Exploring the effectiveness of small-scale green measures in increasing the resilience of Amsterdam to pluvial floods

An analysis of the opportunities of small-scale green measures in three case areas in Amsterdam: Nieuwendam Noordwest-Zuid, Spuistraat Zuid and Rijnbuurt

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Abstract
The aim of this thesis is to explore the opportunities and possibilities of small-scale green measures in Amsterdam as an adaptation tool to increasing cloud bursts and accompanied urban pluvial floods caused by climate change. The main question that is answered is: *To what extent are small-scale green measures able to increase the resilience of Amsterdam to the increasing frequency and intensity of cloudbursts by increasing the water buffer capacity?*

The effectiveness of small-scale green measures is explored at four aspects: the maximum storage capacity per measure, the ability of a measure to decrease the peak of drainage, the ability of a measure to decrease total drainage and the ability of a measure to delay drainage at extreme precipitation events. A general box-model is adapted to each measure to analyse the effectiveness of each selected small-scale green measure. Two precipitation events are used as inputs: the precipitation event of the 28th of July 2014 and a fictional precipitation event of 60 mm in one hour. The two precipitation events show similar results. It can be concluded that all measures contribute to the delay and decrease of the peak and total drainage of precipitation. During both events intensive green roofs are able to prevent drainage. Infiltration strips follow up with a potentital decrease of total drainage of 60%. Less effective in terms of water buffering capacity is the open gutter.

In addition, the potentials of each measure are studied in three case areas in Amsterdam: Nieuwendam Noordwest Zuid, Spuistraat Zuid and Rijnbuurt. The potentials of each measure are presented in opportunity maps per selected case. The potentials that are visualized in the opportunity maps are analysed in more detail in two scenarios. Scenario 1 describes the full-potential of each measure individually per case, while scenario 2 gives a description of a best-fitting combination of measures, a measure-package, per case. The extra water storage capacity that the combination of measures can provide is calculated per case. In Spuistraat the greatest potential of preventing pluvial floods is on rooftops because of the high ability of rooftop measures in Spuistraat to decrease and delay the peak and total drainage. Extensive green roofs could decrease total water on the streets up to 42%. Measures in private gardens could lead to a decrease of 26%. Rijnbuurt is more suitable for measures within private gardens. These measures, for example infiltration strips, could decrease rainwater flow on the street-level up to 48% and a delay of water on the street up to 42% during an event with an intensity of 60 mm per hour. The newer neighbourhood of Nieuwendam has the largest potential in decreasing and delaying the peak and total drainage by small scale green measures. Implementation of for example infiltration strips in private and public areas could prevent water on the street completely during an extreme precipitation event.

Further research should be done to study the possibilities and potentials of each at a local scale. These studies should include local groundwater flows and infiltration rates. In addition, it could be interesting for a process of upscaling to analyse additional neighbourhoods in Amsterdam with different urban typologies. This exploratory study could serve as a stepping stone towards a more general approach that could also be applied in other municipalities in the Netherlands and abroad that struggle with pluvial floods in the present and the future.

Key-words: pluvial flooding, urban water management, resilience, climate change, small-scale green measures, opportunities, water storage, box-model, GIS, Amsterdam, local adaptation.

Samenvatting

Deze scriptie heeft als doel het verkennen van de mogelijkheden en kansen van kleinschalige, fijnmazige groene maatregelen in Amsterdam die kunnen dienen als een strategie om regenwateroverlast veroorzaakt door wolkbreuken te voorkomen. The hoofdvraag die onderzocht is, luidt als volgt: *In hoeverre zijn kleinschalige, fijnmazige groene maatregelen in staat om de veerkracht van Amsterdam te vergroten tegen de toenemende frequentie en intensiteit van wolkbreuken door een toename van de water bufferingscapaciteit van de stad?*

De effectiviteit van fijnmazige, kleinschalige groene maatregelen is verkend op vier afspecten: de maximale opslagcapaciteit per maatregel, de mate waarin een maatregel in staat is de piek van regenwater op straat te doen afnemen, de mate waarin een maatregel in staat is de totale hoeveelheid van regenwater op straat te doen afnemen en de mate waarin een maatregel in staat is om het startpunt van water op straat te vertragen tijdens een extreme regenbui. Een generiek box-model is aangepast naar elk geselecteerde maatregel om de effectiviteit van één m^2 van elke maatregel te analyseren. Twee buien zijn gebruikt als input: de bui die gevallen is op 28 juli 2014 en een fictieve 60 mm per uur bui. De resultaten van de twee buien zijn vergelijkbaar. Geconcludeerd kan worden dat alle geselecteerde maatregelen bijdragen aan het vertragen en afvlakken van die piek van regenwater. Tijdens beiden buien zijn intensieve groene daken in staat om water op straat te voorkomen. Infiltratiestroken met bovengrondse bergen zijn daarna het meest effectief met een totale afname van water op straat van 60%. Minder effectief als het gaat om waterberging is de open goot.

Naast het bepalen van de effectiviteit van één m^2 maatregel, zijn de potenties van geselecteerde maatregelen nader bekeken in drie verschillende gebieden in Amsterdam: Nieuwendam Noordwest Zuid, Spuistraat Zuid and Rijnbuurt. De potenties van elke maatregel zijn gevisualiseerd in kansenkaarten per geselecteerd gebied. De potenties gevisualiseerd in kansenkaarten per geselecteerd gebied zijn verder geanalyseerd in twee scenarios. Scenario 1 beschrijft de potenties van elke maatregel afzonderlijk terwijl scenario 2 een combinatie aan maatregelen, een maatregelpakket, per gebied presenteert. De extra opslag die de maatregelpakketen bieden is berekend per geselecteerd gebied.

In Spuistraat liggen de meeste kansen in de dakmaatregelen vanwege de afname van de piek en het totaal aan water op straat die dakmaatregelen kunnen bereiken. Extensieve groene daken kunnen leiden tot een afname van water op straat van 42%. Maatregelen in private tuinen kunnen zorgen voor een afname van water op straat van 26%. Rijnbuurt is meer geschikt voor maatregelen in private tuinen. In Rijnbuurt kunnen deze maatregelen, bijvoorbeeld infiltratiestroken, leiden tot een afname van 48% en een vertraging tot 42% tijdens een bui met een intensiteit van 60 mm per uur. Recenter gebouwde buurten, zoals Nieuwendam, hebben de grootste totale potentie in afname en vertraging van de piek en het totaal aan water op straat door kleinschalige, fijnmazige groene maatregelen. Het toepassen van bijvoorbeeld infiltratiestroken met bovengrondse berging in privaat en publiek gebied kan water op straat voorkomen.

Verder onderzoek zal op een groter detailniveau de effectiviteit van maatregelen in kaart kunnen brengen. Hierbij is het analyseren van grondwater stromingen en infiltratie ratio's op specifieke locaties belangrijk. Daarnaast is het interessant om tot een opschalingsproces te komen, waarbij deze studie aangevuld dient te worden met analyses van gebieden in Amsterdam met een verschillende stedelijke typologie. Dit onderzoek kan als een verkenningsstudie dienen met een opstap naar een methode die wellicht ook toegepast kan worden in andere gemeenten in Nederland en het buitenland waar eenzelfde regenwater problematiek voorkomt.

Steekwoorden: regenwater problematiek, stedelijk waterbeheer, veerkracht, klimaat verandering, kleinschalige, fijnmazige groene maatregelen, kansen, wateropslag, box-model, GIS, Amsterdam, lokale adaptatie strategiën.

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1. Introduction

1.1 Background

Many citizens of Amsterdam remember July 28th 2014. On this particular day, the city suffered from heavy precipitation events (Amsterdam Rainproof 2015c). Precipitation intensities varied between 40 mm to 70 mm per hour with, at some places, a maximum of 150 mm per hour for a period of 5 minutes (Amsterdam Rainproof 2015c). These short and heavy events, often leading to floods, are known as cloudbursts (KNMI 2014). The cloudbursts of the 28th of July 2014 led to pluvial floods, because the sewer system was not able to drain the peak amounts of rain. Originally, the sewer system is designed for an overflow with a frequency of once every two years (Vergroesen et al. 2013).

In the coming decades, Amsterdam will become more vulnerable to extreme precipitation events. This is due to two major changes: climate change and an increase of the amount of impervious surfaces due to urban densification (Fratini et al. 2012). According to the latest climate predictions by the *Intergovernmental Panel on Climate Change* (IPCC) and the *Koninklijk Nederlands Meteorologisch Instituut* (KNMI), the amount and frequency of cloudbursts will increase in the future. However, the amount and frequency of the increase of cloudbursts are unsure (Alley et al. 2007; Klein Tank et al. 2014). In addition, urban sprawl and further densification of the inner city increase the amount of impervious surfaces leading to an increased inability of rainwater to drain through these surfaces.

An increase in pluvial floods will have economic consequences. Amsterdam is one of the big drivers of the Dutch economy with 811,185 inhabitants (Gemeente Amsterdam 2014). Pluvial floods will thus affect many people. Therefore, it is of great importance to decrease socio-economic damages caused by cloudbursts and accompanied pluvial floods. In order to diminish the increasing vulnerability of Amsterdam towards pluvial floods, its resilience needs to be increased (Voskamp & Van de Ven 2014). Expanding the sewer system is inadvisable due to its technical infeasibility and high costs (European Environment Agency 2012). Therefore, an adaptive strategy needs to be developed and implemented to cope with the increasing intensity and frequency of cloudbursts. The European Flood Risk Directive (EFRD) states that flood risk management plans should aim at applying non-structural measures that contribute to increasing urban resilience and social preparedness (Fratini et al. 2012). The programme Amsterdam Rainproof, an initiative by Waternet and the client of this thesis, is targeting these two aims by using a bottom up approach. Its main target is to make the city of Amsterdam 'rainproof' in 2050 by: generating awareness about the need to increase urban resilience towards pluvial floods, creating added value by smart investment in local innovative solutions to pluvial floods, avoiding damage due to pluvial floods by adopting smart local solutions and mainstreaming rainproof behaviour and thinking in policies of public institutions (Amsterdam Rainproof 2014).

Amsterdam Rainproof is especially interested in so-called green infrastructure. Synergies between blue and green infrastructures can increase resilience to flood risk (Rozos et al. 2013). Green and blue measures are closely related with each other (Voskamp & Van de Ven 2014). By these measures, hydrological and ecological values are protected while providing adaptive measures to deal with urban pluvial flooding (Lawson et al. 2015). References to 'green measures' in the remainder of this thesis will therefore indicate a combination of blue and green infrastructures. Examples of green measures relate to the usage and expansion of green infrastructure in the city through avoidance and removal of impervious surfaces, and by maintaining and expanding the amount of green roofs, private and public gardens etcetera (European Environment Agency 2012). Green measures deliver flood risk management services and environmental and human health benefits (Voskamp & Van de Ven 2014). One of the flood risk management services provided by green measures is the increase in water storage capacity. The water storage capacity is the volume of water that can be temporarily stored during extreme precipitation events in, among others, ponds, the soil, vegetation or other green measures (Vergroesen et al. 2013). Another flood risk management service is the increase in water transport capacity (Vergroesen et al. 2013). An example of such a measure is an open gutter. Open gutters lead water to green areas or surface water where it can be temporarily stored. The above mentioned flood risk management services of green measures are strongly interrelated. However, this thesis has the major focus on the first mentioned flood risk management service, increasing the water storage capacity, since this one is most important in optimising of the urban drainage system (Vergroesen et al. 2013). Small-scale green measures are able to delay and/or decrease the peak of drainage coming from excessive rainwater. This dynamical aspect has not been studied yet for the case of Amsterdam. In addition, there is a lack of information about the quantification and visualization of local opportunities for small-scale green measures in the city. The reduction of these two knowledge gaps give the added value of this thesis.

This thesis investigates the effect of green measures, in terms of water buffering capacity, on the increase in resilience of Amsterdam against pluvial floods by examining three spatial urban typologies in Amsterdam. A cost and benefit analysis of small-scale green-measures is out of the scope of this thesis but will be evaluated in a separate complementary study. To study the delay and/or decrease in the peak of drainage, two precipitation events are used as inputs: the event of the 28th of July 2014 with a duration of 24 hours and a fictional event with an intensity of 60 mm per hour and a duration of one hour.

The main research-question that will be answered in this thesis is sub-divided in three minor questions and reads as follows: *To what extent are small-scale green measures able to increase the resilience of Amsterdam to the increasing frequency and intensity of cloudbursts by increasing the water buffer capacity?*

Sub-questions:

1. How much can each small-scale green measures contribute to the water buffering capacity?
2. What are the potentials for implementing small-scale green measures in three case areas in Amsterdam: Nieuwendam, Spuistraat and Rijnbuurt?
3. What is the total contribution to the water storage capacity if all potentials in each selected case for implementation of green-measures are taken in Nieuwendam, Spuistraat and Rijnbuurt during a 60mm/h precipitation event and during the event of July 28th 2014?

1.2 Aim

The thesis is mainly concerned with the quantification of the extent to which the implementation of small-scale green measures can increase Amsterdam's resilience towards pluvial floods. This includes:

- An analyses of the general effectiveness over time in terms of water storage capacity of selected green-measures
- the investigation of opportunities of each selected green-measure in three case studies presented in opportunity maps and
- a study of the contribution of each scenario, resulting from the opportunity maps, to the total water storage capacity of the urban water system in the selected cases in Amsterdam

Beyond the scope of this study is the analyses of other measures than the selected measures and other cases than the selected cases. The investigation of the technical suitability of selected green-measures on the entire build environment is also out of scope and will not be considered. This thesis serves as an initial study exploring several case studies and can be consulted in further research.

1.3 Thesis structure

The next chapter, chapter 2, explains the theoretical framework and the current state of knowledge of the key concepts used. Chapter 3 starts with an explanation of the study design, followed by a description of the box-model used and an outline of the theory related to the selected green measures and their design criteria. Thereafter, the case study areas will be described, after which the methodology of opportunity mapping and calculations of the scenarios will be explained. Chapter 4 presents the most important results. First, the results of the water buffering capacity per measure will be presented. Secondly, the opportunity maps will be visualized. And last, the results of the scenario calculations will be given. In chapter 5 the results and methods used will be evaluated and discussed. And chapter 6 will present the conclusions and answer to the research questions.

2. Theoretical framework

This chapter describes the current state of the art on key concepts investigated for this thesis (section 2.1) and compares the general box-model with other models (section 2.2).

2.1 Key concepts

The most important key concepts are: global climate change, urban densification, urban pluvial flooding, impacts, resilience, urban flood risk management, green measures, effectivity of green measures and cost and benefit analysis. These concepts are very much interrelated with each other (Figure 1). Global climate change and urban densification together increase urban pluvial flooding (orange arrow Figure 1: positive relation). Urban pluvial flooding can lead to several (in)direct impacts. However, green measures and their effectivity positively influence urban flood risk management, which in turn increases resilience. An increased resilience lowers the amount and intensity of urban pluvial floods (green arrow Figure 1: negative relation) and thereby reduces the (in)direct impacts. A cost and benefit analysis may serve as an economic tool to determine whether green measures are cost-effective and worth the investment. This is nonetheless not part of this study and will be discussed in a complementary study. Each key concept is evaluated in the following sections. Key concepts in this study are presented in Figure 1.

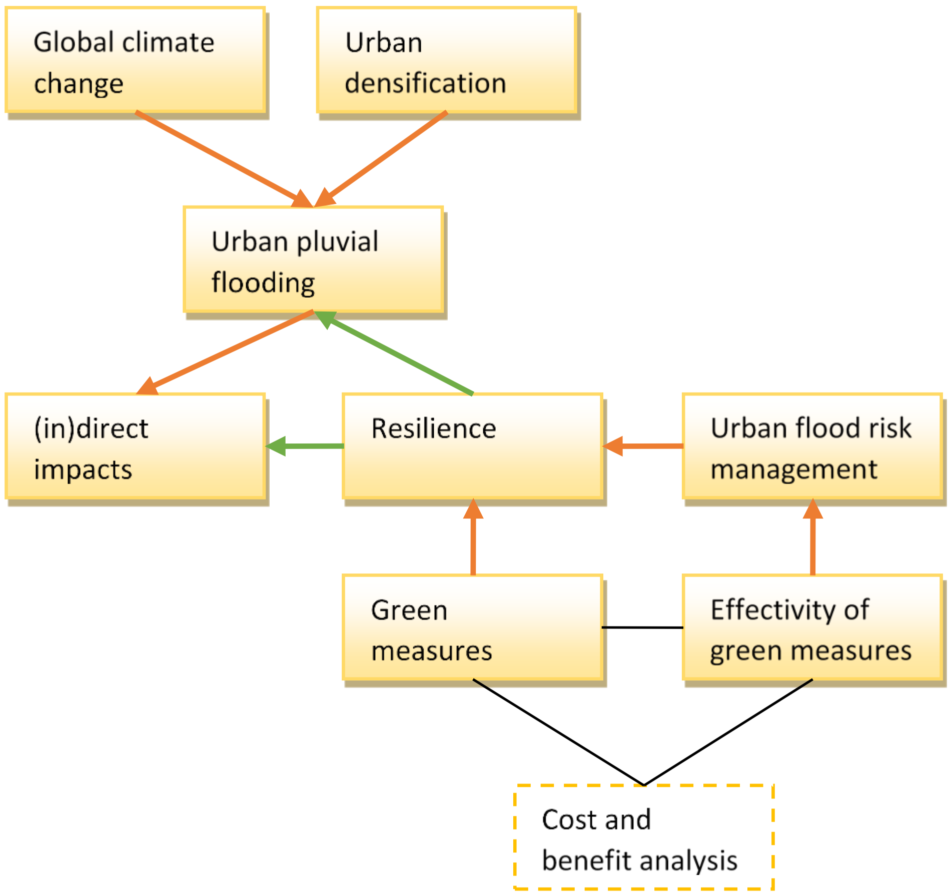

Figure 1: Conceptual model. Orange arrows: positive relation, green arrows: negative relation, dashed yellow box: out of the scope of this study.

2.1.1 Global climate change

According to the latest IPCC scenarios, climate warming will lead to a higher frequency and intensity of heavy precipitation events in the Northern latitudes of Europe (European Environment Agency 2012; Alley et al. 2007). The total amount of wet-day precipitation will increase for all predicted climate scenarios in the future (Sillmann et al. 2013; Alley et al. 2007; Klein Tank et al. 2014). Extreme precipitation events with intensities of more than 25 mm per hour or 10 mm in 5 minutes are called cloudbursts (KNMI 2014). The KNMI-'14 scenarios state that the amount of extreme precipitation events in the Netherlands will especially increase in winter, and the intensity of extreme precipitation events will increase in summer, meaning that there is a higher probability of cloudbursts in the future (Klein Tank et al. 2014).

2.1.2 Urban densification

Amsterdam's vulnerability to pluvial floods has increased due to urbanization. As the municipality grows, the demand for housing increases. To meet the higher housing demand and to limit urban sprawl, the municipality has a policy of higher densification of the city (Gemeente Amsterdam 2011; Vergnes et al. 2014). Urban densification is the development of compact city structures through urbanisation increase in a confined area (Vergnes et al. 2014). The densification policy of Amsterdam leads to a higher density of buildings in smaller areas resulting in a lower percentage of permeable surfaces in the city (Gemeente Amsterdam 2011). The increase of impermeable surfaces due to urban densification ultimately increases vulnerability to pluvial floods, because it complicates infiltration of excessive rainwater.

2.1.3 Urban pluvial flooding

Urban flooding has various causes resulting in different urban flooding types such as coastal flooding, fluvial flooding, groundwater flooding, flooding due to failure of pipes or pumping stations and pluvial flooding (van Riel 2011). Both pluvial and groundwater floods are caused by extreme precipitation events. The distinction between the two is made by looking at the duration of these extreme precipitation events. Groundwater flooding is caused by long periods, weeks or months, of heavy precipitation resulting in an excessive rise of the groundwater table (van Riel 2011). Pluvial floods are caused by short precipitation events with an extremely high intensity; cloudbursts. These cloudbursts cause pluvial floods when the sewer system lacks the capacity to drain the precipitation that has fallen in a couple of minutes to, at maximum, one hour (Falconer et al. 2009).

2.1.4 Impacts of pluvial floods

Pluvial floods can have several direct and indirect impacts. Examples of direct impacts are economic and material damages to houses, buildings and public infrastructures (Zhou et al. 2012). Examples of indirect damages include health impacts on affected residents, lost working hours, inconvenience for pedestrians, traffic delay and loss of recreational value (Sušnik et al. 2015; Zhou et al. 2012; ten Veldhuis & Clemens 2010). Pluvial floods are the natural hazard in Europe's cities with the highest economic and material damages (Fratini et al. 2012; European Environment Agency 2012). The total economic damage of pluvial floods in the Netherlands between 1986 and 2009 was around €674 million (Sušnik et al. 2015).

2.1.5 Urban flood risk management

Urban flood risk management is a management strategy that includes all measures taken to reduce vulnerability to a certain flood hazard (Fratini et al. 2012). In the Netherlands, flood defence has a long-term legal base in formalised standards on the frequency of exceedance of a certain water level (de Graaf 2009).Traditionally, the sewer system was designed on a probability of exceedance every two years. Nowadays, in urban areas, an exceedance standard of once in 100 years is considered acceptable

(Vergroesen et al. 2013). This means that the sewer system may not fail to drain waste water more frequently than once every 100 years. In addition to making exceedance standards more strict, urban flood risk management changes to a more integrative approach in which underground and above ground water systems are combined within a multi-functional and multi-stakeholder approach (de Graaf 2009; Fratini et al. 2012). Flexibility of urban water systems is currently regarded as a key characteristic of urban flood risk management because of the fact that there are large uncertainties on the driving forces that influence urban water management (de Graaf 2009). An example of such an uncertainty is the neglected and conflicting data on the amount and intensities of increased occurrences of cloudbursts in Amsterdam. Such uncertainties make it necessary for an urban water system to easily adapt to changes (de Graaf 2009).

2.1.6 Resilience

A major goal of urban flood risk management is to make a city more resilient to urban floods. The resilience of a system can also be expressed in terms of sensitivity. Sensitivity is defined as the ease of disturbance of the urban system by pluvial floods (Stone, Daanen, Jonkhoff, & Bosch 2013). A lower sensitivity corresponds to a higher resilience in urban disturbances. Resilience is defined as the capability of a system, in this case the urban environment of Amsterdam, to adapt and adjust to internal and external changes (Voskamp & Van de Ven 2014). Urban adaptation is a long-term process focused on increasing the disturbance threshold by improving the adaptive capacity of a city (Voskamp & Van de Ven 2014). Green measures play a key role in socio-economic adaptation strategies for extreme precipitation conditions (Fratini et al. 2012).

