LOWERING THE PEAKS

Reducing pluvial flooding and sewer overflow pollution in a historical city center

Final MSc Thesis Report
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Abstract

Climate change leads to more extreme rainfall in The Netherlands, such as more frequent and more intense rainfall events. In some urban areas, like several Dutch historical city centers, this can lead to pluvial flooding and polluting combined sewer overflows. In this report, these challenges are investigated by research for design, and urban landscape design solutions are explored and applied on the basis of the urban acupuncture theory and the rhizomatic approach. The design is applied to the historical city center of Deventer, a city of 100.000 inhabitants in the East of The Netherlands.

A multitude of different rainwater interventions was investigated, and an applicable set of design guidelines is presented to accelerate future design projects dealing with similar challenges. Furthermore, the most vulnerable areas within the neighborhood are explored by investigating (1) the current sewer system, (2) surface water flows and accumulations during heavy rainfall events, and (3) existing pluvial flooding models. In the end, a site-specific landscape design dealing with pluvial flooding and polluting sewer overflows for the historical city center of Deventer is presented. The final design is a suggestion and a source of inspiration on how the threat of more regular pluvial flooding and combined sewer overflows can be addressed in a historical city center.

It was found that urban rainwater interventions make it possible to prevent pluvial flooding and reduce polluting sewer overflows during 1 in 10 year precipitation events in a historical Dutch city center. However, it should be questioned whether the implementation of the required intervention type and size is also desirable. Furthermore, this research and design shows that climate change adaptation should not just be seen as risk limitation, but can also be an opportunity for cities to become greener, healthier, more biodiverse and more pleasant living environments.

Keywords
Climate change, climate-adaptive design, urban design, historical city center, pluvial flooding, sewer overflows, rainwater interventions

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Preface

This report was made for a MSc thesis project for the Master study program of Landscape Architecture and Planning at Wageningen University and Research, The Netherlands. The objective of this thesis was to investigate how urban rainwater interventions could contribute to reducing pluvial flooding events and extreme drainage peaks within the historical city center of Deventer.

This report consists of:

- A research part, in which a range of urban rainwater interventions is investigated, information about the severity of the current and future pluvial flooding and combined sewer overflows is presented, and the vulnerability of specific sites to urban flooding is assessed.
- Design guidelines, in which the most important outcomes of the research part are presented in a brief summary which can be used to improve and accelerate future design processes in similar environments.
- A design part, in which the information from the research part and the design guidelines are applied to the most vulnerable areas of the city center of Deventer, and are elaborated for the most vulnerable area within the neighborhood.

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1 Introduction

The local newspaper of the Dutch city of Deventer and surroundings published four articles about urban flooding due to heavy rainfall last summer. Some of the titles read: *"A heatwave, thunderstorms and street canoeing: how bizarre weather in the August gripped the East of The Netherlands"* (Luchtenberg & Pol, 2020); and *"Once again a lot of flooding and storm damage due to severe weather"* (De Stentor, 2020). The Royal Dutch Meteorological Institute (KNMI) reports a higher intensity of precipitation and a higher frequency of extreme precipitation events as a result of climate change (KNMI, 2011). As the local newspaper articles indicate, the shift to more extreme weather is very much perceptible in cities in the East of The Netherlands like Deventer. This can lead to several problems in urban areas such as pluvial flooding (see figure 1). In this thesis, landscape design interventions which deal with pluvial flooding and related problems will be explored and implemented.

In 2014, the Intergovernmental Panel on Climate Change (IPCC) presented a report with 4 CO_2-emission scenarios (IPCC, 2014). In this report Representative Concentration Pathways (RCP's) for this century are modelled (figure 2). In the two most extreme scenarios, future emissions are predicted to keep increasing for the coming 50 years. In the two more moderate scenarios, future emissions are predicted to stabilize and to later even decrease. However, this does not mean that climate change will also be stopped, because future climate also depends on committed warming caused by past emissions (IPCC, 2014).

The driver in this research and design is climate change. The process of global warming causes a broad range of climate change effects (EEA, 2019). Urban areas, especially areas with many impermeable surfaces and low amounts of greenery, have a high sensitivity to climate change effects (Runhaar et al., 2012). One of the main issues in these urban areas caused by climate change is more regular pluvial flooding (Parker, 2010). Table 1 shows an increase in frequency of extreme precipitation events for all mentioned climate scenarios. Due to more frequent extreme precipitation events more regular pluvial flooding has occurred in many Dutch cities, and this will increase in the coming years (Van Hattum, 2020).

While some city dwellers might not be concerned about pluvial flooding or might see it as an extraordinary event, as seems to be the case for the people in figure 1, it can for some people be very troublesome or costly. Pluvial flooding can lead to nuisances, such as infrastructure congestion, and can lead to damage to public goods or personal belongings. A neighborhood type that is particularly affected by these issues are historical city centers (Keller et al., 2017). Besides that, these historical neighborhoods often have a combined sewer system, which can lead to an increase in polluting sewer overflows. Sewer overflow is a major cause of pollution to inland surface waters and the receiving coastal waters, which can lead to ecosystem damage (Semadeni-Davies et al., 2008).

Furthermore, since the challenge of pluvial flooding mainly occurs in areas with many impermeable surfaces and low amounts of greenery, it is often the social groups with the lowest prosperity that are most affected by this problem (De Haas, 2017). This is because green in a neighborhood is one of the major push-factors in urban environments, since greenery often increases the housing price in neighborhoods. Therefore, the social groups who have less money to spend often end up in neighborhoods which are vulnerable to pluvial flooding. Furthermore, it can be assumed that the negative consequences of pluvial flooding also have a bigger impact on the livelihoods of these people.

Figure 1: Flooded road in Deventer (Ten Cate, 2010)

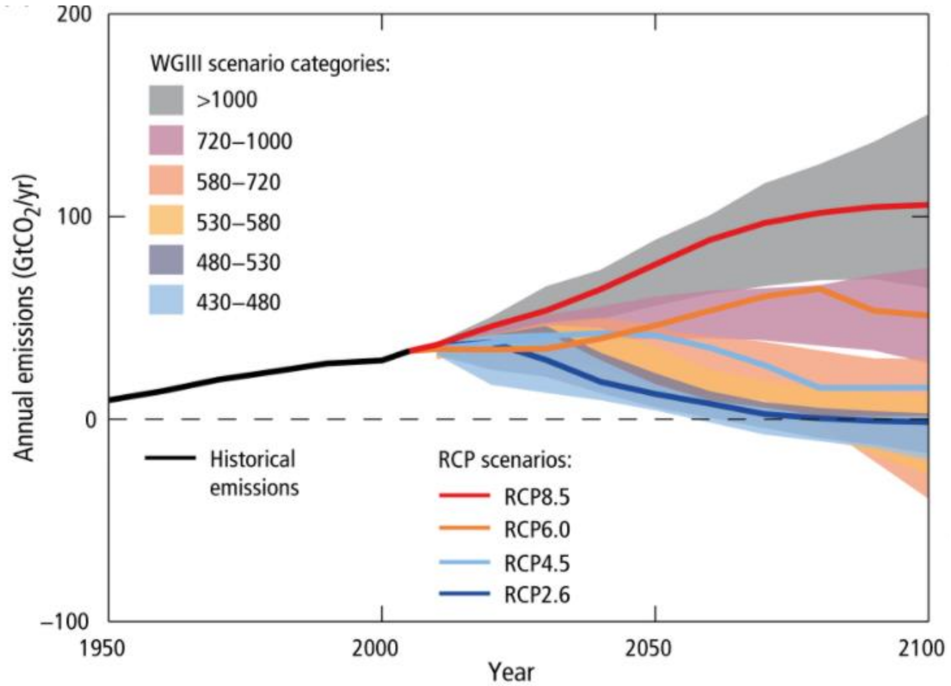
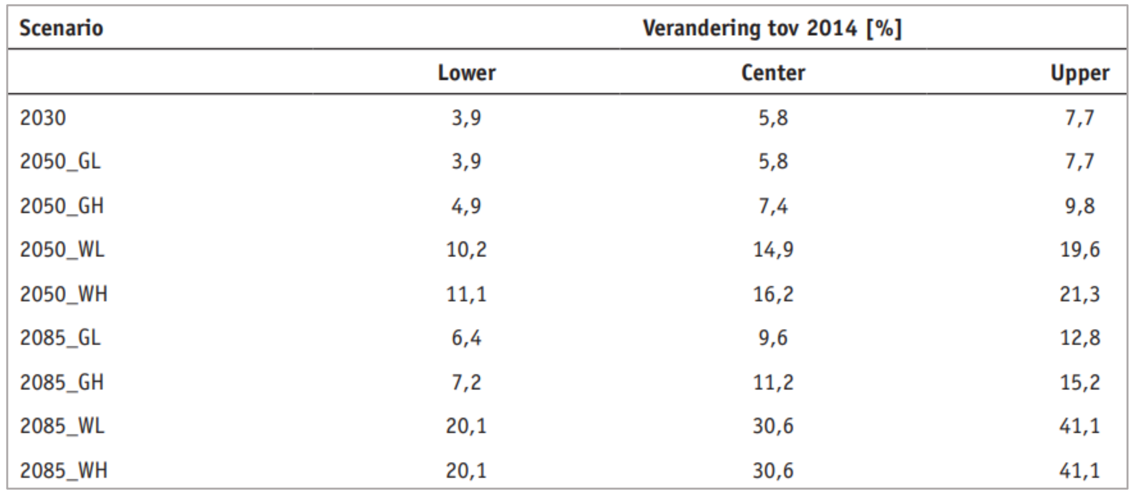


Figure 2: Four different pathways of annual emissions until the year 2100 (from: IPCC, 2014)



Scenario	Verandering tov 2014 [%]		
	Lower	Center	Upper
2030	3,9	5,8	7,7
2050_GL	3,9	5,8	7,7
2050_GH	4,9	7,4	9,8
2050_WL	10,2	14,9	19,6
2050_WH	11,1	16,2	21,3
2085_GL	6,4	9,6	12,8
2085_GH	7,2	11,2	15,2
2085_WL	20,1	30,6	41,1
2085_WH	20,1	30,6	41,1

Table 1: Change (% increase) in the frequency of extreme precipitation events for different climate scenarios relative to the year 2014 (KNMI, 2019)

The problems of pluvial flooding and combined sewer overflows can increase seriously when the frequency and intensity of precipitation increases in the future due to climate change (Van Hattum, 2020). The severity of these climate change effects will only increase in the future, causing a higher potential impact and vulnerability of the area. This relationship is shown in figure 3. The exposure in this figure is the degree to which the system is subject to climate impacts. The sensitivity in the figure is the degree to which the system is susceptible to climate impacts. The adaptive capacity is the ability of the system to cope with the impacts (Stein et al., 2014). The vulnerability is the degree to which the system is likely to experience harm due to climate impact. Based on these relationships, adaptive measures should be taken to counteract potential impacts, and therefore decrease the vulnerability of the area.

Urban pluvial flooding events have been studied extensively in the past. Consequently, various urban landscape adaptation or mitigation methods have been proposed to reduce this problem. However, many of these methods have a big impact on the appearance or the identity of the neighborhood, which makes them not suitable for the dense urban tissue of most historical neighborhoods. Historical city centers require subtle and fitting, yet efficient interventions to reduce rainwater runoff peaks. Currently, little research has been done on this specific theme. Furthermore, much research has been done on the polluting properties of combined sewer system overflows and on minimizing pollution at the end of the system. However, I will look at the beginning of the sewer system in order to reduce drainage peaks and prevent these sewer overflows. Very little research has been done on this approach.

The research and design area of this thesis will be the historical city center of Deventer. Deventer is a city with approximately 100.000 inhabitants. It is located in the East of The Netherlands in the province of Overijssel, close to the province of Gelderland (see figure 4). Deventer is at least 1250 years old, which makes it the fourth oldest city of The Netherlands (Moleveld, 2018). The city center is the oldest part of the city (see figure 5a and 5b).

This location was chosen since the challenges of pluvial flooding and polluting combined sewer overflows are both present here (Municipality of Deventer, 2019). Another reason for this decision was due to the fact that Deventer has a unique historical city center, which means the identity and historical value of this neighborhood should be protected and preserved while dealing with these problems.

While fluvial flooding or river flooding is also a common phenomenon at the river edge of the historical city center of Deventer, this type of flooding will not be investigated in this report. This is because many measures have already been taken to reduce fluvial flooding in Deventer, including the national Room for the River project. Furthermore, applying design measures to reduce fluvial flooding would require interventions of entire different dimensions and variations.

The motive of this thesis is to:

1. Reduce future risk of pluvial flooding events in the city center of Deventer to the current risk level, in order to prevent an increased amount of negative social and financial impacts due to urban flooding.
2. Prevent future pluvial flooding events up to rainstorms currently categorized as 1 in 10 years, in order to prevent negative social and financial impacts of urban flooding.
3. Reduce the risk of future pluvial drainage peaks in the city center of Deventer to the current risk level, in order to prevent an increased frequency of polluting sewer overflows into surface waters.

In order to reach this goal, the functionality and efficiency of different design interventions should be carefully assessed. Furthermore, the design interventions should be fitted carefully into the dense urban tissue of the historical urban landscape.

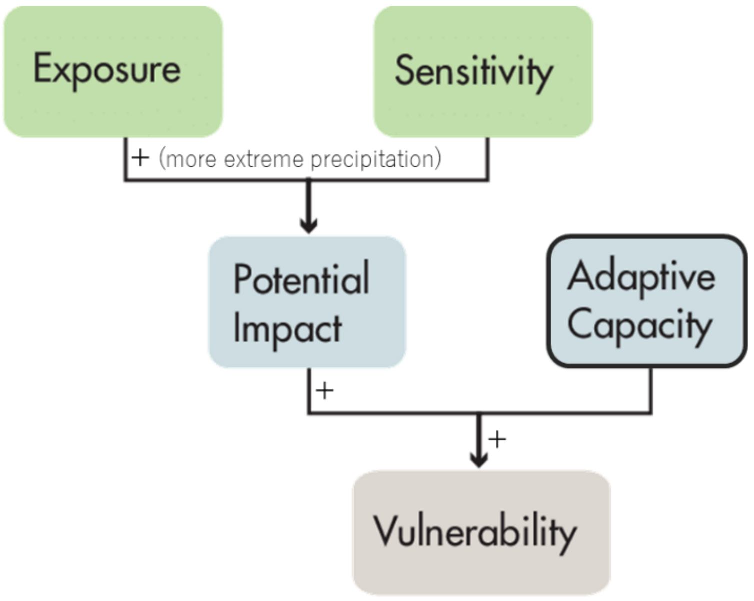


Figure 3: Relationship between the components of climate change vulnerability (Adapted from: Stein et al., 2014)

Figure 4: The city of Deventer within The Netherlands (image made by author)

Figure 5a and 5b: The historical city center of Deventer in 1649 and 2020 (Van Loon, 1649; OpenStreetMap, 2020)

1.1 Thesis framework

Thesis statement

Urban landscape design interventions can be used to reduce the detrimental urban climate change effects of pluvial flooding events and extreme drainage peaks within a historical city center, in particular the city center of Deventer.

Objectives

The main objective of this thesis is to:

Identify and apply the most appropriate urban landscape design interventions which contribute to reducing pluvial flooding events and extreme drainage peaks within the historical city center of Deventer.

Sub-objectives of this thesis are to:

Explore the range of urban landscape design interventions which help to reduce pluvial flooding events and extreme drainage peaks

Create design guidelines for appropriate urban landscape design interventions to reduce pluvial flooding events and extreme drainage peaks in similar cities in the East of the Netherlands or in similar environments.

Design question

How can urban landscape design interventions be implemented in the historical city center of Deventer, in order to reduce both pluvial flooding events and extreme drainage peaks causing polluting sewer overflows?

Research questions

The main research question of this thesis is:

How can urban landscape design in the historical city center of Deventer help to reduce both pluvial flooding events and extreme drainage peaks?

The sub-research questions of this thesis are:

SRQ1: What urban landscape interventions can be used to reduce pluvial flooding events and extreme drainage peaks?

SRQ2: What are the effects of different urban landscape interventions on the reduction of pluvial flooding events and extreme drainage peaks?

SRQ3: Which places within the city center of Deventer are most prone to pluvial flooding events and extreme drainage peaks?

The relationships between these different components of the research and design framework are shown in figure 6.

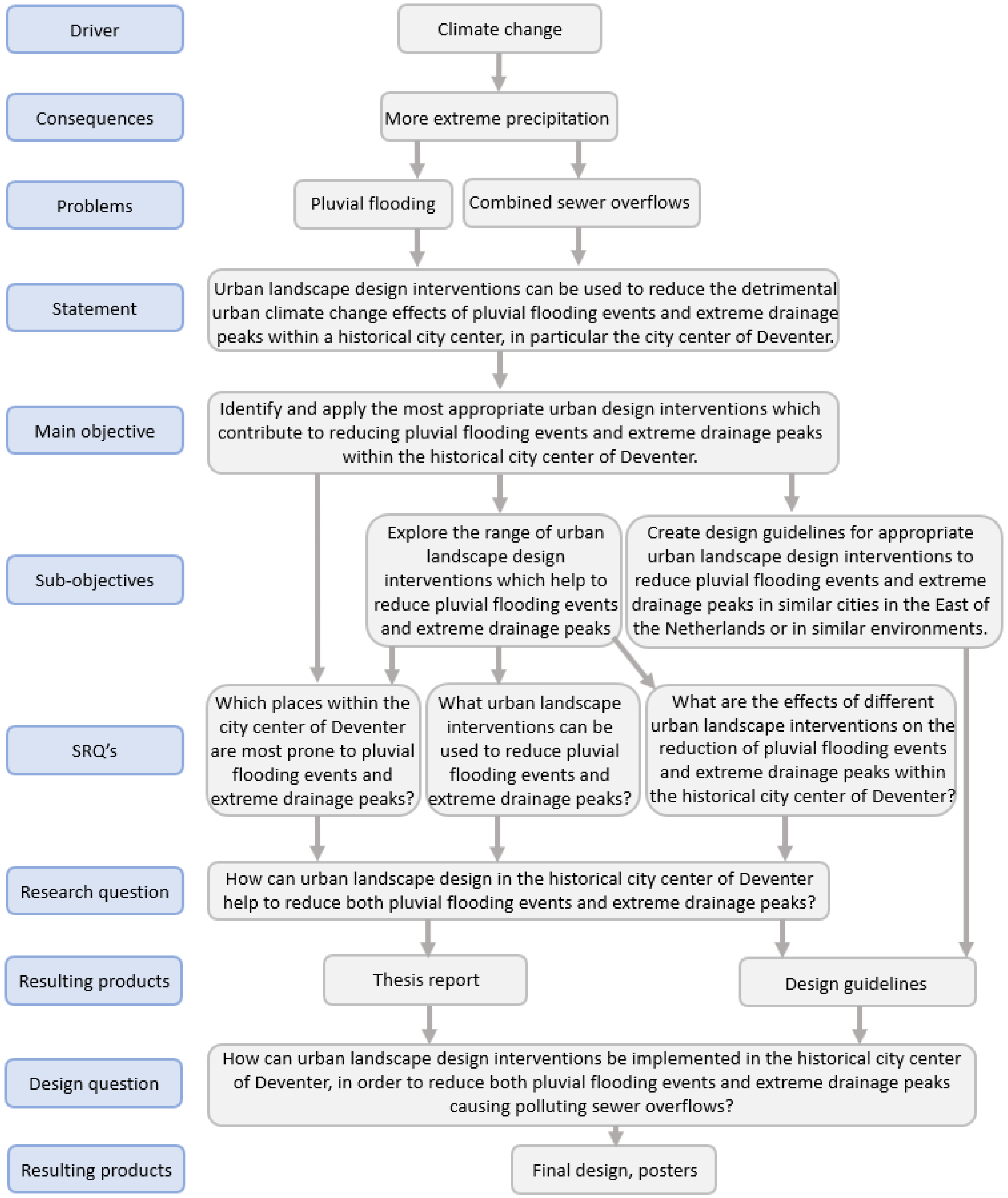


Figure 6: Flowchart of the employed research framework (Figure made by author)

1.2 Key concepts

1.2.1 Pluvial flooding

Pluvial flooding occurs due to extreme precipitation (DHI, 2020). This can happen when the ground cannot effectively absorb the water and when the sewer systems maximum capacity is reached. In many cases the floods are not very deep, but they can cause a lot of damage and inconvenience.

1.2.2 Polluting combined sewer overflows

Combined sewer systems are sewer systems in which both household wastewater and precipitation are transported via one main pipe (see figure 7). In dry weather only household wastewater is drained towards sewage treatment plants via this pipe. If heavy rainfall occurs and the maximum capacity of the system is reached, the rainwater mixed with household wastewater will overflow into surface waters. This often leads to the pollution of surface waters. The pollutants which are often found in these combined sewer overflows include heavy metals, pesticides and other inorganic chemicals (Brombach et al, 2005; Ianuzzi, 1997).

1.3 Theoretical framework

1.3.1 Urban acupuncture

In this research and design process I will make use of the urban acupuncture approach. Urban acupuncture is an urban design method which strategically locates interventions in a city or neighborhood (Houghton et al., 2015). By making use of relatively small-scale interventions in strategically chosen places, the positive effects will revitalize the design sites and the surrounding areas (Lerner, 2014; Hoogduyn, 2014). The intervention will lead to a positive "energy flow" leading to following developments in the neighborhood, for example more green in the neighborhood, a more pleasant microclimate or the attraction of tourists.

1.3.2 Research for design

There are 3 general variations in types of interactions between research and design (Lenzholzer et al., 2013):
- Research *on* design; research is conducted on a finished design in order to inform future designs.
- Research *through* design; the practice of designing is employed as a research method.
- Research *for* design; this aims at improving the quality and reliability of a design by using theoretical evidence.

The main method I will use in this research and design is research on design, also often called evidence-based design. The design will be based on systematic knowledge from empirical research, which will help to make well-informed decisions in the design (Deming & Swaffield, 2011).

1.3.3 Rhizomatic approach

The concept of the rhizome was developed by Deleuze and Guattari (1987), and means that multiple, non-hierarchical entry and exit points are used. In most sewer systems, individual failures at one point can lead to the failure or breakdown of a large part of the system (Seyoum, 2015). The rhizomatic approach is based on the idea that rainwater can spread towards available spaces or trickle downwards to new spaces (Deleuze & Guattari, 1987). This means that if a failure occurs at one point in the system, new ways are found which keeps the system intact.

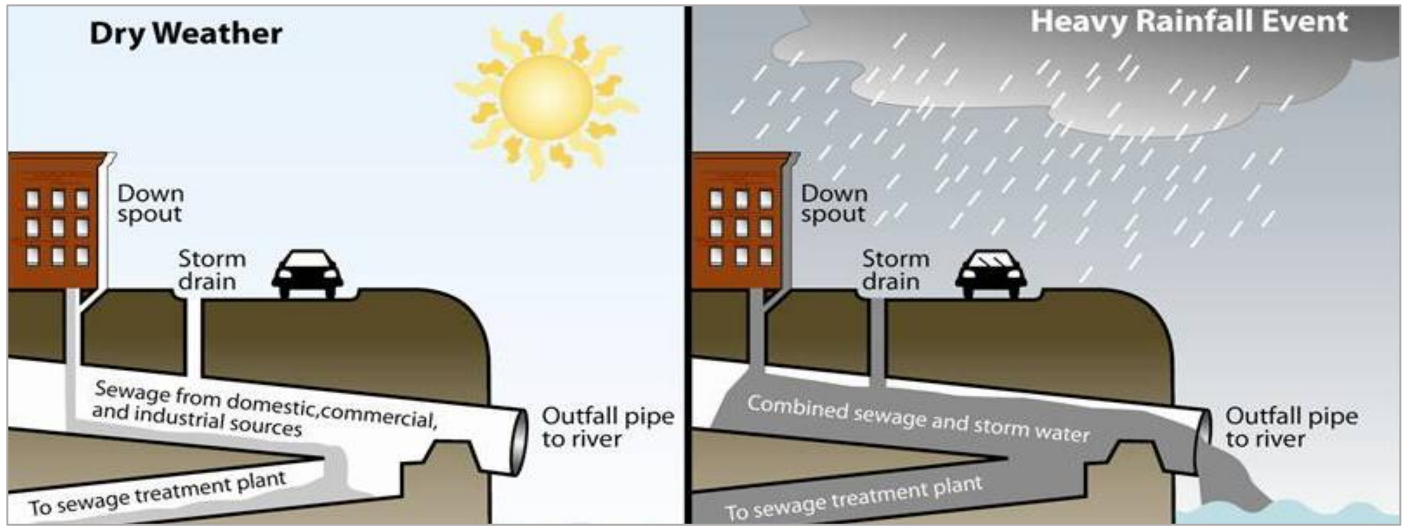


Figure 7: Combined sewers in dry and very wet weather (City of Akron, 2020)

1.4 Methods and materials

1.4.1 Methodology

The thesis process will initially require a lot of research and little designing, and this division will gradually shift during the process towards less research and more designing. This has been represented in a sketch of Sven Ingvar Andersson (figure 8). The sketch shows the design process as a line circling around the apex, which is the final solution. The stripes represent research or facts involved in the process, and the dots represent the sketching and designing. The flower represents the final design resulting from the process.

However, this does not mean the research and design process is a one-way process. It is a complex process which requires multiple iterations. This is shown in figure 9. The main reason for this is that research and design are no standalone elements but interact with each other.

Furthermore, design guidelines will be used as a key link between research and design. Design guidelines are used to translate the research into recommendations for the actual design (Van den Brink et al., 2016). This will be explained more extensively in chapter 1.5.1.

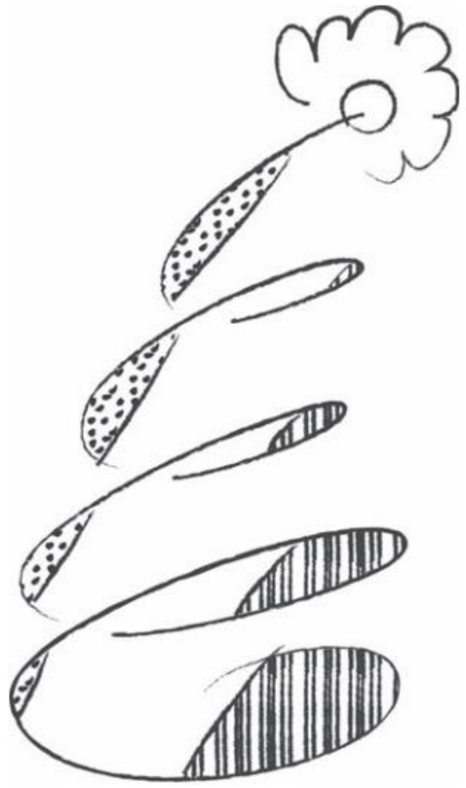


Figure 8: Sketch of the design process by Sven Ingvar Andersson. (Andersson, 1994).

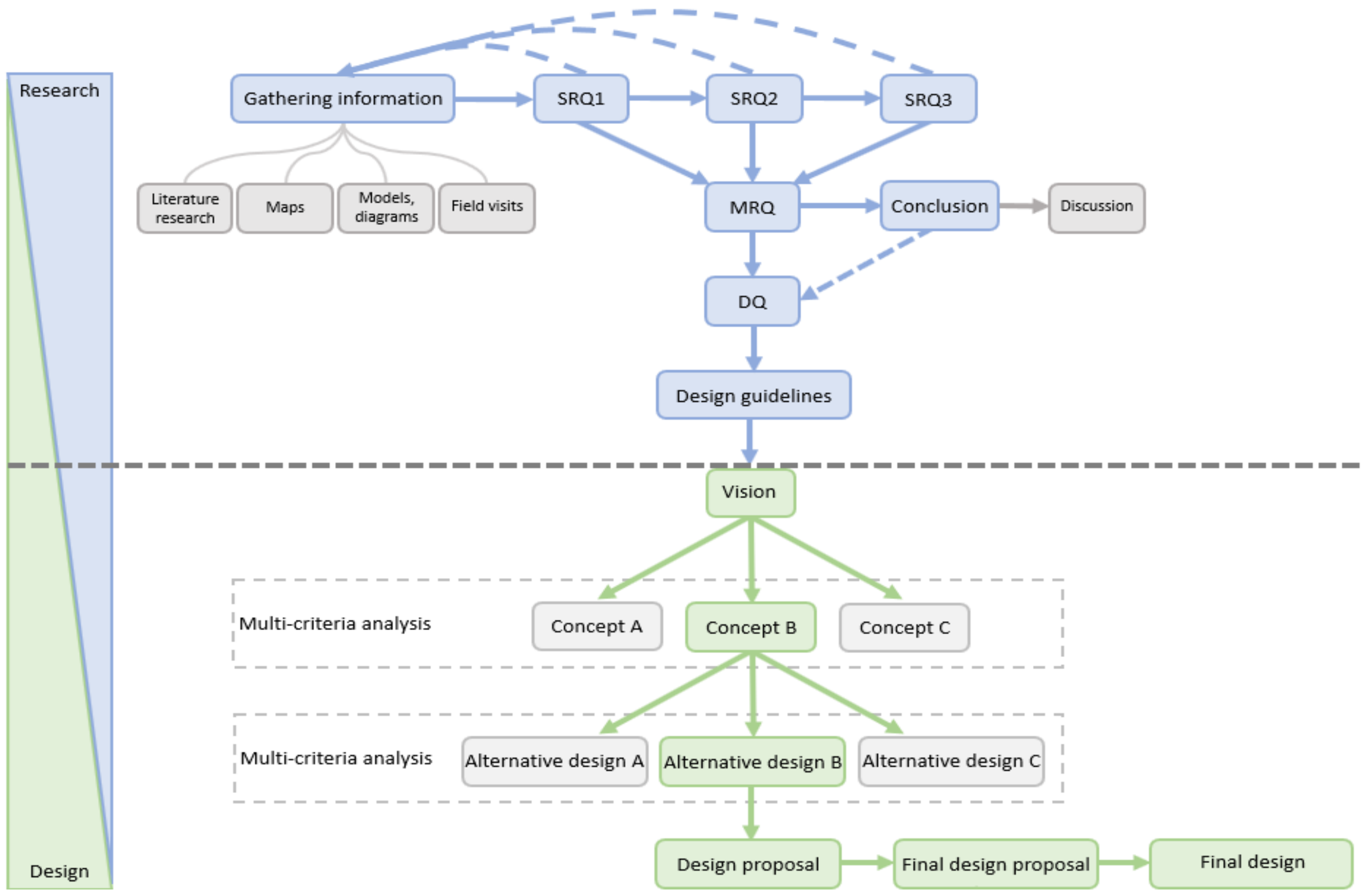


Figure 9: Flowchart of the research and design methodology (Figure made by author)

1.4.2 Materials

In order to initiate the evidence-based design it is essential to collect relevant information. This will be done by:

Material	**Type of data**
Literature research	This can help to find out information about examples of design interventions and their effects, and about new or experimental ways to reduce pluvial flooding and combined sewer overflows.
Maps	Maps should be studied in order to find out what the most problematic areas are within the city center of Deventer, and what design interventions are possible in which specific places.
Existing models, figures and diagrams	These should be used in order to get an understanding of the complex drainage system and to comprehend the effects different climate scenarios. They can also give an indication of the needed capacity of the future drainage system by predicting the amount of household wastewater and frequency and severity of extreme precipitation events.
Field visits	Pictures and sketches of specific sites which are important for the research and design.
Design and visualization software	Digital programs such as Adobe Illustrator and Photoshop which can help to communicate and illustrate the design.

Table 2: research and design materials and the expected type of acquired data (table made by author)

In the end, a final presentation, 3 A1/A0 posters, and a final report including a main masterplan accompanied by a vision, concept, several detailed designs, relevant sections and visualizations will be delivered.

1.5 Use of design guidelines and design proposals

1.5.1 Design guidelines

An important step from the research to design are the design guidelines. According to Van den Brink et al. (2016) the design guidelines serve two main purposes:

- Suggesting a specific direction for the design, by excluding many alternative less suitable directions.
- Offering transferable knowledge which works beyond this specific situation to a broader set of cases. This can only be done if the guidelines are abstractions which can be applied in similar situations.

Furthermore, the design guidelines also serve another purpose outside of this thesis, which is the improvement and acceleration of future design processes (Van den Brink et al., 2016). Creating an applicable set of guidelines provides a useful foundation for future urban landscape design projects dealing with similar problems.

1.5.2 Development of design proposals

Multiple design proposals will be used to transform the acquired knowledge from the research and the design guidelines into a site-specific final design. The design proposals will have iterations to allow improvements to be made and alternative solutions to be explored. The design proposals will be assessed by experts on both urban landscape design and environmental technology and infrastructure.

1.5.3 Significance

An important contribution to the field of landscape architecture are the design guidelines, which can be used in projects dealing with similar challenges. The simplicity of the guidelines will also make it possible for non-experts, like policy-makers or the public, to get an insight in what can be done to reduce climate change related problems in historical urban areas.

Moreover, the final design will have positive properties for the city center of Deventer, which will only become of greater value in the future when the current problems will increase. The frequency of pluvial flooding will be lowered, decreasing financial and social problems due to flooding. Moreover, polluting sewer overflows will be prevented, improving the ecological quality of surface waters. The final design can be an important inspiration for policy makers of the city of Deventer. The final design is no fixed masterplan which cannot be altered; it functions as an advice or example for policy makers and landscape architects on how this complex problem can be tackled.

