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ASSESSING THE IMPACT OF SUB-CATCHMENTS ON THE SEWER SYSTEM AS DECISION SUPPORT FOR THE POSITIONING OF GREEN INFRASTRUCTURE

Master thesis

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submitted by:

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Abstract

Municipal water management has become increasingly complex due to aging infrastructure, climate change, increasing population, pollution and tight community budgets. Diverting storm water through sewer systems is common practice but is neither flexible nor provides additional ecosystem benefits. Therefore, the implementation of nature-based solutions such as green infrastructure has become a common urban drainage concept. The project “FlexAdapt” aims at evaluating stormwater management concepts from a technical, economic, environmental, and organizational point of view, to help small and medium sized communities choose the appropriate type of water management strategy. This thesis serves as a case study for FlexAdapt and executes a sensitivity analysis of the surface area of Wagram on the sewer system during heavy precipitation events. The method offers support for the geographic positioning of green infrastructure measures. An automated decoupling process was created to assess the impact of each catchment on the total and maximum discharge at the combined sewer overflow. A positive correlation was found between the sub-catchment size and both the total and maximum discharge. In the second part of this thesis the retention and infiltration capabilities of green infrastructure measures were assessed. This evaluation found that green infrastructure can realistically provide retention and infiltration capabilities comparable to the complete decoupling of a sub-catchment. Further detailed analyses are required to specify ideal green infrastructure parameters for a given catchment within a municipality.

Zusammenfassung

Die kommunale Wasserwirtschaft ist aufgrund der alternden Infrastruktur, des Klimawandels, der wachsenden Bevölkerung, der Umweltverschmutzung und der knappen Gemeindebudgets immer komplexer geworden. Die Ableitung von Regenwasser durch die Kanalisation ist gängige Praxis, ist aber weder flexibel noch bietet sie zusätzliche Vorteile für das Ökosystem. Daher ist die Umsetzung naturbezogener Lösungen wie beispielsweise grüne Infrastruktur zu einem üblichen Stadtentwässerungskonzept geworden. Das Projekt "FlexAdapt" zielt darauf ab, Regenwassermanagementkonzepte aus technischer, wirtschaftlicher, ökologischer und organisatorischer Sicht zu bewerten, um kleinen und mittleren Gemeinden bei der Wahl der geeigneten Art von wasserwirtschaftlicher Strategie zu helfen. Diese Arbeit dient als Fallstudie für FlexAdapt, wobei eine Sensitivitätsanalyse zur Auswirkung von Einzugsgebieten in Wagram auf das Kanalnetz bei Starkregenereignissen durchgeführt wird. Das Verfahren bietet Unterstützung bei der geografischen Positionierung von grüner Infrastruktur. Ein automatisierter Entkopplungsprozess wurde geschaffen, um die Auswirkungen der einzelnen Einzugsgebiete auf den Gesamt- und Maximalabfluss vom Kanalsystem beim Mischwasserüberlauf zu bewerten. Es wurde eine positive Korrelation zwischen der Größe des Teileinzugsgebietes und des Gesamt- und Maximalabflusses gefunden. Im zweiten Teil dieser Arbeit wurden die Rückhalte- und Versickerungsfähigkeiten von grünen Infrastrukturmaßnahmen bewertet. Diese Bewertung ergab, dass grüne Infrastruktur Rückhalte- und Infiltrationsmöglichkeiten ermöglichen kann, die mit der vollständigen Entkopplung eines Teilgebiets vergleichbar ist. Jedoch sind weitere detaillierte Analysen erforderlich, um bestmögliche Parameter für die grüne Infrastruktur eines bestimmten Einzugsgebietes innerhalb einer Gemeinde festzulegen.

Abbreviations

BRC	Bio-retention Cell
CSO	Combined Sewer Overflow
DHI	Danish Hydraulic Institute
EASAC	European Academies Science Advisory Council
EPA	United States Environmental Protection Agency
ESRI	Environmental Systems Research Institute
GI	Green Infrastructure
GIS	Geographic Information System
GR	Green Roof
IT	Infiltration Trench
LID	Low Impact Development
MOUSE	Model for Urban Sewers
MU	MIKE URBAN
OAT	One-at-a-Time
PE	Person Equivalents
PI	Performance Indicator
RB	Rain Barrel
RG	Rain Garden
RWH	Rainwater Harvesting
SA	Sensitivity Analysis

1. Introduction

Municipal water management faces many challenges. Aging infrastructure, climate change impacts, increasing municipal populations and rising pollution collide with tight community budgets increasing the complexity of water management nowadays.

One of the core tasks of urban water management is the treatment of storm and wastewater. Approximately 95% of the Austrian population is connected to public sewer systems, enabling a sufficient treatment of household and industrial wastewater which contributes to the protection of Austrian water bodies (Assmann et al., 2015). This however is not the case with surface runoff, which may pond on impervious surfaces due to a lack of adequate management measures, be diverted into pipes that discharge directly into receiving water, or be diverted into combined sewer systems that face capacity issues. This poses a threat to human health and the environment due to the pollutants carried in stormwater, and the additional risk of urban flooding. Thus, the demand for and interest in decentralized flexible water management measures is increasing. Decentralized retention measures, which manage rainwater on site, have become more common due to flooding problems, the sealing of surfaces and the overloading of wastewater treatment plants. Furthermore, decentralized rainwater management measures are often favored due to their additional benefits for the surrounding environment, such as contributing to the natural water cycle (Grimm and Achleitner, 2010). The management of urban drainage has seen a significant change within the past years, shifting from narrow focused approaches towards a holistic approach where multiple objectives drive both design and decision-making processes (Fletcher, et al., 2014).

With regard to the possible retention measures, municipalities must make a sound decision regarding rainwater management. In Austria, there are still no decision-making aids that integrate the various aspects of rainwater management and provide a structured process for planners and municipalities. While there have been various international approaches for larger urban areas; currently in Austria rural areas play a greater role, which is where FlexAdapt comes into play (Simperler, et al., 2017).

The project "FlexAdapt"- Development of flexible adaptation concepts for urban drainage of the future- aims at evaluating stormwater management concepts from a technical, ecological, environmental, organizational, financial and societal point of view. In particular, this project focuses on the situation of small and medium-sized municipalities and their individual boundary conditions (e.g. drainage methods, population density and development, financial situation). The core idea is to forego investing in expensive infrastructure and instead implement flexible, decentralized measures that are able to react to various future conditions. The final outcome of this project is a comprehensive framework containing decision-making tools for urban drainage adaptations. FlexAdapt is funded by the Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW) and supervised by the urban water management institutes from the University of Natural Resources and Life Sciences (BOKU), University of Innsbruck and the Technical University, Graz (Simperler, et al., 2017).

One promising rainwater drainage concept, which is both sustainable and flexible, is Green Infrastructure (GI). GI measures restore ecological functions of an area and manage stormwater onsite, reducing pluvial flooding. This thesis conducts a case study in Wagram in the city of Sankt Pölten in Lower Austria for the project FlexAdapt. A sensitivity analysis is performed in order to assess which sub-catchments have the greatest effect on the sewer system, and thus the highest potential for the implementation of GI measures. In the second step of this thesis, sub-catchments with a high effect on the sewer system are equipped with GI in order to assess what outcome could realistically be achieved with such measures in dealing with heavy precipitation events.

2. Objectives

This thesis aims at performing a sensitivity analysis of the surface area of the district Wagram (in the city of Sankt Pölten) on the sewer system as a decision support for the positioning of GI measures. It aims at identifying sub-catchments that have a significant effect on the sewer system during heavy precipitation events through a sensitivity analysis. Furthermore, the impact of decoupling these significant areas from the model is compared with the potential effect of GI measures.

To achieve these objectives, the following research questions are examined:

- Which sub-catchments have the greatest impact on the sewer system during heavy precipitation events?
- Can the implementation of GI measures on selected sub-catchments be compared to the effects of decoupling in the model through the sensitivity analysis?

The following tasks are defined in order to fulfill the above-mentioned objectives:

- Create a 1D model of Wagram, Sankt Pölten and its sewer system from provided GIS data
- Identify the impact of sub-catchments on the sewer system by decoupling each sub-catchment from the sewer network
    - Define performance indicators for evaluating impact on the sewer system
- Compare the potential effect of GI measures on specified sub-catchments to the effects of technical decoupling in the model
    - Define the difference of decoupling measures in the sensitivity analysis to the realistic effect of GI measures

3. Fundamentals

Floods are the most common natural disaster in Europe (Hajat et al., 2005; CRED, 2018). Floods in urban areas can be classified as fluvial or pluvial flooding, where fluvial flooding refers to the rise of water in a river so that the riverbank level is exceeded, while pluvial flooding refers to rain-related floods. Pluvial floods follow intense precipitation events where the drainage system and ground cannot manage the additional water volume, causing surface runoff. While fluvial flooding events often occur over several days or weeks and can affect widespread areas along river bodies, pluvial flooding events tend to take place over a shorter time period and are concentrated to local areas. Furthermore, pluvial floods are identified to be more difficult to forecast and more likely to increase in severity as an effect of climate change (Houston et al., 2011; UNISDR, 2011). The World Health Organization (2013) predicts that heavy precipitation events are likely to become more frequent throughout Europe, affecting millions of people per year. Therefore, there is an increasing need to assess the impact of pluvial flooding as well as possible mitigation measures in vulnerable areas.

3.1 Possible causes of increased pluvial flooding

There are many factors that may lead to an increase in urban flooding. Three of the most common causes found in literature include climate change, increasing urbanization and insufficient sewer systems.

3.1.1 Climate change

There is a wide consensus in literature that the climate is changing. Climate change scenarios predict that the next century will be characterized by an increase in extreme weather events including increasing temperatures, storm frequency and intensity and a sea level rise. According to the European Academies Science Advisory Council (EASAC), the number of floods and other hydrological events globally has doubled since 2004 and quadrupled since 1980 (EASAC, 2017).

In Lower Austria, the average annual temperature is expected to increase by 1.3 – 1.4° by 2021 - 2050 in comparison to 1971 – 2000. The average annual precipitation is expected to increase by 5.6 – 7%. The number of heat days (where the maximum daily temperature is 30°C or above) may increase from around 27 days (between the years of 1971-2000) to 36 days within the next 30 years (ZAMG, 2017). In urban areas, these impacts will result in:

- Greater flooding risk due to high-intensity storm events
- Increased frequency and volume of CSOs
- Longer and more intense heat waves as well as droughts
- Increased urban heat islands
- More unexpected system failures (Foster et al., 2011)

3.1.2 Urbanization

When rain falls, various outcomes are possible due to the severity of the precipitation event and the surroundings onto which it rains. In urban areas, a large percentage of precipitation falls on roofs, streets, parking lots and other impervious surfaces. Water that cannot infiltrate the surface becomes surface runoff, which may flow along the surface and eventually drain through gutters, sewer systems or other engineered collection systems. However, water that does not enter collection systems, remains on the surface and may cause flooding.

The densification of growing cities is nearly inevitable, leading to a predominant amount of impermeable land surfaces. Areas once covered with permeable soil, grassland or other vegetation are now increasingly being covered with impermeable materials such as concrete and asphalt, or are compacted. The low permeability and smooth surface of such areas increases the amount of surface runoff, runoff concentration times, and peak flow rates, increasing the risk of pluvial flooding (Qin et al., 2013; Salvadore et al., 2015; Basnet, 2017). Figure 1 illustrates the relationship between an impervious cover, surface runoff and infiltration. As can be seen, the less pervious the surface is, the greater the amount of surface runoff and subsequently the less infiltration which can take place can be observed.

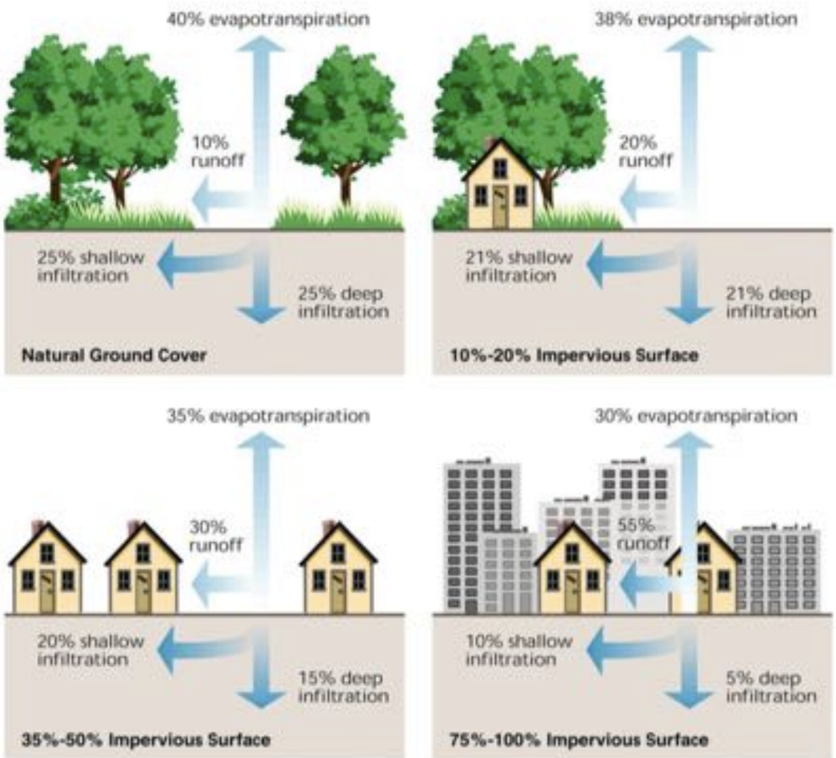

Figure 1: Relationship between impervious cover and surface runoff (The Federal Interagency Stream Restoration Working Group, 2001)

3.1.3 Insufficient sewer systems

As mentioned previously, in most cases, surface runoff starts as overland flow on streets or bare surfaces before entering the underground sewer system through manholes. However, if the intake of the drainage system is reduced or is insufficient for the incoming water volume, only a portion of the water during a heavy precipitation event will be able to enter into the pipes and the remainder will instead be transported on the surface as runoff. If the sewer system is too full, water may flow from the pipe system to the street system, as can be seen in Figure 2 (Mark et al., 2004; Zahnt et al., 2017). It should be stated that simply because surface runoff occurs, it cannot necessarily be implied that the sewer system is insufficient or not working properly. Rather, decision makers must decide on water management systems considering spatial and monetary aspects while taking a certain flood risk into account. For these reasons, drainage systems are designed for frequent (1 to 10 year) precipitation events (Zahnt et al., 2017).

Both short, intensive precipitation events as well as long, moderate precipitation events may overload the sewer system. In combined sewer systems, a reduced intake of water may also be linked to a greater dry weather flow in sewers. If, for example, the domestic water usage in an area increases faster than sewer capacity, a combined sewer system will show a greater dry weather discharge, decreasing the manageable stormwater volume through that sewer system.

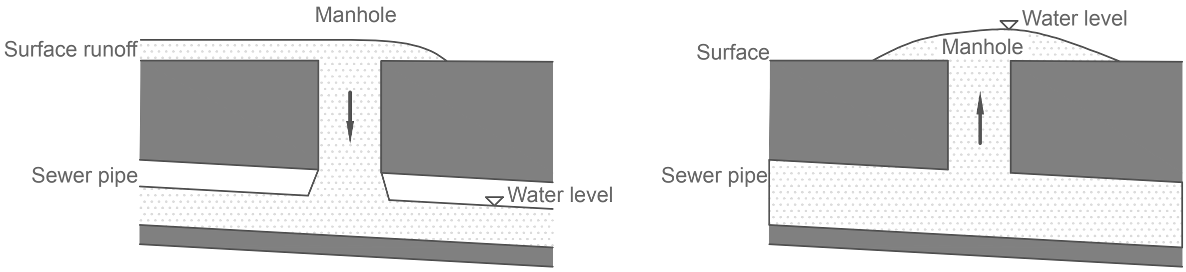

Figure 2: Surface flow from street into partially filled sewer (left) and surface flow from filled sewer to street (right), adapted from (Mark et al., 2004)

3.2 Flood related consequences

According to the EU Floods Directive (2016), flood events have the potential to cause fatalities, the displacement of people, damage to the environment and a negative impact on economic activities. These flood related consequences can be categorized into direct or indirect and tangible or intangible damages, as can be seen in Table 1.

Table 1: Typology of flood damages (Merz et al., 2010)

	Tangible	**Intangible**
Direct	Damage to buildings and property Destruction of infrastructure Erosion of agricultural soil Damage to livestock Evacuation and rescue measures Business interruption in flooded area	Loss of life Injuries Loss of memorabilia Psychological distress Damage to cultural heritage Negative effects on ecosystems
Indirect	Disruption of public services Induced production losses Cost of traffic disruption	Trauma Increased vulnerability Loss of trust in authorities

Tangible consequences are “damages to man-made capital or resource flows which can easily be specified in monetary terms”, whereas intangible damages are difficult or not possible to assess in monetary terms. Direct damages are induced due to the direct, physical contact of floodwater with humans or property; while indirect damages are induced by the direct impacts, yet occur outside of the flood event in time or space (Merz et al., 2010). The tangible effects of the floods in 2013 alone totaled to more than €12 billion in economic losses across nine EU Member States (Jongman et al., 2014). In Austria, the damages of the 300-year flooding event totaled 3 billion euros (BMVIT, 2015). Some of the most common pluvial flood related consequences include wetting, partial flooding and damage to inventory, interiors, facades and gardens (Zahnt et al., 2017).

3.3 Flood prevention

The EU Floods Directive (2016), defines flood prevention as “preventing damage caused by floods by avoiding construction of houses and industries in present and future flood-prone areas; by adapting future developments to the risk of flooding; and by promoting appropriate land-use, agricultural and forestry practices.” The World Bank (2011) emphasizes the importance of an integrated approach to flood risk management, which requires both structural and non-structural measures. Structural measures can be defined as physical constructions or the application of engineering techniques or technology, that help reduce or avoid possible impacts of hazards on structures or systems (e.g. levees, detention ponds, rain gardens). Non-structural measures are measures that do not involve physical constructions but instead use knowledge and practice to reduce the risk and impact of disasters (e.g. public awareness, education, laws) (Prevention Web, 2018).

In the following section, structural measures that are significant for this thesis are discussed; namely the diversion of stormwater through sewer systems and the infiltration and retention of stormwater, in particular through GI.

3.3.1 Diversion through sewer systems

The diversion of surface water may refer to various measures, which divert water from its natural course, to mitigate the impacts of a flood (EPA, 2004). Common diversion measures include the drainage of water through subsurface pipe systems or various forms of open ditches. Subsurface pipe or sewer systems are the most common form of diversion measures in cities.

Sewer systems can be designed as combined sewer systems or separate sewer systems. These two systems are portrayed in Figure 3 under dry and wet weather conditions. Separate sewer systems collect stormwater in one pipe network, while domestic and industrial wastewater is collected in a separate pipe network. The stormwater is usually discharged into the receiving water body without intensive treatment, while the wastewater is transported to a wastewater treatment facility, where it is treated before discharging into a receiving water body. In contrast, combined sewer systems collect surface runoff (stormwater), domestic and industrial wastewater in the same sewer pipes. The collected water is then transported to a wastewater treatment plant. Due to the fluctuations in flow volume depending on dry or wet weather conditions, combined sewer systems are designed to allow an overflow during heavy precipitation events, when the design flow of the sewer system is exceeded. This is enabled through the design of a Combined Sewer Overflow (CSO), which is a discharge of untreated wastewater from a combined sewer system at a point placed before the wastewater treatment plant. Without the possibility to overflow through a CSO, wastewater could back up through the sewer system and overflow in urban areas. However, the discharge of untreated wastewater from a CSO poses a certain risk for human health and the environment, since untreated wastewater and storm water contribute microbial pathogens and other pollutants to the receiving water. Therefore, actions should be taken to reduce the impacts of CSOs or minimize CSO occurrences (EPA, 2004).

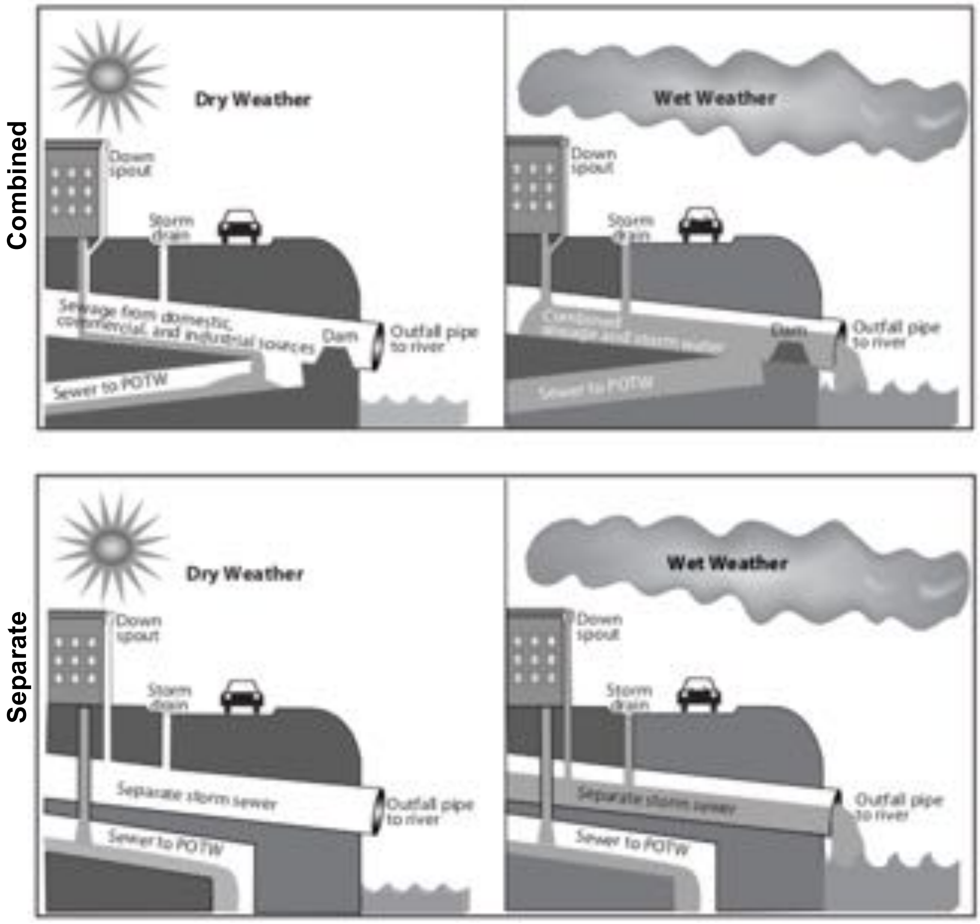

Figure 3: Combined versus separate sanitary sewer systems in dry and wet weather (EPA, 2004)

3.3.2 Green Infrastructure

Traditional urban water management measures, often called “grey infrastructure”, have been shown to have numerous drawbacks. Impervious surfaces and drainage networks can amplify downstream flood peaks; increase pollution from surface runoff, and negatively effect stream ecology and biodiversity (Schubert et al., 2017; Davis and Naumann, 2017; Dhakal and Chevalier, 2017). Grey infrastructure measures usually require higher construction and maintenance costs, and often leads to a false increase in sense of security for the population, which enables urban expansion closer to water bodies and in turn increases exposure if such measures fail (Depietri and McPhearson, 2017). In addition, classic flood management structures often only serve a single objective and do not contribute to the surrounding microclimate, provide ecosystem services or take sustainability goals into account. Thus, alternative flood management measures should be considered.

One evolving water management strategy that both restores ecological functions of an area and manages stormwater onsite is GI. The European Environmental Agency (EEA) (2017) defines GI as “a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services”. The United States Environmental Protection Agency (EPA) provides a similar definition for GI, describing it as an “array of products, technologies, and practices that use natural systems- or engineered systems that mimic natural processes- to enhance overall environmental quality and provide utility services” (EPA, 2018). These definitions express GI as fundamentally including both “natural” and “engineered” components, which aim at providing ecosystem services while managing stormwater.

The ecosystem services, also called ecosystem benefits which GI is known to provide include hazard mitigation, increased land value, improvement in the quality of life and decreasing climate change impacts (Foster et al., 2011; EEA, 2017; Davis and Naumann, 2017). The wide range of benefits in social, environmental and economic aspects highlights the multi-functionality of GI. This means that land dedicated to such measures is able to provide multiple services and contribute to sustainability and resilience within communities (Fosteret al., 2011). Therefore, GI is especially suited for areas that have limited space and require flexible infrastructure measures, which can provide an array of ecosystem services. Specific benefits, which are relevant for this thesis, include an improved management of storm-water runoff, flood prevention, and lowered incidents of CSOs (CCAP, 2011). Other names for GI found in literature include Sustainable Urban Drainage Systems (SUDS), Low Impact Development (LID) measures or Water Sensitive Urban Design (WSUD) (Schubert et al., 2017).

GI measures can provide attenuation and/ or infiltration qualities. Infiltration is defined as the entry of water into the soil through its surface (Kutílek, 2011). This is a pivotal process in the hydrologic cycle, which enables vegetation to access water through roots, contributes to groundwater and replenishes aquifers. Infiltration enables the storage of precipitation and therefore delayed transfer of the water back into the surrounding atmosphere and environment. In addition, water that is infiltrated no longer poses a direct threat for flooding surface areas. GI is also able to control peak runoff rates by slowing and storing runoff on site, also known as attenuation (CIRIA, 2015). As mentioned previously, many pervious surfaces that enable infiltration and the detention of water have been replaced by impervious materials or have been compacted, preventing water from entering the ground and often enhancing the peak rate and volume of runoff. Traditional piped solutions can often no longer keep up with urbanization, higher construction and maintenance costs as well as with the impacts of climate change. Therefore, it has become increasingly important to reintroduce areas and measures that retain water and enable it to enter the ground. The CIRIA SuDS Manual describes that surface runoff, which is not collected for further use, should be managed in the following order:

a) through infiltration
b) by discharging to surface waters
c) by discharging to a surface water sewer or similar drainage system
d) by discharging into a combined sewer (CIRIA, 2015)

Common GI measures include green-roofs, rain gardens, permeable pavement and infiltration trenches. The following sections describe in short the GI measures, which can be simulated in a MIKE URBAN MOUSE Model. GI measures are called LID (Low Impact Development) measures in MIKE URBAN.

3.3.2.1 Bio-retention cells

Bio-retention cells are shallow excavated areas usually below grade, which contain mulch and engineered soil mix and are planted with vegetation that is resistant to extended periods of high moisture and nutrient concentrations. These areas provide infiltration, storage, evaporation and often treatment of captured water (MIKE by DHI, 2018). The primary components include the surface zone, which includes the mulch ground cover and plants, the soil zone, which is often a mixture of sand, fine sediments and organic material, and the storage zone. Bio-retention cells may contain an underdrain for full or partial infiltration, or may be constructed with an impermeable liner and underdrain for filtration only, often referred to as a biofilter. These cells are designed to capture small storm events and contain an overflow or bypass for large storm events. They are well suited for landscaping areas, parks, parking lot islands or areas without tight space restrictions and have shown to provide additional benefits including reducing urban heat islands and reducing thermal aquatic impacts (CVC and TRCA, 2010).