2.1.7 Small-scale green measures

Small-scale green measures are easy-applicable measures that can be both implemented by the government as by the private sector or individual inhabitants of the city. Green measures are in such a way integrated into the urban environment that it increases the aesthetic value of the city (Pötz & Bleuzé 2012). The centralised way that water management has been practiced the last decades is reaching its limits in the urban environment (Pötz & Bleuzé 2012). Small-scale green measures may therefore serve as an alternative coping strategy to water management issues. More green areas in the city improve the water buffering capacity since trees and shrubbery are able to capture rainwater for a certain time. The same holds for combinations of green areas with water surfaces, for example a bioswale, that are designed in such a way that the water level is able to fluctuate (Pötz & Bleuzé 2012). This fluctuation of the water level reflects a temporarily extra storage capacity of the local urban area.

For this study, because of time limitations, a selection of small-scale green measures has been made. This selection was made in cooperation with Amsterdam Rainproof, based on the greenest and most easy applicable measures. The following list gives an overview of the selected measures, which were categorized into four measure-groups according to spatial location:

- Public (inner) gardens and parks: bioswale, infiltration strip, rainwater pond and greening.
- Measures at the street-level: permeable pavement, open gutter and façade garden.
- Rooftop measures: intensive green roof, extensive green roof and water roof.
- Private (inner) gardens: rain barrel, greening, rainwater pond and infiltration strip.

Section 3.3 gives a more detailed description per measure, together with their urban design criteria.

2.1.8 Effectiveness of green measures

Effectiveness can be perceived in several ways. In this thesis, the primarily focus is on effectiveness in terms of the increase in water buffering capacity and in terms of the delay and/or decrease in peak and total flow of rainwater during extreme precipitation events. The longer the measure is able to delay or decrease the peak flow of rainwater, the higher the effectiveness of this measure. The same holds for the water storage capacity. The higher the water storage capacity, the higher the effectiveness of this measure. In urban areas, the majority of the surface is paved and thus impermeable (Hill 2013). Because of this, rainwater flows in a relatively short period of time over the paved surface to the sewer system, surface water or green areas where it can infiltrate. The slower this movement goes, the smaller the vulnerability to pluvial flooding (Hill 2013).

2.2 The Box-model compared with other models

There is a range of models that can be used to analyse the effectivity of green measures to prevent or decrease pluvial floods. These models can be categorized into first order, second order and integrated flow models (Vergroesen et al. 2013). First order models are the most basic ones. They consist of water balances, box-models and GIS (*Geographical Information System*) analyses (Vergroesen et al. 2013). Second order models are somewhat more complex. More data is needed and the running-time of these models is longer. Examples of second order models are 1D sewer system models, 2D flood models or 3D groundwater models (Vergroesen et al. 2013). Integrated flow models are the most complex ones. An example of such a model is 3Di, which is currently being developed by Stichting 3Di and partners. The model of 3Di is able to map water flows and effects of cloudbursts on urban areas in both the current and future situation (3Di Watermanagement Project 2014). However, 3Di is still in development and therefore not ready usable for this thesis. Besides, it is too complex for the exploratory character of this study.

Considering the scope of this thesis, a combination of a water balance and a box-model is sufficient to investigate effectiveness and possibilities of green measures on a local scale. As a general rule, it can be stated that first order models are best-fitting for exploratory, sensitivity studies with the aim to orientate a specific study-field (Vergroesen et al. 2013). A water balance in the form of a box-model can be used to quickly analyse the water storage capacity of several measures. It is easily adaptable and can show quick results. The box-model used in this thesis is further explained in section 3.2.

3 Methodology

This chapter explains the methods used to answer the research questions. It starts with a presentation of the study design (section 3.1), followed by an explanation of the box-model used in this study (section 3.2). Thereafter, each selected measure will be described and their urban design criteria will be presented (section 3.3). These first three sub-sections describe the methodology used in calculating the water buffering capacity per measure. These calculations are independently of location. The methodology then moves from a location-independent approach to local analyses, starting with a short characterisation of the case study areas (section 3.4). The methodology of opportunity mapping in these case study areas will be explained in section 3.5. And last, section 3.6 present the methodology used in calculating storage capacity in each case study area by making use of two scenario's.

3.1 Study design

The exploratory and partly descriptive character of this study reflects the need for both quantitative and qualitative data. The input of data consists of literature study, expert consultation, Geographical Information System (GIS) and box-model calculations. A flow chart of the methodology is presented in Figure 2. For some measures, the general box-model needed to be adapted to these specific measures to be able to use it to calculate the water buffering capacity per measure (yellow boxes in Figure 2). To be able to answer sub-question 2, well-founded decisions needed to be made about which measure to mark as the most effective measure to implement on each location. These decisions are based on the design criteria per measure and a ranking of measures according to their effectiveness. Opportunity maps are created in GIS to present the potential locations for each measure (green boxes in Figure 2). To answer sub-question 3, two scenarios of opportunities for implementation of measures are calculated (blue box in Figure 2). These scenarios are further explained in section 3.6. Each of the presented steps in the flow chart (Figure 2) are further elaborated in the sub-sections below.

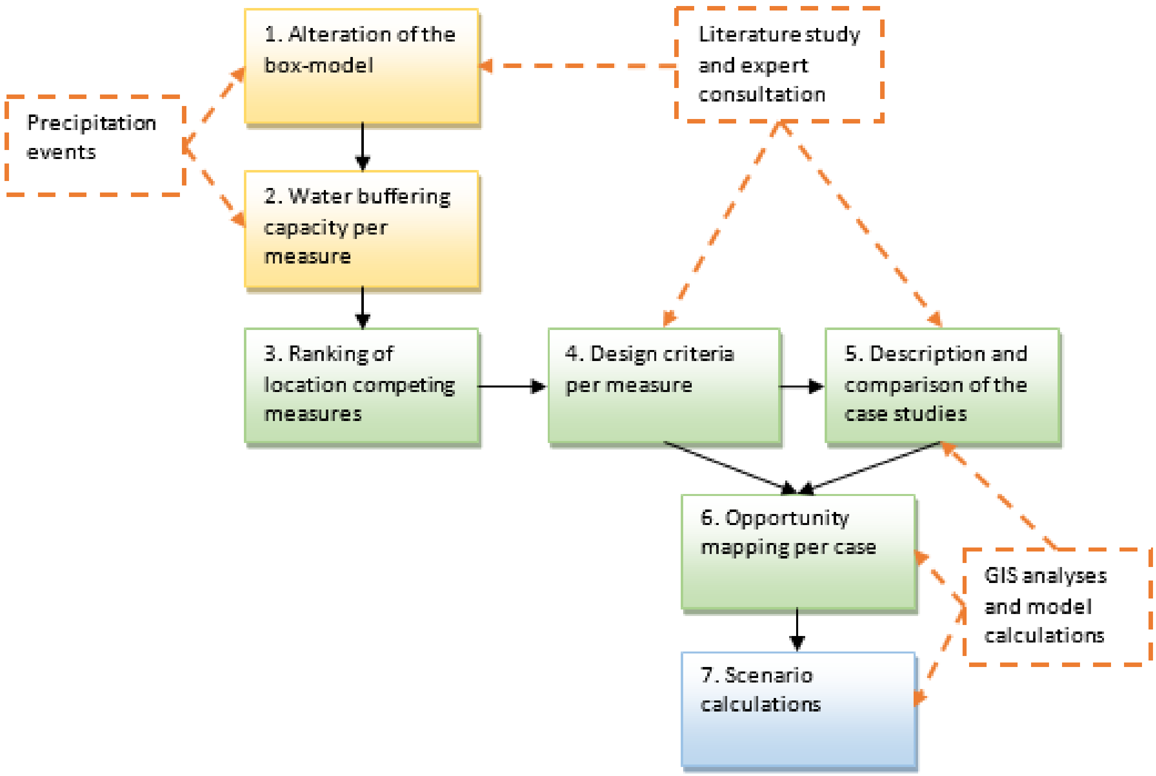

Figure 2: Flow chart of the methodology. Dashed orange boxes and lines: data input, Yellow boxes: steps needed to answer sub-question 1, Green boxes: steps needed to answer sub-question 2, Blue box; step needed to answer sub-question 3.

3.2 Water buffering capacity calculations

Sub-question 1 ("*How much can each small scale green measure contribute to the water buffering capacity?")* aims to explore the effectiveness of small-scale green measures in terms of water buffering capacity and delay and/or decrease of the peak and total flow of rainwater. A general box-model is used to answer this sub-question. Each measure is perceived as a closed system with in- and outflows (Figure 3). The difference between these in- and outflows is the amount of rainwater that is stored in the measure and in the soil (Figure 3). This storage is called S_{max} and refers to the maximum storage capacity measured in litres. The sections below describe the in- and outflows of the box-model. An overview of all assumptions concerning the box-model is given in Appendix 1.

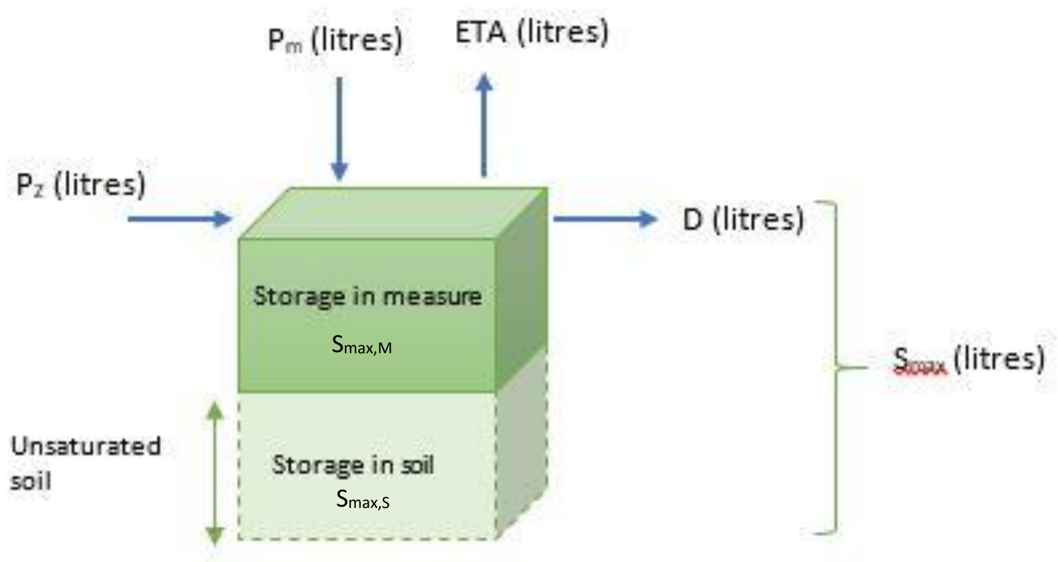

Figure 3: The general box-model. P_m: precipitation fallen on measure (litres), P_Z: precipitation fallen on surrounding area that flows to the measure (litres), ETA: actual evaporation from the measure (litres), D: outflow of water from the measure, from now on called drainage (litres), S_{max}: maximum storage capacity of the measure (mm).

3.2.1 Inflows

The inflows of the box-model per measure consist of P_m and P_Z (Figure 3). P_m is defined as the precipitation that falls on a certain measure, measured in litres.

Eq. 1

$$P_m = P * A_m$$

Where P is the precipitation intensity in mm min^{-1} and A_m is the total area available in m^2 for a certain measure. P_Z is defined as the precipitation that falls on the surrounding area of the measure and flows to the measure in litres, it functions as an inflow to the measure. P_Z is calculated by the following formula:

Eq. 2

$$P_Z = P * A_Z * 0.8$$

$$A_{tot} = A_M + A_Z$$

Where A_{tot} is the total area in m^2, A_Z is the total drainage area minus the area of the measure, 0.8 is a correction for evaporation of rainwater from the surrounding area (based on the assumption that 20% of the rainwater that falls on A_Z evaporates or flows into another direction than A_M). The water buffering capacity calculations per measure will be conducted irrespectively of a certain location. In this case A_m is assumed to be 1 m^2 and A_Z is assumed to be 9 m^2. This means that it is assumed that A_M is 10% of A_{tot} and A_Z is 90% of A_{tot}. In the case of the scenario calculations A_{tot} equals the total case area. This will be explained in section 3.6

Two precipitation events are used as inputs: 24-hours precipitation data of July 28, 2014 and a fictional precipitation event with an intensity of 60 mm per hour with a duration of one hour. The precipitation event of July 28, 2014 results in a cumulative precipitation of 87.87 mm. The fictional precipitation event of 60 mm per hour results in a cumulative precipitation of 60.00 mm. A 60 mm per hour precipitation event is chosen, because a 60 mm per hour event is the standard event used in calculations performed by Waternet and Amsterdam Rainproof. To be able to compare the two events in the same timeframe, it is assumed that the 60 mm per hour event falls between 08:00 and 09:00 at July 28th 2014. This hour is chosen because it corresponds to the highest precipitation peak of the 28th of July 2014 event. The precipitation intensities of the 60 mm per hour event are fictional, with a peak intensity of 15 mm/min after 30 minutes (Figure 4).

The precipitation intensities (P) used for the event of July 28 2014 consists of KNMI radar-data measured in Spuistraat, Amsterdam (Figure 5). It can be observed that there was a peak of precipitation around midnight, followed by a dry period of a few hours (Figure 5). The next peak was in the early morning and continued until noon. An additional assumption of the box-model is the initial storage value of zero. This means that it is assumed that all measures could store S_{max} at the beginning of the events.

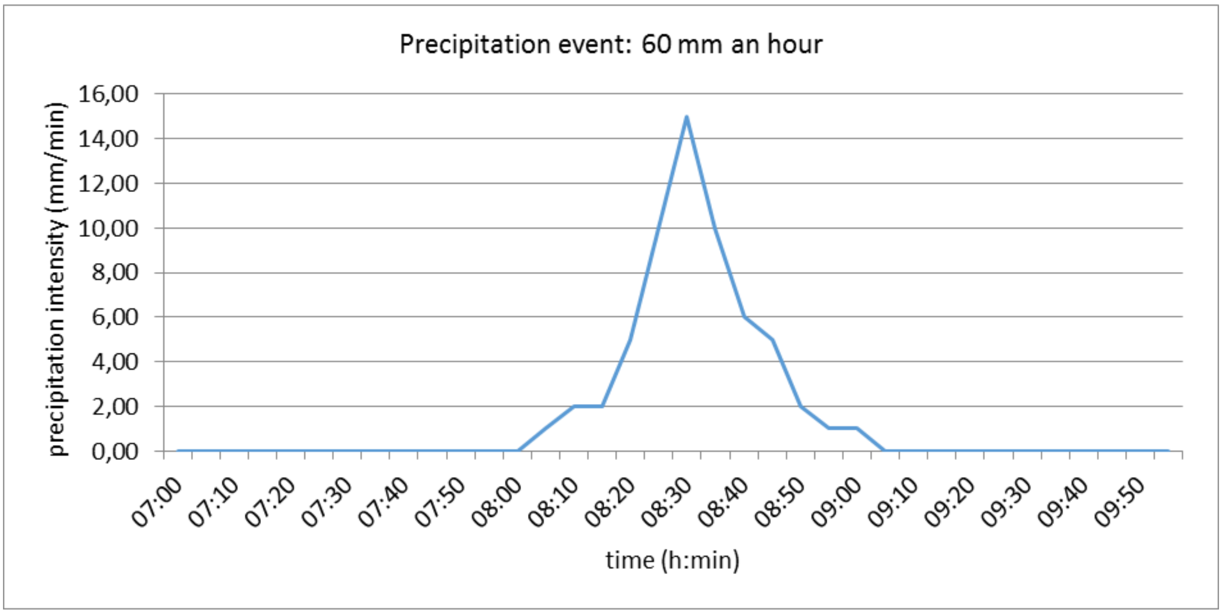

Figure 4: Precipitation data of the 60 mm per hour event

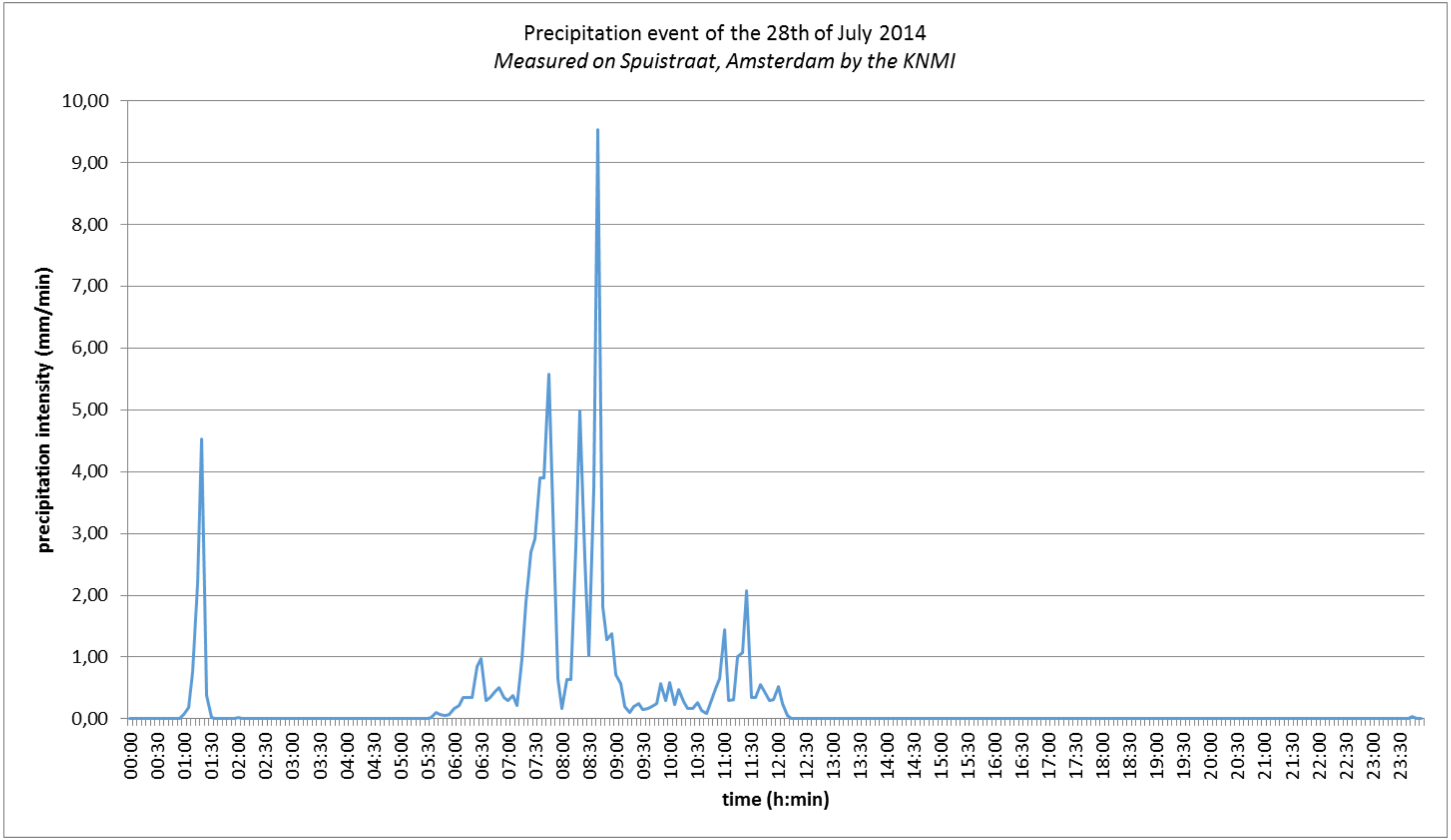

Figure 5: Precipitation data of July 28, 2014

3.2.2 Outflows

The outflows of each measure consist of D and ETA (Figure3). D is an abbreviation for drainage and is defined as the outflow of rainwater from the measure, measured in litres. This drainage may cause water nuisance at the street-level or may flow to the sewer system or surface water. There is only drainage when the maximum storage capacity of a certain measure is reached. To calculate D the following equation is used, when there is no drainage D is equal to zero:

Eq. 3

$$D = (P_m + P_Z) - ETA - (S_2 - S_1)$$

Where $S_2 - S_1$ is the difference in storage within the measure between time 1 and time 2. ETA is defined as the actual evaporation from the measure, measured in litres. ETA is calculated by correcting the potential evaporation (ETP) with a factor. This factor depends on the amount of water already stored in the measure. When the maximum storage capacity of a measure is reached, the factor to correct ETP to ETA is constant. Based on data of the KNMI, ETP is assumed to be 3 mm a day on a summer day in July 2014 (KNMI 2015).

3.2.3 Storage capacity

The maximum storage capacity of a certain measure is calculated by the following formula:

Eq. 4

$$S_{max} = S_{max,S} + S_{max,M}$$

S_{max} is defined as the sum of total storage capacity of each measure and total storage capacity in the soil under each measure, measured in litres (Eq. 4). In calculating the water buffering capacity per measure, location dependent variables are assumed to be constant. The depth of the unsaturated soil is assumed to be 0.5 metres, based on the high groundwater levels in Amsterdam (Waternet 2015). The total water holding capacity in the unsaturated soil is measured by the difference between the field capacity (Θ_{FC}) and the wilting point (Θ_{WP}) (Allen et al. 1998)(Eq.).

Eq. 5

$$WHC = \theta_{FC} - \theta_{WP}$$

Amsterdam has a sandy top-layer that is at some places mixed with gravel (Waternet 2015). As a simplification, the top-layer is assumed to consist only of sand. Sand has an average Θ_{FC} of 0.12 m^3/m^3 and an average Θ_{WP} of 0.045 m^3/m^3 (Allen et al. 1998). Filling in Eq. gives: WHC = 0.12 - 0.045 = 0.08 m^3/m^3. The average WHC of the soil is thus assumed to be 0.08 m^3/m^3. To convert the WHC to millimetres it needs to be rewritten. 0.08 m^3/m^3 equals 80 litres per m^3. When the soil is 0.5 metres deep instead of 1 metres deep the WHC needs to be divided by 2 resulting in 40 litres in a part of the soil with a surface of one m^2 and a depth of 0.5 m. One mm rainwater equals 1 litre of water on one m^2. Therefore, the WHC equals 40 mm.

