (Zarghami & Szidarovszky, 2011). Different actors play different and specific roles in each of the three components of the decision-making process.

Decision aiding activities help to obtain answers to questions which different stakeholders possess in a decision process (Figueira, et al., 2005). To identify and study different alternatives from which the best solution can be achieved, different factors and considerations from the decision-makers come into play. The elements aim to clarify the decision to take place and to promote a line of action that complies with the stakeholder objectives. The elements play a role in the judgment of the available alternatives, and its multiplicity plays an essential role in the complexity of the processes. Under the scope of this report, two main decision-aiding techniques are described: monetary-based techniques and Multi-criteria analysis.

3.5.1 Monetary-based techniques

Monetary based techniques can be categorized as financial analysis, cost-effectiveness analysis, and cost-benefit analysis. Financial analysis is an assessment of how a specific option may impact the costs and revenues of a decision-making organization (Department for Communities and Local Government, 2009). As part of the financial analysis, Regulatory Impact Assessments (RIAs) are included to assess the effects on the budgets and public expenditure of the considered proposal. For a better and precise understanding of the financial effects, budget impacts expressed over an extended period are discounted over each year to present net value.

Cost-effectiveness analysis is a method to evaluate, by comparing different established options, the least-costly way of achieving a specific objective. The objective usually has characteristics that prevent it from being evaluated in monetary terms. Cost-benefit analysis aims to evaluate the expected effects (positive and negative) of a project in monetary terms. The evaluation is based on well-developed economic theories of valuation that rely on two principal aspects: the willingness-to-pay and willingness-to-accept (Department for Communities and Local Government, 2009). Willingness-to-pay is linked to the potential beneficiaries of the options to be implemented, while willingness-to-accept is linked to the negatively-affected parties. As a consequence of evaluating the different options in monetary terms, the attractiveness of each one of them is strongly related to the relationship between benefits and losses. Therefore, the most attractive solution is the one where the benefits exceed the losses.

Monetary techniques have been used for many decades in water resources planning and environmental management, where the alternative with the highest difference between benefits and cost is selected. Problems of this traditional method include evaluating criteria or alternatives in monetary terms. Intangible costs and benefits are presented in different projects, and high inaccuracies can occur at the moment of quantifying the values. Benefits and costs linked to social aspects, as for example social satisfaction and the related increase (or decrease) of social cohesion, can present difficulties when designated as a monetary value (Department for Communities and Local Government, 2009). Additionally, (Loucks & van Beek, 2005) state that a complete use of monetary units to describe the objectives does not address precisely the distributional issue between which stakeholder pays the costs, which stakeholder benefits, and to what extend they benefit or loose. Therefore, the application of multi-criteria analysis, which, by including social aspects, is considered to achieve more realistic solutions for water and environmental management.

3.5.2 Multi-criteria analysis (MCA)

Multi-criteria decision-making methods are suitable tools for approaching complex problems. Usually, these problems feature high uncertainties linked to the establishment of objectives or the inclusion of different perspectives in biophysical and socio-economic systems (San Cristóbal Mateo, 2012). The central role of the MCA is to handle the difficulties encountered by the stakeholders regarding the vast amount of information that can be present in decision processes. Based on monetary and non-monetary objective evaluation, MCA can result in the establishment of a best single alternative, on a ranking process of alternatives, or the determination of acceptable and unacceptable alternatives under specific contexts (Department for Communities and Local Government, 2009).

The high number of variables related to water resources and environmental management problems can be assessed by characterizing different criteria established to achieve defined goals. Under a sustainability framework, social, economic, and environmental objectives are established to achieve the defined goal (Zarghami & Szidarovszky, 2011). The implementation of sustainable urban drainage systems may intend to accomplish environmental, social, economic, and technical objectives, to achieve the goal of handling and managing runoff appropriately in urban areas. In this sense, the main idea of an MCA is to evaluate how different alternatives or projects can fulfill different established criteria (Rosen, et al., 2013).

Balasubramaniam & Voulvoulis (2015) reviewed the application and the appropriateness of MCA for different environmental problems such as Environmental Impact Assessments (EIA), waste management, and water quality and resources. The authors conclude that the nature of the problems addressed by environmental aspects leads to the rise of decision-aid requirements that, in most of the cases, MCA meets.

The construction of an MCA is based on different factors that lead to the evaluation of the alternatives against established criteria, and further evaluation of results. Each step is based on the goals and objectives established for the project. Therefore, all the different components of an MCA must be built from the initial step of establishing the goals. Seven essential steps, illustrated in Figure 20, make-up the process of building and MCA (Department for Communities and Local Government, 2009).

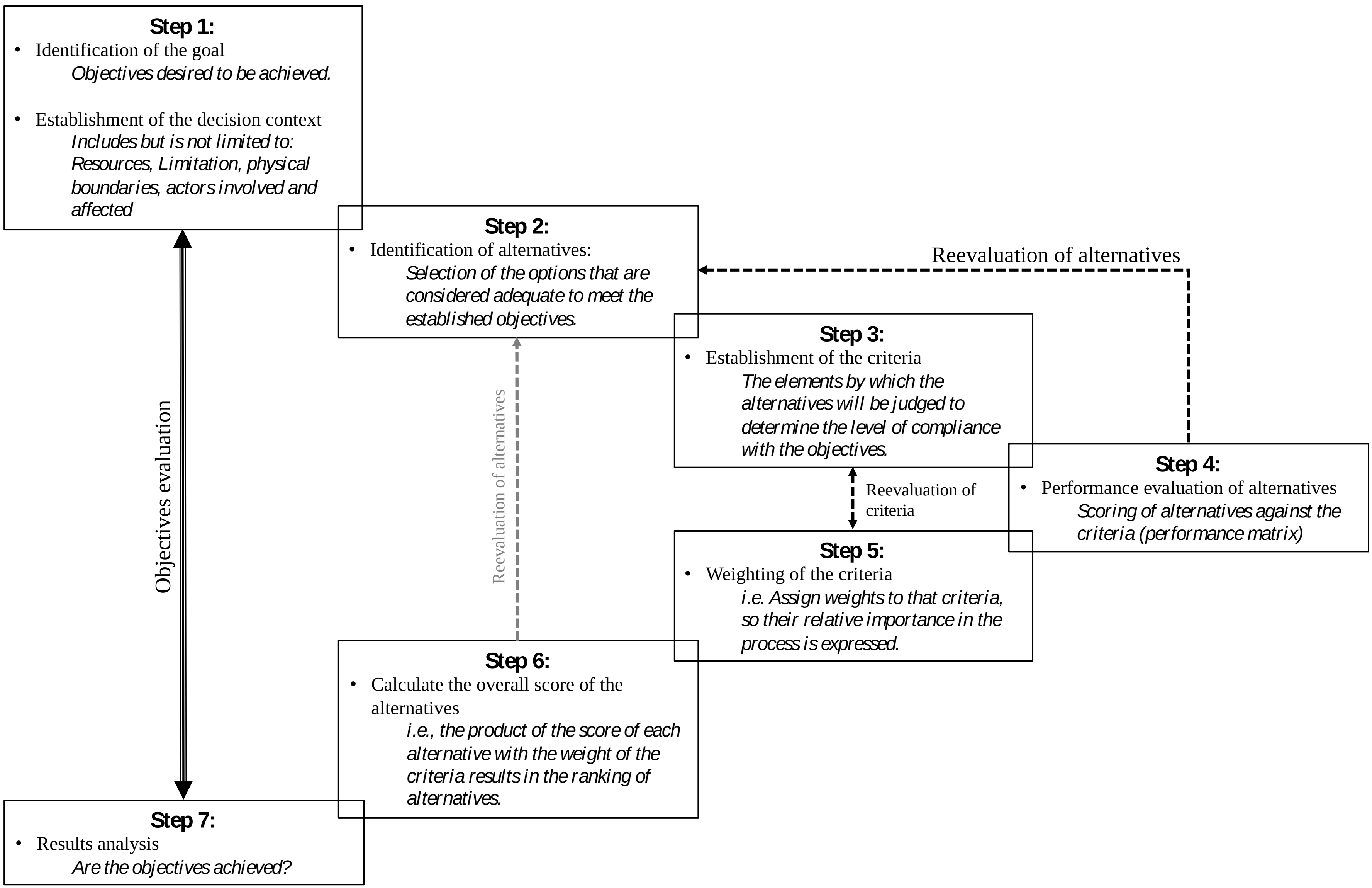

Figure 20: Steps of an MCA. Adapted from (Department for Communities and Local Government, 2009)

3.5.2.1 Identification of the goal and establishment of the decision context

The decision context of an MCA is made up by three components: the stakeholders, the involved parties or key-players, and the aims and objectives (Department for Communities and Local Government, 2009). Stakeholders are defined as the final decision makers in the process. They establish the goals and preferences, expecting positive outcomes of the MCA based on their investments. The main role in the method is to structure the alternatives and criteria of the evaluation. Despite the fact that conflicting priorities and opinions can arise, the MCA method is based on the coherence and consistency of preferences between the parties. MCA is not just limited to the stakeholders' opinions. Key-players need to be identified and involved in the process. Even though the final decision does not rely on them, they have an indirect influence on the project. Any party or individual with a potential contribution to the MCA plays an important role by providing their advice and opinion.

Munier (2011) proposes four entities that should be included in all MCA which intend to solve environmental issues:

- Decision making entity
- Technicians who supply quantitative and qualitative information
- An analyst who process the data
- Citizens

The social and technical aspects of an MCA need to be considered together, based on the impact of the alternatives and their evaluation (Department for Communities and Local Government, 2009). Depending on the magnitude of the impacts, different stakeholder and key-players represent interest groups that will cover the different objectives and criteria.

The context that surrounds the decision-making process (which involves aspects such as the goals, resources, potential problems, strengths, weakness, among others) needs to be characterized, detailed, and apprehended to achieve a line of joint action between the MCA players. As mentioned previously, one of the key aspects of MCA is to achieve a common consensus with regards to the goals to be achieved, and not contradictory goals and opinions that would occur and affect the process. The clarification of the goals helps to define the tasks and further stages of the analysis, keeping the whole process on its course (Department for Communities and Local Government, 2009).

3.5.2.2 Identification and selection of alternatives

The primary source of alternatives is the stakeholders´ experiences and interests. Alternatives can range from policies, to specific projects determined (Department for Communities and Local Government, 2009). When MCAs are used to explore the opportunities for implementation of innovative processes, the number of alternatives can be relatively high. The identification of alternatives is based on acceptable and not-acceptable analysis, usually based on funding opportunities.

Previous research and past implementation are another good source of alternatives. Depending on the specificities of the alternatives, a vast amount of information can be found as part of literature review, depending on the global development and their application. Further steps in an MCA may lead to a reevaluation of the alternatives established previously, creating an iterative process (dotted lines in Figure 20) that lead to more integrate and accurate results (Department for Communities and Local Government, 2009).

3.5.2.3 Establishment of criteria

The criteria are the major established components on which the alternatives are judged, and the final decision is built (Department for Communities and Local Government, 2009). This means that they represent the conditions or restrictions that the project is subject to (Munier, 2011). The criteria are defined based on the categories which are intended to evaluate the performance of the different alternatives. Under a sustainable development framework, the principal categories consist of environmental, economic and social aspects. Ellis et al. (2004) established technical, environmental, social and economic factors as the prime potential sustainability criteria to evaluate and compare urban drainage options. Here, capital and operation-maintenance (O&M) costs, resources use, public acceptability, performance of the alternatives, and maintenance needs are contemplated under the proposed framework (Figure 21).

The criteria need to be flexible and dynamic to be adapted and redefined to meet modifications, or further implementation, of the different aspects that each of the alternatives can include.

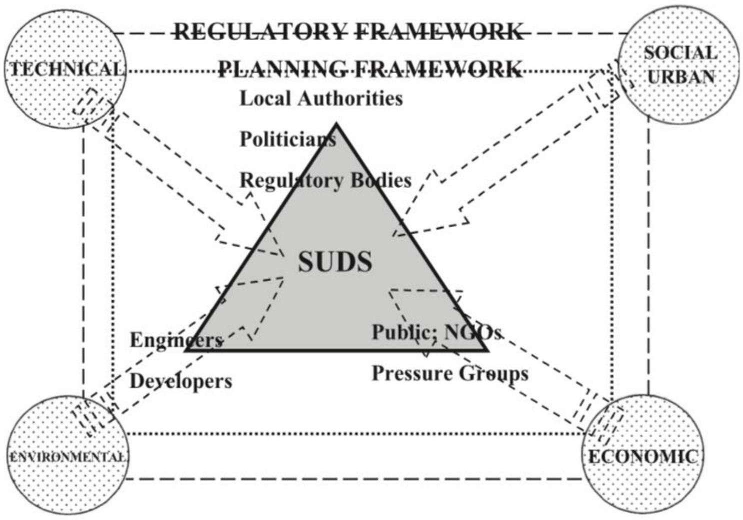

Figure 21: Sustainable Urban Drainage System triangle and the relation to sustainable criteria and stakeholder preferences. Source: (Ellis, et al., 2004)

Criteria come as a result of the specific objectives established in previous stages and are evaluated or quantified by indicators. Indicators contain baseline information and values that quantify or qualify each of the criteria. In this sense, these values diagnose the conditions that describe the properties of each of the criteria and are defined as numeric values or subjective descriptors (Ellis, et al., 2004).

As part of the process, exclusion criteria define specific alternatives as invalid or unsuitable for particular cases. Usually, these exclusion criteria hold a technical or scientific nature, and clarify inherent imperfections, or impairments of the alternatives related to physical constraints (Ellis, et al., 2004). This step in considered in the MCA and evaluated in the initial steps.

The criteria need to follow specific characteristics that are determined by the principal objectives. In this sense, primary requirements and needs for the establishment of criteria can be defined as (Moura, et al., 2011):

- Relevance – Do the criteria correspond to relevant aspects of the process concerning the achievement of the objectives?

- Accessibility – Are the criteria indicators easy to calculate? Are the required data available for its calculation at an acceptable cost?
- Objectivity – Are the indicators ambiguous? Are the criteria understandable for the involved parties?
- Robustness – Does different results from the criteria evaluation tend towards same or similar tendencies?
- Sensitivity – Do the criteria discriminate different strategies correctly? In other words, are the results from two alternatives consistent with the systems´ differences?
- Independence – Are the criteria independent of each other?
- Redundancy – Are the evaluated aspects unique to the defined criteria?

3.5.2.4 Performance evaluation of the alternatives against the criteria

The evaluation of the alternatives is achieved through the implementation of numerical analysis (Department for Communities and Local Government, 2009), which can be done by using real or subjective values that represent the preferences or performance of each alternative against the criteria. The evaluation of alternatives highly depends on the establishment of the criteria. A matrix of evaluation can summarize the process by which the valuation of the different alternatives is attained (Table 5). The matrix of evaluation consists of a simple qualitative description of the process, where the different alternatives are exposed on rows and the different criteria are exposed on columns.

Table 5: Example of a matrix of evaluation of alternatives

Alternatives	Criteria									
	Technical Category			Environmental Category			Social Category		Economic Category	
	C1. Flow Control	C2. Reliability	C3 Durability	C4. Pollution Control	C5. Impact on Soil and Water	C6. Ecological enhancement potential	C7. Public interaction	C8. Location Amenity	C9. Capital Costs	C10. O&M
Wet Retention Pond										
Dry Detention Pond										
Swales										
Infiltration Trenches										
Underground detention										
Manhole filters										
Pervious Pavements										
Green Roof Storage										
Soakaways										

The stakeholders and key-players involved in the process will evaluate each alternative against the criteria, and based on defined parameters and thresholds, the alternatives are further ranked based on the results. The collection of data and information from literature, field work, or modeling supports the scoring of each process.

3.5.2.5 The weighting of the criteria

The weighting of criteria is achieved by comparing the relative importance of each criteria against each other (Department for Communities and Local Government, 2009). The weighting of criteria is usually a very subjective process, and therefore, the values recorded for a process can present high variability when comparing the same criteria in an intent of replicating them into another process. The aim of this step is to rate the importance of each criteria based on the preferences of the stakeholders and key-players. The weighting process reflects the range of difference of the options and the importance of them (Department for Communities and Local Government, 2009).

Despite the fact that the stakeholder may not be experts on the matters discussed, their choice reflects their preferences to achieve the value that they expect to obtain. Therefore, two different approaches are frequently suggested in the literature to achieve the weight (Upadhyaya, 2013):

- Assigning weights through expert opinion
- Assigning weights through stakeholders input.

Different types of criteria weighting are proposed by different authors, for example Martin et al. (2007) proposed a method in which the stakeholders and involved parties separate the established criteria in two groups:

1. Strategic criteria: criteria of major importance to the stakeholder
2. Non-strategic criteria: considered as less important to the stakeholder.

The weights for each criterion are defined by distributing 100% among all of them. Each of the criteria categorized in the non-strategic group is assigned a 1% value, and the remaining percentage is distributed equally among the strategic criteria (Table 6).

Table 6: Weighting method example. Adapted from (Martin, et al., 2007)

		Stake holders			
Criteria		Decision making	Technical	Social	Others (i.e Traffic)
Tehnical	Hydraulic Response	14%	14%	1%	16%
	Risk Management	14%	14%	1%	16%
Environmental	Receiving Water Body	14%	14%	19%	16%
	Pollution Control	14%	14%	19%	16%
Social	Sustainable Development	1%	14%	19%	1%
	Public Interaction	1%	14%	19%	0%
	Aesthectis	1%	14%	19%	1%
Economics	Investment Costs	14%	1%	1%	1%
	Operations & Maintenance Costs	14%	1%	1%	1%
	other costs	14%	1%	1%	0%

3.5.2.6 Final evaluation based on the overall weighted score of the alternatives

The ranking of alternatives is then calculated by multiplying the score (s) of each alternative by the weight (w) of each criterion. By representing $S_{ij,}$ the score of the alternative (i) against the criterion (j), the overall score for the alternative is then defined as (Department for Communities and Local Government, 2009):

$$S_i = w_1 s_{i1} + w_w s_{i2} + \cdots w_n s_{in} = \sum_{j=1}^{n} w_i s_{ij}$$

3.5.2.7 Results analysis

After the final evaluation, the alternatives will be ranked from the most preferred to the least preferred based on the score and criteria weighting. The ranking may also be expressed by numerical values that indicate the preference of an option with regard to another.

This project develops a strategy to support decision making processes aiming to identify, from a range of stormwater alternatives, the potential solution that can be adapted to particular and defined contexts. The study case will show the application of the method where the resulting values are expected to (San Cristóbal Mateo, 2012):

- Describe the integration of interests and objectives of multiple actors.
- Deal with the preferences of each of the key-players and provide accessible and comprehensive information to the parties involved.

- Allow an objective interpretation of results with regards to the defined objectives.

The MCA process includes various criteria that may vary between the actors of the decision-making process. It is possible to identify a list of preferences with regards to specific aspects considered by contemplating separately different and pertinent points of view that are not correlated between each other.

4. Study Area

4.1 The city of Gothenburg

The city of Gothenburg is the second largest city in Sweden, capital of Västra Götaland region, with an urban population of 556,600 inhabitants (City of Gothenburg, 2016). By the year 2035, the city expects to be home to 700,000 inhabitants. During 2016, 2,680 new homes were built, achieving the highest recorded construction rate since mid-1970's. Located on the west coast of the country, the city is characterized by trade and high industrial activities linked to Scandinavia's largest port. Gothenburg's administration has focused its efforts on creating a sustainable society. As a result, the EU directive on Sustainability Reporting was expected to be achieved in the year 2017(Göteborg Stad, 2009).