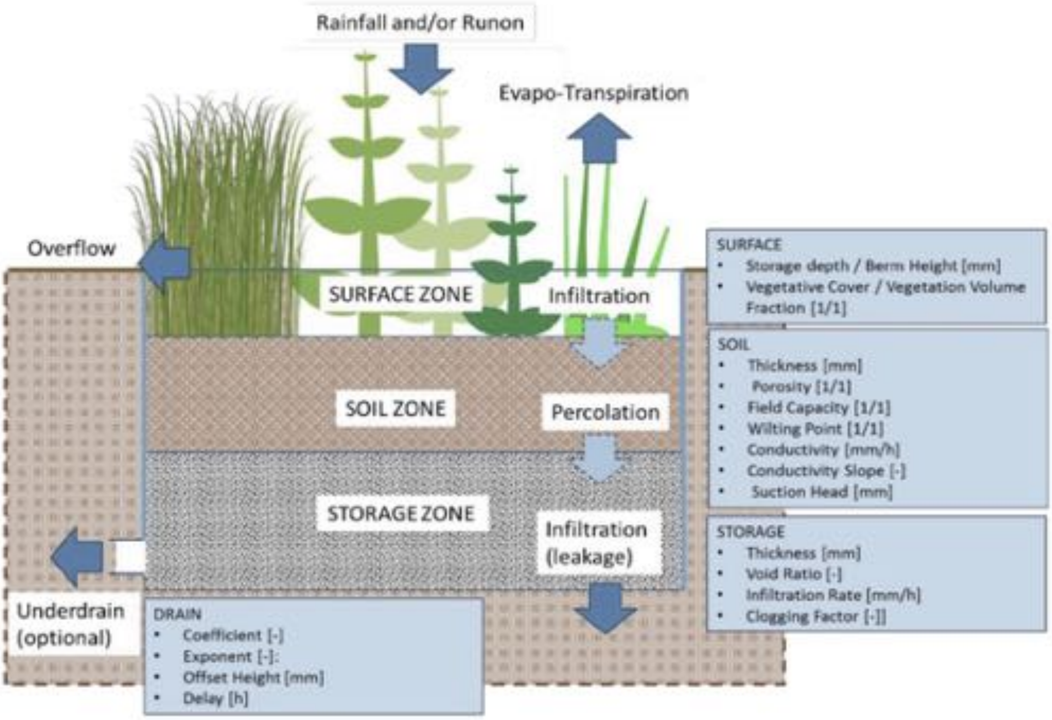

Figure 4: Scheme of a bio-retention cell (MIKE by DHI, 2018)

3.3.2.2 Green-roofs

Roof surfaces in urban areas can amount to 40 – 50% of the total impervious area (Locatelli et al., 2014). Thus, measures that sustainably utilize roof areas can have a great effect on the local water balance and urban flooding. Green roofs are a form of bio-retention cell that are partially or completely covered with plants, which grow in approximately 7 – 40 cm deep soil or other ground cover, on top of a waterproof membrane, placed on building rooftops. Green roofs may also include layers that provide additional drainage, filter capacity or structural benefits such as insulation or structural support. Vegetation can either be spread across the roof or planted in modular trays. Green roofs have the advantage that they do not necessarily require the use of new and additional spaces; existing traditional rooftops can be retrofitted to support vegetation (CIRIA, 2015; Locatelli et al., 2014).

Two main categories of green roofs can be found in literature: intensive green roofs, which require regular watering and maintenance and extensive green roofs, which require very little care (CCAP, 2011; Locatelli et al., 2014). The former includes thick soil layers (>15cm) with large plants and moderate slopes, while the later (3 – 15 cm) usually has a very thin soil layer and can often be placed on existing buildings without structural reinforcement (FLL, 2008; MIKE BY DHI, 2017a). Extensive green roofs usually cover the entire roof area with slow growing, hardy plants such as mosses, succulents and grasses and can be constructed as single-layer (containing one free-draining medium) or multi-layer systems (including a growing medium as well as a separate drainage layer). Intensive green roofs may also include the possibility to store rainwater for irrigation uses. Green roofs with a substrate thickness of 10-20 cm are often constructed as semi-intensive roofs, which include characteristics of extensive and intensive roofs (CIRIA, 2015).

The performance of green roofs regarding the management of stormwater depends on many factors including local climate, pore size distribution, precipitation patterns and building practices including material use and slope. Locatelli et. al. (2014, p. 3238) explain that the performance of green roofs is largely dependent on possible "volume detention, defined as temporary storage and subsequent release [which] results in additional attenuation and time delay of runoff peaks". According to "The SuDS Manual", the possible volume detention is a function of the antecedent soil moisture, substrate depth, roof gradient and the specific characteristics of the drainage layer (CIRIA, 2015).

Green roofs have been observed to reduce annual stormwater runoff by up to 50-60% (CCAP, 2011) and delay peak runoffs between 0 and 30 minutes in comparison to traditional roofs (Locatelli et al., 2014). Furthermore, green roofs have the potential to capture water nutrient pollutants and filter air pollutants such as particulate matter, nitrogen oxide (NO_X), carbon monoxide (CO) and ground-level ozone (O_3) (CCAP, 2011).

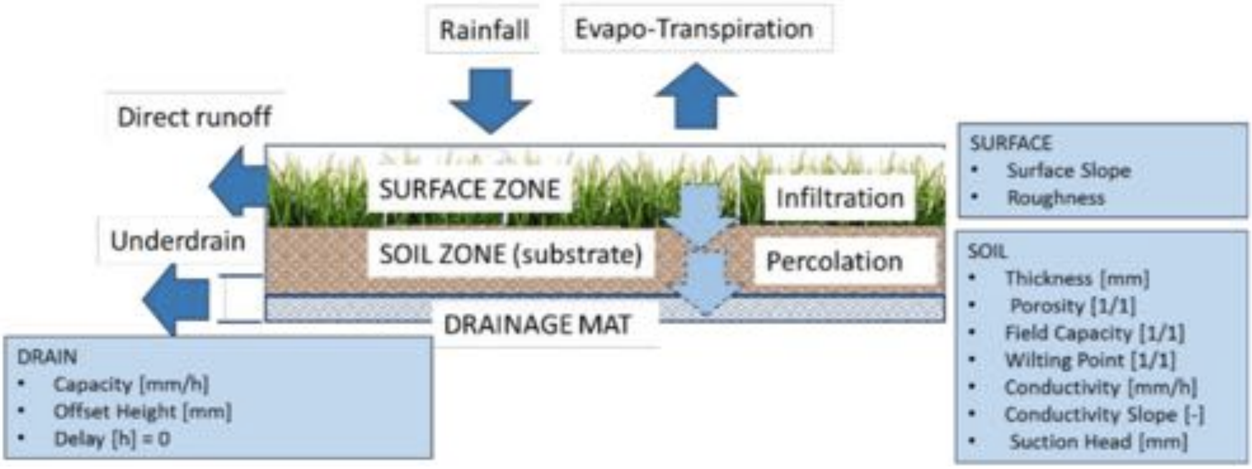

Figure 5: Green roof (MIKE by DHI, 2018)

3.3.2.3 Infiltration trenches

Infiltration trenches are narrow ditches intended to intercept stormwater runoff and provide temporary storage. They are usually rectangular excavations filled with gravel or other porous material, allowing water to collect in the trench and infiltrate into the surrounding soil (CVC and TRCA, 2010). This GI measure is well suited for sites where available infiltration space is limited to narrow strips. Infiltration trenches may be constructed with an underdrain to convey runoff to an offsite area instead of infiltrating it into the surrounding soil (MIKE BY DHI, 2017a). Additional benefits of infiltration trenches include the removal of pollutants, the ability to contribute water back into the water cycle and reduce channel erosion by reducing runoff volumes.

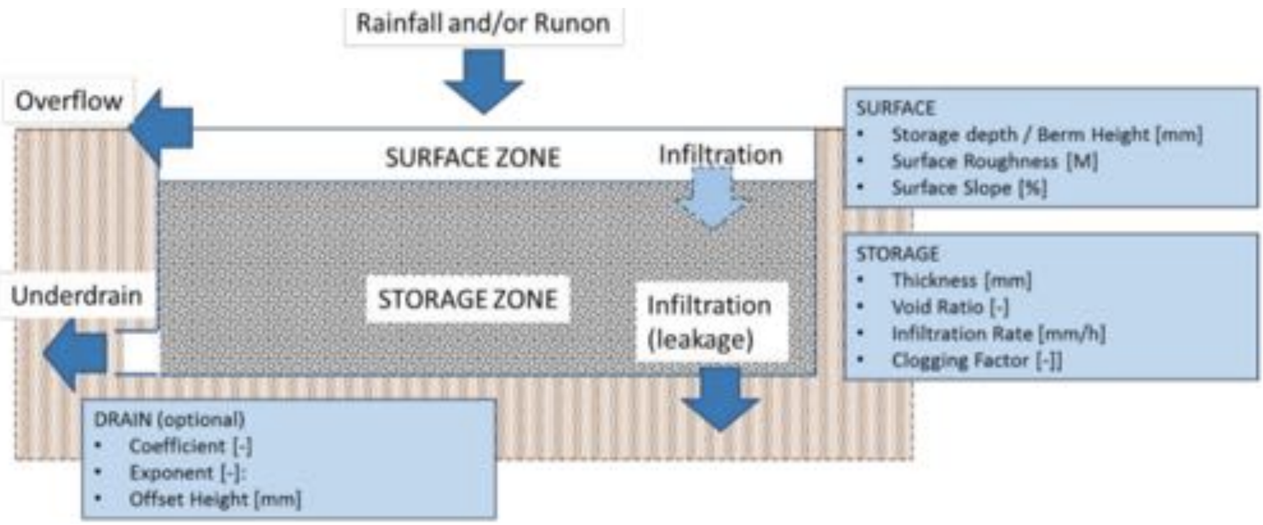

Figure 6: Scheme of an infiltration trench (MIKE by DHI, 2018)

3.3.2.4 Rain gardens

Rain gardens are simplified bio-retention cells that are designed as small gardens with vegetation, which is resistant to both extended periods of high moisture and nutrient concentrations. Rain gardens contain a surface zone and a soil zone, without implementing a gravel bed underneath the engineered soil. They usually do not contain an underdrain.

3.3.2.5 Rain barrels

Rain barrels are containers intended to collect roof runoff during precipitation events, and thus fall under the category of rainwater harvesting (RWH). The collected runoff can either be stored for future re-use or be released. Rain barrels are usually empty containers that have a large collection volume, and may include an underdrain for a controlled release of the stored water volumes. They only collect water from the connected catchment, not from any surrounding areas. (MIKE BY DHI, 2017a). Rain barrels can contribute to a building's water demand, reduce the volume of runoff from a site and provide the attenuation of runoff. However, RWH systems will only reduce peak flow rates in periods where the barrel (or tank) storage is not full, since once full, runoff passes directly to the site drainage system. In this thesis, the rain barrel is equivalent to a cistern due to the large storage volume.

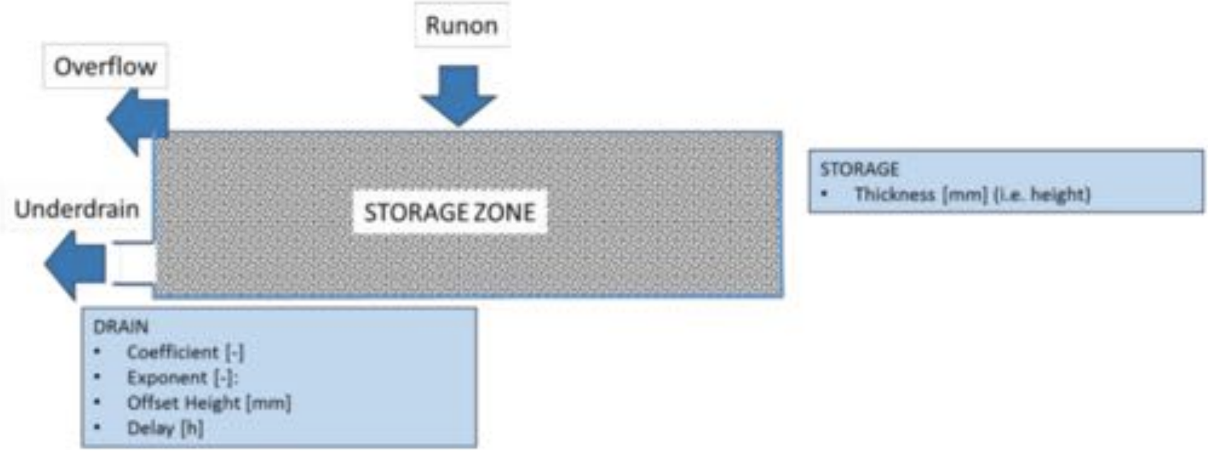

Figure 7: Scheme of a rain barrel (MIKE by DHI, 2018)

3.3.2.6 Vegetated swales

Vegetated swales are open channels designed to attenuate, convey and treat stormwater runoff. Check dams and vegetation in the swale slow flow velocities and enable sedimentation, infiltration, evapotranspiration and filtration (CVC and TRCA, 2010). Simple vegetated swales can be implemented as grass channels or ditches, while enhanced grass swales incorporate features such as check dams or changes in the geometry to improve stormwater management. Swales are particularly effective for draining long stretches of road, which are not located on embankments (unless the swale is lined to prevent stability problems).

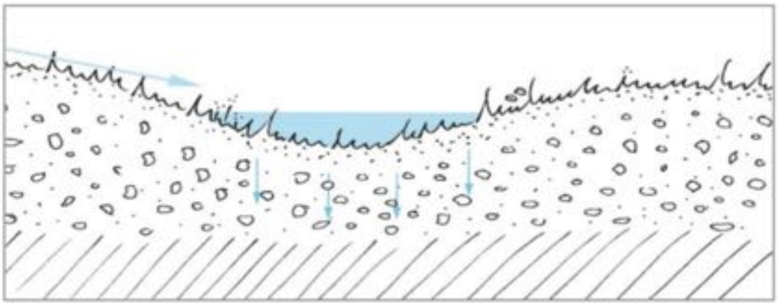

Figure 8: Vegetated swale (MIKE by DHI, 2018)

3.3.2.7 Permeable pavement

Permeable, or porous pavement systems are a variation of traditional pavement designs, which use pervious paving material. The goal of such systems is to create runoff characteristics similar to those of grassland or other vegetated areas (CCAP, 2011). Examples include permeable asphalt or concrete, permeable interlocking concrete units or pavement with openings containing sand or soil and grass. Permeable pavement designs may include features such as:

- a stone reservoir to provide extra runoff storage or structural support,
- a geotextile fabric, which separates dissimilar soils
- a monitoring well, and
- edge restraints, which provide support and prevent rotation.

Permeable pavement enables the infiltration of precipitation into the pavement cover and eventually into the underlying soil. They are most often applied in low to medium traffic areas such as parking lots, driveways, walkways, playgrounds, etc., where limited space exists for other GI measures. In addition to the benefits in storm water management, permeable pavement also provides improvements in water quality, a reduction of the urban heat island effect and a reduction in noise in comparison to dense pavement. (CVC and TRCA, 2010).

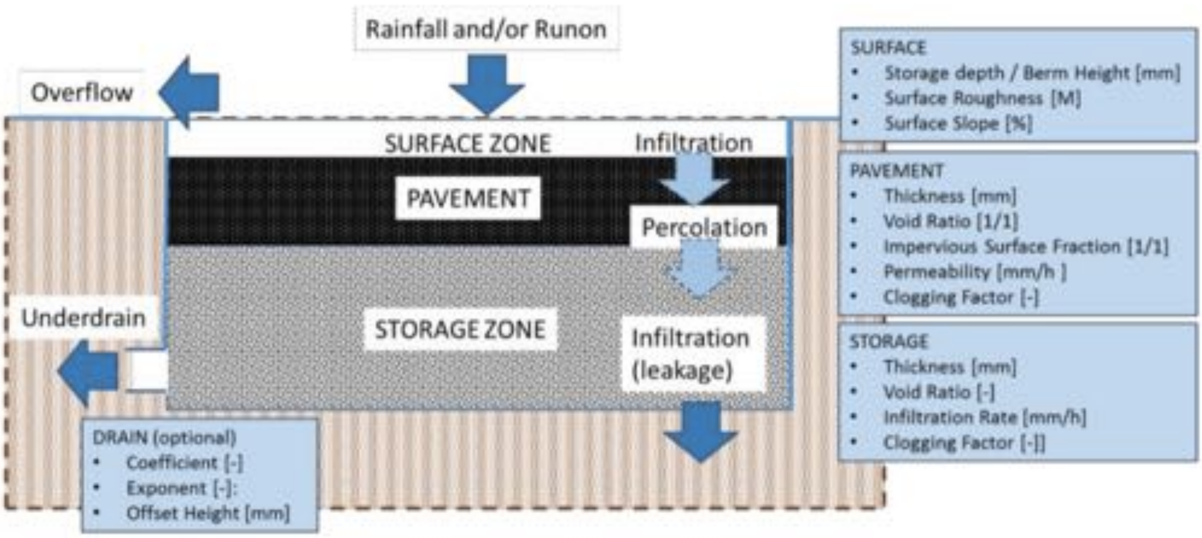

Figure 9: Permeable pavement (MIKE by DHI, 2018)

3.4 Flood modeling

Developments in remote sensing data and computer capability have enabled hydrological models to become a common practice. Urban hydrological models are primarily used (1) to evaluate effects of urbanization on the natural water system and increase knowledge of this system; (2) to fill data gaps, where not enough reliable information is available; and (3) to help forecast future events such as flooding or climate change scenarios (Salvadore et al., 2015). Similarly, the two most common applications for urban drainage models are the analysis of existing sewer systems and the design of new systems.

The analysis of existing sewer systems examines the performance under certain conditions, while the physical characteristics of the system are known. The main physical processes include hydrological inputs such as rainfall and runoff. Urban drainage models should be able to demonstrate the rapid changes in urban catchments during intense precipitation events (Basnet, 2017).

3.4.1 1D Modeling

One-dimensional models are often seen as one of the simplest modeling options, “best suited for representing flows within interconnected networks of channels” (Moffatt and Nichol, 2005). 1D model approaches represent simplified overland surface hydraulics, and are typically used as a standard industry practice. They solve the so-called 1D equations of flow in channels, which include the conservation of mass and conservation of momentum, which are explained in detail in Chapter 4.4.2 Pipes and canals. This means, that a single water level, velocity and flow rate is calculated for each cross section in the model. Furthermore, 1D hydraulic models compute flow velocity perpendicular to the cross section, and only calculate an averaged cross-sectional flow velocity. Point features such as weirs and manholes can also be calculated with 1D models.

The advantages of 1D models include:

- Quick set up and fast computations, even for a large network
- Accurate representation of channel cross-sectional areas at all stages
- Relatively little required field data
- Long time use for flood prediction, therefore generally more powerful capabilities to describe control structures

The disadvantages lie in the inability of a 1D model to describe true two-dimensional characteristics (Moffatt and Nichol, 2005). However, for this thesis a 1D model sufficiently depicts the characteristics and behaviors of the modeled system without exceeding the (time) scope of this work.

According to DHI Austria, 1D/1D stormwater model usually has three main components: the underground sewer system, the overland flow system and the rainfall-runoff hydrology parameters. The underground sewer system and rainfall-runoff are explained in detail in Chapter 4 Material and methods; the overland flow system is not included in this model.

3.4.2 MIKE URBAN

There are many urban flooding modeling packages available both commercially and non-commercially. MIKE URBAN (MU) is a commercial urban water modeling software developed by the Danish Hydraulic Institute (DHI), which is used in this thesis to perform a 1D urban (pluvial) flood model. MU is based on a database for storing network and hydraulic modeling data (MIKE BY DHI, 2017b). It is a Geographic Information System (GIS) based software, specifically based upon the ESRI GeoDatabase. MU is able to perform numeric modeling and provide an interface for the analysis of both urban storm water management and separate or combined waste water systems (Basnet, 2017). The main module of MIKE URBAN is the Model Manager, which includes a common data module for both water distribution and collection systems. The modular structure of MIKE URBAN is shown in Figure 10.

MOUSE (short for Model for Urban Sewers) is an engine created by DHI for modeling complex hydrological and hydraulic processes for urban and stormwater collection systems. A MOUSE network may include the following hydraulic elements (MIKE BY DHI, 2017a):

- Nodes and structures (manholes, basins, outlets and storage nodes)
- Pipes and canals (links)
- Weirs
- Orifices
- Stormwater inlets
- Pumps
- Valves
- Catchments

The MIKE URBAN Collection System CS-Pipeflow enables the hydrodynamic simulation of networks by solving the St. Venant equations throughout the sewer network, allowing the modeling of backwater effects, surcharging in manholes, free surface as well as pressure flow and storage basins (MIKE BY DHI, 2017b).

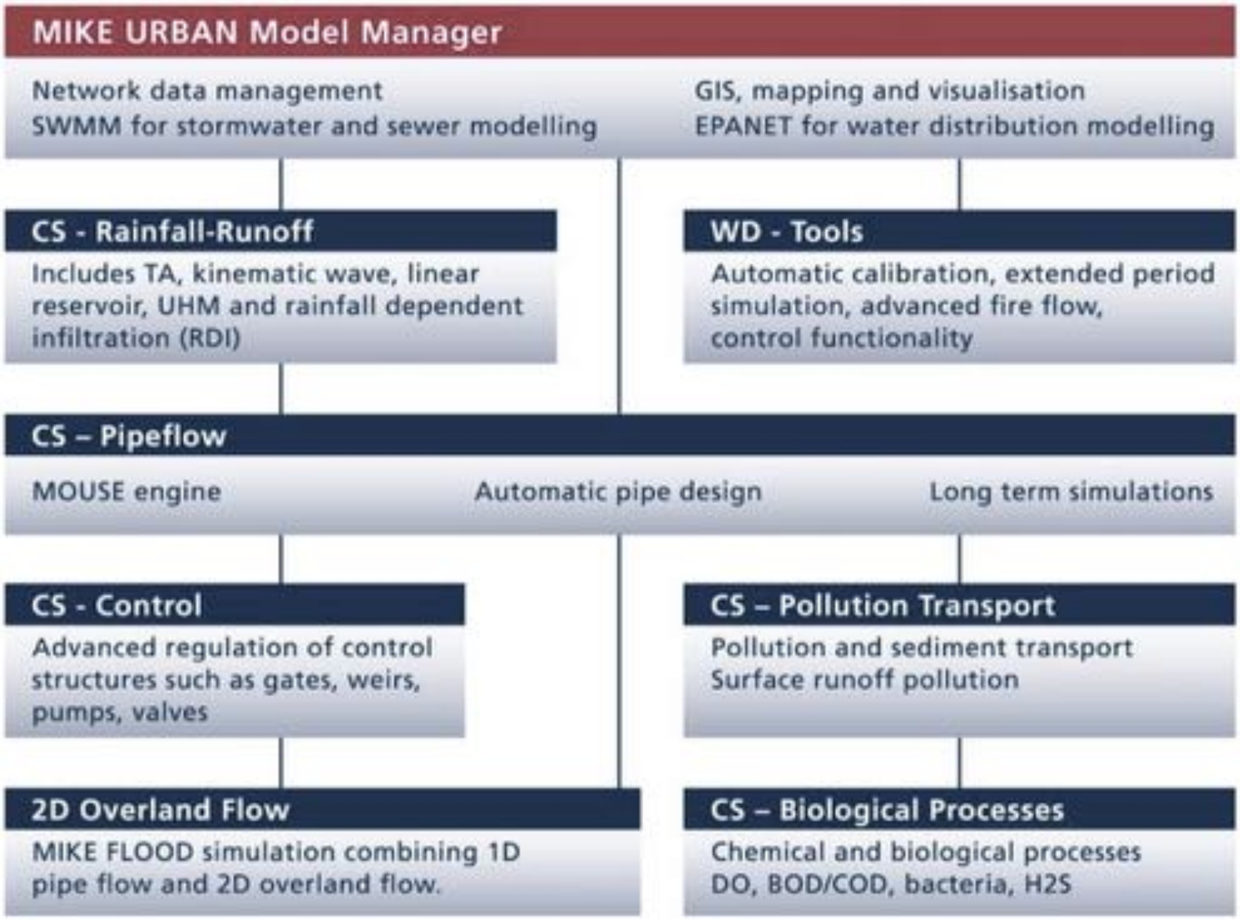

Figure 10: Modular Structure of MIKE URBAN (MIKE BY DHI, 2017b)

3.5 Sensitivity analysis

The use of SA in environmental modeling is increasing for various purposes, including uncertainty assessment, model calibration and decision-making (Pianosi, et al., 2016). The following section describes the basics as well as the methodology of a SA.

The aim of a SA is the exploration of changes in model outputs by changing the model input (Mair et al., 2012) to understand fundamental system behavior (Saltelli et al., 2006). Model input refers to elements that can be changed before model execution, while model outputs are variables obtained after the execution of the model (Pianosi, et al., 2016). Many methods for performing a SA can be found in literature, varying in complexity, based on the modeling area and specific application aims. A SA can either be referred to as local or global depending on whether output variability is achieved by varying the inputs around a reference (nominal) value or across their entire feasible space. While local SAs usually consider model parameters as varying inputs, which assess how their uncertainty alter model performance, global SA may also consider other input factors such as the model’s forcing data or spatial resolution (Pianosi, et al., 2016).

Table 2: Components of a sensitivity analysis

	Definition	General examples	Thesis examples
Model input	Elements which can be changed before execution	Initial state Boundary conditions Forcing data (dynamic model)	Precipitation event Drainage area
Model output	Variables obtained after execution	Temporal and spatial variables Summary variable	CSO efficiency Discharge volume

Another distinction between the types of SA is based on “the sampling strategy used to estimate the sensitivity indices” (Pianosi, et al., 2016). The One-at-a-Time (OAT) method analyzes the change of the model output when altering only one model input parameter in a simulation, while All-at-a-Time methods vary all input factors simultaneously. In the first step of the OAT method, a local SA is performed to evaluate the sensitivity of the model towards a change in the chose input parameter. This requires the input parameter to be changed individually.

In order to evaluate the outcome of the model, performance indicators are chosen. The ultimate goal of performance indicators (PI) is to provide information and represent the type of system behavior that is being examined. Since PIs cumulate relevant data, it is important to choose indicators that offer a sufficient representation of the system behaviors.

4. Material and methods

In order to gain greater understanding of pluvial flooding, flood management measures and urban water modeling approaches, an extensive online literature review was performed. The research was first undertaken as a “top-down” search to accumulate general knowledge. In order to gain more specific understanding of modeling parameters and GI measures a “bottom-up” search was performed. In the next step, a model of St. Pölten and its sewer system was created, which will be explained in detail in the following chapter.