The box-model (Figure 3) is used to calculate four aspects: the storage per measure (S) at a certain point in time at a certain event, the ability of a measure to decrease the peak of drainage, the ability of a measure to decrease the total drainage and the ability of a measure to delay the peak of drainage. S is calculated by the following formula:

Eq. 6

$$S = (P_m + P_Z) - (ETA + D)$$

3.2.4 Alterations of the box-model

The general box-model presented in Figure 3 needs to be adapted to each measure to be usable to calculate S for each measure. The parameters P_m, ETA and D did not need to be changed. Measures that are assumed to not have P_Z are: all rooftop measures and façade gardens. Façade gardens do not have P_Z inflow because they are built with a concrete barrier around them and rooftop measures do not have an area attached to the surface-level from which rainwater is able flow to the rooftop. Measures that do not have $S_{max,S}$ are because water cannot be stored in the soil at the surface-level underneath: rainwater ponds, open gutters and all rooftop measures. At these measures $S_{max} = S_{max,M}$, meaning that the maximum storage equals the maximum storage of the measure. Other factors that influence S_{max} are dependent on the design of the measures. These factors will be explained in section 3.3.

One last factor that influences the maximum storage is the possibility of interception of rainwater by vegetation. The following measures are assumed not be able to have interception by vegetation because of these measures have minimal or no vegetation at the surface-level: rainwater ponds, permeable pavement and open gutters. The average interception by vegetation in the remaining measures is assumed to be 1.70 mm for trees, 1.07 mm for shrubs and 1.05 mm for grasses based on literature study (Aston 1979; Garcia-Estringana et al. 2010; Calder & Wright 1986; Herwitz 1985; Tsiko et al. 2012; Teklehaimanot & Jarvis 1991; Rutter et al. 1975).

3.3 Selected green measures

The design criteria and characteristics per measure are studied and presented per measure-group in the following sub-sections.

3.3.1 Public (inner) gardens and parks

The selected green-measures that can be implemented in public gardens and parks are: bioswales, infiltration strips, rainwater ponds and greening. A bioswale is a vegetated ditch with multiple distinct layers (Boogaard et al. 2003). The top-layer has a ground-improving character leading to an increased infiltration capacity (Vergroesen et al. 2013). The infiltrated water from the top-layer flows into a layer with sand or gravel from which it can infiltrate further into the soil (Vergroesen et al. 2013). There are bioswales with and without an extra drain. Bioswales with an extra drain accelerate water to the surface water. The water coming from bioswales without an extra drain infiltrates to the groundwater table (Vergroesen et al. 2013). In this thesis, the focus is on bioswales without an extra drain. The infiltration rate from bioswales without an extra drain varies from one to ten days depending on the infiltration capacity of the soil (Vergroesen et al. 2013). A bioswale is allowed to have a slope of at maximum 1:3 (or 18-19^0), a depth of 0.3 metres with a width of 0.5 metres and should have a distance of at minimum one metres to the closes buildings (Beenen & Boogaard 2007; Pötz & Bleuzé 2012)(Figure 6). Having these criteria, the minimum total width of a bioswale has been calculated and equals 2.32 metres (Figure 6). Therefore, the minimum area needed to construct a bioswale is 2.32 m^2.

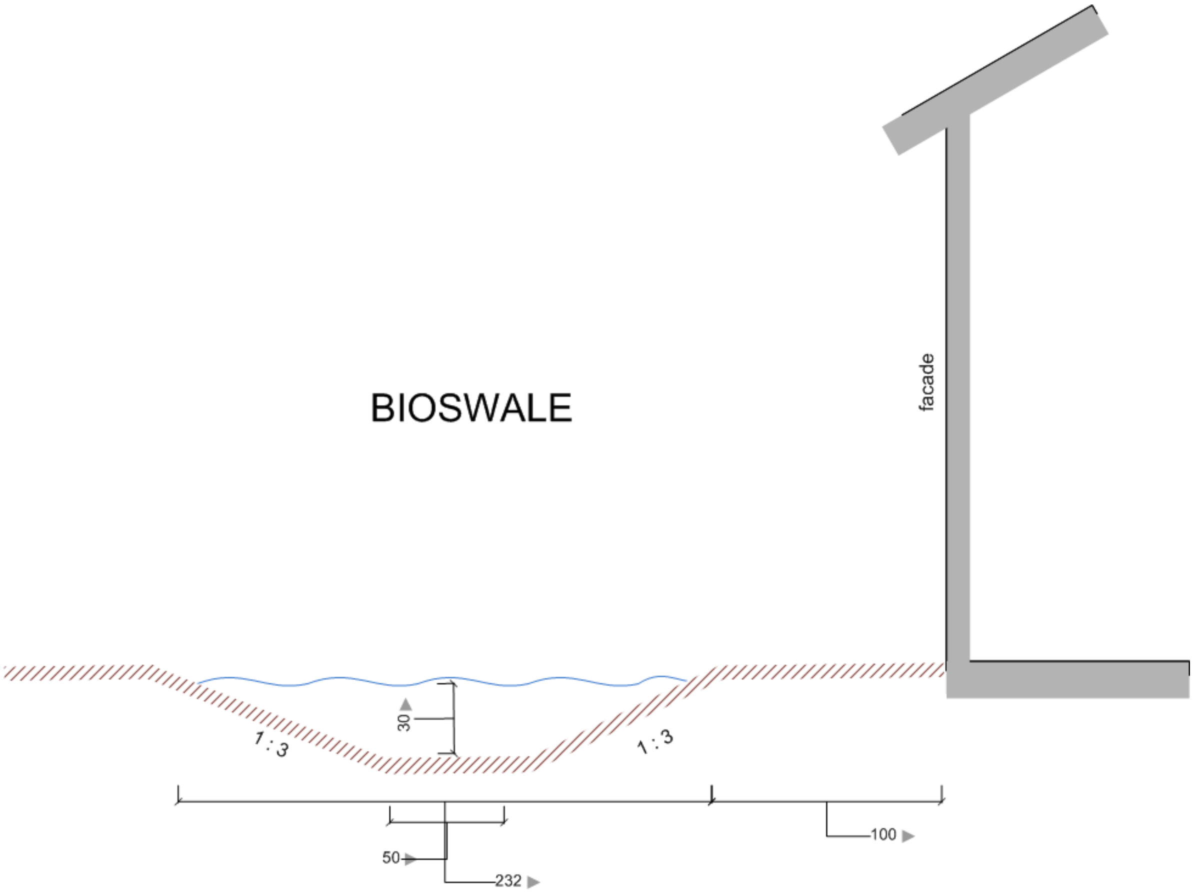

Figure 6: Design criteria of a bioswale

The second measure in the measure-group *Public (inner) gardens and parks* is the infiltration strip with above ground storage and an urban design (Figure 7). In urban areas, the maximum depth of an infiltration strip is 0.3 metres (Pötz & Bleuzé 2012). Infiltration strips need to be built with a minimum distance of 1.50 metres from buildings. This is due to the minimum width of the sidewalks of 1.50 metres (Gemeente Amsterdam 2009). The minimum width of an infiltration strip is 0.6 metres, resulting in a minimum total area of 0.6 m^2 (Figure 7).

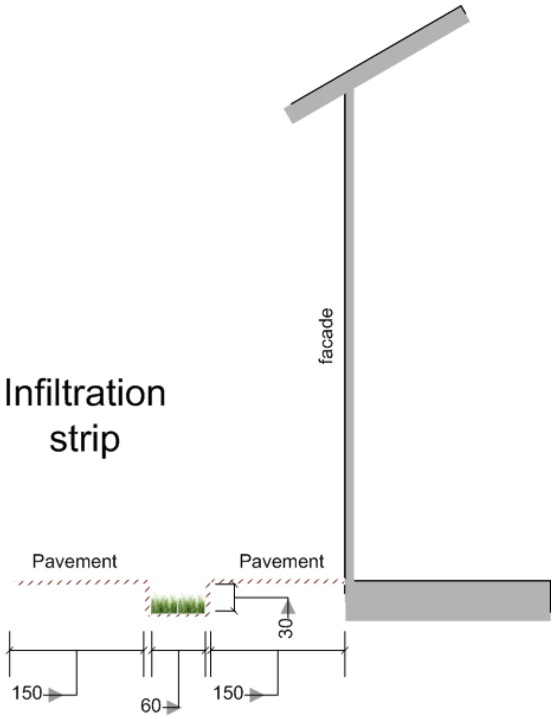

Figure 7: Design criteria of an infiltration strip

The third measure in this measure-group is the rainwater pond. Rainwater ponds can store water by fluctuating the water level. They have an impermeable layer which makes infiltration impossible (Pötz & Bleuzé 2012). A rainwater pond has a maximum slope in urban areas of 1:3 (or 18-19^{0}) and a minimum distance from buildings of 1 metres (Pötz & Bleuzé 2012; Beenen & Boogaard 2007)(Figure 8). Rainwater ponds can have several depths, however a minimum of 1.0 metres is required to prevent blooming of algae (Pötz & Bleuzé 2012). An extra water buffer of 0.3 metres brings the total maximum depth of a rainwater pond to 1.3 metres (Figure 8). The total of design criteria as presented in Figure 8 brings the total minimum size of rainwater pond to 8.39 m^{2}.

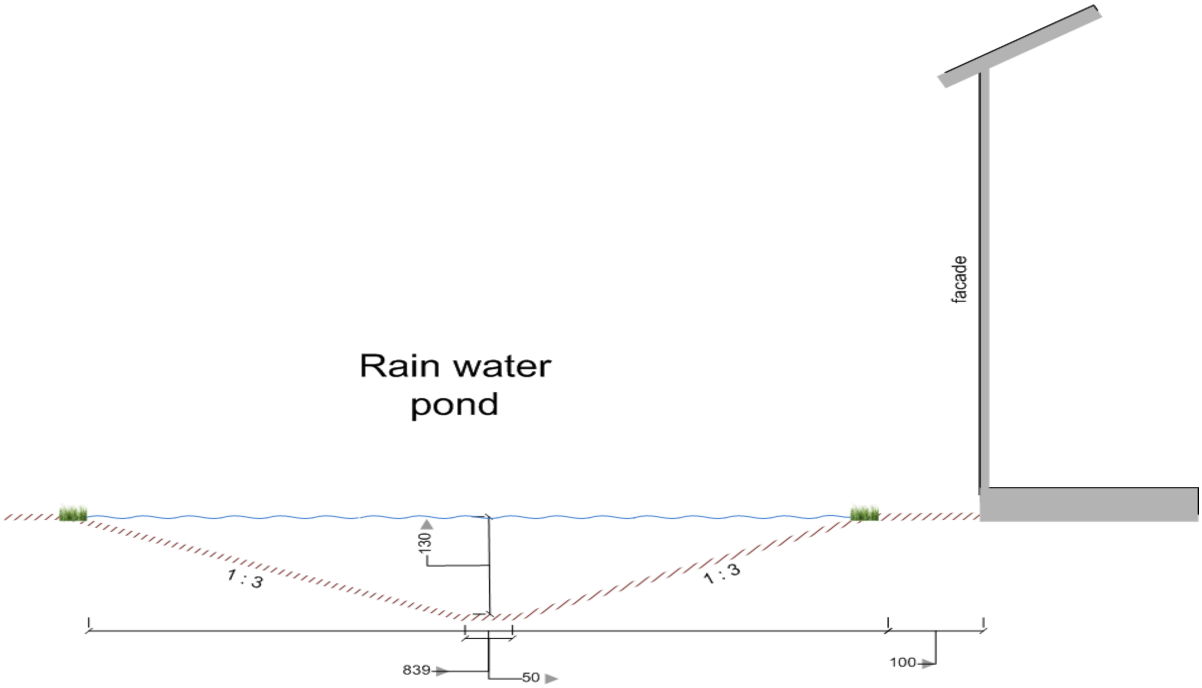

Figure 8: Design criteria of a rainwater pond

Greening does not have specific design criteria. Every paved area can theoretically be transformed into a green area. Public gardens and green areas act similar as private gardens; they can capture overflow of precipitation and act as infiltration sites (Pötz & Bleuzé 2012). Drainage by public gardens and green areas can be increased by lowering the ground level of these areas. When the street level is higher, water can runoff to lower located green areas (Vergroesen et al. 2013).

3.3.2 Measures at the street-level

The following measures can be applied on the street: open gutters, permeable pavement and façade gardens. Open gutters have a lower surface than the surrounding area and are therefore able to collect and drain rainwater to downstream water bodies or green areas (Ahiablame et al., 2013) (Pötz & Bleuzé 2012). Permeable pavement is used to increase infiltration through a paved surface. Water is able to infiltrate in the subsurface via the joints of pavers (Ahiablame et al., 2013). Permeable pavement is especially effective during low-intensity precipitation events (Vergroesen et al. 2013). Façade gardens are different from the other measures at street-level. The municipality gives the possibility to remove a paver next to the façade to make a façade garden (Gemeente Amsterdam 2015a). Façade gardens have a concrete border which makes it impossible for rainwater to flow from the paved sidewalk or street to the façade garden. The minimum width of the sidewalk to construct a façade garden should be 1.80 metres, since a façade garden has a standard width of 0.3 metres and a sidewalk has a minimum width of 1.50 metres (Figure 9) (Gemeente Amsterdam 2009; Gemeente Amsterdam 2015a).

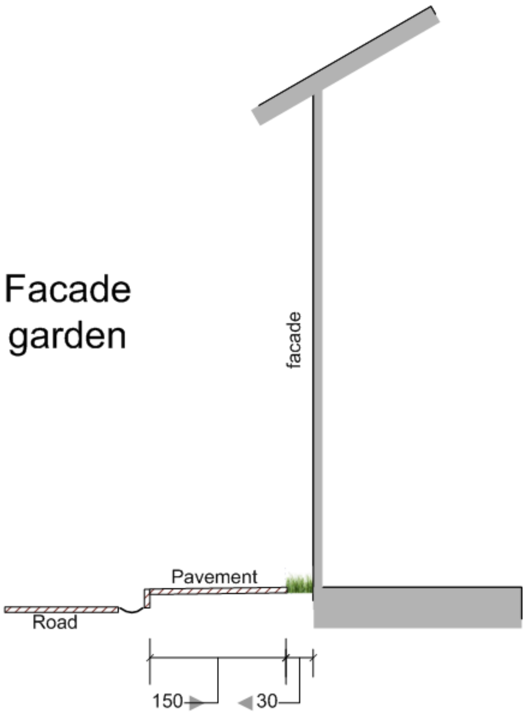

Figure 9: Design criteria of a facade garden

3.3.3 Rooftop measures

Rooftops can constitute up to 50% of urban impervious areas (Speak et al. 2013) and thus form a large contribution to water infiltration and urban water storage. In addition to storage of rainwater, rooftop measures have several other benefits such as reduction of pollution and the urban heat island, and increase of the aesthetic value of buildings (Perini et al. 2013). The following rooftop measures are selected for this study: intensive green roofs, extensive green roofs and water roofs.

Green roofs consist of several layers (Figure 10). The thickness of the vegetation layer determines whether a green roof is intensive or extensive. A green roof with a thickness of at maximum 15 cm is called an extensive green roof (Kennis voor Klimaat 2014). Intensive green roofs have a thickness between 15 and 30 cm and roofs with a vegetation layer of above 30 cm are called rooftop gardens (Kennis voor Klimaat 2014). The vegetation layer on green roofs is able to capture water for a certain period, causing a delay and a decrease in drainage of rainwater to the sewer system (Arcadis and Provincie Utrecht 2010). These hydrological functions of green roofs and water roofs are called retention and detention. Retention is defined as the reducing capacity of the total outflow volume (Palla et al. 2012). Detention reflects the delay in the initial runoff time (Palla et al. 2012). During cloudbursts, green roofs and water roofs can drain a part of the overflow of precipitation (Arcadis and Provincie Utrecht 2010). Water can also be stored in the soil substrate and drainage layer. The amount of water that green roofs are able to store depends on the thickness of the vegetation layer, the surface area of the roof and the evaporation rate. An extensive green roof is able to store around 25-65 mm and an intensive green roof is able to store approximately 30-75 mm. There is a large variability in storage capacity of intensive green roofs due to their large range in thickness of the vegetation layer (Kennis voor Klimaat 2014). Therefore, as an assumption this study used a S_{max} of 25 mm for an extensive green roof and a S_{max} of 75 mm for an intensive green roof in further calculations. The S_{max} of both an extensive as an intensive green roof are probably overestimations. These overestimations are chosen, because this study can be perceived as a best-case study in which the maximum potential will be explored.

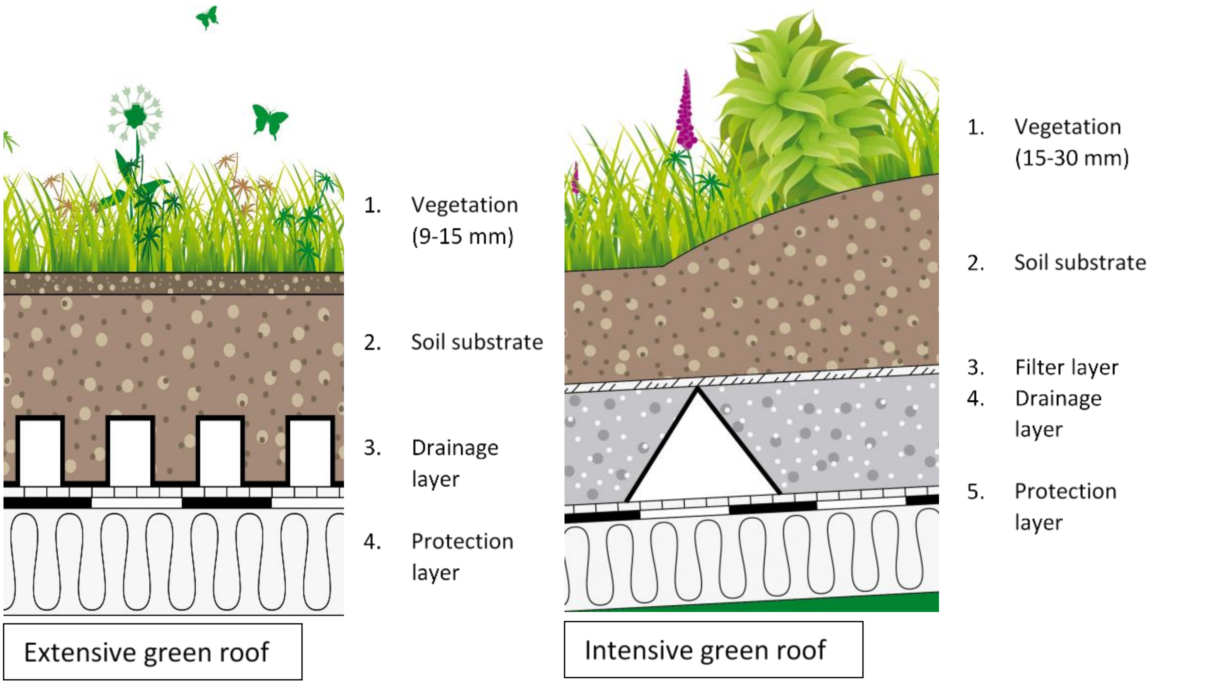

Figure 10: The layers of an extensive and an intensive green roof (Amsterdam Rainproof 2015b; Amsterdam Rainproof 2015a)

In addition to the thickness of the different layers of a green roof, the effectiveness of green roofs depends on the evaporation rate. De evaporation rate determines the storage-capacity clearing rate (Kennis voor Klimaat 2014). In summer, evaporation is higher than in winter because of higher air temperature (Kennis voor Klimaat 2014). Therefore, the effectiveness of green roofs is higher in summer than in winter. The evaporation rate that is evaluated in this study is 3 mm a day, which is the average evaporation of a summer-day in June as estimated by the KNMI (KNMI 2015).

Water roofs act differently from green roofs. For longer periods, water can be stored on the roof. Drainage occurs by either evaporation or drainage pipes (Vergroesen et al. 2013). The storage capacity depends on the maximum storage height of the roof and its surface area. The average height of a water roof is assumed to be 20 mm. Therefore, S_{max} of one m^2 water roof is assumed to be 20 mm. In practice, water roofs might have a larger height, leading to a larger S_{max}. Therefore, it should be noted that the S_{max} of a water roof is highly dependent on the design and height of the roof edge. Probably, an S_{max} of 20 mm is therefore in some cases an underestimation. The evaporation rate of water roofs is on average higher than the evaporation rate on green roofs (Vergroesen et al. 2013). The implementation of water roofs are also somewhat different from green roofs, because the total weight of a water roof is higher than that of a green roof. Buildings built after around 1960 are most times calculated for a maximum carrying capacity of 1 kN/m^2 (Amsterdam Rainproof 2015b). There is no substrate or vegetation layer necessary for a water roof, therefore all the carrying capacity of the roof is available for the storage of rainwater.

3.3.4 Private (inner) gardens

In private (inner) gardens, the following selected green measures can be implemented: greening, infiltration strips and rainwater ponds. Infiltration strips and rainwater ponds are already discussed in previous sections. The design criteria can be found in respectively Figure 7 and Figure 8. Private gardens are a key element in urban green infrastructure (Warhurst et al. 2014). However, urban private green spaces are declining because of, among others, the need for more parking places and a trend towards the creation of paved gardens in the last decennia (Warhurst et al. 2014). Reducing the amount of paved area in gardens could increase the resilience of Amsterdam to pluvial floods by increasing evapotranspiration, infiltration and storage of rainwater (Warhurst et al. 2014; Autixier et al. 2014;Kennis voor Klimaat 2014).