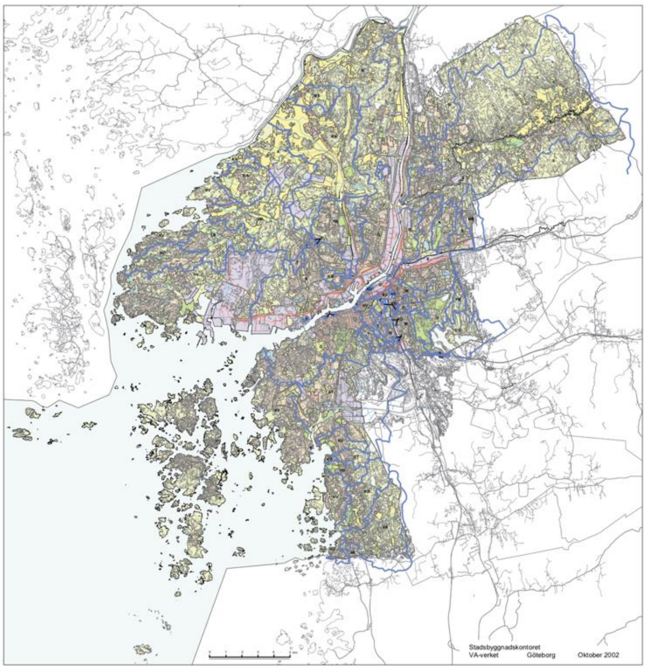

Figure 22: City of Gothenburg. Source: (Göteborgs Stad, 2009)

The city of Gothenburg is characterized by 5000 hectares of impervious surfaces, from which 1460 hectares are drained to combined sewer systems (Lindh, 2013). Like most Swedish cities, Gothenburg's central area is dominated by a combined sewer system network which conveys stormwater and wastewater (Göteborg Stad, 2013). This combined system corresponds to 40% of the entire sewage grid, which consists of more than 2000 kilometers of pipes (Göteborg Stad, 2014). The addition of duplicated sewer system has been implemented along the city in order to create separate sewer systems, leading to a reduction in the discharge of untreated wastewater via CSOs. The separate drainage system implemented has been designed for rain events with a return period of two to five years (Sörensen & Rana, 2013).

Generally, polluted stormwater is discharged untreated to the receiving waters (Lindh, 2013). During overflow conditions, the first flush is captured by the combined systems and directed to the Rya waste water treatment plant (WWTP). The pollutants linked to stormwater runoff have a negative effect on Rya's sludge quality, interfering with their aim and current efforts directed to the reuse of sludge on farmland (l'Ons, 2017). Forty overflow points distributed around the city discharge the exceeding water to the receiving water bodies that mostly converge in the river Göta Älv (Nyström, 2012). The river is also used as the drinking water source of the city. Local projects, such as the one named River City Gothenburg (Centrala Älvstaden), have focused the efforts on promoting an increase in the water quality in order to foment additional benefits such as the interaction between citizens and the water bodies.

Improved wastewater treatment, increased installation of separate sewer systems, and high percentage of connected households have led to a decrease in pollutant loads to receiving waters. After the construction of the wastewater treatment plant Ryaverket, the fraction of stormwater related pollutants in the receiving waters has increased when compared to the sewage effluent (VA-Verket, 2001) Consequently, stormwater treatment has been an increasing interest throughout the last decade. When treatment of stormwater is achieved, an important decrease in the total pollutant load to the receiving water bodies is expected.

The city of Gothenburg is designated as one of the 18 areas in Sweden with significant flood risk (Länsstyrelsen i Västra Götalands län, Enheten för skydd och säkerhet, 2015). Protective measures, involving physical interventions related to surface water, were stablished as part of the Risk Management Plan for Floods in Gothenburg. In order to improve the capacity of the drainage water systems, the city´s stormwater policy has directed its efforts to boost the inclusion of local stormwater treatment options and SUDS.

Regarding stormwater quality, the strategy of the city has focused on reducing the pollution related to traffic and building materials, and the efforts have been directed specially to the most sensitive receiving water bodies (Lindh, 2013). The largest project implemented in the city is a sedimentation pond in Järnbrott, which aims to treat stormwater from a catchment area with a major road and industrial and residential land uses. Other measures installed in the city include underground detention basins, manhole filters, seepage areas, and wetlands. Additionally, to maintain groundwater level and a proper environmental state of the surroundings, local treatment is preferred. Nevertheless, the implementation of local treatment in the city is not always possible due to different factors such as site characteristics.

4.2 Brottkärr

A stormwater treatment system, which consists of an underground retention system and manhole filter, was placed in operation in 2017 in order to treat stormwater in Brottkärr, located south of Gothenburg (Figure 23). The system was built in 2016 by the local traffic office (Trafikkontoret) and operated by Kretslopp och Vatten since then.

Figure 23: Brottkärr area. Source: Google maps

4.1.1 Catchment area

The total catchment area is 25 ha, where two different systems treat the stormwater runoff before it is discharged into Krogabäcken, the receiving water body. A roundabout is located in the middle of the catchment area, where the roads Brottkärrsvägen and Billdalsvägen intercept (Figure 24). The annual average daily traffic (AADT) on Brottkärrsvägen and Billdalsvägen reported for the year 2013 is 5,200 and 10,300 cars, respectively (Trafikkontoret Göteborg Stad, 2013). Additionally, commercial, residential, and construction activities are predominant in the area. A gas station is located in the western corner of the catchment area.

Figure 24: Drainage area (blue line). The red points mark the inlet and the outlet of the treatment systems of interest. The blue point marks the location of a rain gauge. Source: (DHI, 2018)

The ground levels in the area vary between +40 to +70 meters above sea level (Norconsult AB, 2011). The eastern part of the catchment area, which stands as the specific area of interest for this project, is characterized by thin friction soil layers over mountain rocks. As a result, the water infiltration potential is small. Additionally, soil layers entailing a loose clay cover are reported in the northern part of Krogabäcken, with a groundwater table located 1-3 meters below ground level (Norconsult AB, 2011). Low levels of infiltration are estimated in the area.

4.1.2 Current water conditions

Based on the water diversion, the catchment area of interest was divided into three major basins (Figure 25), with a total area of 7.5 ha (Norconsult AB, 2011). A runoff flow of 190 l/s was estimated for a 60-minute-long rain event with a return period of 10 years. It is assumed that these conditions have changed drastically in the last seven years due to the intensive urbanization processes in the area. The stormwater from basins A and B is directed to the treatment system, while the stormwater in basin C flows south to neighboring areas and is later incorporated to existing water systems.

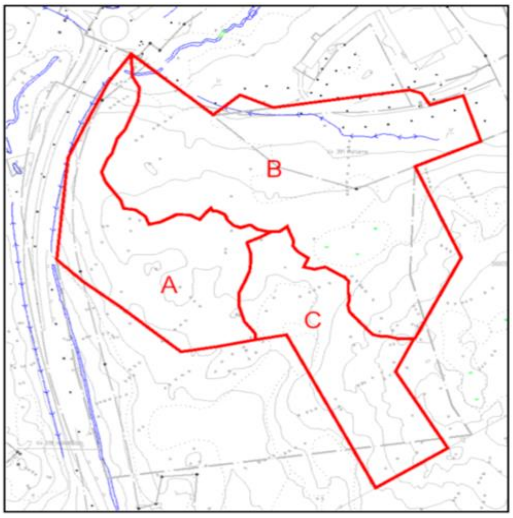

Figure 25: Division of the area in three different basins. Source: (Norconsult AB, 2011)

4.1.2.1 Receiving water body

The runoff water resulting from the area is discharged into the creek Krogabäcken. The creek runs from Oxsjön (northeast of Billdal region) and flows west into the sea via Origohuset and Billdals Park through a 4.2 kilometers long watercourse (Fiskevårdsnätverket Göteborg, 2018). Along its watercourse, the creek encounters woodland regions and urbanized areas characterized by construction activities (COWI AB, 2011). The creek has a high production of sea trout and has been assessed to have a high value, on a regional level, due to its characteristics that lead to high reproduction of the sea trout.

Krogabäcken is defined as a water body sensitive to hydrological loads, increased pollution load, and potential flood problems (Norconsult AB, 2011). Therefore, stormwater detention and treatment process are considered of high importance prior to discharge.

4.1.3 Stormwater treatment systems

4.1.3.1 Primary treatment system

The primary treatment system of Brottkärr area consists of a detention basin, a sand trap, a flow regulator, and a lamella separator located under the roundabout, treating the northernmost part of the catchment area (Figure 24). This system is expected to be under normal operation and is not part of the scope of this project.

4.1.3.2 Secondary treatment system

The treatment system of interest consists of an underground piped detention basin (in Swedish: Rörmagasin) and a manhole filter, located along the eastern side of Billdalsvägen. The stormwater is drained from the southernmost part of the catchment area (basin A, B, and C in Figure 25), which holds a construction site of residential apartments (Figure 26). Heavy traffic, related to the construction activities, is present in the area.

Figure 26: Residential construction area from where the water is drained and treated in the stormwater system of interest

The pipes transport the runoff to a manhole, which in turn works as an overflow structure located at the inlet of the detention system (Point A in Figure 27). Under overflow conditions, the water is discharged by a pipe into a small infiltration area situated on the ground surface. The overflow is later collected in another underground structure and discharged directly into the receiving water body. Under normal conditions, the water is directed to the detention basin.

The underground detention system involves a three-piped structure, where two pipes of 1,000 mm diameter and one pipe of 800 mm detain the water before it is directed into the filter. Sedimentation processes are expected to occur along the 157-meter-long pipe-structure (Figure 27). In spite of that, the outlet of the structure is positioned in the lower part of the system, which prevents the retention of sediments that are transported, almost entirely, to the filter.

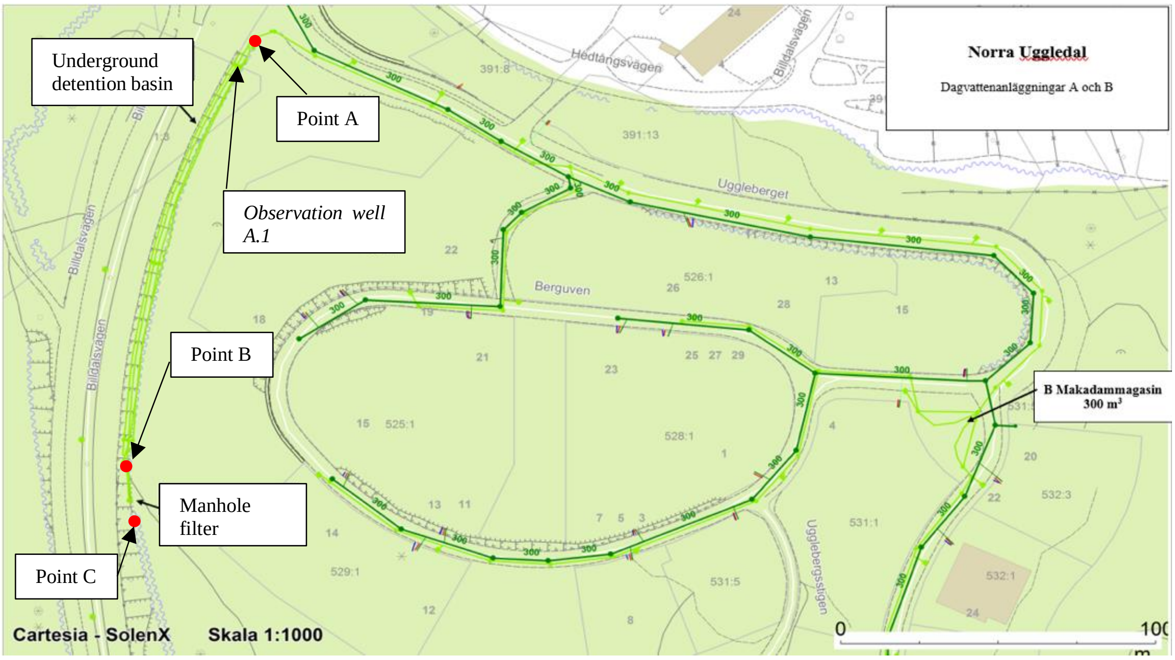

Figure 27: Secondary catchment area. The runoff is conducted through a piped system (dark green lines) to the underground sedimentation basis (light green lines). Source: (Göteborg Stad; Kretslopp och vatten, 2017)

The manhole filter, referred as Hydro-system by the manufacture Dahl Sverige AB, consists of a structure intended to reduce pollutants by the means of sedimentation, filtration, adsorption and precipitation process. The filter has a maximum flow capacity of 12 l/s.

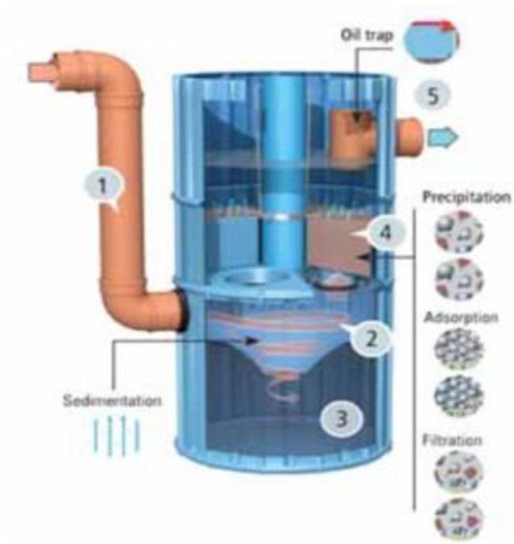

Figure 28: Filter used as part of the stormwater treatment system. Source: (Dahl Sverige AB, n.d.)

The functional principles of the filter are explained based on Figure 28 as follows (Dahl Sverige AB, n.d.):

1. Filter inlet (in this case, the outlet of the underground detention system corresponds to the inlet of the filter)
2. The positioning of the inlet generates a radial flow that promotes sedimentation of the heavier particles.
3. Sediments are collected in a chamber located in the lower part of the structure. Sludge, sand, and heavy sediments are expected to be found in this chamber. The filter maintenance consists in the removal of accumulated sediments.
4. The solids are absorbed by the filter media located in the middle of the structure.
5. The clarified water then is discharged into the receiving water body.

The filter is intended to reduce heavy metals, nutrients, and organic compounds. Details regarding the working ranges of the filter are shown in Table 7.

Table 7: Filtration capacity Hydro system. Source: (Dahl Sverige AB, n.d.)

Parameters	Units	Working range
Conductivity	uS/cm	< 1,500
pH	-	7.0-9.5
Phosphorus	(mg/l)	0.2
Ammonium	(mg/l)	0.3
Cadmium	(mg/l)	<1.0
Zinc	(mg/l)	< 500
Copper	(mg/l)	<50
Lead	(mg/l)	<25
Nickel	(mg/l)	<20
Chromium	(mg/l)	<50
PAHs	(mg/l)	<0.2
Mineral Oils	(mg/l)	<0.2

5. Method

5.1 Sampling campaigns

Investigations on the stormwater treatment system were performed to determine its current operating state (Figure 29). Results of water sampling campaigns carried out by DHI in 2017 were analyzed. The scheme used by DHI consisted of one automatic sampler located in the inlet and another one the outlet of the system (Point A and C, respectively, in Figure 29), allowing an analysis of the behavior of the pollutants in the system. Additionally, new sampling campaigns were structured, modifying the sampling scheme used previously by DHI: Water samples were collected during rain events by three automatic samplers connected to flow meters. This time, the samplers were located purposefully to analyze the pollutant retention of the underground detention basin and the manhole filter separately (Points A, B, and C in Figure 29). GLS compact composite samplers were used to collect the runoff and the flow was monitored by an ADS TRITON+ monitor (Table 8).

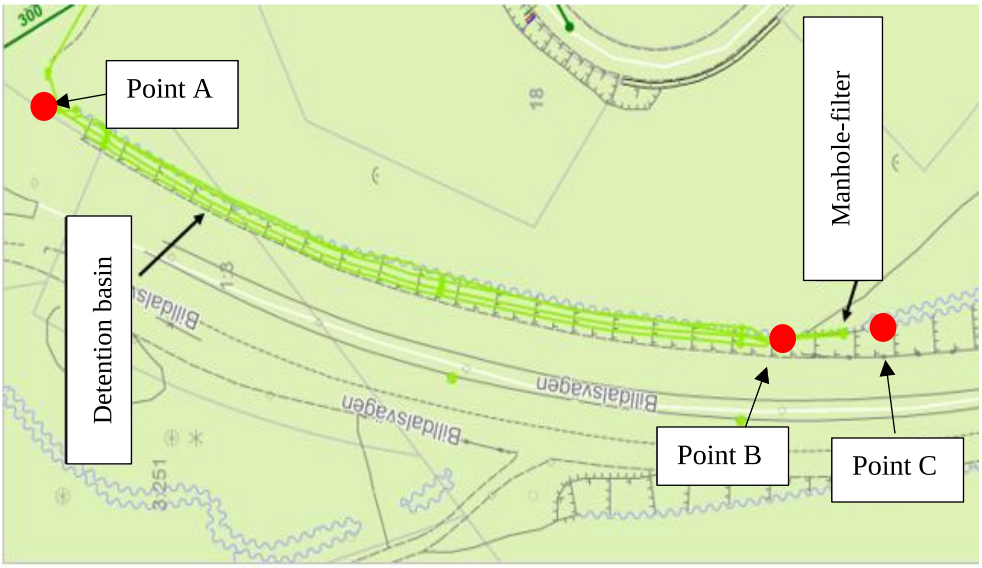

Figure 29: Scheme of the treatment system in Brottkärr. Modified and used with permission from: (Göteborg Stad; Kretslopp och vatten, 2017)

Table 8: Systems used in the sampling campaigns

Manufacturer	System	Equipment	Settings
Telefyne Isco	GLS Compact composite sampler	9.5 liter sampling bottle	*Running time*: 1,000 hours *Max. Number of samples*: 40 *Total volumen of samples:* 220 ml *Pulse activation*: Uplooking ultrasonic depth (4 cm)
ADS Environmental Services	Triton + flow monitor	Peak Combo sensor	-

All three sampling systems were programmed to collect 220 ml in a total amount of 40 samples. The *Up-looking Ultrasonic Depth* setting was chosen to monitor the water flow, and the pulse activation of the water sampler was programmed to work each time the water level raised above 4.00 cm. Due to the probability of back-wave conditions in point B (Figure 29), which can lead to a decrease in water velocities in the system and lack of collected samples, the use of the *Continuous Wave velocity* setting was discarded.

A tracer test was done to determine the hydraulic behavior of the detention basin. Pyranine was used as the fluorescent tracer and was injected in point A (Figure 29), where approximately 4 m^3 water were discharged. The flow of the tracer was monitored along the three-piped-system, and the time of arrival on Point A.1, Point B, and Point C (Figure 29) was recorded. Pont A.1, the observation well, corresponds to a manhole 7 m form the point of discharge. Using a black light, the arrival time of the water was recorded in three different points of the system (Appendix 5.1). In Point B (Figure 29), observations were done in three different manholes to determine the relative importance in terms of water flow of each one of the pipes. For this reason, the measures in point 3 are established as Point B (east), Point B (middle), and Point B (west) (Appendix 5.2).

5.2 BMPs Performance Evaluation

A detailed literature review was developed to obtain information on the performance of the different alternatives for stormwater treatment. The literature review included theoretical studies, manuals, and real installations implemented in different regions around the world. The information was summarized to obtain ranges of expected performance and allow a comparison of the alternatives.