2 Exploring rainwater interventions

What urban landscape interventions can be used to reduce pluvial flooding events and extreme drainage peaks?

2.1 Urban greenery interventions

2.1.1 Use of vegetation

Every living plant contributes to absorbing and storing water (Silva, 2019). This contributes to the adaptation of pluvial floods. Furthermore, vegetation needs permeable surface to grow, which means the soil can absorb more rainwater as opposed to paved surfaces. Urban pluvial flooding adaptation strategies using vegetation as main adaptation method are called “nature-based solutions” (Huang et al., 2020). Nature-based solutions are particularly effective against pluvial flooding caused by high-frequency precipitation events, and also have additional ecological and social benefits. However, they are less effective against pluvial flooding caused by extreme precipitation events over a short period, since the soil and vegetation need time to absorb large quantities of water.

2.1.2 Green walls

Green walls are vertical surfaces with a layer of greenery on the outside (Manso & Castro-Gomez, 2015). The vegetation can grow on, in or next to the wall of a structure (see figure 10). They are often applied on blind façades, but can be applied on many types of walls (Silva, 2019). Green walls most effectively absorb water during low-intensity showers and over longer periods. Some types of green walls also include water detention, which improves the water storing capacities of green walls during high-intensity precipitation. Other advantages of green walls are their aesthetical and sometimes even iconic quality and the improvement of insulation. However, green walls do need a lot of maintenance, both for the drainage system as well as the pruning of the vegetation (Manso & Castro-Gomez, 2015). This leads to relatively high maintenance costs.

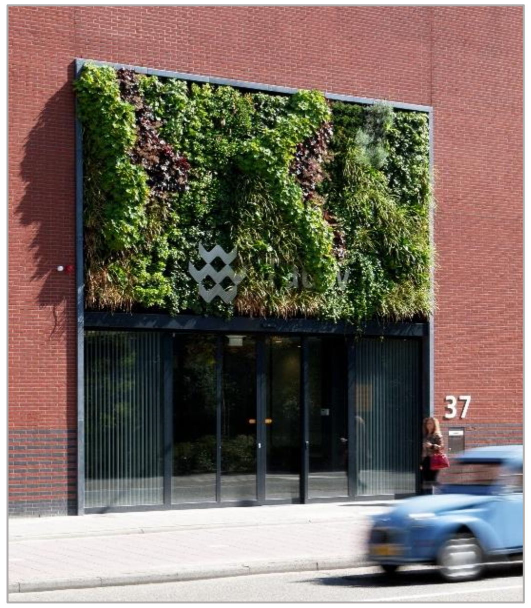


Figure 10: Green wall at the Tauw building in Deventer (Greenfortune, n.d.)

2.1.3 Green roofs

Green roofs are rooftops covered by vegetation (Silva, 2019). Green roofs range from roofs of extensive use, which have a thin bedding and few but very succulent plants (see figure 11), to roofs of intensive use, which generally have a thick soil layer for deep-rooted plants. A portion of the rainwater is absorbed by the plants on the green roofs. The rest of the rainwater is filtered by the green roof and transported. Because of this, green roofs can effectively slow down water especially during high-frequency precipitation, and to a lesser extend during high-intensity precipitation (Ercolani et al., 2018). On a small scale, green roofs have limited effects. However, on a large scale, green roofs have many benefits next to water detention and the reduction of runoff. Green roofs contribute to the reduction of the urban heat island effect (Susca et al., 2011). Furthermore, they can significantly improve the acoustic and thermal insulation of buildings, reducing energy use both in the summer and winter season.

Figure 11: Green roofs at the Havenkwartier neighborhood in Deventer (Deventer stroomt, 2020)

2.2 Bioretention interventions

2.2.1 Bioretention basins

Bioretention basins are excavated parts of the landscape where rainwater is collected and infiltrated (Silva, 2019). If necessary, the infiltrated rainwater can be collected in the main sewer system network. The processes of rainwater retention, evapotranspiration and infiltration are present in these basins. Bioretention basins often consist of a stone granulate layer or gravel layer to improve infiltration and pollutant removal. Bioretention basins can catch multiple pollutants, such as nitrogen, phosphorus and heavy metals (Lucke & Nichols, 2015). The vegetation in bioretention basins should be mostly riparian and can range in size from grasses to trees (Silva, 2019). Bioretention basins are particularly effective in reducing high-intensity precipitation runoff, relieving stress from the sewer system. Bioretention basins work most effectively if there are surface water flows towards the basin. There are two main types of bioretention basins: wet bioretention basins and dry bioretention basins. Wet bioretention basins can also be used as water source for irrigation or firefighting, while dry bioretention basins can be used as submergible park, marketplace or playing field. Dry bioretention basins should not be placed in areas with high groundwater levels, since this would slow down the infiltration and can lead to a shallow layer of surface water, which can lead to mosquito breeding. A Disadvantage of bioretention basins is that overflow measures should be implemented in urban spaces. Moreover, maintenance is needed especially in the initial years, in order to prevent clogging and trash accumulation.

2.2.2 Bioretention planters


Figure 12: Bioretention planter in San Francisco (Madroño Landscape Design Studio, 2017)

Bioretention planters are essentially small bioretention basins, sequentially placed along streets. These planters can consist of multiple grass, shrub and small tree species, and are bounded by a curb (Silva, 2019). Using multiple layers, for example of soil, compost, water-treatment residuals, sand or gravel layers with different porosities, can improve infiltration and the catchment of pollutants (Poor et al., 2019). Bioretention planters are used to store and gradually infiltrate water (Silva, 2019). Because of this, bioretention planters are most efficient when they are combined with water transporting measures, like green roofs or bioswales. Furthermore, bioretention basins work best when there are surface water flows to the planters, so some type of relief can often improve the efficiency of bioretention planters. Moreover, sedimentary traps can be used to prevent clogging of the planters. Advantages of bioretention planters are that they need relatively small spaces, and can be implemented in a lot of different spaces, such as within sidewalks, park boundaries and road seperators (see figure 12). However, bioretention planters should be placed at least 3 meters from building to prevent the infiltrated water to affect building foundations (State of Delaware, 2016).

2.2.3 Bioswales


Figure 13: Bioswale transporting runoff after a rainstorm in Michigan, USA (Watershed council, 2019)

Bioswales are channels that collect, infiltrate and transport rainwater (MMSD, 2020). They are often shallow and consist of grasses and sometimes small bushes (see figure 13) (Silva, 2019). Advantages of bioswales are that they are very effective in catching runoff during high-intensity precipitation events (Xiao & McPherson, 2011). Furthermore, they can be easily retrofitted in existing urban areas in parking lots or along streets (Silva, 2019). They can also be used as physical boundaries or to enhance the aesthetic value of urban areas. Bioswales mainly transport water, which means the infiltration capacities and therefore also the pollution removal capacities of bioswales are limited. Other disadvantages of bioswales are that they are not suitable for areas with extreme rainwater drainage volumes and velocities, because erosion can significantly damage the bioswale system. Furthermore, bioswales should not be implemented too close to buildings in order to prevent building foundation damage due to moisture.

2.2.4 Rain gardens

Rain gardens are gardens located in small depressions, and are designed to temporarily hold and infiltrate rainwater (Dietz & Clausen, 2005). They imitate the natural rainwater absorption of meadows or forests (Silva, 2019). The size of rain gardens vary, but are generally bigger then bioretention planters and smaller than bioretention basins. They often consist of multiple vegetation species, such as grasses, flowers, perennials, bushes and small trees. Generally, a layer of gravel or other porous material is added in the lowest areas of the garden to improve infiltration. This can improve the biodiversity of urban areas. Another advantage of rain gardens is that maintenance is limited, especially after the first year (The Groundwater Foundation, 2020). The rain garden can be connected to a cistern or to the sewer system, which can improve the infiltration speed. However, this can also lead to stress on the system and to lower pollutant removal levels (Dietz & Clausen, 2005).

2.3 Infiltration interventions

2.3.1 Penetrable pavements


Figure 14a, 14b and 14c: Porous, open cell, and interlocking pavements (From: Silva, 2019)

Penetrable pavement are pervious surfaces that allow water to infiltrate through the surface and be absorbed by the underlying soil (Silva, 2019). These pavements reduce the surface runoff during precipitation events (Ferguson, 2005). Penetrable pavements should only be implemented if the soil has high infiltration rates. Furthermore, the robustness of the pavement should be considered by looking at the weight and frequency of traffic, in order to prevent compression of the permeable layers (Silva, 2019). There are 3 general types of penetrable pavements: porous pavement, open cell pavement and interlocking pavement (see figure 14a to c). Porous pavements have voids in their composition, open cell pavement units have one or multiple voids in their form, and interlocking pavements have voids between the pavement units.

2.3.2 Retention crates

Stormwater retention crates are modular stackable crates that can be placed below penetrable surfaces in areas vulnerable to pluvial flooding (Brettmartin, 2020). The crates create an underground void which fills up with water that has seeped through the surface. The crates act as a retention tank during heavy rainfall events, and the water can infiltrate in the sub-soil after the precipitation event. Retention crates can also be used in combination with waterproof geotextile or piping in order to transport the water. It is important to take into account that these crates have a maximum load, and therefore cannot be placed below roads (MacLean et al., 2020).

2.3.3 Infiltration trenches


Figure 15: Infiltration trench between two roads in Georgia, USA (Georgia planning, n.d.)

Infiltration trenches are longitudinal strips located next to roads or sidewalks (Silva, 2019). They redirect run-off water from the surface to the sub-surface (Chahar et al., 2012). They are characterized as long but narrow and shallow depressions. They usually consist of a gravel layer which improves infiltration (see figure 15) (Silva, 2019). This layer is surrounded by a geotextile fabric which allows water to seep through into the soil below. An advantage of this intervention is that a relatively small space is required to implement this. A disadvantage is that the trench may fill up fast and that the water needs time to infiltrate into the sub-soil.

2.4 Reservoir interventions

2.4.1 Artificial detention basins

An artificial detention basin is a depression in the landscape used to store and slowly drain water off-site, which means they release stress from the sewer systems at extreme precipitation events (Burton, 1980). They are usually located in low places in the landscape, to allow gravity-driven water flows to transport water to the basin. Generally the water for these basins is transported by separated sewer systems. The difference with bioretention basins is that the water does not infiltrate the sub-soil but keeps on slowly flowing to other sites (Silva, 2019). Therefore, artificial detention are more suitable to implement in places with a high groundwater table or where water cannot sufficiently infiltrate into the soil. Water basins should always incorporate water-dynamics features like fountains or cascades in order to prevent the water from being stagnant, since stagnant water can become a risk to human health (Nascimento et al., 1999; Silva, 2019). Artificial basins can also be implemented underground, which reduces the use of public space. However, they are often large in size, making it difficult to these implement underground basins in dense urban tissues.

On the household level you could also place rain barrels within this artificial detention basin category (Li & Lam, 2015). The water that is collected from the roof gutters is collected in the rain barrel, and this collected water is generally used for irrigation in periods of low precipitation.

2.4.2 Water plazas

Water plazas are low-lying squares within urban areas which can be submerged during extreme precipitation events (see figure 16) (Johansson, 2019). Since this measure does not create any unusable public spaces, this measure can be easily implemented in dense urban areas. Generally the water for these basins is transported by separated sewer systems or from other drainage measures such as green roofs, green walls, bioswales and rain gardens (Silva, 2019). During dry periods, the squares can have multiple functions, such as amphitheaters, playground or space for fairs. A disadvantage of this measure is that water plazas do not include filtration, which means the present pollutants will remain in the water and can be deposited on the square. Therefore, cleaning of the square is needed every time the square is filled with water.

Figure 16: Water plaza used as playing court during dry periods in Rotterdam, The Netherlands (Bravo,

2.5 Surface drainage interventions

2.5.1 Street channels

Street channels are open drainage systems in a street that are generally complementary to underground sewer systems (Bennett & Mays, 1985). These channels should not receive potentially polluted water, since this can be a threat to human health. They can however receive rainwater, for example water that was been intercepted by other measures, or water that has already been treated (Silva, 2019). Since this measure is clearly visible and offers the opportunity to be part of it, street channels can also change the perception of people, creating awareness for extreme precipitation events and stormwater transport systems. This effect can be increased by adding features like stepping stones, bridges, filters, cascades, waterfalls or pools. These channels can have different shapes, such as narrow lines, narrow square channels or wide shallow meandering channels (see figure 17a to c). While there are many design possibilities for these street channels, the channel should have a sufficiently steep sloping gradient in order for the water to keep flowing. Open street channels do not require a lot of space, which means they can also be used in compacted urban areas. This measure has been used regularly in historical times, and is therefore also be very suitable in many types of historical neighborhoods.

Figure 17a, 17b and 17c: Differently shaped open street drainage channels (City & County of San Francisco, 2015; Atelier GroenBlauw, 2020)

2.5.2 Extended/enlarged waterways

Extended or enlarged natural or artificial waterways can help to drain large volumes of stormwater into existing surface waters, and thereby alleviating stress from the current sewer system and preventing potential pluvial floods (Silva, 2019). This intervention can be very effective at reducing pluvial flooding due to extreme precipitation events. This is why this measure is also often used in Southern Asia, where often water logging problems occur during the monsoon season (Ahmed et al., 2015). However, extending or enlarging waterways is a very drastic and space-consuming measure, which makes this measure generally not suitable for many dense urban areas.

2.5.3 Surface flow barriers

Surface flow barriers are measures that slow down the velocity or entirely stop surface water flows, in order to counteract erosion or to protect certain sites from flooding. Examples of this measure are dikes, raised pathways or buildings, dams, and check dams. Check dams can be implemented in stormwater transporting channels (see figure 18) (Silva, 2019). Check dams reduce the velocity of the water in the channel, which reduces erosion and promotes sedimentation behind these dams. Because of this water can more effectively infiltrate into the soil. In order to prevent mosquito breeding and to promote purification of the water, the appropriate vegetation should be planted behind these dams.

Figure 18: Check dams in a stormwater swale in Chesapeake, Virginia, USA (Chesapeake stormwater network, 2014)

3 Intervention effectiveness

What are the effects of different urban landscape interventions on the reduction of pluvial flooding events and extreme drainage peaks?

3.1 Intervention types

Looking at all the intervention options of last chapter, it is still difficult to decide what is the best measure at a specific site and situation. In order to simplify this decision, all interventions were put into a model in which the required slope and the effectiveness against rainfall event types are determined for each individual measure and weighed against the other measures (see figure 19). This creates a model in which three clear groups can be distinguished:

1. <u>High-frequency rainfall measures</u>: Use of vegetation, green walls, green roofs and bioretention planters. These measures are most effective against high-frequency rainfall, and not so much against high-intensity rainfall. They are mostly rainwater storage or infiltration measures, but can also be the beginning of the rainwater transport system, as is the case for green walls and green roofs.

2. <u>High-intensity rainfall measures</u>: Bioretention basins, rain gardens, penetrable pavements, artificial detention basins, water plazas and extended/enlarged waterways. These measures are very effective against situations in which high quantities of rainfall have to be drained in a short amount of time. In most cases these measures are quite radical and large, but can store or infiltrate large quantities of water when it is needed.

3. <u>Stormwater transportation measures</u>: Bioswales, infiltration trenches, street channels and surface flow barriers. These measures do not exclusively store or infiltrate rainwater, their function is primarily to transport rainwater to places where the rainwater can be infiltrated, stored or transported further. They are most effective at high-intensity precipitation events, since large quantities of water have to be transported from vulnerable places in these situations. These measures do need a sufficient slope to function, since otherwise the water will not be transported by gravity and will stagnate in undesirable places.

For these 3 stormwater drainage measure groups, the effectiveness of the interventions will be determined. Furthermore, other important factors, such as costs, water quality and public awareness, will be taken into account in the multi-criteria analysis.

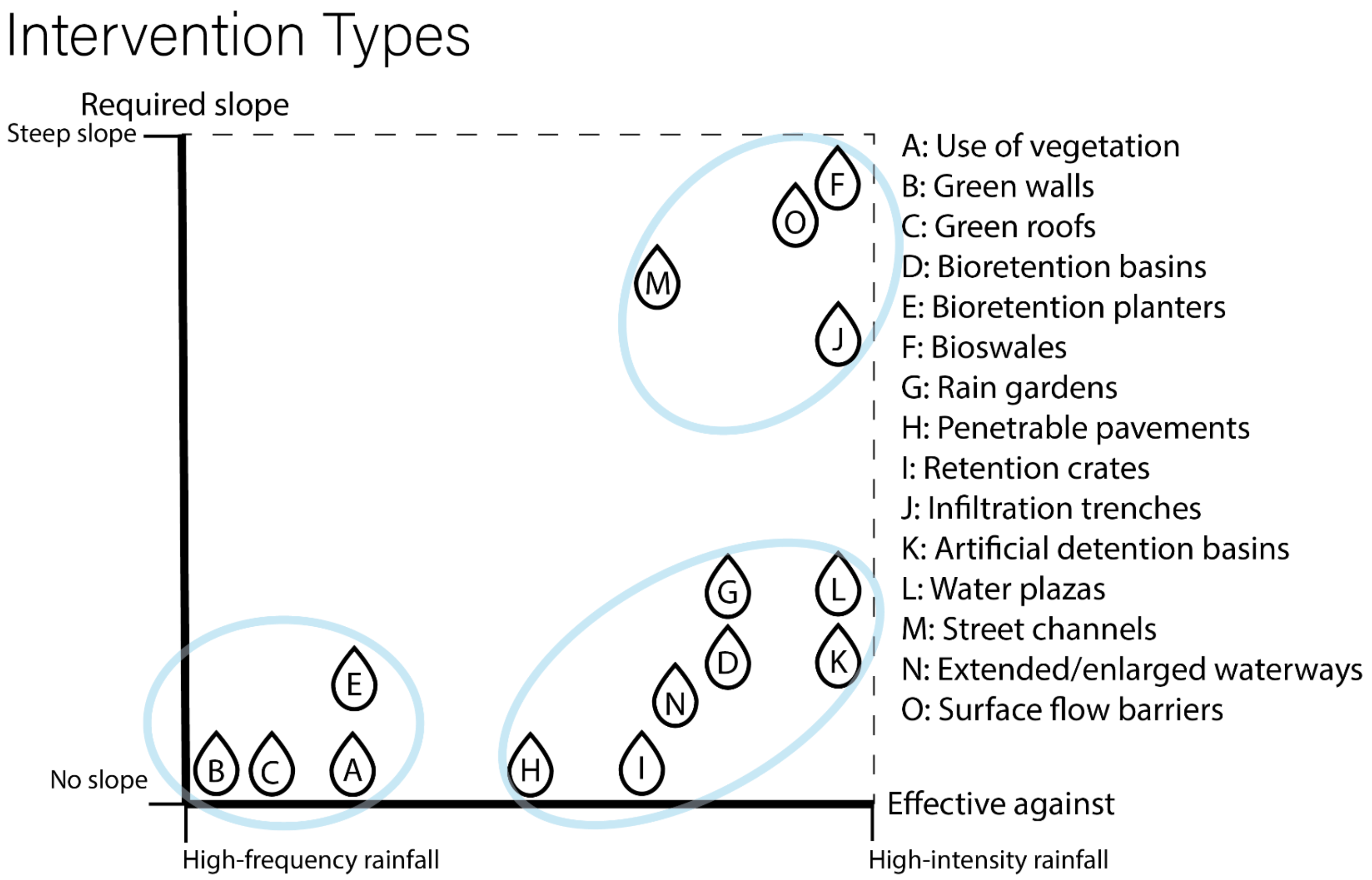


Figure 19: Stormwater drainage intervention types classified into multiple categories (figure made by author)

3.2 High-frequency rainfall measure effectiveness

For high-frequency rainfall measure effectiveness, important factors to take into account are the average retention capacity (in % of the total rainfall) of a certain amount of rainfall in a specific amount of time. The rainfall event that was used in this research to compare the effectiveness of high-frequency rainfall interventions is 10mm precipitation in one hour. This value was chosen for this section, since this value was of frequent occurrence in the examined literature, which made it possible to accurately compare the effectiveness of different intervention types.

3.2.1 Effectiveness of vegetation

The infiltration capacity of soils and the water-absorbing capacity of plants depends highly on climate, the type of soil and type of soil coverage (Thompson et al., 2010). The soil along the river IJssel is lightly loamy, geologically categorized as river clay on river sand (Technical University Delft, 2020). On the higher parts of the neighborhood, mainly in the north-east of the neighborhood, the soil consists of fine cover sand. Retention capacity of vegetation was researched on similar river deposit soils in Rotterdam by Derkzen et al (2015). Since the climate, soil and urban vegetation of Rotterdam and Deventer are very similar, it can be assumed that the results of this research are also applicable to Deventer. Urban green space can be divided into multiple different categories, such as individual trees, herbaceous species, shrubs, garden and woodland (Derkzen et al., 2015). For these different categories, it was found that woodlands have the highest retention capacity (8,7 L/m^2), followed by individual trees (8,3 L/m^2), herbaceous species (8,0 L/m^2) and shrubs (7,3 L/m^2). Gardens were found to have lowest retention capacity out of these categories with 6 L/m^2. A logical explanation for this could be that this low result was found because some of the investigated gardens were (partly) paved. It is important to take into account that these values were found for an average wet day, with 10mm precipitation. If the rainfall is more frequent or more extreme, it can be assumed that the retention capacity of all vegetation types will be lower.

3.2.2 Effectiveness of green walls

There are several types of green walls, which all have different retention capacities (Webb, 2010). For the large majority of green walls, the average retention capacity is between 45% and 75% for 10mm precipitation in one hour. It was found that the retention capacity of green walls is highly dependent of the rainfall intensity (Lau & Mah, 2018). For one specific modular green wall with greenery bags, the retention capacity fell from 87% for 2mm/hour precipitation, to 55% for 5,5mm/hour, to 52% for 42,5mm/hour. This shows that while green walls can intercept a large percentage of the precipitation for low-intensity precipitation events, this percentage drops down quickly at a certain precipitation intensity.

3.2.3 Effectiveness of green roofs

There are two different types of green roofs: extensive green roofs with a thin vegetation layer (often sedum) and soil layer, and intensive green roofs with a thick vegetation layer (often flowering meadow plants) and soil layer (Graceson et al., 2013). This difference can have a relatively large effect on the retention performance of these roofs. Extensive green roofs were found to retain 40% of a 10mm/hour precipitation event, and intensive green roofs were found to retain 48% of this same precipitation event. The retention performance of the green roofs was dependent on the season, with the green roofs being more effective in the spring and summer months due to higher evapotranspiration rates. Green roofs need about 3 dry days to get back to their initial effectiveness after a heavy rainfall event (Lee et al., 2013). This means that if heavy rainfall events are lengthy or successive, the retention performance of green roofs is affected negatively (Gong et al., 2018). Moreover, extreme precipitation events also negatively affect the retention performance of green roofs (Ercolani et al., 2018). Furthermore, in this specific historical neighborhood there is a very low amount of flat roofs. Only some of the newer commercial buildings have flat roofs, but almost all historical buildings have gabled roofs. This means implementing green roofs should only potentially be implemented on these commercial buildings, since it is much more complex and less effective to implement green roofs on gabled roofs compared to flat roofs (Stovin, 2010).

3.2.4 Effectiveness of bioretention planters

For low-intensity precipitation events (<5mm/hour), bioretention planters can take up 85% to 100% of the stormwater runoff (Guerra et al., 2018). However, this reduces significantly during heavy rainfall events, when the retention rate of bioretention planters was found to be 50% to 64%. For a 10mm/hour precipitation event, the retention performance of a 70cm deep bioretention planter filled with 30cm crushed rock below 40cm planting soil was found to be roughly 75%. The drawdown time for this planter was found to be between 1 and 2 hours. The difference between this time and the drawback time of green roofs of 3 days can be explained due to the difference that many bioretention planters have a drainage layer of gravel (or crushed rock in this particular case) and the sub-soil is located directly below this drainage layer. Both of these aspects can increase the drainage speed. An underdrain can also increase the drainage speed. These values show that the retention performance of bioretention planters can be very good for low-intensity rainfall, but the performance can reduce significantly if the intensity of precipitation increases.

3.2.5 Summary

Intervention	**Intervention type**	**Average retention rainfall of 10mm/hour**
Vegetation	Woodland	8,7mm [1]
	Individual tree	8,3mm [1]
	Herbaceous species	8,0mm [1]
	Shrubs	7,3mm [1]
	Gardens	6,0mm [1]
Green wall	Modular green wall	4,5-7,5mm [2]
Green roof	Extensive (sedum)	4,0mm [3]
	Intensive (meadow plants)	4,8mm [3]
Bioretention planter	70cm deep soil + crushed rock planter	7,5mm [4]

[1] Derkzen et al. (2015); [2] Webb (2010); [3] Graceson et al. (2013); [4] Guarra et al. (2018)

Table 3: Retention values of the different high-frequency rainfall measures (table made by author)

Looking at table 3, it is clear that the use of vegetation (especially woodlands, trees and herbs) and bioretention planters have the best retention performance for 10mm rainfall in one hour. Green walls and green roofs have a lower retention performance, which could be due to the fact that these interventions are not directly in contact with the sub-soil, which means that the rainwater cannot be transported into the sub-soil (Graceson et al., 2013). This can also be the reason for the relatively long drawback time of green roofs.

3.3 High-intensity rainfall measure effectiveness

The most important factor to take into account to investigate the effectiveness of high-intensity rainfall interventions is the runoff peak reduction percentage of high-intensity precipitation events, since this has a large effect on the stress on the sewer system and on the probability of pluvial flooding during a precipitation event. In this chapter the peak reduction of a 1 in 10 year precipitation event will be investigated. Therefore, all high-intensity rainfall measures were investigated on this factor.

3.3.1 Effectiveness of bioretention basins

The performance of bioretention basins depends for a large part on the area drained by the basin and the infiltration and evaporation rates of the basin (Davis, 2008). One of the most important factors in determining the effectiveness of bioretention basins is the reduction of the runoff peak during high-intensity precipitation events, which was found to be between 62% and 30%, with 49-58% being the mean reduction range for a drainage area of 0,24ha asphalt (Davis, 2008). This value was confirmed by Bonneau et al. (2020), who found a more than half peak reduction for heavy rainfall events. There is a strong correlation between the water level of the bioretention basin and seasonality, with the basin being almost always full in winter and almost always empty in summer. The runoff peak reduction performance of bioretention basins was found to be very similar to rain gardens (Davis, 2008).

3.3.2 Effectiveness of rain gardens

The size of rain gardens should range from 3% to 43% of the total drainage area, depending on the amount of impervious surfaces in the area, slope and soil type (Stander et al., 2010). This offers little guidance to landscape designers, which led to many different sizes and shapes of rain gardens, and therefore also highly varying performances. The chosen vegetation for the rain garden has a significant effect on the hydrological performance of the rain garden (Yuan et al., 2019). Especially diverse herbaceous flowering perennial mixes, for example provide high hydrological detention performances compared to mown grasses and bare soil. Similar to bioretention basins, the stormwater peak reduction of rain gardens is significantly higher in summer compared to winter (Muthanna et al., 2008). In experimental research of three 2m^2 rain gardens with a drainage area of 8m^2 impervious surface, the high-intensity precipitation runoff peak reduction of rain gardens was found to be between 66% and 76%, depending on the vegetation of the rain garden (Yuan et al., 2019). The lowest reduction was reached with bare soil (66%), followed by mowed grass (70%), and the highest runoff peak reduction was reached with the flowering perennial mix (76%).

3.3.3 Effectiveness of penetrable pavements

Porous concrete was tested by Boogaard et al. (2014) for 8 locations in The Netherlands, and infiltration rates were measures and compared to regular concrete. The porous concrete reached an average infiltration rate of 313mm/hour, while the regular concrete reached 89mm/hour. This shows that permeable pavements can have a large effect on infiltration rates. Hu et al. compared different types of permeable pavements, in order to research their peak flow reduction performance. For this research 1300m^2 of penetrable pavement was modeled with a drainage area of 5.800m^2. Permeable asphalts reached an average peak flow reduction of 21,5%, permeable concretes reached 26%, and permeable interlocking pavers reached 22%. It is important that the permeable pavements are cleaned after rainstorms, since clogging of permeable pavements due to fine particles in the pores can reduces the effectiveness of penetrable pavements significantly (Hu et al., 2018). Peak flow reduction of clogged penetrable pavements can be 37-65% less than the peak flow reduction of penetrable pavements in good conditions.

3.3.4 Effectiveness of retention crates

The effectiveness of retention crates depends a lot on the permeability of the surface layer on top of the crates, and on the groundwater level (Drake et al., 2016). If the permeability of the surface layer on top is very low, then the retention crates below it will also not contribute much to a high peak reduction for heavy rainfall events. If the groundwater level is high, the captured water cannot be infiltrated sufficiently into the soil, decreasing the peak reduction and drawback time. Stewart et al. (2017) researched an underground cell of retention crates below a permeable pavement of 48m^2 for a drainage area of 1000m^2, and found a peak reduction of about 60%.

3.3.5 Effectiveness of detention basins and water plazas

In this section, artificial detention basins and water plazas are treated simultaneously, since water plazas are in essence artificial detention basins in urban areas with alternative recreational functions. While the hydrological performance of artificial detention basins and water plazas might seem to be very similar to bioretention basins, there still are some important differences. Bioretention basins infiltrate water, while artificial detention basins and water plazas have an underdrain (Wissler et al., 2020a). The runoff peak reduction of an 480m^2 artificial detention basin draining 28.600m^2 of impervious area was found to be 52%. So while bioretention basins and artificial detention basins have different ways of draining the runoff water, the resulting peak reduction for extreme rainfall events is very similar. Also, artificial detention basins and water plazas should be cleaned regularly, since the effectivity of these basins can be reduced with up to 41% if sediments and other fine particles are not removed from the basin on regular basis (Wissler et al., 2020b).

3.3.6 Effectiveness of extended/enlarged waterways

The effectiveness of extended/enlarged waterways depends a lot on the location and the size of the enlargement (Damodaram & Zechman, 2013). In Norway, a hydrological simulated model was employed by Kalantari et al. (2014) to predict the effect of enlarged waterways during heavy rainfall events. This was done for a very big drainage area of 450.000m^2, but the intervention size of 10.000m^2 was also relatively large. A peak reduction of 25-35% was found, depending on the intensity and duration of the rainfall. The heavier the rainfall and the longer the duration, the larger the peak reduction.

3.3.7 Summary

Intervention	**Intervention surface size**	**Drainage area and type**	**Intervention size to drainage area ratio**	**Peak reduction for heavy rainfall events**
Bioretention basin	28m^2	2.400m^2 asphalt	1,17%	49-58% [1]
Rain garden	2m^2	8m^2 impervious surface	25%	66% - 76% [2]
Penetrable pavement	1300m^2	5.800m^2 residential area	22,41%	21,5% - 26% [3]
Penetrable pavement + retention crates	48m^2	1.000m^2 impervious surface	4,8%	±60% [4]
Artificial detention basin and water plaza	480m^2	28.600m^2 impervious surface	1,68%	52% [5]
Extended/enlarged waterway	10.000m^2	450.000m^2 urban area	2,22%	25-35% [6]

[1] Davis (2008); [2] Yuan et al. (2019); [3] Hu et al. (2018); [4] Steward et al. (2017); [5] Wissler et al. (2020a); [6] Kalantari et al. (2014)

Table 4: Runoff peak reduction values of different high-intensity rainfall measures (table made by author)

Table 4 shows that the high-intensity measures have very different peak reduction percentages. However, it is difficult to compare results because of the different sizes of the measures, the drainage surfaces and materials, and the rainfall event intensity, duration and frequency. However, the strengths and weaknesses of the measures compared to other measures can be identified. It is evident that the different stormwater basins, such as bioretention basins, rain gardens and artificial detention basins have relatively high peak reduction capacities. This is very important for combatting high-intensity rainfall events. Penetrable pavements have a relatively low peak reduction capacity, but an advantage of this measure is that there is no extra space needed for to implement penetrable pavements. Extended or enlarged waterways can be efficient for drainage on a large scale, but does need a lot of space, which means that this measure is quite radical for a historical city center.

3.4 Stormwater transportation measure effectiveness

3.4.1 Effectiveness of bioswales

Bioswales are used extensively in the USA for roadside stormwater management, but in The Netherlands they are often used in urban settings (Mobron et al, 2019; Purvis et al, 2019). A bioswale consisting of engineered soil (75% lava rock and 25% loam) of 10,4m long, 2,4m wide and 0,9m deep was researched by Xiao and McPherson (2011) on its hydrological performance of reducing runoff peaks of a 181m^2 asphalt parking lot. The bioswale reduced stormwater runoff by 88,8% compared to a similar parking lot without an adjacent bioswale. This high value shows that bioswales can be very effective in reducing runoff peaks. Furthermore, bioswales are mostly emptied within 24 hours because of their infiltration and water-transporting properties (Beenen & Boogaard, 2007). However, infiltration performance and therefore also the runoff peak reduction performance can be affected negatively if the groundwater table is shallow (Locatelli et al., 2015).