4.1 Material

The material used in this thesis includes the software MIKE URBAN provided by DHI Austria, the digital, geographical information provided by ÖSTAP Engineering & Consulting GmbH and rainfall data from the Austrian Hydrographical Service (ehyd). The following software has been used:

- MIKE URBAN 2017, Service Pack 2 by DHI
- ArcMap 10.5 by Esri
- Microsoft Excel by Microsoft Corporation
- Visual Studio Code by Microsoft Corporation

The geographical information files include:

- Land use coverage including buildings, road network etc. – shape files, polygons
- Manholes, basins and other special constructions – points
- Sewers – polylines

All geographic data is projected in the coordinate system MG_Austria_GK_East.

4.2 Study area

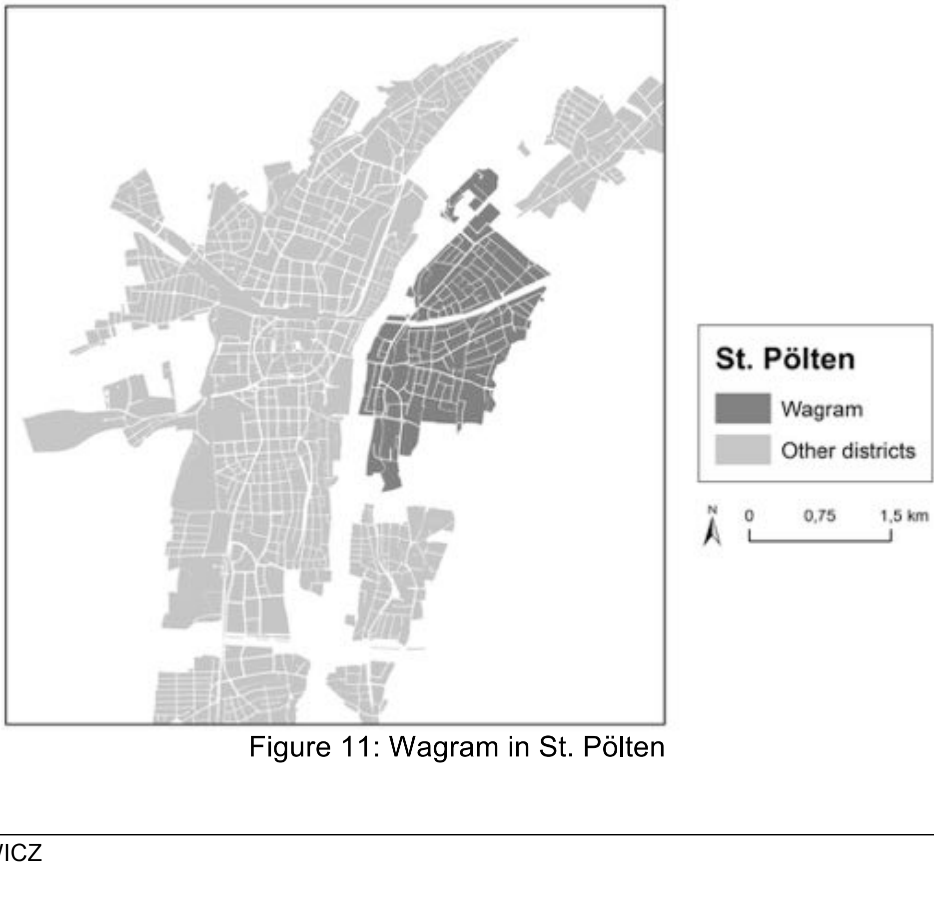

Figure 11: Wagram in St. Pölten

The study area of this thesis is the district Wagram in the city of Sankt Pölten (abbreviated St. Pölten). St. Pölten is the capital of the state of Lower Austria and lays at an elevation of approximately 270 meters above sea level between the eastern Northern Alps and the alpine foothills, between the Molasse Zone and Vienna Basin. The climate is temperate with an annual rainfall of 663 mm and an annual temperature of approximately 9.5°C (ZAMG, 2010). St. Pölten shows a variety of land cover types including agricultural areas (53%), forests (15%) and building areas (13%) (Magistrat der Stadt St. Pölten, 2015). The city center contains pedestrian zones, paved roads and residential areas that largely represent impermeable surfaces. The river Traisen runs through the city and is the receiving water for most CSOs. The annual mean discharge of the Traisen is 14.0 m^3/s (BMNT, 2018). Wagram is an area of St. Pölten to the east of the river Traisen and the city center. Wagram has a population of approximately 6,500 and covers an area of around 1,040 hectares.

4.3 Precipitation events and runoff

In this thesis a hydrological (precipitation-runoff) model is created. Hydrological models transform representative precipitation into a runoff hydrograph through the connection to a hydraulic system. This transformation is calculated through numerous computations that describe the land phase, or runoff phase, of the hydrological cycle. Surface runoff is typically generated through precipitation. In this model the precipitation is given in the form of time series; specifically defined as a sequence of values for rainfalls with time and date labels (MIKE by DHI, 2018). For MOUSE Surface Runoff computations, the time series must be stored as a time series with rainfall intensity (dfs0 format), which is then imported to MIKE URBAN as a Catchment Load Boundary Condition. The model calculates the rain intensity for each time step, so that the rain volume applied by the model is contained in the same interval of that of the input data, as illustrated in Figure 12.

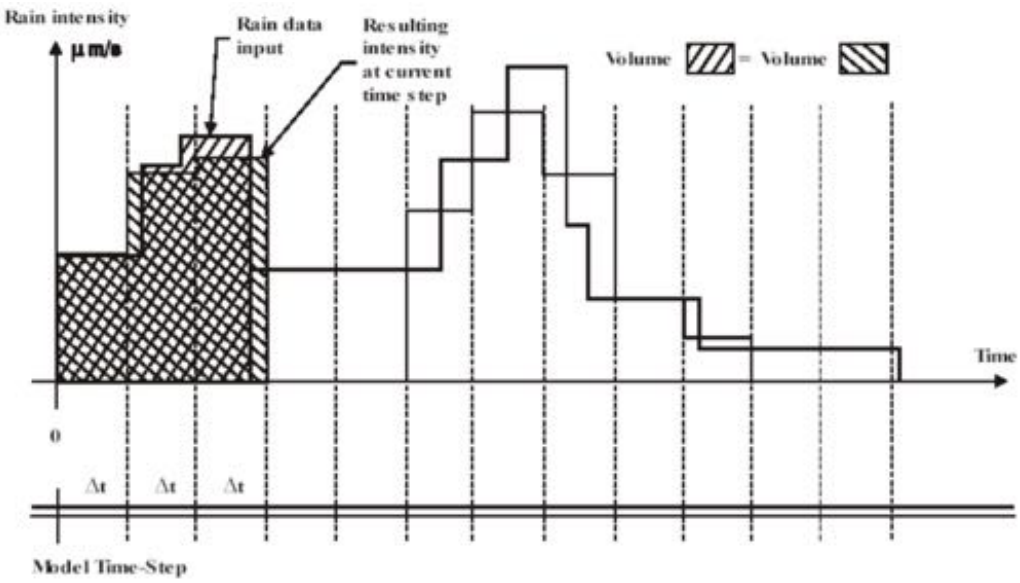

Figure 12: Rain input versus model applied data (MIKE BY DHI, 2002)

The simulations performed in this thesis use the following rainfall events, which are also displayed graphically in the Appendix:

- T1: 1- year, 60 min Euler II design storm event
- T5: 5-year, 60 min Euler II design storm event
- T30: 30-year, 60 min Euler II design storm event
- 6h: six-hour-long, measured precipitation event

Runoff occurs when the rain depth exceeds the specified initial loss of the catchment, and stops when the accumulated rain depth is again below the specified loss. Runoff starts after the rain depth on a catchment has exceeded the initial loss, accumulates in downstream direction from one cell to the next, and stops when the rain depth on the catchment is below the initial loss. Therefore, the volume in every cell is calculated as a continuity balance between the inflow to the cell, rainfall (multiplied with the cell area) and the outflow to the downstream cell. Runoff computations are based on the volume continuity and the kinematic wave equation. In order to calculate runoff, first the effective precipitation intensity must be known. Effective precipitation is defined as the “precipitation, which contributes to the surface runoff” (MIKE BY DHI, 2002) and is calculated by subtracting various losses from the total precipitation and is calculated as follows:

$$(1) \qquad I_{eff}(t) = I(t) - I_E(t) - I_W(t) - I_I(t) - I_S(t)$$

$$I_{eff} \geq 0$$

where:

$I(t)$ … actual precipitation at time t

$I_E(t)$ … evaporation loss at time t

$I_W(t)$ … wetting loss at time t

$I_I(t)$ … infiltration loss at time t

$I_S(t)$ … surface storage loss at time t (MIKE BY DHI, 2002)

Precipitation is assumed to be distributed uniformly over the catchments in the model area. When it starts to rain, a part of the precipitation causes the surface to wet if it is dry. If the surface is already wet, the wetting loss is set to zero. Infiltration is the water loss due to storage in the surface of the catchment, dependent on many factors such as soil porosity, moisture content, groundwater level, surface conditions, etc. Evaporation is not considered in this model using the Time-Area Method, but is relevant for the GI simulations using Model B.

4.4 Model set up

The first step in creating the model is to define and import the 1D network data. The data was provided by ÖSTAP Engineering & Consulting GmbH in the form of ESRI shapes, points and lines. These were first processed and reviewed in ArcMap and then imported using the MIKE URBAN Import/Export Wizard. The following section describes the network components including nodes and structures, pipes and catchments.

4.4.1 Nodes and structures

In MIKE URBAN the “Nodes and Structures” editor includes manholes, basins and outlets. Each node or structure is identified by an ID and geographically defined through X and Y coordinates. Both the ID and the coordinates were imported from the provided GIS data. Circular manholes are defined as vertical cylinders, characterized by their ground and invert (bottom) elevation, diameter and outlet shape. In MIKE URBAN basins are a type of node associated with structures such as tanks, reservoirs, basins or natural ponds (MIKE by DHI, 2017c). There are no basins in the model of Wagram St. Pölten.

The manholes in the model are considered to be open at the top, which means that when water reaches the ground level, it is able to leave the sewer system and spill on the ground surface. In this case, MOUSE creates an artificial basin over the node with a surface area 1000 times larger than the node’s defined surface (MIKE BY DHI, 2017a). The model includes 824 manholes and two outlets.

Outlets in the model are nodes that interact with receiving waters such as a river, lake or sea. In MIKE URBAN receiving waters at outlets are considered large enough to omit backwater effects. In this model both outlets lead into the river Traisen in the north of Wagram. In reality, one outlet discharges into the municipality's main collector. Outlets are defined by the outlet bottom elevation [m] and water surface elevation at the outlet [m] (MIKE by DHI, 2017c).

4.4.2 Pipes and canals

The MIKE URBAN links are specified as a conduit between two nodes, which can either be a straight line or drawn polyline an may be specified as a circular, rectangular, O shaped or egg-shaped pipes or as any closed or open cross section shape. The diameters range between 150 mm and 1900 mm. Circular and egg-shaped pipes are implemented.

The flow in MIKE URBAN links is considered unsteady and is computed with the MOUSE Pipe Flow Model, which solves the Saint Venant equations assuming that:

- Water is incompressible and homogeneous
- The bottom slope of the pipe is small enough to consider the cosine of the angle of the bottom of the pipe with horizontal to equal one
- The wavelengths are large in comparison to the water depth ensuring that the flow direction is parallel to the direction of the pipe
- The flow is sub-critical, where the Froude number Fr < 1

The Saint Venant Equations consist of the continuity equation:

$$(2) \qquad \frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0$$

where

Q … discharge [m^3/s]

A … cross-section of flow area [m^2]

x … longitudinal distance [m]

t … time [s] (MIKE by DHI, 2017c)

and the one-dimensional conservation of momentum equation:

$$(3) \qquad \frac{\partial Q}{\partial t} + \frac{\partial (\alpha \frac{Q^2}{A})}{\partial x} + gA\frac{\partial y}{\partial x} + gAl_f = gAl_0$$

where

y … flow depth [m]

g … acceleration of gravity [m/s^2]

α … velocity distribution coefficient

l_0 … bottom slope

l_f … friction slope (MIKE by DHI, 2017c)

These equations are valid for free surface flow, which is assumed in all pipes that are not pressurized (MIKE by DHI, 2017c). This is valid for this model since no pressurized pipe stretches are implemented in Wagram.

Weirs represent a functional relation, where either two nodes of a MOUSE network are connected, or only one node is connected, enabling a free flow out of the collection system. Weirs are defined by their computational method, weir type, crest level and width, as well as weir orientation (MIKE BY DHI, 2017a). In this model all weirs are specified as free overflow, rectangular weirs. MOUSE provides two computation methods for free overflow weirs:

1. Flow computation based on the energy loss coefficient and weir orientation
2. Flow computation based on the standard rectangular overflow weir formula using a user-specified discharge coefficient

The standard overflow weir formula is given as:

$$(4) \qquad Q_{weir} = C_H \cdot B \cdot \sqrt{2g} \cdot (H)^{\frac{3}{2}}$$

where

Q_{weir} … weir discharge

C_H … $2/3\ C_d$

C_d … discharge coefficient

B … width of the weir [m]

H … water depth above the weir crest level [m] (MIKE by DHI, 2017c)

The model includes 1 weir, which has the following measurements:

Table 3: Weir measurements

MUID	Crest level [m]	Crest width [m]	Discharge coefficient	Weir type
RUE17	256.25	15.2	0.43	Rectangular

4.4.3 Catchments

The catchments are based on land use data provided by ÖSTAP Engineering & Consulting GmbH, which is based on the digital cadastral map. Catchments represent the level of spatial discretization of the hydrological model, where storm runoff and infiltration are generated based on model parameters and input data (MIKE BY DHI, 2017a). The sub-catchments in Wagram based on the digital cadastral map are shown in Figure 13.

Urban areas show a great variety in ground cover, which influence runoff propagation and retention according to individual characteristics. Therefore, parameters such as imperviousness of land cover types must be considered. Imperviousness describes the inability of a material, or in this case land cover, to permit infiltration. Completely sealed surfaces have an imperviousness of 100%, while surfaces that do not contribute to runoff at all have an imperviousness of 0%. MIKE URBAN requires both the geometrical area of a catchment as well as the runoff area of a catchment to be specified. The runoff area can be understood as the area of a catchment from which runoff is expected; calculated by multiplying the total geometrical area with the imperviousness value. The imperviousness is given as a percent, which is used to define what percent of the catchment's geometrical area is imperviousness and therefore runoff relevant. Therefore, the runoff area is not equal to the total project area. It is assumed that runoff relevant area is hydraulically connected, meaning that the runoff drains into the collection system. In this model, the runoff coefficient is assumed to be the same as the percent imperviousness for simplification reasons. However, this is not always the case, since pervious materials can also generate runoff.

In this model, certain land use types are considered to be irrelevant for rainfall runoff. Land that is covered by agriculture, forests or gardens is considered to enable enough infiltration and/or runoff detention to not classify as runoff relevant. Therefore, these areas were removed from the model to prevent unnecessary calculations and simulation time. The values in Table 4 were used for the respective land use types and are based on values provided by ÖSTAP Engineering & Consulting GmbH. The original descriptions of the sub-catchments from the digital cadastral map, on which the land use types are based, can be found in the Appendix.

Figure 13: Wagram Catchments based on digital cadastral map

Table 4: Imperviousness values by land use type

Land Use	Imperviousness [%]
Agriculture, forests, shrubs	0
Parks, cemeteries, recreational areas, gardens	0
Railways	30
Urban manufacturing or industrial (operating) areas	30
Roads, parking lots, paved surfaces	60
Roofs	65

Dry weather flow based on Person Equivalents (PEs) was implemented in the model as a catchment load. The PEs value was adopted from data provided by ÖSTAP Engineering & Consulting GmbH. Next a diurnal pattern for smaller cities was chosen, assuming that the daily water consumption is 130 liters per person and day. The diurnal pattern used can be found in the Appendix. Additional water flow of 14.6 l/s was added for the paper factory in the south west of Wagram.

In the model rainfall data acts as a boundary condition for the hydrological model and is specified through the MOUSE model boundary system. Figure 14 shows the six-hour, measured precipitation event used in this model.

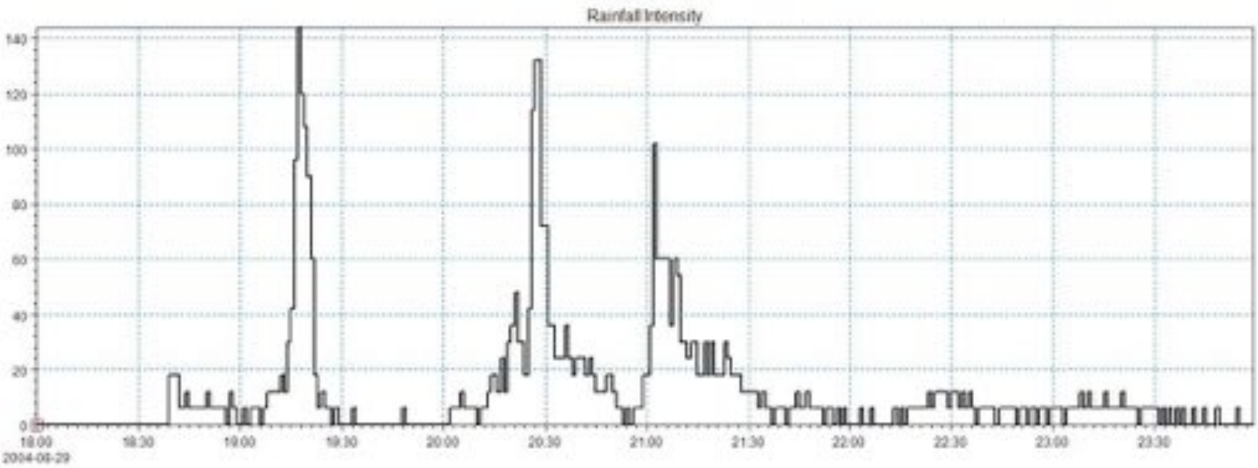

Figure 14: Time series showing rainfall intensity [mm/h] of 6h precipitation event

In order to transfer the runoff generated on the catchment into the sewer network, the MOUSE model must include connections between the defined catchments and the collection network. The catchments were connected to the sewer system using the MU Catchment Connection Wizard. Some catchment connections were then reconnected manually, since some manholes were connected to a large number of catchments while other manholes nearby had no connections. This is not only unrealistic, but also poses a threat for flooding from a manhole with too many catchment connections. Manual reconnections were predominately performed in the south of Wagram near the paper factory.

Next, a “surface runoff model” was chosen as the hydrological model for the catchment. Surface runoff models only compute surface runoff, which implies a discontinuous runoff hydrograph where flow starts as a result of rainfall and ceases back to zero after the end of a rainfall event. Therefore, these models are ideal for densely urbanized areas where a dominant amount of surface runoff is generated on impervious surfaces (MIKE BY DHI, 2017a). A scheme of the hydrological modeling process in MIKE URBAN is shown in Figure 15.

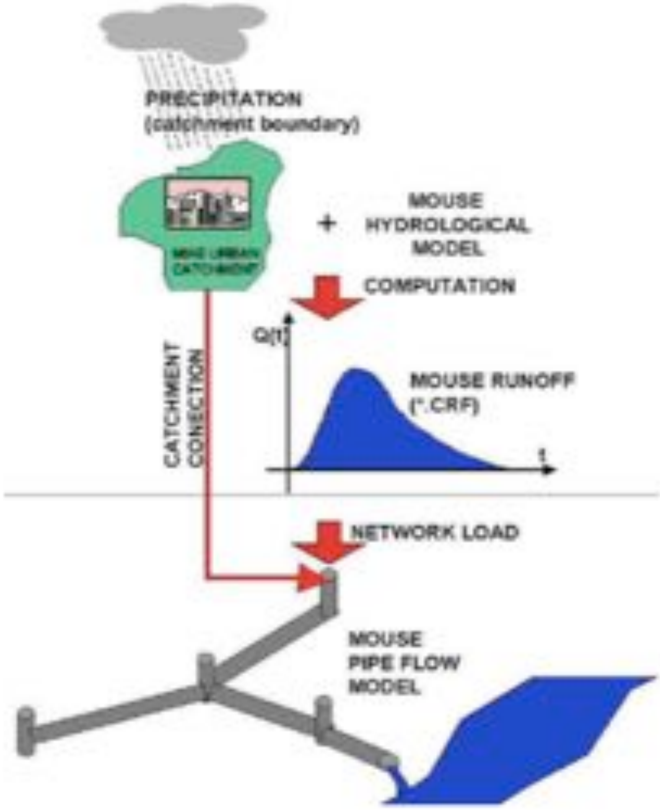

Figure 15: Illustrated flow of information in hydrological modeling (MIKE BY DHI, 2017a)

Various surface runoff concepts are available in MOUSE, namely:

- Model A- Time-Area Method,
- Model B- Non-linear Reservoir (kinematic wave) Method
- Model C- Linear Reservoir Method, in two sub-variants
  - Model C1 - Dutch runoff model
  - Model C2 - French runoff model
- UHM- Unit Hydrograph Model

Model A (Time-Area Method) was chosen for the first simulations. The Time-Area Method uses the time-area curve, where the runoff amount is controlled by the initial loss, size of the runoff contributing area and by the hydrological loss. The time-area curve and the concentration time construe the shape of the runoff hydrograph. The runoff hydrograph signifies the catchment shape and reaction speed to a rain event. This is explained in further detail in Chapter 4.4.3 Catchments. Model B (Kinematic Wave) is used for the GI simulations. This runoff computation is based on hydrological losses such as infiltration and on runoff routing given by the kinematic wave formula (MIKE BY DHI, 2002).

As mentioned previously, the Time-Area Method (Model A) is used for surface runoff computation in this thesis, where the runoff is controlled by the initial loss, size of the contributing (runoff) area and by the continuous hydrological loss. The runoff model data include general, model-specific catchment data and model parameters. While the general catchment data is independent of the runoff model (including catchment size, connection points and catchment coordinates), model specific data depends on the surface runoff concept used. The model parameters used to calculate runoff include concentration time, initial loss and the reduction factor. The concentration time defines the amount of time [min] required for water to flow from the most distant part of the catchment to the outflow point. The initial loss defines the precipitation depth required to cause surface runoff. The (hydrological) reduction factor accounts for losses due to evapotranspiration, infiltration, etc. Model A does not use a specific method for the computation of infiltration. Instead, infiltration is approximated proportionally to rainfall intensity by specifying the hydrological reduction factor (MIKE by DHI, 2015). The parameters used for this Time-Area curve are shown in Table 5.

Table 5: Parameters Time-Area

Parameter set ID	Time of concentration [min]	Initial loss [m]	Reduction factor
-DEFAULT-	7	0.0006	0.90

The Time-Area model in MIKE URBAN uses predefined tabulated time-area curves, which represent the contributing part of the catchment surface as a function of time. In this model the default time-area curve TACurve1 for rectangular catchments, is used. In the second step of running the model, GI is implemented, which requires the surface runoff Model B (Kinematic wave). In this surface runoff computation, flow is computed as in an open channel, taking only gravitational and friction forces into consideration. The amount of runoff is regulated by hydrological losses and the size of the runoff contributing area. The hydrological losses used in Model B include wetting loss, storage loss, start infiltration, end infiltration, Horton's exponent and the Manning number. The default hydrological parameters were used for Model B in this thesis and are shown in the following table.

Table 6: Hydrological parameters for Model B

Parameter	Impervious		Pervious		
	Roof	Flat area	Small Inf.	Medium Inf.	Large Inf.
Wetting [m]	5.00E-5	5.00E-5	5.00E-5	5.00E-5	5.00E-5
Storage [m]	-	6.00E-4	1.00E-3	1.00E-3	2.00E-3
Start inf. [m/s]	-	-	1.00E-6	1.00E-5	2.00E-5
End inf. [m/s]	-	-	5.00E-7	1.00E-6	5.00E-6
Exponent [s^{-1}]	-	-	1.00E-3	1.50E-3	1.50E-3
Inverse Exp. [s^{-1}]	-	-	5.00E-6	1.00E-5	5.00E-5
Manning [$m^{1/3}s^{-1}$]	80	70	30	30	12

4.5 Running the simulation and performing the sensitivity analysis

The simulation is run with the computation engine MIKE 1D. In the first step, the runoff model is executed, which requires the definition of MIKE URBAN catchments, catchment connections, the hydrological model and precipitation event. The six-hour, measured precipitation event is used. After completing the runoff computation, the runoff data is used as a hydraulic load of the collection network before running the network model (MIKE BY DHI, 2017a). The simulation without any altered input parameters is hereon referred to as the “base simulation”.

After running both the runoff and the network simulation, the sensitivity analysis could be performed. The performance indicators chosen in this thesis to evaluate the outcome of the model are ideal for urban water management and include the CSO maximum and total discharge values. As mentioned previously, the sensitivity analysis in this thesis is performed as an OAT (One-At-a-Time) method, where one model input parameter is altered. In order to evaluate which sub-catchments in St. Pölten have the greatest potential for GI, each sub-catchment is decoupled from the model individually. However, performing this method manually would incorporate decoupling each catchment by hand, running the model, reconnecting the catchment to the model and then repeating this for every single defined sub-catchment. Considering that the model includes 3761 catchments, it is clear that manually performing the SA is not efficient. Therefore, a Python script was written to automatically perform the sensitivity analysis to reduce the total simulation time and avoid manual errors. While the technical implementation of decoupling sub-catchments requires the individual disconnection from the network, the realization of decoupling measures in the model is performed by setting the area of each sub-catchment to zero.

Figure 16 shows the scheme of the Python script. First, as has already been mentioned, the runoff model was run manually without any alterations. The runoff simulation in MIKE URBAN produces a .m1dx (MIKE 1D engine specific) file as well as a log and summary file. The .m1dx file contains runoff information for the sewer network and catchments. The original .m1dx file is then reproduced 3761 times; totaling at one file for each catchment. These copies are identical to the original .m1dx file, except that the drainage area of one catchment is set to zero. This means, for example, that the first copy of the.m1dx file is identical to the original except that the drainage area of the first catchment (in numerical order) has been changed to zero, in the second copy the second catchment is set to zero, and so on.

In the second step, all 3761 altered .m1dx files are sent to the MIKE 1D engine in order to calculate rainfall runoff data. This produces .html logging files and one RR.res1d file per catchment. The model is then run as a network simulation in the third step, using each RR.res1d file as an input for one simulation. The network simulation produces one .res1d and .html logging files, which contains information on the sewer network and catchments. The .html “Summary” files are used to evaluate the effect that each catchment has on the sewer network by comparing the maximum and total discharge at the CSO.