3.4 Case study areas

Amsterdam has a large history in water management with the majority of the city being built on pile foundation due to subsidence caused by peat decomposition in the soil (de Gans 2011). To prevent buildings and streets from subsidence, the surface level of large parts of the city are increased with a layer of sand (de Gans 2011). This underpins the assumption of a sandy top-layer. The analysis of opportunities for green measures needs to have a local focus, because each area in Amsterdam has different opportunities concerning green measures. Therefore, three (sub-) neighbourhoods in Amsterdam are selected as case studies: Spuistraat-Zuid, Nieuwendam Noordwest Zuid and Rijnbuurt, which is a part of the Rivierenbuurt (Figure 11). Each of the cases differ in sewer system and urban typology. Using GIS, differences in urban typology between the three cases have been signalized: different housing densities, different distances towards surface water and different housing structures

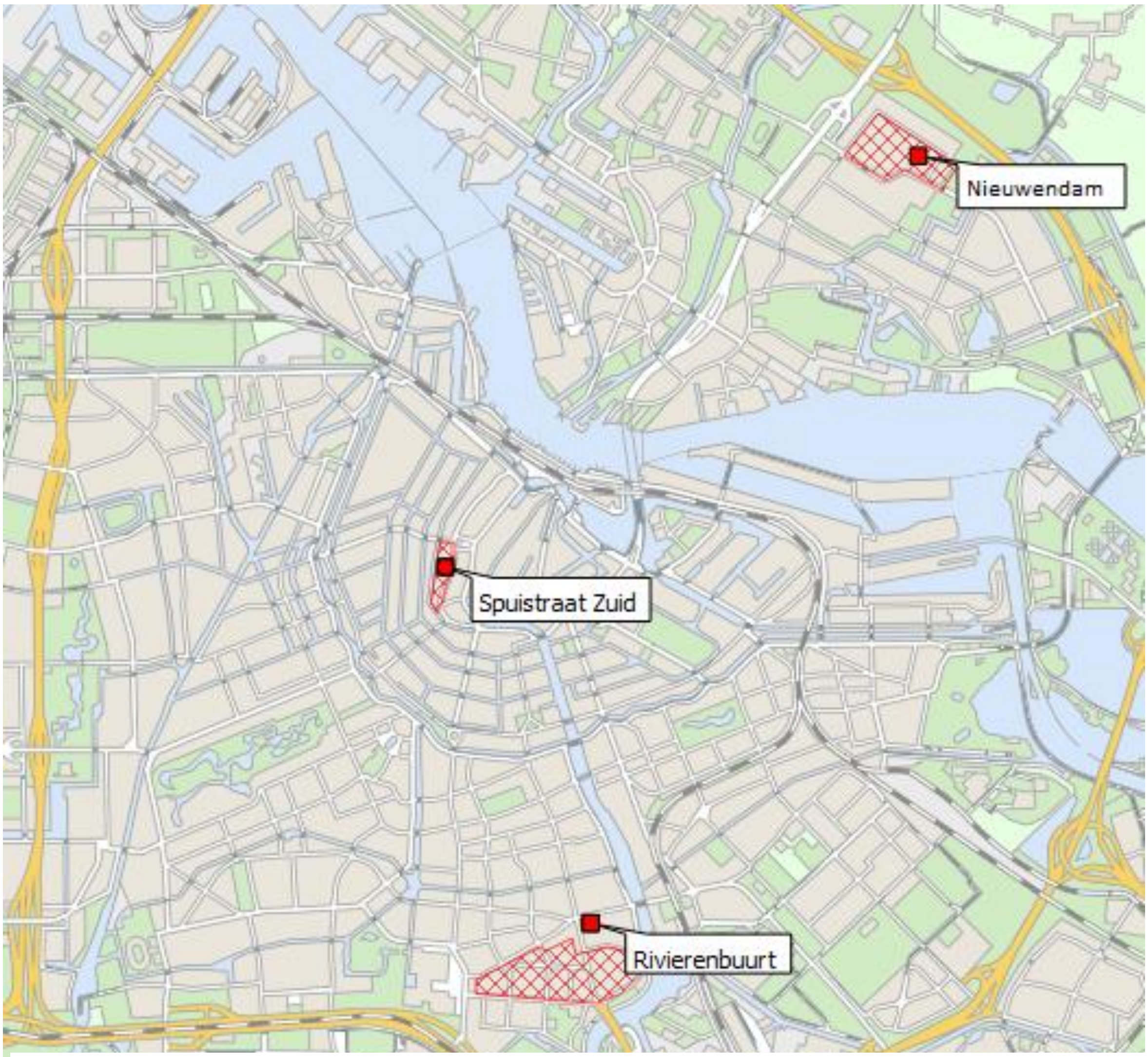

Figure 11: Locations of the three cases in Amsterdam

and heights (Table 1). The differences in urban typology are qualitatively analysed and presented relative to each other, due to missing quantitative data.

Table 1: Comparison of characteristics per case relative to the other cases

	Spuistraat-Zuid	Rijnbuurt	Nieuwendam Noordwest Zuid
Amount of green area	low	average	high
Amount of paved area	high	average	low
Amount of public space	low	average	high
Area (m^2)	59,355	1,634,552	263,836
Average building year	<1900	1930-1940	1960-1970
Average distance to surface water	short	long	average
Building density	high	average	low
Heights of buildings	average	Low	high
Type of sewer system	mixed	Separated	separated
Width of streets	narrow	Average	wide

The Spuistraat-Zuid area, referred to as Spuistraat, is part of the old city centre (

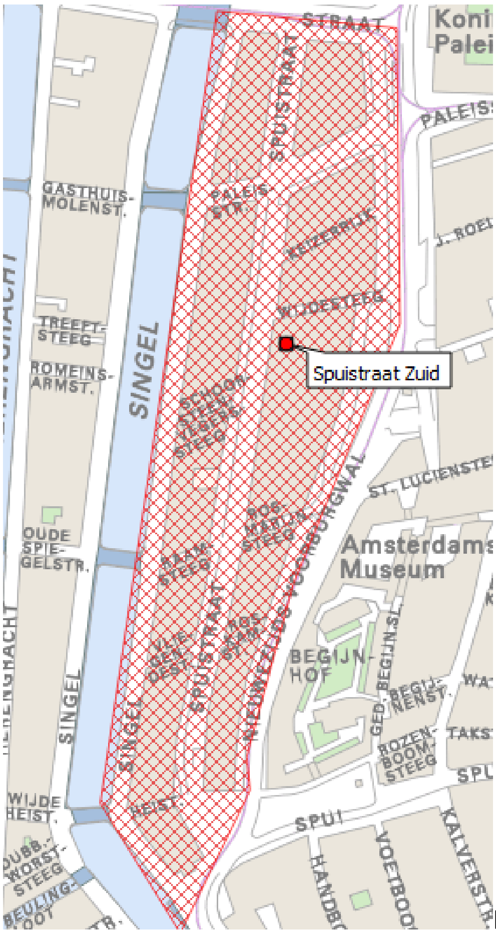

Figure 12). As shown in Table 1, it has the highest building density and the least green spaces of the selected cases. The buildings in Spuistraat are constructed between 1300-1650 (Ponten & Visser 2010). The Spuistraat is the case with the highest building density and the oldest buildings relative to the two other cases. Part of the consequences of an old city centre is the existence of a mixed sewer system that collects rainwater and sewer water in one pipe (Stichting Rioned 2009b). The area has been raised with an average layer of 3.6 metres of sand, the lower limit of the sand layer is on average -2.3 m NAP and the average surface level is +1.11 m NAP (Ponten & Visser 2010).

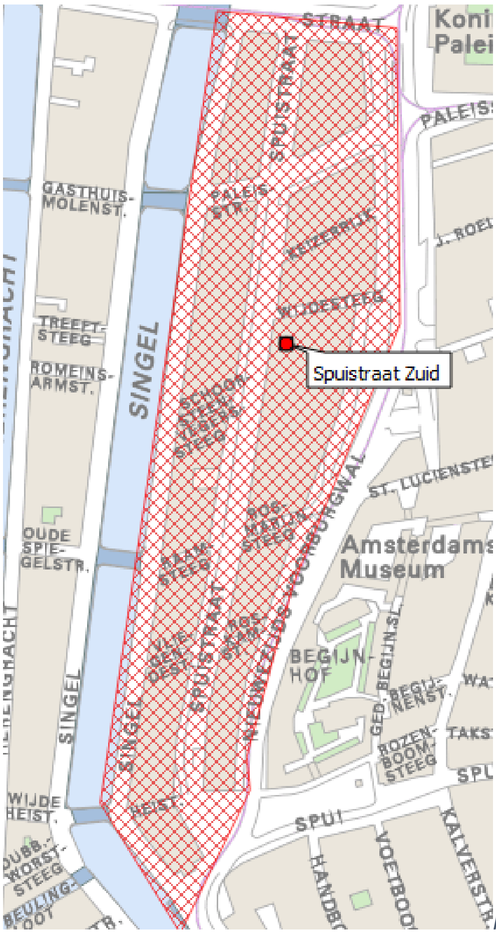

Figure 12: Map showing the location of Spuistraat

Rijnbuurt is located in the South of Amsterdam and is part of the bigger Rivierenbuurt (Figure 13). As shown in Table 1, Rijnbuurt has the longest average distance to surface water and the building density is average relative to the other two cases. Most of the buildings were constructed between 1920 and 1934. This means that this area is built later than Spuistraat. In addition, Rijnbuurt has a separated sewer system (Ponten & Visser 2007). A separated sewage system collects rainwater and sewer water in two separated pipes (Stichting Rioned 2009a). Since 1934, the Rijnbuurt area has been raised with an average layer of 4.3 metres of sand (Ponten & Visser 2007). The lower limit of the sand layer is on average -3.9 m NAP and the surface level of the area is on average +0.59 m NAP (Ponten & Visser 2007).

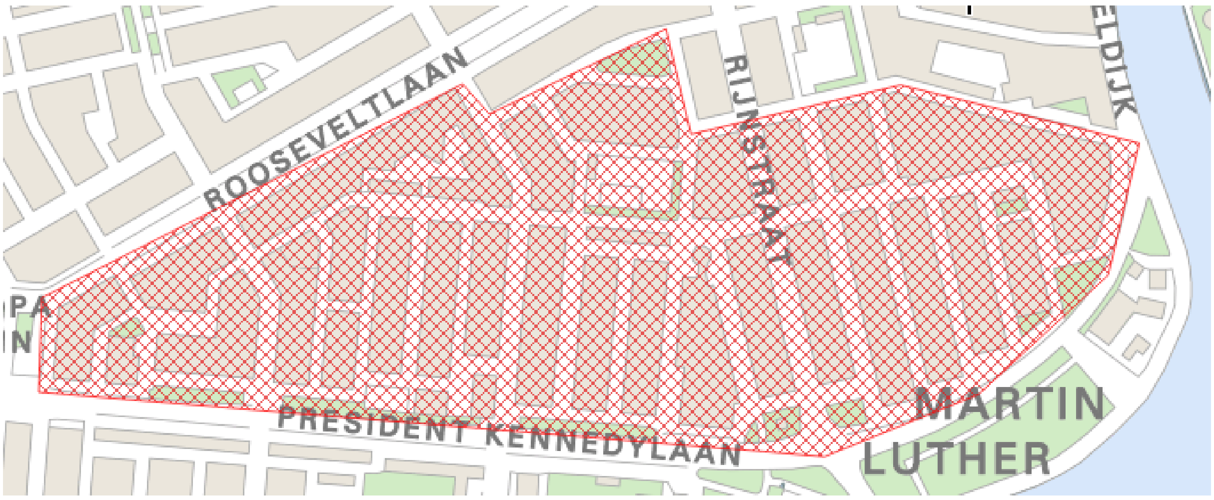

Figure 13: Map showing Rijnbuurt

Nieuwendam Noordwest Zuid, from now on referred to as Nieuwendam, is located in Amsterdam Noord (Figure 14). Nieuwendam is a relatively new district with buildings constructed around 1960-1970. As shown in Table 1, it has the highest amount of green area relative to the other cases. The majority of the build area consists of high-rise, mainly social rented houses owned by housing corporations. Nieuwendam has a separated sewer system (Waternet 2015). The average surface level of Nieuwendam is -3.4 m NAP (Waternet 2015). In addition, Nieuwendam has complications concerning infiltration of water in the soil. Levees are used to reclaim parts of the land in Amsterdam Noord because of the relatively low surface level. It is unclear where in the soil of Nieuwendam these levees are located, which complicates water management as infiltration is much slower in the clayish levees. These levees may also result in a so-called '*badkuip-effect*', meaning that infiltrated water is blocked by impermeable layers of clay and therefore not able to leave the area through the soil (Waternet 2015). Therefore, measures that are primarily focused on infiltration will not be analysed in this area, because these need a very local approach.

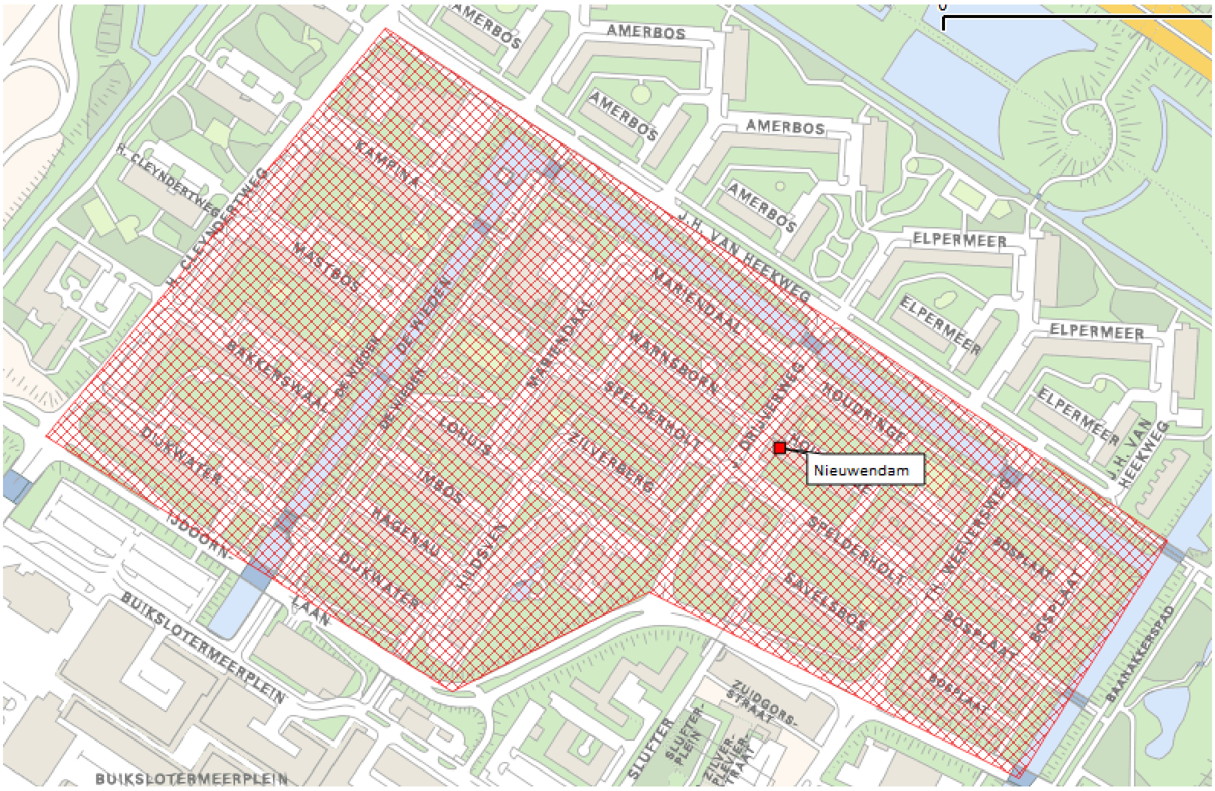

Figure 14: Map showing Nieuwendam

3.5 Opportunity mapping

Each case differs in characteristics and therefore in best implementation strategy per selected measure. Not all selected green measures are applicable in each case. Sub-question 2 ("*What are the potentials for implementing small-scale green measures in three case areas in Amsterdam: Nieuwendam, Spuistraat and Rijnbuurt?*") is answered by making opportunity maps that present the locations where the selected measures can be implemented per case. These maps are constructed using GIS, aerial photos and Google Earth. The following GIS maps were used: slope of the roofs, *Grootschalige Basiskaart Amsterdam* (GBKA), map of functions, WOLK and a map of the locations of buildings owned by housing corporations (Gemeente Amsterdam 2015b; Waternet 2015). As mentioned in section 3.4, the infiltration capacity of the soil in Nieuwendam is uncertain because of clayish levees in the subsoil. This results in excluding selected measures that primarily depend on infiltration: permeable pavements and open gutters. In Nieuwendam, the majority of public spaces is already greened. Therefore, additional greening will not significantly contribute in increasing the water buffering capacity and is therefore excluded from the opportunity maps. Last, the majority of buildings are owned by corporations and have garages at the ground floor leaving no space for façade gardens. Therefore, façade gardens are excluded from the opportunity maps of Nieuwendam as well. The measures that are included in the opportunity maps of Nieuwendam are: bioswales, infiltration strips, all rooftop measures and rainwater ponds.

The highly densified and crowded area of Spuistraat results in little opportunities for measures at the street level. Almost all roads in this area are touristic main roads, therefore implementing open gutters are not an option since these are assumed to be only implemented at small, minor roads. In addition, there is little available area for public (inner) gardens and parks. Implementation of greening of public spaces, bioswales, infiltration strips and rainwater ponds in public areas is not possible in Spuistraat. The measures that will be included in the opportunity maps of Spuistraat are measures from the following measure-groups: rooftop measures and private (inner) gardens, as well as permeable pavement at small, minor roads.

Compared with the other cases, the Rijnbuurt has relatively many opportunities for green measures. All selected measures are included in the opportunity maps. The steps that are taken in creating opportunity-maps for each case are presented per measure-group.

First, for *Public (inner) gardens and parks*, polygons are created in GIS for all public areas in each case. Thereafter, each polygon area is calculated in GIS. Third, an estimation has been done whether to implement public greening, bioswales, infiltration strips or rainwater ponds at each polygon of public green space. This estimation is based on the area of the polygon, the design criteria per measure (section 3.3) and the effectiveness of each measure (section 4.1). If measures compete on location, the most effective and best-fitting measure, according to their design criteria, is perceived as the best opportunity. The effectiveness of each measure is based on the ranking of selected measures (section 4.1). This ranking is an outcome of the water buffering capacity calculations per measure. In public gardens, parks and public green areas the area of each individual rainwater pond, bioswale and infiltration strip is increased to its maximum area instead of the area presented at the design criteria in section 3.3. Last, the total area of opportunities per measure is calculated using GIS and Excel.

For *Measures at the street-level*, all roads per case study will be analysed using GIS and Google Earth. First, small, minor, non-asphalt roads without tramlines are marked with polygons in GIS as opportunities for permeable pavement. The area of each polygon is calculated using GIS. Thereafter, the total area of opportunities for permeable pavements are summarized for each case in different tables. Second, small, minor roads that have a width over 3.7 metres and a distance to surface water or green spaces less than 100 metres are marked as opportunities for open gutters. The opportunities are marked by creating lines in GIS. The total length of these lines is calculated in GIS. Thereafter calculations are made for each case to get the total area of open gutters. The total length of the open gutters is multiplied with the width, which is 0.2 metres, to get the total area. Third, an estimation is done about the percentage of facades available for facade gardens at each street. This percentage varies between 20%, 40%, 60% and 70%. The total length of the facades is multiplied by the accompanying percentage in each street. These lengths are summarized to get a total length of opportunities for facade gardens per case. The lengths are multiplied by the width of a facade garden, which is 0.3 metres, to get the total area.

Polygons are created using GIS, for *Rooftop measures* as well. Each flat roof per case makes a polygon. The polygon areas are calculated in GIS. An estimation has been made whether to implement an intensive or extensive green roof or a water roof. This estimation is based on building year of the roof, roof materials and accompanying design criteria (section 3.3), and on the effectiveness of each measure. If measures compete on location, the most effective and best-fitting measure is perceived as the best opportunity. The oldest roofs are not suitable for intensive green roofs or water roofs, due to the heavy load. Therefore, it is assumed that in Spuistraat only extensive green roofs are applicable. Last, the total area of opportunities per measure is calculated using GIS and Excel.

Similar to public areas, polygons are created for each *Private (inner) garden* per case study. Each polygon area is calculated in GIS. Because there was not enough detailed information in GIS or on aerial photos about the current percentage of green over-paved areas in private gardens, different scenarios are made resulting in different opportunities. The scenarios of the ratio between the current green area and the current paved area are: 20%, 40% and 60%. An estimation has been done whether to implement greening, an infiltration strip or a rainwater pond. This estimation is based on the area of the polygons, the physical criteria per measure and the effectiveness of each measure. In each polygon, a maximum of one rainwater pond and infiltration strip is perceived as an opportunity. Contradictory with rainwater ponds and infiltration strips in public areas, the size of a rainwater pond and infiltration strip in private gardens corresponds with the design as presented in section 3.3. This approach is chosen to prevent opportunity maps from presenting the total area of a private garden as an opportunity for a rainwater pond. The total area of opportunities per measure is calculated using GIS and Excel

3.6 Scenario calculations

The potential contribution to the water buffering capacity of the opportunities in each case area, visualised in the opportunity maps, are calculated and analysed using two scenarios. Scenario 1 analyses the full-potential of each measure in each case study irrespectively of other measures in the area using the 60 mm per hour event. Section 3.6.1 explains the methodology of scenario 1 calculations.

Scenario 2 presents a 'best-combination' of measures, a measure package, per case area, using both precipitation events. The total water buffering capacity per measure package is calculated in scenario 2. Section 3.6.2 explains the methodology of scenario 2 calculations. The two scenario provide an answer to sub-question 3 *("What is the total contribution to the water storage capacity if all potentials in each selected case for implementation of green-measures are taken in Nieuwendam, Spuistraat and Rijnbuurt during a 60mm/h precipitation event and during the event of July 28th 2014?").*

3.6.1 Scenario 1

Based on the results of the opportunity maps, different areas per measure per case area are available. An outcome of the opportunity maps per case area is the total potential area available per measure per case area, this is called A_m. The aim of Scenario 1 is to present the full potential of each measure individually in each case area by calculating the total storage potential (S_{tot}) per measure in each case area using the fictional event of 60 mm per hour. This total storage potential is calculated using the total available area per measure. This total area is used in the general box-model as A_m. The in- and outflows and maximum storage capacity are calculated per measure per case area using the box-model. As already stated in 3.2.1, A_m is defined as the total area available for a certain measure in m^2 and A_{tot} is the total area of a certain case in m^2. In addition, to remain consistent, the potential evaporation (ETP) is multiplied by A_m and the maximum storage capacity of a certain measure is multiplied by A_m. The only alteration to the general box-model as described in section 3.2, is the equation that is used to calculate P_Z. In both Scenario 1 and Scenario 2, P_Z is calculated as follows (Equation 7):

Eq. 7

$$P_Z = (P * A_{tot} - P_M) * 0.8$$

The results of the box-model calculations will be analysed per measure in each case area at three aspects:

- The delay of drainage caused by a certain measure
- The decrease of the peak of drainage caused by a certain measure
- The total decrease of drainage caused by a certain measure

For example, when analysing extensive green roofs in Spuistraat Figure 15 could be analysed (see next page). The decrease of the peak of drainage is illustrated by X and the delay of drainage is illustrated by Y (Figure 15). The total decrease of drainage can be observed as the decrease in total drainage of the blue line compared with the orange line (Figure 15). To calculate the ability of a certain measure to cause a delay in drainage, the starting point of drainage in the situation with the implementation of the total area available for a certain measure at a certain case area is compared with the starting point of drainage in the situation in which no measures are implemented and thus no extra water storage is created. The delay in drainage is measured in minutes.