3.4.2 Effectiveness of infiltration trenches

An infiltration trench of 40m long, 5,4m wide and 1,3m deep was researched by Lewellyn et al. (2016) on its infiltration performance. The drainage area is 930m^2 of impervious surface. The infiltration trench consists of 85% sand, 10% fines, and 5% organics. The peak reduction performance of the infiltration trench was on average 93%, with the lowest capture being 59% for heavy rainfall events (Lewellyn et al., 2016). The storage time of infiltration trenches varies from about 24 hours to 72 hours (Chahar et al., 2012). This means that if the time between extreme precipitation events is shorter than this time, the excess stormwater should be transported to other places, or overflows should be implemented in order to prevent overflows. These results show that infiltration trenches are very effective against high-intensity rainfall, but not so much against high-frequency rainfall.

3.4.3 Effectiveness of street channels

While open street channels do not promote infiltration, they can be very effective in transporting rainwater with very small space requirements (Xiao et al., 2007). An open gutter of 20m long, 0,1m wide and 0,1m deep was researched by Xiao et al. (2007) on its heavy rainfall peak reduction for a 695m^2 residential area, and the peak reduction performance was found to be 56%. This peak reduction effectiveness is inferior to the bioswales and infiltration trenches, but there is far less space needed for this particular intervention. Furthermore, the drawback time of street channels is very short (0-2 hours) if the capacity of the channel and the drainage system is sufficient. This is because street channels do not have any infiltration time, but only transport the stormwater.

3.4.4 Effectiveness of surface flow barriers

In this section check dams will be discussed, since the other mentioned surface flow barriers (dams, dikes, and raised buildings) are not suitable or proportional to implement in this specific historical neighborhood. Check dams can significantly improve the performance of bioswales for moderate and low-intensity rainfall events, but slightly reduce the performance during high-intensity rainfall events (Davis et al., 2012; Winston et al., 2019). Winston et al. (2019) found that a 33,5m long, 6,4m wide, 0,4m deep bioswale reduced 48% of heavy rainfall peak flows (>38mm) before rock check dams were implemented, and 44% after the check dams were implemented. For small rainfall events (<19mm) the peak flow reduction improved with the implementation of check dams, from 30% to 67%, and for moderate rainfall events (19-38mm) the peak flow reduction also improved substantially. The height and spacing of the check dams is very important for the flow and infiltration performance of the bioswale (Al-Janabi et al., 2020). Little spaced and high check dams generally improve the infiltration rate, but decrease the flow and therefore the peak reduction of the bioswale. No significant change was found between the drawback time of bioswales with or without check dams (Winston et al., 2019). Therefore the drawback time of bioswales without check dams will be used for this category.

3.4.5 Summary

Intervention	Intervention surface size	Drainage area and type	Intervention size to drainage area ratio	Peak reduction for heavy rainfall events	Drawback time
Bioswales	10,4m x 2,4m (24,96m^2)	181m^2 asphalt	13,79%	88,8% [1]	0-24 hours [2]
Infiltration trenches	40m x 5,4m (216m^2)	930m^2 impervious surface	23,23%	93% [3]	24-72 hours [4]
Street channels	20m x 0,1m (2m^2)	695m^2 residential area (>50% impervious)	0,29%	56% [5]	0-2 hours [5]
Surface flow barriers	Swale 33,5 x 6,4m (214,40m^2) with 2 check dams	4.600m^2 impervious surface	4,66%	44% [6]	0-24 hours [6]

[1] Xiao & McPherson (2011); [2] Beenen & Boogaard (2007); [3] Lewellyn et al. (2016); [4] Chahar et al. (2012); [5] Xiao et al. (2007); [6] Winston et al. (2019)

Table 5: Runoff peak reduction values of different stormwater transport measures (table made by author)

Table 5 shows that there is a large range in peak reduction capacity and drawback times for the different stormwater transport interventions. Similarly to the high-intensity rainfall measures, it is difficult to compare the peak reduction capacity and drawback time of the interventions because of the different sizes of the measures, drainage surface and material, and the different rainfall event intensity, duration and frequency. However, some strengths and weaknesses of interventions can be identified. Bioswales and infiltration trenches have a very high peak reduction, but also need a large surface. Infiltration trenches have a long drawback time, since the only way of transporting stormwater is by infiltration into the subsoil. Street channels do not need much space, and also have a very low drawback time, but the downside of street channels is that they have a much lower peak reduction than bioswales or infiltration trenches. Surface flow barriers in bioswales improve infiltration during low and moderate rainfall events, especially if they are high and there is little spacing, but this at the expense of the water flow during heavy rainfall events.

3.5 Multi-criteria analysis

In order to include other important factors in the intervention assessment, a multi-criteria analysis was created. The factors that are assessed in this analysis are:

- Surface needed for the intervention;
- Costs of the intervention compared to traditional sewer system;
- Water quality of the water in the intervention after interception;
- Environmental benefits (such as: urban heat reduction, air quality improvement, habitat creation, groundwater recharge, etc.) of the intervention;
- Public awareness for climate change and extreme precipitation events created by the intervention;
- Ability to combine the intervention with other urban functions (such as: recreation, infrastructure, energy production, etc.);
- Aesthetical potential of the intervention in a historical city center.

These criteria are based on the criteria for performance assessment as described by Alves et al. (2018). The effectiveness of the interventions, as researched in the sections before, was not taken into consideration in this assessment. This is because the effectiveness of interventions is a fundamental aspect in this research and design, and should weigh more in the assessment than these other mentioned aspects. Therefore, the effectiveness assessment should be taken into account separately from this multi-criteria analysis.

In table 6, + and – scores on a 6-point scale were used to indicate the positive or negative aspects of each intervention for different criteria. A very positive value (e.g. little space required, low costs, good water quality) for a specific criterium is indicated as + + +, and a somewhat positive score is indicated as +. The same scoring system applies for the negative scores, from very negative (- - -) to somewhat negative (-).

The + and - values in this analysis are based on the scientific literature mentioned in chapter 2 and this chapter. Nevertheless, all of these aspects for all different intervention types cannot objectively be compared with quantitative data in the same experimental environment and for the same rainfall events, at least not in the scope of this thesis. Therefore, the values used in this multi-criteria analysis are subjective to a certain extent. Thus, if contradictory values are found in scientific research this multi-criteria analysis is open for debate and potential adjustments. However, for this research and design the values shown in table 6 were found for the multi-criteria analysis.

Furthermore, the assessed criteria in the multi-criteria analysis have varying significances, depending on the situation. Which factor is found to be important also strongly depends per target group. For example, it can be assumed that residents of the neighborhood would discard the costs factor, since they are not the party financing the construction of the interventions. On the other hand, it can be assumed that the municipality of Deventer and the province of Overijssel would mark costs as one of the most important factors. Because of this strong difference, no multiplier was allocated to any of the aspects in this research. Furthermore, allocating a multiplier to a specific factor is a very subjective process. However, if in other situations certain aspect are objectively or democratically determined to be more important than others, multipliers could be allocated to specific factors. This will alter the final score for the assessed interventions.

Lastly, the experience of people on the interventions has an effect on some of the assessed criteria, such as the public awareness for climate change and extreme precipitation events that can be created by implementing the intervention, and the aesthetical potential of the intervention. However, measuring this by empirical research can only be done after the intervention is implemented. This means that if an intervention is implemented here or in a similar environment and situation, empirical research could help to get a better view on the scores for the mentioned criteria, and could potentially alter the scores for these criteria. Furthermore, it would make the scores for these criteria, and therefore also the final scores, more objective.

Because of the presence of subjectiveness and varying significances within the multi-criteria analysis, slight individual and final score differences should not be seen as immutable facts. Slight score differentials, such as a final score difference of 1 or 2 points, gives a slight preference to the higher scored intervention, but is still arguable. It should be considered which criteria are found to be the most important in the given situation.

Looking at the final scores of the interventions, it is clear that results of the high-frequency rainfall interventions and the stormwater transport measures are relatively high and close together. For the high-intensity rainfall interventions the final scores are relatively spread, with some of the interventions reaching negative final scores. When considering interventions, it is important to both look at effectiveness and the individual scores and final scores of the multi-criteria analysis. Furthermore, the specific location and situation should be addressed. For example, in very dense urban tissues interventions with low surface requirements or interventions which can be combined with other functions should be implemented. Furthermore, in very public places it could be decided to implement measures which create awareness for pluvial flooding and climate change, or measures with high aesthetic potential.

Intervention	**Category**	**Surface needed**	**Costs**	**Water quality**	**Environmental benefits**	**Awareness created**	**Combine with other functions**	**Aesthetical potential**	**Final score**
Vegetation	High-frequency rainfall measures	+	+ +	++	+++	-	+	+ +	**10**
Green walls		+ +	- -	+	++	+ + +	-	+ +	**7**
Green roofs		+ +	-	+	+	+ +	-	+	**6**
Bioretention planters		+ +	+	+	+++	+	+ +	+ +	**12**
Bioretention basins	High-intensity rainfall measures	- -	+	-	+	+	- -	+	**-1**
Rain gardens		-	- -	+ +	+++	+ + +	+ +	+ + +	**10**
Penetrable pavements		+ + +	- -	-	- -	+	+	+	**1**
Retention crates		+ + +	+	- -	- -	-	- -	- -	**-5**
Artificial detention basins		- -	+	- - -	- -	+ +	-	- -	**-7**
Water plazas		+	- -	- - -	- -	+ + +	+ + +	+	**1**
Extended/enlarged waterways		- - -	- - -	-	++	+ +	-	+ +	**-2**
Bioswales	Stormwater transportation measures	-	-	+ +	++	+ +	-	+ +	**5**
Infiltration trenches		-	-	+ +	+	+ +	-	+ +	**4**
Street channels		+ +	+ +	-	- -	+ + +	+	+	**6**
Surface flow barriers		+	+	+	-	+	- -	-	**0**

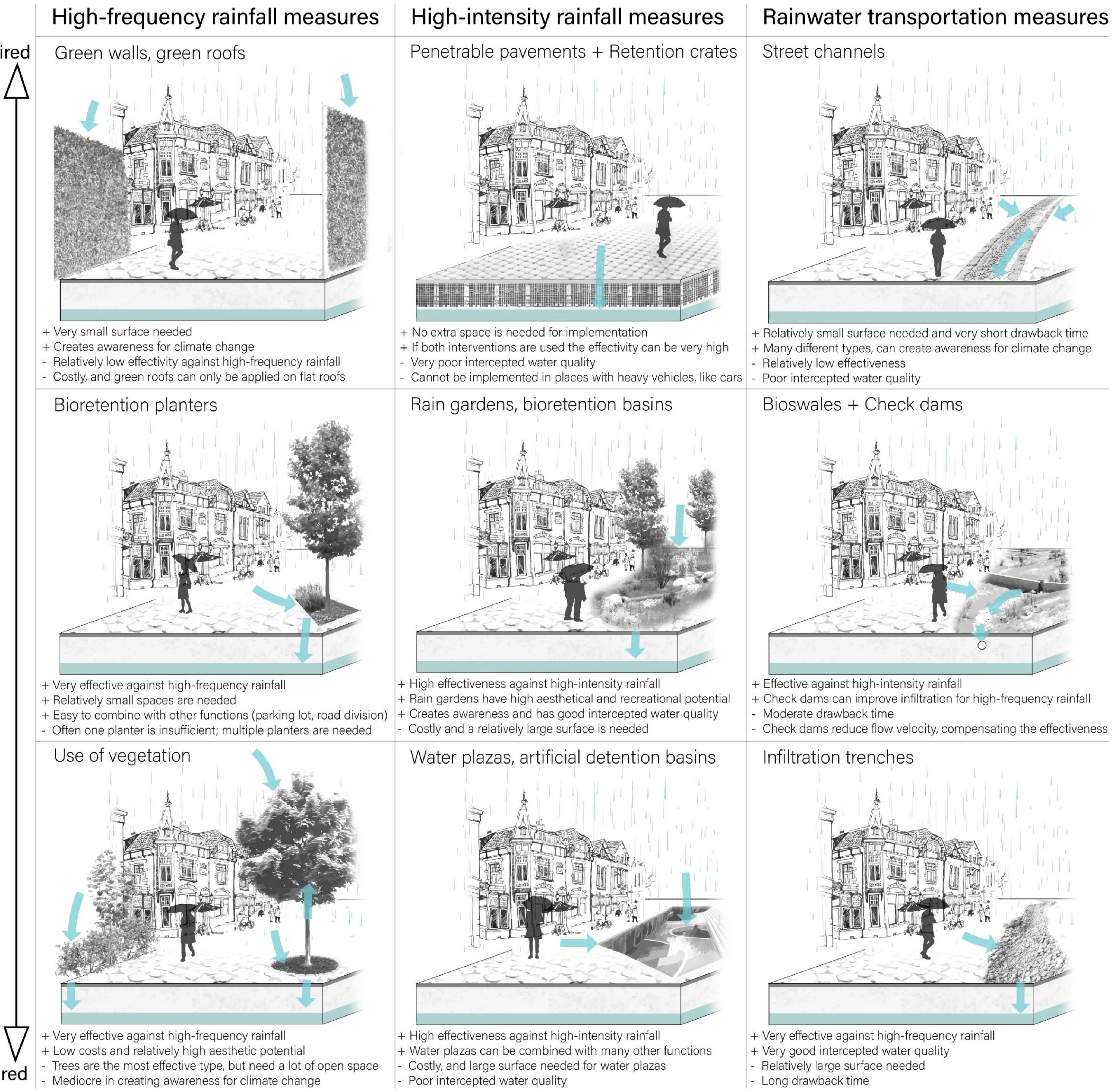
Table 6: Multi-criteria analysis of all explored interventions (table made by author)

3.6 Design guidelines

For each urban rainwater category, the 3 interventions with the most potential for historical city centers have been included in the design guidelines (see figure 30). These design guidelines can be seen as a brief and simple summary of the most important outcomes of the general research part of the thesis. Because of their simplicity, they can be very useful to transfer knowledge to non-experts. Furthermore, they can also help to improve and accelerate future design processes in similar situations (Van den Brink et al., 2016).

The design guidelines in figure 20 show the 3 intervention categories, a range of the required space for the interventions, an indication of what the intervention might look like, a representation of the main water flows during heavy rainfall events, and the most important positive and negative aspects of each individual intervention. Especially the latter should be used to distinguish between the different interventions in each category, in order to make an informed choice about using a specific intervention in a certain site.

In the next chapters, the research and these design guidelines will be applied on the city center of Deventer, to make informed choices on the location of the design interventions and the type of design interventions.



High-frequency rainfall measures	High-intensity rainfall measures	Rainwater transportation measures
Green walls, green roofs + Very small surface needed + Creates awareness for climate change - Relatively low effectivity against high-frequency rainfall - Costly, and green roofs can only be applied on flat roofs	**Penetrable pavements + Retention crates** + No extra space is needed for implementation + If both interventions are used the effectivity can be very high - Very poor intercepted water quality - Cannot be implemented in places with heavy vehicles, like cars	**Street channels** + Relatively small surface needed and very short drawback time + Many different types, can create awareness for climate change - Relatively low effectiveness - Poor intercepted water quality
Bioretention planters + Very effective against high-frequency rainfall + Relatively small spaces are needed + Easy to combine with other functions (parking lot, road division) - Often one planter is insufficient; multiple planters are needed	**Rain gardens, bioretention basins** + High effectiveness against high-intensity rainfall + Rain gardens have high aesthetical and recreational potential + Creates awareness and has good intercepted water quality - Costly and a relatively large surface is needed	**Bioswales + Check dams** + Effective against high-intensity rainfall + Check dams can improve infiltration for high-frequency rainfall - Moderate drawback time - Check dams reduce flow velocity, compensating the effectiveness
Use of vegetation + Very effective against high-frequency rainfall + Low costs and relatively high aesthetic potential - Trees are the most effective type, but need a lot of open space - Mediocre in creating awareness for climate change	**Water plazas, artificial detention basins** + High effectiveness against high-intensity rainfall + Water plazas can be combined with many other functions - Costly, and large surface needed for water plazas - Poor intercepted water quality	**Infiltration trenches** + Very effective against high-frequency rainfall + Very good intercepted water quality - Relatively large surface needed - Long drawback time

Figure 20: Design guidelines (figure made by author)

4 Vulnerable sites

Which places within the city center of Deventer are most prone to pluvial flooding events and extreme drainage peaks?

4.1 Extreme precipitation events in The Netherlands

In The Netherlands, most extreme precipitation events occur in the summer due to thunderstorms (KNMI, 2020a). The weather has been observed daily for over more than a century in The Netherlands, and multiple extreme precipitation events have taken place during this time. The term heavy or extreme precipitation event will be used in this report for precipitation over 25mm in one hour or more than 50mm in one day, which is the same definition as the KNMI is using (KNMI, n.d.). 1 in 10 year precipitation and more extreme events have other definitions, which are included later in this report in section 4.4.3 and figures 30a, b and c.

1917, 1948, 1960, 1966 were all years with extreme local or regional rainfall in the summer (KNMI, 2020a). Also in the more recent years 2002, 2003, 2006 and 2014 heavy rainfall occurred. Climate change is causing a hotter climate in The Netherlands, which correlates with more heavy rainfall events in hot periods (DHI, 2020). Figure 21a implies that the intensity of heavy rainfall events is increasing, which corresponds to this development. Furthermore, the amount of days with extreme precipitation are also increasing. This is implied in figure 21b. This means that especially urban areas in The Netherlands might encounter pluvial flooding problems in the future, because of the limited capacity of some sewer systems and the many hard surfaces preventing the ground from absorbing large amounts of water (DHI, 2020; Runhaar et al., 2012).

4.2 Predictions for the future

In order to predict the frequency and intensity of future precipitation events, multiple climate models were compared. Multiple models are used since current climate models still have multiple uncertainties, such as large grid boxes, incomplete amount of factors included, and imperfect understanding of the earth's system (Flato et al., 2014). Comparing multiple climate models provides a good indication of the mean values and extremes of different models, allowing for a more complete and reliable analysis of future climate impacts, such as precipitation. De predicted daily precipitation values of 2040-2070 of five different climate models were compared against the average daily observed precipitation values of The Netherlands of 1980-2010.

Current climate models can predict temperature change more precisely than precipitation change in The Netherlands (Raäisaänen, 2007). All used climate models agree on an increase in temperature in The Netherlands, but precipitation is very difficult to predict for The Netherlands. This is because The Netherlands are on a border between the north of Europe, which will be wetter in the future, and the south of Europe, which will be dryer in the future. Some models predict an increase of precipitation in The Netherlands because of climate change, while other models predict a decrease in precipitation. The difference between the models can for example be seen in figure 22. Because of this uncertainty, 2070 was chosen as a cut-off point of the 30-year period. Precipitation after 2070 is incredibly difficult to predict, and the current model values for this factor will therefore most likely not be very accurate.

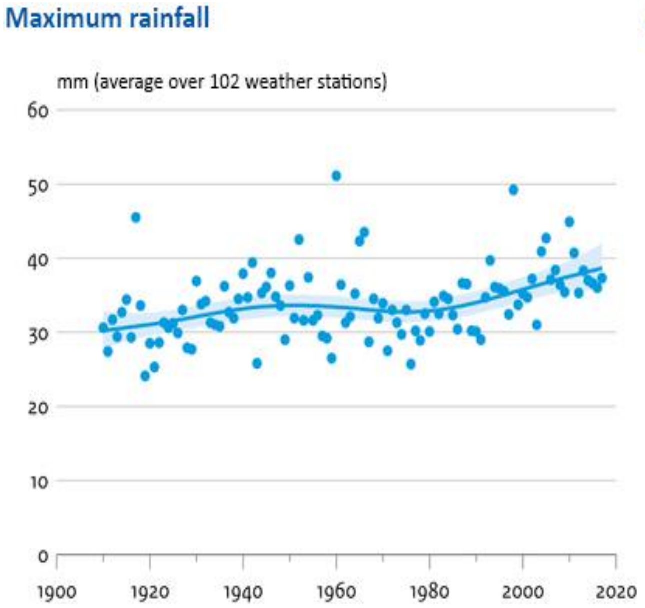


Figure 21a: Trend of the maximum daily rainfall per year (Adapted from: CLO, 2018)

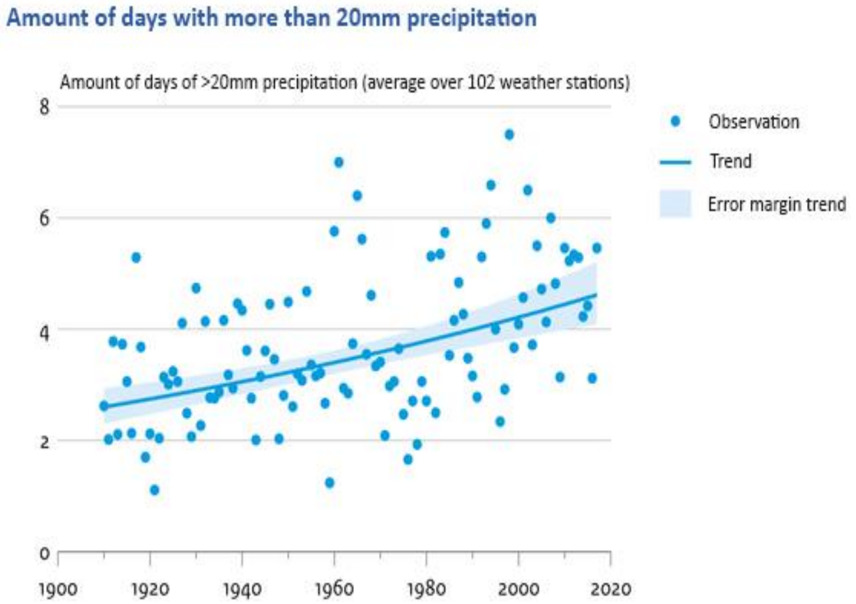


Figure 21b: Trend of the amount of days with extreme precipitation (Adapted from: CLO, 2018)

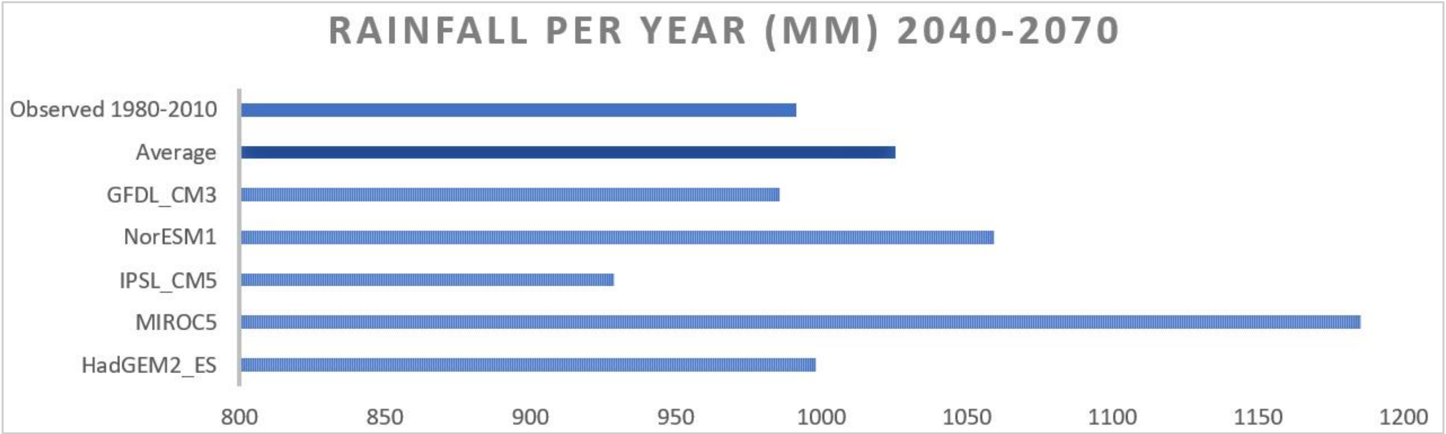


Figure 22: Rainfall in mm per year predicted by 5 climate models (Figure made by author)

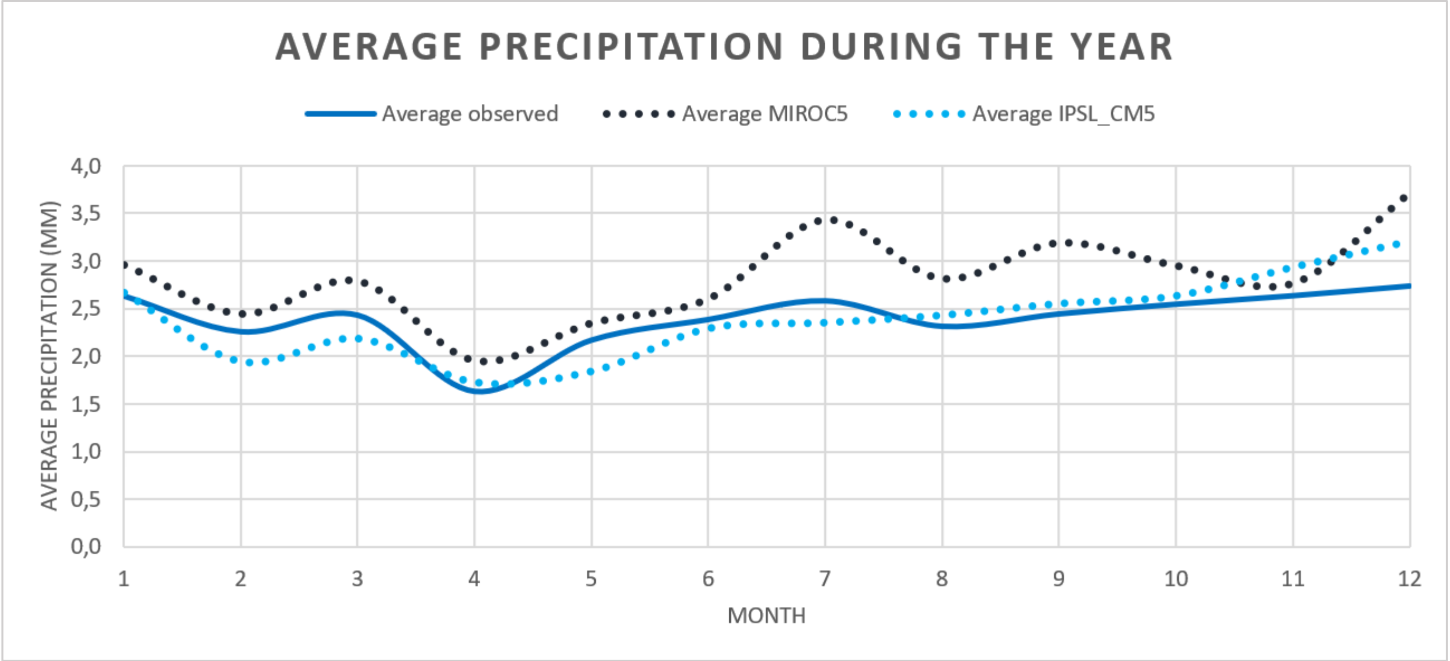


Figure 23: Average rainfall during the year predicted by the most extremely low and high climate model compared to the observed average of 1980-2010 (Figure made by author)

The daily observed values for the years 1980-2010 come from the WFDEI historical meteorological data set, provided by Weedon et al. (2014). The 5 climate models that were used for the precipitation assessment are:

- GFDL_CM3: bias-corrected meteorological data as simulated by Geophysical Fluid Dynamics Laboratories, global coupled model version 3 (Donner et al., 2011).
- NorESM1: bias-corrected meteorological data as simulated by the Norwegian Earth System, model 1 (Bentsen et al., 2013).
- HadGEM2_ES: bias-corrected meteorological data as simulated by the British Hadley Centre, global environmental model-earth system 2 (Jones et al., 2011).
- MIROC5: bias-corrected meteorological data as simulated by the Japanese Model for Interdisciplinary Research on Climate, version 5 (Watanabe et al., 2010).
- IPSL_CM5: bias-corrected meteorological data based on simulations by the French Institut Pierre Simon Laplace, climate model 5 (Dufresne et al., 2013).

Figure 22 shows that the employed climate models predict a relatively small increase in annual rainfall, from approximately 990mm to 1025mm per year. In figure 23 the observed annual average precipitation is compared against the climate model with the lowest predicted annual precipitation (IPSL_CM5) and the climate model with the highest predicted annual precipitation (MIROC5). This figure does not only show the difference in predicted rainfall between climate models, but it also shows a high probability of an increase in average precipitation in the summer. In figure 24 the average of the maximum daily precipitation for every month in the year is shown for the observed values and the same climate models. This figure shows that the peak of maximum daily precipitation will increase significantly in spring and in the summer, while it will decrease somewhat in the winter. This means that extreme precipitation events in the future will most likely mainly take place in the warmer periods of the year, especially in the summer.

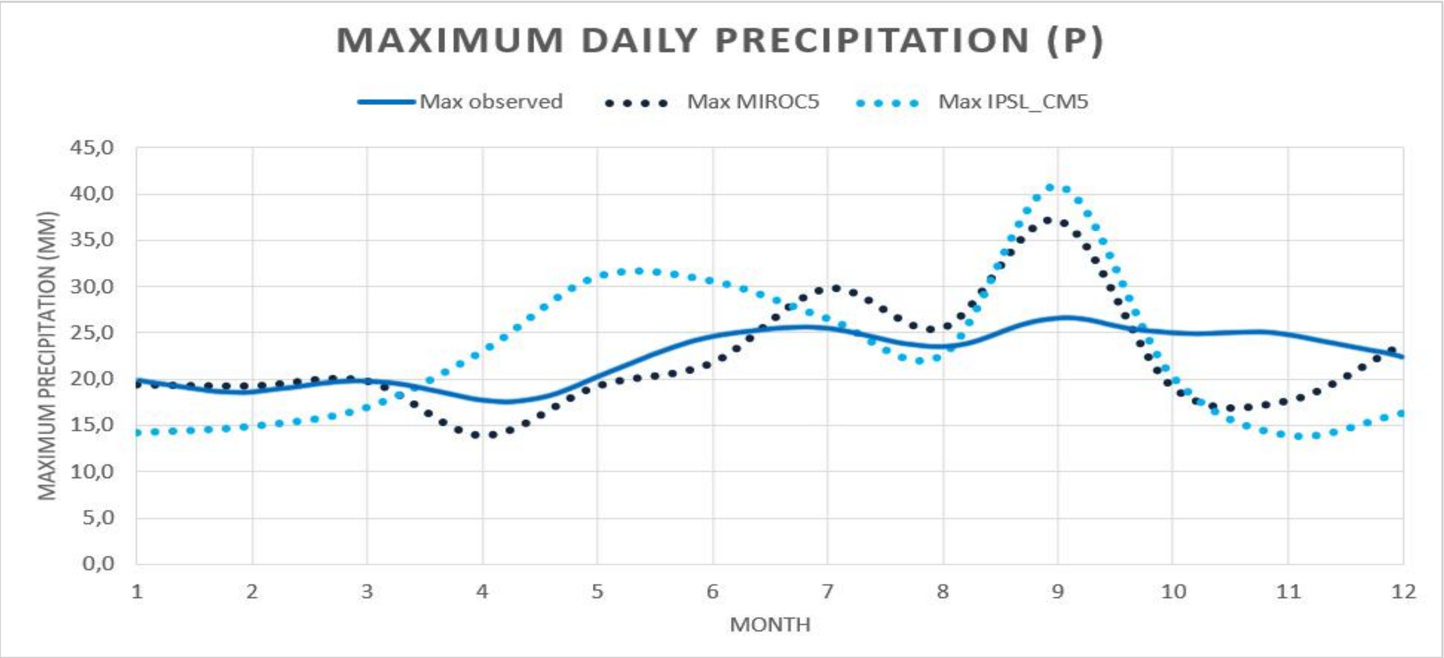


Figure 24: Maximum rainfall during a year predicted by the most extremely low and high climate model compared to the observed average of 1980-2010 (Figure made by author)

4.3 Sewer system vulnerability

4.3.1 Functionality and monitoring

The sewer system in the historical city center of Deventer consists of only combined sewers (Municipality of Deventer, 2014). More than 75% of this combined sewer network consists of concrete sewers. The remaining <25% is made from other materials, such as plastics (PVC, polypropylene), stoneware or cast iron. The time of construction of the current sewer systems is shown in figure 25, and is based on a report of the municipality of Deventer (2014). Both the material and the age of the sewer system have an influence on the condition of the sewer system, and therefore on the need for repair or replacement of the sewer. In the last 10 years, about 1/3rd of the sewer system in the city center of Deventer has been cleaned and inspected. Since 2008, it is considered whether it is possible to disconnect the sewer from the rainwater drainage system before sewers are replaced.

Before 1970, mainly concrete sewers and cast iron household connections were used (VPB, 2008). The majority of the sewers had a diameter of 0,3m diameter, but also sewers below 0,25m diameter were used. Nowadays only polypropylene pipes are implemented, and in some cases concrete sewers are used if pipes over 0,5m diameter are needed (Municipality of Deventer, 2020). All new sewers are required to have a diameter over 0,315m. These regulations mean that newer sewer systems are made from more smooth, chemical resistant and deterioration resistant materials, and generally have a higher diameter. This means that the older sewer pipes can have more problems with deterioration and discharging high quantities of water. Clusters of older sewers have been indicated by the dotted circles in the figure.