5.3 Multi-criteria analysis

A multi-criteria analysis was developed to compare different stormwater management alternatives under defined criteria. The purpose of the multi-criteria analysis was not to propose the best solution. The objective was to identify and rank possible solutions that can be adapted in Gothenburg, based on the information gathered from the literature review on the performance of BMPs, local preferences (e.g. specific interests form Kretslopp och Vatten), global and regional trends (e.g. increase in the adaptation of sustainable options in urban environments such as green roofs in Sweden), and environmental requirements.

Through interviews with the stakeholder, Kretslopp och Vatten, the stormwater management alternatives of interest for the city were established. Additionally, information of interest for the MCA was produced through discussions with different key-players, which encompass the sustainability framework (Figure 21). Chalmers University of Technology participated in the process as the party expert in the technical and environmental aspect. The departments Culture and Leisure (in Swedish: Kultur och Fritid) and Society and Environment (in Swedish: Samhälle och miljö) from the city-districts Västra Hisingen and Örgryte-Härlanda, respectively, participated in the process as the expert parties in the social aspects.

The information gathered along the MCA process was used as an input in a model using the software Web-hipre (available at: http://hipre.aalto.fi): a software used for the structuring of decision problems and multicriteria evaluations.

5.4 Limitations

The hydraulic analysis and water sampling were performed exclusively in the installations selected. The resulting information is expected to support the criteria that constitute the MCA. Data required for the other BMPs and established criteria were obtained from the literature; performance data highly rely on the local conditions on which the studies were developed. Therefore, significant uncertainties can be created when the information is applied to other regions. Sweden is of particular interest due to its cold climate characteristics, where the implementation of grassed systems (which make up a significant fraction of the BMPS) can be restricted due to a decrease in the performance during cold periods. The city of Gothenburg is characterized by a limited number of structural BMPs, which include few sedimentation lagoons, rain gardens, manhole filters, grassed swales, and filter strips. As a consequence, information on a local level was preferred, but not always ascertained due to a limited existence of performance data.

It was not possible to determine with certainty a place of interest for future implementation of stormwater management projects in Gothenburg. Therefore, it was decided to carry out the MCA at the city level. The analysis at the city level generates a lack of certainty in the results, due to the high importance in determining a place to implement urban drainage systems. The selection of a site determines precisely the local conditions in which the study is established, which include: hydrologic conditions, anthropogenic activities developed in the area, environmental conditions and impacts of the pollutants in the water, social restrictions due to the behavior and preferences of the affected communities, and spatial and local constraints. As a result, the results of the MCA do not include but do consider exclusion criteria. The exclusion criteria acquaint different elements that must be stipulated based on the local and site-specific conditions of the study, based on the considerations of the different key-players.

The assessment and description of domestic wastewater, which interacts with stormwater in combined sewer systems, was not included.

6. Results

6.1 Sampling campaigns

6.1.1 Water quality

Water samples were not collected in 2018 due to problems presented during the installation of samplers, which delayed the beginning of the sampling campaigns. Besides, the following months corresponded to one of the warmest spring months in the last decades in Sweden, accompanied with low precipitations in Göteborg (SMHI, 2018), which prevented the sampling campaigns to be carried out. As a consequence, the water quality analysis relied on previous sampling campaigns.

Water sampling was commissioned to DHI Sverige AB by Kretslopp och Vatten in the year 2017. Two sampling systems were used to collect flow-proportional composite samples to measure the incoming and discharged pollutant concentrations. The first sampling system, composed by an ADS3600 flow meter and a SIGMA water sampler, was located in the inlet of the system (Point A, Figure 29). Additionally, the second sampling system, constituted by a Triton+ flow meter and an ISCO water sampler, was located at the outlet (Point C, Figure 29). The water samples were triggered to operate based on the water level.

Results in Table 9 form part of the document prepared by DHI Sverige AB and presented to Kretslopp och Vatten in January 2018 (DHI, 2018). Table 9 shows the pollutants selected and involved in the analysis, which are divided into four main groups: Nutrients, metals, oil index, and organic compounds. DHI reports the PAHs divided into different categories: PAH-L corresponding to low molecular weight compounds (152-178 g/mol) such as acenaphthene and acenaphthylene; PAH-M corresponding to medium molecular weight compounds (around 200 g/mol) such as fluoranthene and pyrene; and PAH-H as high molecular weight compounds (202-278 g/mol) such as benz[a]anthracene, benzo[b]fluoranthene, benzo[j]fluoranthene (Agency for Toxic Substances and Disease Registry, 1995). Additionally, due to its high importance in water contamination, Benzo(a)pyrene, a PAH-H, is reported separately. Appendix 3 show the hydrographs reported during the sampling period.

Table 9: Concentration of pollutants measured at the inlet and the outlet for each of the three days of sampling: Adapted from: (DHI, 2018).

** The right-most column shows the maximum concentrations of pollutants allowed at the discharge points in receiving water bodies for the city of Gothenburg. Source: (Göteborg Stad, 2013)*

	Parameter	Day 1		Day 2		Day 3		Target values at emission point [µg/l] *
		Inlet [µg/l]	Outlet [µg/l]	Inlet [µg/l]	Outlet [µg/l]	Inlet [µg/l]	Outlet [µg/l]	
Nutrients	Total P	17	17	5.3	510	210	1300	50
	Total N	5500	5400	270	510	866	1300	1250
Metals	Arsenic	0.89	0.86	0.58	0.48	0.47	0.77	15
	Lead	0.65	0.54	0.2	0.2	0.2	0.2	14
	Cadmium	0.79	0.26	3.2	0.22	0.03	0.03	0.4
	Copper	14	12	7.5	4.2	8.2	6	10
	Chromium	2.1	1.8	3.8	2.8	15	6.1	15
	Nickel	3.2	2.3	3.4	2	0.52	1.9	40
	Zinc	53	23	60	7.8	3	3	30
	Mercury	0.006	0.005	0.006	0.005	0.005	0.005	0.05
	Oil	100	700	100	200	900	500	1000
Organic Compounds	PAHL	40	9700	40	40	40	41	-
	Benso(a)pyrene	0	0.013	0	0	0	0.026	0.05
	PAHM	48	440	60	19	130	200	-
	PAHH	25	240	92	94	240	460	-
	Suspended Solids	45000	5400	15000	110000	650000	0	25000
	PAH	75	10000	150	79	370	700	-

Table 9 show higher concentrations of pollutants at the outlet of the system, compared to the incoming water. Similar results were found in reports from studies developed in the city of Stockholm on stormwater treatment filters (Alm, et al., 2015; Dromberg, 2009). The use of filters showed detrimental stormwater quality due to high concentrations of pollutants in the media: contaminants may leach from the filter material induced by high water flows and by improper and malfunctioning structures. Additionally, this phenomenon can occur due to resuspension of retained sediments in the basin when high water flows. The third rain event sampled (2017-08-04) shows the highest number of detected pollutants and higher concentrations at the outlet of the system than the inlet. Thirteen of the seventeen pollutants exhibited insignificant retention or an increase in concentration between the inlet and outlet. Measurements from event 3 show lower water flows in the inlet in comparison with the previous sampling events (2017-06-12 and 2017-07-31). The reasons for the increased concentrations at the outlet are not clear.

All three events show retention of metals (mostly Pb, Cd, Cu, Cr, Ni, and Zn) yet higher concentrations of organic compounds in the outlet. Event 2 shows substantial retention of PAHs although no retention of suspended solids was registered. These results are considered inconclusive due to the correlation of hydrophobic organic compounds, some metals, and suspended solids concentrations in contaminated water (Butler & Davies, 2004; van der Perk, 2012).

Table 9 shows the guidelines values of pollutants at the point of discharge established for the city of Gothenburg (Göteborg Stad, 2013). The high concentrations of organic pollutants measured may be related to the construction activities that are present in the area at the time of sampling. It is assumed that a spills of petroleum derivates could occur in the days leading up to the first sampled event measured. The pollutants could have been retained in the system and washed away at the start of the runoff event, leading to high concentrations in the outlet. Also, it is possible a mismatch in time between the inlet and outlet samplers due to difficulties in the programming of automatic samplers. This situation may cause a delay in the activation of the inlet samplers that happen to miss the first flush, which is then captured by the outlet samplers. The oil index concentrations were also elevated in samples from Event 1.

The results show that low concentrations of heavy metals enter the system (Table 9). All the measured values in the inlet, except for Cd, Cu, and Zn, meet the target values of the city of Gothenburg. After treatment, the concentrations of Cu are the only ones which are not compliant. It is important to recall that heavy metals and organic pollutants are of particular importance due to the impacts linked to bioaccumulation and biomagnification in organisms, such as the trout that are found downstream of Krogabäcken. On the other hand, the nutrient concentrations do not comply with the guideline values, and the concentrations in the outlet exceed the levels in the inlet. The reasons for these occurrences are not entirely clear.

The time between the activation of the two automatic samplers was stated as 30 s, but no further analysis of the detention time in the three-piped system was performed. The delay time is an essential aspect of the reduction potential of detention basins. Resuspension of sediments can easily occur because the outlet is located in the bottom part of the basin, leading to clogging on the filter or direct discharge via the overflow structure during high flows. However, it is assumed that the three-piped-system aims at peak flow reduction, and not to achieve a high reduction of pollutants.

In order to determine the behavior of the water within the system, and to determine which of the three pipes receives the largest volume of water, a tracer test was performed using Pyranine. The discharge of water at point A (Figure 29) was not measured accurately, but it is estimated that the water flow corresponds to 3-4 m^3 in 15-18 min (3.3 – 3.7 l/s). The water has higher flow and present shorter arrival times in the central pipeline (Table 10). As a consequence, the automatic water sampler was installed in the middle pipeline in Point B (Figure 29).

Table 10: Water delay time and flow velocity measured in three different points along the detention basin (Point

Time	Location	Velocity (m/s)
0:04:15	A.1	-
0:04:46	B (middle)	4.7
0:09:40	B(west)	0.43
0:11:45	B(east)	0.31
0:12:45	Filter	0.27
0:15:50	Outlet	0.2

The results of the tracer test are also considered inconclusive since the volume of water discharged, and its related flow, is minimal and does not give a good indication of how the system works during rainfall events. It is interesting to study how the system behaves during heavy rain events where it handles large amounts of water. This would reveal the reduction of peak flows achieved by the detention system, which promotes proper functioning of the filter and adequate water discharges to the erosion sensitive water body. The pyranine concentrations at the measurement points should be considered to study the transport of contaminants within the system, and clearly understand the distribution of water and the levels of pollutants in each of the pipelines.

Further visits to the treatment system led to the following observations:

1. The manhole filter was lacking the overflow structure (Appendix 4). Under normal operating conditions, this overflow structure creates a relative high-pressure system that drives the water through the filter media. The lack of this structure allows the water to pass directly through this void space. As a consequence, the water does not pass through the media and is led directly into the outlet of the filter, and further discharged into the receiving water body. The remedial actions required were taken by installing the missing piece appropriately. Needs for media maintenance and cleaning were also identified.
2. The corrective cleaning actions performed on the filter showed a low and insufficient amount of filter media. As a consequence, it is assumed that the media does not hold the structural requirements for proper contact between the water and the media. Therefore, low retention of pollutants is foreseen.

6.2 Comparative analysis of stormwater treatment options

Appendix 6 presents the results of the literature review conducted on the performance of the stormwater treatment alternatives described in Section 3.3.3. The performance factors included in the comparison are divided into technical, environmental, social, and economic categories. These factors correspond to the benchmarks used in the MCA analysis to evaluate the criteria. Their inclusion in the MCA is further exposed in Table 13.

The pollutant removal efficiency and hydraulic performance of BMPs present high variabilities. It is clear that the highly dynamic hydrological phenomena in natural and urban environments lead to high variability in the reported results. The dynamic nature of stormwater and high diversity of site-specific aspects need to be taken into account when evaluating the performance of individual BMPs. The different activities in the catchment area, the characteristics of the society, the characteristics of the local precipitation events and the urbanistic characteristics of the catchment area, design of the structures, and the recurrence of monitoring and maintenance operations are some of the factors that influence the pollutant reduction potential of each of the stormwater treatment structures. Moreover, the global variability of the characteristics of the receiving water bodies leads to a problematic determination of satisfactory performance of the systems to achieve environmental objectives (e.g., receiving water quality standards and flood protection). There is a need for new knowledge about BMPs´ performance to address the lack of data. Nevertheless, with the information gathered, an expected reduction of pollutants and hydraulic performance for each of the BMPs can be asserted. It should be noted that higher uncertainties where found in the analysis of the reduction potential of organic pollutants.

Through literature research, it was evidenced that most BMPs are efficient systems that generate satisfactory results concerning the reduction of pollutants, control of water flow, social benefits and, in some cases, biological benefits. In turn, the costs of implementation, operation, and maintenance are much lower compared to conventional treatment systems. However, a lack of information was identified concerning detailed design criteria that can satisfy the information needs that lead to more reliable and effective systems. The information found throughout the literature review is usually general information, where specific information that can lead to better performance of each BMP is usually missing. It is important to emphasize that the data found regarding SUDS include, in most cases, the social components and benefits of each system; something that is not directly taken into account in conventional treatments design processes. Throughout the literature, it is evident the emphasis that is given to the possibilities of better use of the land encompassing and achieving social and environmental benefits. The global trend in the West hemisphere towards sustainable development has led to the generation of valuable information regarding SUDS, as well as the implementation of successful water drainage options.

The International BMP database (http://www.bmpdatabase.org) is an important tool that contains global information on the implementation and development of more than 600 different urban drainage systems. The last summary report, published in 2016, identifies the lack of information available for specific BMPs with regards aspects such as (Clary, et al., 2017):

- Retention of fecal indicator bacteria such as enterococcus and E. coli
- Pervious pavements general information

Construction and maintenance costs are an essential aspect in the selection of stormwater treatment alternatives. High variability of associated costs was encountered throughout the literature review. Similar to the performance of the system, the costs are associated with site-specific characteristics and local and regional economic aspects. The importance of monitoring and maintenance needs (and their related costs) was evidenced by the literature study and is considered an essential aspect that needs to be emphasized, due to its correlation with the reliability, durability, and performance of the different systems. Monitoring and maintenance needs are commonly not contemplated by regional and local authorities throughout the entire lifecycle of the system. Failures associated with the lack of monitoring and maintenance were reported in all the stormwater treatment systems. Likewise, public risks (e.g., fire hazards in green gardens and deterioration of obligatory public awareness signs in dry detention basins and wet ponds that create public hazards) are associated with lack of monitoring and maintenance activities.

6.3 Multi-Criteria Analysis

The information from the MCA, which aims to evaluate the different BMPs presented in section 3.3.3 and compared in section 6.2, led to the results presented in the next section based on the procedure stated by Department for Communities and Local Government (2009) and presented in Section 3.5.2.

6.3.1 Identification of the goal and establishment of the decision context

The objective of the multicriteria analysis is to evaluate different alternatives for the adequate management of stormwater in the city of Gothenburg, within the sustainability context. The evaluation criteria must consider environmental, economic, social, and technical aspects to cover the main problems to which a decision-making method is exposed. The process must include different key-players (including the stakeholders) to incorporate the established evaluation categories and to evaluate in a precise and concise way the performance of the alternatives according to the criteria.

The party with the highest interests and potential outcome investments, Kretslopp och Vatten was defined as the principal stakeholder for this process. Kretslopp och Vatten is the responsible department for handling and managing the water resources for the municipality of Gothenburg. Chalmers University of Technology, defined as a key-player, participated in the generation, analysis, and discussion of the data that was used in the process. Between the previously mentioned parties, the alternatives and criteria were established and evaluated. The departments Culture and Leisure and Society and Environment from the city-districts Västra Hisingen and Örgryte-Härlanda participated as social key-players in the evaluation and weighting of the stormwater treatment alternatives against the criteria. Table 11 shows information about the key-players involved in the process.

Table 11: Key-players involved in the MCA

Keyplayers	Field of Expertise	Organization	Position
1	*Technical - Environment*	Chalmers University of Technology	Docent
2	*Technical - Environment*	Chalmers University of Technology	Professor
3	*Technical - Environmental - Economic*	Kretslopp och Vatteen - City of Gothenburg	Project Engineer
4	*Technical - Environmental - Economic*	Kretslopp och Vatteen - City of Gothenburg	Stormwater Engineer
5	*Social*	Culture and Leisure - City of Gothenburg	Head of Section
6	*Social*	Society and Environment - City of Gothenburg	Development Leader

6.3.2 Identification and selection of alternatives

Nine stormwater treatment alternatives were selected based on the SUDS manual presented by Woods-Ballard et al. (2015). Among them, the two treatment alternatives which are currently installed in the area of interest were included in the analysis. The decision to include alternative options was made by the author of this thesis together with Kretslopp och Vatten, aiming to cover alternatives that could achieve appraisable results in the flow management and reduction of contaminants. The interests of Kretslopp och Vatten, based on the feasibility of implementation in the city, were most important in the selection of the evaluated alternatives, presented in Table 12.

Table 12: Stormwater treatment alternatives for evaluation

Alternatives	
Wet Retention Pond	Manhole filters*
Dry Detention Pond	Pervious Pavements
Swales	Green Roof Storage
Infiltration Trenches	Soakaways
Underground detention*	

** System placed in Brottkärr*

Since the possibilities of implementation are seen at the city level and are not evaluated for a specific treatment site, a subsequent analysis should be carried out after choosing the site for treatment to be able to perform an initial area profiling. The initial profiling may lead to the judgment of suitable and unsuitable stormwater treatment option based on the site-specific characteristics. This evaluation can be accomplished by considering exclusion criteria (see section 6.3.3.1). As a consequence, the "*Business as Usual*" (BAU) scenario, which would describe the situation where no stormwater management system is implemented in the area, was not included in the city-level analysis. Nevertheless, it is highly recommended to include and analyze the BAU scenario when developing an analysis for a specific site.

6.3.3 Establishment of criteria

The definition of performance criteria was established as a function of the four principal characteristics – technical, environmental, social, and economic – defined in the objective of the MCA. Each of the four primary categories was divided into specific parameters, which in turn were divided into the defined criteria that were evaluated using specific benchmarks (summarized in Table 13):

- The technical and hydraulic performance of the treatment options were evaluated as regards to two parameters: hydraulic response and technical quality. The hydraulic response effectiveness relates to the *flow control criteria*, which is evaluated in terms of peak flow and volume reductions. The technical quality parameter relates to two different criteria: *system reliability* and *system durability*. These criteria were evaluated in terms of probability of failure and lifespan, respectively.
- The environmental performance of the treatment options was assessed as regards to two parameters: water pollution control and impact on the biophysical surrounding environment. The impact on the biophysical surrounding environment comprises the *impacts on soil* and *groundwater* criteria (evaluated as the negative impacts that could result in contamination of the surrounding soil and the groundwater) and the *impact on the ecological habitat and diversity* (evaluated as a positive impact that could lead to improving the biological diversity in the area).
- The social performance of the treatment option was assessed as regards to other two parameters: public exposure and aesthetics. The public exposure parameters associate directly with the *public interaction criteria*, which is evaluated in terms of public safety hazards and information requirements; and the potential for implementation of recreational activities. The aesthetics parameters associate directly to the *location amenity criteria*, which is evaluated in terms of the aesthetic value of the systems and potential loss of public land (land requirements).
- The economic performance of the treatment options was assessed as regards to two parameters, which in turn define two criteria: *capital costs* and *operation and maintenance costs* (O&M). The capital cost criteria are evaluated in terms of materials and construction costs, while the operation and maintenance criteria are evaluated in terms of monitoring and maintenance needs, and the associated costs.