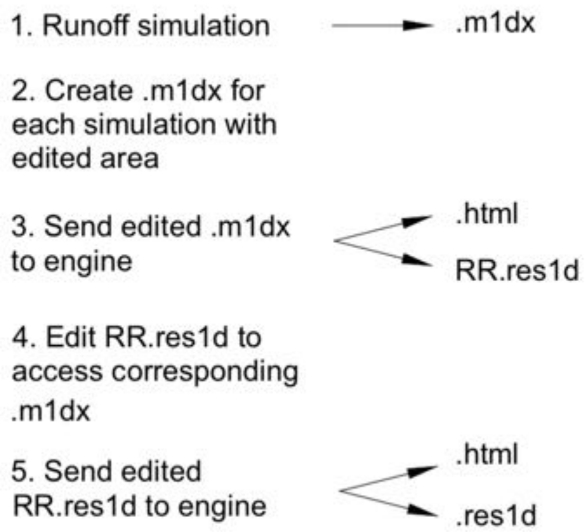

Figure 16: Scheme of automated decoupling process through Python script

4.6 Implementing green infrastructure

In the second step of this thesis, GI was implemented on two sub-catchments to determine the necessary extent of such measures to completely manage the initiated runoff, and thus be comparable to the complete decoupling of the catchments as was previously performed. One building and one street section, which showed a high impact on the sewer system in the SA, were chosen for the GI analysis. The chosen catchments are shown in Figure 17. The GI measures evaluated for the building were green roofs (GR) and a rain barrel (RB), while bio-retention cells (BRC), rain gardens (RG) and infiltration trenches (IT) were each implemented on the street section.

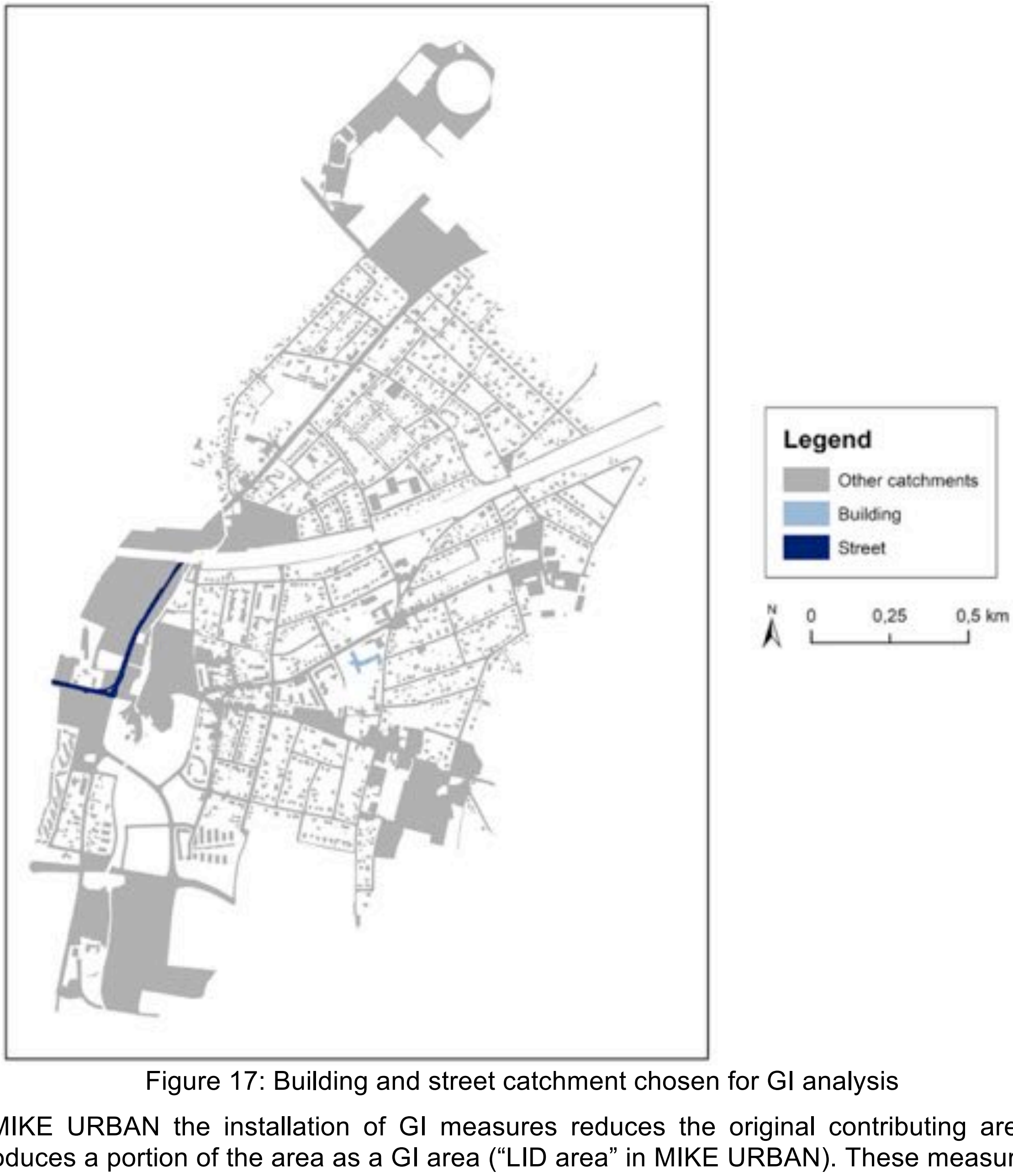

Figure 17: Building and street catchment chosen for GI analysis

In MIKE URBAN the installation of GI measures reduces the original contributing area and introduces a portion of the area as a GI area ("LID area" in MIKE URBAN). These measures are advanced methods for calculating effective precipitation by considering storage and infiltration. The runoff from GI measures are routed using the same calculations and parameters as used for the entire catchment and results in a composite hydrograph which includes (1) the runoff from the catchment reduced by the area connected to the GI measure and (2) the runoff from the GI measure (MIKE BY DHI, 2017a). In this analysis, the input parameters of the GI measures were altered until the runoff from the catchment was zero, meaning that all precipitation is stored and does enter the sewer system. This was performed for all rain events, totaling at one set of GI parameters per rain event and GI type.

GI can be modeled in MIKE URBAN using one of two approaches: the catchment-based approach or the drainage network-based approach. In this thesis the catchment-based approach is used, where GI measures are deployed and evaluated for individual catchments, directed at sizing the chosen measure. MIKE URBAN requires a “collecting area” and a “unit area” for each installed GI measure. The collecting area is the total tributary area, whose runoff is collected or treated by the GI unit, including the area of the measure itself. This is the runoff relevant area of the catchment (see 4.4.3 Catchments for the specification of the runoff relevant area). The unit area is the surface area of the GI unit itself (MIKE BY DHI, 2017a).

The building chosen is a public building in Wagram, which has a total roof area of approximately 2730 m^2, and a runoff relevant area (collecting area) of 955.23 m^2. The unit area was set at 955.22 m^2 since at the time that the simulations were performed setting the unit area equal to the collecting area generated no runoff due to settings in MIKE URBAN.

The street section chosen for the GI analysis is one of the largest street sections in the model and has a total area of 3761.4 m^2. Satellite images were used to approximate how much area around the street section could realistically be used for GI, as can be seen in Figure 18. It was assumed that GI would be implemented with a width of 1m totaling at 400 m^2.

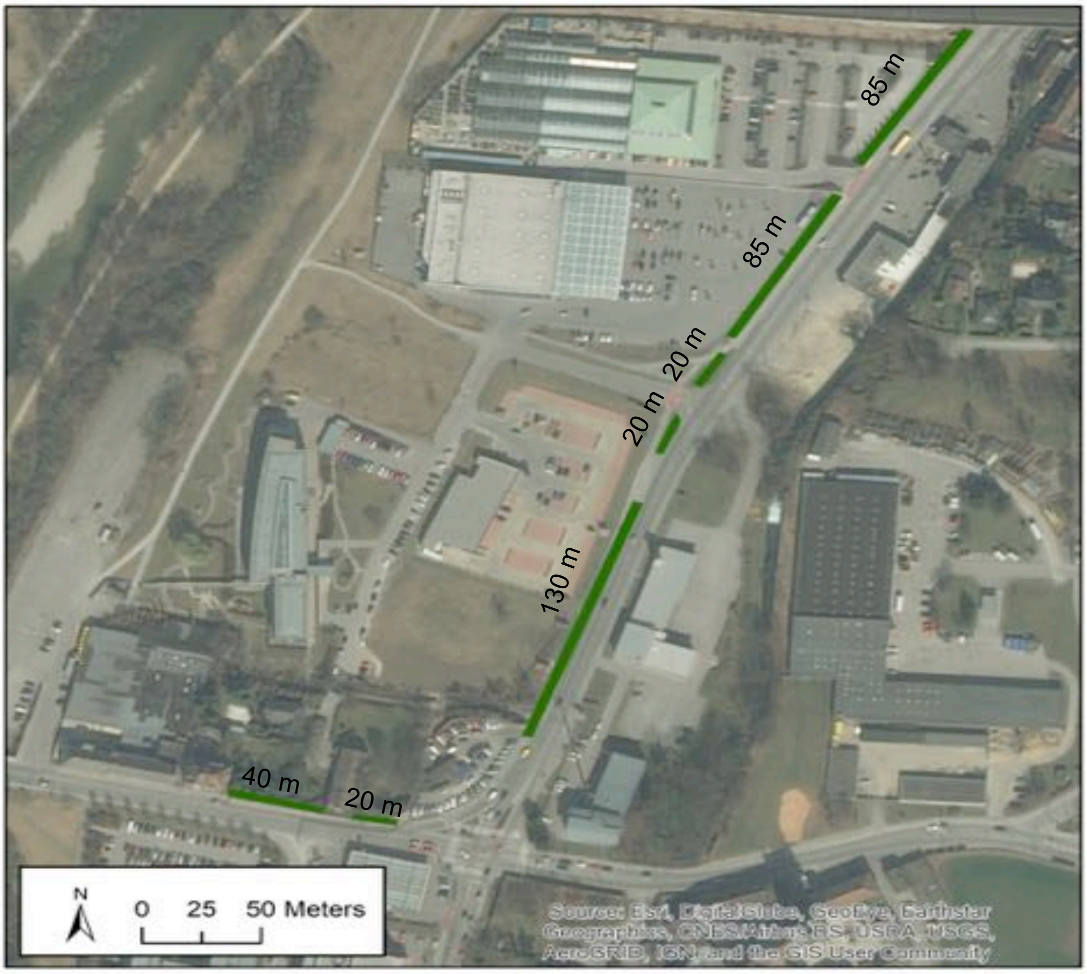

Figure 18: Maximum area available for GI implementation along street (Esri, 2019)

The GI parameters in MIKE URBAN are divided under various tabs, which represent different layers and functional elements of the GI measure, namely: surface, soil, pavement, storage, drain and drainage mat. The input parameters for all GI measures besides the rain barrel were varied based on a range according to the study by Leimgruber et al. (2018), which investigated the sensitivity of input parameters ("water balance components") for green roofs, bio-retention cells and infiltration trenches and compared to DHI documentation on LID Controls. The main outcome was the identification of the most influential and non-influential parameters. Since Leimgruber et al. (2018) did not examine rain gardens, the surface and soil parameters were chosen in the range of the surface and soil parameters for a bio-retention cell. The input parameters and their range are shown in Table 7. Since rain gardens were not assessed, values ranges were adapted from the ranges given for bio-retention cells. The input parameters for the rain barrel were based on the SuDS Manual (CIRIA, 2015), which recommends two approaches for calculating the required volume of a rain barrel: (1) based on 5% of the annual property water demand or (2) based on 5% of the annual runoff yield. In order to calculate the annual water demand, the population equivalent (PE) must be known. This data was included in the catchment data. Furthermore, the exact volume needed to store each rain event entirely was calculated. The runoff volume is calculated using the following equation:

$$(5) \qquad Y_R = A \cdot e \cdot AAR \cdot 0.05$$

where

Y_R … runoff volume (yield)

A … collected runoff area (m^2)

e … runoff coefficient

AAR … average annual rainfall depth (mm) (MIKE by DHI, 2017c)

Once the size of the GI measures for each rainfall event was calculated, the runoff generated from the catchments is determined for each set of GI parameters and for every rain event. For instance, the set of parameters needed to manage a 5-year, 60-minute rain event is also applied under the boundary condition of the one-year, 30-year, and six hour rain event to determine the catchment's runoff.

Table 7: GI types used in model and parameter ranges based on (Leimgruber et al., 2018)

	Parameter	Green roof	Bio-retention cell	Rain garden	Infiltration trench
Surface	Storage height [mm]	0 - 80	150 - 300	150 - 300	0 - 300
	Vegetative cover [-]	0 – 0,2	0 – 0.2	0 – 0.2	0
	Surface roughness [M]	2.8 - 25	2.8 - 25	2.8 - 25	33 - 83
	Surface slope [%]	2 - 100	0 - 10	0 - 10	0 - 10
Soil	Thickness [mm]	40 - 200	300 - 2000	300 - 2000	-
	Porosity [1/1]	0.36 – 0.65	0.3 – 0.55	0.3 – 0.55	-
	Field capacity [1/1]	0.1 – 0.35	0.01 – 0.2	0.01 – 0.2	-
	Wilting point [1/1]	0	0	0	-
	Conductivity [mm/h]	18 - 100	50 - 140	50 - 140	-
	Conductivity slope [-]	30 - 55	30 - 55	30 - 55	-
	Suction head [mm]	50 - 100	50 - 100	50 - 100	-
Storage	Height [mm]	-	150 - 1500	-	900 - 3650
	Porosity [-]	-	0.2 – 0.4	-	0.2 – 0.4
	Infiltration capacity of surrounding soil [mm/h]	-	7.2 - 72	-	7.2 - 72
Drainage Mat	Thickness [mm]	13 - 50	-	-	-
	Void fraction	0.2 – 0.4	-	-	-
	Roughness [M]	33 – 100	-	-	-

5. Results and discussion

5.1 Results from the sensitivity analysis

In order to ensure the validity of the model results, data was compared to a model created by ÖSTAP Engineering & Consulting GmbH. This included removing areas, which are not relevant for rainfall runoff such as agricultural areas, forested areas and gardens to reduce simulation time. Figure 19 shows the runoff relevant catchments that were used for the simulations. It is important to note that the sensitivity analysis was performed using the 6-hour rainfall event.

Figure 19: Wagram without runoff irrelevant catchments

The exclusion of pervious surfaces that are not connected to the drainage network was necessary in order to avoid unrealistically high loading of the drainage network during heavy precipitation events, such as the 6-hour rain event used in the simulation. If these areas were included in the model, runoff (which cannot be infiltrated or return to the water cycle otherwise) would flow into the sewer system, potentially becoming a significant fraction of the total runoff, and eventually causing urban flooding if the sewer capacity is exceeded (MIKE by DHI, 2015). Instead, it was assumed that runoff that is generated on pervious surfaces, which are not connected to the sewer, ponds on the catchment it is generated on until it evaporates or eventually infiltrates into the surface. An alternative to excluding these areas entirely would be to divide them into a large number of smaller sub-catchments based on runoff relevant characteristics, which can be connected to multiple network nodes. For example, instead of assuming that all runoff generated on a large field enters the sewer system through one manhole, the field could be divided into smaller sub-catchments based on their slope direction, imperviousness, or other runoff relevant characteristics, and then be connected to manholes. Runoff from sub-catchments would thus enter the sewer system more evenly dispersed.

Figure 20: Deviation of total discharge per catchment

The catchment connections were generated automatically, based on spatial proximity. This resulted in the connection of multiple catchments to one manhole. This is not necessarily unrealistic, since runoff from various areas may run to the same manhole. However, the sub-catchments are partially quite large, which may lead to unrealistically high amounts of water entering the system at one point. In reality, runoff from large areas such as a field or parking lot will flow in various directions, entering the sewer system at multiple points. Again, the division of sub-catchments into smaller areas may provide interesting results.

Figure 21: Deviation of maximum discharge per catchment

The sensitivity analysis was performed by theoretically decoupling single catchments from the network model to evaluate their individual impact during precipitation events on the sewer system. The total discharge, along with the maximum discharge, at the CSO were compared to the base simulation, where all catchments were connected to the sewer system. The base simulation showed a total discharge of 11,143 m^3 and a maximum discharge of 1.927 m^3/s.

Figure 20 and Figure 21 show the deviation of the total discharge and maximum discharge respectively. A deviation of 0.1% in total discharge corresponds to 11.14 m^3, 0,5% to 55,72 m^3, 1% to 111,43 m^3 and 2% to 222,86 m^3. The darker red a sub-catchment is, the greater the impact of that catchment on the sewer system is. At first glance, both maps show similar results, however the number of sub-catchments with a greater deviation are higher for the total discharge when decoupled from the sewer system. Only nine catchments have an effect equal to a deviation of 0.5 percent or higher regarding the maximum discharge, in comparison to 21 sub-catchments that initiate a deviation of 0.5 percent or higher in total discharge. While the maximum, or peak discharge is strongly dependent on precipitation intensity, the total discharge volume is associated with the total storm discharge and storm duration. Higher storm intensities and thus increased maximum CSO discharges may result in changes in the natural river flow fluxes. Sandoval et al. (2013) found that CSO “water quantity characteristics” are largely dependent on the maximum rainfall intensity while the CSO pollutant concentrations correlate with the duration of the rainfall, and pollutant loads are influenced by the dry weather duration before the considered precipitation event. These considerations are relevant regarding the impact on the receiving water body.

It is immediately noticeable that larger catchments show a greater deviation of total discharge in the network. Small catchments, such as private homes and small street sections have an insignificant effect on the sewer network. However, larger catchments such as the industrial areas in the south west of Wagram show a greater effect. This can be observed for street, building and industrial area catchments. The correlation between catchment size as a percent of the total catchment area in the model and deviation in discharge was assessed using the Microsoft Excel CORREL function, which uses the following equation to calculate the correlation coefficient:

$$(6) \qquad Correl(X,Y) = \frac{\sum(x-\bar{x})(y-\overline{y})}{\sqrt{\sum(x-\overline{x})^2 \sum(y-\overline{y})^2}}$$

where $\bar{x}$ and $\bar{y}$ are the means of each sample x and y (Microsoft, 2019). The correlation is displayed graphically in Figure 22 and Figure 23.

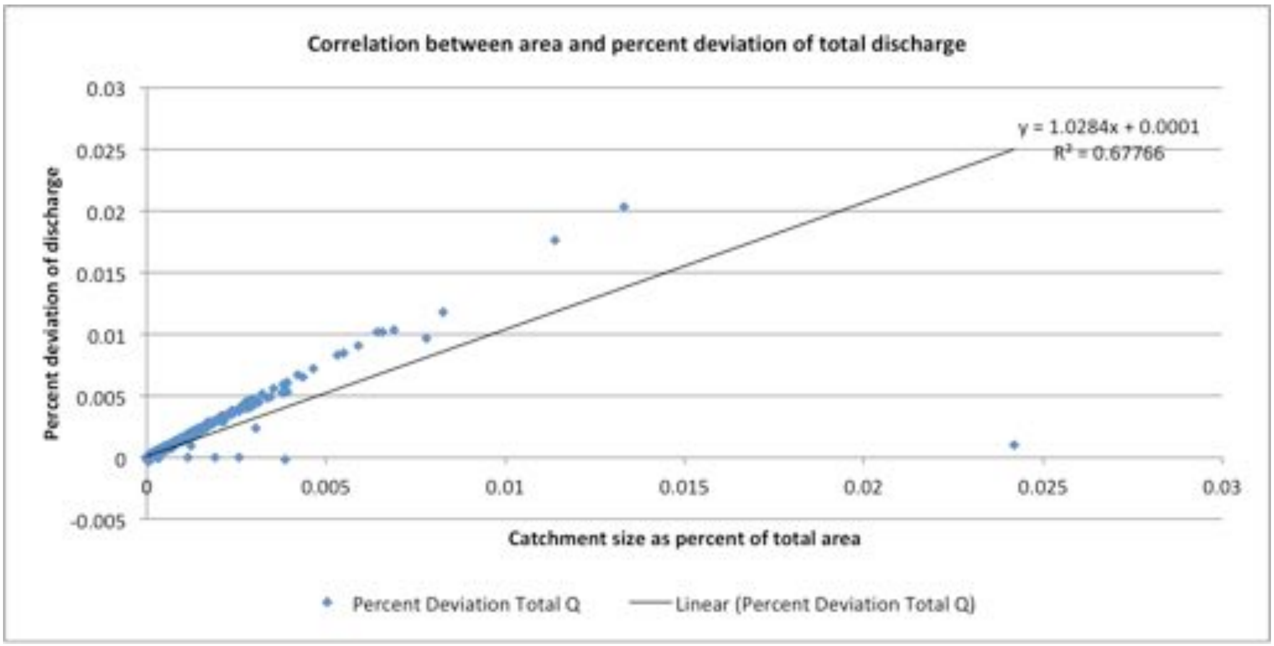

Figure 22: Correlation between area and deviation of total discharge

A positive linear correlation of 0.82 with a coefficient of determination (R^2) of 0.67 was found between the impervious area of a catchment and the percent deviation of the total discharge, and a positive linear correlation of 0.73 with a coefficient of determination of 0.53 was found between catchment size and the percent deviation of the maximum discharge. The R^2 values show that the regression predictions can explain approximately half of the total variation. As can be seen in the graphs, the regression line more accurately represents the data for smaller catchments than for larger catchments. The correlation between the area and deviation of discharge is weaker for larger catchments, especially regarding the deviation of maximum discharge. This is interesting since it could be assumed, that the greater a sub-catchment is, the more water is diverted into the sewer system and hence the greater the discharge is. The points that fall directly on the x-axis correspond to no measured deviation of discharge. The largest sub-catchment has an area of 0,8 ha and corresponds to 2.4% of the total catchment area in the model. However, this sub-catchment doesn't have as great of an effect on the discharge as would be predicted by the regression line.

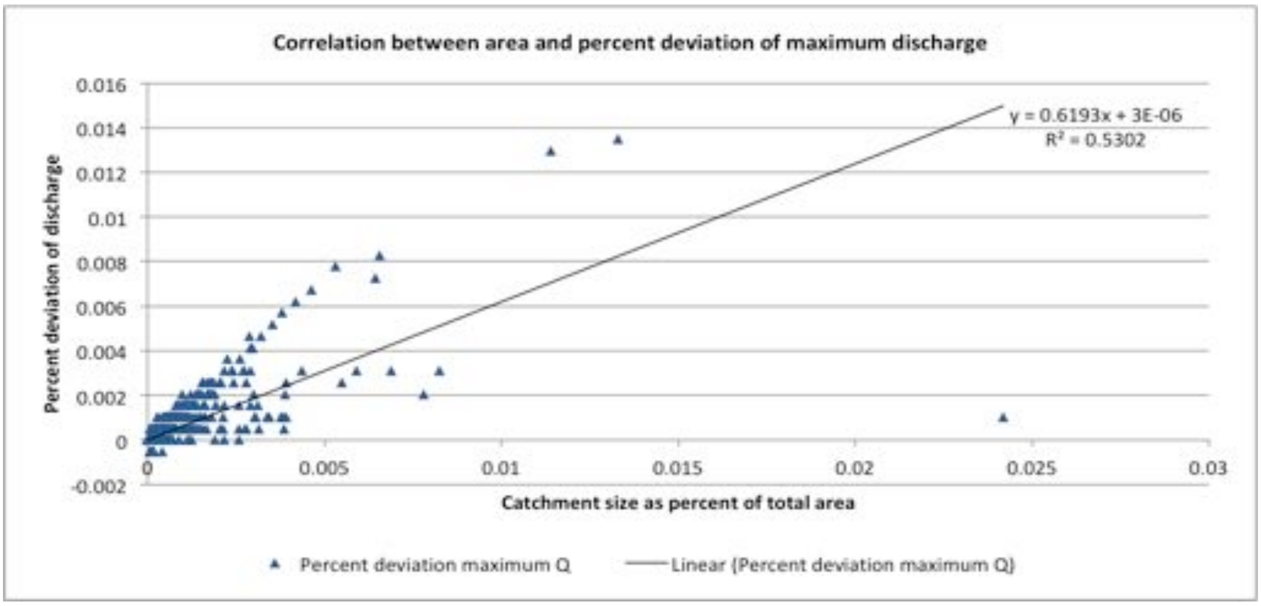

Figure 23: Correlation between area and deviation of maximum discharge

The correlation was also calculated between the percent imperviousness and discharge, however no significant correlation was found between the percent imperviousness and the total discharge (0.05) or maximum discharge (0.05). Although in general the imperviousness of a sub-catchment has an impact on the discharge, it is assumed that since the area of the catchments varies greatly within the model, no correlation can be found. No significant correlation was found between person equivalents and total (-0.21) or maximum (-0.23) discharge. A visual interpretation of the maps (Figure 20 and Figure 21) suggests that sub-catchments in the north, closer to the CSO, have a significant effect on the sewer system. However, the sub-catchments close to the CSO that show a deviation in discharge of 0,1% or greater are also large in size, which may also explain this result. No significant mathematical correlation (0.05) between the distance of a sub-catchment from the CSO and deviation in discharge could be found. This results in the question, if such a sensitivity analysis is beneficial for determining the ideal geographical position of GI measures. Although no correlation was found in this thesis, it can be argued that the results are strongly dependent on the input parameters. The division of sub-catchments into smaller areas, or the calculation of the effect of a sub-catchment on the sewer system per square meter may provide interesting results. Since the most time intensive step of this thesis was programming the automatic decoupling process, this now existing code can easily be used to further investigate the model using various input parameters.

5.2 Results from the implementation of GI

In the second part of this thesis, the possible effects of implementing GI on catchments, which showed a significant effect on the sewer network, is assessed. The study conducted by Leimgruber et al. (2018) shows typical ranges for GI input parameters as well as how sensitive the long-term runoff volume of the GI measures is to the alteration of single parameters. The parameters that showed a significant effect on the runoff volume were altered in this thesis in order to find sufficient GI measures. Two catchments were chosen to perform the analysis on: one large, public building and one large, frequented road section. Before GI was implemented, the runoff from both catchments using both Model A and Model B was assessed. As can be seen in Table 8, the accumulated flow generated from the building and street catchment under each rain event is similar for both runoff models. The runoff volumes vary slightly due to the difference in input parameters required for the model. However, since the values are relatively similar and no further comparisons are made between the catchments using Model A and Model B, these differences are irrelevant for any further results.

Table 8: Catchment runoff without GI

Catchment	**Rain event**	**Accumulated flow [m^3]**	
		Model A	**Model B**
Building	T1, 1h	12.05	11.88
	T5, 1h	22.77	23.43
	T30, 1h	34.91	36.56
	6h	58.99	64.73
Street	T1, 1h	45.04	46.8
	T5, 1h	85.77	92.25
	T30, 1h	131.6	144.0
	6h	231.9	254.9

In the following sections, the set of parameters used are referred to using the abbreviation of the GI measure plus the number representing the annularity of the precipitation event. For example, the set of parameters for the green roof, which is able to manage the one-year, 60 minute precipitation event, is abbreviated as: GR1, and so on.