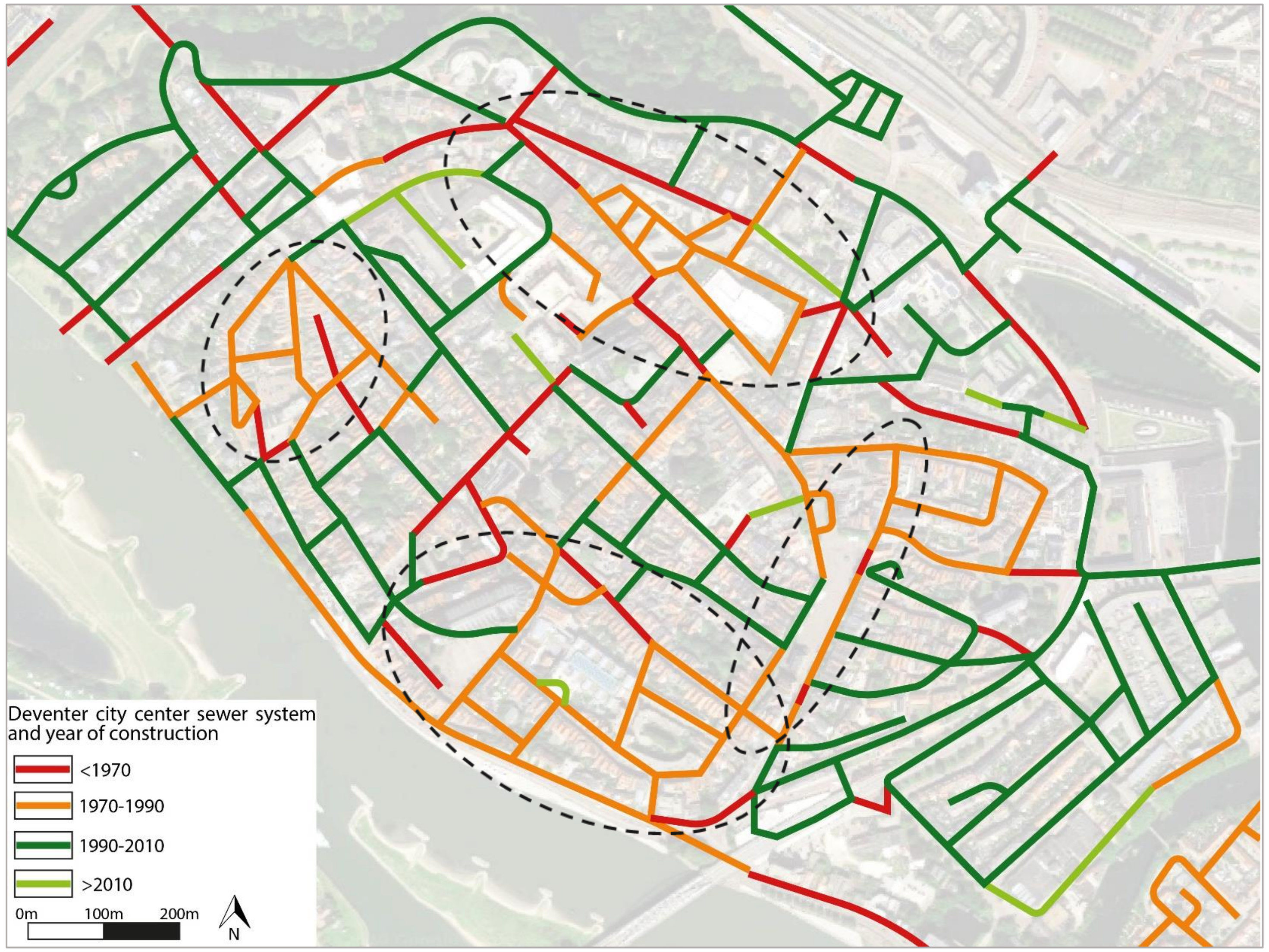


Figure 25: Deventer city center sewer system year of construction (Figure made by author)

4.3.2 Overflows and treatment

As explained in chapter 1.2.2, combined sewer systems are equipped with overflows. These allow untreated rainwater and wastewater in extreme precipitation events to flow into surface waters, in order for the sewer system to not overload the sewer system. For the sewer system of the historical city center of Deventer, these overflows are all located along the river IJssel. The exact location of the sewer overflows can be seen in figure 26. The sewage treatment plant is the end of the sewer system, and is located to the north-west of the neighborhood. There is also an overflow location just before the sewage treatment plant.

4.4 Site-specific challenges

4.4.1 Soft and hard surfaces

The location and the amount of soft surfaces in an urban area can have a big influence on the frequency and severity of urban flooding (Lennon et al., 2014; Runhaar et al., 2012). This is because soft surfaces absorb rainwater and slow down rainwater drainage, while rainwater predominantly flows over hard surfaces resulting in a high peak discharge. This high peak discharge can overload the sewer system, causing pluvial flooding and combined sewer overflows.

In the city center of Deventer, most soft surfaces are located on the edges of the neighborhood, in relatively low areas. This can be seen in figure 27. Especially surface waters, such as the river IJssel and the neighborhood-surrounding channel “the Singel”, are surrounded by relatively large green surfaces. In the densely built-up center of the neighborhood, the soft surfaces can be mostly characterized as courtyards or small gardens. There are very few parks or other large natural areas in the city center. Because of the high amount of hard surfaces in the city center, problems regarding surface flows and accumulation can occur during heavy rainfall events (Municipality of Deventer, 2019).

4.4.2 Surface flows and accumulations

Because of the relatively large changes in elevation (see figure 28a and 28b) and the high amount of hard surfaces in the city center of Deventer, surface flows can form during heavy rainfall events. The biggest surface flow directions can be seen in figure 29. This figure also makes it visible where the surface water accumulates. This is in relatively low areas. The sewer system in these places should be functioning optimally in these places, because besides the rainwater from these specific places, the rainwater from the surface flows is drained via this sewer. If the sewer system cannot discharge all this water and the ground cannot absorb all the water either, pluvial flooding will occur.

Figure 27: Soft and hard surfaces in the city center of Deventer (Figure made by author)

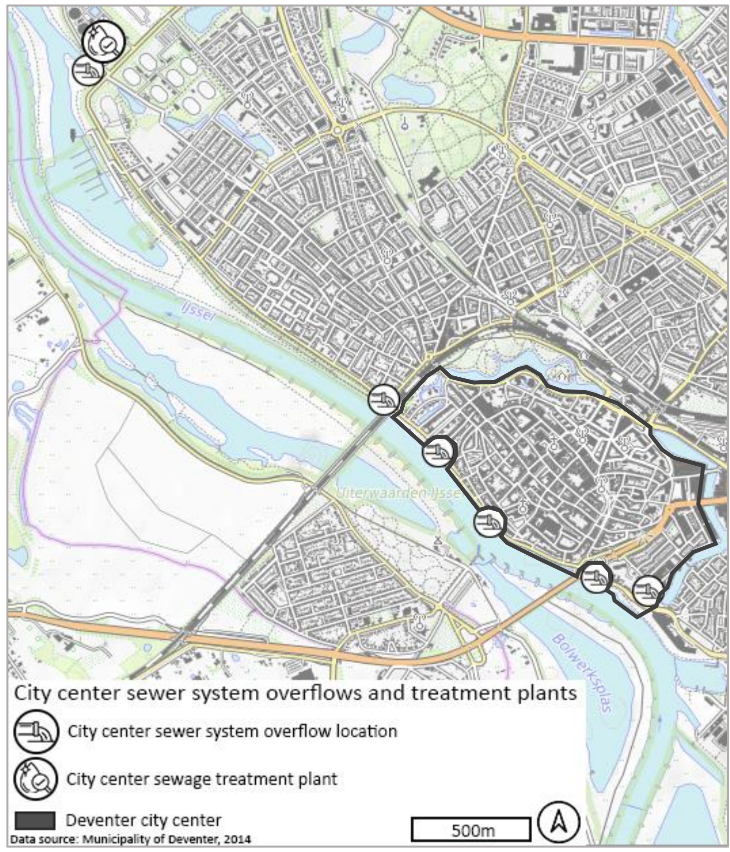


Figure 26: Deventer city center sewer system overflows and treatment plant (Figure made by author)

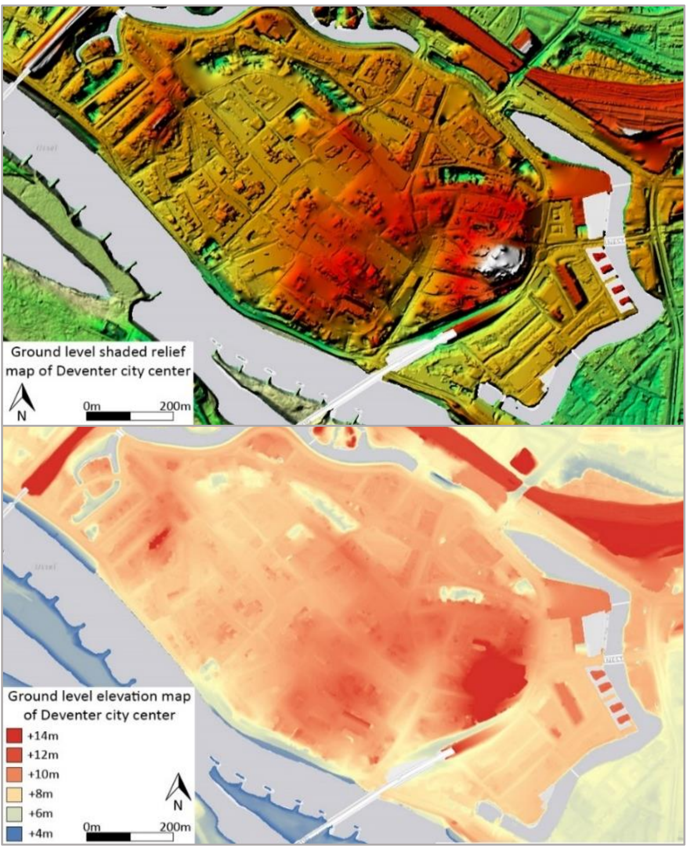


Figure 28a and 28b: Shaded relief map and elevation map of Deventer city center (Adapted from: AHN, 2020)

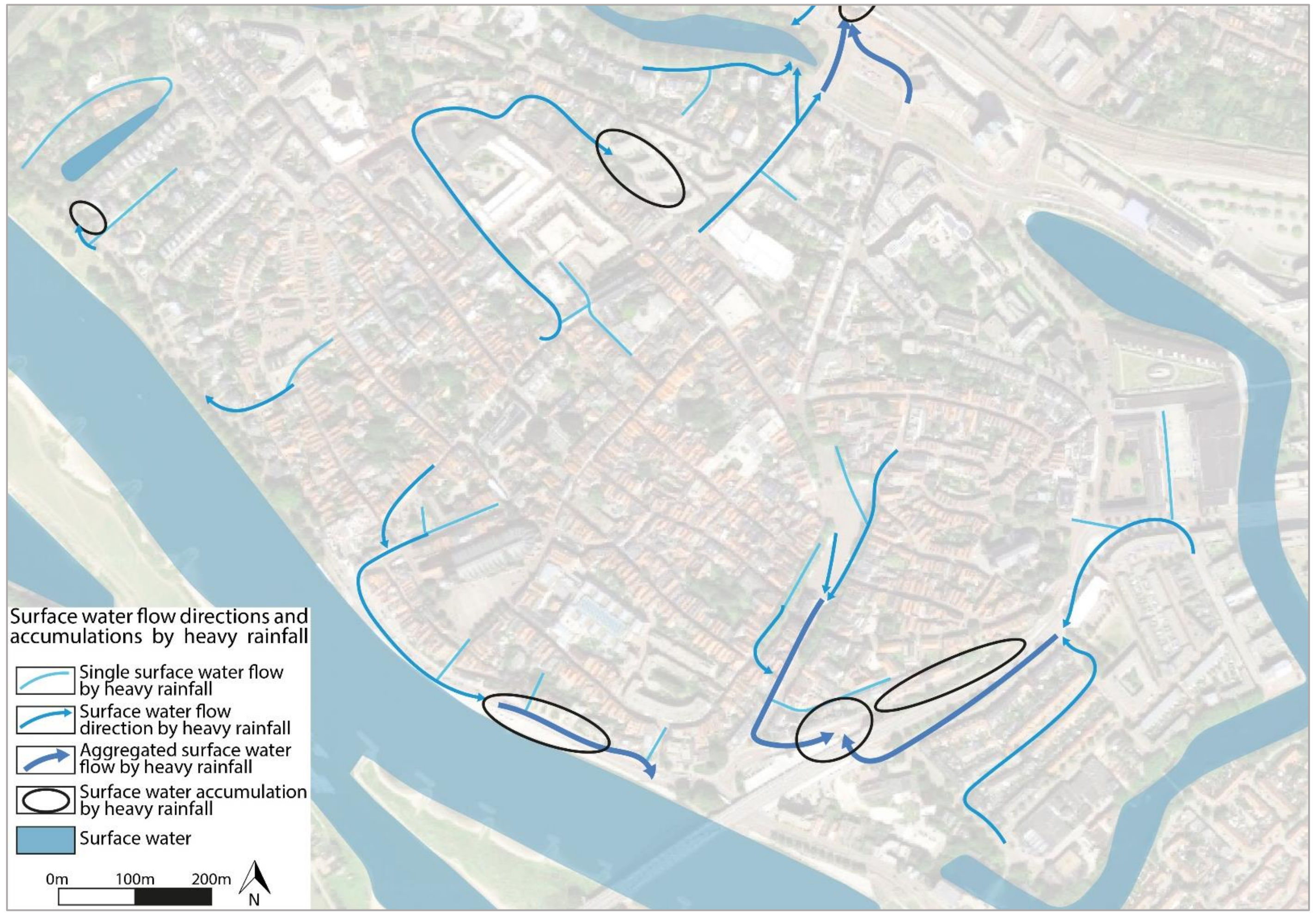


Figure 29: Rainwater surface flows and accumulations in city center of Deventer (Figure made by author)

4.4.3 Surface water depth after extreme events

In order to map the sites in the city center of Deventer that are vulnerable to pluvial flooding, two existing climate impact models were compared and combined. The first impact model that was employed is a local model developed by the Deventer-based engineering firm Tauw (2020), which shows surface water depth for current rainstorms of 1 in 10 years and 1 in 100 years. The second impact model is a national model developed by Deltares, and shows the surface water depth for current rainstorms of 1 in 100 years and 1 in 1000 years (Klimaateffectatlas, 2020). The models from these institutes were very much in accordance with each other, which strengthens the validation of these surface water depth models. These 2 models were combined to create 3 impact models for the historical city center of Deventer (see figure 30a to c). The intensity and duration of the rainstorm is indicated in the figure legend. For example, a 1 in 10 year precipitation event means 36mm of rain in 45 minutes. The 1 in 100 and 1 in 1000 year rainstorms may seem inconsiderable because of the low frequency of these events. However, as identified in the previous paragraph, the maximum rainfall in summer will most likely increase severely causing these extreme events to become more frequent. Nevertheless, design interventions will be presented mainly for areas vulnerable to 1 in 10 year precipitation, because dealing with areas vulnerable to 1 in 100 and 1 in 1000 year precipitation will need a great amount of more research and design work, which is beyond the scope of this thesis. However, measures dealing with 1 in 10 year precipitation will also have positive consequences for the vulnerability to even more extreme rainfall events.

The sites vulnerable to pluvial flooding correspond largely with the low areas on the elevation map of the city center (figure 28a and 28b), and with the surface flow accumulation sites (figure 29). The figures show that mainly low streets and squares with little vegetation are prone to pluvial flooding. In the most vulnerable places urban landscape interventions should be implemented, in order to relieve stress from the sewer system in these places. By doing this the sewer system will not exceed its capacity, which will prevent pluvial flooding and sewer overflows. In the next chapter, a large range of urban landscape interventions which deal with pluvial flooding will be explored.

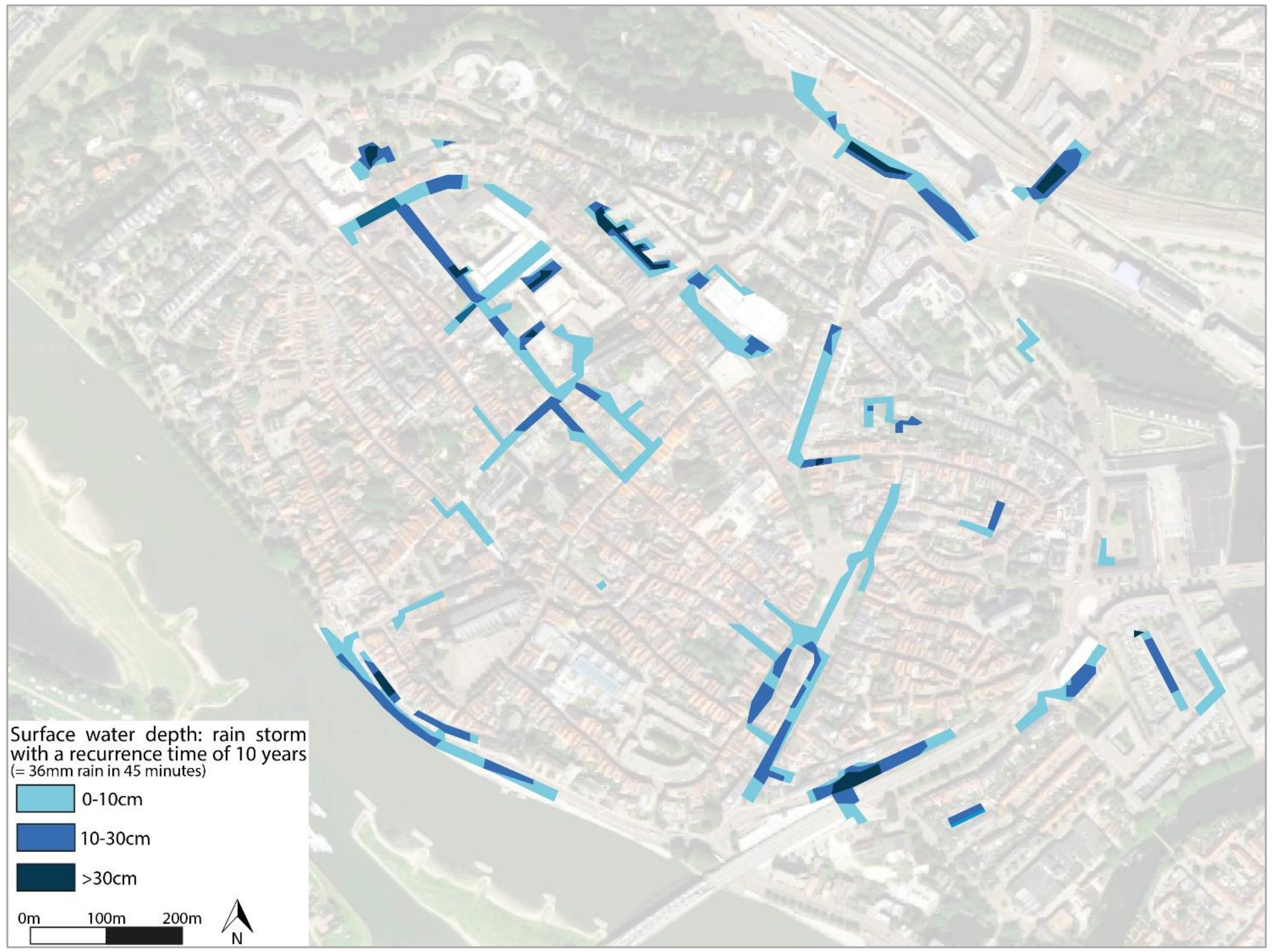


Figure 30a: Surface water depth after a rainstorm of 1 in 10 years (figure made by author)

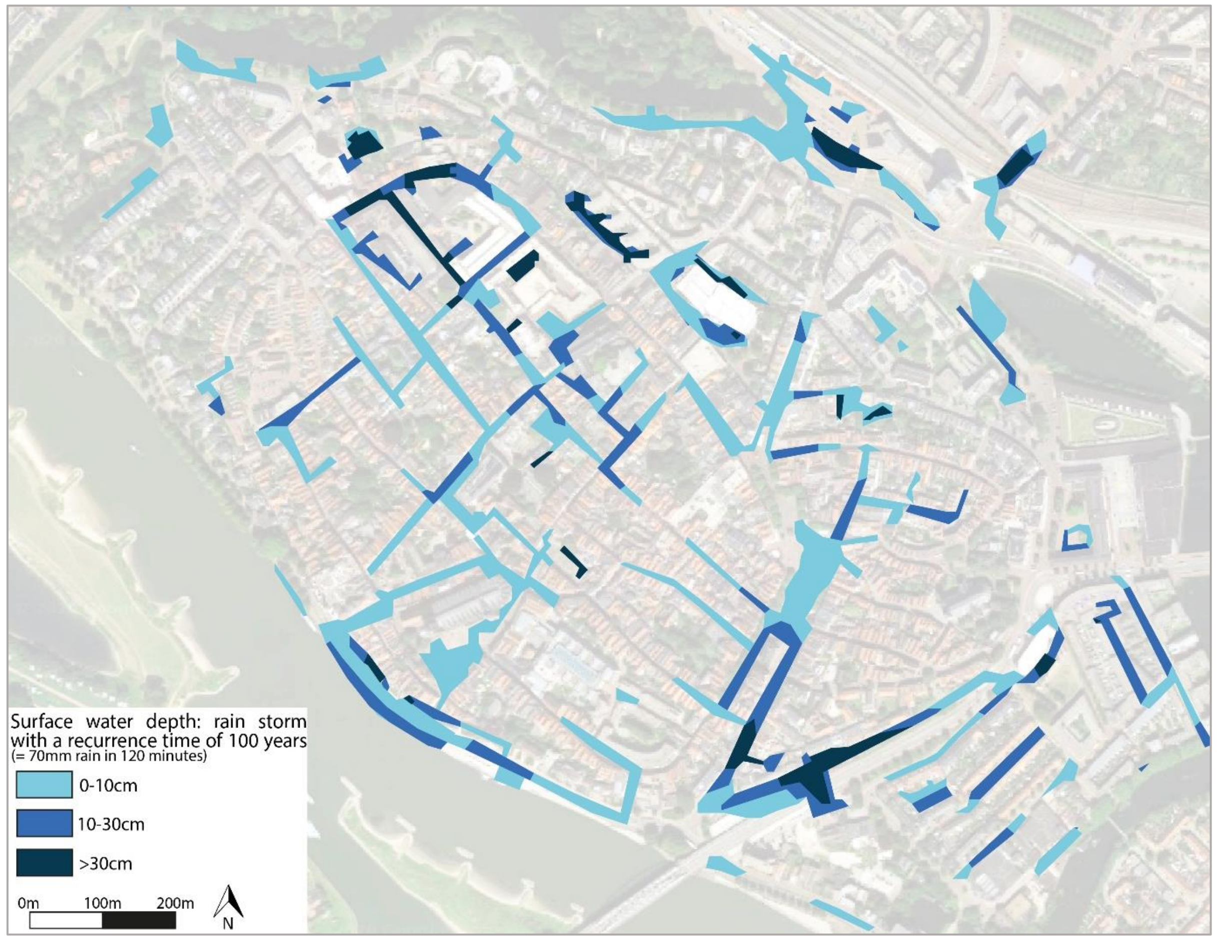


Figure 30b: Surface water depth after a rainstorm of 1 in 100 years (figure made by author)

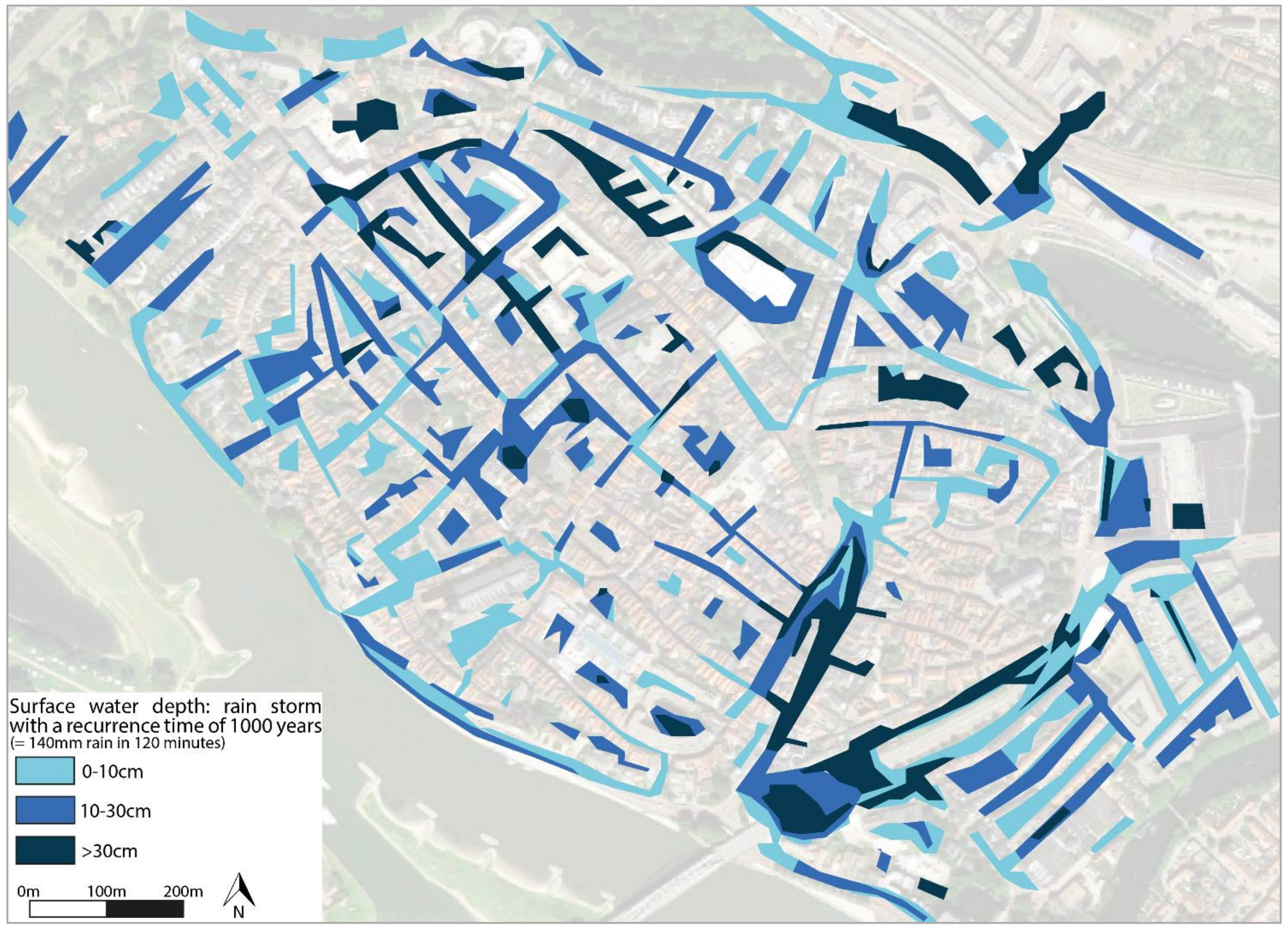


Figure 30c: Surface water depth after a rainstorm of 1 in 1000 years (figure made by author)

5 Site-specific design analysis

How can urban landscape design interventions be implemented in the historical city center of Deventer, in order to reduce both pluvial flooding events and extreme drainage peaks causing polluting sewer overflows?

5.1 Design assessment and site-specific risk analysis

5.1.1 Specific vulnerable areas

In order to determine the exact locations of design interventions in the neighborhood, first the general most vulnerable areas should be defined. Based on the sewer system age analysis, the general flows and accumulation analysis, and the three different surface water depth analyses, there are some clear vulnerable areas in the neighborhood corresponding across all these analyses (see figure 31 below). These areas are clearly visible in the 1 in 10 year rainfall surface water depth analysis, and have been numbered (see figure 32). These most vulnerable areas will be investigated in more detail. The most northern vulnerable area, the station square and surroundings, has recently already been redesigned and constructed by Palmbout Urban Landscapes and landscape architecture office BleekerNauta (Palmbout Urban Landscapes, 2020; BleekerNauta, n.d.). This was mainly done to improve the infrastructure layout close to the city station, but also to deal with pluvial flooding by implementing more green areas. Therefore, this specific area will not be included in the detailed risk analysis. However, the ability of this design to deal with extreme rainfall events will briefly be assessed in the next section. This will be done to gain inspiration for the design section in this thesis, to find positive points and well thought-out solutions for rainwater drainage, but also to suggest points of improvement.

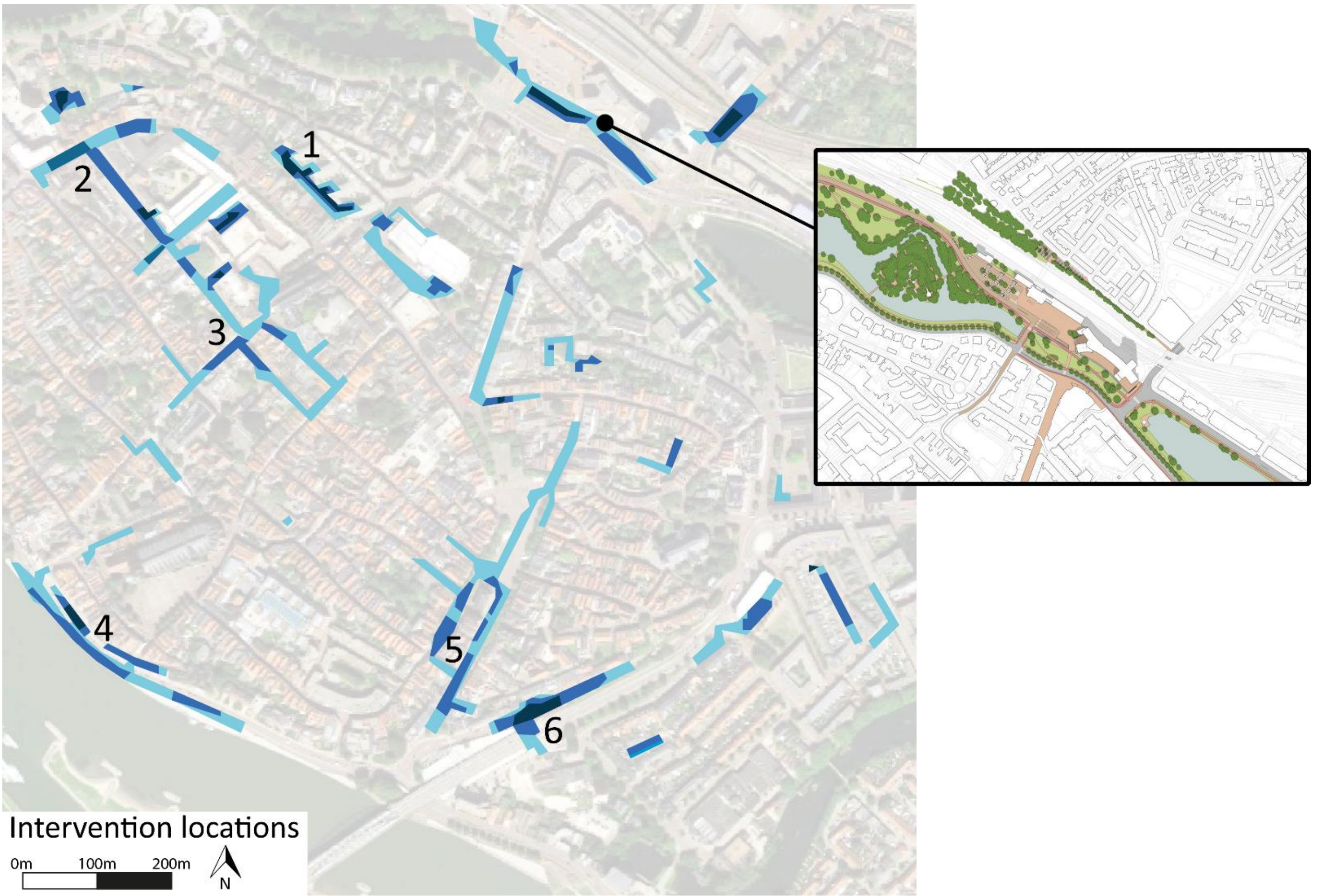


Figure 32: General intervention locations based on the vulnerability analysis (figure made by author)

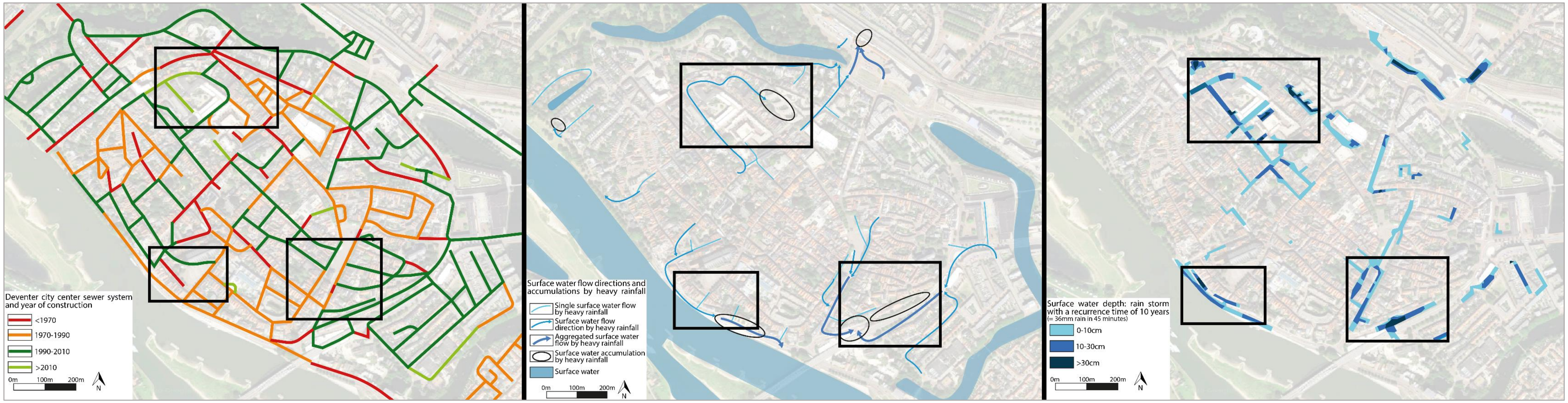


Figure 31: Corresponding vulnerable areas over the different vulnerability analysis maps (figure made by author)

5.1.2 Design assessment

As shown in figure 33a and b, the new design of the station square and surroundings has brought some main changes to the urban landscape. Figure 32a shows that the canal, which connected the historical north and south waterway to surround the whole historical city center, was filled in to make more space for vegetation and pathways. Furthermore, the tree lane next to the road was removed. Figure 32b shows that trees and flower boxes on the station square were replaced by elevated green strips, which also function as seating places. In figure 34, a 3D model of the new design is shown, which gives an overview of the structure of the new design. However, it is important to note that most of the trees shown in the 3D model have not matured yet, and will most likely not reach the presented height and size during the current decade.