Table 13: Categories, parameters, criteria, and benchmarks used for the stormwater performance

Categories	Parameters	Criteria	Benchmarks
Technical and Hydraulic (Tech)	*Hydraulic response*	C1. Flow Control	Ability to reduce peak flows and water volumes
	Technical quality	C2. System Reliability	Probability of failure
		C3. System Durability	Expected lifespan
Environment (Env)	*Pollution control*	C4. Pollution Retention	Total solids expected retention
			Biochemical Oxygen Demand (BOD) retention
			Nutrient retention
			Heavy metal retention
			Organic Pollutants
	Impact on the biophysical surrounding environment	C5. Impact on the soil and groundwater	Impacts on the groundwater
			Impacts on the surrounding soil
		C6. Ecological enhancement potential	Potential improvement on biodiversity
Social (Soc)	*Public Exposure*	C7. Public interaction	Public risks - Information/awareness requirements
			Potential on recreational activities
	Aesthetics	C8. Location Amenity	Aesthetic value
			Loss of Public land / land requirements
Economic (Econ)	*Capital Costs*	C9. Capital costs	Material and construction costs
	O& M	C10. Operation and Maintenance costs	Monitoring and maintenance needs
			Costs associated

Each one of the established criteria presented in Table 13 holds flexibility that allows them to be applied to all stormwater management systems, regardless of the place where they are intended to be implemented. Nevertheless, in contrast to what is stipulated in section 3.5.2.3, the lack of independence of some established criteria can be identified. For example, there is a negative correlation between the monitoring and maintenance needs of the alternatives and their hydraulic performance, the technical quality, and the percentage of pollutant retention. Lack of monitoring and maintenance risks relate to lower reliability, performance, and pollutant retention. As a consequence, the implementation of monitoring and maintenance needs in BMPs is emphasized. Another example of the interdependence of criteria is the reduction of public risks associated with increased contaminant retention. Therefore, it can be stated that the criteria comply with most of the relevant requirements in the Sustainable Urban Drainage Systems context (such as objectivity, robustness, sensitivity), but are not independent of each other, which results in a degree of redundancy.

6.3.3.1 Exclusion criteria

Despite the fact that SUDS are low-cost alternatives compared to conventional treatment systems, economic constraints play an essential role in the validation or invalidation of different stormwater systems during decision-making processes. Additionally, specific features of the individual stormwater treatment systems can restrain their use and invalidate their implementation in particular sites (e.g., it is unreal to pretend to install only wet or dry ponds around an entire city due to their high land requirements). Although it is regarded as a subjective aspect, the particular preferences of local authorities or private companies, generally based on previous experiences, also restrict the use of different alternatives.

An initial application and suitability analysis, directed to achieve an objective evaluation of alternatives, can be obtained using exclusion criteria. Table 14 displays different physical constraints which would commonly need to be addressed at the moment of considering the suitability of stormwater treatment systems in a specific site. It is necessary to emphasize that economic (e.g., budget) or social (e.g., community opposition) are also restrictive factors that can exclude different alternatives from the analysis.

Table 14: Exclusion criteria examples. Adapted from: (Ellis, et al., 2004)

Exclusion criteria	**Assessment**	**Effects**
Space Availability	*Yes/No*	*Limits the use of high area demanding systems*
High concentrations of contaminants	*Yes/No*	*Excludes the use of BAU scenario*
Groundwater vulnerability and water table depth	*Yes/No*	*Limits the use of infiltration techniques, while increases the risk of groundwater pollution.*
Water Pollution risk	*Yes/No*	*Pre-treatment systems can be required, demanding more area and resources.*
Soil permeability	*Low/Medium/High*	*Control the use of infiltration techniques and other systems*
Risks of high concentrations of sediments	*Yes/No*	*Limits the use of infiltration systems*
Vehicle/Pedestrian traffic	*Low/Medium/High*	*Suitability/unsuitability for the use os pervious pavements*
Permanent Water Flow	*Yes/No*	*Limits the use of wet retention basis*

The establishment and use of exclusion criteria depend to a large extent on the site-specific characteristics and the alternatives considered by the decision-making agents.

6.3.4 Performance evaluation of the alternatives against the criteria

The analysis of the performance of the alternatives with respect to the established criteria was carried out within each key-player group, described in section 6.3.1. The different groups decided, according to their knowledge and expertise, which criteria categories they were willing to evaluate, and which they preferred not to analyze to prevent a higher uncertainty in the results. It is essential to recognize that a determining factor which affects the results in an MCA is the subjectivity related to the experience, knowledge, expertise, and preferences of each key-player.

Quantitative indicators where established to indicate the performance of each alternative against the criteria: a scale from 0 to 5 was employed. The definition of each of the quantitative values depends on each criterion. Therefore, low or high potential of adequate performance was given a specific score. Appendix 7 details the scores which each of the key-players assigned to the alternatives in the analysis. It can be evidenced that some decided not to perform the scoring of some criteria, based on their lack of knowledge in those specific topics. Table 15 discloses the matrix of evaluated alternatives, with the average of the scores given by all the key-player.

Table 16 presents the standard deviation of the scores, which helps to identify the degree of variability in scoring by the key-players. The economic category presents no standard deviation because only Kretslopp och Vatten scored this category. On the other hand, the social key-players only scored the social category, causing this category to be the only one scrutinized by all the actors.

Table 15: Matrix and evaluation of alternatives.

Alternatives	Criteria									
	Technical Category			Environmental Category			Social Category		Economic Category	
	C1. Flow Control	C2. Reliability	C3 Durability	C4. Pollution Control	C5. Impact on Soil and Water	C6. Ecological enhancement potential	C7. Public interaction	C8. Location Amenity	C9. Capital Costs	C10. O&M
Wet Retention Pond	3.3	4.5	5.0	4.2	4.0	3.8	2.5	2.7	5.0	4.0
Dry Detention Pond	4.3	2.5	5.0	3.3	3.3	2.8	3.3	3.5	5.0	4.0
Swales	3.3	3.5	3.5	3.4	2.8	3.3	3.0	2.7	5.0	4.0
Infiltration Trenches	4.3	1.5	2.3	3.6	1.8	1.5	2.9	2.9	3.5	2.0
Underground detention	2.8	3.8	3.3	1.8	4.8	1.0	2.6	2.3	3.5	3.0
Manhole filters	0.3	1.5	0.5	3.0	4.9	1.0	3.3	2.3	4.0	1.5
Pervious Pavements	4.3	1.5	2.3	3.0	2.3	0.5	3.0	3.0	3.0	2.3
Green Roof Storage	2.5	2.5	2.8	2.4	4.4	3.8	3.7	4.3	4.0	2.8
Soakaways	4.3	2.5	2.5	2.0	1.5	1.0	3.4	2.6	2.5	3.5
	5 - Adequate 0 - Inadequate	5 - High 0 - Low	5 - Long 0 - Short	5 - High 0 - Low	5 - Low 0 - High	5 - High 0 - Low	5 - Low 0 - High	5 - High potential 0 - Low Potential	5 - Low 0 - High	5 - Low 5 - High

Table 16: Evaluation´s standard deviation

Alternatives	Criteria									
	Technical Category			Environmental Category			Social Category		Economic Category	
	C1. Flow Control	C2. Reliability	C3 Durability	C4. Pollution Control	C5. Impact on Soil and Water	C6. Ecological enhancement potential	C7. Public interaction	C8. Location Amenity	C9. Capital Costs	C10. O&M
Wet Retention Pond	1.8	0.7	0.0	0.6	1.1	1.8	0.5	0.3	-	-
Dry Detention Pond	0.4	0.7	0.0	1.1	1.1	1.1	1.1	0.9	-	-
Swales	0.4	2.1	0.7	0.1	0.4	1.1	0.4	0.2	-	-
Infiltration Trenches	1.1	0.7	0.4	0.0	0.0	0.7	0.6	1.5	-	-
Underground detention	1.1	1.1	0.4	0.1	0.4	1.4	0.1	0.3	-	-
Manhole filters	0.4	0.7	0.7	0.5	0.2	1.4	1.1	0.3	-	-
Pervious Pavements	1.1	0.7	0.4	0.0	0.4	0.7	0.4	0.5	-	-
Green Roof Storage	2.1	0.7	0.4	0.6	0.9	0.4	0.3	0.7	-	-
Soakaways	1.1	0.7	0.7	0.1	0.7	0.7	1.4	0.5	-	-

Despite their bias and subjectivity, the results only present a considerable variation in the scoring of the following criteria:

- Flow control: the criterion with the highest variability between the scores.
  - *Wet retention ponds*: The scores assigned to flow control were 4 (Chalmers University of Technology) and 2 (Kretslopp och Vatten). As evidenced in the performance evaluation of alternatives, wet retention ponds have a high ability to reduce peak flows but have low-to-none ability in reducing the water volume. Therefore, based on the results, further analysis will be recommended to determine whether it is appropriate to consider these two reductions (peak flow & volume) in separate criteria to allow more in-depth analysis and discussion.
  - *Green roofs:* The scores assigned were 4 (Chalmers University of Technology) and 1 (Kretslopp och Vatten). Green roofs present a low reduction potential of peak flows. However, studies report volume reduction in the sewer systems of up to 50% of the precipitation associated with the implementation of green roofs in Sweden.
- Reliability:
  - *Swales:* The scores assigned were 5 (Chalmers University of Technology) and 2 (Kretslopp och Vatten). It is not clear which factors were taken into account by the scoring actors. However, in the literature, problems associated to the clogging of inner pipes in the swales´ structures are currently reported. Further research is required to achieve a more profound and conclusive analysis.
- Ecological enhancement potential: The criterion presents the second highest variability between the scores. The wet retention pond is the alternative which deserves special attention:
  - *Wet retention ponds:* The scores assigned were 2.5 (Chalmers University of Technology) and 5 (Kretslopp och Vatten). This aspect is of particular interest due to the great variety of factors that can be considered and affect the results of the evaluation. It is worth to highlight the fact that, in wet retention systems where the concentrations of pollutants are very high, the enhancement of biodiversity implies a negative impact. On the other hand, wet retention basins with low levels of pollution represent an area with a positive impact on biodiversity. These aspects need to be considered in a further in-site analysis of the expected system.

6.3.5 Weighting of the criteria

Each key-player assigned a percentage to each of the criteria to identify their preferences, and thus, present the importance considered by each of their expertise fields in the process of evaluation. The categories of criteria were assessed as presented in Table 17.

Table 17: Criteria Weighting results

Criteria		Key players		
		Kretslopp och Vatten	*Chalmers University of Technology*	*City of Gothenburg*
Technical Category	C1. Flow Control	5%	15%	9%
	C2. Reliability	10%	15%	5%
	C3. Durability	5%	5%	7%
Environmental Category	C4. Pollution Control	20%	25%	23%
	C5. Impact on Soil and Water	5%	8%	11%
	C6. Ecological enhancement potential	10%	3%	6%
Social Category	C7. Public interaction	4%	15%	20%
	C8. Location Amenity	6%	5%	10%
Economic Category	C9. Capital Costs	15%	2%	3%
	C10. O&M	20%	8%	7%

The analysis of the results shows:

- The results correspond to the expected outcomes, in which the social actors determine higher importance to the social criteria when compared to the other key-players; the decision-making actors determine a higher value for the economic aspects; the technical and environmental actors achieve a more equitable evaluation. Each of the parties identify the environmental category as the most important one. However, Kretslopp och Vatten grants to the economic category the same percentage as the environmental category (35%).
- The awareness of monitoring and maintenance operations was evidenced. The three key-players determined, within the economic category, higher weight for the O&M criteria rather than in the initial costs. The literature commonly reports system failures due to lack of monitoring and maintenance. It is considered that the mentioned awareness does not correspond to what usually occurs with already established systems, especially those that are close to reaching their expected life-time.
- Within the social category, the higher importance of controlling public risks and their associated information requirements is evident in two of the three actors, relating to the aesthetic potential and public comfort of the systems. The reason behind this preference from one of the three key-players is not clear and would require further analysis.

It is essential to highlight, over again, that subjectivity also plays an essential role in this stage. The results can vary significantly even within groups with the same expertise.

6.3.6 Final evaluation based on the overall weighted score of the alternatives

The results of the MCA for the three scenarios are shown in Table 18. The ranking of alternatives, resulting from the analysis for each of the three actors involved, is presented individually in Figures 30-32. The Y-axis corresponds to the values contributed by each of the criteria to the final results of the alternatives.

- Figure 30 shows the results based on the weights granted by Chalmers University of Technology to the criteria. The preference ranking is:
  (1) Wet retention basins
  (2) Dry detention basins
  (3) Swales
  (4) Green roofs
  (5) Infiltration basins
  (6) Soakaways
  (7) Pervious pavements
  (8) Underground detention
  (9) Manhole filter

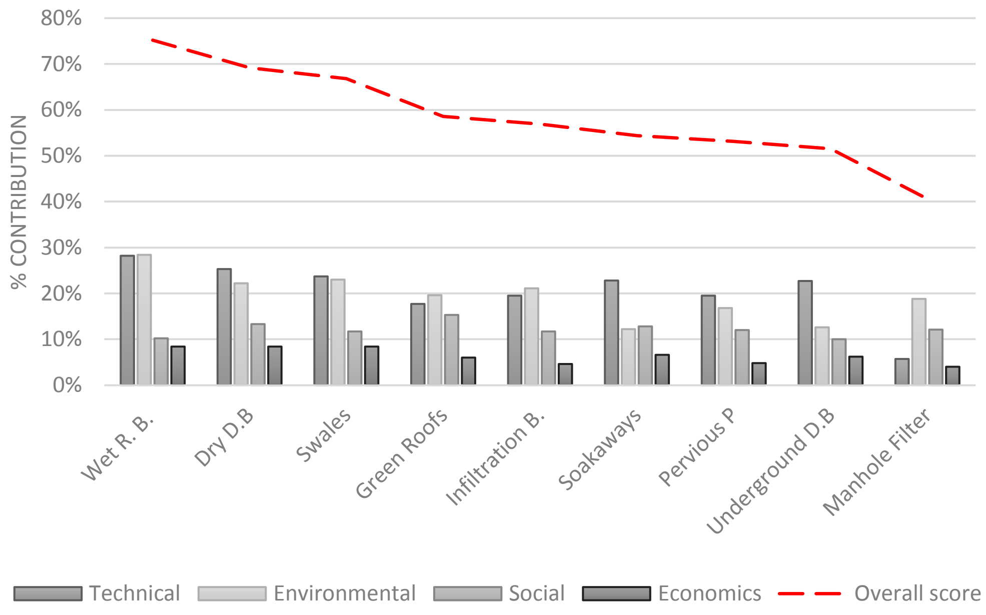

Figure 30 Preferred ranking of BMPs by Chalmers University of Technology

- Figure 31 shows the results based on the weights granted by Kretslopp och Vatten to the criteria. The preference ranking is:
  (1) Wet retention basins
  (2) Dry detention basin
  (3) Swales
  (4) Green roofs
  (5) Underground detention
  (6) Infiltration basins
  (7) Soakaways
  (8) Pervious pavements
  (9) Manhole filter

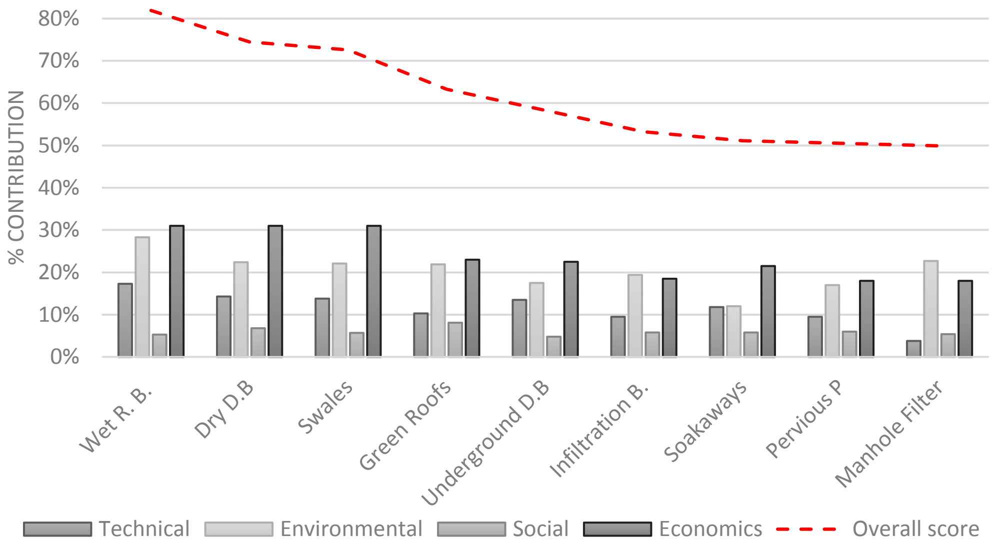

Figure 31 Preferred ranking of alternatives by Kretslopp och Vatten

- Figure 32 shows the results based on the weights granted to the criteria by the departments Culture & Leisure and Development & Environment from The City of Gothenburg. The preference ranking is:
  (1) Wet retention basins
  (2) Dry detention basin
  (3) Swales
  (4) Green roofs
  (5) Infiltration basins
  (6) Pervious pavements
  (7) Soakaways
  (8) Underground detention
  (9) Manhole filter

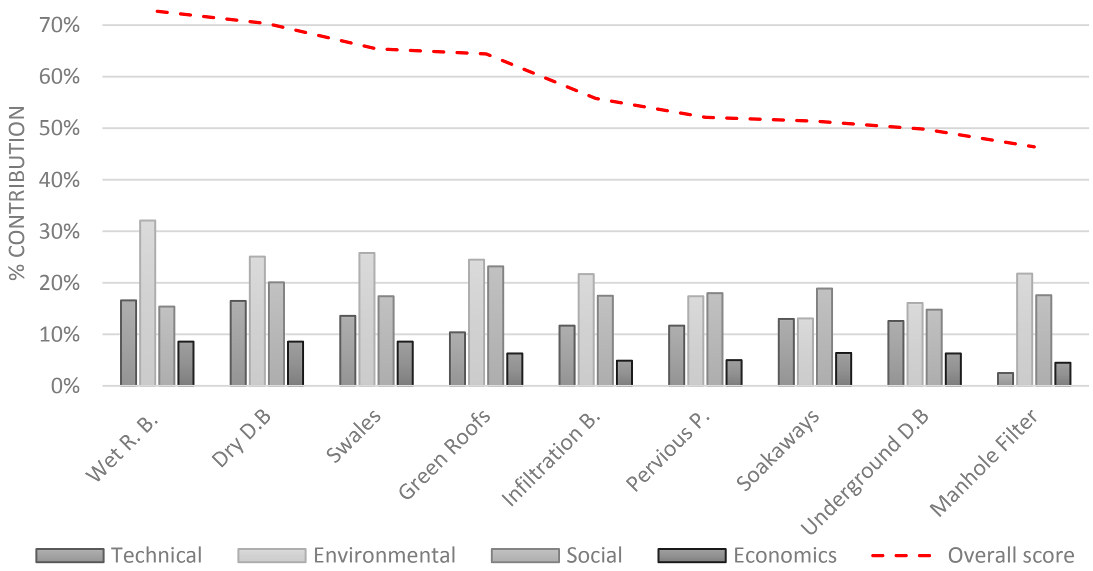

Figure 32 Preferred ranking of alternatives by Gothenburg City (social actors)

Table 18: Compiled MCA results based on the alternatives' scoring values and criteria weights

	Alternatives	Wet R. B.	Dry D.B	Swales	Green Roofs	Infiltration B.	Soakaways	Pervious P	Underground D.B	Manhole Filter
Chalmers University of Technology	Technical	0.28	0.25	0.24	0.18	0.20	0.23	0.20	0.23	0.06
	Environmental	0.28	0.22	0.23	0.20	0.21	0.12	0.17	0.13	0.19
	Social	0.10	0.13	0.12	0.15	0.12	0.13	0.12	0.10	0.12
	Economics	0.08	0.08	0.08	0.06	0.05	0.07	0.05	0.06	0.04
	Overall score	*0.75*	*0.69*	*0.67*	*0.59*	*0.57*	*0.54*	*0.53*	*0.52*	*0.41*
Kretslopp och Vatten	Technical	0.17	0.14	0.14	0.10	0.10	0.12	0.10	0.14	0.04
	Environmental	0.28	0.22	0.22	0.22	0.19	0.12	0.17	0.18	0.23
	Social	0.05	0.07	0.06	0.08	0.06	0.06	0.06	0.05	0.05
	Economics	0.31	0.31	0.31	0.23	0.19	0.22	0.18	0.23	0.18
	Overall score	*0.82*	*0.75*	*0.73*	*0.63*	*0.53*	*0.51*	*0.51*	*0.58*	*0.50*
Social actors	Technical	0.17	0.17	0.14	0.10	0.12	0.13	0.12	0.13	0.03
	Environmental	0.32	0.25	0.26	0.25	0.22	0.13	0.17	0.16	0.22
	Social	0.15	0.20	0.17	0.23	0.18	0.19	0.18	0.15	0.18
	Economics	0.09	0.09	0.09	0.06	0.05	0.06	0.05	0.06	0.05
	Overall score	*0.73*	*0.70*	*0.65*	*0.64*	*0.56*	*0.51*	*0.52*	*0.50*	*0.46*

7. Discussion & Recommendations

7.1 The Stormwater treatment system in Brottkärr

Although the results from the sampling campaigns indicate retention of metals and nutrients, and compliance with several values stipulated in Gothenburg's Water Discharge Guidelines (Table 9), there are still problems associated with the high concentrations of organic contaminants and Cu, proper installation and functioning of the system, and its high monitoring and maintenance demands. The presence of pollutants in the water is likely due primarily to the construction activities in the area and determines its treatment needs to reach the guideline values. The discharge of contaminated water into Krogabäcken remains the fundamental concern due to the presence of trout and the sensitive state of the river concerning pollution and flooding.