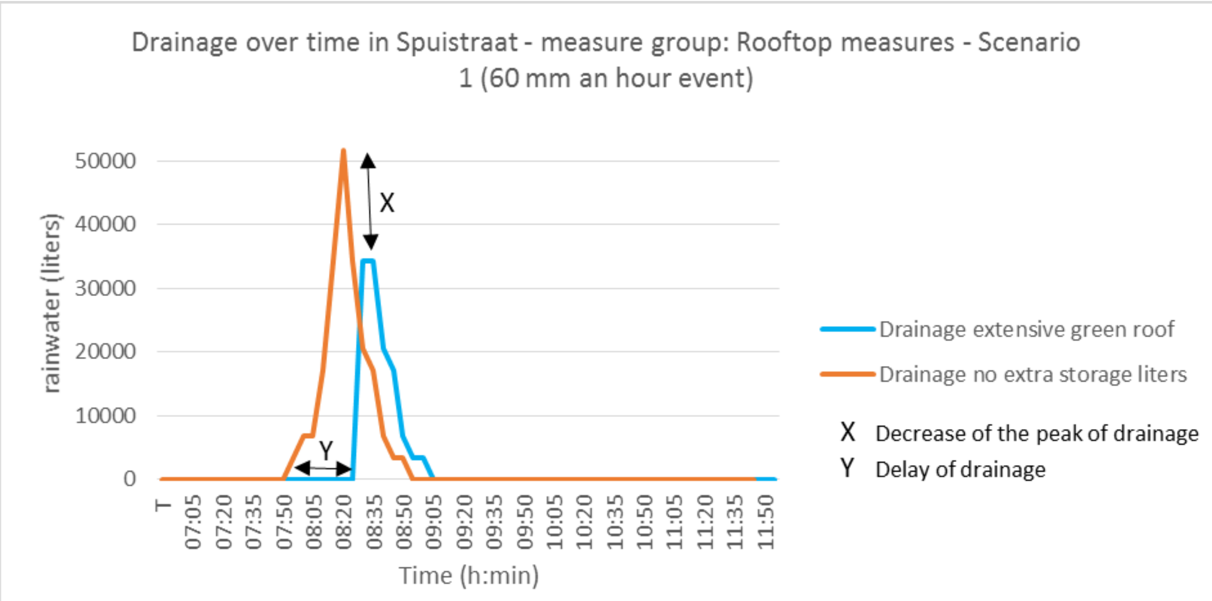

Figure 15: A comparison of drainage between implementation of extensive green roofs and no extensive green roofs.

The decrease of the peak of drainage is defined as the decrease of the maximum amount of drainage caused by implementation of a certain measure. It is calculated by the following formula, and measured in percentage:

Eq. 7

$$Decrease\ of\ the\ peak\ of\ drainage(\%) = \frac{(D_{max} - D_{max,M})}{D_{max}} * 100$$

Where D_{max} is the maximum drainage in litres during a certain event at a certain case area and $D_{max,M}$ is the maximum drainage in litres during a certain event at a certain case area when the total area available for a certain measure is implemented.

The total decrease of drainage is defined as the decrease of the total drainage caused by the implementation of a certain measure. It is calculated and measured in the same way as the decrease of the peak of drainage:

Eq. 8

$$Total\ decrease\ of\ drainage(\%) = \frac{(D_{tot} - D_{tot,M})}{D_{tot}} * 100$$

D_{tot} is the total drainage when there are no measures implemented in litres, during a certain event at a certain case area. $D_{tot,M}$ is the total drainage in litres during a certain event at a certain case area when the total area available for a certain measure is implemented.

3.6.2 Scenario 2

Instead of analysing measures individually and irrespectively of other measures in a certain case area, combination of measures per case area are analysed in Scenario 2, using both described precipitation events. These combinations of measures are formed into a 'measure package' per case. This results in three packages of measures: a measure package for Nieuwendam, for Spuistraat and for Rijnbuurt. Packages of measures are made according to the most effective measure at a certain location based on calculation presented in section 4.1. For example, rooftops in Rijnbuurt can be used for intensive green roofs, extensive green roofs and water roofs. However, according to the definition of effectiveness in this thesis (section 2.1.8) and the calculation in section 4.1, intensive green roofs are most effective. Therefore, the package of green measures in Rijnbuurt included only intensive green roofs and no extensive green roofs or water roofs at rooftops at which the implementation of all three rooftop measures is technically possible.

For each measure-group a different approach is used in deciding which measure to include in the package of measures per case. The most effective measure within *Public (inner) gardens and parks*, based on calculations presented in section 4.1, will be implemented. According to the design criteria minimum areas of respectively 2.32 m^2, 0.6 m^2 and 8.39 m^2 are needed to implement a bioswale, an infiltration strip and a rainwater pond. The residual area can be used for public greening. The decision about the measures within the measure group *Measures at the street-level* is relatively easy. Façade gardens, open gutters and permeable pavement do not compete on location and are assumed to be able to be implemented next to each other. To decide which *Rooftop measure* can be implemented most effectively at each location, each rooftop is analysed on their technical feasibility for each measure. For example, in Spuistraat the rooftops are assumed to have a too low carrying capacity for intensive green roofs and water roofs due to the building year of the houses in this area. With GIS, GoogleEarth and additional information from the World Wide Web, the building year of each rooftop is estimated. Rooftops build after 1960-1970 are assumed to be able to have a large enough carrying capacity for water roofs and intensive green roofs. Extensive green roofs are assumed to be able to be implemented on all flat roofs irrespectively of the building year.

The measure group *Private (inner) gardens* asked for a relatively different approach. Due to lacking information, three scenarios of the current amount of paved area in private (inner) gardens have been made. Private gardens are either currently 20%, 40% or 60% paved. Furthermore, all measures within this measure group compete on location. Therefore, it is assumed that every private garden can implement one rainwater pond, two infiltration strips and the residual area will be assigned to greening. The rainwater pond and infiltration strips will have the area as presented in the design criteria. The most effective measure, based on calculations presented in section 4.1, will be implemented first. The residual area will be assigned to the second-most effective measure. The last residual area will be assigned to greening.

After the measure packages are formed, box-model calculations are done per measure package per precipitation event. Just as in Scenario 1, Equation 7, 8 and 9 are in this scenario used. This means that the only change to the box-model as described in section 3.2 is the formula for calculating P_Z, which becomes Equation 7. The total area of all measures included in a measure package is added up and used as A_m in the box-model calculations. The inflow of the precipitation from the surrounding area is calculated identically as in scenario 1. The maximum storage capacity of a certain measure package is calculated using the following formula:

Eq. 9

$$S_{max} = \frac{\sum S_{max,1} + S_{max,2} + \cdots + S_{max,i}}{i} * A_{tot}$$

By using equation 10, the storage capacity of all measures included in a certain measure package is averaged. In the box-model calculations, this has the implication that the whole measure-package is perceived as one box with in- and outflows. Among the inflows is P_z. In practice, rooftop measures and façade gardens do not have P_z, but they are still included in this measure-package. This thus leads to an overestimation of drainage of the measures without P_z that are included in the measure-package. Because of the explorative character of this study, this assumption is justified.

Eq. 10 shows that the average of the maximum storage capacity per m^2 of the measures within the measure package per case is multiplied with the total area of the case.

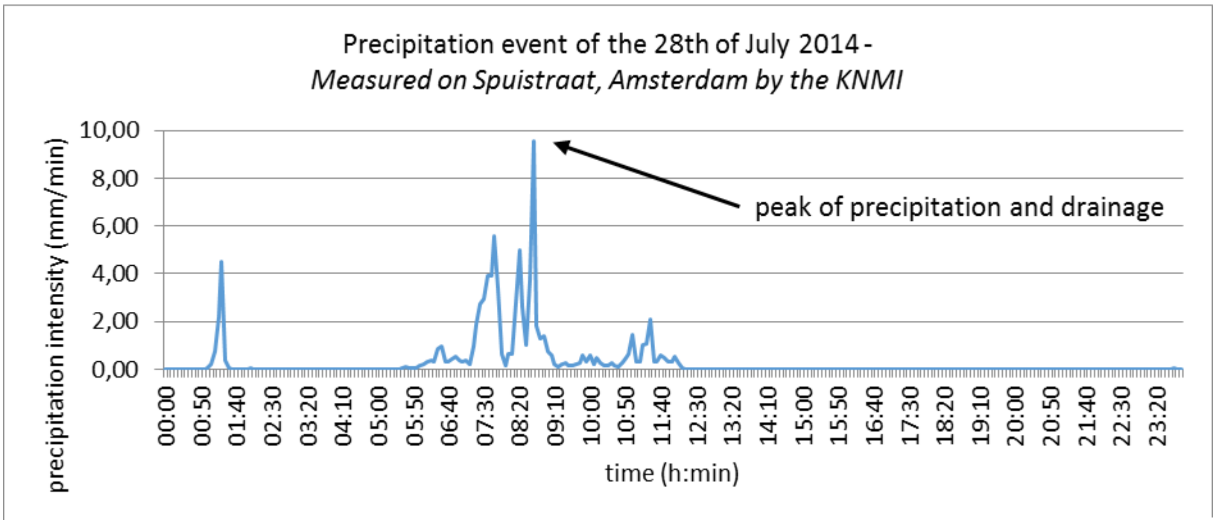

Figure 16: the peak of drainage during the July 28 2014 event, see black arrow

The delay of drainage, the decrease of the peak of drainage and the total decrease of drainage is analysed using the same methodology as in Scenario 1 (Figure 15, Eq. 7 Eq. and Eq. 8). The precipitation event of July 28 2014 shows several peaks (Figure 16). Therefore, the highest peak is chosen as a reference when analysing the decrease and delay of the peak of drainage (Figure 16).

4 Results

This chapter presents the results, starting with the results of the calculations of the water buffering capacity per measure (section 4.1). Section 4.2 presents the opportunity maps. The scenario calculations are presented in section 4.3.

4.1 Water buffering capacity per measure

The water buffering capacity is calculated per selected measure. For each measure the following specifics will be calculated for both the fictional 60 mm per hour precipitation event and the July 28 2014 precipitation event:

- S_{max}: the maximum storage capacity (in mm)
- The decrease of total drainage caused by implementation of a certain measure (in percentage)
- The decrease of the peak of drainage caused by implementation of a certain measure (in percentage)
- The delay of the peak of drainage caused by implementation of a certain measure (in percentage)

Table 2 presents the maximum storage capacity of each selected measure. These maximum storages is calculated based on the design criteria per measure as presented in section 3.3 or found in literature.

It can be observed that infiltration strips have the highest maximum storage capacity and open gutters have the lowest.

Table 2: S_{max} per measure

Measure	Smax (mm)	Source
Infiltration strip	341,27	Based on design criteria as presented in section 3.3
Bioswale	182,33	Based on design criteria as presented in section 3.3
Rainwater pond	88,41	Based on design criteria as presented in section 3.3
Intensive green roof	75,00	Kennis voor Klimaat 2014
Greening	41,27	Based on design criteria as presented in section 3.3
Permeable pavement	41,27	Based on design criteria as presented in section 3.3
Facade garden	41,27	Based on design criteria as presented in section 3.3
Extensive green roof	25,00	Kennis voor Klimaat 2014
Water roof	20,00	Based on design criteria as presented in section 3.3
Open gutters	4,71	Based on design criteria as presented in section 3.3

Figure 17, Figure 18 and Figure present the decrease and delay of total drainage and the decrease of the peak of drainage caused by implementation of a certain measure. Tables of the delay and decrease of total drainage and the decrease of the peak of drainage in absolute numbers and percentages can be found in Appendix 2. The results show great differences and similarities between the two precipitation events in the ability of a measure to delay drainage. The most important similarity is that intensive green roofs are able to prevent drainage completely, meaning that they cause a maximum delay of drainage, during both precipitation events. In addition, at both precipitation events the delay of the peak of drainage caused by open gutters is minimal. At all other observations, the delay of the peak of drainage caused by a certain measure is lower at the July 28th 2014 event than at the 60 mm per hour event. This could be caused by the total peak of precipitation to be higher at the July 28th 2014 event than at the 60 mm per hour event.

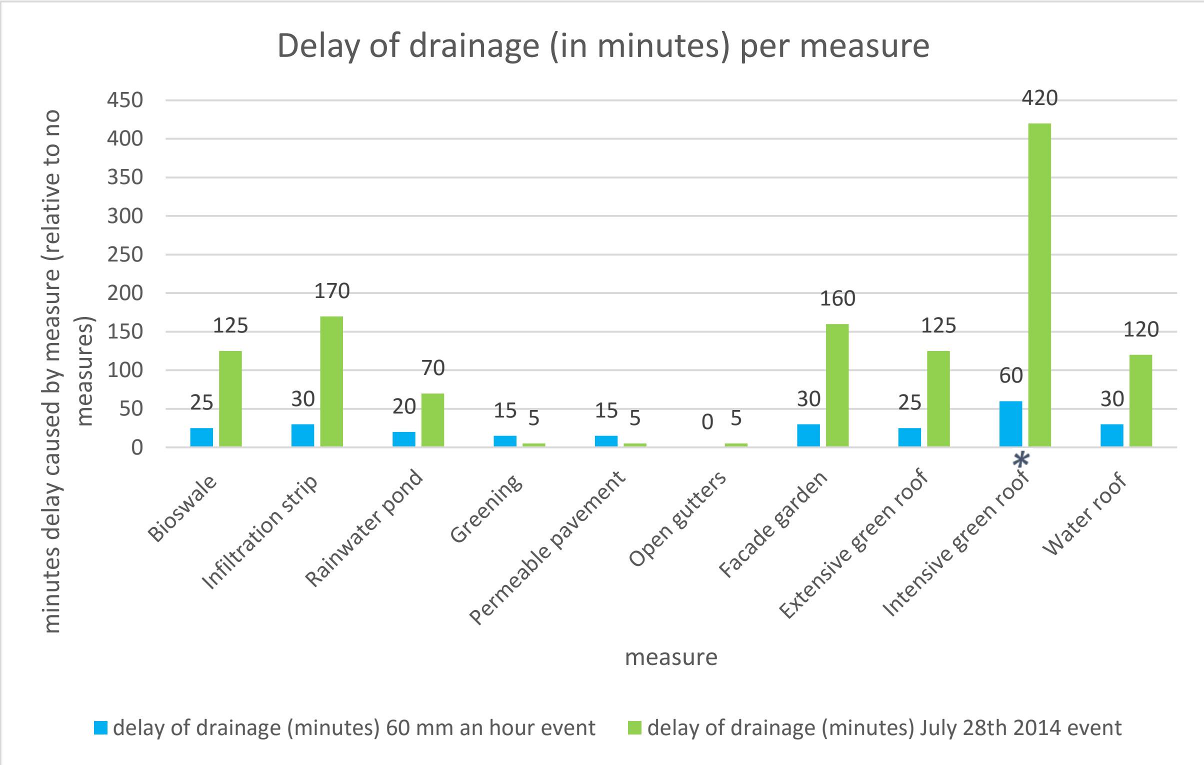

*Figure 17: delay of drainage in minutes, per measure. *Intensive green roofs are able to cause a maximum delay of respectively 60 and 420 minutes which coincide with the duration of the peak of the precipitation event.*

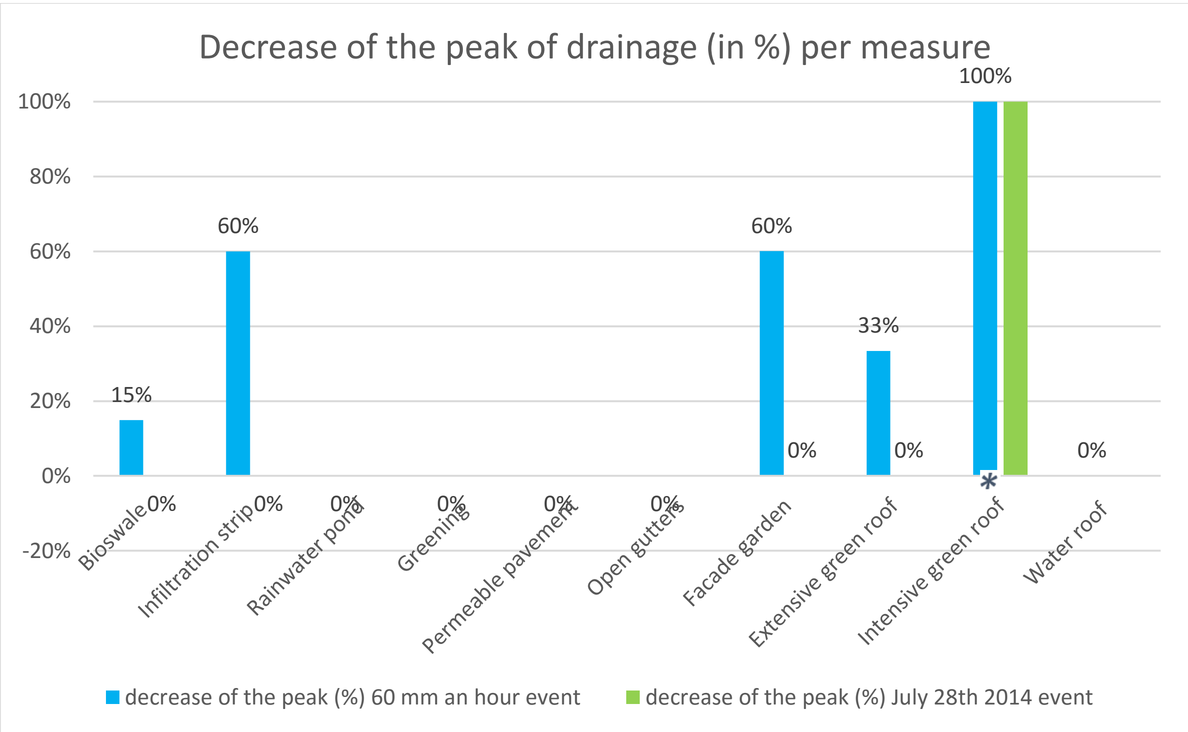

*Figure 18: Decrease of the peak of drainage in percentage, per measure. *Intensive green roofs are able to cause a maximum decrease of the peak of 100%, meaning that this measure prevents drainage completely.*

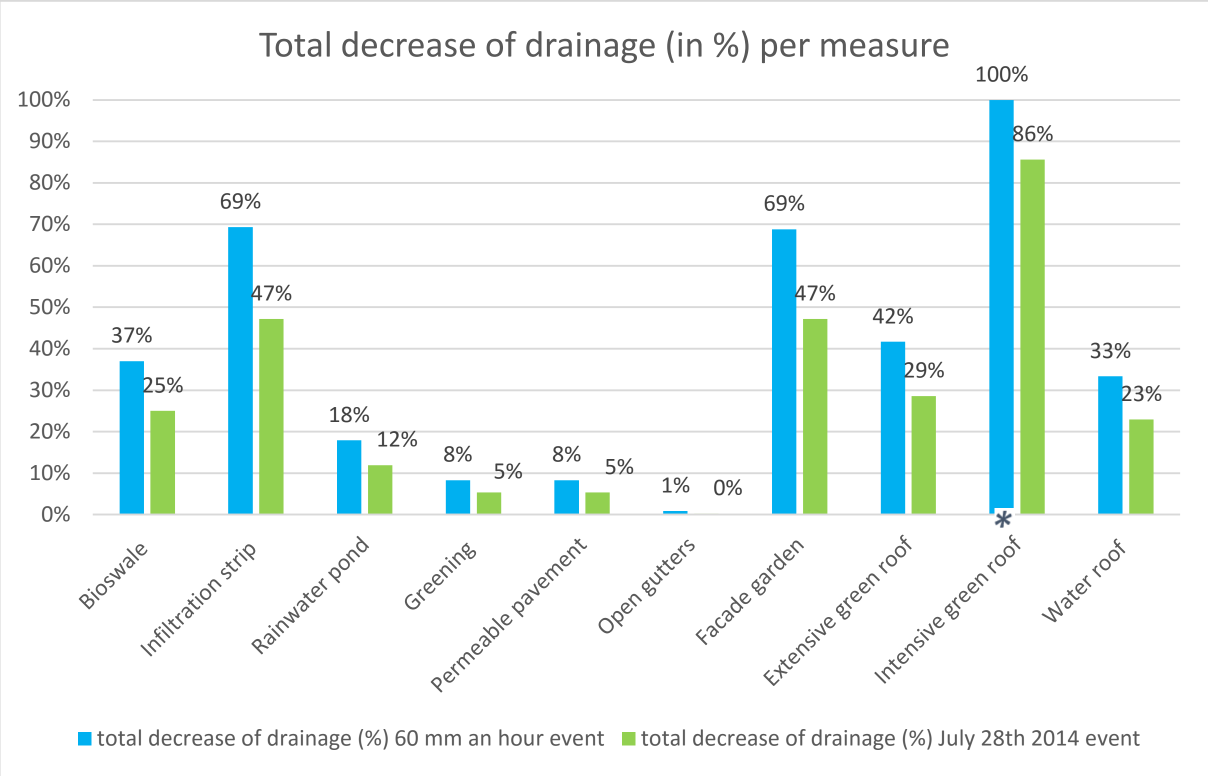

*Figure 19: total decrease of drainage in percentage, per measure. *Intensive green roofs are able to cause a maximum decrease of the peak of 100% during the 60 mm an hour event, meaning that this measure prevents drainage completely.*

The decrease of the peak of drainage caused per measure is presented in Figure 18. The results show great differences between both precipitation events. During the 28th of July 2014 event, only intensive green roofs are able to cause a decrease of the peak. It is remarkable that bioswales, infiltration strips, façade gardens and extensive green roofs are able to substantially decrease the peak of drainage during the 60 mm per hour event, while these measures are not able to cause a decrease during the July 28th event. This can be caused by the difference in timespan of both events. The peak of the July 28th of 2014 event was 420 minutes, while the peak of the 60 mm an hour event was 60 minutes. This difference in duration can result in different performances of selected measures.

The total decrease of drainage per measure is presented in Figure. Intensive green roofs and infiltration strips are able to cause the highest decrease of drainage. The total decrease of drainage for each measure is much higher than the ability of a measure to decrease the peak of drainage. This could be explained by the fact that once the S_{max} of a certain measure is reached, which is happening at a peak of precipitation and drainage, drainage will have the same height as the inflows of rainwater. Thus, once a measure cannot store any more water the amount of rainwater that falls will all collect at the street-level outside of the measure. When this is happening, a measure is not able to decrease the peak of drainage anymore. Observing the total decrease of drainage therefore is relevant to study more detailed the ability of a measure to prevent drainage. Almost all measures are able to decrease total drainage by more than 30% during the two extreme precipitation events that are studied. Open gutters and water roofs are less effective in terms of the delay and decrease of drainage.