5.2.1 Building

The roof area of the building covers a total area of 2730 m^2 and a percent imperviousness of 65%, totaling at a total collecting (runoff contributing) area of 955.23m^2. Green roofs with varying intensities as well as rain barrels were simulated as runoff management measures for the building.

5.2.1.1 Green roof

Green roofs contain a surface layer, soil layer and a drainage mat. Various intensities of green roofs are modeled on the building area. Leimgruber et al. (2018) found that the soil thickness, porosity and field capacity had a noticeable influence on the runoff volume. The greatest effect was found for the soil thickness: the thicker the soil layer is, the smaller the runoff, since the retention function of the green roof is increased. Therefore, the soil layer thickness was chosen as the parameter to alter in this analysis to manage the various precipitation events. Porosity and field capacity show a similar behavior to a much smaller extent. The other parameters were found to be statistically non-influential (Leimgruber et al., 2018) and were therefore chosen within the value range, but not further altered.

The storage height was modeled at 10 mm, as this value is realistic for both an extensive and intensive green roof. Vegetative cover, which describes the fraction of the surface storage filled with vegetation, was assumed to be 0.1. This value is the median of the parameter range given by Leimgruber et al. (2018). The surface roughness for the green roof is assumed to be between dense underbrush and short prairie, at M = 5, which also lies within the range given by Leimgruber et al. (2018). The surface slope was chosen at 10%, which provides enough of a slope to avoid water logging without hindering stormwater retention performance (Wilkinson et al., 2015). The values chosen for the soil parameters are all chosen around the median of the range given by Leimgruber et al. (2018) besides the wilting point, which was chosen at the MIKE URBAN default value 0.1 since this was not assessed in the mentioned study. The porosity was chosen at 0.4, which is more conservative than the median 0.5 to take a wider range of natural soils into consideration. The thickness of the drainage mat was modeled at 30 mm (rounded from the median of 31.5), while the void fraction was chosen at the maximum of the given range, since the documentation published by DHI (LID Controls in MIKE URBAN) states a typical range from 0.5 to 0.6 (MIKE BY DHI, 2002). The Manning's number was also chosen in accordance to this documentation, which states the use of n-values from 0.1 to 0.4. This corresponds to M values ranging from 2.5 to 10.

Table 9: Values used for green roof

		GR1	**GR5**	**GR30**	**GR6h**
Surface	Storage height [mm]	10	10	10	10
	Vegetative cover [-]	0.1	0.1	0.1	0.1
	Surface roughness [M]	5	5	5	5
	Surface slope [%]	10	10	10	10
Soil	Thickness [mm]	**78**	**145**	**221**	**584**
	Porosity [1/1]	0.4	0.4	0.4	0.4
	Field capacity [1/1]	0.2	0.2	0.2	0.2
	Wilting point [1/1]	0.1	0.1	0.1	0.1
	Conductivity [mm/h]	60	60	60	60
	Conductivity slope [-]	40	40	40	40
	Suction head [mm]	80	80	80	80
Drainage mat	Thickness [mm]	30	30	30	30
	Void fraction	0.4	0.4	0.4	0.4
	Roughness [M]	5	5	5	5

The simulations show that an extensive green roof (soil thickness of 78 mm, total height 118 mm) is necessary to manage the one-year rain event, meaning that no runoff is generated from the catchment. A semi-intensive green roof (soil thickness 145 mm, total height 185 mm) is required to manage the five-year rain event and an intensive green roof (soil thickness 221 mm, total height 261 mm) is required to manage a thirty-year rain event. In order to manage the six-hour precipitation event, a soil thickness of 584 mm would be required totaling at a height of 624 mm. An analysis was performed to assess how much runoff would be generated from the catchment for each rain event using each set of parameters. The results are shown in Table 10. It can be seen that the five-year precipitation event would generate runoff of 0.37 m^3 from the roof if the green roof was measured to manage a one-year rainfall event, and 1.82 m^3 during a thirty-year, one-hour precipitation event. During the six-hour rainfall event, 26.32 m^3 would be generated according to the simulations. Green roofs in the model are able to significantly reduce the runoff created by the Euler II design storm events using realistic parameters. However, the six-hour precipitation event generates a large amount of runoff if the green roof is constructed to manage the one, five, or thirty-year rain event. This may be due to the long duration and relatively high intensity of the rainfall event. The amount of runoff generated during such a long and intense rainfall event despite the implementation of a green roof should be evaluated. If the aim of constructing a GI measure such as a green roof is to reduce the peak flow and thus flood risk, the GI measure should provide a significant retention effect even during an intense precipitation event. For example, the maximum tolerable runoff volume from an individual sub-catchment, which does not lead to an increased flood risk, should be compared to the runoff generated with an installed GI measure.

Table 10: Generated rainfall runoff [m^3] from building using green roof

Rain event	Green roof parameter set			
	GR1	GR5	GR30	GR6h
T1	0	0	0	0
T5	0.37	0	0	0
T30	1.82	0.09	0	0
6h	26.32	10.16	5.14	0

The results show realistic thicknesses for the green roof for the one-year, five-year and thirty-year rainfall event. The soil thicknesses correspond to an extensive, semi-extensive and intensive green roof, respectively. While it cannot be said that the thickness required to manage the six-hour rain event is unrealistic, the weight associated with a thick build up must be considered. In general, the thicker the layers are, the heavier the green roof is. This should be deliberated when choosing a green roof, especially when retrofitting an existing rooftop.

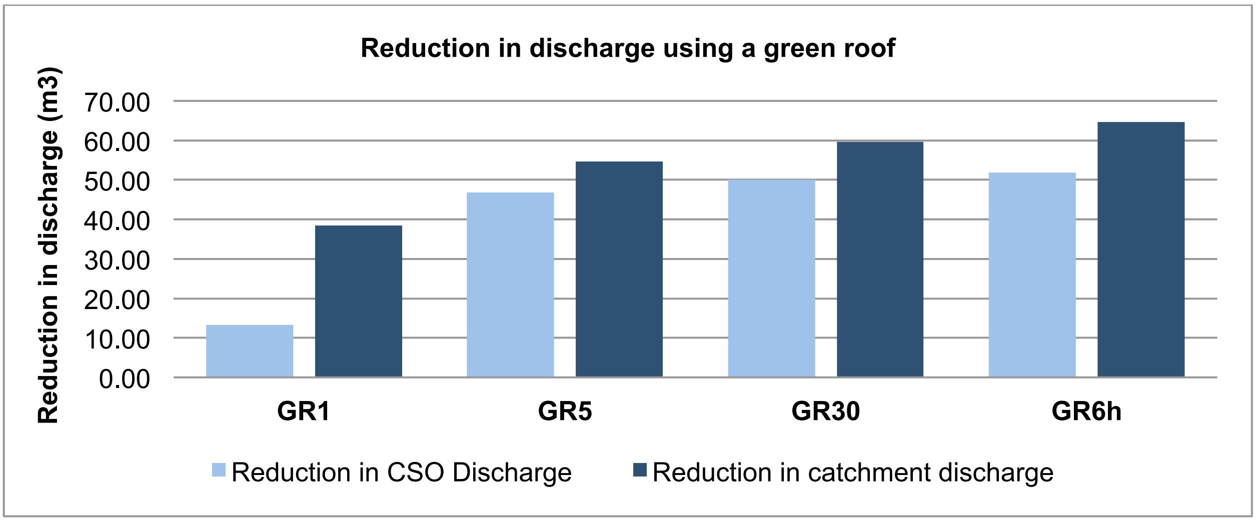

Figure 24: Reduction in CSO versus catchment discharge under the six-hour precipitation event using various green roof construction intensities

In a third analysis the reduction in discharge from the catchment was compared to the reduction in discharge at the CSO during the six-hour precipitation event using the various green roof construction intensities. As can be seen in Figure 24 the reduction in discharge from the catchment is greater than the reduction that can be measured at the CSO. The difference is largest for the green roof constructed to manage a one-year rainfall event (25.21 m^3). This shows that while thicker green roofs could provide valuable retention not only within the catchment they are implemented on but also for the sewer system at the CSO. While the retention capability of the green roof with the smallest intensity can be measured at the CSO it is much smaller than that of the next larger green roof simulated. The simulations also show a difference in maximum discharge at the CSO. While the base simulation showed a maximum discharge of 1.927 m^3/s, the implementation of the green roof constructed to manage the one-year and five-year precipitation event decreased the maximum discharge to 1.924 m^3/s, and the green roof constructed to manage the thirty-year and six-hour precipitation event decreased the maximum discharge to 1.918 m^3/s. This analysis shows that already the implementation of medium sized green roofs may provide noticeable retention effects and thus a reduction in peak flow, ultimately reducing flood risk.

5.2.1.2 Rain barrel

The SuDS Manual (2015) recommends sizing a rain barrel for water conservation systems on the smaller value of either 5% of the annual runoff yield of the contributing surface or 5% of the annual property water demand. The values displayed in Table 11 were used for calculating the dimensions of the rain barrel. The 5% annual runoff yield was calculated using equation (5) whereby the runoff coefficient is taken into consideration in the runoff relevant area, assuming that the runoff yield is equivalent to the percent imperviousness. The population equivalent (PE) is 86.5. This value was based off of data provided. Furthermore, the volume required to manage a one, five and thirty-year, 60 minute precipitation event was modeled, as is displayed in Table 12.

Table 11: Values used for calculation of rain barrel volume

Runoff relevant area [m^2]	955.23
Average annual rainfall [mm]	663
PE	86.5
Water demand m^3/ PE & day	0.13
5% annual property demand [m^3]	**206.24**
5% annual runoff yield [m^3]	**31.67**

Table 12: Storage volume required to manage precipitation events

	RB1	RB5	RB30	RB6h
Storage volume [m^3]	13.60	25.70	39.40	65.56

The analysis shows that sizing the rain barrel to store 5% of the annual property demand would require the greatest volume and would be able to store the entirety of any of the simulated rain events. In contrast, sizing the rain barrel to store 5% of the annual runoff yield would only provide enough volume to entirely manage the one-year and five-year, 60-minute rainfall events. The difference between the volume needed to manage the six-hour rain event and the volume calculated to store 5% of the property's demand is 140.68 m^2. The large differences in volumes highlights the importance of defining the goal of the rain barrel: flood management, where the main goal is to reduce the amount of runoff or fully manage a particular statistical rainfall event; or water conservation, which aims at capturing enough water to fulfill a certain amount of the water demand. Systems designed to capture enough water to meet a percent of the building's demand are often not large enough to capture extreme rainfall events (CIRIA, 2015). In this thesis, due to the high PE of the public building, the volume that corresponds to 5% of the annual property demand is very large. The size of a rain barrel is also associated with certain financial and space considerations. It may not be efficient to construct a very large rain barrel, depending on the specified goal. In this thesis, as the main focus is on flood management, a smaller volume would suffice in managing the runoff generated from heavy precipitation events, as long as the rain barrel is empty, or nearly empty, before the storm event. This is a crucial consideration in rain harvesting for flood mitigation, since previous precipitation, and thus stored rain, can tremendously impact the retention capacity of a GI measure.

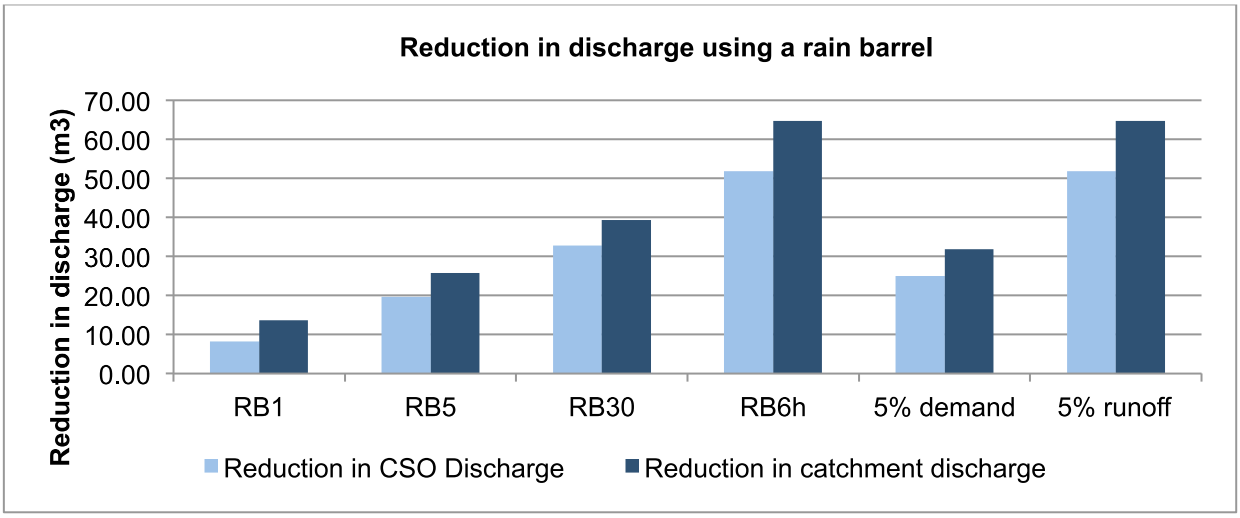

Figure 25: Reduction in CSO versus catchment discharge under the six-hour precipitation event using various rain barrel construction intensities

The difference in the reduction in discharge from the CSO versus the reduction in discharge from the catchment was also examined for the implementation of various rain barrels. Figure 25 shows that similarly to the results from the green roof, the reduction in CSO discharge is smaller than the reduction in discharge directly from the catchment. The larger the rain barrel is, the more precipitation is held back and thus the greater the achievable flood reduction is.

5.2.2 Street

The street section chosen for the GI simulations is the second largest street catchment in the model. The total area of the street section, which was chosen for the GI analysis, is 3761.4 m^2. In the model, this area is the collecting area. In order to simplify the comparison of a particular GI measure for each precipitation event, constant values were chosen for each individual layer parameters for every rainfall. Instead of varying certain layer parameters, as was done for the building sub-catchment, the unit area was altered for each GI type under each precipitation event for the street section.

5.2.2.1 Bio-retention cell

Bio-retention cells contain a surface layer, soil layer, storage layer and optionally an underdrain, which this model did not include. The values for the layers were chosen in accordance to Leimgruber et al. (2018) (see Table 7 for typical value ranges). The authors found the most influential parameter for the runoff volume to be the storage seepage rate, the berm height, the conductivity and the soil thickness, in descending order. Storage seepage rate and conductivity affect the emptying time, while berm height and soil thickness affect the retention capacity of the bio-retention cell (Leimgruber et al., 2018).

Table 13: Values used for the bio-retention cell

		BRC1	BRC5	BRC30	BRC6h
	Unit area [m²]	**117**	**220**	**337**	**344**
Surface	Storage height [mm]	300	300	300	300
	Vegetative cover [-]	0.1	0.1	0.1	0.1
	Surface roughness [M]	5	5	5	5
	Surface slope [%]	5	5	5	5
Soil	Thickness [mm]	1200	1200	1200	1200
	Porosity [1/1]	0.4	0.4	0.4	0.4
	Field capacity [1/1]	0.2	0.2	0.2	0.2
	Wilting point [1/1]	0.1	0.1	0.1	0.1
	Conductivity [mm/h]	100	100	100	100
	Conductivity slope [-]	40	40	40	40
	Suction head [mm]	80	80	80	80
Storage	Height [mm]	800	800	800	800
	Porosity [-]	0.30	0.30	0.30	0.30
	Infiltration capacity [mm/h]	40	40	40	40

As is shown in Table 13, the storage height of the bio-retention cell is modeled at the maximum depth given by Leimgruber et al. (2018). Surface roughness was chosen at 5, which corresponds to a vegetation cover between dense underbrush and short prairie. Vegetative cover, surface slope, soil thickness, soil porosity, conductivity, conductivity slope, suction head, storage height, storage porosity and infiltration capacity were all chosen at approximately the median value of the parameter range given by Leimgruber et al. (2018). The wilting point was set at the MIKE URBAN default value 0,1 and the field capacity was set at 0.2 since this value must be greater than the wilting point.

The simulations show that bio-retention cells (with the above mentioned parameter values) covering a total area of 117 m^2 would be able to manage a one-year, 60 minute Euler II rain event, which is equivalent to 3.1% of the total collecting area. 220 m^2, or 5.8% of the collecting area is needed to entirely manage a five-year, 60 minute Euler II precipitation event; and 337 m^2, or 8.9% of the collecting area would be required to manage the 30-year rain event. The greatest unit area is required to manage the six-hour rain event. This area is 7 m^2 greater than the area required for the thirty-year Euler II precipitation event. According to these simulations all runoff from the street section generated by the various precipitation events can be managed with bio-retention cells using less than 400 m^2. Therefore it can be assumed, that GI can manage various heavy precipitation events in a manner comparable to the complete decoupling of the street catchment. Table 14 shows the accumulated runoff from the catchment using each GI parameter set under each precipitation event.

Table 14: Generated rainfall runoff (accumulated flow) [m^3] from street using bio-retention cell

Rain event	BRC1	BRC5	BRC30	BRC6h
T1	0	0	0	0
T5	34.51	0	0	0
T30	82.47	33.24	0	0
6h	146.5	64.08	0.32	0

This table shows that constructing a bio-retention cell to manage a one-year precipitation event would still lead to relatively high runoff volumes during the other modeled rainfall events. The runoff from a five-year, one hour precipitation event would be reduced from approximately 90 m^3 to 34.5 m^3, while the six-hour precipitation event would be reduced to almost half, from around 250 m^3 to 146.5 m^3. In comparison, the construction of a bio-retention cell to manage a five-year rainfall event would reduce the runoff of the 30-year and six-hour precipitation event to less than half. However, the difference in unit area required to manage the one-year versus five-year rainfall event is 103 m^2, which may make a substantial difference depending on the specifics of the bio-retention cell and conditions of the location where the GI measure should be installed. The comparison between the 30-year and six-hour precipitation event shows that only 0.32 m^3 runoff would be generated as accumulated flow from the street sub-catchment during the most intense of the modeled precipitation events. In order to manage this additional volume, only an additional 7m^2 unit area would be required. This is interesting since the difference in runoff generated from the catchment with a bio-retention cell built to manage either a one or five-year rainfall event is almost twice as high during the six-hour precipitation as during the thirty-year precipitation event. The difference in unit area required for the five-year versus the thirty-year precipitation event is 117 m^2. The small difference between the 30-year and six-hour precipitation event may be due to the simulation durations. Although more rain falls during the six-hour rainfall event, there is also more time for the rain to infiltrate into the GI measure, and utilize all layers.

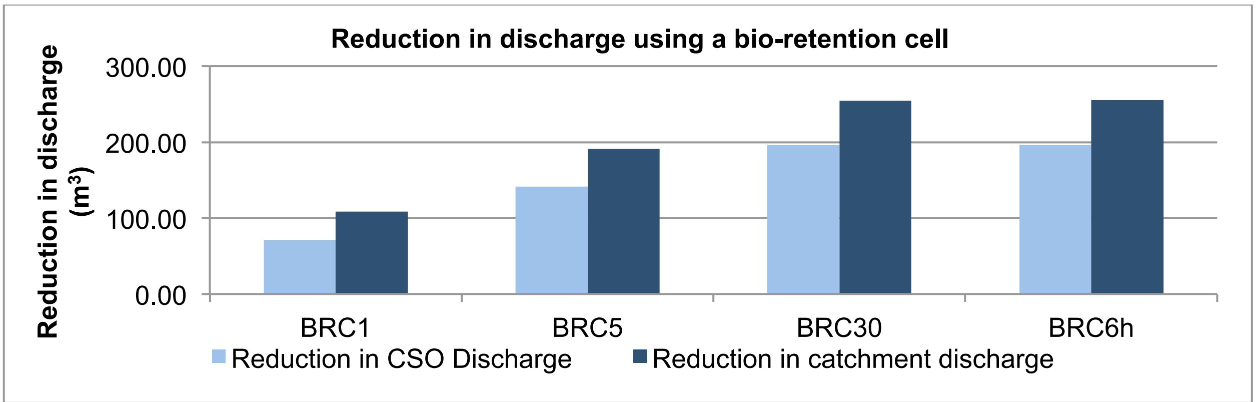

Figure 26: Reduction in CSO versus catchment discharge under the six-hour precipitation event using various bio-retention cell construction intensities

The reduction in discharge from the CSO is smaller than the reduction in discharge from the catchment when implementing bio-retention cells in various construction intensities. In contrast to the green roof, the smallest difference between the CSO and catchment discharge is using the bio-retention cell designed to manage a one-year precipitation event when examining absolute values of the results. The smallest relative difference between the CSO and catchment discharge is found for the bio-retention cells that can manage the thirty-year and six-hour precipitation event (23%). Thus one can infer that the larger the retention capacity of a bio-retention cell is within a catchment, the larger the retention effect measured at the CSO is. This implies that the maximization of space dedicated to GI should be pursued in order to achieve the greatest retention and thus eventually flood reduction effects.

5.2.2.2 Infiltration Trench

Infiltration trenches include a surface layer, storage layer and optionally an underdrain, which was not implemented in this model. The values chosen for the individual parameters of each layer are shown in Table 15. In this model the surface storage height was chosen at 300 mm, which is the maximum of the value range given by Leimgruber et al. (2018). The infiltration trenches were modeled without vegetative cover and with a surface roughness of 50, which corresponds to Manning's M for cultivated soils. The other parameters were chosen at values that approximately correspond to the median of the value ranges specified by Leimgruber et al. (2018).

The results of the simulations show a similar pattern to the previous GI measures. The smallest unit area is needed to manage the one-year rain event, while the largest unit area is required to manage the six-hour rain event. All runoff from the street section generated by the simulated precipitation events can be managed with an infiltration trench using less than 400 m^2 (which was the maximum area available for GI, see Figure 18).

Table 15: Values used for the infiltration trench

		IT1	IT5	IT30	IT6h
	Unit area [m^2]	**61**	**115**	**175**	**245**
Surface	Storage height [mm]	300	300	300	300
	Vegetative cover [-]	-	-	-	-
	Surface roughness [M]	50	50	50	50
	Surface slope [%]	5	5	5	5
Storage	Height [mm]	2200	2200	2200	2200
	Porosity [-]	0.25	0.25	0.25	0.25
	Infiltration capacity [mm/h]	40	40	40	40

The runoff generated (accumulated flow) using each set of parameters with each precipitation event is shown in Table 16. The unit area required to fully manage each precipitation event increases more steadily than with the bio-retention cell. The difference in unit area between the one versus five-year, five versus thirty-year, and thirty-year versus six-hour precipitation event is 54 m^2, 60 m^2, and 70 m^2 respectively. Table 16 shows that the runoff from the street during the six-hour rainfall event would still amount to approximately 71 m^3 if infiltration trenches constructed to manage a thirty-year rainfall event were installed. Since the duration of the simulations using the one-year, five-year and thirty-year rainfall event is only one hour, it is clear that the full storage layer cannot be utilized assuming the infiltration capacity specified. Therefore, increasing the unit area, and thus the surface area on which precipitation can accumulate, has a great effect on the retention capacity of the infiltration trench.

Table 16: Generated rainfall runoff [m^3] from street using infiltration trenches

Rain event	IT1	IT5	IT30	IT6h
T1	0	0	0	0
T5	38.68	0	0	0
T30	90.32	42.86	0	0
6h	190.80	134.20	71.31	0

The examination of the reduction in discharge from the CSO versus from the catchment shows similar results to the previous GI measure. The reduction in CSO discharge is generally lower than the reduction in catchment discharge. The largest relative difference between the CSO and catchment discharge can be found for the smallest constructional intensity of the infiltration trench. The larger the area dedicated to the implementation of infiltration trenches is, the greater the retention effect is, and thus the less water is diverted through the sewer system to the CSO.

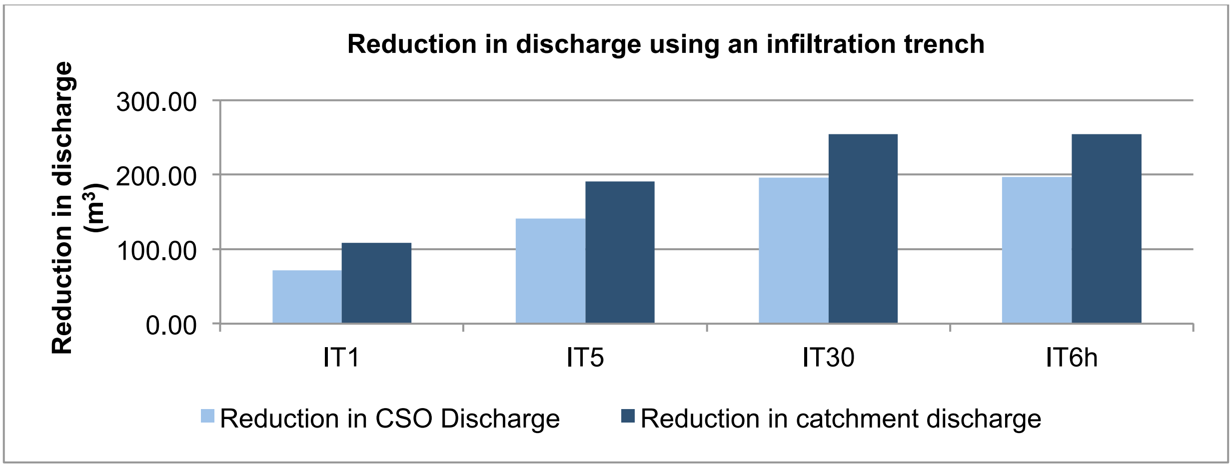

Figure 27: Reduction in CSO versus catchment discharge under the six-hour precipitation event using various infiltration trench construction intensities

5.2.2.3 Rain garden

Rain gardens are simplified bio-retention cells that are designed as small gardens with vegetation, containing only a surface zone and a soil zone. Since Leimgruber et al. (2018) did not investigate values for rain gardens; value ranges were adapted from the ranges given for bio-retention cells. The values chosen for the layer parameters is displayed in Table 17.

It can be seen that using the same surface and soil parameters for the assessment of the bio-retention cell (compare Chapter 5.2.2.1 Bio-retention cell) and the rain garden result in the same required unit area to manage each precipitation event. 117 m^2 of area dedicated to rain gardens would have to be constructed to fully manage the one-year rain event, 220 m^2 would be needed to manage the five-year precipitation event, 344 m^2 would have to be constructed as rain gardens to manage the thirty-year precipitation event, and 344 m^2 would be required for the six-hour rainfall event. The runoff (accumulated flow) generated using each set of parameters with each precipitation event is shown in Table 18. These results are also identical to those generated for the bio-retention cell. This suggests that due to the short simulation period, the entirety of the bio-retention cell storage capacity cannot be utilized, and thus provides the same runoff management as the rain garden. The comparison of the reduction in CSO versus catchment discharge therefore also shows identical results to that of the bio-retention cell.