The replacement of the canal and the tree lane next to the road for a green space will most likely increase the vulnerability of the station area to pluvial flooding and combined sewer overflows. This is because in the initial situation, the trees could absorb and store water and rainwater could easily be drained from surrounding hardened surfaces to the large canal. In the new situation, there is currently very little vegetation and no open water surfaces. This means that some water can be infiltrated in the soft surface along the road, but during an extreme precipitation event the infiltration performance of this surface may not be sufficient. This can lead to saturation of the soil and potential pluvial flooding on the surrounding roads and hard surfaces and sewer overflows of the combined sewer system.

It can be assumed that the vulnerability of the station square itself to pluvial flooding and polluting sewer overflows has decreased slightly because of the new design implementation. In the initial situation, the trees and flower boxes accounted for a very small soft surface area, but these features would not infiltrate a lot of water during extreme precipitation events due to the limited soft surface ratio. However, the trees could still intercept water in their leaves. Since the trees could only intercept a limited amount this would not make a big difference during extreme precipitation events. This could have led to pluvial flooding and sewer overflows, because this means that much of the rainwater would have been drained by the combined sewer system, which could have overloaded the sewer system. In the new situation more soft surfaces have been added in the form of green strips. Besides the green strips, trees have been added between the station bus stops, as can be seen in figure 34. This will also increase the infiltration and drainage performance of the station square. A disadvantage of the elevated green strips is that rainwater from the surrounding hard surfaces cannot flow into the green strips, because of the high edges. Therefore, this water will still end up in the combined sewer system. From a climate adaptation standpoint, it would have been better to create green spaces on ground level and seating places on a higher level, so that rainwater can flow towards the green spaces and infiltrate into the soil.

5.1.3 Site-specific risk analysis

For the site-specific risk analysis a layer approach will be used (see figure 35). First, the physical urban landscape will be investigated, to find the possible intervention locations within the urban tissue. Then, the elevation and slopes will be addressed, in order to find the areas where water will flow from, and the areas where water will flow to and accumulate during heavy rainfall events. Subsequently, the detailed surface flows will be investigated, in order find out where to implement the measures to most effectively reduce these flows during heavy rainfall events. Especially sites were surface flows congregate should be addressed, since these lead to filling and eventual flooding of surface depressions (Klijn & Schweckendiek, 2012). Lastly, surface water depth risk after extreme events will be investigated in detail, in order to determine where flooding problems will occur if no interventions are implemented. Combining all these different layers will lead to a comprehensive and detailed risk analysis of the vulnerable areas. With the help of these analyses, it is possible to find out the best options for the location and type of the design interventions.

Figure 33a and b: Comparisons of the design of the station square and surroundings before and after the new design was approved and the construction started in 2011 (Images from: Google maps, 2021)

Figure 34: 3D model of the new design of the Deventer station square and surroundings (BleekerNauta, n.d.)

Since this layer approach mainly focusses on pluvial flooding, it is important to note that combined sewer overflows can also occur when no pluvial flooding occurs, due to high-frequency rainfall gradually accumulating in the sewer system (Jean et al., 2018). Therefore, high-frequency rainfall interventions should also be implemented in these vulnerable areas, to prevent polluting sewer overflows.

In the next sections of this chapter, a 1 in 10 year rainfall event will be used as benchmark, since the interventions should be able to prevent pluvial flooding up to precipitation events of this severity. However, it can be assumed that these interventions implemented to reach this benchmark will also prevent pluvial flooding and reduce combined sewer overflows during 1 in 2 year or 1 in 5 year extreme precipitation events. Furthermore, it can be assumed that these interventions will also prevent pluvial flooding and reduce combined sewer overflows during high-frequency rainfall events, since also high-frequency rainfall measures are added and this type of rainfall leaves more time for infiltration of excess water into the soil.

For vulnerable area 1, named “De Doelen”, the site-specific risk analysis is shown in figure 36. For this specific area, the most vulnerable area is situated on the east of the map and is located between buildings. This area is used as parking lots and entrance road to the surrounding buildings, and consists of mostly hard surfaces. As the figure shows, many small surface flows come from the roofs of the buildings and pathways between the buildings. A bigger, congregated surface flow comes from the west to the most vulnerable area. An effective approach to relieve stress from this vulnerable area would be to reduce the supplying flows, as well as improving the draining capacity of the vulnerable area itself.

The site-specific risk analysis of vulnerable area 2 (the Nieuwstraat) is shown in figure 37. The most vulnerable areas in this specific area are many of the relatively low streets, shown in the center of the map. Many of the small red spots on the map are garages or cellars that are vulnerable to flooding during heavy rainfall events. The potential flooding of the streets is caused to a large extend by the supplying surface flows from the west and south-east of the vulnerable area.

For the third vulnerable area (the Bagijnenstraat), the site-specific risk analysis is shown in figure 38. Compared to the previous 2 areas, this area is not very vulnerable for surface water accumulation. However, this area is the start of a large potential surface stream, flowing to the more vulnerable areas to the north. Much of this water comes from roofs and streets in the center and southern part of the map.

The site-specific risk analysis for vulnerable area 4 (de Welle) is shown in figure 39. The most vulnerable site in this area is a main street located near the edge of the river IJssel. This street also floods sometimes in winter when the river water level is very high, causing traffic problems (NRC, 2011). The supplying flows come from the roofs and streets on higher elevations. In this location, only implementing stormwater transport measures can be sufficient, since the river can serve as a large rainwater basin.

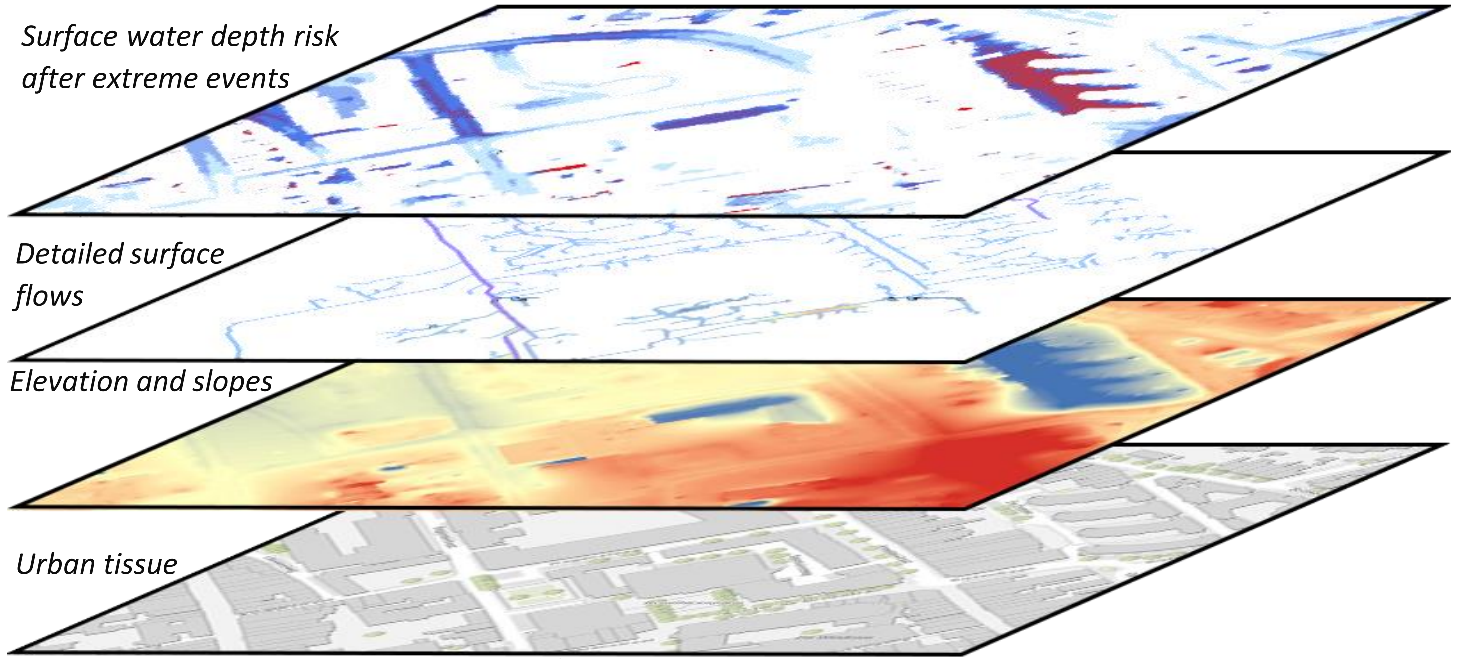


Figure 35: Several distinguished layers of determined vulnerable areas, in order to pinpoint the best locations for landscape interventions (figure made by author)

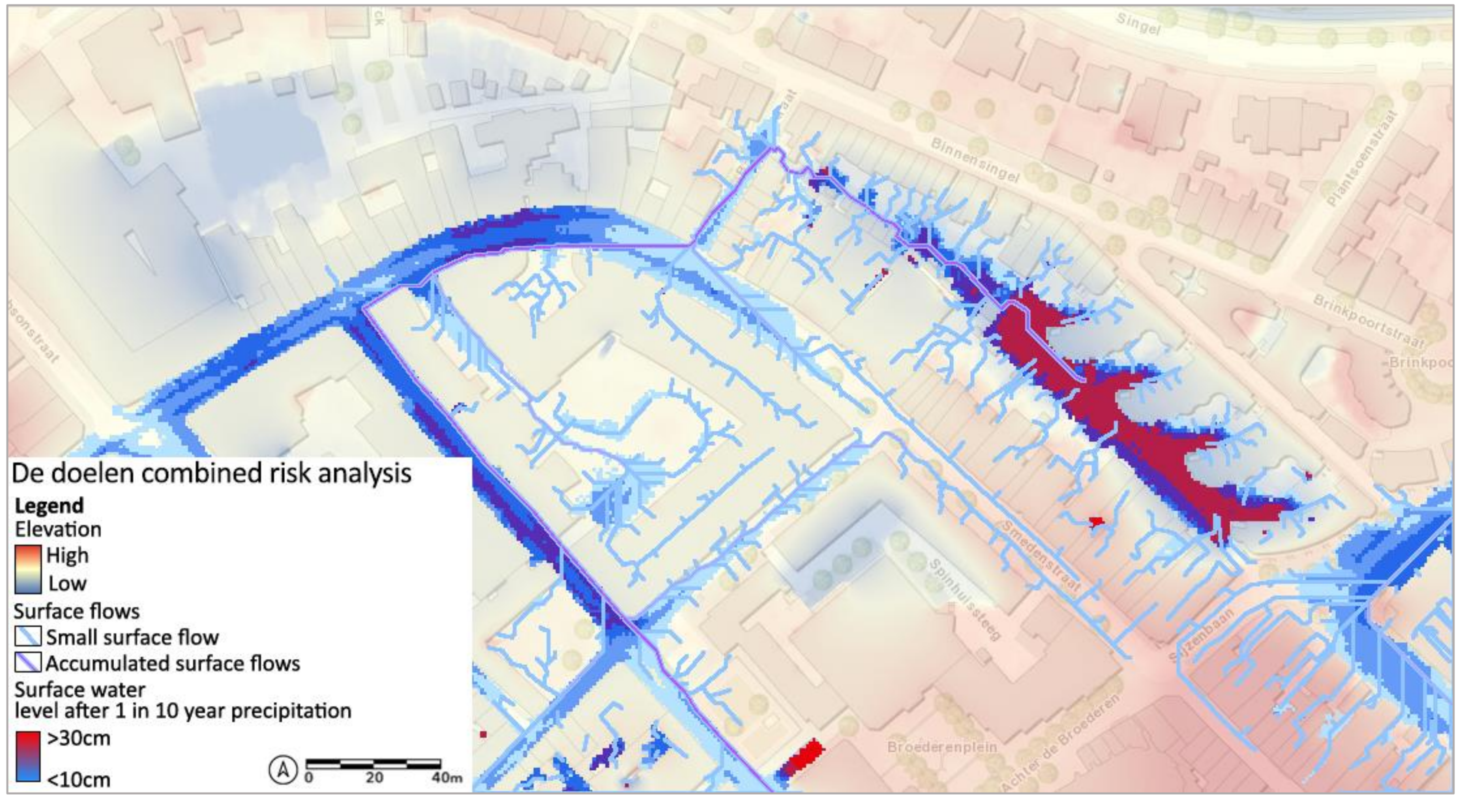


Figure 36: Site-specific risk analysis for vulnerable area 1, De Doelen (figure made by author)

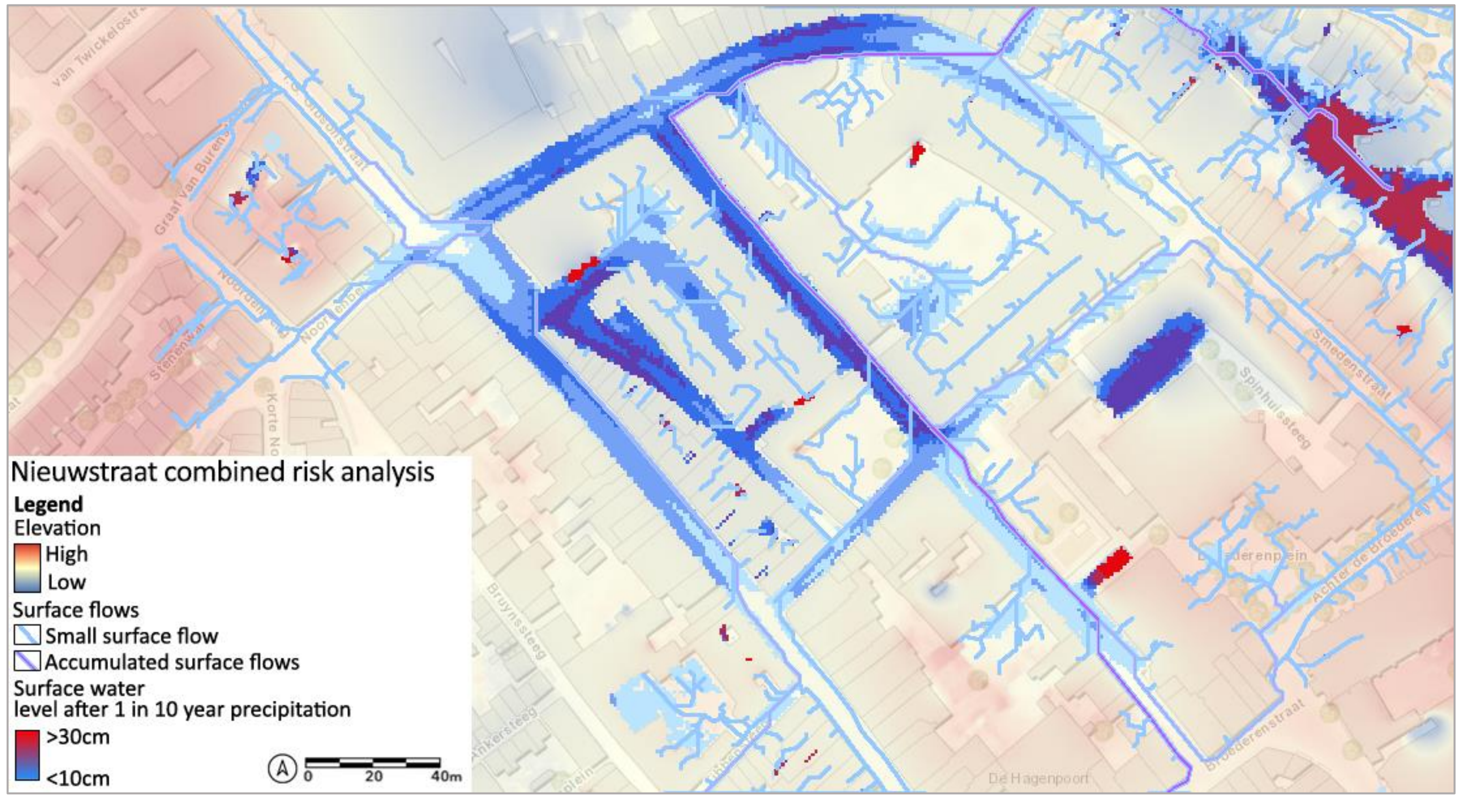


Figure 37: Site-specific risk analysis for vulnerable area 2, the Nieuwstraat (figure made by author)

For vulnerable area 5, the Brink, the site-specific risk analysis is shown in figure 40. This area is relatively not very vulnerable to surface water accumulation. However, a large surface flow is formed in this area, because many smaller flows merge here. The flows come from both the east and west, and congregate in the middle.

For the last vulnerable area (the Bokkingshang), the site-specific risk analysis is shown in figure 41. This location includes the site that is most prone to pluvial flooding in the neighborhood. This vulnerable area mostly consists of streets, a parking garage and other impermeable surfaces, and is located in a surface depression. The large supplying flows come from the north, north-east and south-east. In order to avoid a pluvial flooding event of this severity, the supplying surface flows should be reduced, and the peak flow reduction capacity of the vulnerable area itself should be improved drastically.

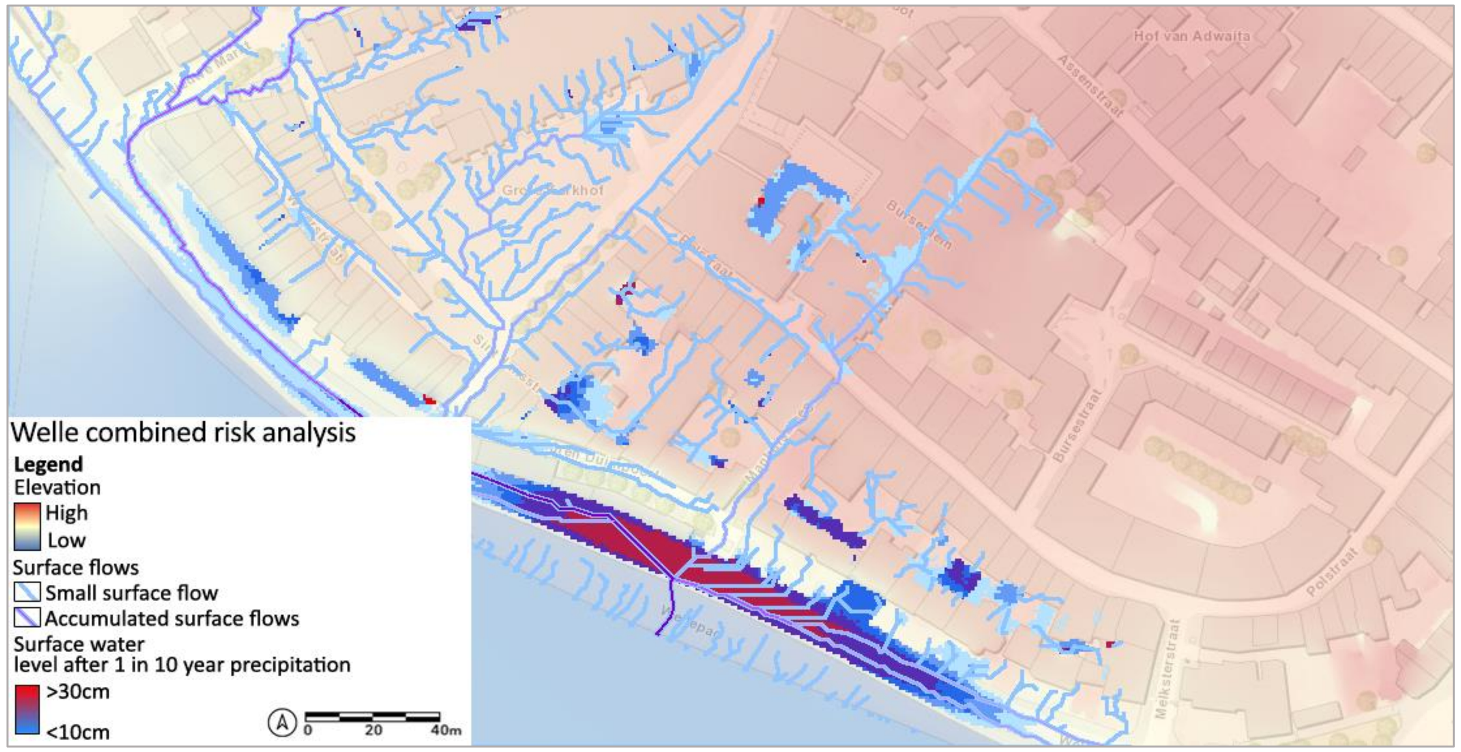


Figure 39: Site-specific risk analysis for vulnerable area 4, the Welle (figure made by author)

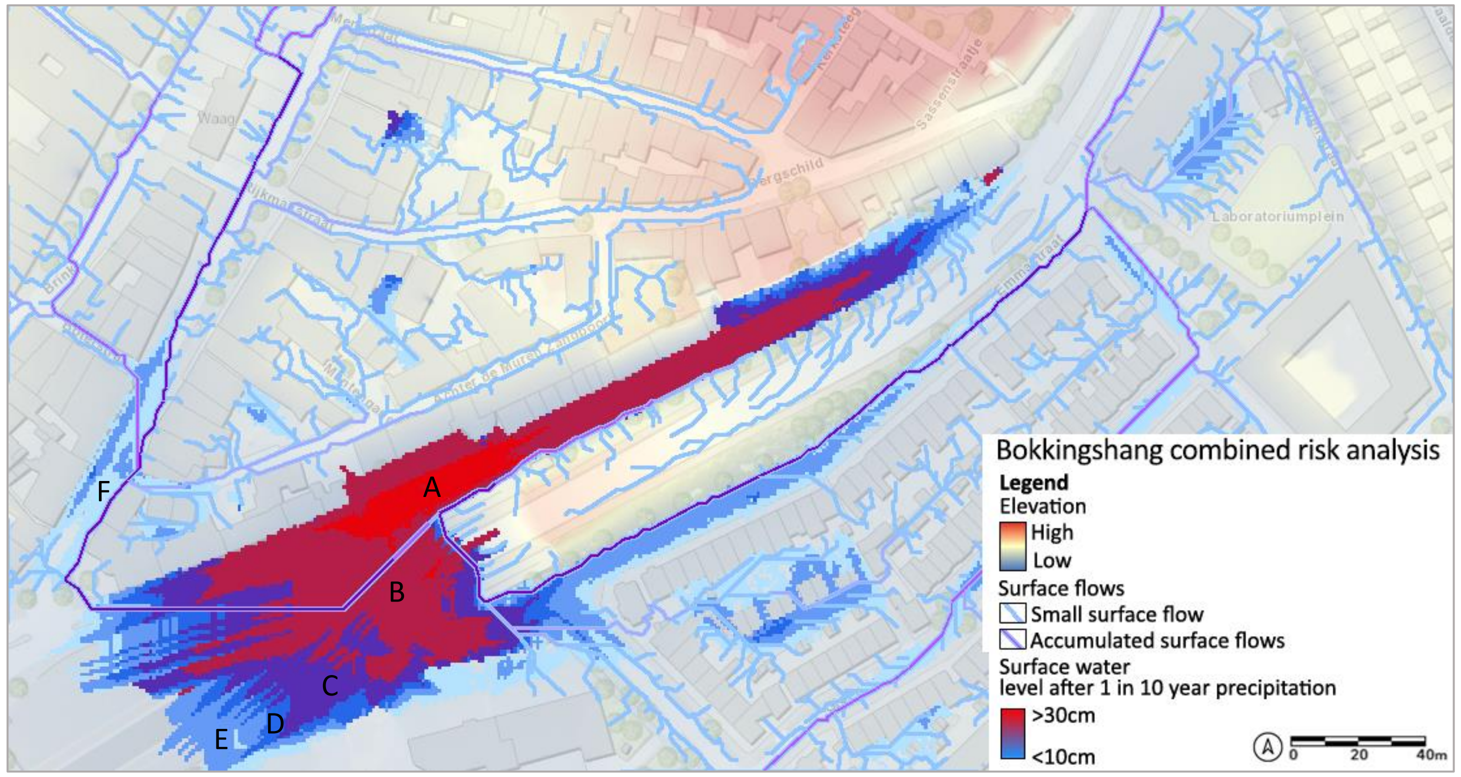


Figure 41: Site-specific risk analysis for vulnerable area 6, the Bokkingshang (figure made by author)

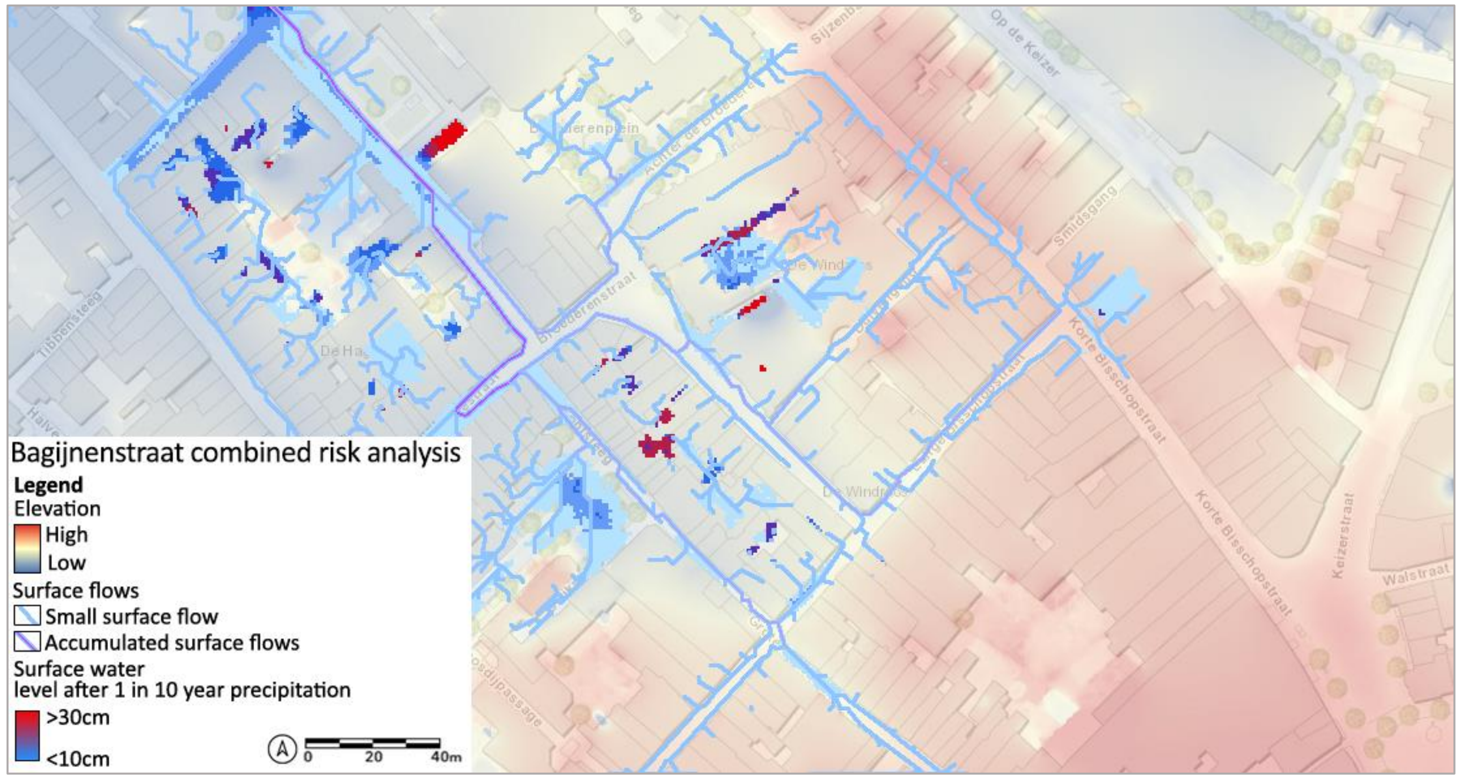


Figure 38: Site-specific risk analysis for vulnerable area 3, the Bagijnenstraat (figure made by author)

Figure 40: Site-specific risk analysis for vulnerable area 5, the Brink (figure made by author)

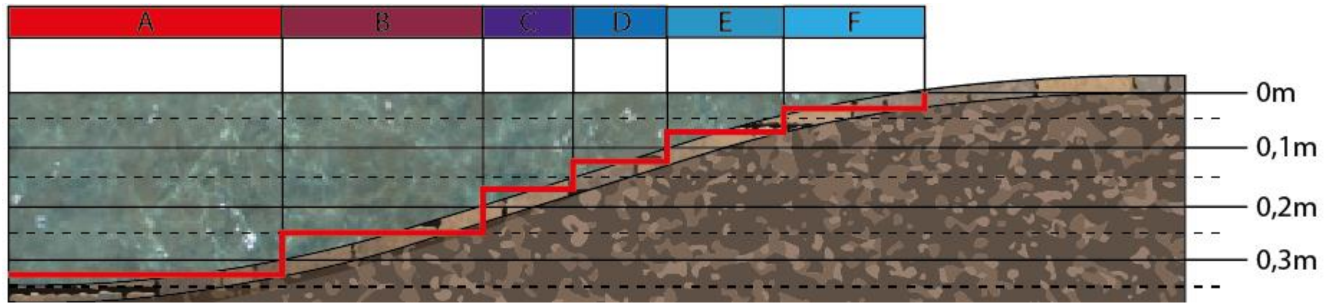


Figure 42: Actual situation and estimation of the surface water depth categories in De Bokkingshang after 1 in 10 year precipitation (figure made by author)

5.2 Hydrological quantification

In order to determine the size of the interventions, the amount of excess water should be calculated. In order to do this, it was calculated that an individual pixel of the surface water layer from the site specific risk analysis was equal to 0,1476m^2. This number is the same for each of these maps, since all risks analyses are represented on the same scale. With this number, the excess water surface for each of the 6 different surface water depth categories A-F (as shown in figure 41 and 42) can be calculated for the vulnerable areas. Then, with the help of the average surface water depth for each category as shown in figure 42, the amount of surface water can be calculated for each of the categories A-F. The total amount of excess water that derives from this calculation is a good indication of the amount of water that should be drained by the landscape interventions to completely prevent urban flooding during a 1 in 10 year precipitation event (36mm rainfall in 45 minutes). The results from these calculations can be found in the tables 7 to 9. The results indicate that the area De Bokkingshang (vulnerable area 6) will have the most pluvial flooding after a 1 in 10 year precipitation event, with approximately 1819,11m^3 of excess water. The areas De Welle (562,80m^3) and De Doelen (393,31m^3) are indicated to be the second and third most vulnerable area, but are substantially less problematic in terms of quantity of excess water.

To give an indication of the size of the high-intensity rainfall measures, 1819,11m^3 of excess water in De Bokkingshang area is equal to 1.819.110 liters of water and requires a rainwater basin size of roughly 43x43x1m. For De Welle, 562,80m^3 of excess water is equal to a basin of approximately 24x24x1m. Lastly, for De Doelen 393,31m^3 of excess water is equal to a basin of approximately 20x20x1m. However, this assumes that no evaporation, infiltration or drainage from the basin takes place.

Evaporation in the Netherlands generally ranges from 0 to 7mm per day (KNMI, 2020b). In summer the evaporation is the highest, on average about 3mm per day. This means that for high-intensity rainfall of 45 minutes the evaporation is very low. Besides that, the evaporation rate heavily depends on the weather, and has minor influence on surface waters in The Netherlands. Therefore, it can be assumed that evaporation rate has minor influence on 1 in 10 year precipitation, and will not be taken into consideration in this rough calculation.