Based on above presented comparisons between the ability of measures to decrease or delay the peak and total drainage, measures are ranked according to their effectiveness. Only the measures that compete on location are ranked. Measures that compete for public spaces are bioswales, infiltration strips, rainwater ponds and greening. According to Figure , Figure 18 and Figure, the ranking of these measures is as follows, from most to least effective:

1. Infiltration strip
2. Bioswale
3. Rainwater pond
4. Greening

Measures that compete for rooftops are: extensive green roofs, intensive green roofs and water roofs. According to Figure 17, Figure 18 and Figure, the ranking of these measures is as follows, from most to least effective:

1. Intensive green roofs
2. Extensive green roofs
3. Water roofs

Measures that compete on location in private gardens are infiltration strips, bioswales and greening. According to Figure 17, Figure 18 and Figure, the ranking of these measures is as follows, from most to least effective:

1. Infiltration strips
2. Bioswales
3. Greening

The other measures do not compete on location and do therefore not need to be ranked. However, when looking at the overall effectiveness of the selected measures it can be concluded that infiltration strips are most effective at public and private (inner) gardens and parks. Intensive green roofs are most effective at rooftops. Open gutters score lowest at every factor and are therefore perceived to be the least effective of the selected green measures. However, all measures contribute to the water buffering capacity by decreasing and delaying the peak and total amount of drainage of rainwater.

4.2 Opportunity maps

The opportunity maps serve as a visualisation of the potentials for implementation of small-scale green measures in each case study. The next page presents the opportunity maps of the three selected cases (Figure). For a more detailed map per case, see Appendix 3. The potentials per measure-group differ per case (Table 3). It can be observed that in Nieuwendam the measure-groups *Rooftop measures* and *Private (inner) gardens* have the most potential because they have a potential area that is largest in percentage terms relative to the other measure-groups. In Spuistraat, the measure-group *Rooftop measures* has the largest potential. And in Rijnbuurt, both measure-groups *Rooftop measures* and *Private (inner) gardens* have relatively the largest potential. It is noticeable that in every case, the private measures (*Rooftop measures* and *Private (inner) gardens*) have the largest potential in terms of area but not in terms of percentage.

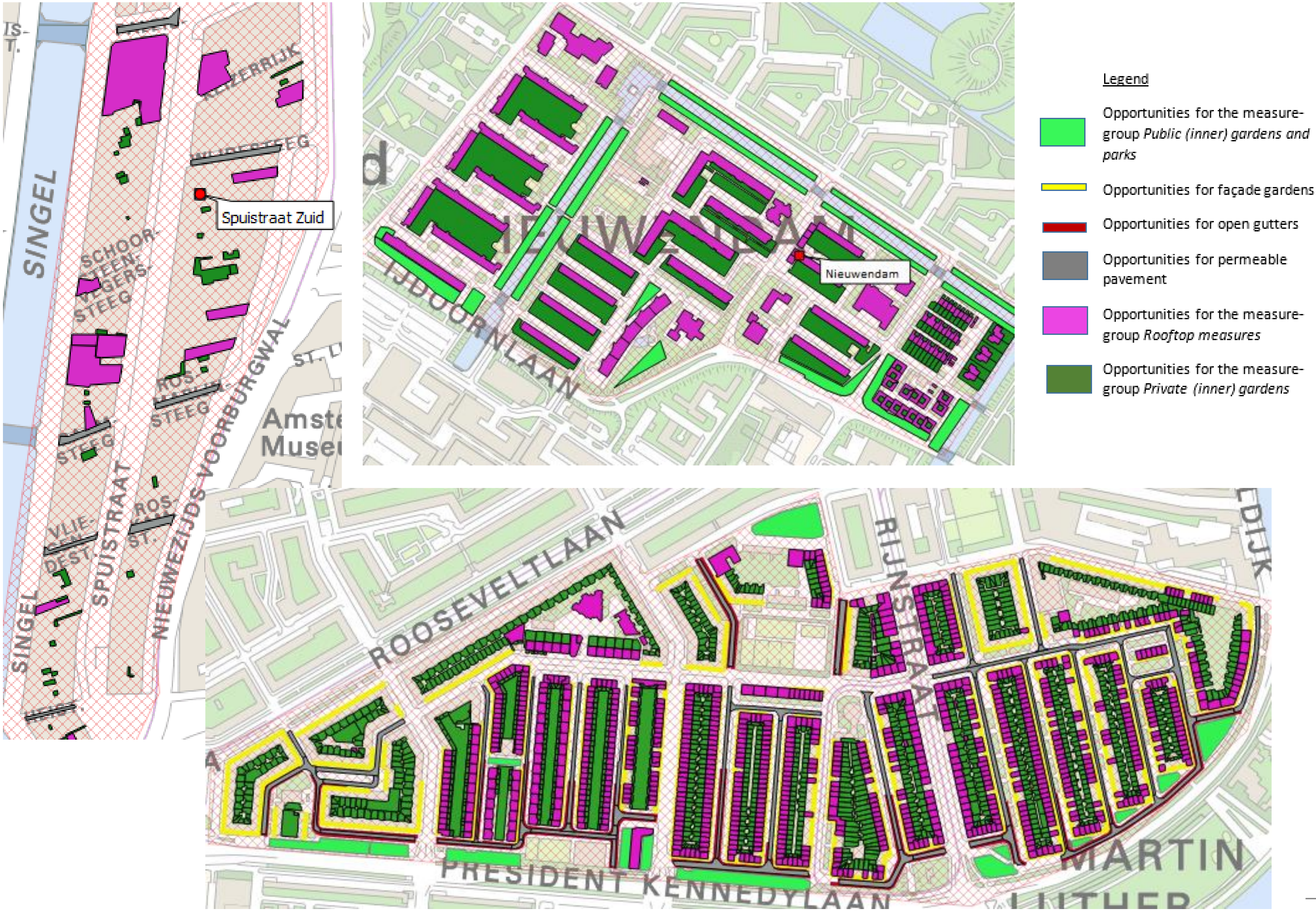

Figure 20: opportunity maps

Table 3: potentials of measures per case in terms of m²

Case	Nieuwendam		Spuistraat		Rijnbuurt	
	Area (m^2)	% of total area	Area (m^2)	% of total area	Area (m2)	% of total area
Total area	263,836	100	59,355	100	1,634,552	100
Potentials of the measures-group *public (inner)gardens and parks*	7,604	2.88	0	0	13,749	0.84
Potentials of the measures-group *measures at street-level*	0	0	726	1.22	25,800.07	1.58
Potentials of the measures-group *rooftop measures*	41,735	15.82	3,441	5.80	72,248	4.42
Potentials of the measures-group *private (inner)gardens*	40,824	15.47	708	1.19	83,029	5.08
→ in case 20% currently paved	8,164.8	3.09	141.6	0.24	16,605.8	1.02
→ in case 40% currently paved	16,329.6	6.19	283.2	0.48	33,211.6	2.03
→ in case 60% currently paved	24,494.4	9.28	424.8	0.72	49,817.4	3.05

4.3 Scenario calculations

4.3.1 Scenario 1

The total area for each measure (A_M) is calculated using the opportunity maps. For example, 7,604 m^2 is available for infiltration strips at public areas in Nieuwendam (Table 3). And 7,604 m^2 is also available for bioswales at public areas in Nieuwendam (Table 3). This means that in this example the effectivity in terms of the water buffering capacity of an area of 7,604 m^2 of both infiltration strips and bioswales in Nieuwendam will be explored. Thus, the in- and outflows of all measures are calculated using the total areas of Table 3. Table 4 presents the total area available for each measure per case area combined with the total storage in litres that each measure has with this total area, irrespectively of other measures. The precipitation event of 60 mm per hour is used as input. The S_{tot} of all measures cannot be summed per case, because this scenario perceives every measure individually irrespectively of where the potentials of other measures are located. If these potentials were summed, there would be overlap in area. Table 4 shows the measure-groups and specific measures that have the most potential to increase the water buffering capacity in each case study. The measures in the public areas with the most potential are marked green and the measures in the private areas with the most potential are marked yellow in the table. It can be observed that in all case studies infiltration strips have the most potential in increasing the water buffering capacity in public and private areas in terms of increasing the total storage. Intensive green roofs in private areas in Nieuwendam have a large potential as well.

Table 4: Maximum storage per measure during the 60 mm/h per hour precipitation event. A_M: total potential area available for a certain measure (m²), Stot: total of rainwater stored at a certain measure at the event of 60 mm per hour (litres).

Polygons/lines opportunity maps	**Measure**	**Nieuwendam**		**Spuistraat**		**Rijnbuurt**	
		A_M (m²)	S_{tot} (litres)	A_M (m²)	S_{tot} (litres)	A_M (m²)	S_{tot} (litres)
public (inner) gardens and parks	bioswale	7,604	1,386,422	0	-	13,749	2,506,827
	infiltration strip	7,604	2,595,035	0	-	13,749	4,692,154
	rainwater pond	7,604	672,269	0	-	13,749	1,215,549
	greening	0	-	0	-	13,749	567,454
facade garden	facade garden	0	-	0	-	1,233	50,888
open gutters	open gutters	0	-	0	-	851	4,010
permeable pavement	permeable pavement	0	-	726	29,963	23,716	978,817
flat roofs	extensive green roof	41,735	1,043,375	3,441	86,025	72,248	1,806,200
	intensive green roof	41,735	3,130,125	0	-	72,248	5,418,600
	water roof	41,735	834,700	0	-	72,248	1,444,960
private gardens	infiltration strip	40,824	13,932,106	708	241,620	83,029	28,335,509
	rainwater pond	40,824	3,609,249	708	62,594	83,029	7,340,593
	greening	40,824	1,684,906	708	29,221	83,029	3,426,809

Calculations of above presented areas per measure per case area in the box-model result in differences in drainage over time between measures in each case area. The ability of a measure to delay and/or decrease the total and peak of drainage is analysed. Absolute numbers of the amount of litres and minutes that measures are able to decrease and/or delay the peak can be found in Appendix 5. The following subsections will present relative percentages of the decrease and delay of the peak and total drainage caused by selected measures.

4.3.1.1 Nieuwendam

Figure 22 presents an overview of the decrease of the peak and total drainage in Nieuwendam caused by the selected measures. Intensive green roofs and infiltration strips in Nieuwendam cause the largest decrease in both the peak as the total drainage. These measures are able to prevent drainage completely by having a total decrease of the peak and total drainage of 100% (Figure 22). Infiltration strips in public areas, extensive green roofs and rainwater ponds in private areas follow with a respectively 36%, 42% and 40% decrease of total drainage. Infiltration strips in public areas area able to decrease total drainage by a larger extent than infiltration strips in private areas. This may be caused by the larger area of infiltration strips relative to private gardens than relative to public areas.

The total decrease of drainage caused by a certain measure is, just as in the water buffering calculations per measure, higher than the decrease of the peak of drainage caused by a certain measure (Figure 22). When comparing the ability of measures to delay drainage results are similar (Figure 21). Intensive green roofs and infiltration strips at private gardens are able to cause the largest delay of drainage. Remarkably is that rainwater ponds in public areas, that score relatively high at the water buffering calculations per measure (section 4.1), score relatively low in Nieuwendam. This could be caused by the relatively small area available for measures within the measure-group *Public (inner) gardens and parks* in Nieuwendam (Table 3).

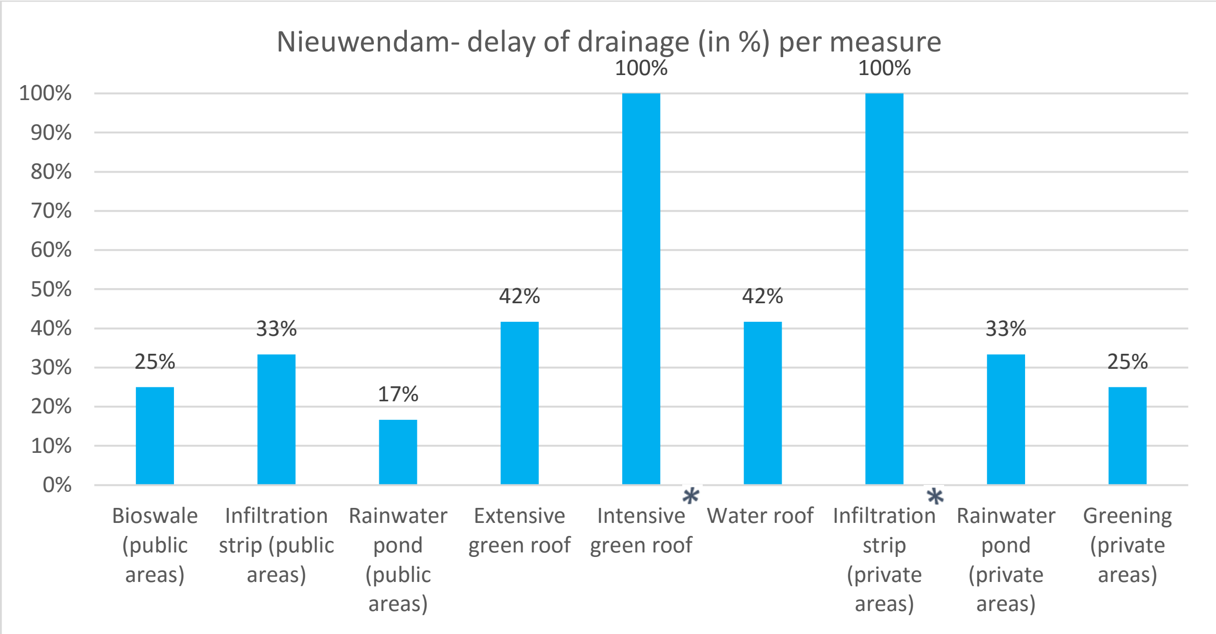

*Figure 21: decrease of the peak of total decrease of drainage in Nieuwendam, scenario 1. *Intensive green roofs and infiltration strips are able to cause a maximum decrease of the peak of 100%..*

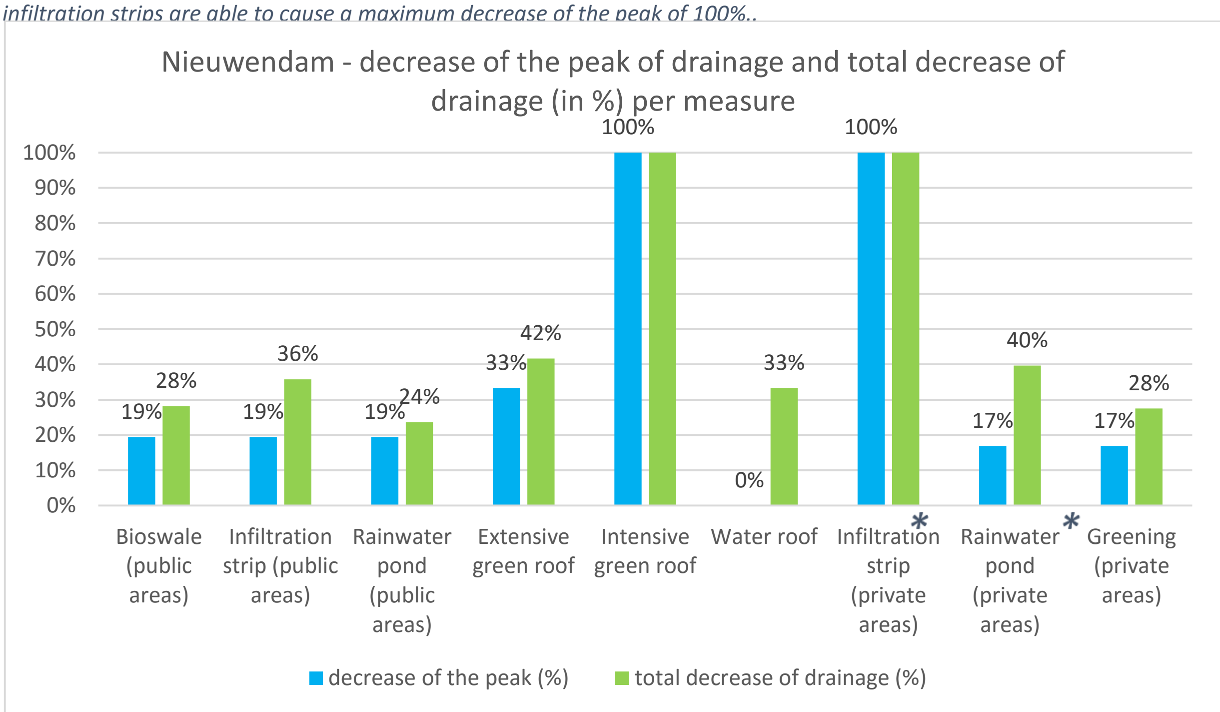

*Figure 22: the delay of drainage caused by measures in Nieuwendam, scenario 1. *Intensive green roofs and infiltration strips are able to cause a maximum delay of drainage of 60 minutes, which coincide with the duration of the peak of the precipitation event.*

4.3.1.2 Spuistraat

Figure 23 presents an overview of the decrease of the peak and total drainage in Spuistraat caused by the selected measures. Measures in Spuistraat cause a relatively low decrease of the peak and total drainage compared with Nieuwendam. Extensive green roofs are able to cause the highest decrease, however this decrease is only between 30-40% compared with a 100% decrease of infiltration strips in private gardens and intensive green roofs in Nieuwendam. The same observation holds for the ability of measures in Spuistraat to delay drainage (Figure 24). The measures permeable pavement and greening in private areas are not able to cause a delay of drainage. Extensive green roofs are able to the largest delay of drainage (25 minutes) and infiltration strips area also able to cause a substantially delay of drainage (15 minutes).

The ability to decrease the peak of drainage is almost equal for permeable pavement, infiltration strips, rainwater ponds and greening (Figure 23). When S_{max} of these measures is reached, the height of the peak of drainage between measures is equal, because all incoming precipitation flows out of the measure as drainage. The equal decrease of the peak is caused by the fact that these measures reach S_{max} within the same range of five minutes. This causes the decrease of the peak of drainage to be equal: namely the precipitation inflow at that time.

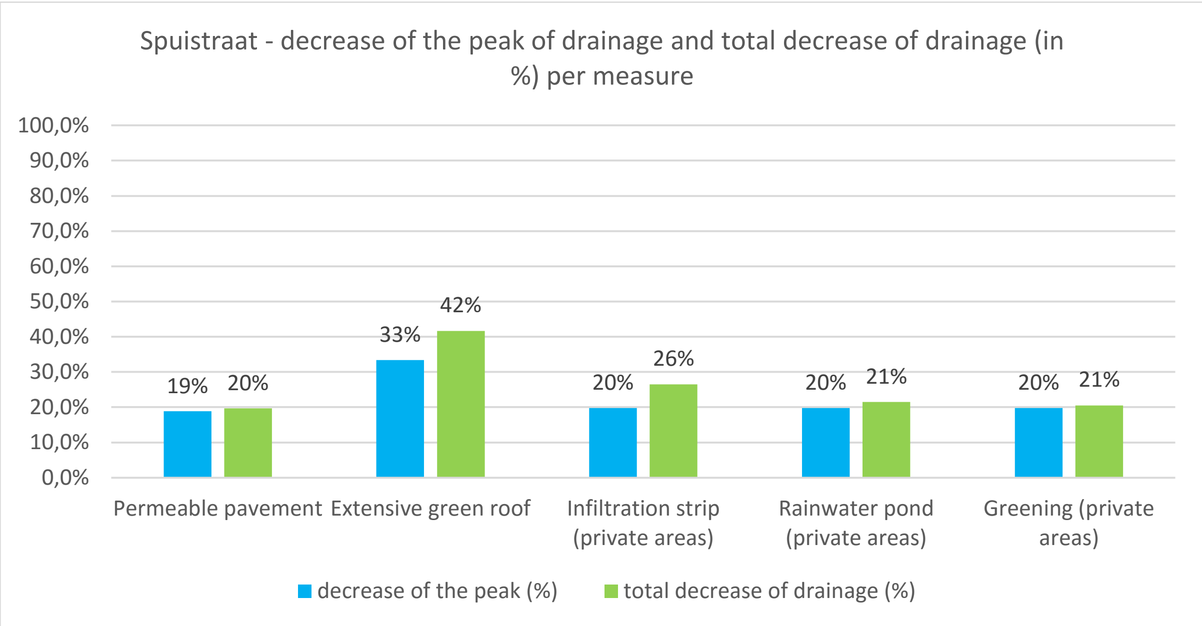

Figure 23: decrease of the peak and total decrease of drainage in Spuistraat, scenario 1

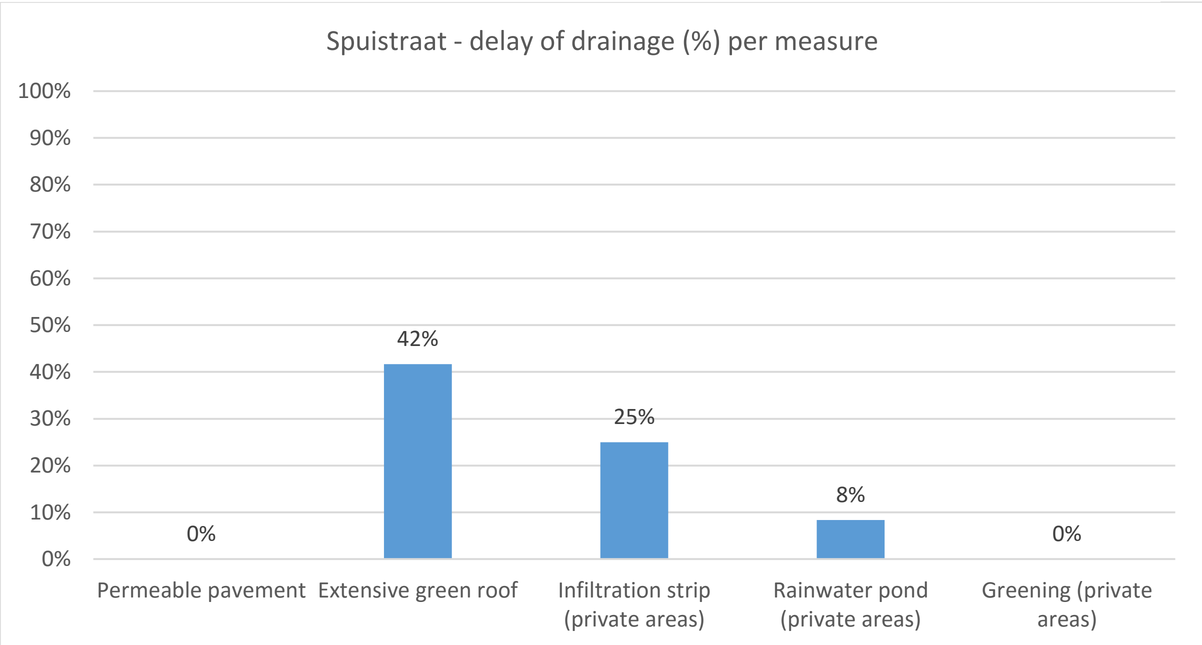

Figure 24: the delay of drainage caused by measures in Spuistraat, scenario 1.