Table 17: Values used for the rain garden

		RG1	RG5	RG30	RG6h
	Unit area [m^2]	**117**	**220**	**337**	**344**
Surface	Storage height [mm]	300	300	300	300
	Vegetative cover [-]	0.1	0.1	0.1	0.1
	Surface roughness [M]	5	5	5	5
	Surface slope [%]	5	5	5	5
Soil	Thickness [mm]	1200	1200	1200	1200
	Porosity [1/1]	0.4	0.4	0.4	0.4
	Field capacity [1/1]	0.2	0.2	0.2	0.2
	Wilting point [1/1]	0.1	0.1	0.1	0.1
	Conductivity [mm/h]	100	100	100	100
	Conductivity slope [-]	40	40	40	40
	Suction head [mm]	80	80	80	80

Table 18: Runoff generated for each parameter set under each precipitation event

Rain event	RG1	RG5	RG30	RG6h
T1	0	0	0	0
T5	34.51	0	0	0
T30	82.47	33.24	0	1.01
6h	146.50	64.08	0.32	0

5.2.2.4 Comparison between bio-retention cell and rain garden

The identical results of the simulations of the bio-retention cell and rain garden may imply that the storage volume of the bio-retention cell is not utilized. In other words, the precipitation that falls onto the street section stays within the surface storage volume or infiltrates into the soil, but does not further seep into the storage layer during the rainfall event. This can be seen in Figure 28. The graphic shows that the surface to soil flow peaks with the initial inflow of water to the catchment, decreases temporarily and again increases shortly after the peak of rainfall on the catchment around minute 21 of the simulation. In the last 30 minutes of the simulation the surface to soil flow decreases to approximately the same rate as the inflow to the catchment. The soil to storage flow remains at zero throughout the entire simulation period. Using the average permeability values for the soil, the underground storage capacity cannot be fully utilized. It is assumed that the conductivity of the soil is chosen at values, which do not enable water to pass through the soil into the storage layer during the simulation duration. Since the precipitation event implemented is very short and intense, and the simulation duration is only one hour, this explains why the bio-retention cell and rain garden result in the same required unit area. Although the bio-retention cell modeled includes a storage layer with a height of 800 mm, totaling in an additional volume of 28.1 m^3, 52.8 m^3, 80.88 m^3 and 82.56m^3 using the parameter set to manage the one-year, five-year, 30-year and six-hour precipitation event respectively, the thickness of the soil layer and conductivity values chosen do not allow water to pass into the storage layer within the one-hour simulation period.

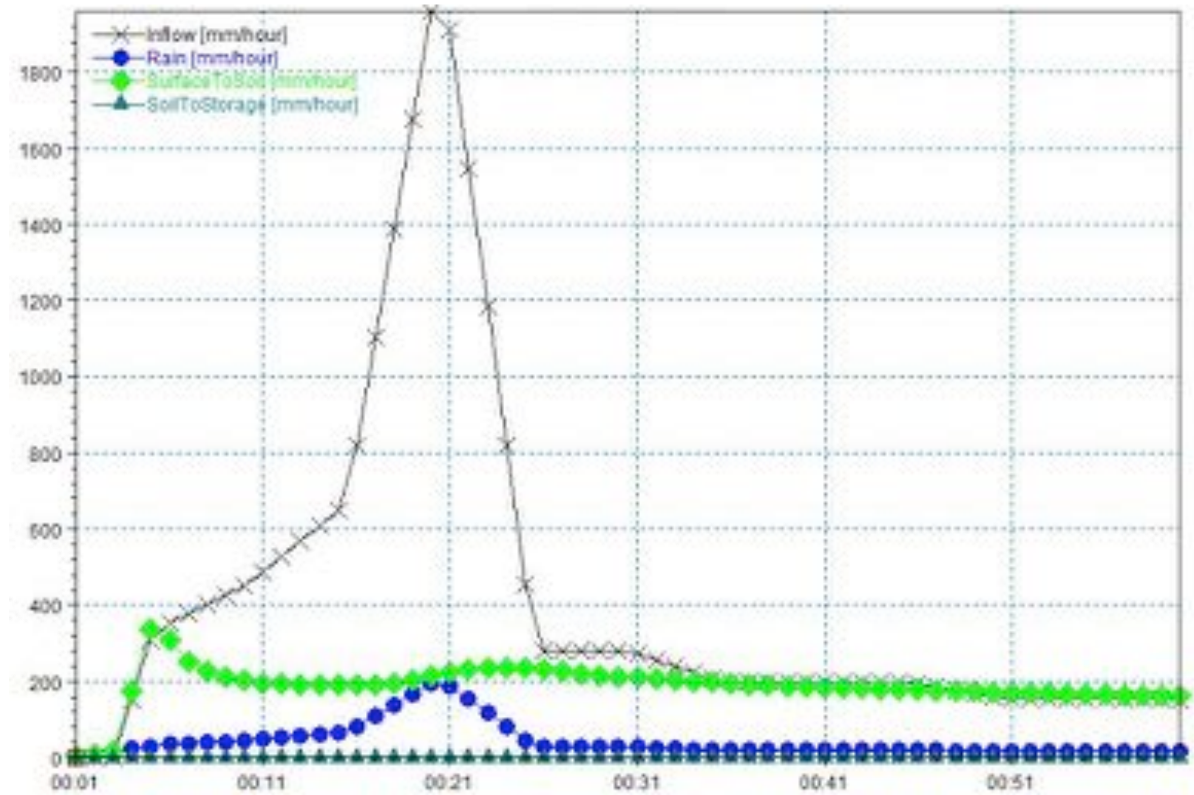

Figure 28: Flow statistics for street catchment with bio-retention cell during 30-year rainfall

5.2.2.5 Comparison between bio-retention cell, infiltration trench and rain garden

In the last step of the analysis the bio-retention cell, infiltration trench and rain garden were compared to each other. To enable a comparison between the three GI measures, which have varying layers and typical value ranges, the same values were chosen for each parameter within the same layer type. This means that within one comparison the surface parameters for all three GI measures are equal, the soil parameters are equal for the bio-retention cell and rain garden (the infiltration trench does not have a soil layer), and all storage layer parameters are the same for both the bio-retention cell and the infiltration trench (the rain garden does not have a storage layer). The comparison was calculated using the one-hour, five-year rainfall event. However, the simulation period was extended from one to six hours in order to be able to observe processes within the layers over a longer period of time after the precipitation has stopped. The values chosen for each parameter are shown in Table 19. In the first comparison, the parameter values used for the bio-retention cell in Section 5.2.2.1. were adopted besides the soil thickness, which was decreased from 1200 mm to 300 mm to assess the impact of the soil layer. Two other sets of parameters were assessed, which are referred to as Comparison 2 and Comparison 3. In the second comparison the values from Comparison 1 were adopted besides the thickness of the surface layer, which was decreased from 300 mm to 150 mm. In the third comparison, once again the parameter values from Comparison2 were used, however the soil conductivity parameters were altered. The conductivity was increased from 100 to 140 mm/h and the suction head was increased to 100 mm. The flows calculated by the model within the GI measure are shown at the bottom of the table. The inflow/ run-on refers to the precipitation generated on the sub-catchment not covered by the GI measure, which then “runs on" to the GI measure. The amount of run-on as well as rain depends on the size of the GI measure, since the greater the GI measure is, the more rain falls directly onto the measure, reducing the amount of run-on.

Table 19: Parameter values and flow results for the comparison between the bio-retention cell, infiltration trench and rain garden

		Comparison 1			Comparison 2			Comparison 3		
		BRC	**IT**	**RG**	**BRC**	**IT**	**RG**	**BRC**	**IT**	**RG**
	Unit area [m²]	**243**	**188**	**243**	**368**	**249**	**368**	**333**	**249**	**332**
Surface	Storage height [mm]	300	300	300	**150**	**150**	**150**	150	150	150
	Vegetative cover [-]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Surface roughness [M]	5	5	5	5	5	5	5	5	5
	Surface slope [%]	5	5	5	5	5	5	5	5	5
Soil	Thickness [mm]	**300**	-	**300**	300	-	300	300	-	300
	Porosity [1/1]	0.4	-	0.4	0.4	-	0.4	0.4	-	0.4
	Field capacity [1/1]	0.2	-	0.2	0.2	-	0.2	0.2	-	0.2
	Wilting point [1/1]	0.1	-	0.1	0.1	-	0.1	0.1	-	0.1
	Conductivity [mm/h]	100	-	100	100	-	100	**140**	-	**140**
	Conductivity slope [-]	40	-	40	40	-	40	40	-	40
	Suction head [mm]	80	-	80	80	-	80	**100**	-	**100**
Storage	Height [mm]	800	800	-	800	800	-	800	800	-
	Porosity [-]	0.3	0.3	-	0.3	0.3	-	0.3	0.3	-
	Infiltration capacity [mm/h]	40	40	-	40	40	-	40	40	-
Flows	Inflow/ run-on [m³]	*96.2*	*97.7*	*96.2*	*92.8*	*96.1*	*92.8*	*93.8*	*96.1*	*93.8*
	Rain [m³]	*6.8*	*5.3*	*6.8*	*10.3*	*7.0*	*10.3*	*9.3*	*7.0*	*9.3*
	Infiltration [m³]	*54.1*	*44.6*	*87.4*	*80.8*	*59.1*	*80.7*	*74.9*	*59.1*	*83.9*
	Surface runoff [m³]	*0.04*	*0.0*	*0.04*	*0.04*	*0.0*	*0.02*	*0.02*	*0.0*	*0.02*
	Final storage [m³]	*48.9*	*58.4*	*15.6*	*22.3*	*43.9*	*22.4*	*28.2*	*43.9*	*19.1*

In the first comparison, the soil and storage parameters are chosen at approximately the median of the value range given for bio-retention cells by Leimgruber et al. (2018), besides the thickness of both layers. In the first comparison both the surface and soil thickness were set at 300 mm. While the value ranges specified by the authors are similar for the bio-retention cell and the infiltration trench, the later generally has no vegetative cover, higher surface roughness values, a greater storage height and lower porosity of the storage volume. The following figures graphically display the flow statistics for the various GI measures under the three comparison value sets found in Table 19. The simulation period shown in the graphics is approximately the first hour of the simulation, during the rainfall event. The graphics showing the full simulation period can be found in the Appendix.

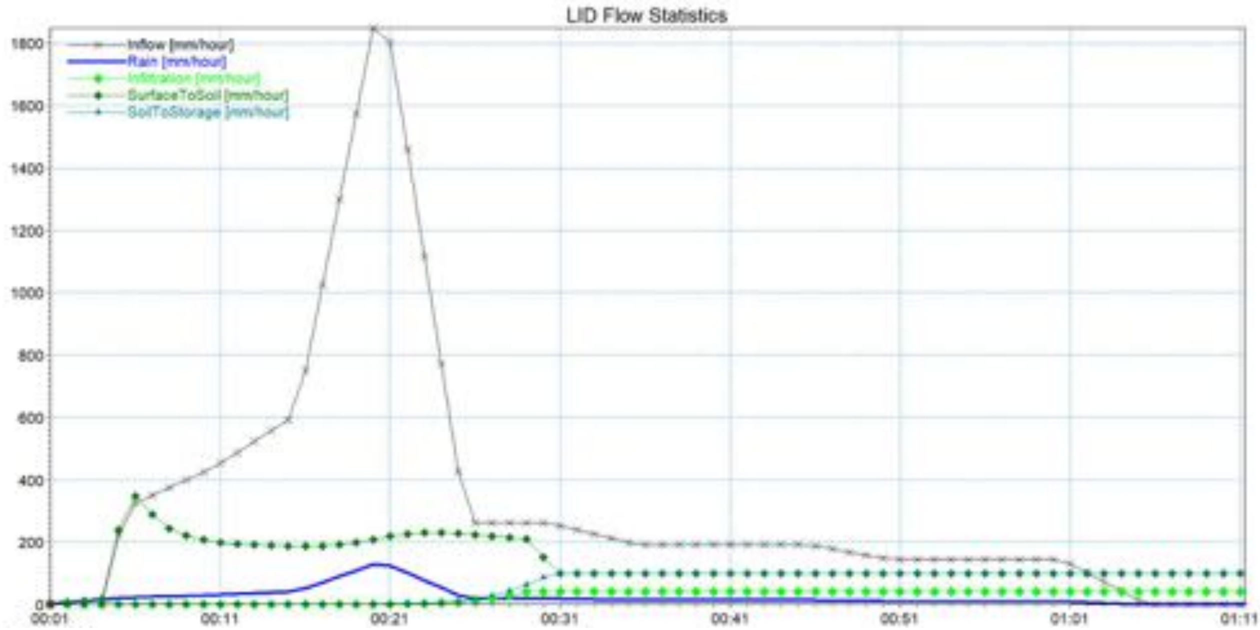

Figure 29: Flow statistics for bio-retention cell using values specified under Comparison 1

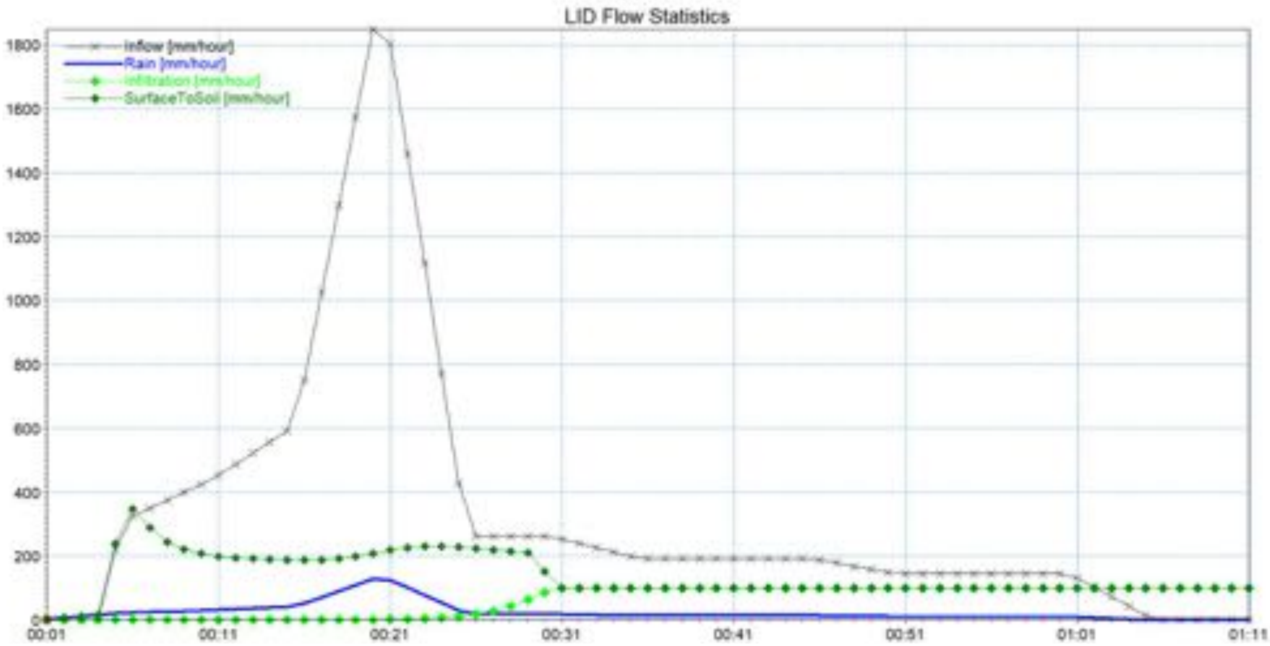

Figure 30: Flow statistics for rain garden using values specified under Comparison 1

As can be seen when comparing Figure 29 and Figure 30, the flow statistics of the bio-retention cell and rain garden are nearly identical, besides the fact that the rain garden does not have a soil to storage flow, due to the absence of the storage layer. In the bio-retention cell, the surface to soil flow peaks in minute 5 at a rate of 347.8 mm/h and then slowly decreases until reaching a steady rate at minute 31. Starting at 00:21 of the simulation the soil to storage flow increases with the infiltration and reaches its maximum at 100 mm/h at 31 minutes where it intersects with the surface to soil flow. The infiltration rate reaches its maximum of 40 mm/h in minute 29 of the simulation, which remains at this rate for the remainder of the simulation. The surface to soil and soil to storage rate remain equal until 03:48 of the simulation, where the surface to soil rate decreases to zero. The soil to storage rate gradually decreases to 3.3 mm/h by the end of the six-hour simulation. The flows in the rain garden show a similar pattern, besides that the surface to soil rate intersects with the infiltration into surrounding soil instead of with the soil to storage flow as in the bio-retention cell. These differences are quantified in the flows displayed at the bottom of Table 19. The total infiltration for the rain garden is 87.4 m^3 in comparison to 54.1 m^3 for the bio-retention cell. Due to the storage layer the bio-retention cell is able to store 48.9 m^3 of precipitation while the rain garden only stores 15.6 m^3.

Using the values under Comparison 1, the infiltration trench requires a unit area of 188 m^2 to manage the five-year precipitation event. This area is 34 m^2 smaller than the area required for the other two GI measures. The flows in Table 19 show that the amount of rain that falls onto the infiltration trench directly is lower (due to smaller unit area), while the inflow or run-on is higher. Furthermore, a difference between the bio-retention cell and rain garden versus the infiltration trench can be seen in regards to the infiltration and final storage. Since the infiltration trench does not have a soil layer, the water that passes through the surface layer directly enters the storage layer or infiltrates into the surrounding soil. Therefore, it can be inferred that the storage layer has a greater effect on the retention capacity for the infiltration trench than for the bio-retention cell. The inflow, rain, infiltration and surface to storage flows are shown graphically in Figure 31. The most noticeable flow is from surface to storage, which is nearly identical to the inflow of rain onto the GI area for the first 19 minutes of the simulation period. After approximately 19 minutes the storage limit is reached, causing the surface to storage rate to decrease to the infiltration rate. This means that only the amount of water, which is able to infiltrate into the surrounding soil, can further enter the storage layer. The high rainfall intensity causes water to pass through the surface very quickly, as can be seen in Figure 31. Since the infiltration trench only has a surface and storage layer, the surface layer plays an important role in filtering the rain for this GI measure. If rain rushes through the surface layer of the infiltration trench, processes that contribute to the filter capabilities of soil cannot occur. This should be considered in regards to water quality goals.

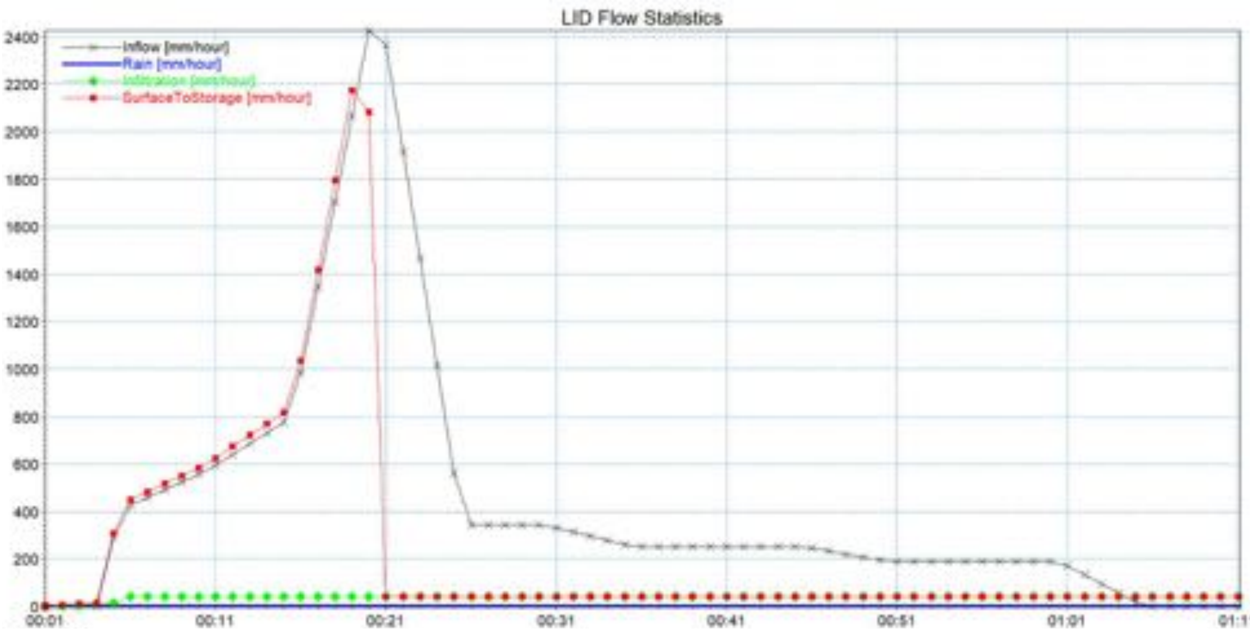

Figure 31: Flow statistics for infiltration trench using values specified under Comparison 1

The second set of parameter values (Comparison 2) simulated a thinner surface storage layer (150 mm versus 300 mm). In total the bio-retention cell has a height of 1250 mm (compared to 1400 mm under Comparison 1), the infiltration trench has a total height of 950 mm (compared to 1100 mm under Comparison 1) and the rain garden has a total height of 450 mm (compared to

600 under Comparison 1). This corresponds to a decrease in thickness of 11% for the bio-retention cell, 14% for the infiltration trench and 25% for the rain garden.

The flows of the bio-retention cell and rain garden are shown in Figure 32 and Figure 33 respectively. The surface to soil flow increases with the inflow into the bio-retention cell and peaks at 263.4 mm/h in minute 8 of the simulation. This flow then decreases before rising slightly after the peak of the rain event, and then decreases to the soil to storage rate of 100 mm/h in minute 35 of the simulation period. The surface to soil flow remains at 100 mm/h until 02:25 of the simulation before abruptly stopping. The soil to storage flow decreases steadily from 100 mm/h at 02:25 to 2.04 mm/h by the end of the six hour simulation. It can be seen that the flows in the bio-retention cell are very similar for the values chosen in Comparison 1 and Comparison 2, however the surface to soil and soil to storage flows significantly decrease at 03:49 of the simulation in Comparison 1, which happens at 02:25 in Comparison 2. This shows the significance of the additional 125 m^2 of GI area in quickly diverting water away from the surface. The infiltration rate increases with the soil to storage flow and reaches its maximum in minute 32 at 40 mm/h. Although the rain garden requires the same unit area, the flows show slight differences. Similarly to the bio-retention cell, the surface to soil flow increases with the inflow into the rain garden, peaks at 262.9 mm/h in minute 8 and decreases to the infiltration rate of 100 mm/h at minute 35, which is how it remains until the end of the simulation period.

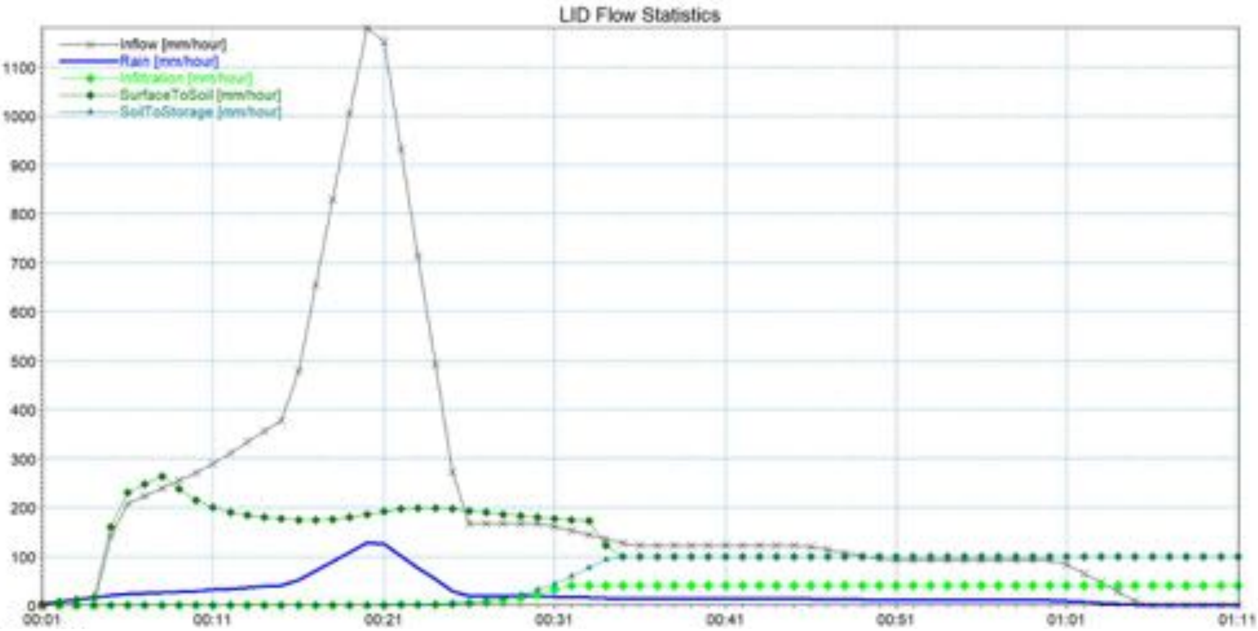

Figure 32: Flow statistics for bio-retention cell using values specified under Comparison 2

Figure 34 shows the flow statistics for the infiltration trench using the values specified under Comparison 2. The flows in Comparison 1 and Comparison 2 are similar, besides that the surface to storage rate is lower than the inflow in Comparison 1, yet higher than the inflow in Comparison 2. This is explained by the larger unit area of the infiltration trench in Comparison 2. Since more rain falls directly onto the GI measure, less runs onto the unit area. Furthermore, the surface to storage rate eventually decreases to zero at 04:26 of the simulation, while the surface to storage rate remains equal to the infiltration rate in Comparison 1 from 00:21 until the end of the simulation.

The change in surface storage height has a noticeable effect on the retention capacity of all three GI measures. The unit area must be increased by 125 m^2 for the bio-retention cell and rain garden, while the required area is only 61 m^2 larger for the infiltration trench. This shows the importance of the storage layer for the infiltration trench, while the surface storage layer seems to be more important for the bio-retention cell and rain garden. The soil layer reduces the rate of water passing through the GI measure, which can also be seen in the previous figures.