The construction activities that currently occur in the area considerably affect the water quality and further, the high concentrations of solids associated with these activities also affect the operation of the filter. Activities performed in construction sites such as earth moving works, paving, house construction and temporary wastewater discharges, relate to high concentrations of suspended solids and nutrients in stormwater (Sillanpää & Koivusalo, 2015). It can be assumed that after the termination of the construction activities in the area, resulting in a lower discharge of sediments and pollutants in general, the performance of the system can improve, leading to a lower release of contaminants into Krogabäcken. It is essential to install, as soon as possible, a new filter media according to the treatment needs and manufacturer's recommendations. Additionally, it is recommended to perform continuous monitoring and maintenance operations in the system while the construction activities are present. After the termination of these activities, such monitoring actions need to continue for a period of time to achieve proper knowledge of the systems, which can lead to more conclusive results concerning its operation and the potential of contaminants reduction. Filter capacity, performance, and efficiency can be optimized by implementing proper monitoring schemes that lead to adequate maintenance practices (Erickson, et al., 2010). The durability and long-term operation of stormwater alternatives is dependent on the monitoring and maintenance actions (Jefferies, et al., 2009).

Previous reports on the pollutant reduction potential in stormwater filters do not show adequate results (Alm, et al., 2015; Dromberg, 2009). Regular evaluation of the system is recommended due to the development of the urban area, which leads to a continuous increase of impervious areas and an increment in the intensity of pollutant generating activities. It is essential for the city of Gothenburg to determine which systems achieve a significant reduction of pollutants, under which scenarios these can be installed, and which are the surrounding factors that can profoundly impact the operating conditions of the system. Particular attention must be placed when considering systems such as manhole filters. Media clogging is the main limiting factor in the use of stormwater treatment filters (Kandra, et al., 2014).

The implementation of manhole filters is not viable when it is intended to handle stormwater from large catchment areas due to its low capacity of peak flow and water volume control (Woods-Ballard, et al., 2015). That is why water detention systems are usually installed before the water quality treatment systems. The implementation of manhole filters in small catchment areas can be a viable alternative, but its effectiveness depends on many factors linked to the catchment area. That is why the determination of the characteristics and activities occurring in the area is fundamental at the moment of selecting an adequate treatment alternative.

The pollutant removal efficiency of stormwater filters is highly dependent on the characteristics of the filter media. Waste products such as sawdust and pine barks have been reported to exhibit important retention of hydrophobic organic compounds (Björklund & Li, 2015). Generic mulch and processed jute also achieve retention of metals and benzo(a)pyrene under controlled conditions (Wojtenko, et al., 2001). The removal of pollutants highly depends on factors such as the surface area of the filtering media in contact with the water. The practicality of the implementation of these methods in the field needs further study due to problems associated with the reduction in the hydraulic capacity of the filters linked to clogging incidents, which is a major problem in stormwater filters and biofilters (Hatt, et al., 2006). It is also important to keep in mind that after its useful life is over, the filter media becomes waste which entails treatment requirements and remediation.

It is considered essential to align ideas and actions among the different actors that carry out the construction and operation of the stormwater treatment systems throughout the city of Gothenburg. Entities such as Trafikverket (the Swedish Transport Administration) and Trafikkontoret (the municipal traffic department) need to be included in the analysis and discussions of the operating state of the treatment systems installed in the roads throughout the city and municipalities. These analyses must include factors such as:

- The current activities in the catchment area and their pollution intensity.
- The activities planned to be carried out in the area, their lifetime, and pollution intensity.
- The current state of the area concerning water and air pollution.
- The operation and maintenance needs of the different stormwater alternatives considered.
- The expected pollution reduction of the system.
- The sensitivity of the receiving water bodies.
- The public exposure and interaction with the system.
- All the stormwater systems which are installed along the water path before it is discharged into the receiving water body.

The alignment between the different responsible entities will lead to better results in terms of pollution mitigation, lower costs in the operation and maintenance of the systems, and the constant improvement in the implemented technologies around the city.

7.2 Comparative analysis of stormwater treatment options

In general terms, the comparison of the performance of different BMPs for the various analyzed aspects presents high uncertainties (see Appendix 6). The information resulting from the literature review corresponds to a statistical summary of the expected performance of stormwater systems. This information is intended to give a general idea about the performance of each of the alternatives but cannot be taken as a definitive and forceful message. An analysis of catchment area characteristics is considered a crucial aspect that determines the system´s performance. Particular BMPs have been reported to work appropriately in areas while failing in others due to regional and local characteristics (e.g., grassed BMPs work less efficiently in cold climate regions) (Wang, et al., 2017). Design manuals should be focused on local aspects, considering the different features of a region, and not on general guidelines.

The implementation of the SUDS should not be seen as a single stormwater management system located in one specific site. Instead, the management of stormwater should be seen at a local and regional level considering the entire water path from sources to receiving water bodies (Bastien, et al., 2010; Jefferies, et al., 2009). Separate analyses along the entire water path should be done to identify the water management necessities in the different sub-catchments. Multiple sites, where local management of water is achieved, results in a whole water management scheme that works by stages as a water treatment train, resulting in a more robust system (Jefferies, et al., 2009). Figure 12 shows the different zones that can be defined along the water path (inlet and source control, site control, and regional control) in which specific alternatives can be placed.

The sole participation of the municipalities as the entities responsible for stormwater quality is not enough. Different statutes must be implemented to demand the inclusion of constructors and inhabitants in the integrated management of stormwater, attacking the generation of pollutants and the production of runoff at the source (upper parts of the water path). An excellent example of this, is the use of green roofs and infiltrations lawns in private property, which involves land owners to decrease water quantities reaching the sewer systems. The inclusion of different actors promotes the generation of knowledge and nurtures the awareness of the problem, thus creating better conditions for the networks to function. When the implementation of inlet-source and site control alternatives is not possible, end-of-pipe solutions are necessary to mitigate the water quality and quantity problems.

7.3 MCA Discussions

It is essential to evoke that a highly influential factor on the outcomes of an MCA is the subjectivity related to the experience, knowledge, and expertise of each key-player. Subjectivity also plays a prominent role in the alternative scoring stage, but is more evident in the criteria weighting stage, where the key-players define their preferences explicitly. Despite the high subjectivity of the MCA analysis, the inclusion of different and diverse actors is of vital importance if it is to generate more accurate, inclusive, and efficient results. The definition of the objectives can be more complex among a higher number of actors, but it is considered that the discussions created, to allow the determination of a more realistic context, generates better results.

The actors included in the present study can be counted as the first approach for future MCA implementations, but they are not sufficient in the achievement of a more detailed analysis. The influence and participation of other types of actors throughout the city of Gothenburg plays an essential role in the scope of in-depth analysis. For example, Trafikkontoret is the department responsible for the construction of the different stormwater management systems related to road construction activities. Additionally, as evidenced in Section 3.2.3, traffic is an important source of pollutants. Hence, it is critical for Kretslopp och Vatten to participate in the design and construction stages of the alternatives planned by Trafikkontoret, and to include these actors when analyzing the potential implementation of urban drainage systems for road runoff. Adequate communication and joint work can lead to the implementation of better alternatives with lower operation and maintenance costs without affecting the performance. In turn, the inclusion of the environmental department of the city of Gothenburg should be considered in the MCA to align the stormwater management objectives with local plans that include monitoring, reporting, and proposal of actions aimed to the protection of the city's water bodies.

Table 19 proposes different actors in Gothenburg which are thought of vital importance in the implementation and achievement of adequate and sustainable stormwater management. For example, the Green strategy for a dense and Greener city (in Swedish: Grönstrategi för en tät och grön stad) of Parks and Nature Management (in Swedish: Park- och naturförvaltningen), which aims to increase the green areas in the city for social and ecological benefits, can be aligned with stormwater management practices by the use of BMPs. Table 19 does not intend to establish these actors as the only participants on which responsibilities rely. The site-specific analysis, which should include a whole study of the catchment area and the anthropogenic and biological activities present, should result in the accurate determination of the key-players of interest for an MCA. Private parties, district administrators, and the Construction, Surveying and Planning department could also contribute in a high extend to the effective management of the stormwater.

Table 19: Suggested entities to be included in future in-site analysis.

Entity	English Name
Miljöförvaltningen	Department of Environment
Förvaltningen kretslopp och vatten	Department for Sustainable Waste and Water
Trafikkontoret	Department of Traffic
Park- och naturförvaltningen	Department of Parks and Nature Management
Stadsbyggnadskontoret	Department of City Planning
Byggande, lantmäteri och planarbete	Department of Construction, surveying and Planning
Kulturförvaltningen	Department of Culture Administration
Stadsdelsförvaltningar	District Administrators

The selection of alternatives, as well as the evaluation criteria, must be chosen and determined among the actors involved and their preferences. The determination and analysis of a specific site of alternative implementation are essential in the process of obtaining adequate results. The method of exclusion criteria needs to be used during the determination of alternatives, thus avoiding unnecessary costs related to the consideration of non-viable options. In turn, the BAU scenario needs to be considered to evaluate the need for stormwater management accurately. Additionally, it is recommended to perform the criteria selection by including at least one more key-player, and not only the stakeholder. Consequently, the criteria contained in this study consists of a starting point for further analysis. The criteria selected presents interdependency problems among them, creating redundancy in the evaluation. Öztürk (2006) exposes different methods to handle the redundancy and inter-dependency of criteria. It is assumed that the redundancy and dependency of criteria can be reduced by performing the MCA analysis in a specific place and by including different actors who allow the identification of a broader spectrum of evaluation criteria.

The method used in the scoring of alternatives entails a high uncertainty due to the lack of dialogue and discussion among the participants. As exposed in Section 6.3.4 and Appendix 7, each participant scored the alternatives based on their willingness, knowledge, and expertise. The method required then a further analyzes and calculations in which the final result was achieved by calculating average values of the individual scoring. As a consequence, the uncertainty in the results increased. A substantial reduction in the standard deviation in the alternatives´ scoring can be achieved by conducting group discussions and collective determination of the performance results. To improve the method, it is recommended to carry out this exercise through workshops, in which people with expertise and related knowledge meet to discuss each of the alternatives against the criteria categories, expecting to achieve a single agreed value.

Although the results vary between key-players, wet retention basins, dry detention basins, swales, and green roofs are ranked the top four BMPs in all the analyses. The uncertainty associated with the subjectivity and preferences of the key-players plays an essential role in the results. Martin et al. (2007) report the results of an MCA for stormwater management, where the BMPs preferred by three different key-players resulted in infiltration system (such as infiltration trenches and soakaways) ranked on top for every case. It is considered that the extrapolation and comparison of results are not feasible due to the mentioned subjectivity of the involved key-players and its related uncertainty. In a local aspect, due to the difficulties on the implementation of infiltration systems in Gothenburg linked to the low permeability of the soils, it is assumed that these systems did not obtain a considerable value in the results of this study.

The results of the MCA show the preferences of the different actors concerning the criteria categories under the sustainable development framework used. Although the three key-players point to the environmental category as the principal aspect, sharp differences were evidenced in the criteria weighting stage regarding the social category. Gothenburg, as a city focused on the achievement of Sustainable Development, needs a greater integration of the social aspects into the urban and environmental objectives associated with urban drainage. The study shows an opportunity to improve the integration and inclusion of the mentioned social aspects into local engineering and urban planning systems, achieving results that align better with the objectives of the city. As shown, BMPs are an excellent alternative to embrace environmental, social, and economic aspects into the achievement of local urban drainage goals. This integrated approach can lead to the future implementation of better urban drainage alternatives, whose overall and long-term performance can exceed the one evidenced in Brottkärr area.

8. Conclusion

Pollution from diffuse sources, which is commonly transported by stormwater in urban and suburban areas, currently restricts the compliance of environmental objectives and standards in Gothenburg. Even though the term stormwater is not contemplated explicitly in the Swedish Environmental Code, diverse instruments and programs, including stormwater management plans, have been established to accomplish the different environmental objectives. Several entities in the city work together to mitigate and reduce stormwater pollutants discharged to receiving water bodies, such as the river Göta Älv, or to Rya wastewater treatment plant.

Although the results are inconclusive, there is substantial evidence to support the hypothesis that the stormwater management system installed in Brottkärr does not operate appropriately in terms of water quality improvement: outlet concentrations of several pollutants exceed inlet concentrations as well as water quality guidelines established for the city. Additional studies conducted in Sweden support the findings and demonstrate the high requirements of operation, monitoring, and maintenance of manhole filters. Different methods with lower operation and maintenance needs may yield better results in the treatment and handling of stormwater.

The literature analysis showed that BMPs include a large variety of alternatives destined to handle appropriately runoff volume and pollutant concentrations in stormwater; in this study, nine specific BMPs of interest for the city were evaluated further. Many of these alternatives not only include economic and environmental benefits such as lower construction costs (when compared to traditional water treatment systems) and significant retention of pollutants, but also have a high potential for ecological and social gains such as the enhancement of biodiversity and inclusion of recreational activities. The multiplicity of variables associated with these systems leads to analyses that may exhibit great complexity.

A multi-criteria analysis is a simple tool that could effectively support decision-making processes intended to solve complex environmental issues, for example, stormwater management. Its robustness highly depends on the inclusion of the different actors that make up the urban environments, achieving an adequate and integrated analysis of the environmental problems present in the area. The main factors that lead to the establishment of a valuable MCA for stormwater management are: an adequate analysis of the catchment area; inclusion of the affected actors; stipulation of the evaluation criteria; and establishment and reevaluation of the alternatives of interest. The information required to determine the evaluation criteria depends on the knowledge and preferences of the stakeholder and key-players involved. This condition entails a high subjectivity of the method, as was evidenced in this study. However, the inclusion of different experts in each of the variables considered in the project analysis can generate satisfactory results in the environmental, economic, and social field. The results of the MCA show the ranking of alternatives, where wet retention basins, dry detention basins, swales, and green roofs are the four alternatives preferred by the key-players involved in the study. The other five options occupy different position in the ranking, varying according to the stakeholder or key-player considered. Due to the general characteristics of the study, which was based on a city level, and the lack of exclusion criteria that could describe a specific site of implementation, the results are considered inconclusive. Nevertheless, the results are considered a starting point, where the misalignment between the social and the technical aspects was evidenced. This misalignment reveals improvement opportunities that should be considered in the specific evaluation of future projects aimed at the installation of urban drainage systems under the sustainability framework. Besides, the process shows, and details, several elements considered essential for the implementation of MCA in future stormwater projects, including the mentioned exclusion criteria, the inclusion of the different key-players involved in the development of urban areas, and the subjectivity of the method with the proposed ways in which it can be diminished. The information contained, and the method used, are considered an excellent pedagogical tool that increases the knowledge on the performance of the different available technologies and allows the exhaustive evaluation and identification of the relevant criteria that must be considered within stormwater management, to achieve Gothenburg's sustainability goals.