4.3.1.3 Rijnbuurt

Figure 25 presents an overview of the decrease of the peak and total drainage in Rijnbuurt caused by the selected measures. All selected measures have a similar ability to decrease the peak and total drainage in Rijnbuurt compared with Nieuwendam. Intensive green roofs cause a 100% decrease of the peak and total drainage in Rijnbuurt. Remarkable is that façade gardens have a high potential in decreasing drainage. This could be caused by the assumptions the box-model calculations for façade gardens. Façade gardens have a concrete barrier which prevents rainwater from the surrounding area to flow into the façade garden. However, this barrier also prevents rainwater from flowing out of the façade garden until a certain extent. This means that façade gardens are the only measure that due to this barrier have little drainage and therefore are able to decrease the peak and total drainage by a great extent. In addition, extensive green roofs, water roofs and infiltration strips in private gardens have a relatively more potential in decreasing the amount of drainage. All other measures are able to decrease the amount of drainage by 20-30%.

The delay of drainage in Rijnbuurt differs between selected measures (Figure 26). Rainwater ponds, greening, permeable pavement and open gutters are not able to delay drainage by any amount. Intensive green roofs are able to cause the highest delay of drainage, followed by façade gardens.

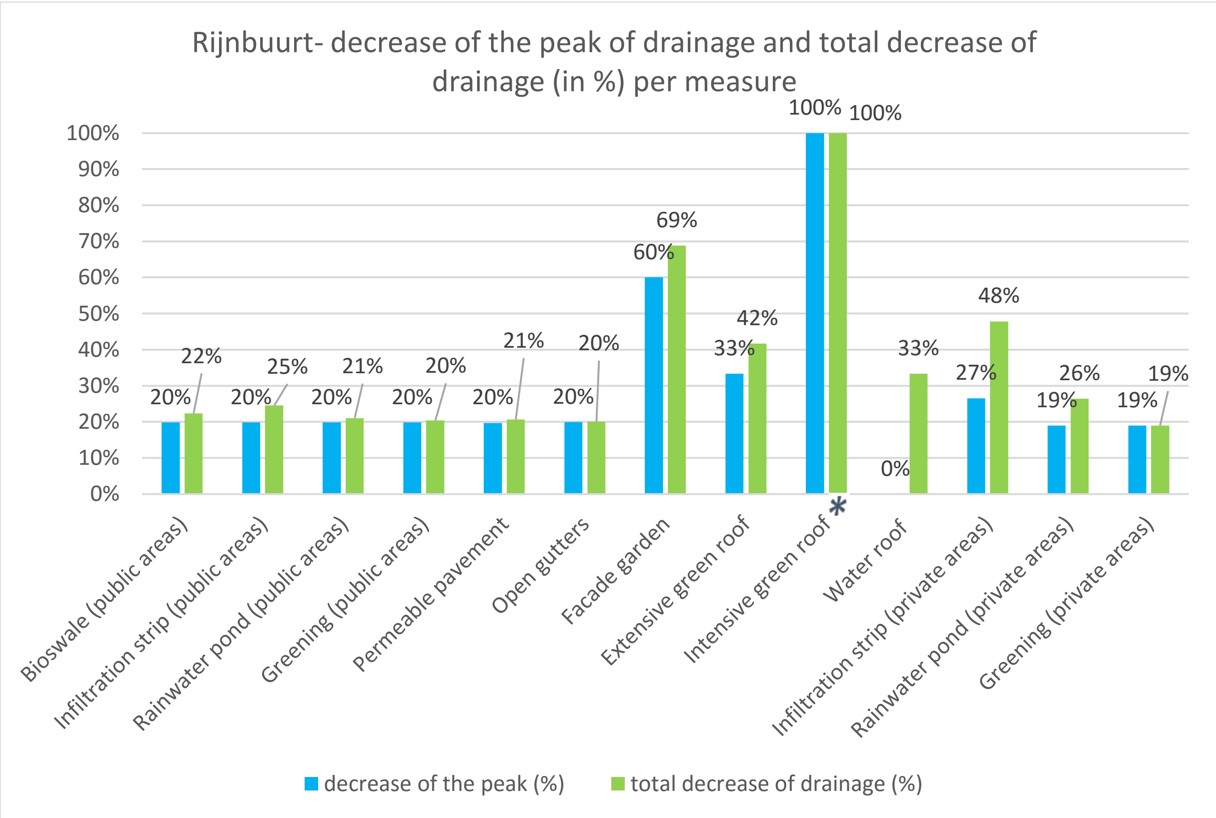

*Figure 25: decrease of the peak of drainage in Rijnbuurt, scenario 1. *Intensive green roofs are able to cause a maximum decrease of the peak of 100%.*

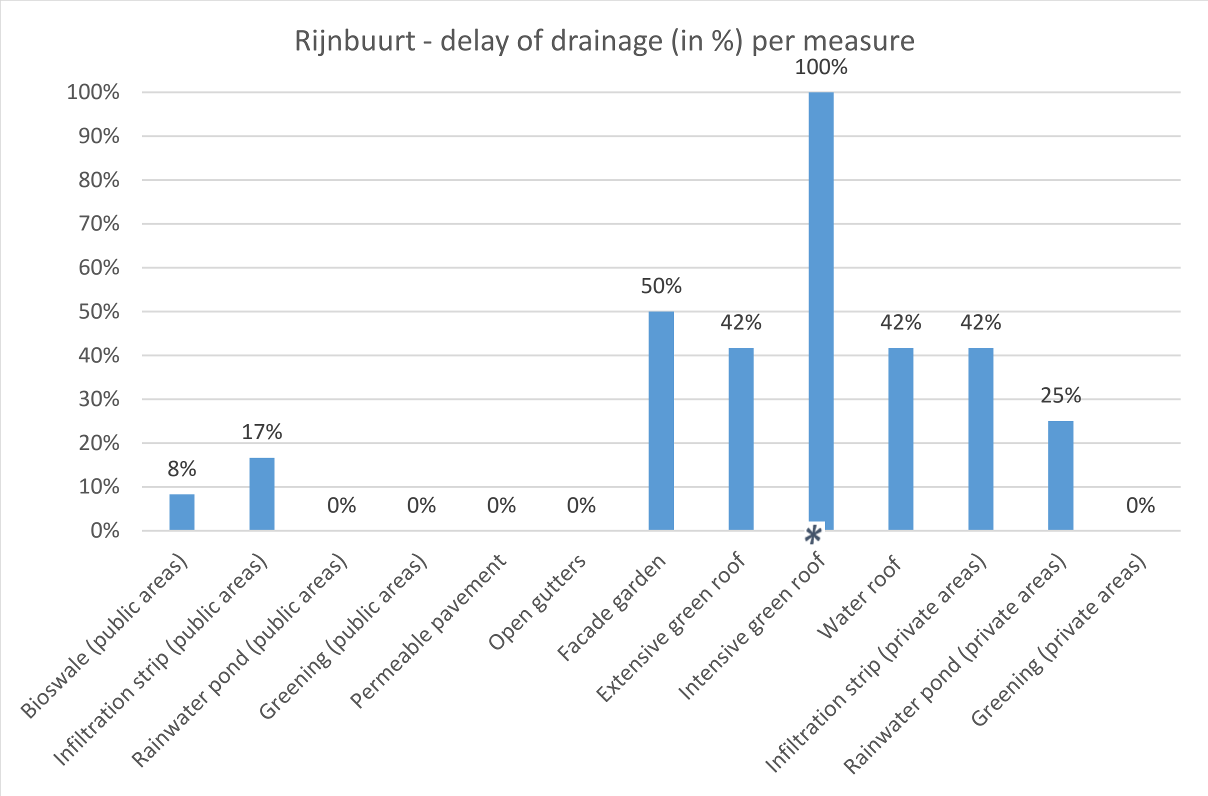

*Figure 26: the delay of drainage caused by measures in Rijnbuurt, scenario 1. *Intensive green roofs are able to cause a maximum delay of drainage of 60 minutes, which coincide with the duration of the peak of the precipitation event.*

4.3.2 Scenario 2

The measure packages per case based on the effectiveness calculations per measure (section 4.1) and the opportunity maps (section 4.2) are made according to the described methodology (section 3.6). Both precipitation events are used as inputs in the box-model calculations in this scenario. The results are presented in Table 5. As one could see from Table 5 the measure package Nieuwendam does not include greening of public areas, façade gardens, open gutters and permeable pavement. Greening is not included because it is the least effective measure in public areas and the total of public area in Nieuwendam is potentially feasible for bioswales, infiltration strips or rainwater ponds. In the measure package Spuistraat no measures of the group public (inner) gardens and parks are included, because of the unsuitability and absence of public spaces for these measures in Spuistraat. The same holds for façade gardens and open gutters. Intensive green roofs and water roofs are not applicable because of the building year of the rooftops in Spuistraat. In Rijnbuurt only intensive green roofs and water roofs are not applicable. This is also due to the building years of the rooftops in this area.

The total area and maximum storage capacity of each measure package is presented in Table 6.

Table 5: measure packages per case

		Measure package Nieuwendam	Measure package Spuistraat	Measure package Rijnbuurt
Measure-group	**Measure**	**A_M (m^2)**	**A_M (m^2)**	**A_M (m^2)**
Public (inner) gardens and parks	Bioswale	6,264	0	6,612
	Infiltration strip	20	0	1,380
	Rainwater pond	1,033	0	4,132
	Greening	0	0	1,625
Measures at the street level	Façade garden	0	0	1,233
	Open gutters	0	0	851
	Permeable pavement	0	726	23,761
Rooftop measures	Extensive green roof	38,921	3,441	72,248
	Intensive green roof	744	0	0
	Water roof	2,070	0	0
Private gardens, in case 20% is currently paved	Greening	5,793	100	10,198
	Rainwater pond	272	9	5,662
	Infiltration strip	39	17	779
Private gardens, in case 40% is currently paved	Greening	14,409	121	21,866
	Rainwater pond	385	66	10,554
	Infiltration strip	45	22	800
Private gardens, in case 60% is currently paved	Greening	23,949	305	37,136
	Rainwater pond	470	94	11,869
	Infiltration strip	47	25	817

Table 6: The total area (in m^2) and maximum storage capacity (in Litres) per measure package

Total measure packages	Nieuwendam		Spuistraat		Rijnbuurt	
	A_M (m^2)	**S_{max} (litres)**	**A_M (m^2)**	**S_{max} (litres)**	**A_M (m^2)**	**S_{max} (litres)**
Total (20% paved scenario)	55,156	6,093,027	4,293	461,263	128,481	11,499,623
Total (40% paved scenario)	63,891	7,057,973	4,376	470,181	145,062	12,983,696
Total (60% paved scenario)	73,518	8,121,459	4,591	493,282	161,664	14,469,649

Absolute numbers of the amount of litres and minutes that the above presented measure packages are able to decrease and/or delay the peak can be found in Appendix 6. The following subsections will present relative percentages of the decrease and delay of the peak and total drainage caused by each measure package.

4.3.2.1 Nieuwendam

Figure 27 and Figure 28 present the results of scenario 2 of measure package Nieuwendam. It can be observed that there is no difference between the scenarios of current pavement in the ability of the measure package to decrease the peak of drainage. This is caused by the situation that of these different paving scenario's the maximum storage capacity is reached within the same range of five minutes, meaning that these scenarios reach maximum storage capacity at approximately the same point in time. Therefore all incoming rainwater flows out at as drainage. And because the amount of inflow of all pavement-scenarios is equal, the decrease of the peak of drainage is also equal. Additionally, the differences of storage in the different paving scenarios is relatively small. This causes S_{max} to be reached within the same five minutes range.

Furthermore, it can be observed that the during the July 28 2014 event the differences in current paving have a larger influence on the ability of the measure package to decrease total drainage than during the 60 mm per hour event. This means that measures within the measure-group *Private (inner)* *gardens* are more important in reducing the total drainage during the July 28 2014 event than during the 60 mm per hour event.

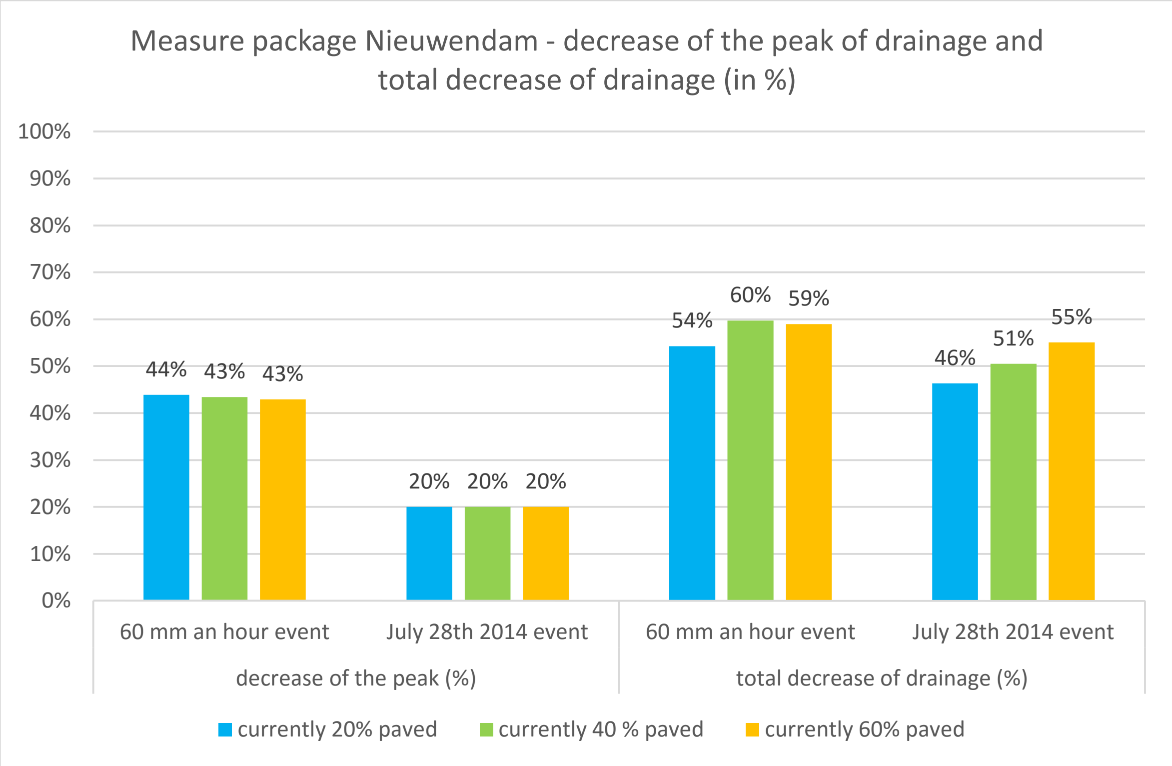

Figure 27: decrease of the peak and total drainage caused by measure package Nieuwendam, scenario 2

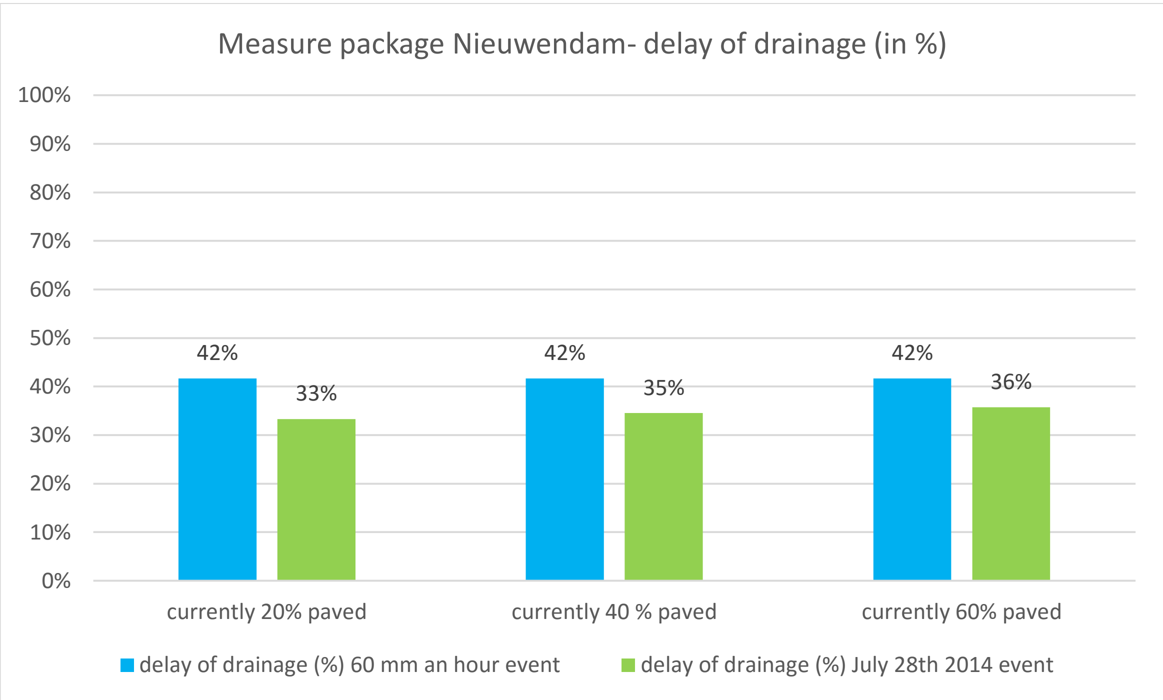

Figure 28: delay of drainage caused by measure package Nieuwendam, scenario 2

When looking at the delay of drainage the difference in the amount of gardens that are currently paved is smaller. This means that measures within the measure-group *Private (inner) gardens* are of relatively low influence in delaying drainage. During the 60 mm per hour event the measure package

Nieuwendam is able to cause a larger delay in drainage than during the July 28 2014 event. This could be explained by the difference between the two events in timespan of the event. For example, a five minutes delay is a larger share of a one-hour event, than of a seven-hour event.

4.3.2.2 Spuistraat

Figure 29 and Figure 30 present the results of scenario 2 of measure package Spuistraat. The measure-package of Spuistraat shows similar results to the measure package of Nieuwendam, concerning the ability to decrease the peak and total drainage. Again, it can be observed that there is no difference between the scenarios of current pavement in the ability of the measure package to decrease the peak of drainage. The reason for this is the same as in Nieuwendam. S_{max} of the different paving scenarios is reached within the same range of five minutes. Therefore all incoming rainwater flows out at as drainage. And because the amount of inflow of all pavement-scenarios is equal, the decrease of the peak of drainage is also equal.

One striking difference between Nieuwendam and Spuistraat is that both precipitation events coincide with 18-20% reduction of the peak of drainage caused by measure package Spuistraat, this differs from Nieuwendam. This could be explained by the type of measures that are included in measure package Spuistraat. No measure from the measure-group *Public (inner) gardens and parks* are implemented in Spuistraat, while these measures have a large area in the measure package of Nieuwendam.

Another observation is that the difference of the ability of measure package Spuistraat to decrease the total drainage between the different scenarios of current paving is much smaller than in measure package Nieuwendam. This could be explained by the fact that total area of measure within the measure group *Private (inner) gardens* relative to the total case area is smaller compared with the same ratio in Nieuwendam.

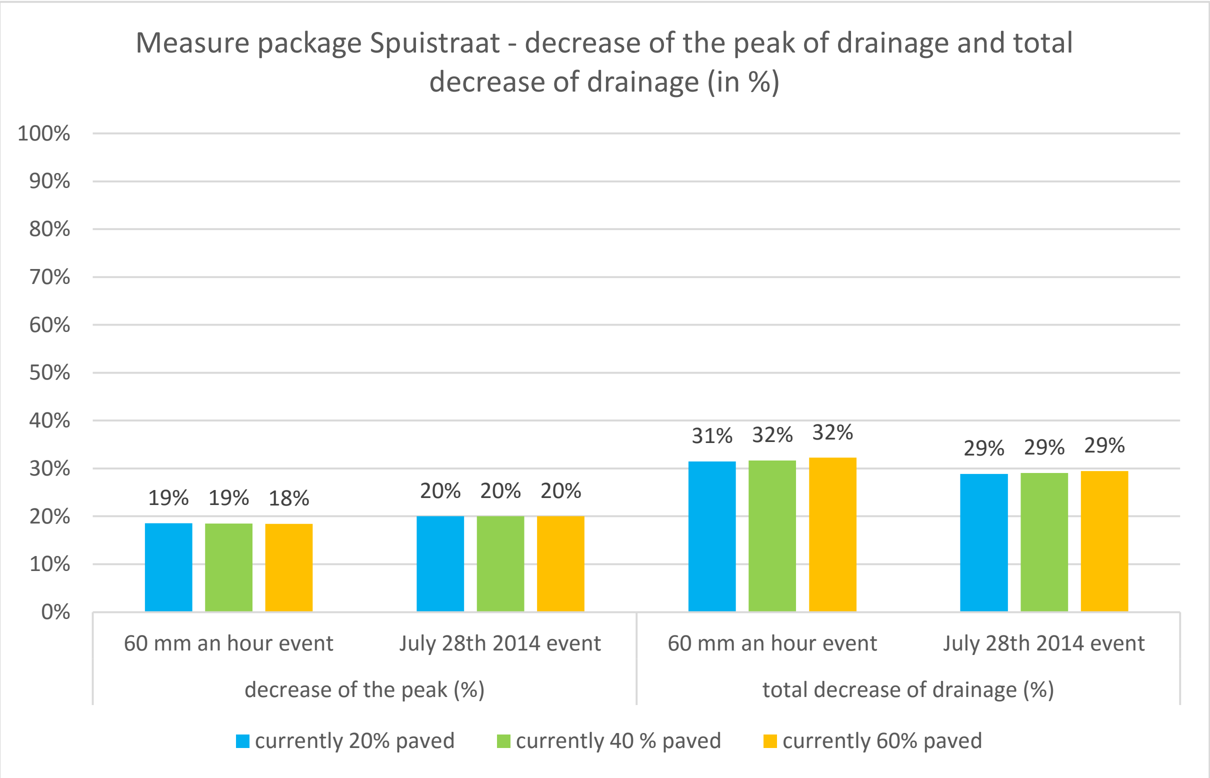

Figure 29: decrease of the peak and total drainage caused by measure package Spuistraat, scenario 2

The delay of drainage caused by measure package Spuistraat is lower than the delay caused by measure package Nieuwendam. This is due to the fact that the total area of the measure package relative to the case area is lower in Spuistraat than in Nieuwendam, resulting in a relative lower extra storage capacity. However, still measure package Spuistraat is able to delay drainage with 12-33% (Figure 29). This reflects a delay of approximately 15-20 minutes during the 60 mm per hour event and 50-55 minutes during the July 28 2014 event.