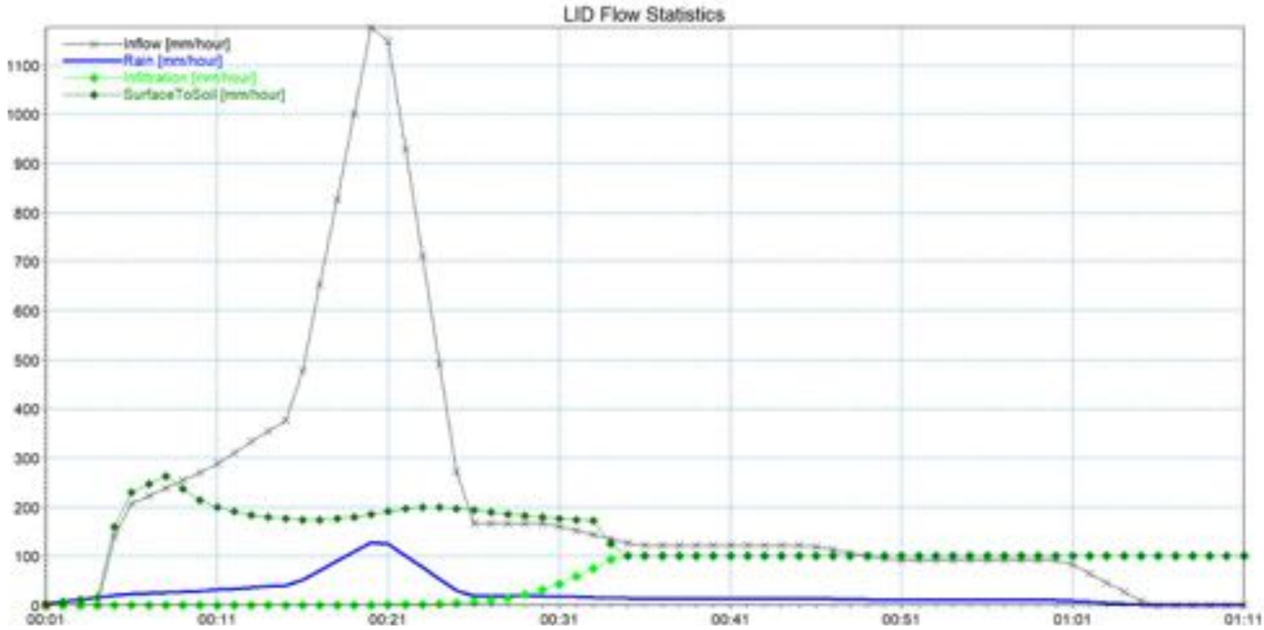

Figure 33: Flow statistics for rain garden using values specified under Comparison 2

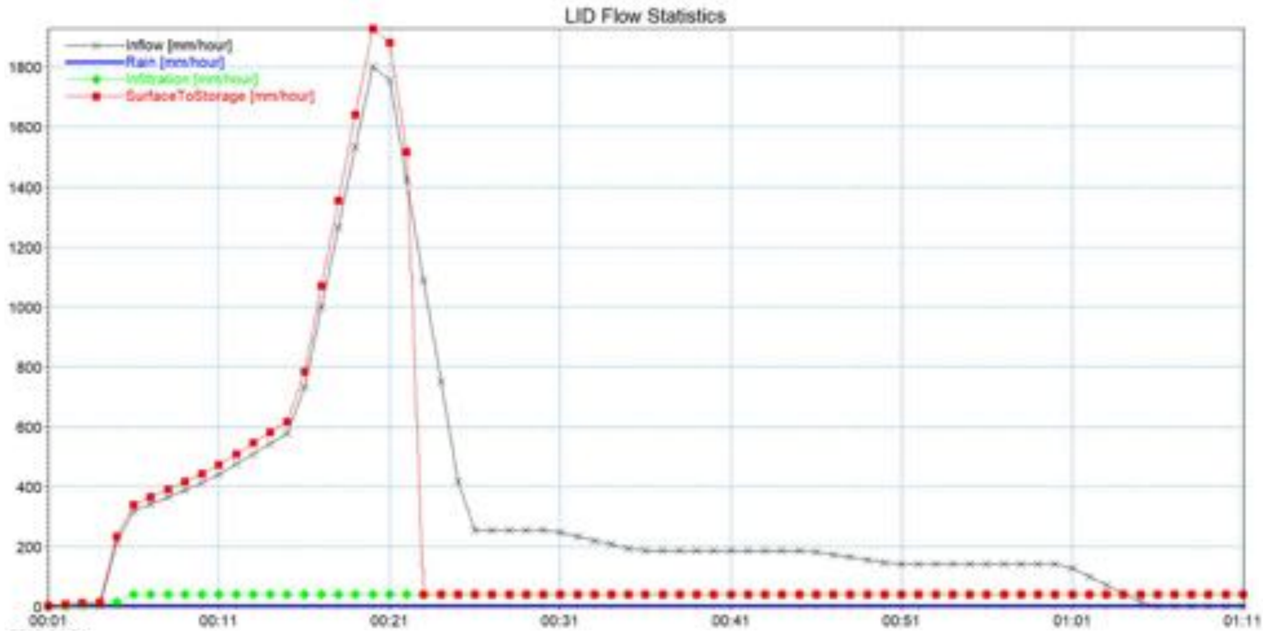

Figure 34: Flow statistics for infiltration trench using values specified under Comparison 2

The third comparison between the bio-retention cell, infiltration trench and rain garden used the same values from Comparison 2, only changing the conductivity and suction head of the soil. Again, the bio-retention cell and rain garden would require equal unit areas to manage a five-year, one-hour precipitation event using the specified values. The flows show a very similar pattern to those from the simulations using the values specified under Comparison 1 and 2. The unit area required for the bio-retention cell and rain garden is 35 m^2 smaller than the area required when using the values specified under Comparison 2. No values were changed for the infiltration trench between Comparison 2 and 3. Due to the increase in conductivity of the soil, water is able to enter the soil and storage layer at a faster rate. While in the bio-retention cell the surface to soil rate decreases to 0 at 02:25 and the soil to storage rate decreases from 100 mm/h at 02:25 to 2.04 by the end of the simulation in Comparison 2, both flows drastically decrease within the first two hours of the simulation in Comparison 3. However, it is interesting that the infiltration rate decreases to zero in Comparison 2, yet stays at 40 mm/h in Comparison 3.

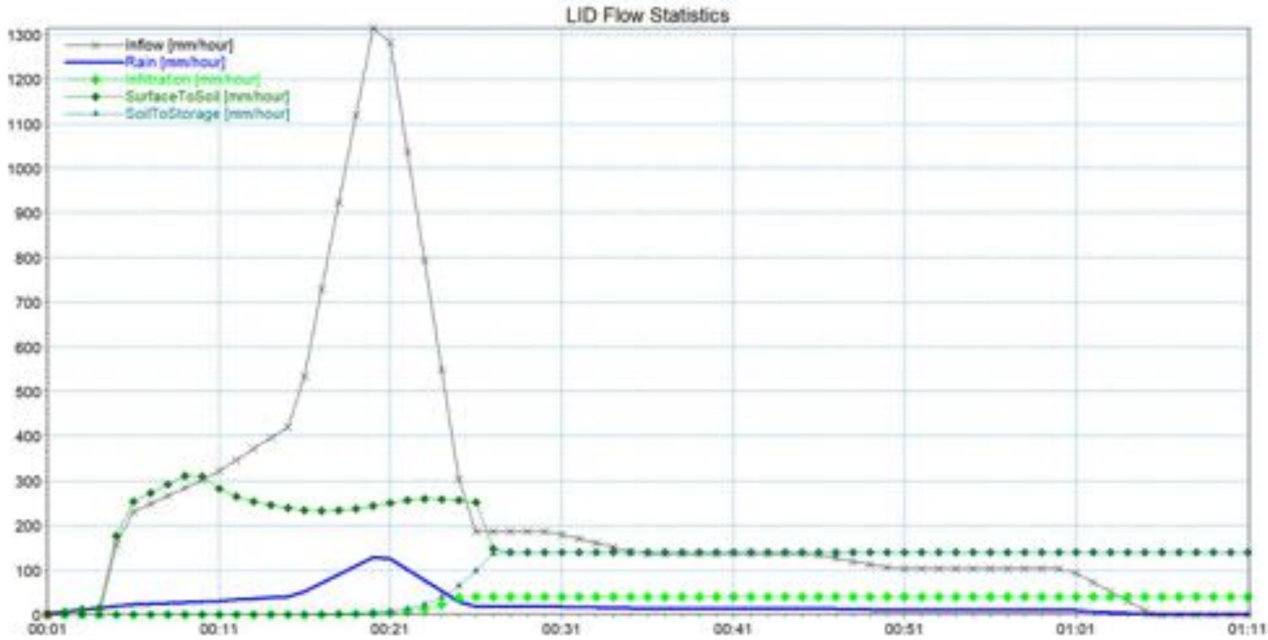

Figure 35: Flow statistics for bio-retention cell using values specified under Comparison 3

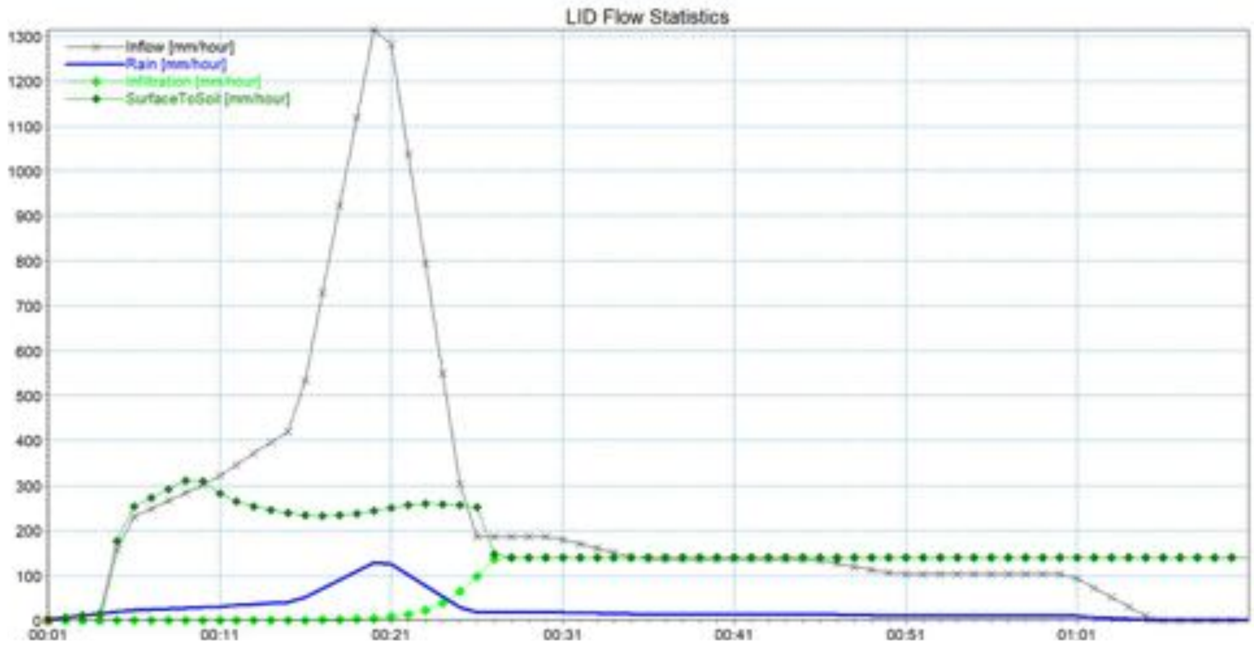

Figure 36: Flow statistics for rain garden using values specified under Comparison 3

The simulations show large differences between the required GI intensity (e.g. height, volume) to fully manage the various precipitation events for each GI measure. This highlights the necessity to specify which goal should be followed for the implementation of GI, e.g. flood management, water conservation or a combination of both. Additional existing boundary conditions, such as financial and spatial considerations, should also be taken into account.

6. Conclusion and outlook

This thesis performed a sensitivity analysis of the sub-catchments in the district Wagram on the sewer system during heavy precipitation events to support the decision making process for the geographic positioning of GI. The following paragraphs detail further topics and considerations that could provide results at a higher level of detail.

With regard to the model itself, input parameters and boundary conditions have a pronounced effect on the results. The input parameters include the sewer system (pipes, manholes, outlets), catchments (also referred to as sub-catchments) and boundary data such as rainfall events. The sub-catchments were created using land use data based on the digital cadastral map. Catchments that were assumed to be runoff irrelevant were not included, such as agricultural areas and gardens. Future analyses using smaller catchment areas and including pervious areas would provide more precise results. However, the desired outcomes should be considered in advance regarding the objectives of the simulations, time considerations, and available data. The more precise the results should be, the more data is required, leading to an increase in simulation times and analysis effort. Furthermore, catchment connections were generated automatically, based on spatial proximity. This resulted in the connection of multiple catchments to one manhole. This is not necessarily unrealistic, since runoff from various areas may run to the same manhole. However, the sub-catchments are partially quite large, which may lead to unrealistically high amounts of water entering the system at one point. In reality, runoff from large areas such as a field or parking lot will flow in various directions, entering the sewer system at multiple points.

In a first step OAT sensitivity analysis was performed to assess the impact of each catchment on the sewer system, based on performance indicators. The performance indicators evaluated were total and maximum discharge at the sewer system's weir. The assessment of both the deviation in total and maximum discharge shows similar results. Many catchments that have a significant effect on the sewer system regarding total discharge also have a significant impact on the maximum discharge. However, it can also be seen that a greater number of catchments effect the sewer system by one or more percent regarding the total discharge than the maximum discharge from the CSO. In both cases, the sensitivity analysis showed that the size of sub-catchments is positively correlated to both the total (Correl = 0.81) and maximum (Correl = 0.71) discharge at the sewer system outlet. This result was predicted, since in general it can be stated, that more runoff accumulates on larger areas, when comparing catchments with the same or similar runoff coefficient. However, no correlation was found between the geographical location of a catchment and the discharge. This may be due to the chosen catchment sizes, which vary greatly. As mentioned previously, an assessment of the model including a greater number of smaller catchments could provide interesting results. However, the more complex the model is, the greater the duration for both the set-up and running of the model is. No correlation between person equivalents or percent imperviousness and the total or maximum discharge was found. This is an interesting outcome, as this value was assumed equal to the runoff coefficient of each catchment type, which relates the amount of runoff to the amount of precipitation received. It is assumed that the lack of correlation may be due to the large differences in sub-catchment size. Another reason may be the percent imperviousness values chosen. The values in this model range between 30 and 60%. Greater differences between the values may enhance the correlation. Further analyses, which evaluate the correlations between certain input and output parameters, could provide more information on the sensitivity of the model.

In a second step, the effect of GI measures on two catchments, which showed a significant impact on the sewer system, was evaluated. Green roofs and rain barrels were implemented on a public building sub-catchment, and bio-retention cells, infiltration trenches, and rain gardens were chosen for the street sub-catchment. The values used for the GI parameters for the street catchment were chosen in accordance to a study published by Leimgruber et al. (2018), who performed a global sensitivity analysis of water balance components of a green roof, bio-retention cell and infiltration trench to identify influential and non-influential parameters. In this model, most parameters were selected close to the median of the value range specified in that study. Each set of parameters was tested under the specified precipitation events to calculate the required GI area to fully manage each rainfall event. Many factors including available space, financial means and the surrounding climate should be considered when implementing GI in a community. The simulations show that the implementation of GI can realistically provide retention and infiltration capabilities comparable to the complete decoupling of a sub-catchment from the sewer system. However, the short, intense rainfall events may result in greater calculated required GI constructional intensities. Future state of the art assessments should include long-term rainfall series modeling instead of using an event based design method as was used in this thesis. However, this was not the aim of the thesis. Furthermore, each GI measure has several parameters, some of greater influence than others. The parameter values used thus have a great effect on the outcome of the simulations using GI measures. Although it would be of interest to know which parameters are the most effective or efficient in managing stormwater, an extensive analysis would have to be performed. Since the aim of this thesis was to generally assess if GI can provide retention and infiltration capabilities comparable to the complete decoupling of a sub-catchment, an extensive analysis was not performed on the GI parameters and possibilities. Such an analysis exceeds the extent of this thesis, but would be recommended for future assessments. Furthermore, an analysis could be performed including multiple areas with implemented GI measures, instead of assessing the runoff from selected sub-catchments. This would give a more realistic overview of the effect of GI measures on the sewer system as a whole.

An additional degree of detail could be achieved through setting up the model differently. The model used was run as a 1D model, which was sufficient for this thesis. As an alternative, a 2D overland model could be used, which would provide a more realistic distribution of the rainfall load and hence a realistic flow routing over the terrain. According to MIKE by DHI (2015), this would also contribute to the quality of results for urban catchments with distributed green surface between buildings and roads. However, the complicity, data requirements and simulation time are significantly higher for 2D models. Therefore the additional effort in such a model must be weighed to the expected benefits.

The model was run using the MIKE URBAN runoff Model A (Time Area Method) and Model B (Kinematic Wave), which are both surface runoff models. The parameters chosen for these models were based on the MIKE URBAN default, which may create a bias in the results. Future models should use values that are realistic for the specified geographic area. Continuous hydrological runoff models can also be used in MIKE URBAN, such as the Rainfall Dependent Infiltration model (MOUSE RDI model). This model provides detailed, continuous modeling of the complete land, or runoff, phase of the hydrological cycle (MIKE BY DHI, 2017a). This is particularly interesting for urban, rural and mixed catchment analyses. This could take further considerations such as pollution and hydraulic load over a longer period of time into account. Another interesting addition to this analysis would be the use of the MIKE URBAN climate change tool, which modifies time series of precipitation, temperature and potential evapotranspiration according to the geographic location and year based on the IPCC report.

In conclusion, this thesis found that performing a sensitivity analysis of the effect of sub-catchments on the sewer system might be a valuable tool for municipalities for the geographic positioning of GI, depending on the input parameters chosen and simulation goals. However, data requirements, the necessary level of detail, and question of scale should be considered when creating the model.

7. Summary

There is a wide consensus in literature that the current rate of greenhouse gas emissions will result in changes in the climate including global warming and an increase of extreme weather events (IPCC, 2018). An increase in weather extremes is likely to lead to an increase in heavy precipitation events and thus flooding. In order to mitigate flooding consequences, it is important to manage storm and wastewater. However, increasing urbanization and the increase of impervious areas in cities continuously adds pressure on existing sewer systems. These underground systems have often become too small to manage storm and wastewater accordingly, leading to pluvial flooding as well as a pollution threat of receiving waters. In addition, new building developments and extensive renovations met by tight community budgets raise the question as to which available water management systems can fulfill community goals both now and in the future. The necessity to implement alternative, flexible water management strategies is evident.

One evolving water management strategy that has shown to restore ecological functions in an area and manage stormwater onsite is GI. GI is described as technologies and practices which use a combination of natural and engineered components to simulate natural systems, which provide ecosystem services (EPA, 2018; EEA, 2017). A wide range of GI measures can be found in literature, which focus on the attenuation and/or infiltration of runoff. The core aim of these measures is to control peak runoff rates by slowing and storing runoff on site, and/or enabling the entry of water into the soil, thus enabling the storage and slow release of water back into the surrounding atmosphere and environment (CIRIA, 2015). These processes shift the urban water cycle in the direction of a natural water balance and have shown to provide an array of ecosystem services to communities, contributing to sustainability and resilience goals (Foster et al., 2011).

In Austria, decision-making aids that integrate various aspects of rainwater management while providing a structured process for planners and municipalities for small and medium-sized communities do not exist. International approaches that focus on larger urban areas can be found in literature, but differ in several respects including the sewer system type (combined versus separated sewer systems), building density and thus available space for solutions, as well as economic boundaries. The project “FlexAdapt” - Development of flexible adaptation concepts for urban drainage of the future- aims at evaluating stormwater management concepts from a technical, ecological, environmental, organizational, financial and societal point of view. The final outcome of this project is a comprehensive framework containing decision-making tools for recommendations on long-term urban drainage measures (Simperler, et al., 2017).

By conducting a case study in Wagram in the city of Sankt Pölten, this thesis concludes that performing a sensitivity analysis of sub-catchments on the sewer system is a helpful tool in the decision making process for the geographic implementation of GI. Furthermore, GI can provide retention and infiltration capabilities comparable to the complete decoupling of sub-catchments from the sewer system. The following steps were implemented in this thesis:

- Literature review
- Set-up / construction of model
- Sensitivity analysis through the automatic decoupling of sub-catchments
- Implementation of GI

The sensitivity analysis is performed in order to assess which sub-catchments have the greatest effect on the sewer system, and thus the highest potential for the implementation of GI (GI) measures. This should provide a possible method for municipalities to assess which areas would be most effective and thus efficient for the implementation of GI. In the second step of this thesis, sub-catchments with a high effect on the sewer system are equipped with GI in order to assess what outcome could realistically be achieved with such measures in dealing with various precipitation events.

The data used for the thesis is largely provided as geographical information through ÖSTAP Engineering & Consulting GmbH. In a first step, the model is built in MIKE URBAN, including sewer network features such as pipes, nodes and canals, as well as sub-catchments. In order to assess which sub-catchments have the greatest influence on the sewer system, a sensitivity analysis is performed, where each sub-catchment is individually decoupled from the model, and the deviation of the discharge at the CSO is calculated. In order to conduct the sensitivity analysis an automated script in Python is created since the manual, individual decoupling of all 3761 catchments would not be viable. To mimic the decoupling of each catchment, each simulation set the area of one individual catchment to zero before running the rainfall runoff and network simulation.

The sensitivity analysis revealed a positive correlation between the size of a sub-catchment and both the total and maximum discharge at the CSO. This result was expected, since more runoff accumulates on larger areas, when comparing catchments with the same or similar runoff coefficient. The sub-catchments that show a significant effect on the sewer system are similar regarding both the total and maximum discharge from the CSO. However, the percent deviation from the base simulation is generally lower regarding the deviation of maximum discharge. No other significant correlations were found in this thesis. Although the maps showing the percent deviation in total and maximum discharge visually suggest a greater effect for catchments close to the CSO, no mathematical correlation could be found between the distance from the CSO and the deviation in discharge caused by the decoupling of the sub-catchment. This poses the question if the sensitivity analysis performed is beneficial in providing information for the geographical positioning of GI. Many input parameters including the varying sub-catchment size in the model may have an impact on this result. Since the automatic decoupling process has been created in this thesis, further analyses using this method can easily be performed and may elucidate the results found in this thesis.

In the second part of this thesis, the possible effect of GI measures on two catchments with a significant impact on the sewer system was evaluated. The aim was to assess if GI could provide retention and infiltration capabilities comparable to the effect of completely decoupling a sub-catchment from the model. A building and a street section were chosen for this analysis. Green roofs and a rain barrel were implemented on the building, while bio-retention cells, infiltration trenches, and rain gardens were implemented on the street catchment. Each GI measure was modeled under various parameter sets, in accordance to four precipitation events: a one-year, five-year and thirty-year, 60-minute rainfall event as well as one intense, six-hour rainfall event. This study showed that GI measures could provide enough retention and infiltration capacity within a realistic degree concerning both construction intensity and spatial circumstances. However, the parameters were chosen at values within a realistic range, not specifically adjusted to the boundary conditions of the community. Since the aim of this thesis was to generally assess if GI can provide retention and infiltration capabilities comparable to the complete decoupling of a sub-catchment, an extensive analysis was not performed on the GI parameters and possibilities. Such an analysis exceeds the extent of this thesis, but would be recommended for future assessments.

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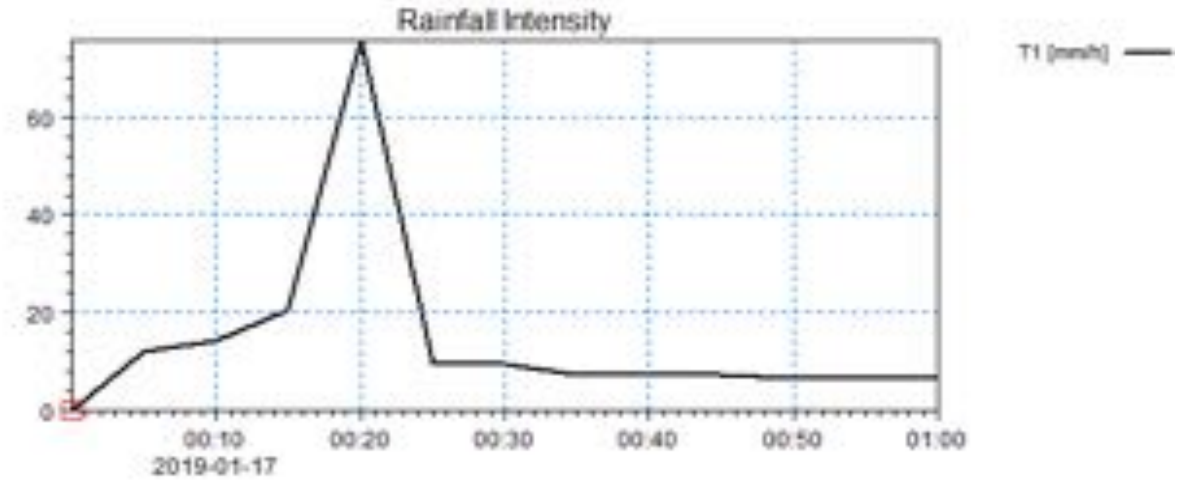
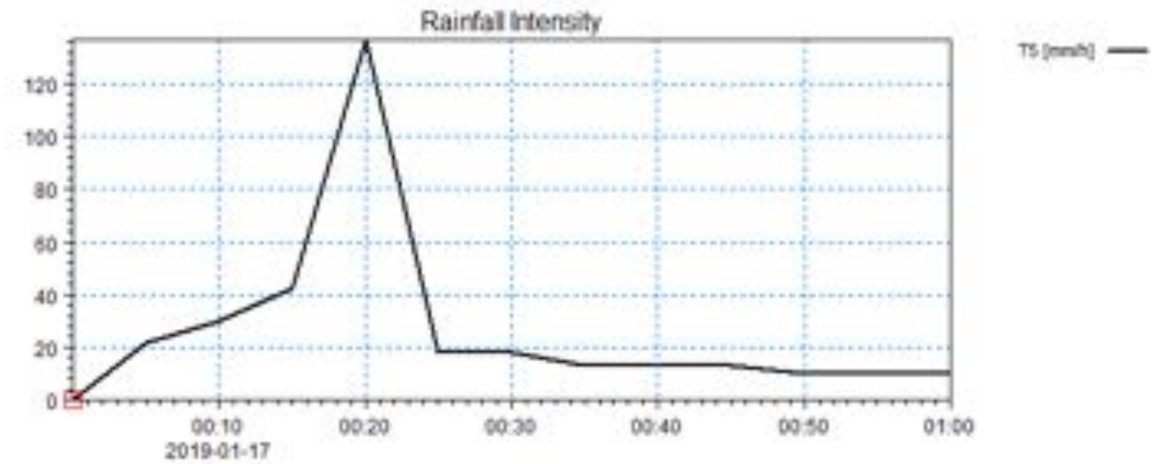
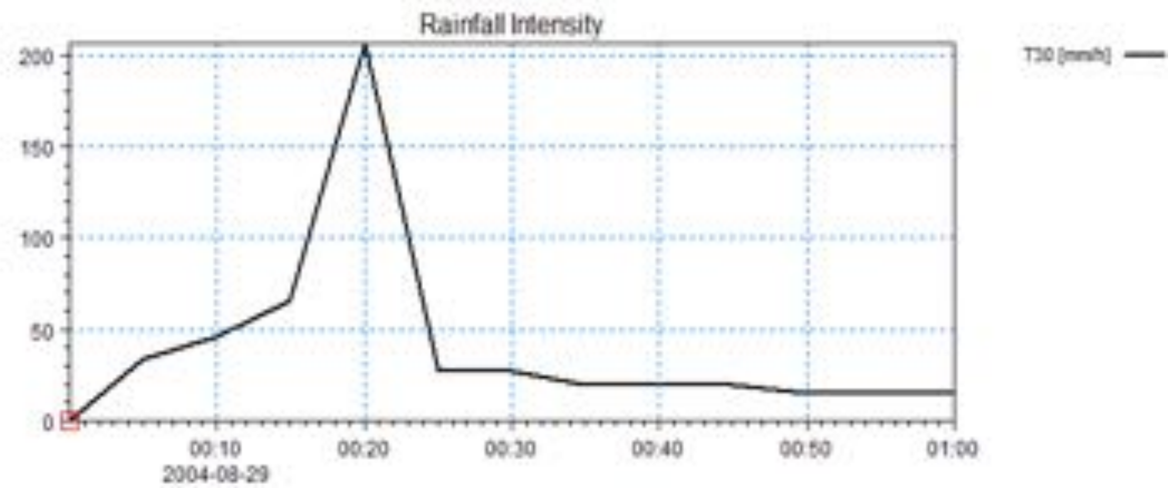
Appendix