Category (average depth)	Pixels	Surface area (m^2)	Surface water (m^3)
A (0,325m)	433	63,93	20,78
B (0,250m)	2.277	336,16	84,04
C (0,175m)	3.096	547,07	95,74
D (0,125m)	5.157	761,35	95,17
E (0,075m)	6.301	930,24	69,77
F (0,025m)	7.535	1.112,42	27,81
Total	24.799	3751,17	**393,31**

Table 7: Surface water quantification for 36mm rainfall in 45 minutes for area De Doelen (table made by author)

Category (average depth)	Pixels	Surface area (m^2)	Surface water (m^3)
A (0,325m)	75	11,07	3,60
B (0,250m)	5.237	773,16	193,29
C (0,175m)	7.059	1.042,15	182,38
D (0,125m)	3.828	565,14	70,64
E (0,075m)	8.282	1.222,70	91,70
F (0,025m)	5.741	847,57	21,19
Total	30.222	4.461,79	**562,80**

Table 8: Surface water quantification for 36mm rainfall in 45 minutes for area De Welle (table made by author)

Category (average depth)	Pixels	Surface area (m^2)	Surface water (m^3)
A (0,325m)	3.949	583,01	189,48
B (0,250m)	26.732	3946,55	986,64
C (0,175m)	14.599	2155,31	377,18
D (0,125m)	7.893	1165,27	145,66
E (0,075m)	6.780	1000,96	75,07
F (0,025m)	12.215	1803,35	45,08
Total	72.168	10.654,45	**1.819,11**

Table 9: Surface water quantification for 36mm rainfall in 45 minutes for area De Bokkingshang (table made by author)

The infiltration rate of permeable pavement in combination with an infiltration bed and drainage pipe system on similar soil was investigated by Dempsey and Swisher (2003), who found a relatively constant infiltration rate of 170mm/h. This is equal to approximately 128mm in 45 minutes. This infiltration rate can reduce substantially due to lack of maintenance or due to compression of the pavement or infiltration bed (Bean et al., 2007). The coarse stone aggregate infiltration bed of 1,6m deep was found to contain a porosity of 40%, which means that 40% of the total size of the infiltration bed can be used for rainwater retention. A disadvantage of this measure is that the infiltration bed is located below the surface, which means the infiltration has to take place before the basin is reached. In contrast, for rain gardens and water plazas the basin intercepts water before the infiltration or drainage from the basin takes place.

The infiltration rate of a rain garden consisting of a similar soil type and grain size to the soil in the city center of Deventer was investigated by Dietz & Clausen (2005). It was found that this soil type, in combination with a 10,2cm perforated under-drain 2m below the surface, could accommodate an infiltration rate of 38mm/h (Dietz & Clausen, 2005). This is equal to approximately 30mm infiltration in 45 minutes. This rate can be improved if the under-drain is placed closer to the surface, or if the grain size of the soil above the under-drain is increased (e.g. coarse sand or gravel).

The drainage rate of a water plaza depends on the size and structure of the separate sewer system connected to the water plaza. For a water plaza in 's-Hertogenbosch (The Netherlands) of 750m^2 and 0,4m deep, the drainage rate was relatively constant and approximately 225m^3 in 2 hours, which is 84,4mm drainage in 45 minutes (Boogaard et al., 2015; Boogaard et al., n.d.). Water plazas can also be combined with porous pavements and retention crates, in which case the infiltration rate also has an effect on the drainage rate of the rainwater (Amsterdam Rainproof, 2020).

For the largest estimated basin surface size of 43x43m, this would mean that porous pavements on this surface could drain 236,67m^3 in 45 minutes, followed by water plazas with 156,06m^3, and finally rain gardens with 55,47m^3. These numbers can be subtracted from the total amount of excess water for this site (1819,11m^3), which means that the basin surface size of the intervention can be reduced. For the other two vulnerable sites this effect also plays a role, but the infiltration effect is less impactful since the required surface size of the interventions is smaller.

Another aspect that can have a significant influence on the required size for the high-intensity rainfall intervention is the used stormwater transport measures. While street channels do not infiltrate the rainwater, bioswales and especially infiltration trenches already drain some of the water before it reaches the high-intensity rainfall intervention.

The infiltration performance of infiltration trenches depends on the groundwater level and soil type; deep groundwater tables and very permeable soils improve the performance of infiltration trenches (Locatelli et al., 2015). According to Locatelli et al (2015), infiltration trenches can infiltrate 33-43mm/h, depending on the soil type and groundwater level. This is equal to 24,75-32,25mm in 45 minutes for loamy to sandy soils, which is 28,5mm on average.

The infiltration performance of bioswales also depends on the groundwater level and soil type, but also on the potential implementation of check dams (Winston et al., 2019). Monrabal-Martinez et al. (2018) found that bioswales were able to drain approximately 11mm/h, which is equal to 8,25mm in 45 minutes. However, the infiltration capacity can be improved by the infiltration of check dams, but this will negatively affect the flow rate during high-intensity rainfall events (Winston et al., 2019).

Furthermore, while bioretention planters are most effective against high-frequency rainfall, they also infiltrate rainwater during high-intensity rainfall. It was found that bioretention planters could infiltrate 25-32mm/h for extreme rainfall events, depending on the design, soil and vegetation of the planter (Guerra et al., 2018). This is 28,5mm/h on average, which is equal to 21,4mm infiltration in 45 minutes.

Finally, the rainwater interception performance of 0,5m thick, fully foliated green walls for heavy rainfall events was found to be approximately 25mm/h, which is equal to 18,8mm in 45 minutes (Tiwary et al., 2015). However, this performance is very dependent on the wind direction and speed, since green walls are vertical interventions and can intercept more rainwater if the wind blows water towards the green wall.

If there are flat roofs in the neighborhood, green roofs can be also be implemented to intercept rainwater. Intensive green roofs with sedum vegetation can only retain 8mm of water, because the less infiltration bed is very thin (Villareal, 2007). Extensive green roofs have a thicker infiltration bed, and can retain on average 38,3mm (Baryła et al., 2017). Green roofs have an infiltration rate of 8mm/h (Speak et al., 2013). This is equal to 6mm in 45 minutes.

With the help of these indications for the drainage capacity of the different intervention types, the required size of the interventions and the most optimal type of intervention can be determined accurately. This will be done in the next section, where the design of the interventions in the vulnerable areas will be investigated.

5.3 Site-specific design implementation

In this section, the landscape interventions will be applied to the vulnerable areas, taking the quantity of excess rainwater after 1 in 10 year precipitation into account. Of course, this is not the only possible configuration and distribution of the intervention types and sizes. Other possible solutions could be composed with the help of the design guidelines, and the quantification and sizing of the interventions can be done relatively easily with the help of the calculations in this chapter. However, the intervention types and sizes as described in this section will deal effectively with high precipitation rainfall and also high-frequency rainfall, and can completely retain and drain the excess rainwater of 1 in 10 year precipitation. Furthermore, the image and atmosphere of the historical city center is taken into account, as well as the factors mentioned in the multi-criteria analysis.

For vulnerable area the Bokkingshang, a total of 1819,11m^3 excess water after 1 in 10 year precipitation has to be drained to prevent urban flooding. In table 10, the applied interventions and the surface size of the interventions is shown, together with the infiltration and drainage within 45 minutes and the retention capacities of the interventions. In figure 43, the implementation of the interventions in the vulnerable area is shown.

Table 10 clearly shows that the high-intensity rainfall measures (the first 3 interventions) drain high-intensity rainfall most effectively. In this case extensive green roofs also infiltrate relatively high quantities of water, but this is due to the fact that the surface area of this intervention is very large. Furthermore, the basins of rain gardens and the water plaza also intercept relatively large quantities of water. The reason some retention values are not shown in the basin column is that the basins of these interventions are used after the water is infiltrated. This means that only the amount of water that has been infiltrated or drained is retained in the basin, but not any extra water.

In order to prevent flooding is this area, the supplying surface flows to the area with the most severe flooding should be intercepted by interventions. In most cases, this has been done with street channels, since there is not much space in the dense urban tissue for larger interventions. In the east of the vulnerable area, two extensive green roofs were added to large commercial buildings, in order to limit excess rainwater coming from these large roofs. Furthermore, bioretention planters are implemented mainly to limit high-frequency rainfall flows, but also reduce high-intensity rainfall. In the norths of the vulnerable area, the street channels are directed to a water plaza, which is located in front of an important historical building, “De Waag”. The reason that a water plaza was placed here is that there are often events and markets on this square, which can still continue if the water plaza is dry.

Moreover, in the area where many surface flows come together during heavy rainfall events, permeable pavements are added to drain a large part of the excess water. Permeable pavement is possible here, since these streets are relatively narrow, and there is very little and slow-driving traffic. If the infiltration bed consists of a material with porosity of 40%, which is common for permeable pavement infiltration beds, the infiltration has to be 30cm deep in order to intercept the total amount of infiltrated water of the permeable pavement in the 45 minutes of 1 in 10 year precipitation.

Besides that, the vulnerable area itself should also be able to infiltrate and drain more rainwater during heavy rainfall events. In order to do this, rain gardens were added in areas which are landscape depressions and where currently no buildings are located. These rain gardens were connected by underground pipes to better distribute the water over the rain gardens. Furthermore, green walls were added around a parking garage to intercept some of the rainwater coming from these floors, but also to reduce the effect of high-frequency rainfall. Also, an infiltration trench was added besides a large slope to infiltrate the excess water coming from the road above this slope.

In total, these interventions intercept or drain 1474,6m^3 of the 1819,1m^3 excess water after 45 minutes of 1 in 10 year precipitation. This means that 344,5m^3 of excess water is left, which is drained by a separate sewer pipe, leading directly to the river in the south-west. This polypropylene pipe will be 160m and has a slope of 20mm/m. The pipe will have to drain 344,5m^3 in 45 minutes to drain all the leftover excess water, which is equal to 127,6L/s. The required diameter of the pipe can be determined

Intervention	**Surface area (m^2)**	**Infiltration or drainage in 45 minutes (m^3)**	**Retention in basin (m^3)**
Rain gardens	983,0	29,5	589,8
Water plaza	364,6	30,6	182,3
Permeable pavement	4424,2	512,4	-
Green walls	141,0	2,7	-
Extensive green roofs	2284,7	87,5	-
Bioretention planters	34,5	1,0	3,5
Infiltration trench	198,0	5,6	29,7
Total	8430,0	**669,3**	**805,3**

Table 10: Drainage and retention capacity for the landscape interventions of area De Bokkingshang (table made by author)

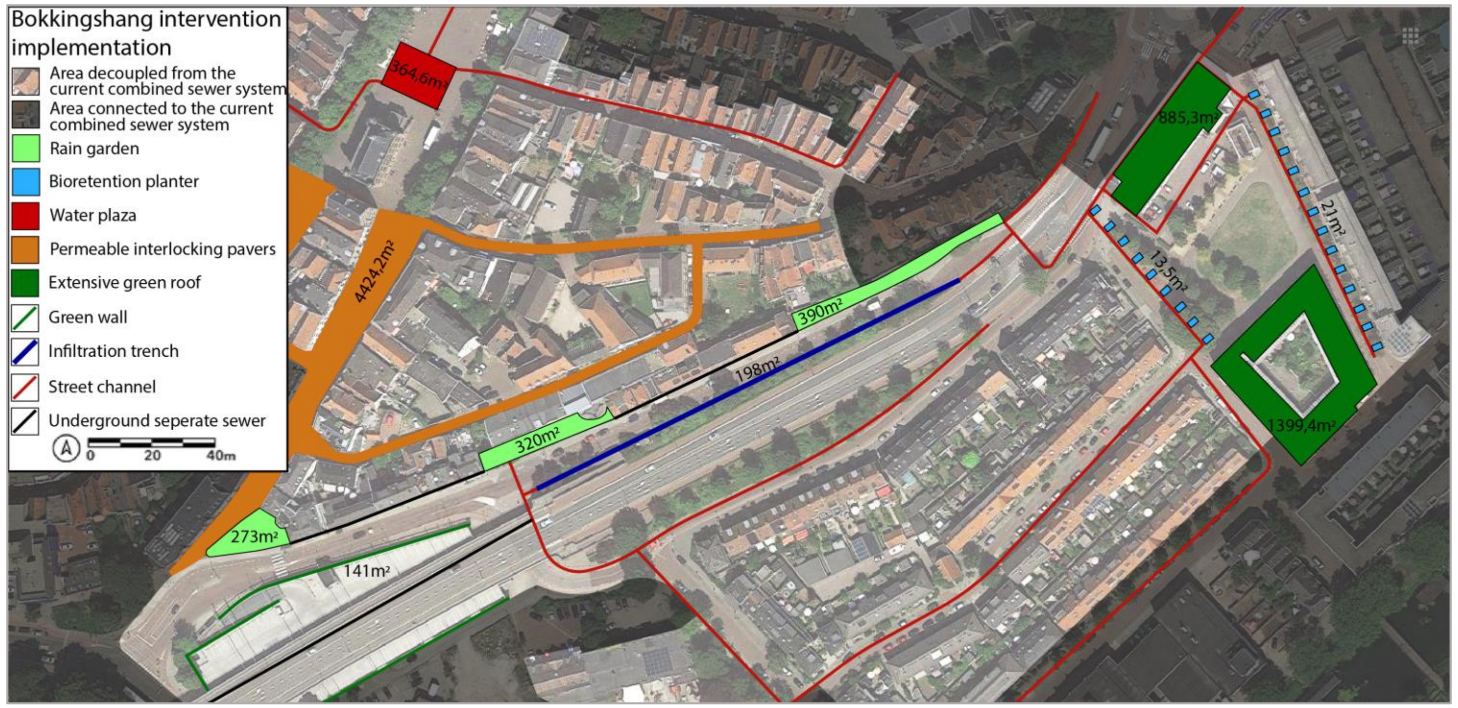


Figure 43: Intervention implementation for De Bokkingshang (figure made by author)

with the chart in appendix I. Looking at the blue lines in this figure, the diameter of the pipe should be approximately 0,3m to drain all the excess water of 1 in 10 year precipitation events.

For vulnerable area De Welle, a total of 562,80m^3 excess water should be drained in order to prevent urban flooding. In table 11, the infiltration or drainage capacity and the retention capacity of the implemented interventions as seen in figure 44 is shown.

For this vulnerable area, most of the excess water is transported by street channels to the river, which functions as a large basin for the excess water. Therefore, it is not necessary to implement large basin interventions in this area, which means the retention capacity for this area is minimal. However, interventions which improve infiltration and drainage from this vulnerable area were implemented. For example, extensive green roofs were added on the city hall to improve intercept rainwater during heavy rainfall events, since the roof on this large building was the start of a large surface flow during heavy rainfall events which led to flooding on the main road in the south of the area. Furthermore, bioretention planters were added next to a main square, to intercept much of the rainwater flowing from this square and the surrounding streets during heavy rainfall events. Permeable pavements were added to some of the most problematic areas in relatively narrow streets with little and slow traffic, in order to prevent surface flows from flooding the main road in the south.

In total, these interventions intercept or drain 364,6m^3 of the 562,8m^3 excess water after 45 minutes of 1 in 10 year precipitation. Therefore, 198,2m^3 of excess water still has to be drained by the street channels next to the main road in the south, which transport the excess water to the river. An underground polypropylene pipe of 12m was implemented to connect the street channels on both sides of the road with each other. This pipe has a slope of 50mm/m and has to drain 198,2m^3 in 45 minutes, which is equal to 73L/s. With the help of the green lines in appendix I, it was determined that the diameter of the pipe should be approximately 0,2m.

Intervention	Surface area (m^2)	Infiltration or drainage in 45 minutes (m^3)	Retention in basin (m^3)
Permeable pavement	2673,1	342,2	-
Extensive green roofs	548,4	21,0	-
Bioretention planters	10,5	0,3	1,1
Total	3232,0	**363,5**	**1,1**

Table 11: Drainage and retention capacity for the landscape interventions of area De Welle (table made by author)

Figure 44: Intervention implementation for De Welle (figure made by author)

For vulnerable area De Doelen, a total of 393,31m^3 excess water should be drained in order to prevent urban flooding. For this vulnerable area, all the excess water should be intercepted by the interventions since the river or other surface waters are located relatively far from this vulnerable area. In table 12, the infiltration or drainage capacity and the retention capacity of the implemented interventions is shown. In figure 45, the implementation of the interventions in vulnerable area De Doelen is shown.

In this area, many street channels were implemented to transport the rainwater through narrow but sloped streets to high-intensity rainfall interventions. A bioswale was also added in one of the wider and more sloped streets, to promote infiltration and effectivity against high-intensity rainfall. The street channels and bioswale lead to rain gardens or permeable pavements. Extensive green roofs were added on some of the larger buildings, in order to prevent surface flows during heavy rainfall events starting from these large roofs. Intensive green roofs were added to some buildings in the north-west, in order to stop the small surface flows coming from these roofs during heavy rainfall events. Green walls were added to a large apartment complex in the middle of the vulnerable area in order to intercept some of the rainwater, but also to create awareness for climate change and extreme rainfall events and to improve the urban microclimate in summer. Furthermore, bioretention planters were added to the most vulnerable site to intercept rainwater during high-intensity precipitation events, but mainly also during high-frequency precipitation events.

In total, these interventions can intercept or drain 418,3m^3 excess water after 45 minutes of 1 in 10 year precipitation, which should be ample to prevent 1 in 10 year precipitation flooding and sewer overflows.

Intervention	Surface area (m^2)	Infiltration or drainage in 45 minutes (m^3)	Retention in basin (m^3)
Rain gardens	462,2	13,9	138,7
Permeable pavement	847,1	108,4	-
Green walls	250,0	4,7	-
Intensive green roofs	1476,2	11,8	-
Extensive green roofs	2979,2	114,1	-
Bioretention planters	16,5	0,5	1,7
Bioswale	154,9	1,3	23,2
Total	6186,1	**254,7**	**163,6**

Table 12: Drainage and retention capacity for the landscape interventions of area De Doelen (table made by author)

Figure 45: Intervention implementation for De Doelen (figure made by author)

5.4 Vegetation

Many of the mentioned interventions, such as rain gardens, bioretention planters and bioswales, need appropriate vegetation. The vegetation should be planted based on the soil type, groundwater level, exposure to sunlight, exposure to flooding, and aesthetics. Since most vegetation will be planted in locations which will intercept or accumulate rainwater, the chosen vegetation should be resistant to wet soil and occasional flooding.

The great majority of plants that will be used in the design of the stormwater interventions for the historical city center of Deventer are native plants. The reason for this is that native plants are best adapted to the local climate and soil conditions, and non-native species have the risk to become an invasive species (Alpert et al., 2000). All the plants that can be used in the design of the stormwater interventions for the historical city center of Deventer are shown in figure 46, and are classified by their ability to withstand wet soils and frequent flooding and their preferred exposure to sunlight. The native flowers, grasses, ferns, and shrubs that are shown in the figure are some of the plants that were mentioned by Yuan et al. (2017) and Dunnett (2021) as appropriate plants for bioretention interventions, because of their ability to withstand periodic saturation and flooding, but also potential drought. The native trees that are shown in the figure are some of the trees that were mentioned by Amsterdam Rainproof (2021) as trees that can grow in wet soils and are resistant to periodic flooding, but are also resistant to periods of drought. It was also mentioned that these trees are often classified as climate-trees, since they are resistant to climate change circumstances, but also provide cooling in urban environments. The complete planting matrix with more comprehensive information about all the vegetation species can be found in appendix II.

Scanlon (2020) mentions 4 other important aspects of planting design for green rainwater interventions in urban environments which will be included in the design of the stormwater interventions. These 4 aspects are:

1. Ground cover. Plants with relatively shallow rooting depths are effective in retaining rainwater during heavy rainfall events.
2. Seasonal themes. Plants flowering in varying seasons provide visual impact for people and interest for pollinators. The chosen vegetation for the interventions in the city center of Deventer with the corresponding seasonal themes are shown in figure 47. In all seasons there are some beautiful and eye-catching plants, but in spring and summer the vegetation will be particularly colorful.
3. Filler. All of the available soil should be planted, in order to avoid highly-competitive species to take up the available space and compete against the other species.
4. Structural planting. Structure in the planting is important to preserve sight lines, and ensures that plant species are in the most optimal locations for their growing conditions. For the interventions in the city center of Deventer the block planting structure will be used, which is a formal aesthetic including groups of plants and small blocks of interest in relatively simple patterns (Scanlon, 2020). Advantages of this planting structure is that sightlines can easily be embedded in the planting structure, and it is relatively easy to maintain due to relatively simple patterns and groups of plant species.

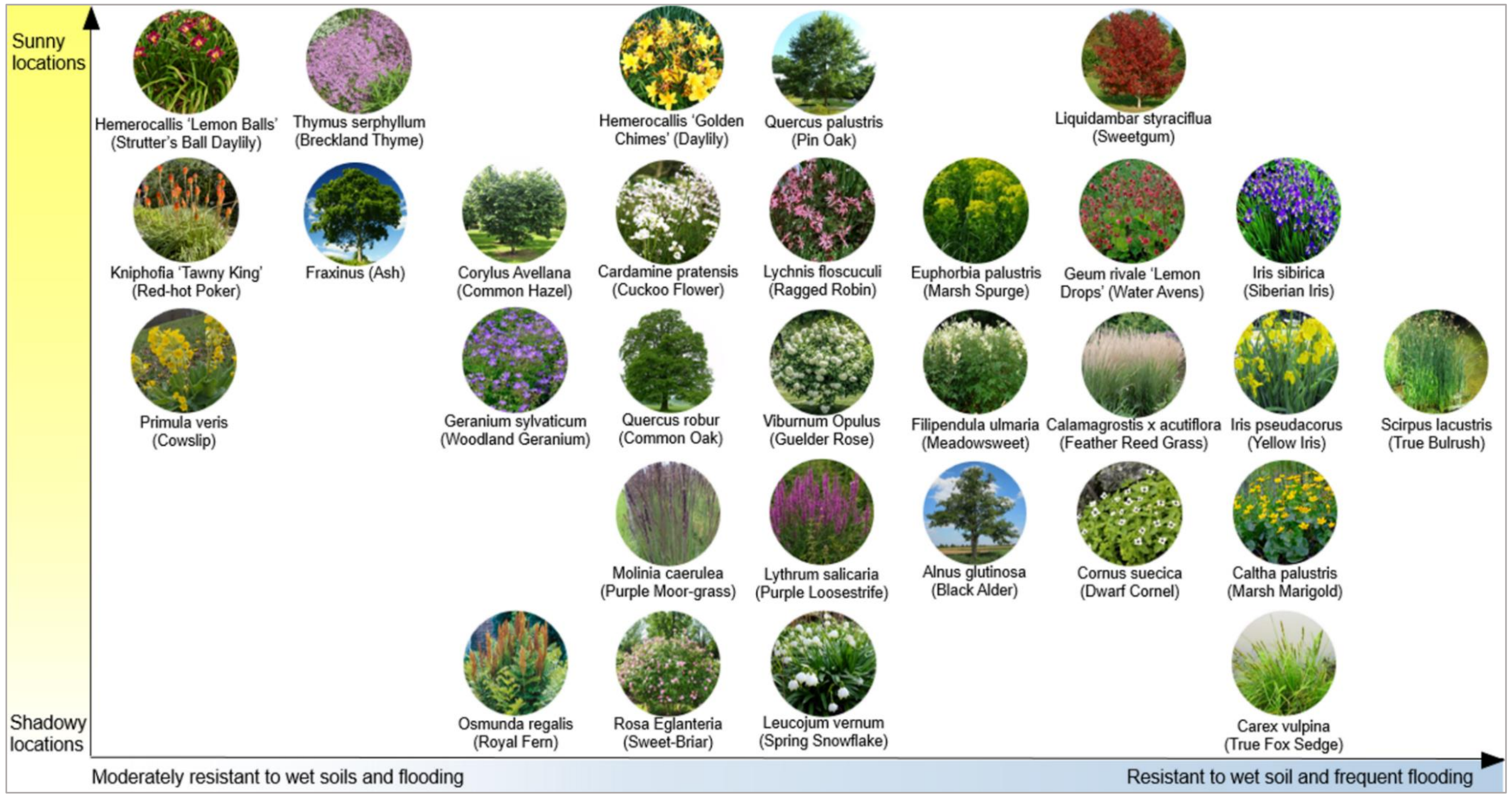
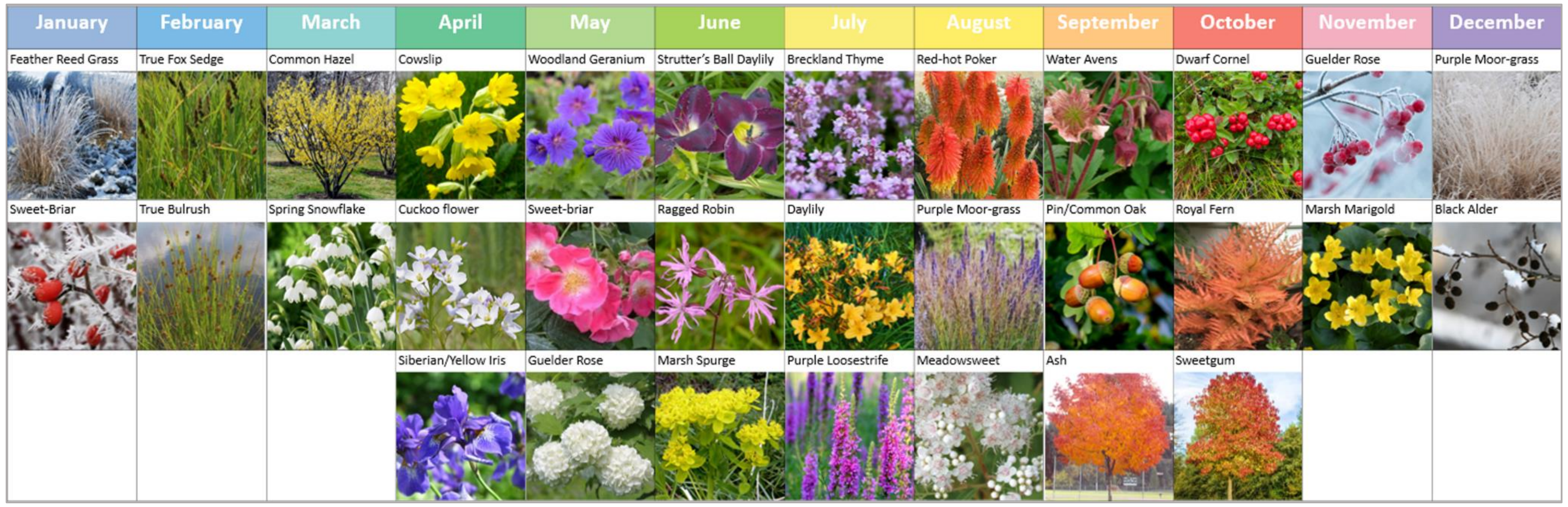


Figure 46: Vegetation scheme showing all possible species and their resistance to sunlight exposure, wet soil and flooding (figure made by author)



January	February	March	April	May	June	July	August	September	October	November	December
Feather Reed Grass	True Fox Sedge	Common Hazel	Cowslip	Woodland Geranium	Strutter's Ball Daylily	Breckland Thyme	Red-hot Poker	Water Avens	Dwarf Cornel	Guelder Rose	Purple Moor-grass
Sweet-Briar	True Bulrush	Spring Snowflake	Cuckoo flower	Sweet-briar	Ragged Robin	Daylily	Purple Moor-grass	Pin/Common Oak	Royal Fern	Marsh Marigold	Black Alder
			Siberian/Yellow Iris	Guelder Rose	Marsh Spurge	Purple Loosestrife	Meadowsweet	Ash	Sweetgum		

Figure 47: Vegetation scheme showing periods of interest for the different plant species during the year (figure made by author)

6 Detailed design

Site-specific design for the most vulnerable area within the historical city center of Deveter

6.1 Masterplan De Bokkingshang

A detailed design will be made for De Bokkingshang for the design part of this thesis. This area was chosen because in section 5.2 it was identified that this area was the most vulnerable to pluvial flooding and combined sewer overflows within the city center of Deventer. The design for De Bokkingshang will function as example on how rainwater interventions can be designed for a historical city center.

This vulnerable area was named after De Bokkingshang street, which is the street which was predicted to get the most pluvial flooding after a heavy rainfall event. It is located just north and parallel to the main street in this area, which leads to the bridge over the river IJssel. On the other side of De Bokkinshang street, there is the historical city wall, and mainly commercial buildings. Until 2011, these buildings were mainly used for prostitution. Currently there are only a few buildings left which are used for prostitution. Gentrification has taken place in this street, and most of the properties are now renovated and used as commercial buildings.

This design aims to not only address pluvial flooding and combined sewer overflows in this street and the entire vulnerable area, but also to give people a chance to experience and enjoy urban nature and rainwater collection, and to improve the environmental conditions and microclimate, to promote biodiversity and to improve public health.

With the help of the intervention implementation maps of chapter 5.3, a masterplan was created for vulnerable area De Bokkingshang. This masterplan is shown in figure 48. The plan shows how the interventions are located especially in the parts of the area which are most prone to flooding, but are also located in surrounding areas to intercept supplying surface streams during heavy rainfall events. Furthermore, it shows how very little has to be changed to the current urban tissue and infrastructure; many of the interventions are multifunctional, and most of the interventions are implemented in spaces which are currently not built up and not widely used. In the next sections of this chapter detailed designs for individual interventions will be shown and explained. The outlined interventions will be elaborated in plan maps, sections and visualizations.

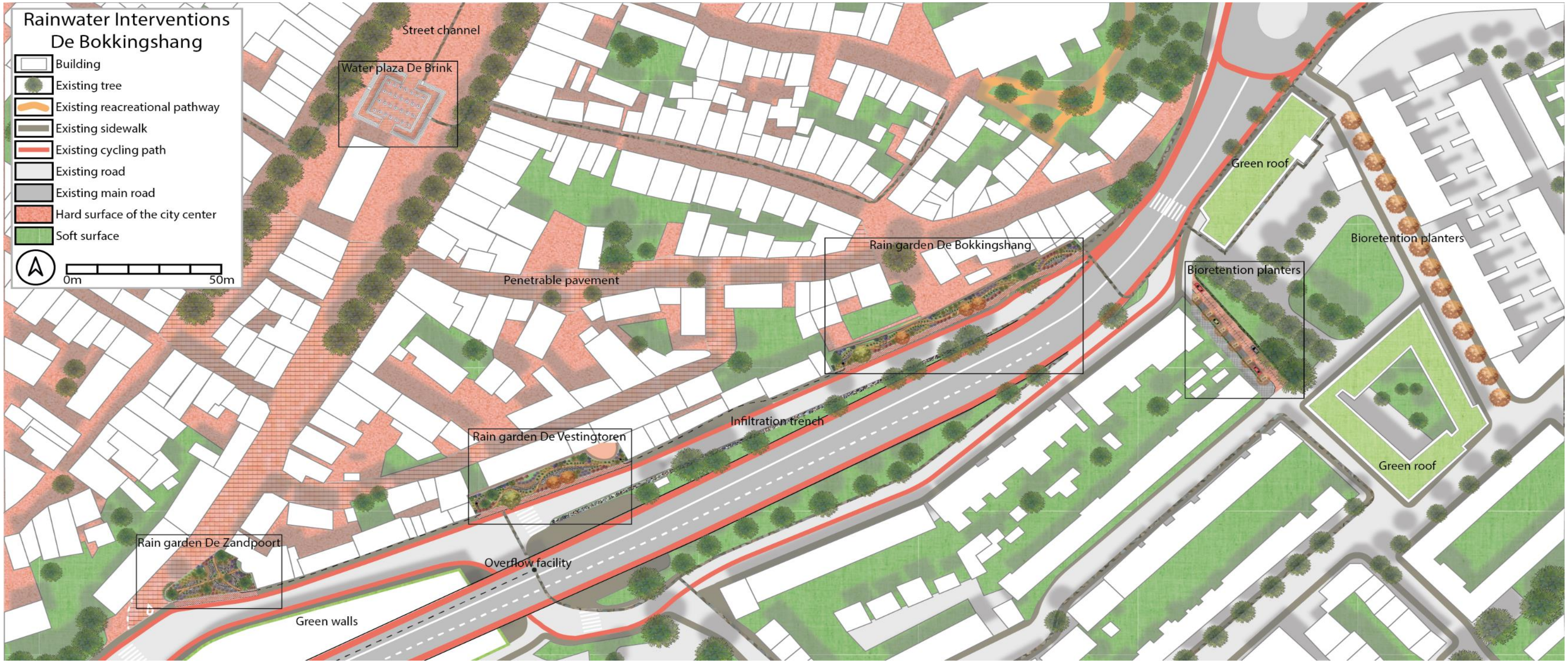


Figure 48: Rainwater interventions within vulnerable area De Bokkingshang (figure made by author)

6.2 Design penetrable pavement

The penetrable pavement as implemented in vulnerable area De Bokkingshang is based on permeable pavement designs by Alam et al. (2019) and Smith (2020), and consists of multiple layers (see figure 49). The top layer consists of permeable pavers with voids between the individual pavers to allow water to pass through this layer quickly. The pavers are laid in an interlocking pattern for firmness and similarity with the pavement used in the rest of the historical neighborhood. The underlying layer is an open graded bedding, which keeps the pavers in place while also accommodating the needed water flow through this layer. The following layer is an open-graded base reservoir, which can store the water for some time. The next layer is a bigger open-graded base reservoir, with a higher void ratio for more water storage capacity. These layers are surrounded by geotextile, which separates and contains the reservoir layers from the soil and bedding around it and prevents the layer materials from getting mixed.