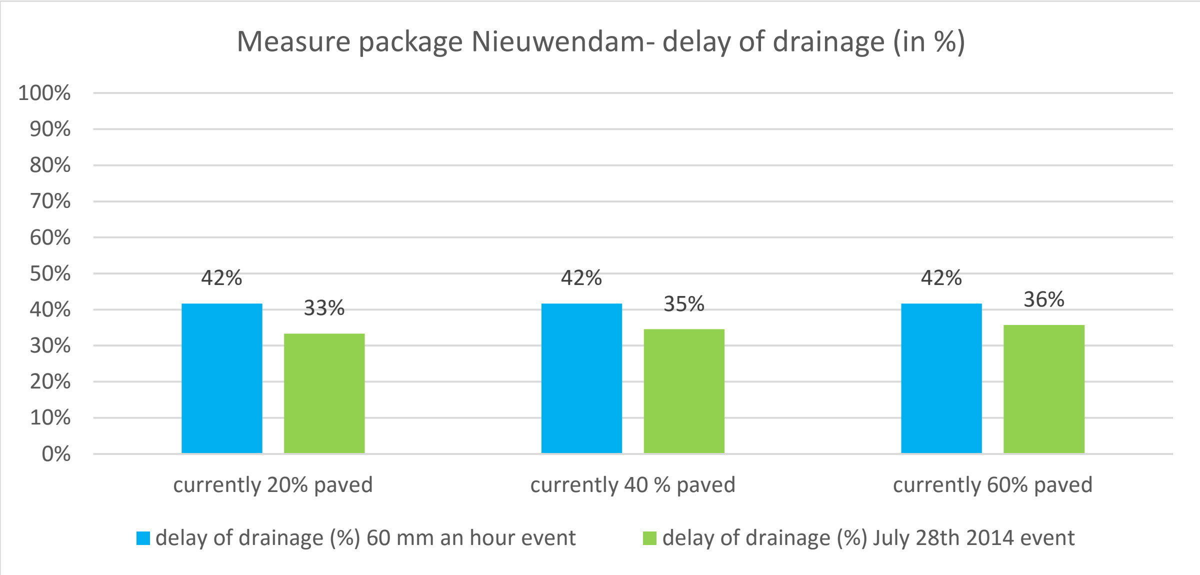

Figure 30: delay of drainage caused by measure package Spuistraat, scenario 2

4.3.2.3 Rijnbuurt

Figure 31 and Figure 32 present the results of scenario 2 of measure package Rijnbuurt. Compared with measure package Nieuwendam, the ability of measure package Rijnbuurt to decrease the peak and total drainage is relatively low. However, this decrease is relatively the same compared with measure package Spuistraat. The decrease of the peak caused by measure package Rijnbuurt is at both events and with all scenarios of current paving 18-20% (Figure 31). The ability of the measure-package to decrease the peak is again equal between the three paving scenarios. This is for the same reasons as in Nieuwendam and Spuistraat, namely because S_{max} is reached at approximately the same point in time between the paving scenarios. This results in all inflow, flowing out as drainage. And because the amount of inflow of all pavement-scenarios is equal, the decrease of the peak of drainage is also equal between the three paving scenarios.

The total decrease of drainage caused by measure package Rijnbuurt varies between 28-34%. The total decrease of drainage during the 60 mm per hour event is relatively higher than during the July 28^{th} 2014 event. The delay that measure package Rijnbuurt is able to achieve varies between 15-20 minutes for the 60 mm an hour event and between 35-60 minutes for the 28^{th} of July 2014 event.

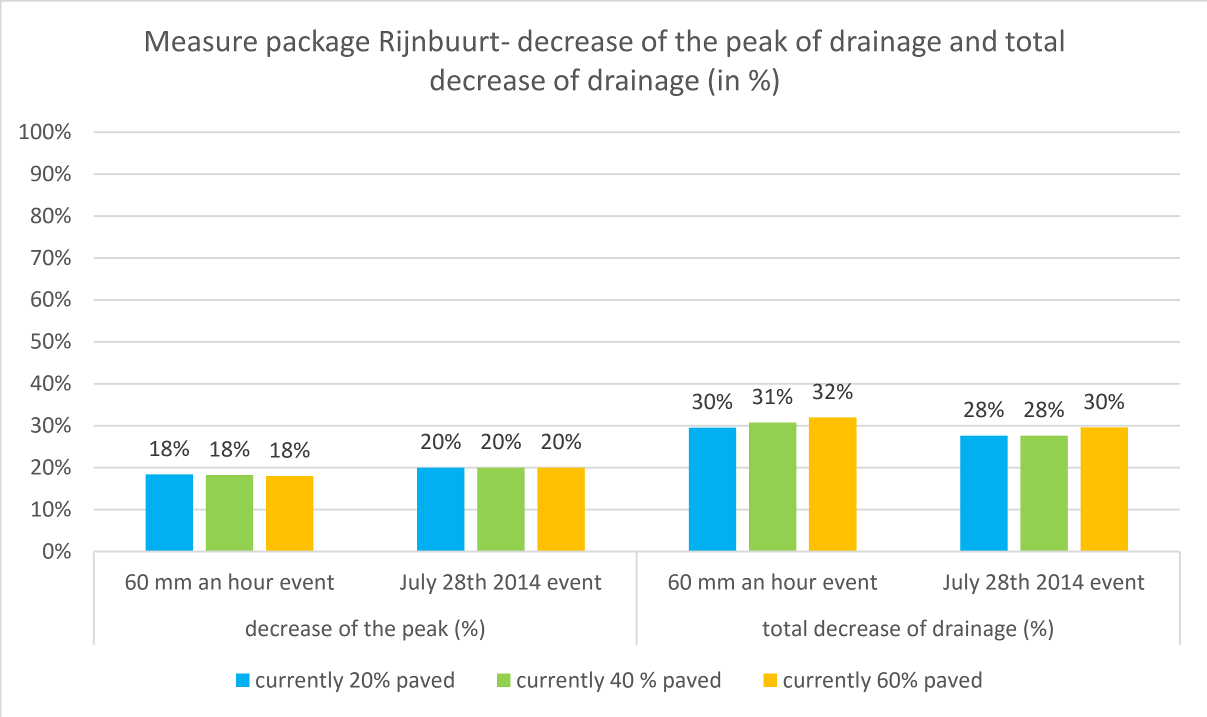

Figure 31: decrease of the peak and total drainage caused by measure package Rijnbuurt, scenario 2

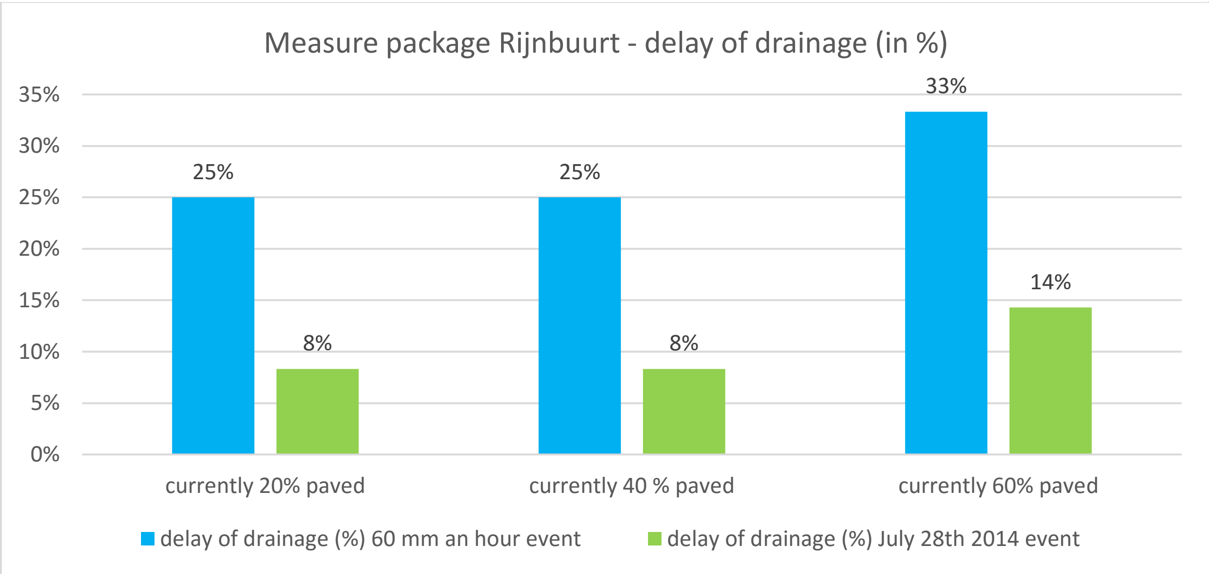

Figure 32: delay of drainage caused by measure package Rijnbuurt, scenario 2

5. Discussion

This chapter will explain the advantages and setbacks of each part of the methodology. In addition, this study will be put in a broader perspective. First, the advantages and limitations of the water buffering capacity calculations will be discussed (section 5.1). Thereafter, the methods used in ranking and describing the design criteria of the selected measures will be criticized and the possibilities and disadvantages of the opportunity maps will be presented (section 5.2). Third, the method used in the scenario calculations will be evaluated (section 5.3). Fourth, the broader issue of implementation of green measures will be explored (section 5.4). And finally, the methods in calculating the scenarios will be discussed (section 5.5).

5.1 Water buffering capacity calculations

First of all, it needs to be clear that this study should be perceived as a best-case exploration to the effectiveness of selected measures. By assuming all measures to have an initial storage of zero, the results lead to an overestimation of reality. Further research could be done in which a worst case scenario could be analysed and compared with this best-case study to explore the range in which selected measures behave in terms of water buffering capacity during cloudbursts.

The use of the general box-model was sufficient for the explorative character of this study. Since this thesis has the aim to explore the opportunities of green measures in Amsterdam to increase water buffering capacity in the city, a box-model brings enough detail to study this specific field within urban water management. Water balances are easy to use and one of the most central and simple equations present in the study of hydrological processes (Hendriks 2009). Visualizing water balances in a general box-model makes these balances and the box-model even more valuable (Vergroesen et al. 2013). However, when more detail is needed to specify the most efficient implementation of small-scale measures at a very local level, the general box-model used in this thesis may have some drawbacks. One of the assumptions made in the box-model calculations is the constant depth of the unsaturated soil (0.5 metres). This assumes a constant groundwater level of the soil. Compared with groundwater measures by Waternet (2015) this assumption seems to be an underestimation. This means that the values for $S_{max,S}$ are underestimations, meaning that the soil could have a higher storage capacity then was assumed. This limitation is however almost negligible because of the extremely high groundwater levels in Amsterdam. In addition, keeping in mind the exploratory character of this study together with the attempt to be able to carry out the first water buffering capacity calculations independent on location, this assumption is justified. The larger the difference is between the groundwater level and the surface level, the more water can be stored in the soil (Vergroesen et al. 2013). According to measures by Waternet (2015) the selected cases differ in groundwater tables, surface levels and thickness of the sandy top-layer. The Spuistraat-Zuid area has the highest surface level and highest thickness of the unsaturated zone and therefore the highest storage capacity of the soil (Waternet 2015). Nieuwendam Noordwest-Zuid has the lowest surface level and a relatively shallow unsaturated zone (Waternet 2015). In addition, the sandy top-layer of all case areas in Amsterdam is that high that the assumption made of a 100% sandy the top-layer is justified.

Nieuwendam is a somewhat different case relative to the others, because of impermeable clayish levees in the soil. Besides the difficulty caused by these levees, Nieuwendam also contains a relatively high variation in the thicknesses of the raised sandy top-soil (Waternet 2015). Considering the limited information on local soil compositions, the conclusions taken from this case may be limited at a very local scale and further research may be required.

Another variable assumed to be constant is the slope of the surface level. Because of this assumption, the model could be less accurate in screening dynamic water drainage on a very local scale. Nonetheless, in two of the three selected cases (Nieuwendam and Rijnbuurt) the slope gradient is relatively small and could thus be neglected. At areas with almost no gradient, rainwater flows over smaller distances which results in a better prediction of the amount and timing of drainage by the box-model (Vergroesen et al. 2013). At areas with a larger gradient, the slope of the surface level greatly influences the drainage of rainwater. A slope gradient causes an acceleration in discharge of rainwater (Vergroesen et al. 2013). This acceleration influences the amount and the timing of the in- and out-flows of the box-model. Due to the many gradient differences in Spuistraat the box-model may therefore be of limited significance at a very local scale. Further research is required to study the influence of the slope of the surface level on the in- and out-flows of the box-model.

Another aspect that could be included in further research is the local infiltration rates. In the water buffering capacity calculations of this study, infiltration rates were insignificant because the box-model was used independent of a certain location. Therefore, infiltration rates were assumed to be constant. Whenever similar calculations needed to be done for a specific location, infiltration rates should be taken into account. By introducing this additional aspect in future research, a more detailed calculation of the water balance on a certain location can be made. Closely related to the infiltration rate is the assumption that 20% of the precipitation fallen on the surrounding area of a measure is evaporated or flown into another direction before it reaches the measure. This percentage could differ in reality because of the influence of the infiltration rate on rainwater at the surface-level.

In addition to local infiltration rate, the evaporation rate may vary per location as well. The choice for a general value of ETA reflects the assumption of a constant microclimate per measure. According to studies done by Xiao et al (1988) the microclimate may differ at a very local scale. This is affecting evaporation rates, leaf drip and other hydrological processes in vegetation (Xiao et al. 1998). Besides, other hydrological aspects may be slightly different at each location or time. For example, the retention efficiency of green roofs is season specific. The amount of rainfall that has fallen the days before the cloudbursts influence the evapotranspiration rates of green roofs (Speak et al. 2013). Retention efficiency is also influenced by the Antecedent Dry Weather Period (ADWP). This is the inter rain event recharge potential. The lower the ADWP's, the lower the retention (Speak et al. 2013). July 2014 was a very dry period. Therefore the effect of the ADWP and amount of rainfall fallen in the days before is low. To get to a more precise calculation, the ETA value of the particular day of the precipitation event should be used in the box-model. This ETA value should be specified for each vegetation or surface type. However, the variation in ETA between different vegetation and surface types is almost negligible. Therefore, using one value of ETA was sufficient given the exploratory character of this study.

Two different precipitation events were used as inflows of the box-model. Both events were relatively extreme precipitation events; cloudbursts. It could be useful in further research to study effects of small-scale green measure during relatively lighter precipitation events. In addition, the precipitation fallen on the surrounding area of the measure was used as a second inflow in the box-model. This inflow was corrected with 20% for evaporation. This percentage was based on evaporation rates from paved surfaces. Not all surroundings may be totally paved, therefore this evaporation rate might differ per location in reality. Given the aim of this study an assumption needed to be made. It was not possible, given available time, to estimate a more precise evaporation rate at each specific surrounding area per measure per location.

5.2 Opportunity mapping

The ranking of selected green measures was very useful in making the opportunity maps. It was based on the maximum storage capacity and drainage per measure. The ranking of these measures should not be used for other purposes than making opportunity maps, because this ranking was based on subjective analyses of presented graphs per measure. For the purpose of making the opportunity maps in this study, the ranking was sufficient because it helped making a choice between location competing measures.

The opportunity maps serve as a tool to visualize possibilities of selected green measures at certain locations. In this study the areas per measure as presented in the opportunity maps were used as input for the calculations of two scenarios. Opportunity mapping is used more often in stakeholder meetings with the aim to develop certain adaptation strategies. One example of a tool that uses the method of opportunity mapping is Phoenix. Phoenix is a touch table application that is used in interactive sessions (Koekoek 2014). The Adaptation Support Tool is a similar tool (European Environment Agency 2015). To get to a practical opportunity map showing realistic possibilities at a certain location in Amsterdam as perceived by relevant stakeholders, the opportunity maps in this thesis could be used as an input in an interactive stakeholder session using a tool like Phoenix or the Adaptation Support Tool. This could be analysed in further research.

5.3 Scenario calculations

The calculations of scenario 2 served as a stepping stone for more extensive further studies to chain-effects of green measures. The total measure package is used as input for the box-model. This resulted in the need to middle the maximum storages of all measures within the measure package as a value for the total maximum storage of a certain measure package. Within the scope of this research this could have not been done differently. In addition, differences of P_Z between measures within the measure package are not calculated due to the approach of calculating a measure package as a whole. This led to an overestimation of drainage for measures that have a lower P_Z than the average of the measure package. Further studies should be done to eliminate these overestimations. This could be achieved by for example using a 3D-model that has a much higher level of detail. An example could be to use the model *3Di* in the future. This model is not completely developed yet and can therefore not be used for this purpose at the moment. Another tool that can be useful in further calculations is Raintools, which is developed by Rioned. Raintools is less complex than 3Di, easier to use and enables calculations of linkages between small-scale green measures. Further research could be done to especially calculate the measure packages of scenario 2 in a tool like Raintools.

5.4 Implementation

The scenarios are used such as that all opportunities for implementation of green measures were taken. The actual implementation of selected measures depends on other factors as well. For example, available budget, image of the neighbourhood, cooperation of different stakeholders etcetera. Although it may be more cost efficient to implement additional measures in ongoing projects, it may be worth considering the applicability of novel measures. Factors influencing the need to explore novel measures include: the increase of Amsterdam’s population size and density; the frequent expansion and building of new houses resulting in a decrease of water storage capacity and the increased rainfall predicted in future events. These aspects are without the scope of this study, but are nevertheless interesting topics for further research.

5.5 Upscaling and future prospects

Three cases have been selected as examples of three urban typologies of Amsterdam. For the purpose of upscaling this study, the city can be categorized in six urban typologies which are comparable in technical and spatial characteristics: the historical centre, the 19th/begin 20th century belt, post-war districts, residential areas along the IJ, industrial areas along the IJ and the highly urbanized business transformation zones (Amsterdam Rainproof 2015a). Spuistraat belongs to the historical centre, Rijnbuurt to the 19th/begin 20th century belt and Nieuwendam belongs to the post-war districts. This study may serve as an exploration of an approach towards the described urban typologies of Amsterdam Rainproof and can serve as a stepping stone to an upscaling process.

In addition, the field of study towards practical solutions to prevent pluvial floods is from great importance for municipalities in the Netherlands and abroad. Municipalities choose more often for implementation of small-scale green measures next to the traditional technical solutions (Stichting Rioned 2015). However, there is little research done with the same level of scale as this study. Literature is lacking when analysing different small-scale green measures at the relatively large level of scale of a neighbourhood. Most literature is written about for example experiments on a certain type of extensive green roof at a particular climate and a particular roof. This type of literature is useful but needs to be complemented with a neighbour-hood approach. In this sense, the subject of this study can be perceived as very innovative. Small-scale green measures have proven to be a robust method for storage and drainage of precipitation. Therefore, this study may be a starting point for investigating the potentials of small-scale green measures in other municipalities.

6. Conclusions

The extent to which selected small-scale green measures are able to increase the resilience of Amsterdam to the increasing frequency and intensity of cloudbursts by increasing the water buffering capacity has been studied. The results showed promising opportunities for selected measures as a strategy to prevent and/or decrease pluvial floods in parts of Amsterdam because of the extra storage that is created by these measures. Some measures or combinations of measures are able to completely prevent drainage in that particular area during the selected precipitation events and others are able to cause a delay and/or decrease of the peak and total drainage. This shows that the selected small-scale green measures could serve as a strategy to prevent or lower the risk for pluvial floods in Amsterdam.

Climate change will lead to an increase in the frequency and intensity of cloudbursts. The implementation of small scale green measures could serve as a tool to capture the increasing cloudbursts in the future. In old city centres like Spuistraat, the greatest potential of increasing the water storage capacity is on rooftops. Extensive green roofs could decrease total water on the streets up to 42%. Measures in private gardens could lead to a decrease of 26%. Another measure that is relatively effective and easy to implement in the crowded city centres is permeable pavement. In the old city centre, green measures could cause a delay of 42% during a 60 mm per hour precipitation event.

Neighbourhoods built in the 30s and 40s, outside the historic city centre with Rijnbuurt being an example, have a relatively high potential for measures within private gardens. These measures, for example infiltration strips, could decrease rainwater flow on the street-level up to 48% and a delay of water on the street up to 42% during an event with an intensity of 60 mm per hour. In addition, measures on the rooftops could contribute largely to decreasing total water on the streets as well in this type of neighbourhoods.

The newer neighbourhoods built around the 60s and 70s, for example Nieuwendam, have the largest potential for implementation of small-scale green measures to prevent pluvial floods. Most times, these neighbourhoods have large public and private green areas. These areas could be greened further or used for rainwater ponds, bioswales or infiltration strips. Depending on the local circumstances, implementation of for example infiltration strips in private and public areas could prevent water on the street completely during an extreme precipitation event.

Further research could be done to analyse the potentials of small-scale green measures in industrial areas, urbanized business areas and areas built in the 90s and 00s to get a full grasp of small-scale green measures city-wide. This may be the starting point for investigating the potentials of small-scale green measures nationally and internationally.

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Abbreviations

A	Total drainage area (m^2)
A_M	Total area of a measure (m^2)
ETA	Actual evaporation (mm/min)
ETP	Potential evaporation (mm/min)
D	Drainage or the outflow of water from the measure (litres)
D_{max}	The maximum drainage in litres during a certain event at a certain case
$D_{max,m}$	The maximum drainage in litres during a certain event at a certain case area when the total area available for a certain measure is implemented
D_{tot}	The total drainage in litres during a certain event at a certain case area
$D_{tot,m}$	The total drainage in litres during a certain event at a certain case area when the total area available for a certain measure is implemented
P	Precipitation intensity (mm/min)
P_M	Precipitation that falls on a certain measure (litres)
P_Z	Precipitation inflow from the surrounding area (litres)
S	The maximum storage in the measure and the unsaturated soil below the measure at a certain point in time at a certain event (mm)
S_1	Storage at time 1 (litres)
S_2	Storage at time 2 (litres)
S_{max}	The maximum storage in the measure and the unsaturated soil below the measure (mm)
$S_{max,M}$	The maximum storage in the measure (mm)
$S_{max,S}$	The maximum storage in the unsaturated soil below the measure (mm)
T_{Smax}	The time between the start of the first precipitation and the point when maximum storage capacity is reached (min.)
T_{Dmax}	The time between the first precipitation and the point when drainage is at its maximum (min.)
WHC	The water holding capacity (m^3/m^3)
Θ_{FC}	Field capacity (m^3/m^3)
Θ_{WP}	Wilting point (m^3/m^3)