Attachment 1: Rainfall intensity of one-year, 60-minute precipitation event



Attachment 2: Rainfall intensity of five-year, 60-minute precipitation event



Attachment 3: Rainfall intensity of thirty-year, 60-minute precipitation event

Attachment 4: Imperviousness based on (German) classifications in the digital cadastral map

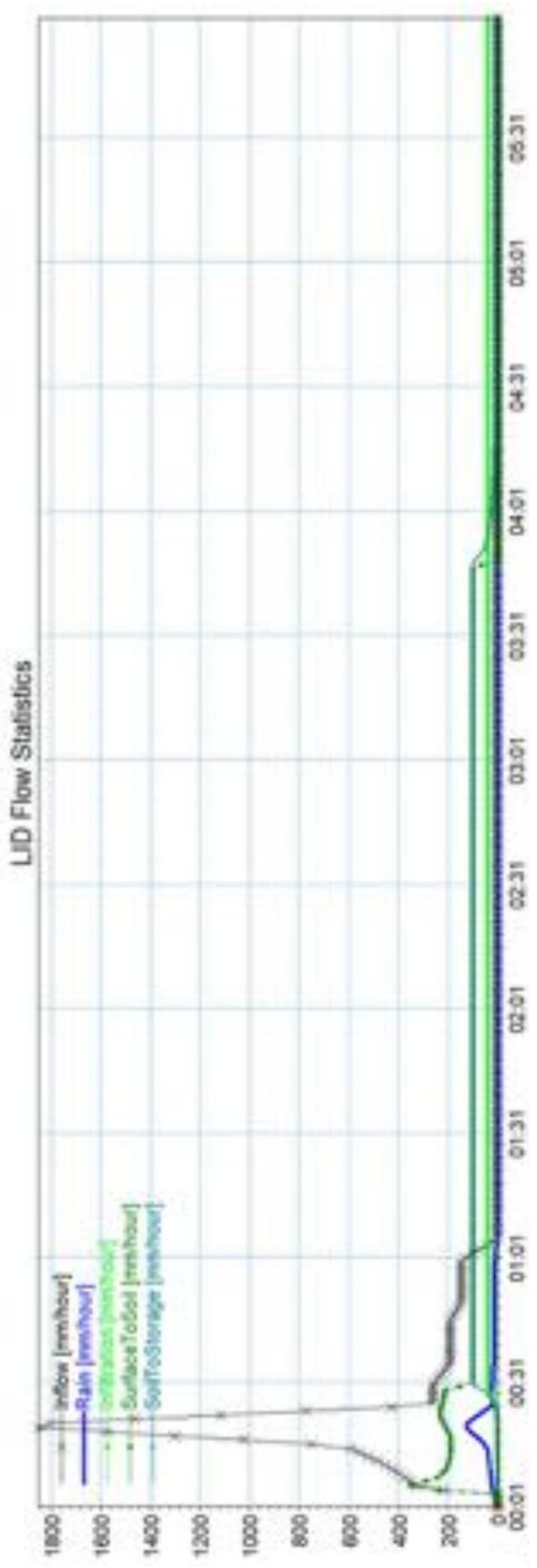
German Description	English Description	Imperviousness [%]
Betriebsfläche	Industrial (operating) surface	0,8
Freizeitfläche	Recreational area	0
Garten	Garden	0
Gebäude	Building	0,65
Gebäudenebenfläche	Ancillary area	0,6
Gewässerrandfläche	River bank	0
Landwirtschaftlich genutzt	Agricultural area	0
Parkplatz	Parking lot	0,6
Schienenverkehrsanlage	Railways	0,3
Straßenverkehrsanlage	Streets	0,6
Verbuschte Fläche	Dense vegetation	0
Verkehrsrandfläche	Road verge	0
Wald	Forest	0
Weingarten	Vineyard	0

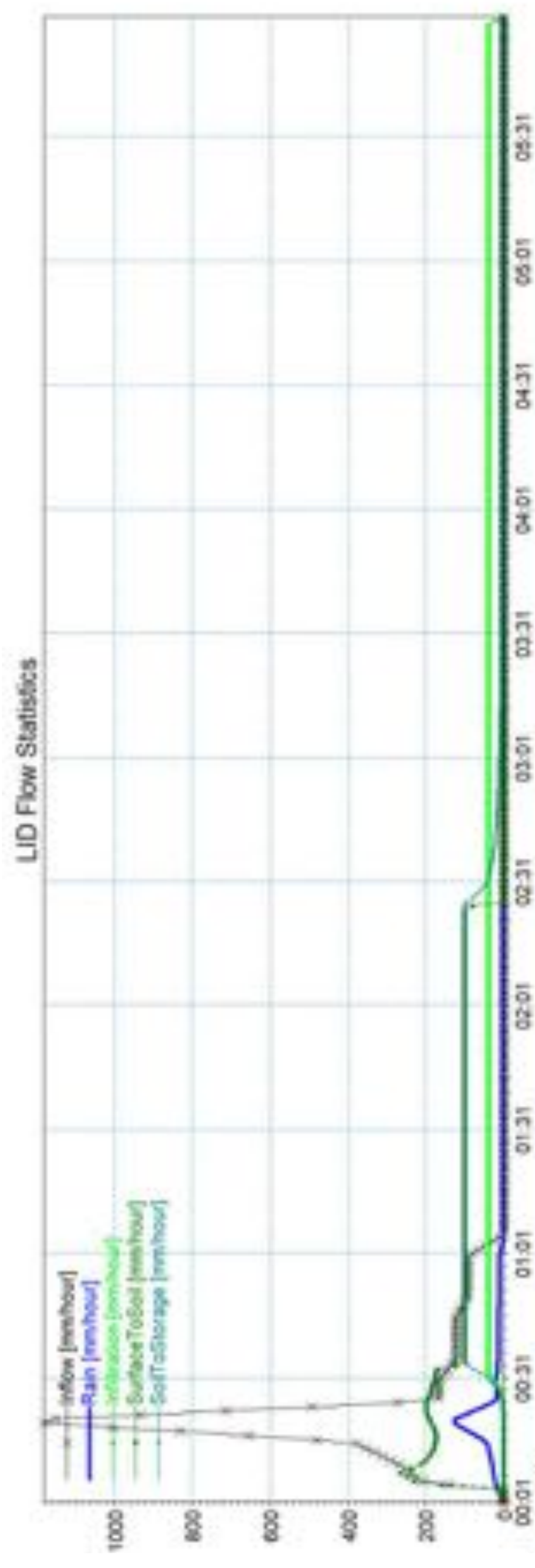
Attachment 5: Alterations made to catchments based on water law

Catchment No.	Contact Name	Description of water law (German)	Changes made
1956	BARA PKW-Werkstätte Peter Göndle GmbH	"Versickerung der Niederschlagswässer von den Dachflächen (25,71 sl) und Verrieselung der Niederschlagswässer vom Parkdeck und übrigen Verkehrs- und Parkflächen (25,02 l/s) auf Eigengrund.	Set drainage area of building to 0
2018	BARA PKW-Werkstätte Peter Göndle GmbH	"Ableitung der Niederschlaswässer von Verkehrs- und Parkflächen des nordöstlichen Bereichs (28,07 l/s)" …	Set drainage area to half (from 0,04 to 0,02)
1660	BARA KINO	"Ableitung der Niederschlagswässer des 92 Stellplätze umfassenden Parkplatzes in Sickermulden auf Gst. Nr. 595"	Set drainage area from 0,101 to 0,0505 since parking lot is bigger than 92 parking spots
1503	BARA Motorradhandel GmbH	Versickerung der Dachflächen	Set drainage area to 0
3340, 3344	BARA Franz Hummer	"Einleitung der gesamten Dachwässer des Betriebsgebäudes auf den Gst.Nr. 28, 29/1, 29/4, .34, […] in den rechten Traisenwerksbach" (bei 5 jährigem, 5 minütigem Regenereignis)	Set drainage area to 0

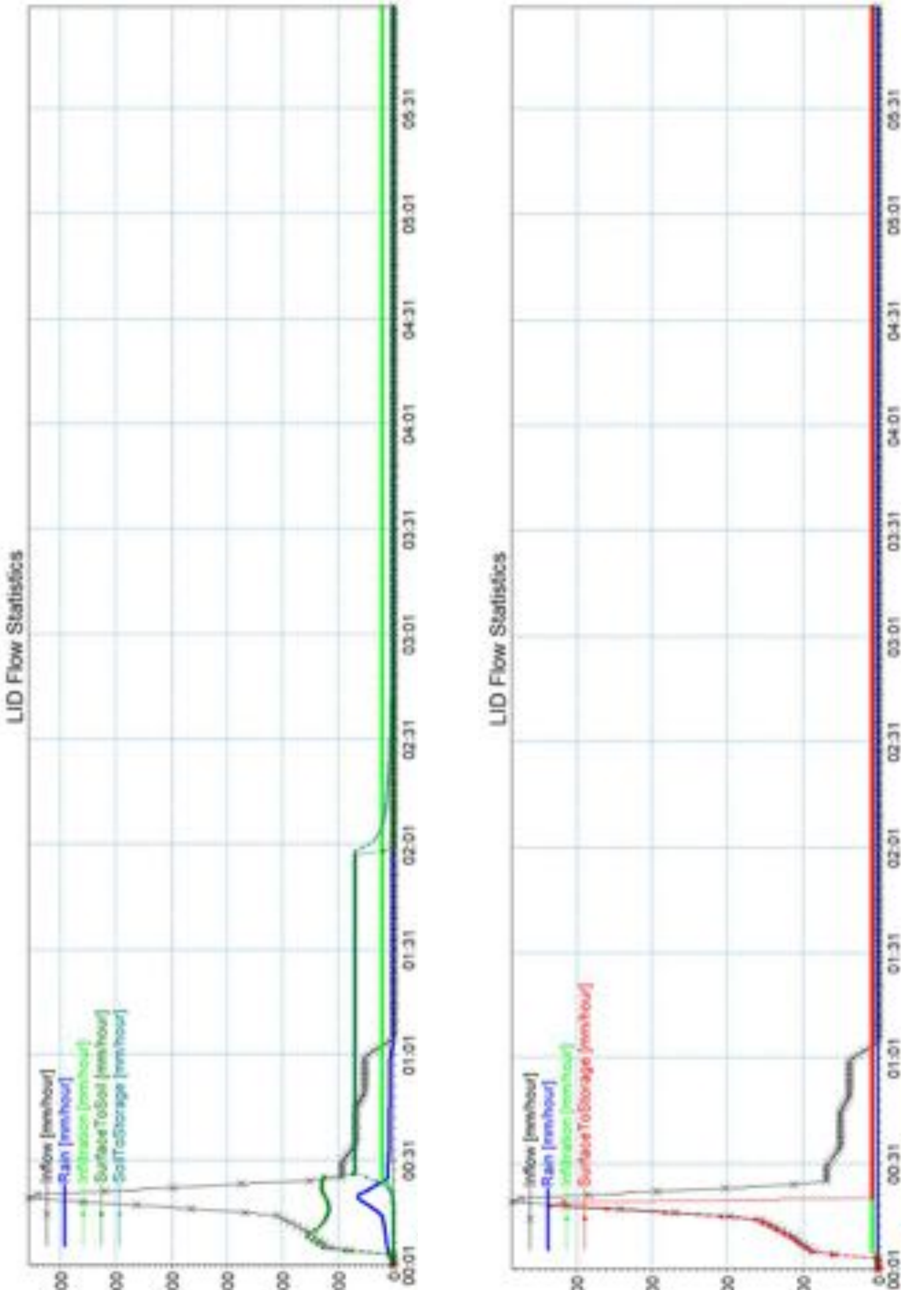
Attachment 6: Diurnal pattern used for dry weather flow according to (Gujer, 2007)

Time of day	Percent of daily demand
00 – 01	2,0
01-02	1,0
02-03	0,5
03-04	0,5
04-05	0,5
05-06	2,0
06-07	3,0
07-08	3,0
08-09	4,0
09-10	4,0
10-11	6,0
11-12	8,0
12-13	10,5
13-14	9,0
14-15	8,0
15-16	4,0
16-17	3,0
17-18	3,0
18-19	7,0
19-20	7,5
20-21	4,5
21-22	4,0
22-23	3,0
23-24	2,0

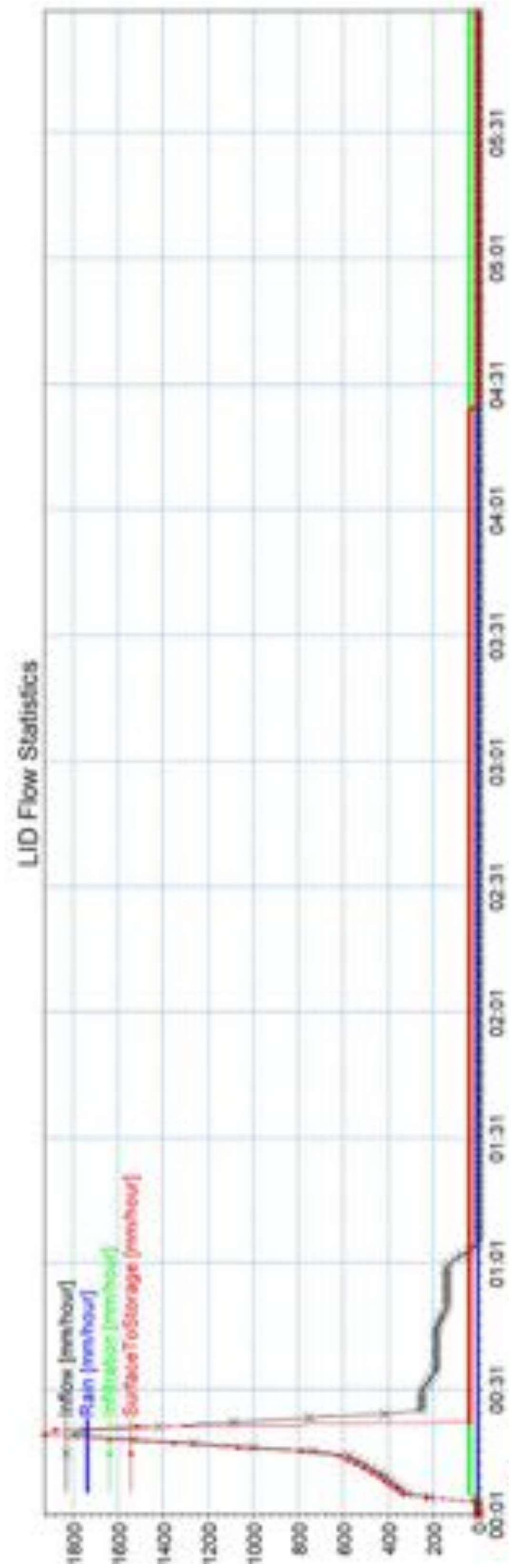


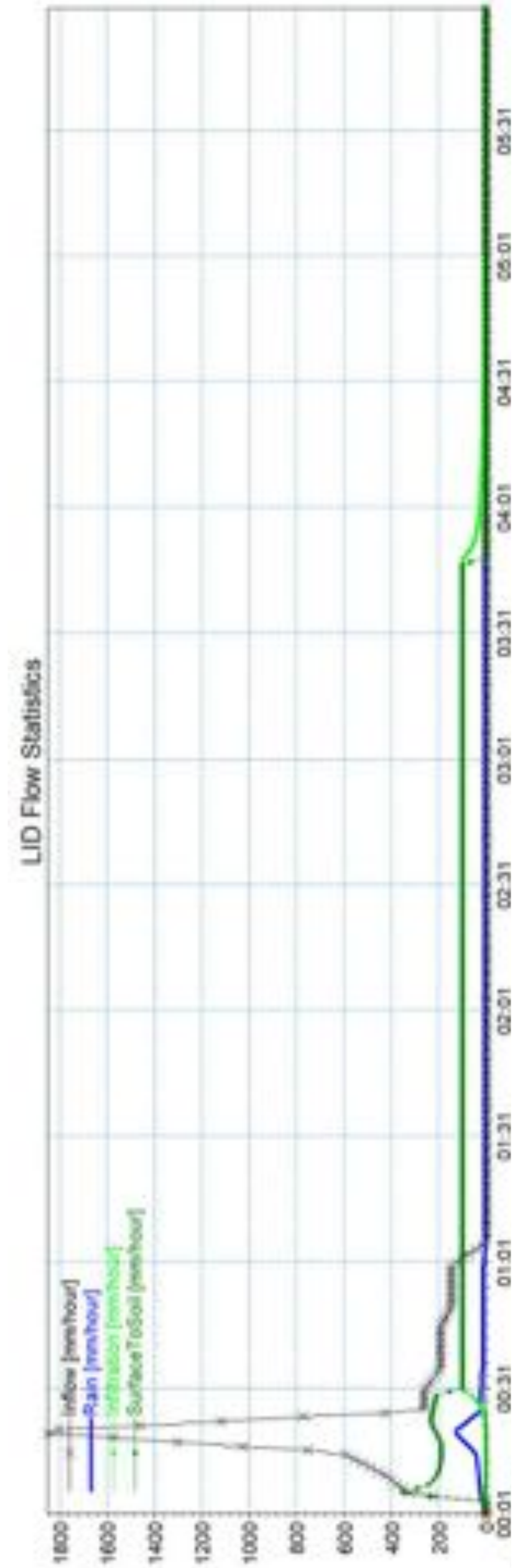


Attachment 7: Flow statistics for bio-retention cell using values specified under Comparison 1 (left) and Comparison 2 (right)

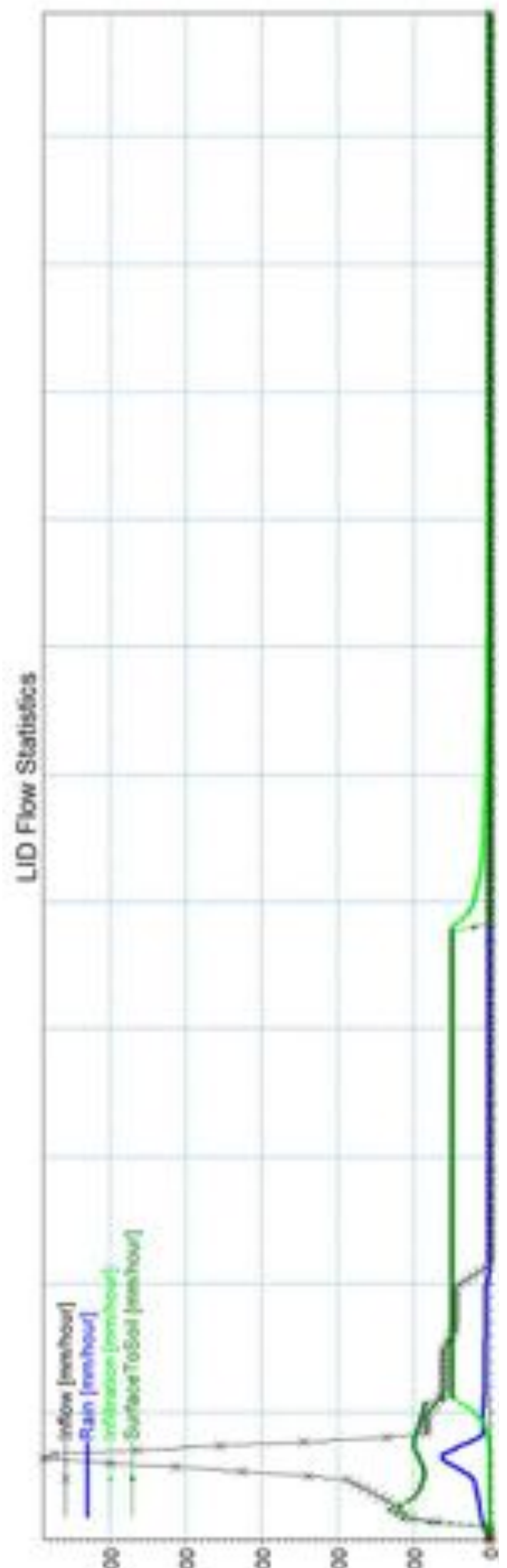


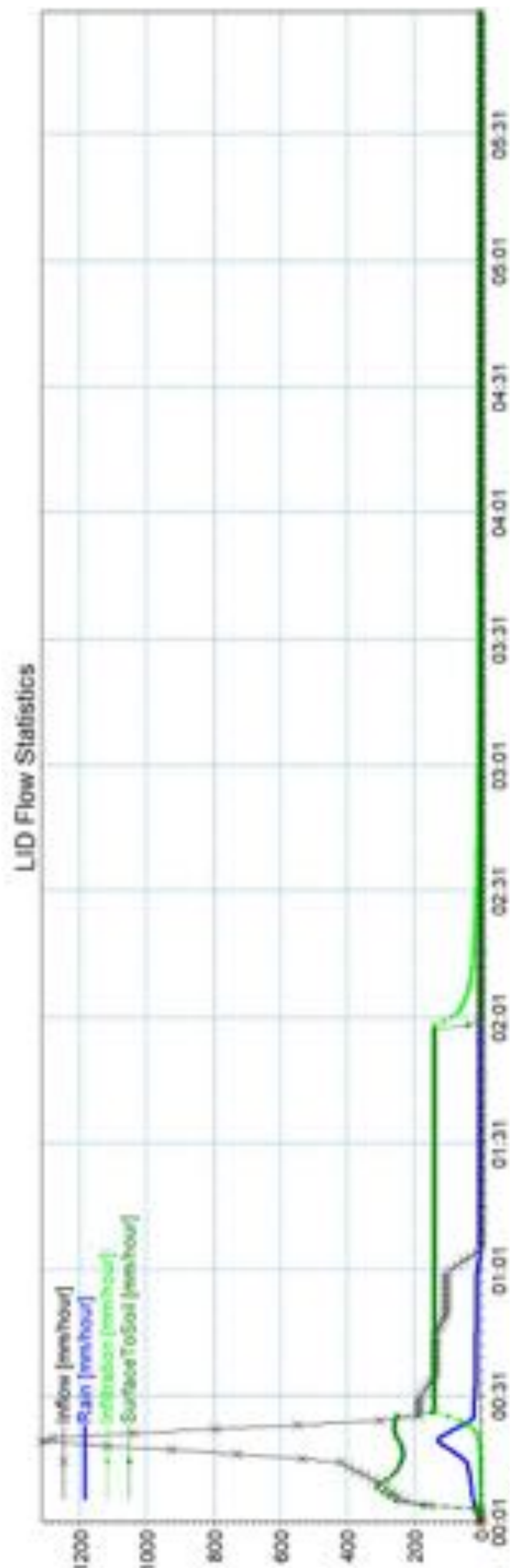
Attachment 8: Flow statistics for bio-retention cell using values specified under Comparison 3 (left) and for infiltration trench using values specified under Comparison 1





Attachment 9: Flow statistics for infiltration trench using values specified under Comparison 2 and 3 (left) and for rain garden using values specified under Comparison 1 (right)





Attachment 10: Flow statistics for rain garden using values specified under Comparison 2 (left) and Comparison 3 (right)

Curriculum Vitae

Personal Information

Date of birth	05.11.1992
City of birth	La Jolla, California
Nationality	Austria, USA (dual citizenship)
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Education

2015 – 2019	**Master of Science** Water Management and Environmental Engineering at the University of Natural Resources and Life Sciences, Vienna
10/2010 - 2015	**Bachelor of Science** Environment and Bio-resource Management at the University of Natural Resources and Life Sciences, Vienna. Bachelor thesis: Research on climate change and its impact on sea level rise- Who can afford it?
09/2007 - 06/2010	**High School Diploma (Matura)** Graduated with honors from the bilingual Gymnasium Draschestraße, Vienna 1230
1998 - 2007	Elementary and middle school in Encinitas, California, USA

Work Experience

09/2018	**Office of the Government of Lower Austria, Water Group – Water Management** Intern Contribution to the study on groundwater management in Sankt Pölten (Lower Traisental) through the analysis of data and digital visualization based on groundwater sensitivity and extraction measures
08/2017	**Office of the Government of Lower Austria, Water Group – Water Management** “Top Ten” intern Independent project on the recording and evaluation of hydro morphological remediation measures in Lower Austria - Statistical analysis and categorization of information - Presentation of possible digital visualization measures

08/2016	**Team Kernstock Ziviltechniker GmbH** Intern - Various tasks regarding the digital sewer and water supply register - Auditing of construction company invoices - Elaboration of a cost estimate for the construction of a municipal water supply system
07/2014 – 08/2015	**Therefore Corporation** Marketing Associate - Content creation - Translations - Assistance in event management
09/2013 - 02/2014	**University of Natural Resources and Life Sciences, Vienna** Student assistant in the Institute for Water management, Hydrology and Hydraulic Engineering - English translation and correction of the course notes “Uncertainties in Ecosystem Modeling” for Professor Dr. Karsten Schulz
10/2012 - 02/2013	**University of Natural Resources and Life Sciences, Vienna** Student assistant in the Institute for Water management, Hydrology and Hydraulic Engineering. - Composition of the course notes (booklet) for students - Translation and correction of existing course notes in close cooperation with Professor Dr. Cedomil Josip Jugovic - Delivery of the final lecture for the course “Hydraulic Engineering and Water Management” at the Institute for Water Management, Hydrology and Hydraulic Engineering

Qualifications

Languages	English:	Native
	German:	C2 - Proficient
	Spanish:	A2 – Intermediate
Software	Microsoft Office, iWorks:	Advanced
	AutoCAD:	Proficient
	GIS:	Advanced
	EPANET, EPA SWMM:	Intermediate
	MIKE URBAN:	Proficient
	BaSYS:	Basics
	R (Programming):	Basics
	Python (Programming):	Basics
	Wordpress:	Advanced
	Adobe InDesign / Illustrator	Advanced
Additional	Sindbad Hub-manager since 2019	

Affirmation

I certify, that the master thesis was written by me, not using sources and tools other than quoted and without use of any other illegitimate support.

Furthermore, I confirm that I have not submitted this master thesis either nationally or internationally in any form.

Vienna, May 7, 2019, Tessa Klimowicz