In this and many of the other interventions, a perforated underdrain pipe is used below the intervention. These underdrains can discharge excess water if the soil substrate below the intervention cannot take up all the water during a precipitation event. The underdrain pipes are perforated at the top half, to allow water to enter the pipe if the surrounding gravel layer is saturated with rainwater. The soil and gravel layers laying on top of the pipe function as filters, which will remove particles from the rainwater. Because of this, the water in the underdrain will be relatively clean. The rainwater that is intercepted by a perforated underdrain is collected in an interconnected network of pipes between the interventions, leading to the river IJssel. The river is relatively close to the interventions in this vulnerable area. The water from the underdrain network can be discharged in the river directly, since the gravel layers on top of the underdrains filter out the debris and small particles in the water that is intercepted by the interventions.

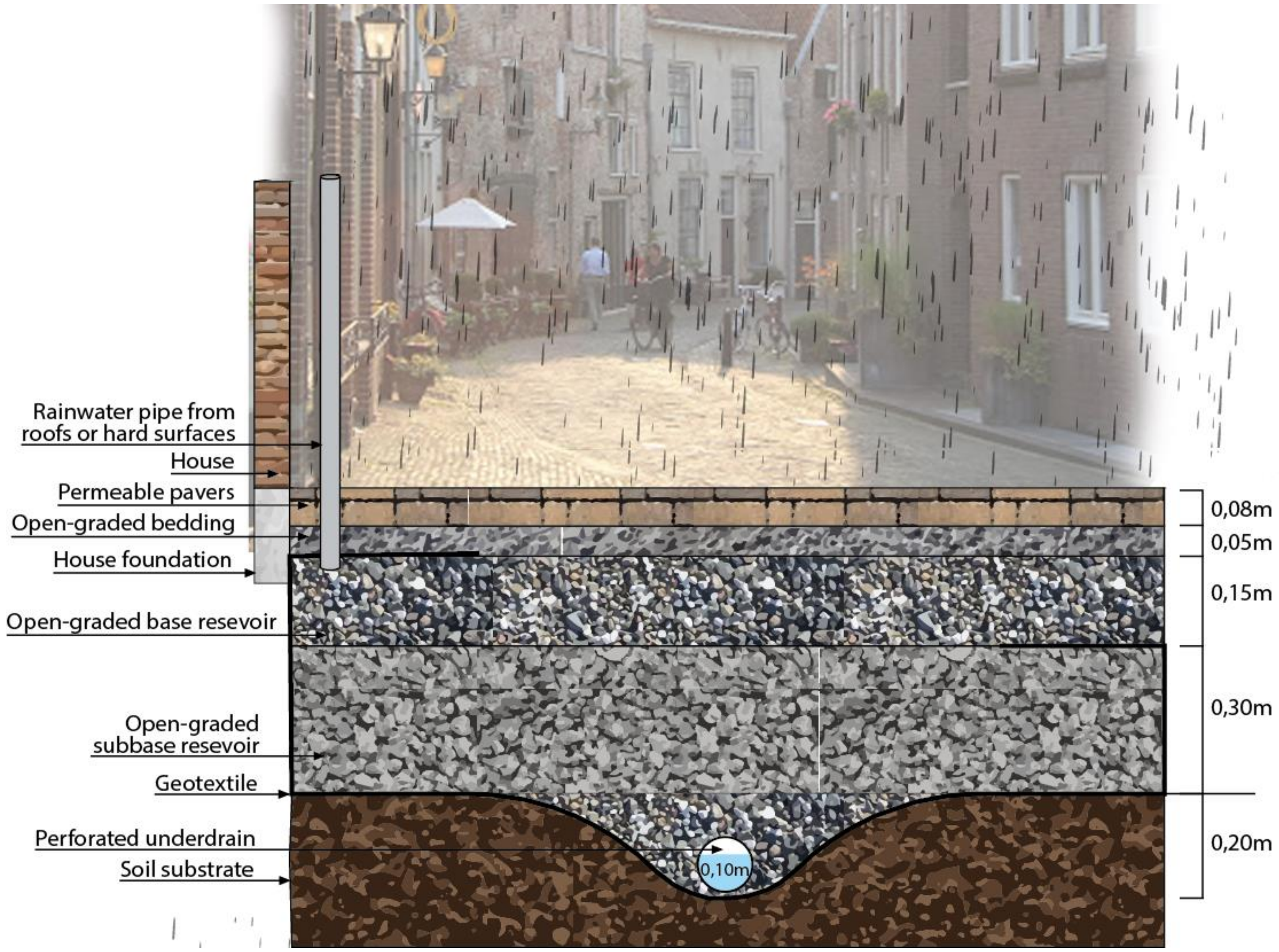


Figure 49: Cross-section of a penetrable pavement as implemented in vulnerable area De Bokkingshang (figure made by author)

The rainwater discharge pipes of the roofs of buildings connected to the rainwater interventions can be connected to the rainwater interventions, in order to further reduce the chance of combined sewer overflows. The rainwater pipes of buildings can for example be connected to the reservoirs of the rain gardens or bioretention planters, can be connected to base reservoirs of permeable pavements, or can be connected to street channels.

It is important to clean infiltration interventions like permeable pavements regularly, in order to avoid pores in the infiltration materials to be filled with debris or small particles. This is especially the case for permeable pavements. If the pores in the infiltration material are filled with debris or small particles, the functionality of the intervention will decrease.

6.3 Design Stormwater transport measures

The infiltration trench in De Bokkingshang is located between the street which is most prone to pluvial flooding, and a big slope which bears a main road leading to a bridge over the river. During heavy rainfall events, a lot of rainwater will flow from these two areas towards the infiltration trench. The design of the infiltration trench in De Bokkingshang is shown in figure 50. The infiltration trench design is based on a design by Stauffer (2020) and works in the first place as a reservoir, intercepting and temporarily storing the rainwater in the highly porous gravel and stone granulate layers. When rainwater accumulates in the trench, some of the rainwater will infiltrate through the permeable geotextile into the soil substrate. If the infiltration rate of the soil does not suffice, the excess water will be discharged via the infiltrated underdrain. This means the underdrain here is used as assurance measure, and will only function during extreme rainfall events.

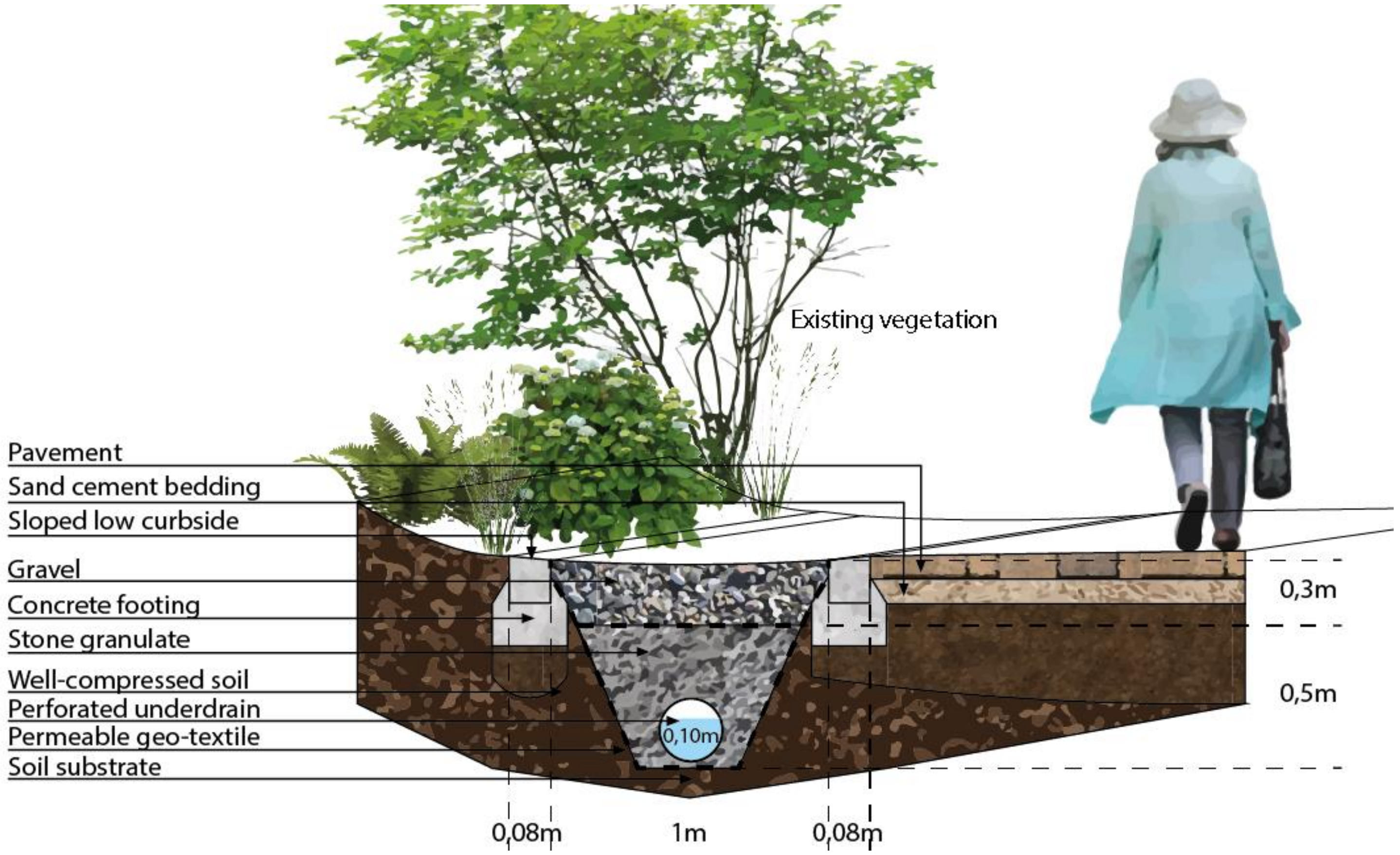


Figure 50: Cross-section of an infiltration trench as implemented in vulnerable area De Bokkingshang (figure made by author)

The elected shape of the street channels is a shallow and wide, which provides more safety for cyclists and pedestrians in the streets of the historical city center than deep and narrow street channels would (see figure 51). Furthermore, they can create awareness for climate change and pluvial flooding due to their visual appeal and high visibility of the stormwater in the channel.

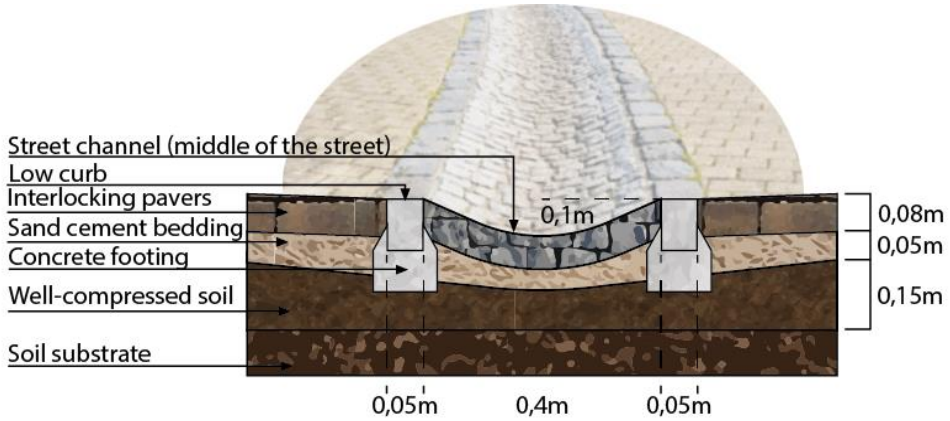


Figure 51: Cross-section of a street channel as implemented in vulnerable area De Bokkingshang (figure made by author)

6.4 Design water plaza

In figure 52, the design of the water plaza in vulnerable area De Bokkingshang is shown. The water plaza is located on one of the main squares of Deventer, De Brink. The water plaza lies in front of a monumental and eye-catching historical building, named De Waag. This is a 16th-century weighing house, where goods of merchants were weighed (Museum de Waag, 2021). It is the oldest weighing house of The Netherlands, and it is currently used as a museum. The water plaza is named after this building. The design of the square consists of straight corners and lines, which is in similarity with the design of the main square and surrounding buildings.

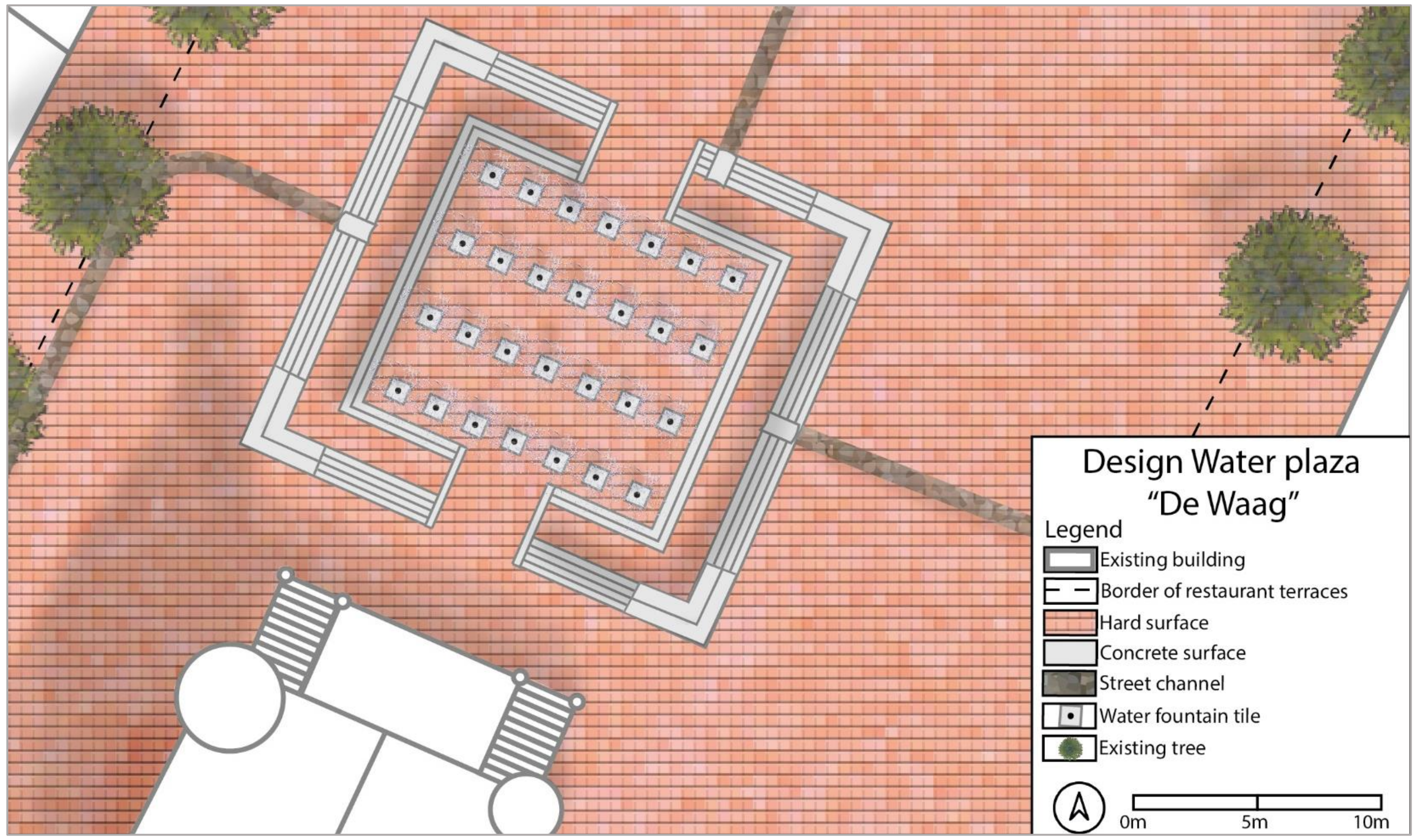


Figure 52: Design map of the water plaza in vulnerable area The Bokkingshang (figure made by author)

Figure 53: Cross-section of the water plaza in vulnerable area The Bokkingshang (figure made by author)

The style of the water plaza is formal. No striking colors, shapes or ornaments are used, but instead the water plaza blends in well with the surrounding buildings. The plaza is rectangular, almost a square, with an elevated middle platform. The middle platform has a multitude of water fountains embedded in the pavement, which can accentuate and enhance the view on the historical Waag building if they are activated. Furthermore, the water fountains add a playful element and a soothing sound element to the square. Every week a market is held on the Brink square, which can also continue on the middle square of the water plaza. The water plaza does not only intercept rainwater which directly lands in the plaza, but also drains water from the street channels which come from surrounding housing blocks.

In figure 53, a cross-section of the water plaza is shown. This section shows how the low edges of the plaza will intercept rainwater first, which will be drained by a linear cut in the middle of the low section. This intercepted water will be filtered and pumped towards the water fountains. This water will then flow to the edges of the square again, which means the water can be reused. The stairs on the sides of the plaza can be used to get to the middle platform, but can also be used as sitting space to relax or enjoy the view. Overflow facilities are implemented in the highest step of the stairs. These will only function during extreme precipitation events, and will prevent overflow of rainwater plaza to the Brink square.

Visualizations of the water plaza during clear weather and heavy rainfall are shown in respectively figure 54a and 54b. During clear weather, the plaza can be used for playing, markets and sitting on the stairs. During heavy rainfall events, the plaza is used for rainwater interception and storage. However, the fountains can still be used if the plaza is filled for less than 0,4m.

Figure 54a: Visualization of the water plaza in vulnerable area The Bokkingshang in a clear weather situation (figure made by author)

Figure 54b: Visualization of the water plaza in vulnerable area The Bokkingshang during a heavy rainfall event (figure made by author)

6.5 Design bioretention planters

The design of the bioretention planters in De Werfstraat in vulnerable area De Bokkingshang is shown in figure 55. In this specific area, the bioretention planters are used as elements to divide the parking lots along the street. The parking lots are each 6m long, which provides space for the cars to park but also space to access the hood or trunk of the car (TUDelft, n.d.). The street is sloped, which means rainwater landing on the street either flows to the hedgerow and playground on the one side of the street, or to the bioretention planters. This also means that supplying streams flowing through this street during heavy rainfall events, will be drained on both sides of the street.

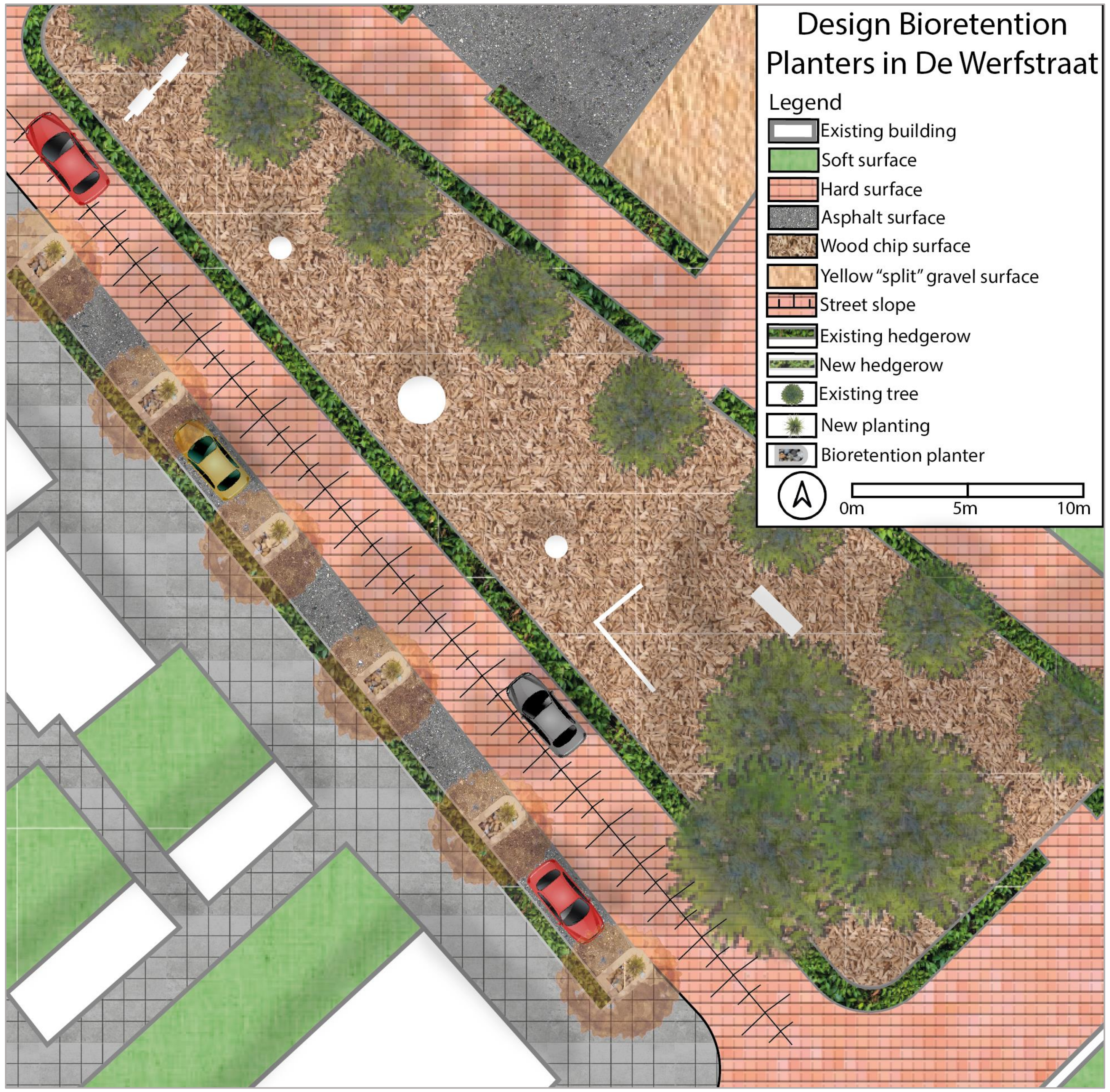


Figure 55: Design map of the bioretention planters in De Werfstraat in vulnerable area The Bokkingshang (figure made by author)

In figure 56, a visualization of bioretention planters in the more eastern located Hallenstraat during clear weather is shown. This visualization shows how the sweetgum trees in the bioretention planters with the rust colored leaves during autumn add to the industrial atmosphere of the buildings and houses in this area. Furthermore, it shows how the high native grasses and flowering plants fit well with the small urban park on the other side of the road. The bioretention planters provide spaces on the sidewalk where people can stand still for a moment and have a chat.

Figure 56: Visualization of the bioretention planters in De Hallenstraat in vulnerable area The Bokkingshang (figure made by author)

A cross-section of a bioretention planter as implemented in the Bokkingshang area is shown in figure 57. The layered design is based on a bioretention planter design as described by Silva (2019). During a rainfall events, rainwater will flow from the street or sidewalk into the bioretention planter. During light rainfall events, all rainwater will be infiltrated into the soil or taken up by the plants. A shallow gravel layer is added on top of the tree roots, to ensure that the roots will receive sufficient water. During heavy rainfall events, water will reach the gravel layer in the lowest part of the planter, and will flow down to the stone granulate layer below. These layers have a high void ratio, and therefore function as rainwater storage reservoirs. If the infiltration performance of the soil substrate below the storage layers is not sufficient to drain all the rainwater, the storage layers and the retention planter basin itself will fill up with water and the perforated underdrain will be filled up. Similarly as for the infiltration trench, the underdrain is here also used as assurance measure, to ensure that the planter will not overflow during heavy rainfall events. The planting in the bioretention planter is resistant to very wet soils and frequent flooding, and flourish in semi-shady or sunny locations. Furthermore, the sweetgum trees, purple moor-grass and feather reed grass are beautiful throughout the whole year, while the water avens will be especially beautiful during their flowering period in summer.

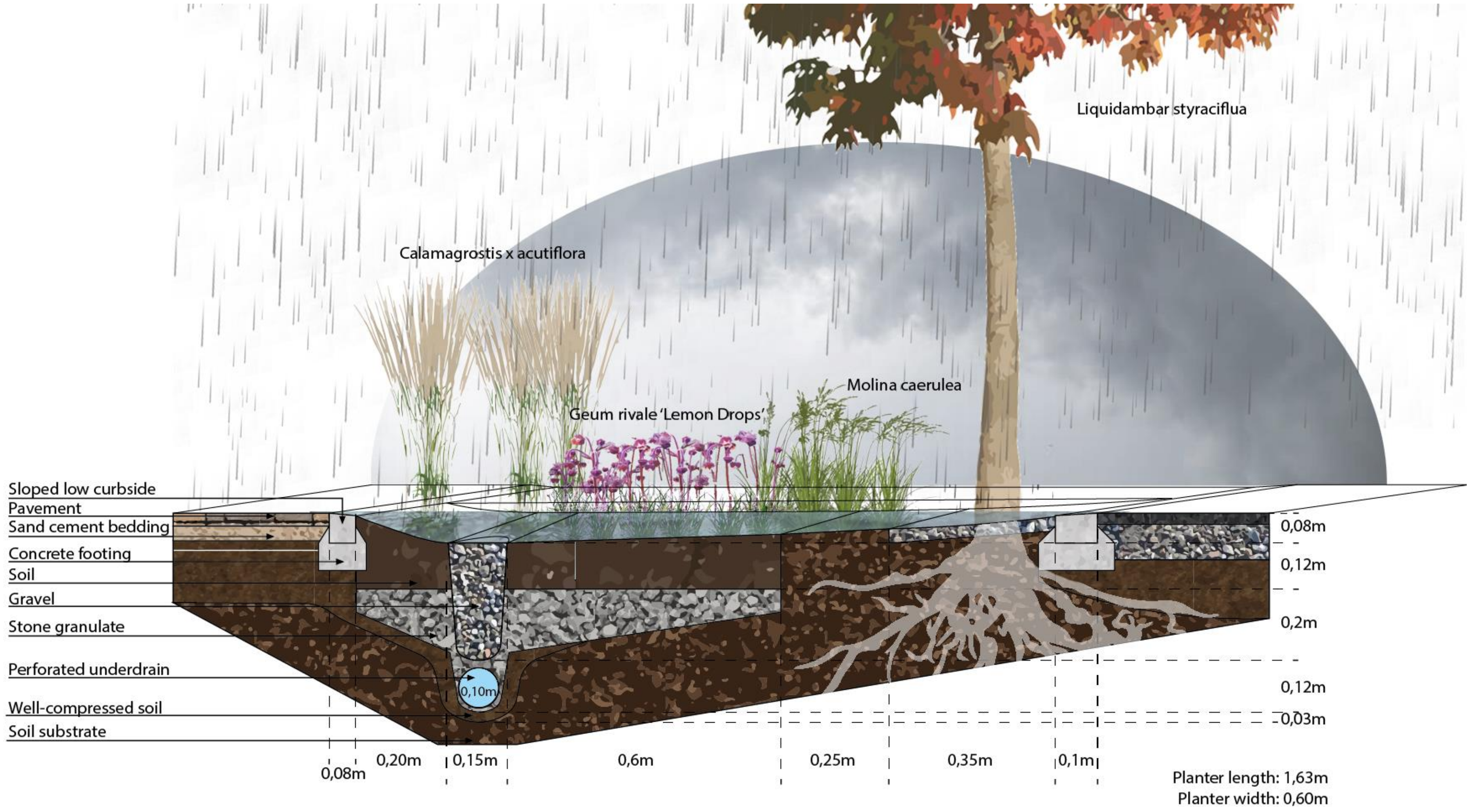


Figure 57: Cross-section of a bioretention planter during a heavy rainfall event in vulnerable area The Bokkingshang (figure made by author)

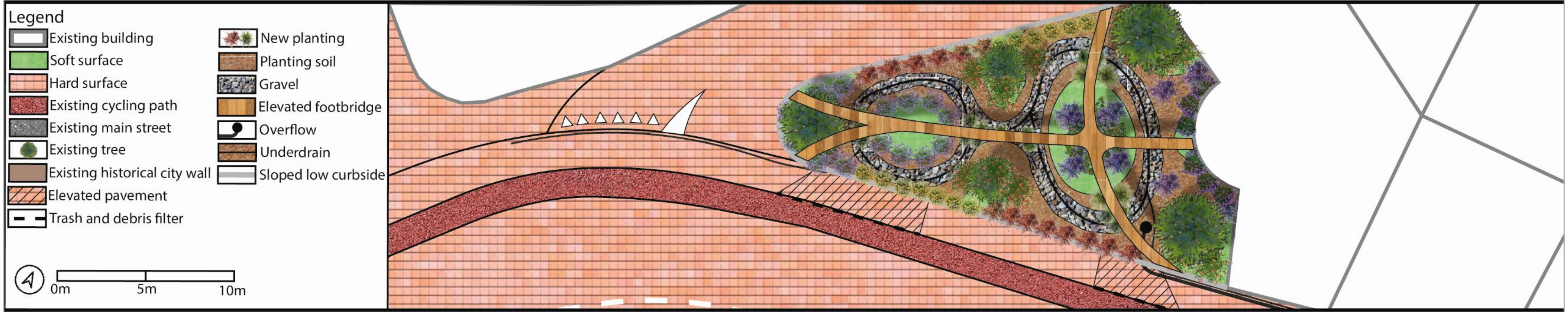
6.6 Design rain gardens

In figure 58, a cross section of the middle rain garden in De Bokkingshang area is shown. The location of this section A-A' is shown in the rain garden design maps in figure 59. The rain garden layering is based on rain garden designs and guidelines from Silva (2019) and Massachusetts clean water (2020). Rainwater will either fall in the rain garden itself, flow from street channels into the rain gardens, or will enter the raingardens via adjacent streets below the elevated parts of the sidewalk. Some parts of the sidewalk are elevated to allow water to flow into the rain garden, but this also provides the opportunity to remove trash and debris which would flow with the rainwater into the rain garden during heavy rainfall events. In order to avoid trash and debris getting into the plants and gravel layers of the rain garden, a trash and debris filter should be added in front of the elevated sidewalk. The location of the elevated sidewalks and filters can be found in figure 59.

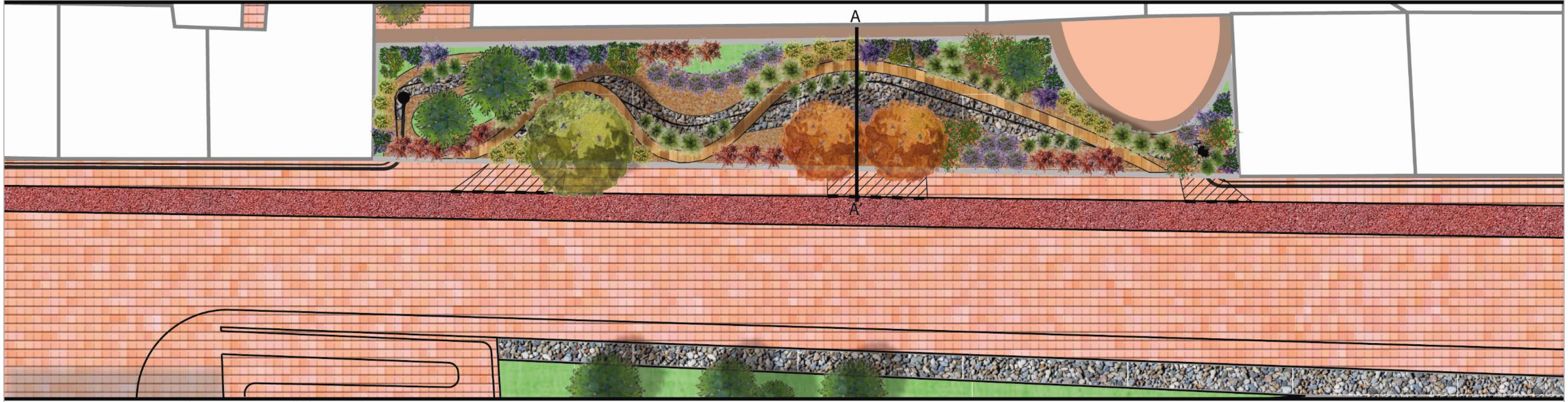
All three rain gardens consist of soil layers on the edges and a lower gravel layer in the center. A stone granulate storage layer lies below the soil layers, to promote infiltration and provide a rainwater retention reservoir. If the gravel and stone granulate layer are saturated and infiltration performance of the soil substrate does not suffice to drain all the rainwater intercepted by the rain garden, the rain garden itself will fill up and the perforated underdrain will start to function. The maximum ponding depth of the rain gardens is 0,5m. If this depth is reached during extreme weather events, the rainwater will flow into the overflow facilities, which will distribute the excess rainwater to the other rain gardens. A elevated boardwalk is added in the rain garden, so that it is possible to stroll through the rain garden in most weather situations.