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Appendix 1 Time and Spatial effects of contaminants on receiving water bodies

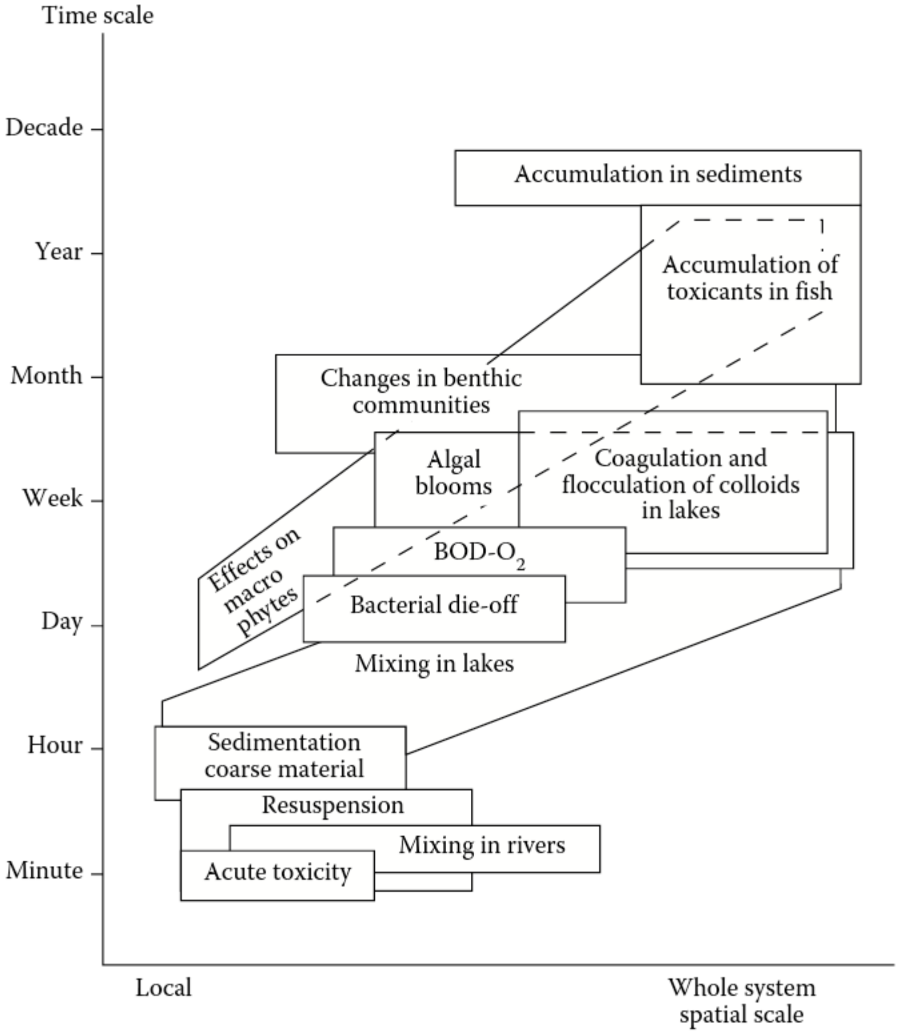

Figure 33: Time and Spatial effects of contaminants in the receiving water bodies. Source: (Butler & Davies, 2004)

Appendix 2 Advantages and disadvantages of separate and combined sewer systems

Table 20: Advantages and disadvantages of combined and separate sewer systems. Source: (Butler & Davies, 2004)

Separate system	*Combined system*
Advantages No CSOs – potentially less pollution of watercourses.	**Disadvantages** CSOs necessary to keep main sewers and treatment works to feasible size. May cause serious pollution of watercourses.
Smaller wastewater treatment works.	Larger treatment works inlets necessary, probably with provision for stormwater diversion and storage.
Stormwater pumped only if necessary.	Higher pumping costs if pumping of flow to treatment is necessary.
Wastewater and storm sewers may follow own optimum line and depth (for example, stormwater to nearby outfall).	Line is a compromise, and may necessitate long branch connections. Optimum depth for stormwater collection may not suit wastewater.
Wastewater sewer small, and greater velocities maintained at low flows.	Slow, shallow flow in large sewers in dry weather flow may cause deposition and decomposition of solids.
Less variation in flow and strength of wastewater.	Wide variation in flow to pumps, and in flow and strength of wastewater to treatment works.
No road grit in wastewater sewers.	Grit removal necessary.
Any flooding will be by stormwater only.	If flooding and surcharge of manholes occurs, foul conditions will be caused.
Disadvantages Extra cost of two pipes.	**Advantages** Lower pipe construction costs.
Additional space occupied in narrow streets in built-up areas.	Economical in space.
More house drains, with risk of wrong connections.	House drainage simpler and cheaper.
No flushing of deposited wastewater solids by stormwater.	Deposited wastewater solids flushed out in times of storm.
No treatment of stormwater.	Some treatment of stormwater.

Appendix 3 Hydrographs

Figure 34 and Figure 35 shows the hydrographs in Point A and Point B, respectively. Three different results are exposed:

- Blue graph: Water level in the system (meters)
- Green graph: Water velocity (m/s)
- Red graph: Water flow (m3/s)

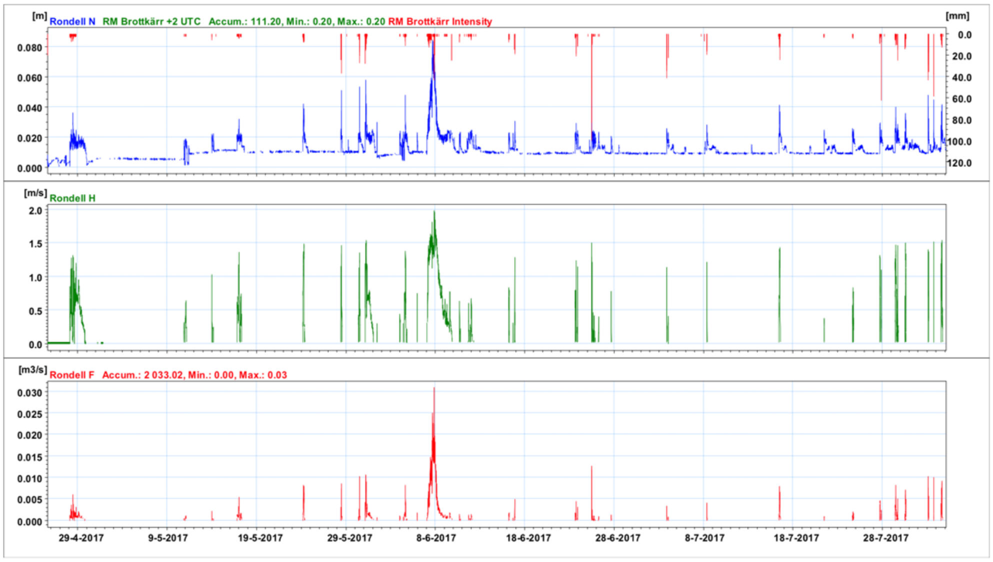

Figure 34: Inlet hydrograph. Used with permission from: (DHI, 2018)

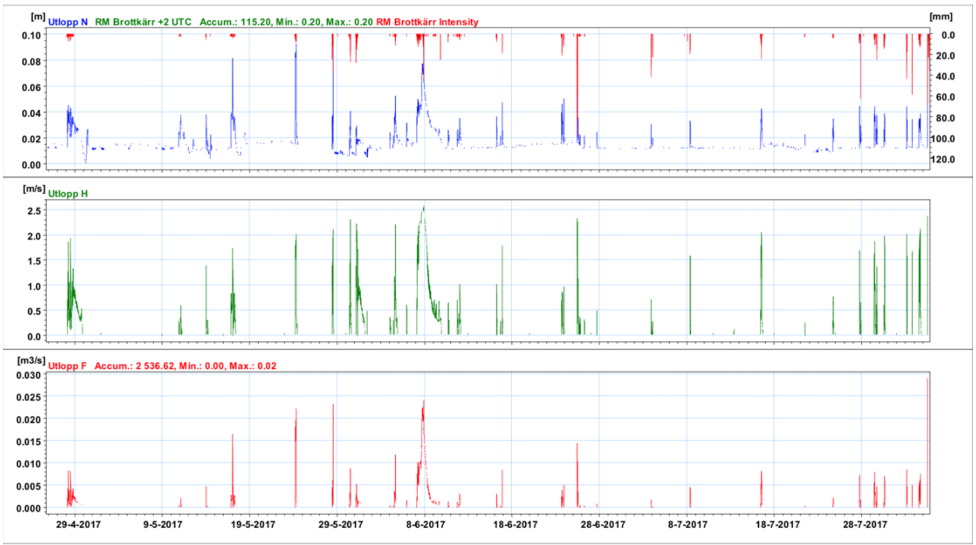

Figure 35 Outlet hydrograph. Used with permission from: (DHI, 2018)

Appendix 4 Remedial actions on the filter

Figure 36: Filter Before the reparations

Figure 37: Filter after the reparations

Appendix 5 Tracer test information

Appendix 5.1 Time delay measuring points

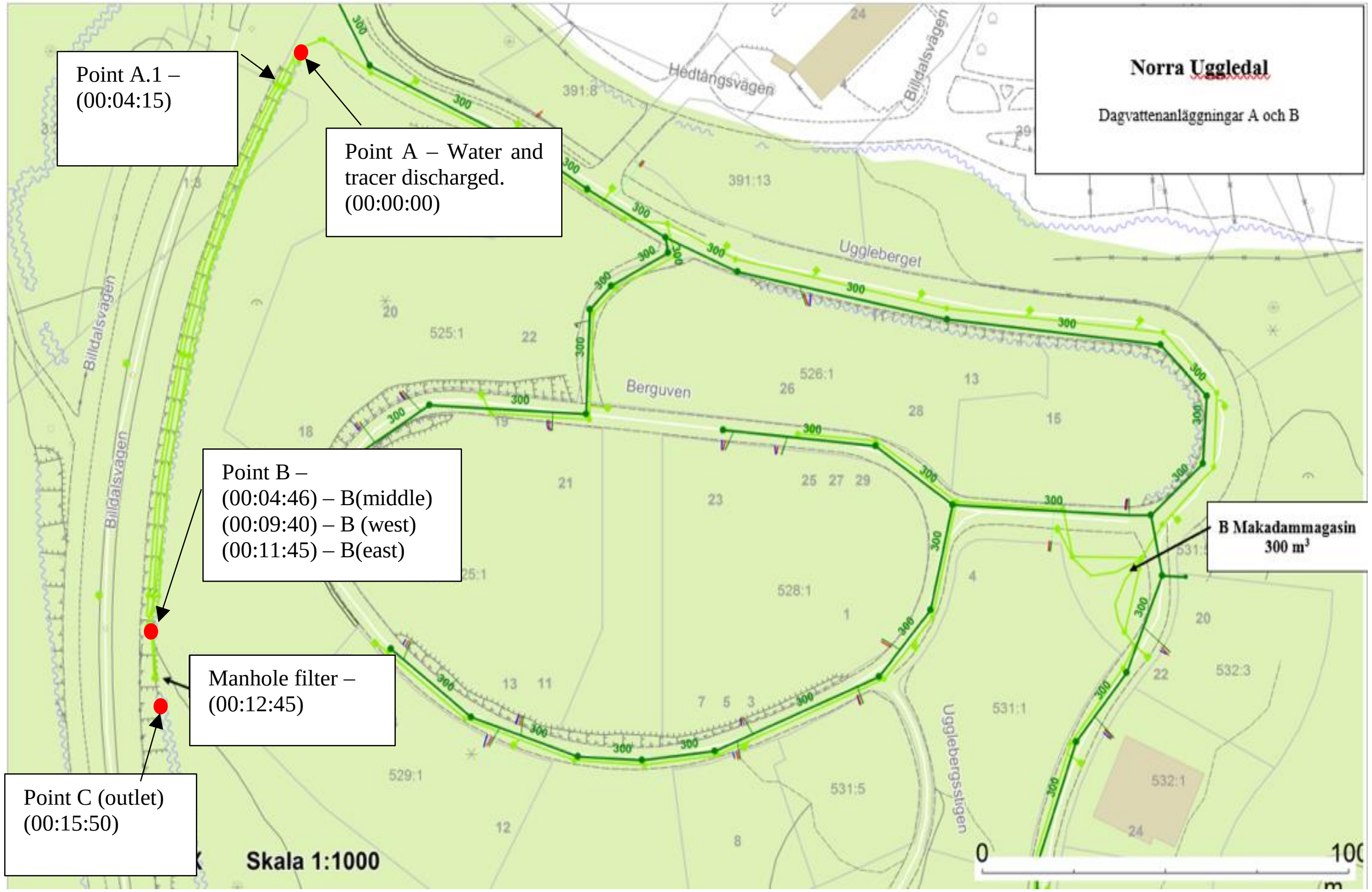

Figure 38: Tracer test measuring points

Appendix 5.2 Point B measurements

Figure 39: Manholes in Measuring Point B

Appendix 6 Stormwater management systems' performance evaluation

Appendix 6.1 Technical performance

Appendix 6.1.1 Hydraulic response- Water flow control performance

Alternatives	Water flow control		
	Peak flow (PF)-Volume Reduction (V)	*Comments*	*Sources*
Wet Retention Pond	Medium (PF) - No reduction (V)	Wet-retention ponds possess no ability to reduce overall the runoff volume. Hydraulic efficiencies highly depend on length-to-width ratios.	Battiata, et al., 2010; Hancock, et al., 2010; Al-Rubaei, Ph.D., et al., 2017
Dry Detention Pond	High (PF) - Low (V)	Runoff reduction highly depends on the design of the system. Some systems achieve 100-year peak flow and have problems with 2-year peak flows. (20-90%)	Jotte, et al., 2017; E2STORMED Project, 2015
Swales	Medium(PF)- Low (V)	Highly dependent on rain event characteristics. Total volume and flow magnitudes are significantly reduced in rainfall of low precipitation (40-60%). Due to their limited storage volumes, swales work primarily as flow conveyance during significant rain events. Wet swales present 0% reduction.	Davis, et al., 2012; Jotte, et al., 2017; Battiata, et al., 2010; Corson, 2006; Weiss, et al., 2010
Infiltration Trenches	High (PF)-High(V)	Possess an essential reduction in peak flows (50-90%). Nevertheless, their performance is highly dependant on the rain intensity.	Jotte, et al., 2017; Song, et al., 2018; Battiata, et al., 2010
Underground detention	High(PF)-No Reduction (V)	Runoff reduction highly depends on the design of the system.	E2STORMED Project, 2015
Manhole filters	No reduction (PF) - No reduction (V)	No runoff reduction can be achieved. Filters contain structures that discharge the water without treatment under overflow conditions.	
Pervious Pavements	High (PF) -High (V)	(45-75%) High reductions. Nevertheless, freezing conditions affect the performance of the system. Runoff control can be affected by a 50% when compared to temperatures of 20 Degrees Celsius.	Andersen, et al., 1999; Bäckström, 1999; Battiata, et al., 2010
Green Roof Storage	Low (PF) - Moderate (V)	This system achieves considerable water volume reduction capacity. 50% of annual runoff volume reductions have been reported.	Stahre, 2006; Jotte, et al., 2017; Rowe, 2011; Battiata, et al., 2010
Soakaways	High (PF)- High (V)	(30-80%). Highly dependent on the infiltration rates of the adjacent soil or structures.	Transport Infrastructure Ireland, 2015; Locatelli, et al., 2015

Appendix 6.1.2 Technical Quality performance

Appendix 6.1.2.1 System Reliability

Alternatives	System Reliability		
	Probability of Failure	*Comments*	*Sources*
Wet Retention Pond	Low to Moderate	Failure phenomenon are highly related to the lack of maintenance and inadequate design. Lack of monitoring and maintenance actions is regularly evidenced in these systems, which commonly lead to hydraulic malfunctions.	Al-Rubaei, Ph.D., et al., 2017
Dry Detention Pond	High	Fouling scenarios are linked to high concentrations of suspended solids in the system inflow, faulty design, and lack of monitoring and maintenance.	Jotte, et al., 2017
Swales	High	This system presents a high risk of blockage in the internal pipes.	Jotte, et al., 2017
Infiltration Trenches	Highest	Infiltration trenches are classified as the BMP with the highest probability of failure. The exposure to high loads of sediments creates clogging situations.	Jotte, et al., 2017; United States Environment Protection Agency, 1999
Underground detention	Low to Moderate	This system presents failure mechanisms such as buoyancy, joint separation, and failure by static and dynamic loadings.	
Manhole filters	Moderate to High	This system presents a high probability of failure due to clogging related to high concentrations of suspended solids and oil in the system's inflow.	Dromberg, 2009; Alm, et al., 2015
Pervious Pavements	Moderate to High	This system presents a moderate probability of failure under high sediment load conditions, low permeability soils, or heavy vehicular traffic (~75%)	United States Environmental Protection agency, 1999
Green Roof Storage	Moderate to high	The reliability of this system highly depends on waterproofing layers and vegetation design. High costs are associated with the failure of the system.	Vijayaraghavan, 2016
Soakaways	Moderate	As an infiltration device, these systems present a high probability of failure, which increases during wet seasons due to clogging and high sediment loadings.	Jotte, et al., 2017

Appendix 6.1.2.1 System Durability

Alternatives	Durability		
	Expected Lifetime	*Comments*	*Sources*
Wet Retention Pond	Long	Expected lifetime of 20-50 years	Peluso & Marshall, 2002; Corson, 2006
Dry Detention Pond	Long	Expected lifetime of 20-50 years	Corson, 2006
Swales	Moderate to Long	Expected lifetime of 15-20 years	Peluso & Marshall, 2002
Infiltration Trenches	Short to Moderate	Expected lifetime of 5-15 years	Corson, 2006
Underground detention	Moderate to Long	Expected lifetime of 25-75 years	E2STORMED Project, 2015
Manhole filters	Short to Moderate	High rates of unit replacement.	
Pervious Pavements	Moderate to Long	Expected lifetime of 20 - 40 years	Peluso & Marshall, 2002; E2STORMED Project, 2015
Green Roof Storage	Long	Expected lifetime of 40 years.	U.S. Department of the Interior, n.d.; E2STORMED Project, 2015
Soakaways	Long	Expected lifetime of 20-50 years	E2STORMED Project, 2015

Appendix 6.2 Environmental performance

Appendix 6.2.1 Pollution control

Appendix 6.2.1.1 Total solids reduction

Alternatives	Total Solids		
	Expected reduction	*Comments*	*Sources*
Wet Retention Pond	78-90%	TS removal performance is highly variable depending on the pond, catchment, and rain event characteristics. Water detention time is a crucial aspect of the design, as well as the first flush detention time.	Fassman, 2012;Drake, et al., 2016; National Academies of Sciences, Engineering, and Medicine, 2014; United States Environmental Protection agency, 1999
Detention Pond	66-93%%	TS removal performance is highly variable depending on the catchment area and rain event characteristics. Highly dependent on site and particle characteristics. Vegetated detention ponds present high pollutant retention potentials.	Jotte, et al., 2017; Fassman, 2012;Drake, et al., 2016; National Academies of Sciences, Engineering, and Medicine, 2014; Corson, 2006
Swales	30-90%	Highly dependent on site and particle characteristics	National Academies of Sciences, Engineering, and Medicine, 2014; Weiss, et al., 2010; Corson, 2006
Infiltration Trenches	70-99%	High removal potential of suspended solids along the linear structure.	Jotte, et al., 2017; United States Environment Protection Agency, 1999; Corson, 2006
Underground detention	80-90%	TSS removal performance is highly variable depending on system's design, catchment, and rain event characteristics. Underground detention systems which include sedimentation processes achieve higher retention of pollutants.	Jotte, et al., 2017; Drake, et al., 2016
Manhole filters	15-95%	TSS removal performance is highly dependent on the filtering method, structural design of the filter, and filter media.	International Stormwater BMP Satabase, 2014
Pervious Pavements	50-95%	The retention of Suspended solids highly depends on the type of pervious pavement.	Legret, et al., 1999; Pagotto, et al., 2000; Novotny, et al., 2010; United States Environmental Protection agency, 1999
Green Roof Storage	90%	A direct correlation exists between the magnitude of the rain event, the surrounding atmospheric concentrations of pollutants, and the number of solids in the effluent.	Novotny, et al., 2010
Soakaways	30%		E2STORMED Project, 2015; Woods-Ballard, et al., 2015

Appendix 6.2.1.2 Biochemical Oxygen Demand reduction

Alternatives	Biochemical Oxygen Demand		
	Expected reduction (literature)	*Comments*	*Sources*
Wet Retention Pond	29-53%	Highly dependent on the physical and chemical processes on the pond, as well as in the climate characteristics of the area. The use of sequenced anaerobic cells increases the retention.	Middlesex University, 2003;Scholes, et al., 2008; United States Environmental Protection agency, 1999
Detention Pond	30-90%	Highly dependent on the volume of water detained. Higher retention of oxygen-consuming substances is achieved when higher water levels are reached during the detention.	Scholes, et al., 2008; Harper, Ph.D., P.E., 1995
Swales	13-61%	Highly dependent on design aspects such as the length of the swale, vegetation (when included), and percolation material used.	Weiss, et al., 2010; Scholes, et al., 2008
Infiltration Trenches	70-80%	Highly dependent on design aspects such as the depth of the infiltration trench	United States Environment Protection Agency, 1999; Scholes, et al., 2008
Underground detention	<10%	Low pollutant retention potential due to purposes of the systems, which tend to control water flows and/sediments, but where chemical processes are not intended to occur.	Jotte, et al., 2017
Manhole filters	Inconclusive information	Highly dependent on the filtering media.	Scholes, et al., 2008; Alm, et al., 2015
Pervious Pavements	90%	High retention of pollutants resulting from anaerobic decomposition within the pavement structure	Tota-Maharaj & Scholz, 2013
Green Roof Storage	No exposure	These contaminants in green roofs areas are usually related to the decomposition of vegetation cover, but no exposure is associated with them. Therefore, the concentrations are considered as insignificant.	Li & Babcock, 2014
Soakaways	Low		Scholes, et al., 2008

Appendix 6.2.1.3 Nutrients reduction

Alternatives	Nutrients		
	Expected reduction (literature)	*Comments*	*Sources*
Wet Retention Pond	10-50% TN 20-94% TP	The retention is highly dependent on the species and the mechanisms present in the system (e.g., algae uptake, settling and sedimentation) which reduce each species of nutrients.	Middlesex University, 2003; National Academies of Sciences, Engineering, and Medicine, 2014; Corson, 2006
Detention Pond	0-40% TN 10-94% TP	The retention is highly dependent on the species and the mechanisms present in the system (e.g., adsorption, biodegradation, filtration achieved by filtration structures) which reduce each species of nutrients.	Jotte, et al., 2017; Koch, et al., 2014; National Academies of Sciences, Engineering, and Medicine, 2014; The Center for Watershed Protection, 2013; Corson, 2006
Swales	0-50% TN 20-85% TP	The retention potential is highly dependent on the species, as well as the vegetation (and its health) present in the swale. The removal of grass clipping after mowing removes nutrients and improves the performance of the system.	Weiss, et al., 2010; Koch, et al., 2014; Middlesex University, 2003; National Academies of Sciences, Engineering, and Medicine, 2014; Corson, 2006
Infiltration Trenches	40-80%TN 20-75% TP	Phosphorus and Nitrogen are accumulated in the infiltration trenches. The removal rates highly depend on specific design characteristics.	American Society of Civil Engineers (ASCE), 2000; Middlesex University, 2003; Corson, 2006
Underground detention	0% TN 0-20% TP	Underground detention basins have low efficiency in the retention of pollutants due to their impermeable characteristics.	Baish & Caliri, 2009
Manhole filters	Inconclusive information	Nutrients retention potential is highly dependent on the filter structure and media characteristics.	Dromberg, 2009; Alm, et al., 2015
Pervious Pavements	25-85% TN 20-80% TP	Highly variable based on area and pervious pavement characteristics.	Pagotto, et al., 2000; Novotny, et al., 2010; United States Environmental Protection agency, 1999; The Center for Watershed Protection, 2013
Green Roof Storage	(-)50% - 32%	Green roofs, in some cases, can be a source of nutrients due to excess use of fertilizers.	Rowe, 2011
Soakaways	30%	The surrounding growth of grass is linked to the low removal rates of nutrients in soakaways.	Woods-Ballard, et al., 2015

Appendix 6.2.1.4 Heavy metals reduction

Alternatives	Heavy Metals		
	Expected reduction (literature)	*Comments*	*Sources*
Wet Retention Pond	20-90%	These systems are recognized to achieve a high retention of metals.	Middlesex University, 2003; United States Environmental Protection agency, 1999; Corson, 2006
Detention Pond	0-60%	Dry detention basins are considered to achieve moderate retention. The retention potential is highly dependent on the species and the characteristics of the system and rain events.	Birch, et al., 2007; Corson, 2006; United States Environmental Protection Agency, 1999; Woods-Ballard, et al., 2015
Swales	70-90%	The efficiency of swales in metal reduction is highly dependent on the ionic species. Heavy metals with large particulate fractions are removed more efficiently.	Middlesex University, 2003; Scholes, et al., 2008; United States Environmental Protection Agency, 1999; Yousef, et al., 1981
Infiltration Trenches	70-90%	The removal efficiency highly depends on the state (soluble or particulate), and the infiltration capacity of the surrounding soil.	American Society of Civil Engineers (ASCE), 2000; Middlesex University, 2003
Underground detention	40%	Considered to achieve low retention of metals. Highly dependent on the sedimentation processes that occur in the system.	E2STORMED Project, 2015; Woods-Ballard, et al., 2015
Manhole filters	Inconclusive information	Highly dependent on the media and porosity of the filter. Old and used filters have higher retention of pollutants than newly installed filters, which in some cases emission pollutants have been reported.	Dromberg, 2009; Alm, et al., 2015
Pervious Pavements	20-60%	Highly dependent on the catchment area and site characteristics. Previous pavements in residential areas show a high metal retention potential.	Pagotto, et al., 2000; United States Environmental Protection Agency, 1999
Green Roof Storage	>70%	Highly dependent on the state (particulate or soluble) and season of the year. Cold season affects the retention of pollutants. Highly dependent on the atmospheric concentrations.	Rowe, 2011; United States Environmental Protection Agency, 1999
Soakaways	50%	The removal efficiency highly depends on the state (soluble or particulate), and the infiltration capacity of the surrounding soil.	E2STORMED Project, 2015

Appendix 6.2.1.5 Heavy metals reduction

Alternatives	Organic Pollutants		
	Expected reduction (literature)	*Comments*	*Sources*
Wet Retention Pond	60-90%	These systems are recognized to achieve a high retention of organic pollutants.	Middlesex University, 2003; Lavieille, 2005
Detention Pond	Inconclusive information	Highly dependent on the basin configuration and the time and volumen water retntion.	
Swales	0.36	Limited information	Middlesex University, 2003
Infiltration Trenches	50-90%	Limited information. Highly linked to the removal of suspended solids.	Middlesex University, 2003
Underground detention	40%	Limited information. Highly linked to the removal of suspended solids.	
Manhole filters	Not reported/Inconclusive information	Old and used filters have a higher retention of pollutants than newly installed filters, which in some cases emit pollutants.	Alm, et al., 2015; Dromberg, 2009
Pervious Pavements	50-90%	Limited information. Highly linked to the removal of suspended solids.	Pagotto, et al., 2000
Green Roof Storage	No expected reduction	Low expected exposure to these types of contaminants.	
Soakaways	50%	Present little to no retention of high soluble compounds. Limited information. Highly linked to the removal of suspended solids.	Middlesex University, 2003; Woods-Ballard, et al., 2015

Appendix 6.2.2 Impact on soil and water

Appendix 6.2.2.1 Impacts on the groundwater

Alternatives	Impact on the ground water		
	Infiltration rate	*Comments*	*Sources*
Wet Retention Pond	Low	The problems are mainly related to system leaks, which, in turn, are related to problems due to the lack of maintenance of the structures. No infiltration is expected.	Al-Rubaei, Ph.D., et al., 2017
Detention Pond	Moderate	Moderate impact of the surrounding soils. The accumulation of contaminants can lead to mobilization of pollutants linked to the failure of the system.	Jotte, et al., 2017
Swales	Low-Moderate	High interaction with the groundwater. Low to moderate impacts reported in semi-arid regions.	Weiss, et al., 2010
Infiltration Trenches	High	High interaction with the groundwater. Groundwater tables of 1.5/3 meters depth are particularly exposed.	Locatelli, et al., 2015; Natural Water Retention Measures. European Comission, 2015
Underground detention	None	No interaction with the groundwater table.	
Manhole filters	None	No interaction with the groundwater table.	Assmuth, 2017
Pervious Pavements	Moderate	High interaction with the groundwater. Groundwater tables of 1.5/3 meters depth are particularly exposed.	Natural Water Retention Measures. European Comission, 2015
Green Roof Storage	None	No interaction with groundwater table	Natural Water Retention Measures. European Comission, 2015
Soakaways	High infiltration rates	High interaction with the groundwater. Groundwater tables of 1.5/3 meters depth are particularly exposed.	Jotte, et al., 2017; Natural Water Retention Measures. European Comission, 2015

Appendix 6.2.2.2 Impacts on the exposed soil

Alternatives	Impact on soil		
	Erosion / Sediment control	*Comments*	*Sources*
Wet Retention Pond	Moderate	These systems intend to collect contaminants in the site of implementation, leading to a build-up of pollutants which need to be handled by remediation techniques. Erosion problems can be detected.	Natural Water Retention Measures. European Comission, 2015; Al-Rubaei, Ph.D., et al., 2017
Detention Pond	Moderate	Moderate impact of the surrounding soils. These systems intend to collect contaminants in the site of implementation, leading to a build-up of pollutants which need to be handled by remediation techniques.	Natural Water Retention Measures. European Comission, 2015
Swales	Low	These systems intend to collect contaminants in the site of implementation, leading to a build-up of pollutants which need to be handled by remediation techniques. These systems are considered to have the lower impact than basins due to the system's dimensions.	Natural Water Retention Measures. European Comission, 2015
Infiltration Trenches	Low	Contaminants are intended to be collected in the percolating areas of the system.	Natural Water Retention Measures. European Comission, 2015
Underground detention	None	-	Natural Water Retention Measures. European Comission, 2015
Manhole filters	None	-	Natural Water Retention Measures. European Comission, 2015
Pervious Pavements	Low	Contaminants are intended to be collected in the percolating areas of the system.	Natural Water Retention Measures. European Comission, 2015
Green Roof Storage	Low	Low impact of the substrate used. Remediation techniques need to be considered.	Natural Water Retention Measures. European Comission, 2015
Soakaways	Moderate	Significant accumulation of pollutants in the sediments which can mobilize through weakening of bonds.	Hossain, et al., 2007; Natural Water Retention Measures. European Comission, 2015

Appendix 6.2.2 Ecological enhancement potential

Appendix 6.2.2.1 Biodiversity enhancement potential

Alternatives	Potential Enhancement in biological diversity		
	Potential improvement on biodiversity	*Comments*	*Sources*
Wet Retention Pond	Moderate- High	Can strongly favor biodiversity and habitat value. Highly dependent on the water quality	Middlesex University, 2003; Corson, 2006
Detention Pond	Low-Moderate	Can favor biodiversity and habitat value.	Natural Water Retention Measures. European Comission, 2015; Corson, 2006
Swales	Low-Moderate	Enhancement potential is strongly related to the artificial vegetation planting techniques.	Middlesex University, 2003; Corson, 2006
Infiltration Trenches	None	-	Middlesex University, 2003; Corson, 2006
Underground detention	None	-	
Manhole filters	None	-	
Pervious Pavements	None	-	
Green Roof Storage	Moderate habitat Value	Highly related to the artificial planting and public exposure.	Werthman, 2007
Soakaways	Low	Poor to none ecologic potential	Transport Infrastructure Ireland, 2015

Appendix 6.3 Social performance

Appendix 6.3.1 Public interaction

Appendix 6.3.1.1 Perceived risks and information requirements

Alternatives	Perceived risks and information requirements		
	Risks (R) - Awareness requirements (AR)	*Comments*	*Source*
Wet Retention Pond	High (R) - High (AR)	May require approval from safety authorities.	American Society of Civil Engineers, 2014
Detention Pond	High (R) - High (AR)	May require approval from safety authorities.	American Society of Civil Engineers, 2014
Swales	Low (R)- Low (AR)	This system works with shallow water depths. Swale design should minimize standing water to prevent vectors and pests. Residents with swales need to be trained on maintenance requirements.	American Society of Civil Engineers, 2014; Peluso & Marshall, 2002
Infiltration Trenches	Low (R)- Low (AR)	Ideal for use close to playing fields, recreational areas and public spaces.	Natural Water Retention Measures. European Comission, 2015
Underground detention	No public interaction	Underground structure with no public interaction.	-
Manhole filters	No public interaction	Underground structure with no public interaction.	-
Pervious Pavements	Moderate (R)- Moderate (AR)	Highly dependent on the area of installation. Residents with pervious pavements need to be trained on maintenance requirements.	The Center for Watershed Protection, 2013
Green Roof Storage	Moderate (R)- Moderate (AR)	It is not usually design for public access. However, fire risks and vector proliferation can occur.	Jotte, et al., 2017; American Society of Civil Engineers, 2014
Soakaways	No public interaction	Underground structure with no public interaction.	-

Appendix 6.3.1.2 Potential for recreational activities

Alternatives	Potential for recreational activities		
	Potential	*Comments*	*Source*
Wet Retention Pond	Moderate - High	Wet basins are often considered a community amenity where different recreational activities can be established.	Jotte, et al., 2017; American Society of Civil Engineers, 2014
Detention Pond	High	Dry detention basins sometimes consist of urban areas destined as public spaces which are part of the flood management system. Playgrounds or other recreational activities are intended to occur in the area.	American Society of Civil Engineers, 2014
Swales	None - Low	Can take part of the urban space, but they do not contain a potential for recreational activities.	Natural Water Retention Measures. European Comission, 2015
Infiltration Trenches	None	Can take part of the urban space, but they do not contain a potential for recreational activities.	Natural Water Retention Measures. European Comission, 2015
Underground detention	None	No public access	
Manhole filters	None	No public access	
Pervious Pavements	None - Low	The potential use of the space for a wide range of activities is considered as an enhancement aspect of the amenity level of pervious pavements.	Natural Water Retention Measures. European Comission, 2015; Woods-Ballard, et al., 2015
Green Roof Storage	None- Low	Highly dependent on the design of the spaces. Not typically design for public access.	Jotte, et al., 2017; American Society of Civil Engineers, 2014;Natural Water Retention Measures. European Comission, 2015
Soakaways	Low	No direct interaction with the superficial area. Nevertheless, these systems consist of an underground structure which allows the occurrence of different activities	

Appendix 6.3.2 Location Amenity

Appendix 6.3.2.1 Visual environment aesthetic value

Alternatives	Visual environment		
	Aesthetic Value	*Comments*	*Source*
Wet Retention Pond	High	Wet basins are often considered a community amenity. It is essential to hide the presence of drainage structures and maintain low pollution levels.	Jotte, et al., 2017; American Society of Civil Engineers, 2014; United States Environmental Protection Agency, 2009
Detention Pond	Moderate- High	Dry detention basins sometimes consist of urban areas destined as public spaces which are part of the flood management system.	Natural Water Retention Measures. European Comission, 2015
Swales	Moderate- High	Selective planting on the swales could enhance aesthetic value, especially in areas characterized by roads.	Middlesex University, 2003
Infiltration Trenches	Low	Low aesthetics and cultural value. Selective planting on the surrounding area could enhance aesthetic value	Natural Water Retention Measures. European Comission, 2015
Underground detention	None	No aesthetic value.	
Manhole filters	None	No aesthetic value.	
Pervious Pavements	Low - Moderate	Highly dependent on the visual aspects of the surface materials and the surrounding environment.	Woods-Ballard, et al., 2015; Natural Water Retention Measures. European Comission, 2015; The Center for Watershed Protection, 2013
Green Roof Storage	Moderate- High	Considered to be aesthetically pleasing.	Jotte, et al., 2017; Werthman, 2007
Soakaways	None	No aesthetic value.	Natural Water Retention Measures. European Comission, 2015

Appendix 6.3.2.2 Public land use/requirements

Alternatives	Area Requirements		
	Land Requirements	*Comments*	*Source*
Wet Retention Pond	High	Consists of non-linear areas which require a significant amount of territory.	Corson, 2006
Detention Pond	Moderate-High	Consists of non-linear areas which require a significant amount of territory. Depending on the design, these systems can enhance the space uses.	Corson, 2006
Swales	Moderate	Linear areas with low to moderate area requirements.	Corson, 2006
Infiltration Trenches	Minimal land take	Linear areas with low to moderate area requirements.	Natural Water Retention Measures. European Comission, 2013-2015
Underground detention	No loss of public land		
Manhole filters	No loss of public land		
Pervious Pavements	Favors land use	The potential use of the space for a wide range of activities is considered as an enhancement aspect of the amenity level.	Woods-Ballard, et al., 2015
Green Roof Storage	Favors land use	The potential use of the space for a wide range of activities is considered as an enhancement aspect of the amenity level. Used in high density areas.	Jotte, et al., 2017
Soakaways	No loss of public land		

Appendix 6.4 Economic performance

Appendix 6.4.1 Capital costs

Appendix 6.4.1.1 Approximate simplified unit costs

Alternatives	Material and construction costs		
	Relative Costs	*Comments (Approximate simplified unit costs)*	*Source*
Wet Retention Pond	Low	9-100 €/m3. 6-7% of investment is required on civil-engineering works	Middlesex University, 2003; Environmental Protection Agency - Region I, 2016; E2STORMED Project, 2015
Detention Pond	Low	9-91 €/m3. High variability and dependency on the area where it is established (different costs between rural vs. urban areas)	Middlesex University, 2003; Peluso & Marshall, 2002; E2STORMED Project, 2015
Swales	Low	15 - 30 €/m (linear) 7.6 - 15 €/m3	Middlesex University, 2003; E2STORMED Project, 2015
Infiltration Trenches	Moderate- high	200 €/m3	Environmental Protection Agency - Region I, 2016; E2STORMED Project, 2015
Underground detention	High	150- 1500 €/m3	Middlesex University, 2003; Environmental Protection Agency - Region I, 2016
Manhole filters	Low	Dependent on media filter. Usually low-cost units.	E2STORMED Project, 2015
Pervious Pavements	Moderate- high	150-500 €/m3	Middlesex University, 2003; Environmental Protection Agency - Region I, 2016
Green Roof Storage	Moderate- high	100-300 €/m2	Jotte, et al., 2017; Dakin, et al., 2013; Novotny, et al., 2010; E2STORMED Project, 2015
Soakaways	Moderate	3 €/m2 treated area; 150 €/m3 stored volume	Jotte, et al., 2017; Middlesex University, 2003

Appendix 6.4.2 Operation and Maintenance

Appendix 6.4.2.1 Monitoring and maintenance needs

Alternatives	Monitoring and maintenance needs		
	Relative frequency	*Comments*	*Source*
Wet Retention Pond	Low	(>1 time/ year) Monitoring on the accumulation of sediments is required. Requires special supervision after relatively large rainfall events. Control structures need to be inspected semiannually and repaired as needed. Removal of sediments must be done every 5 years.	Kang, et al., 2008; Al-Rubaei, Ph.D., et al., 2017
Detention Pond	Low	(>1 time /year) These systems require monitoring on the accumulation of sediments. Additionally, they require special supervision after relatively large rainfall events. Control structures need to be maintained semiannually, as well as embankments and side slopes.	Kang, et al., 2008; Peluso & Marshall, 2002
Swales	Low	(1 time / 10 years). Very low maintenance needs. Sediments build up monitoring is recommended to prevent damming effect. The avoidance of vehicle and pedestrian traffic prevents compaction which in turn heads to a lower maintenance needs. Sediments removal is recommended to be done at least every 5 years.	Middlesex University, 2003; Peluso & Marshall, 2002
Infiltration Trenches	High	(>2 times/year) Very susceptible to clogging. Trenches need to be inspected regularly and the debris removed.	Middlesex University, 2003; Peluso & Marshall, 2002
Underground detention	Moderate	(1-2 times/year). These systems require individual and specialized monitoring due to their underground characteristics. The identification of failure mechanisms is not easily observed.	Kang, et al., 2008
Manhole filters	Moderate - High	(>1 time /year) Highly dependent on the type of filter and catchment area characteristics. High risks of clogging, especially in areas under urbanization processes. High rates of replacement of filter media needs, as well as protective caps (that work as a pre-treatment), have been reported.	Dromberg, 2009
Pervious Pavements	High	(1-12 times/ year) Failures are commonly associated with faults in construction. Clogging caused by the regular deposition and accumulation of fine sediments has been reported. Requires special monitoring and supervision in winter and cold season.	Al-Rubaei, et al., 2013; Novotny, et al., 2010; Kang, et al., 2008
Green Roof Storage	High	(>2 times /year) Lack of supervision can lead to fire hazards. Constant maintenance of irrigation systems and plant mowing is required.	Jotte, et al., 2017; Dakin, et al., 2013; Kang, et al., 2008
Soakaways	Low monitoring needs	Nevertheless, an initial period of frequent monitoring is recommended to determine the rate of sediment accumulation.	Jotte, et al., 2017; Transport Infrastructure Ireland, 2015