Figure 58: Cross-section of rain garden De Vestingtoren in vulnerable area The Bokkingshang (figure made by author)

Design Rain Garden "De Zandpoort"



Design Rain Garden "De Vestingtoren"



Design Rain Garden "De Bokkingshang"

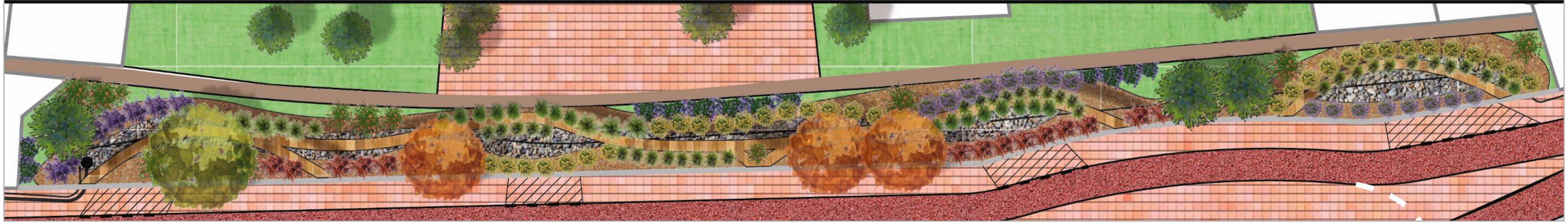


Figure 59: Design map of the three rain gardens in vulnerable area The Bokkingshang (figure made by author)

In figure 59, the designs of all three rain gardens in De Bokkingshang area is shown. It also shows the placement of cross-section A-A', which is shown in figure 58. The most western rain garden is named "De Zandpoort". This name can be literally translated to "The Sandgate" and is named after the former 14th-century city gate of Deventer which was located here (Dumbar, 1732). This is the most wide rain garden of the three rain gardens, and has a design which is based on an island structure. The edges of the garden have a relatively steep slope, which leads to the lower gravel infiltration layer. There are 2 small islands in the middle of the gravel bed, which provides space for planting in the middle of the rain garden.

The middle rain garden is named "De Vestingtoren". This name comes from the tower of the city wall in the rain garden. The name "De Vestingtoren" can be literally translated to "The Fortress Tower". This rain garden has a meandering shape, which refers to the nearby river IJssel. The gravel bed is created in the shape of a meandering river. The planting is added in the higher elevated parts of the rain garden which will flood regularly, representing the floodplains of the river.

The most eastern rain garden is named "De Bokkingshang". This name derives from the name of the vulnerable area, and also the adjacent street of the rain garden. The Bokkingshang street used to be a harbor quay where red herring was hung to dry; "Bokking" can be translated to red herring, and "hang" can be translated to hanging. This rain garden has a dry creek bed design. The linear shape of the rain garden makes it possible to implement a gravel infiltration layer in the shape of a creek along the length of the rain garden. Grasses are planted along the creek bed and larger plants are added at the sides of the rain garden to highlight the shape of a creek.

In figure 60, the planting plan for rain garden De Vestingtoren is shown. Creeping plants or grasses are represented as rounded surfaces. The larger flowering plants and ferns are displayed as filled round shapes, and the shrubs and trees are represented as empty circles. The size of the plants are displayed by the sizes of the circles. Furthermore, the most eye-catching colors of the plants are represented by the colors of the shapes.

The planting plan is based on the most suitable planting conditions for the plants, as was shown in figure 46. Besides that, the seasonality and color profile of the plants was taken into consideration. The plants are divided in such a way that there are some interesting planting features all over the rain garden throughout all seasons. Moreover, along the pavement of the adjacent street mostly plants with warm flower colors were used. Along the historical city wall, mostly lighter flower colors such as white and yellow were used, since this will stand out against the brown color of the city wall. However, some striking flower colors were used in both these areas to stand out from the rest. The vegetation is not mixed but planted in blocks, so that the maintenance is easier to execute and sightlines could be better embedded in the planting plan.

In figure 61a and 61b, visualizations of rain garden De Vestingtoren during clear weather and a heavy rainfall event are shown. During clear weather, the elevated boardwalk in the rain garden can be used to wander over and admire the grasses and flowering plants. During a heavy rainfall event, the boardwalk can still be used. If the rain garden is filled with rainwater it will make it more exciting and adventurous to walk over the boardwalk. The filling of the rain garden can also create awareness for extreme precipitation and pluvial flooding.

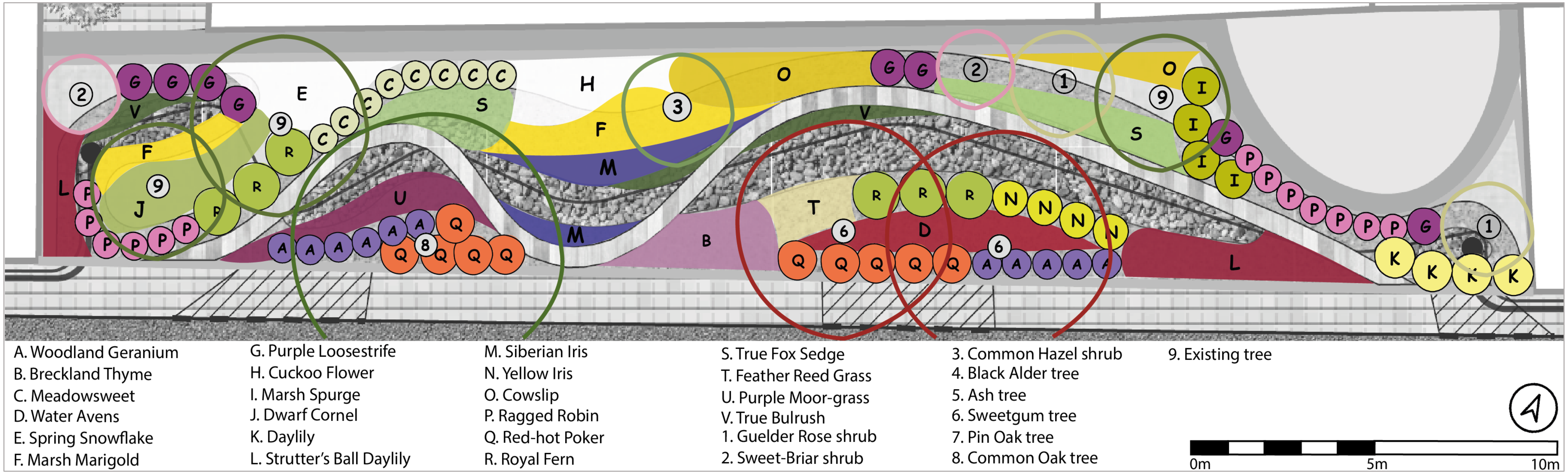


Figure 60: Planting plan of rain garden De Vestingtoren (figure made by author)

Figure 61a: Visualization of rain garden De Vestingtoren in a clear weather situation (figure made by author)

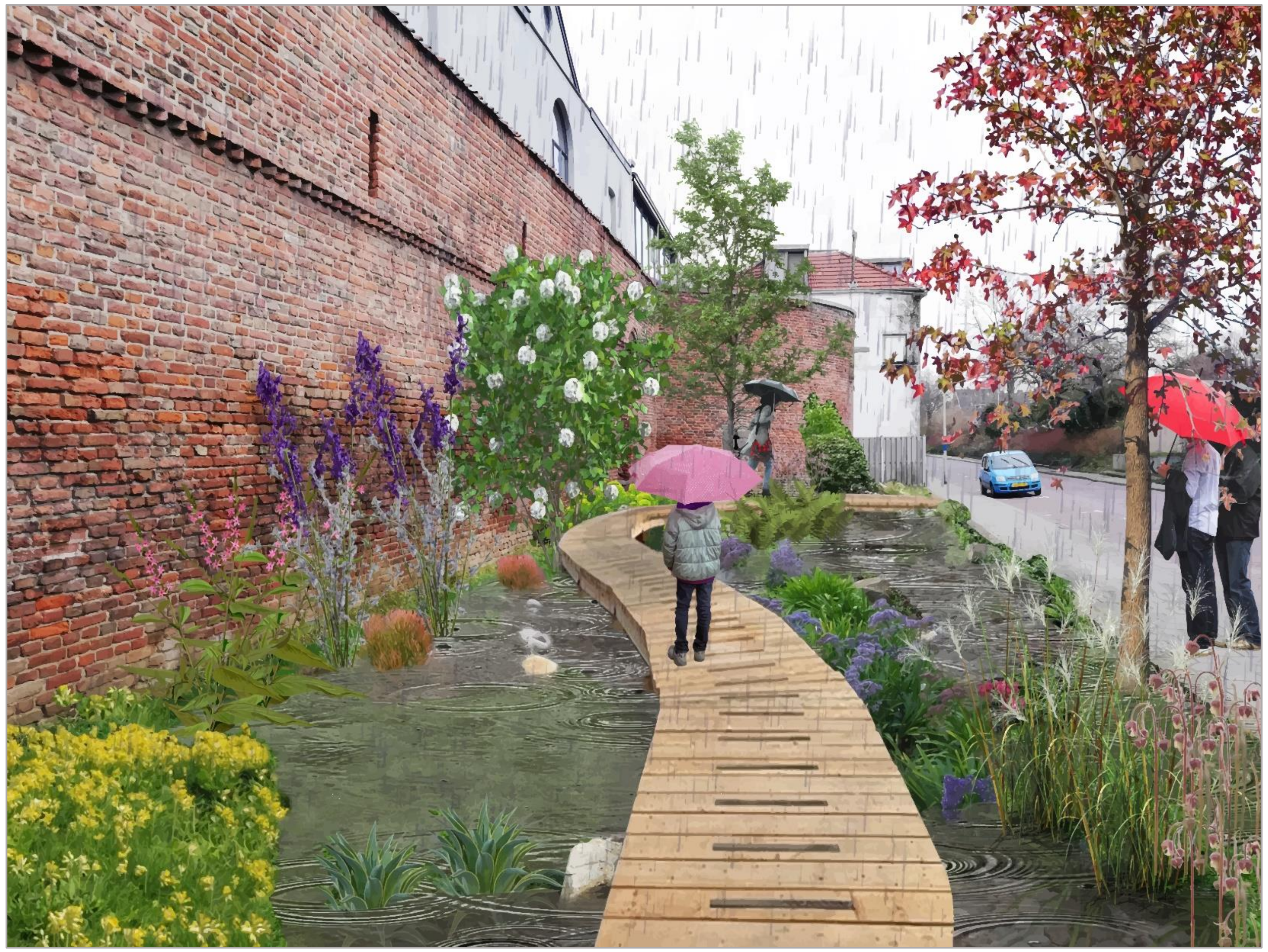


Figure 61b: Visualization of rain garden De Vestingtoren during a heavy rainfall event (figure made by author)

7 Discussion and conclusion

How can urban landscape design in the historical city center of Deventer help to reduce both pluvial flooding events and extreme drainage peaks?

7.1 Discussion

7.1.1 Reflection on researched rainwater interventions

Before the design phase is started, the use of green or grey rainwater solutions should be addressed. In this thesis, mainly green solutions are used because of their benefits in the fields of urban cooling, air purification, biodiversity, multifunctionality, costs and aesthetics. However, grey rainwater solutions can in some situations and also be appropriate in some locations within the urban environment. Grey rainwater solutions often need less surface space then green solutions, are often very effective at draining high-intensity rainfall, and might in some cases also be cheaper or easier to implement than green solutions. In order to determine the best type or combination of rainwater interventions, the range of possibilities for the specific location should be assessed carefully, and the pros and cons of both intervention types should be weighed against each other.

While thinking about implementing urban rainwater interventions it is also important to think about whether the costs of the interventions justify the implementation of it. The costs of the construction should be weighed against the risk and costs of potential damages. The risk of pluvial flooding depends on multiple factors, such as the vulnerability to pluvial flooding and the severity of precipitation events, like a 1 in 10 year precipitation event. The costs of damage can be divided into 2 main categories; measurable costs and immeasurable costs. Measurable costs are damages to buildings, infrastructure and goods. Immeasurable costs are, for example, damage to historical heritage and ecosystems, and emotional damage. Since the risk of pluvial flooding is a predication and the costs of damage cannot always be measured, it can be very difficult to determine how much rainwater interventions should be constructed to justify the implementation. However, it is very important to address damages with immeasurable costs, since the costs of the recovery of these damages, like damage to historical buildings or precious ecosystems, can be very high.

When the type, size and quantity of urban rainwater interventions has to be determined, the question of “what is possible?” and “what is desirable?” should be asked. It can be assumed that in many cases it is *possible* to completely prevent pluvial flooding and combined sewer overflows during a 1 in 10 year precipitation event. In some cases it might even be possible to completely prevent this during a 1 in 100 or 1 in 1000 year precipitation event. However, it should be carefully assessed whether this is also *desirable*. Completely preventing these very extreme but rare precipitation events would require a lot of space, labor and funds, which would in many cases outweigh the benefits of these interventions. A compromise will have to be found in order to implement rainwater interventions in the most desirable manner.

7.1.2 Reflection on the use of theory

The theory used and elaborated in this research and design can be applied to other similar neighborhoods. However, it should be addressed that the urban environment and climatic conditions are changing constantly, which has an effect on urban flooding models. The used model should be reliable and up-to-date in order to give the most exact information as input for the design. Furthermore, the research and design in this report will be most reliable to use in other historical Dutch neighborhoods. Newer or foreign neighborhoods may have other sewer types and systems, and might consist of different building types or a different urban tissue. However, when these differences are addressed most data from this research and design may still prove to be useful. Whenever data from this research and design are used in other situations, local differences should always be kept in mind as they might provide new solutions or challenges to the design.

Besides that, the application of theory might lead to unexpected challenges during the implementation. Before the design is actually implemented, it cannot be guaranteed that pluvial flooding and polluting sewer overflows during a 1 in 10 year precipitation event will be prevented completely in the design area. However, it can be assumed that pluvial flooding and combined sewer overflows during heavy rainfall events will definitely be reduced. Furthermore, many of the interventions in the design are green rainwater solutions, which provide a significant amount of additional benefits to the neighborhood. Examples of this are urban heat island reduction, habitat creation and air purification. These benefits should also be taken into consideration when a decision has to be made about implementing urban rainwater interventions.

Looking from a broader perspective, we should think about changing the way we build cities in order to better deal with climate change. In current cities, many kinds of problems are arising due to the changing climate. The problem of pluvial flooding and combined sewer overflows is one example, but urban heat islands, droughts and storms also pose a threat to many cities. This process also works the other way around: human activities in cities, such as transport and industry, are a major contributor to climate change. This means this development is a vicious circle, in which both detrimental effects amplify each other. If we change the way we think about cities and build cities we can break this vicious circle. On the one hand, we can provide better living conditions and well-being to those living in cities. On the other hand, cities could help to mitigate climate change, and therefore reduce the detrimental effects of climate change on cities. In order to reach this goal, we should not only focus on adapting our current urban areas. We should also focus on using alternative building methods and new technologies to reduce and mitigate the effects of climate change and the consequence of extreme weather events as an integral part of new urban developments.

7.1.3 Reflection on the research and design relevance

This research and design differs from preceding literature in the urban rainwater adaptation field since the analysis of vulnerable areas and detailed supplying surface water flows and accumulations is combined with the design of small-scale rainwater interventions. This integral approach combines (1) scientific theory and knowledge with (2) an creative and intuitive design approach to reach a design that is evidence-based but also fits within the current urban tissue, style and atmosphere of the neighborhood. In preceding literature, either one of these two aspects was elaborated, or both aspects were elaborated on watershed scale. However, this larger regional scale cannot be compared to the small scale of this research and design, since the analysis, calculations and especially the types of measures are very different.

The design guidelines in this research are unique in this field because of the categorization and ranging of interventions, but also because of the interventions types and descriptions itself. In literature, most rainwater design guidelines mostly describe rainwater interventions for other environments, such as urban areas in general, other neighborhood types or areas outside of cities. Besides that, these preceding rainwater design guidelines often describe just one category of interventions, such as only green or grey interventions, or only rainwater transport or rainwater interception interventions. The design guidelines in this thesis are really specified for historical neighborhoods with a dense urban tissue, and describe different categories of interventions to create a complete network of urban rainwater interventions.

To create a stronger support base for this research and design approach, it is recommended for future research to focus on elaborating this approach which combines research and design on the small scale. Besides that, more pluvial flooding models or pluvial modelling approaches should be developed, so that rainwater interventions can be implemented in other vulnerable areas in different cities and neighborhoods. Furthermore, these models should also be created more regularly for less extreme rainfall events, because it can be assumed that in some vulnerable areas 1 in 5 year or 1 in 2 year precipitation events can already cause pluvial flooding.

7.2 Conclusion

In this thesis, landscape design interventions dealing with pluvial flooding events and polluting sewer overflows were investigated for the historical city center of the Dutch city of Deventer, and with the help of the research outcomes a landscape design was made for the most vulnerable area within this neighborhood.

There is a clear trend in The Netherlands towards more intense and more frequent rainfall events, especially in the warmer periods of the year. This can lead to more pluvial flooding events and polluting sewer overflows in cities in the Netherlands. Historical city centers are a neighborhood type in which these challenges are especially present, and will be significantly more severe in the future.

For the city center of Deventer, it was determined that many of the current sewers are aged and have proved to be inadequate for recent heavy rainfall events. Urban landscape interventions can help to relieve pressure from the sewer system by intercepting rainwater during heavy rainfall events, which will reduce polluting sewer overflows and pluvial flooding. Furthermore, vulnerable sites within the neighborhood were identified. In the center of the neighborhood there are very few green areas and many hard surfaces, which can lead to less rainwater infiltration and more surface flows and accumulations during heavy rainfall events. These surface flows and accumulations were also investigated separately, which led to a better insight in several areas which are vulnerable to surface water accumulations. These vulnerable areas are generally low areas within the neighborhood with many impervious surfaces. Next to that, models showing the surface water depth after heavy precipitation events were combined and investigated. The results of these models show that the areas which are prone to pluvial flooding after heavy rainfall events are mainly low areas and correspond largely with the surface accumulation sites. Especially the low streets and squares with little vegetation in the neighborhood are prone to pluvial flooding.

A multitude of landscape interventions was explored, and categorized into three categories: high-frequency rainfall interventions, high-intensity rainfall interventions, and stormwater transport interventions. For all individual interventions in these three categories an effectiveness assessment and a multi-criteria analysis was done. The outcomes and individual scores for each intervention were used to create design guidelines. The design guidelines provide a simplified summary of the most important outcomes of the research part of the thesis. These guidelines can be used by landscape architects and policy-makers to improve and accelerate future design processes in similar environments, and can also be used by non-experts. The effectiveness assessment, multi-criteria analysis and design guidelines all show how the most appropriate type and configuration of rainwater intervention depends very much on the location, the available space, and the type of precipitation that is aimed to be reduced.

The location, type, size and quantity of rainwater interventions determines how much rainwater will be drained during high-frequency and high-intensity precipitation events. Many aspects, such as the current rainwater problems in the neighborhood, the costs and the desirability of rainwater interventions, should be weighed carefully against the potential to prevent a certain amount or frequency of urban flooding and combined sewer overflows and the additional advantages of urban green interventions, in order to make an informed choice about implementing rainwater interventions in a historical city center.

A site-specific risk analysis was used to determine areas within the city center of Deventer that are highly vulnerable to pluvial flooding events. Six different vulnerable areas were identified within this neighborhood. With the help of site-specific risk analysis for each of these areas, these six areas were determined to be three different flow and accumulation systems during heavy rainfall events. A hydrological quantification of a 1 in 10 year precipitation event was performed with the help of the stormwater accumulation data in the site-specific risk analyses. With the outcomes of this quantification the dimensions of the rainwater interventions could be determined. A Suggestion for the implementation of rainwater interventions to deal with 1 in 10 year precipitation events in each of the three most vulnerable areas was given.

In order to answer the design question of this thesis, a landscape design was made to prevent pluvial flooding and reduce combined sewer overflows during 1 in 10 year precipitation events. This was done for the area which was determined to be the most vulnerable to pluvial flooding and polluting combined sewer overflows within the city center, De Bokkingshang. The plants of the vegetated rainwater interventions used in the site-specific design were selected based on their preferred soil type and groundwater level, preferred exposure to sunlight, resistance to regular flooding, seasonal aesthetics, and whether the plant is native to The Netherlands. Several plan maps, cross-sections, schemes and visualizations were made to clarify the design and to further elaborate on the intervention functionality, aesthetics and ambiance.

The final design of this thesis is not presented as a fixed masterplan for the city center of Deventer. The final design is a suggestion and a source of inspiration for researchers, local- and national policy-makers, and landscape architects about how more regular pluvial flooding and polluting sewer overflows can be addressed in a historical city center. The proposed design can be easily adjusted with the help of the design guidelines and the hydrological quantification explained in this report.

This research and design shows that urban rainwater interventions can not only address the vulnerability of a neighborhood to pluvial flooding and polluting sewer overflows, but they can also play a major part in making neighborhoods greener and creating spaces where people can come together. The combination of these two functions of urban rainwater interventions shows that climate change adaptation is not only risk limitation, but can also be an opportunity to make cities greener, healthier, more biodiverse and more pleasant living environments.

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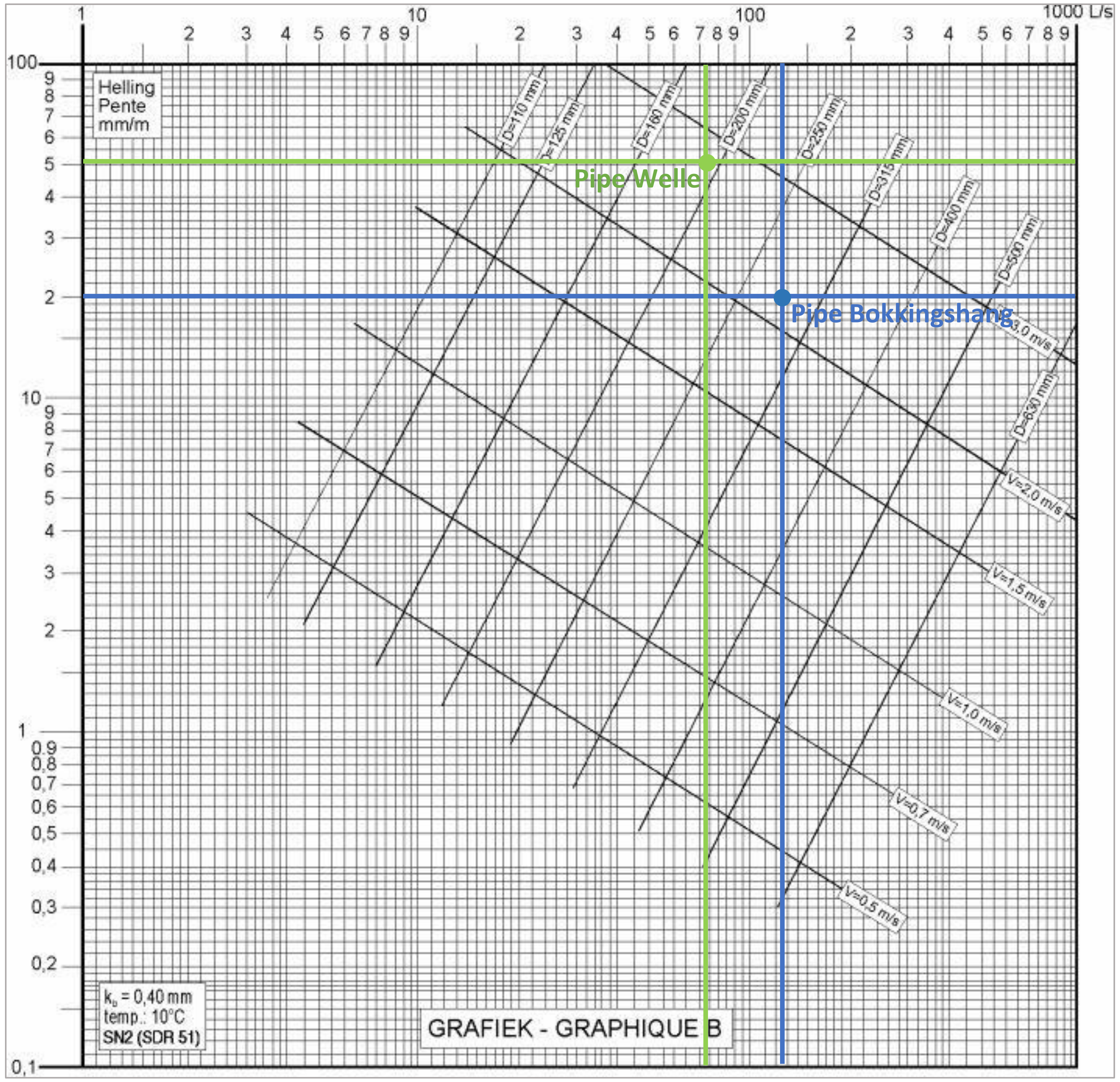
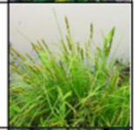
Appendix I



Appendix I: Chart to determine the appropriate plastic sewer pipe diameter, based on the slope and the required drainage quantity (Government of Flanders, 2020)

Appendix II

Latin name	English name	Family/variety	Soil conditions	Flood resistance	Exposure	Size	Appearance
Geranium sylvaticum	Woodland Geranium	Native flowering plants	Moderately wet soil	Resistant to some flooding	Semi-shade	Up to 75cm tall, 60cm wide spread	
Thymus serphyllum	Breckland Thyme	Native flowering plants	Moist soil	Resistant to some flooding	Full sun	Up to 8cm tall, 32cm wide spread	
Filipendula ulmaria	Meadowsweet	Native flowering plants	Wet soil	Resistant to frequent flooding	Semi-shade	75-120cm tall, 45-60cm wide spread	
Geum rivale 'Lemon Drops'	Water avens	Native flowering plants	Very wet soil	Resistant to frequent flooding	Full sun – semi-shade	Up to 40cm tall, 30cm wide spread	
Leucojum vernum	Spring snowflake	Native flowering plants	Wet soil	Resistant to flooding	Full shade	12-35cm tall, 15-25cm wide spread	
Caltha palustris	Marsh Marigold	Native flowering plants	Very wet soil	Able to grow in shallow surface waters	Full shade – semi-shade	15-40cm tall, 30-60cm wide spread	
Lythrum salicaria	Purple Loosestrife	Native flowering plants	Wet soil	Resistant to flooding	Full shade – semi-shade	60-120cm tall, 60-90cm wide spread	
Cardamine pratensis	Cuckoo flower	Native flowering plants	Moderately wet soil	Resistant to flooding	Full sun – semi-shade	40-60cm tall, 15-45cm wide spread	
Euphorbia palustris	Marsh Splurge	Native flowering plants	Wet soil	Resistant to frequent flooding	Full sun – semi-shade	60-90cm tall, 60-90cm wide spread	
Cornus suecica	Dwarf Cornel	Native flowering plants	Very wet soil	Resistant to frequent flooding	Full shade – semi-shade	10-25cm tall, 30-38cm wide spread	
Hemerocallis 'Golden Chimes'	Daylily	Native flowering plants	Moderately wet soil	Resistant to flooding	Full sun	Up to 90cm tall, 80cm wide spread	
Hemerocallis 'Lemon Balls'	Strutter's Ball Daylily	Native flowering plants	Moist soil	Resistant to little flooding	Full sun	60-90cm tall, 30-60cm wide spread	
Iris sibirica	Siberian Iris	Native flowering plants	Very wet soil	Able to grow in shallow surface waters	Full sun – semi-shade	25-80cm tall, 30-60cm wide spread	
Iris pseudacorus	Yellow Iris	Native flowering plants	Very wet soil	Able to grow in shallow surface waters	Semi-shade	90-120cm tall, 60-75cm wide spread	
Primula veris	Cowslip	Native flowering plants	Moist soil	Resistant to little flooding	Semi-shade	Up to 25cm tall, 25-30cm wide spread	
Lychnis floscuculi	Ragged Robin	Native flowering plants	Wet soil	Resistant to flooding	Full sun – semi-shade	35-40cm tall, 30-60cm wide spread	
Kniphofia 'Tawney King'	Red-hot Poker	Flowering plants	Moist soil	Resistant to little flooding	Full sun – semi-shade	Up to 120cm tall, 90cm wide spread	
Osmunda regalis	Royal Fern	Native ferns	Moderately wet soil	Resistant to some flooding	Full shade	60-160cm tall, 60-150cm wide spread	
Carex vulpina	True Fox Sedge	Native grasses	Very wet soil	Able to grow in shallow surface waters	Full shade	30-100cm tall	
Calamagrostis x acutiflora	Feather Reed Grass	Native grasses	Very wet soil	Resistant to frequent flooding	Semi-shade	125-175cm tall	
Molinia caerulea	Purple Moor-Grass	Native grasses	Moderately wet soil	Resistant to flooding	Full shade – semi-shade	Up to 90cm tall	
Scirpus lacustris	True Bulrush	Native grasses	Very wet soil or shallow water	Able to grow in shallow surface waters	Semi-shade	120-150cm tall	
Viburnum Opulus	Guelder Rose	Native shrubs	Wet soil	Resistant to flooding	Semi-shade	3-3,6m tall, 3,5-4,5m wide spread	
Rosa Eglanteria	Sweet-Briar	Native shrubs	Moderately wet soil	Resistant to flooding	Full shade	2,4m tall, 2,4m wide spread	
Corylus Avellana	Common Hazel	Native shrubs	Moderately wet soil	Resistant to some flooding	Full sun – semi-shade	4-8m tall, 3-6m wide spread	
Alnus glutinosa	Black Alder	Native trees	Wet soil	Resistant to frequent flooding	Full shade – semi-shade	10-25m tall, 10m wide spread	
Fraxinus	Ash	Native trees	Moist soil	Resistant to some flooding	Full sun – semi-shade	21-24m tall, 15-18m wide spread	
Liquidambar styraciflua	Sweetgum	Trees	Very wet soil	Resistant to frequent flooding	Full sun	10-15m tall, 7-9m wide spread	
Quercus palustris	Pin Oak	Trees	Wet soil	Resistant to flooding	Full sun	15-21m tall, 12-15m wide spread	
Quercus robur	Common Oak	Native trees	Moderately wet soil	Resistant to flooding	Semi-shade	25-30m tall, m wide spread 8-15	

Appendix II: Planting matrix (Figure made by author)

Personal learning objectives reflection

The first learning objective I set for myself to work on during the thesis process was to separate the main issues from the side issues. In my personal learning objectives I mentioned that I tended to sometimes lose myself in searching for endless amounts of more and more detailed information, while this very specific information is often not that useful for answering the (sub-)research question. Because of this, my aim was to keep the different sections of the report concise. I mentioned that my work plan would help me to keep track of the time I set for the different sections of the report.

During the thesis process, my work plan and also the page limit of the thesis report always kept me focused on writing concise pieces of text and not spending too much time on one section or product. Although I did go into depth for some subjects of the thesis, I feel that I kept the report quite concise, and especially focused on the main issues. Sometimes, I felt it was necessary to dive deep into specific literature, since I needed critical information to, for example, or complete calculations. However, I do not think this distracted me from the main goal of my thesis.

When I started working on the research and design of the thesis, I quickly found out that my work plan was not always accurate or possible. The order of the work plan was accurate in general, but I noticed that working on the different sections of the report was much more of an iterative process than I initially expected. In some situations, I finished a section of the work plan quicker than expected, but then I found out later that I needed additional information in this section. However, the general deadlines I set for myself in my work plan were really helpful to help me focus on what I should finish, and if I was still on schedule with my work. The next time I create a work plan I should embed more uncertainty or iteration in the work plan, but I should keep the general deadlines of each report section.

Another personal learning objective I set was that I would like to learn to use calculations, diagrams and models in the design. I mentioned that I took some courses on climate and urban environmental infrastructure, but I have not used this theory extensively in my designs. I mentioned that it could be very useful to use this theory in the design process, since this could help me to create a scientific foundation as supporting evidence for the design. Furthermore, I mentioned that the design guidelines would help me to translate the calculations and the subsequent outcomes into a design.

I used a lot of models, diagrams and calculations in my thesis. Firstly, I used weather and climate models as foundation for my problem statement, and as illustration of the problem. Besides that, I used existing pluvial flooding models from engineering companies to investigate the most vulnerable areas within the city center. Furthermore, I used diagrams to, for example, divide rainwater interventions into three different categories, which would later prove to be very useful to create design guidelines and a site-specific intervention implementation. Lastly, I used many, especially rough, calculations to make an assumption about how much rainwater should be drained by the interventions. In short, I think calculations, diagrams and models were very useful for the development of my thesis, but also a critical element. Without this information it would be very hard to make certain accurate assumptions, and many design choices would be unfounded. A good example of this is the sizing of the interventions. Without the pluvial flooding models and the hydrological quantification calculations, it would be very hard to determine the dimensions, how many, and what type of interventions should be implemented.

The last personal learning objective I set was to not go into depth on one specific design too early, because this can take a lot of time. I mentioned that I am a quite rational designer, and when I would find an effective solution I sometimes tended to fully focus on this solution. Because of this I could overlook alternative solutions, which could potentially be more suitable for a specific case. I mentioned that the research phase and the design guidelines would help me with this by providing a direction for the design. However, I also mentioned that I should still explore and test a range of alternative sketches and designs within this specific direction.

I think I can still very much improve in this aspect. During the design phase, I made multiple sketches and I tested different design options within the neighborhood. However, when I found a suitable solutions, I started to develop this design without sometimes looking at positive aspects from different alternative designs. Because of this I sometimes later found out that some elements in the design did not work well, which meant that I lost time redesigning this specific aspect. I could have saved this time by considering these aspects earlier.

In the end, I think that I reached most of my personal learning objectives, but there are definitely also some learning objectives that can still be improved. Especially creating and working according to a work plan is a learning goal that can still be improved, as well as considering positive aspects from alternative design sketches. I am doing my landscape architecture internship later this year, and I hope that I will improve these learning objectives as well during this period. However, I believe that this thesis definitely made me a more independent and complete researcher and designer.