Appendix 6.4.2.2 Operation and maintenance associated costs

Alternatives	Operation and maintenance associated costs		
	Relative costs	*Comments (Approximate simplified unit costs)*	*Source*
Wet Retention Pond	Low	0.15-5 €/m3/year. 3-5% of initial construction costs	Middlesex University, 2003; E2STORMED Project, 2015
Detention Pond	Low	1-10% of the total construction costs. (0.3 - 1.52 €/m3/year)	Kang, et al., 2008; Middlesex University, 2003; Barr Engineering Company, 2011; Peluso & Marshall, 2002
Swales	Moderate	0.03-0.16 €/m2/year 5-7% of initial construction costs	Middlesex University, 2003; Erickson, et. al, 2010; Peluso & Marshall, 2002; E2STORMED Project, 2015
Infiltration Trenches	Moderate - High	5-20% of the total construction costs	Middlesex University, 2003; Kang, et al., 2008
Underground detention	High	1.5 €/m3 stored volume/year	E2STORMED Project, 2015
Manhole filters	Inconclusive information	Highly dependent on the type of filter and catchment area characteristics	
Pervious Pavements	Moderate	0.3 - 1.52 €/m3/year; 0.08-3 €/m2/year	Middlesex University, 2003; Erickson, et. al, 2010; E2STORMED Project, 2015
Green Roof Storage	Moderate - High	Irrigation and drainage systems required. 0.2-45 €/m2/year	Jotte, et al., 2017; Dakin, et al., 2013; E2STORMED Project, 2015
Soakaways	Low	0.15 €/m2 treated area 0.1-24.2 €/m3/year	Jotte, et al., 2017; Middlesex University, 2003)

Appendix 7 Scoring of alternatives

Appendix 7.1 Technical-Environment (Chalmers University of Technology)

Alternatives	Criteria									
	Technical Category			Environmental Category			Social Category		Economic Category	
	C1. Flow Control	C2. Reliability	C3 Durability	C4. Pollution Control	C5. Impact on Soil and Water	C6. Ecological enhancement potential	C7. Public interaction	C8. Location Amenity	C9. Capital Costs	C10. O&M
Wet Retention Pond	4.5	5.0	5.0	3.7	3.3	2.5	2.5	2.5	-	-
Dry Detention Pond	4.5	3.0	5.0	2.5	2.5	2.0	2.3	2.8	-	-
Swales	3.5	5.0	4.0	3.3	2.5	2.5	3.3	2.8	-	-
Infiltration Trenches	3.5	2.0	2.0	3.6	1.8	2.0	3.0	2.8	-	-
Underground detention	3.5	3.0	3.0	1.7	4.5	2.0	2.8	2.3	-	-
Manhole filters	0.5	1.0	0.0	3.3	4.8	2.0	2.8	2.5	-	-
Pervious Pavements	3.5	1.0	2.0	3.0	2.0	1.0	2.8	2.5	-	-
Green Roof Storage	4.0	2.0	3.0	2.8	3.8	3.5	3.5	4.5	-	-
Soakaways	3.5	3.0	2.0	1.9	2.0	1.5	2.8	2.8	-	-

Appendix 7.2 Technical-Environment-Economic (Kretslopp och Vatten – Göteborg Stad)

Alternatives	Criteria									
	Technical Category			Environmental Category			Social Category		Economic Category	
	C1. Flow Control	C2. Reliability	C3 Durability	C4. Pollution Control	C5. Impact on Soil and Water	C6. Ecological enhancement potential	C7. Public interaction	C8. Location Amenity	C9. Capital Costs	C10. O&M
Wet Retention Pond	2.0	4.0	5.0	4.6	4.8	5.0	3.0	2.6	5.0	4.0
Dry Detention Pond	4.0	2.0	5.0	4.1	4.0	3.5	3.0	3.4	5.0	4.0
Swales	3.0	2.0	3.0	3.4	3.0	4.0	3.3	2.9	5.0	4.0
Infiltration Trenches	5.0	1.0	2.5	3.6	1.8	1.0	2.3	1.5	3.5	2.0
Underground detention	2.0	4.5	3.5	1.8	5.0	0.0	2.5	2.0	3.5	3.0
Manhole filters	0.0	2.0	1.0	2.7	5.0	0.0	2.5	2.0	4.0	1.5
Pervious Pavements	5.0	2.0	2.5	3.0	2.5	0.0	2.8	3.0	3.0	2.3
Green Roof Storage	1.0	3.0	2.5	1.9	5.0	4.0	3.5	4.9	4.0	2.8
Soakaways	5.0	2.0	3.0	2.1	1.0	0.5	2.5	2.0	2.5	3.5

Appendix 7.3 Social (Kultur och fritid-Göteborg Stad)

Alternatives	Criteria									
	Technical Category			Environmental Category			Social Category		Economic Category	
	C1. Flow Control	C2. Reliability	C3 Durability	C4. Pollution Control	C5. Impact on Soil and Water	C6. Ecological enhancement potential	C7. Public interaction	C8. Location Amenity	C9. Capital Costs	C10. O&M
Wet Retention Pond	-	-	-	-	-	-	2.0	3.0	-	-
Dry Detention Pond	-	-	-	-	-	-	4.5	4.5	-	-
Swales	-	-	-	-	-	-	2.5	2.5	-	-
Infiltration Trenches	-	-	-	-	-	-	3.5	4.5	-	-
Underground detention	-	-	-	-	-	-	2.5	2.5	-	-
Manhole filters	-	-	-	-	-	-	4.5	2.5	-	-
Pervious Pavements	-	-	-	-	-	-	3.5	3.5	-	-
Green Roof Storage	-	-	-	-	-	-	4.0	3.5	-	-
Soakaways	-	-	-	-	-	-	5.0	3.0	-	-

Appendix 8 Web-hipre

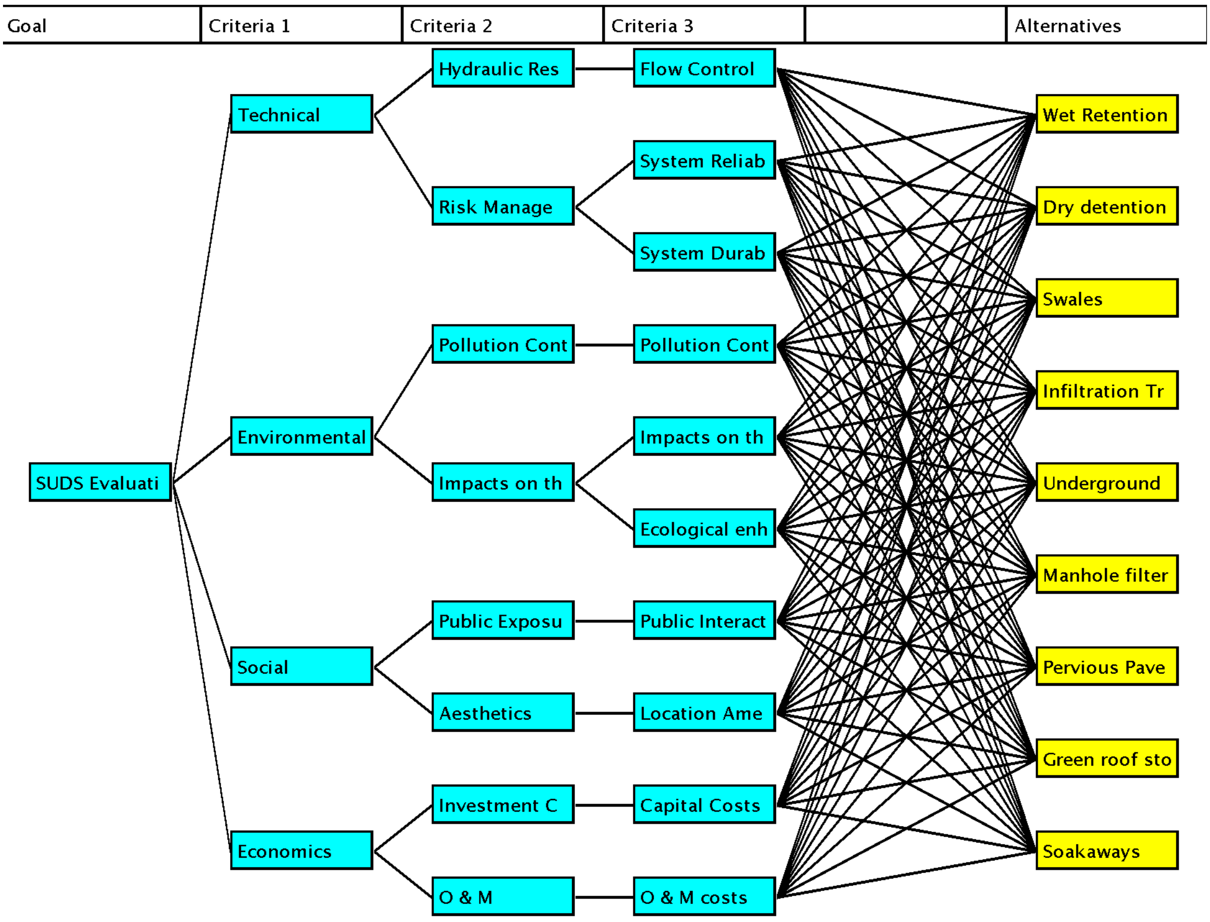

Figure 40 Web-Hipre Model

Appendix 9 Percentage distribution of the criteria in the result of the MCA

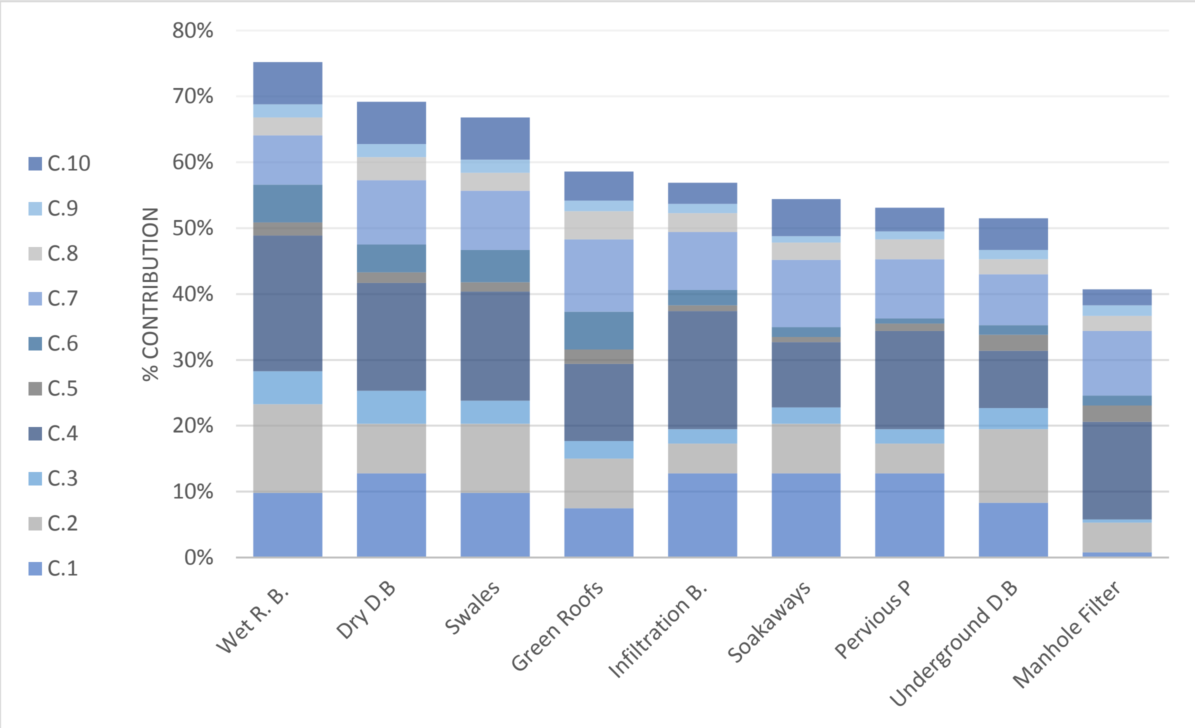

Figure 41: Chalmers University of Technology detailed MCA results

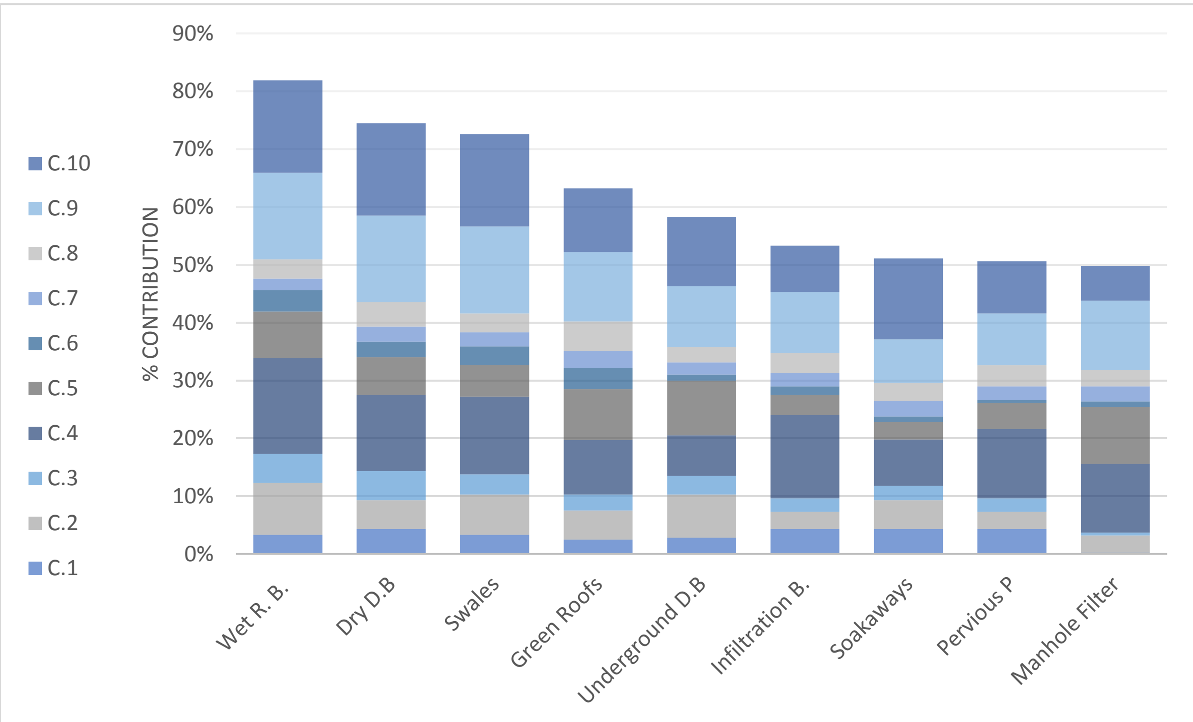

Figure 42: Kretslopp och Vatten´s detailed MCA results

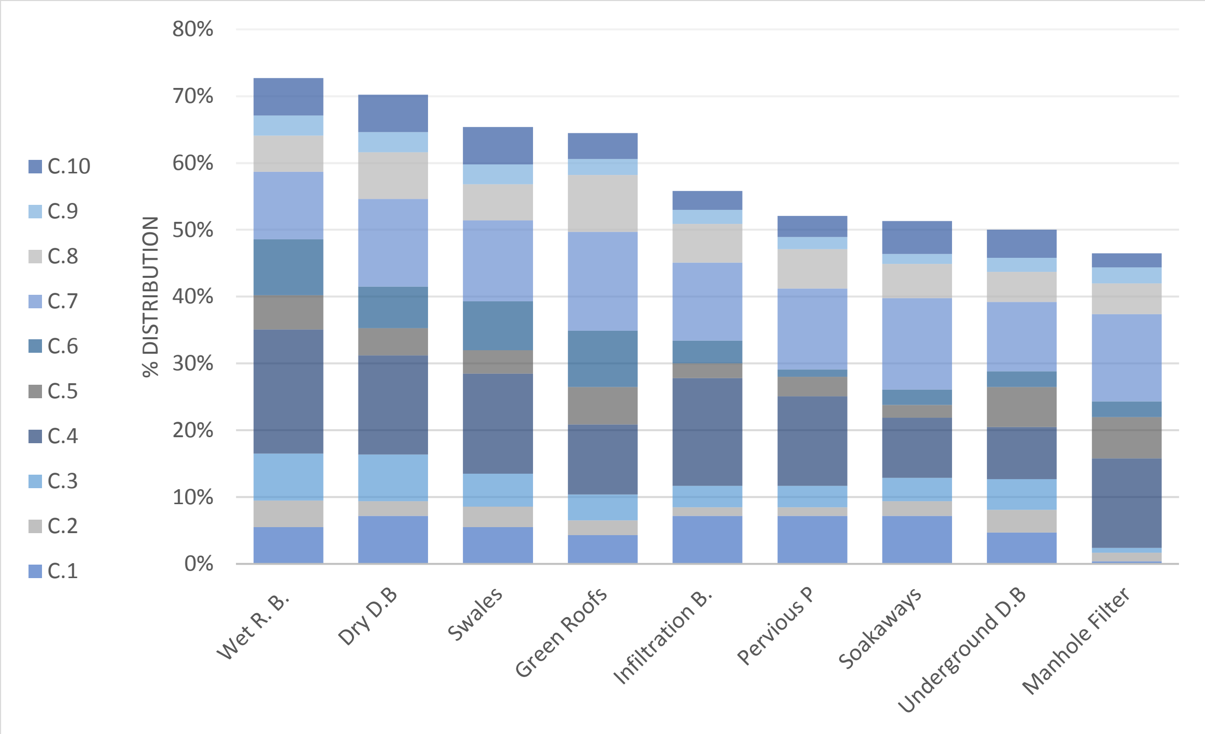

Figure 43: Gothenburg City (social actors) detailed MCA results.

Categories	Parameters	Criteria	Benchmarks
Technical and Hydraulic (Tech)	*Hydraulic response*	C1. Flow Control	Ability to reduce peak flows and water volumes
	Risk Management	C2. System Reliability	Probability of failure
		C3. System Durability	Expected lifespan
Environment (Env)	*Pollution control*	C4. Pollution Retention	Total solids expected retention Bio-chemical Oxygen Demand (BOD) retention Nutrient retention Heavy metal retention Organic Pollutants
	Impact on the biophysical surrounding environment	C5. Impact on the soil and groundwater	Impacts on the groundwater Impacts on the sorrounding soil
		C6. Ecological enhancement potential	Potential improvement on biodiversity
Social (Soc)	*Public Exposure*	C7. Public interaction	Public risks - Information/awareness requirements Potential on recreational activities
	Aesthetics	C8. Location Amenity	Aesthetic value Loss of Public land / land requirements
Economic (Econ)	*Capital Costs*	C9. Capital costs	Material and construction costs
	O& M	C10. Operation and Maintenance Costs	Monitoring and maintenance needs. Costs associated